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**Higher-order space harmonics in leaky-wave antennas and their
applications in wireless systems**

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applications in wireless systems**

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DEDICATION

To my parents and my love

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RÉSUMÉ

Ces dernières années, des recherches importantes ont été menées pour répondre à la forte demande des normes de communication sans fil de cinquième génération (5G). À cet égard, des efforts considérables sont déployés pour développer différents composants radiofréquence (RF) pour la gamme de fréquences 2 (FR2) allant de 24,25 GHz à 52,6 GHz pour la prochaine future bande passante standard des communications sans fil. En outre, en raison de la croissance rapide des réseaux et de la demande de transmission de données sans fil à plus haut débit, la bande passante devient un problème crucial pour les ingénieurs de conception de systèmes. Deux solutions potentielles pourraient être appliquées pour surmonter un tel problème en termes d'utilisation d'un fonctionnement multibande et d'une diversité de polarisation. Auparavant, le fonctionnement multibande était mis en œuvre via différentes configurations d'antenne, ce qui nécessitait l'utilisation d'ouvertures séparées. En outre, l'application de la diversité de polarisation nécessite généralement l'utilisation de transducteurs orthomodes non planaires, ce qui entraîne un encombrement du système. Par conséquent, la principale motivation de cette thèse est axée sur le développement de matériel intégré planaire à profil bas et à faible coût à la fréquence des ondes millimétriques (mmW) pour être adapté à la mise en œuvre des futures communications sans fil 5G et leurs applications connexes.

Cette thèse exploite et propose un concept très original d'harmonique spatial d'ordre supérieur (HSH) qui permet de réaliser différentes configurations d'antennes. La nouveauté présentée dans cette thèse réside dans l'étude du principe de fonctionnement du HSH qui nous fournit une ligne directrice pour la conception d'antennes à fuite (LWA) avec différentes performances basées sur la technologie de guide d'onde intégré au substrat (SIW). Un tel concept nous permet de réaliser une antenne avec les capacités d'être à faisceau unique, à faisceaux multiples, à bandes multiples, à double mode et à double polarisation en plus du fonctionnement à faisceau fixe et à faisceau de balayage à partir d'une seule ouverture qui peut satisfaire les exigences de la communication 5G et leurs applications connexes. Une procédure de conception analytique complète est présentée avec des vérifications par des simulations pleine onde et des mesures de prototypes.

Pour commencer, les comportements fondamentaux de HSH dans une structure SIW périodique sont théoriquement analysés. Les équations pour les conditions d'excitation de HSH et leur constante de propagation associée des modes fondamentaux et d'ordre supérieur dans une cellule unitaire SIW périodique sont étudiées. Outre la contribution de HSH en tant qu'onde rapide associée à la sélection du substrat, la permittivité, la périodicité, la largeur effective d'une cellule unitaire SIW et les fréquences de coupure de mode sont étudiées, analysées et démontrées. En

outre, les différences entre le fondamental et le HSH sont également étudiées et leur contribution à différentes caractéristiques d'antenne mises en évidence et leurs compromis expliqués.

De plus, la plupart des LWA périodiques fonctionnent généralement dans leurs premières fréquences de bande passante. Cependant, le fonctionnement des LWA périodiques à leurs fréquences de bande passante supérieures reste inconnu. À cet égard, nous avons étudié ici le comportement du fondamental et du HSH d'une structure périodique à leur fonctionnement en bande passante supérieure pour différentes caractéristiques d'antenne. De plus, étant donné que la plupart des systèmes de communication 5G récents doivent fonctionner dans différentes fréquences de bande de fonctionnement. À cet égard, nous introduisons une ligne directrice pour la conception de LWA avec la capacité de fonctionner en double bande et triple bande en utilisant le concept HSH avec différentes combinaisons de fréquences de bande passante où nous avons étudié différentes performances d'antenne telles le comportement constant de propagation, la plage de balayage, la bande passante, la puissance rayonnée et l'efficacité du rayonnement. De plus, les performances de compromis de différents HSH à différentes fréquences sont mises en évidence et étudiées.

De plus, les LWA périodiques souffrent généralement du problème de la bande d'arrêt lorsque leur faisceau croise l'angle large. Ici, le problème de bord de bande de différents HSH à différentes fréquences de bande d'arrêt est étudié et une solution est fournie pour surmonter le problème de correspondance qui permet à l'antenne de maintenir ses performances dans une plage acceptable pendant qu'elle fonctionne à des fréquences de bande d'arrêt.

Tirer parti des fonctionnalités HSH et les appliquer au concept de diversité de polarisation pourrait être très bénéfique en tant que facteur essentiel des applications du système sans fil 5G. Dans ce travail, le concept de HSH appliqué à une forme hybride de guide d'onde diélectrique non radiatif (NRD) et SIW de deux modes orientés orthogonaux. L'effet du couplage de mode sur les différentes caractéristiques d'antenne telles la constante de propagation, le rapport de fuite, et la variation de la plage de balayage de chaque polarisation, est étudié et analysé. Un point majeur à considérer ici est que la plupart des DP-LWA sont susceptibles de fournir un fonctionnement à faisceau fixe. Par conséquent, dans ce travail et pour la première fois, un DP-LWA multifonctionnel avec la capacité de fournir un fonctionnement simultané à faisceau fixe et à balayage est démontré. Une telle topologie est nouvelle où différentes tâches sont définies pour être assignées à chaque polarisation d'antenne à travers une ouverture commune qui peut suffisamment réduire le volume des systèmes de communication sans fil. Plusieurs prototypes de LWA sont démontrés comme preuves de concept, et les résultats expérimentaux montrent un très bon accord avec leurs homologues de simulation et d'analyse.

ABSTRACT

In recent years, significant investigations were conducted to satisfy the high demand of the fifth-generation (5G) wireless communication standards. In this regard, tremendous efforts are made to develop different radio frequency (RF) components for the frequency range 2 (FR2) as 24.25 GHz to 52.6 GHz for the next future standard bandwidth of wireless communications. Besides, due to the rapid growth of networks and demand for higher speed wireless data transmission, bandwidth becomes a crucial issue for system design engineers. Two potential solutions could be applied to overcome such an issue in terms of utilizing multi-band operation and polarization diversity. Previously, the multi-band operation was implemented through different antenna configurations, which requires using separate apertures. Besides, applying polarization diversity usually requires the use of non-planar orthomode transducers which results in bulkiness of the system. Therefore, the main motivation of this thesis is focused on the development of planar low profile and low-cost integrated hardware at millimeter-wave frequency (mmW) to be suitable for implementation on future 5G wireless communication and their related applications.

This thesis exploits and proposes a highly original concept of higher-order space harmonic (HSH) which enables us to achieve different antenna configurations. The novelty presented in this thesis lies with investigating the principle operation of HSH which provides us a guideline for designing leaky wave antennas (LWAs) with different performance based on substrate integrated waveguide (SIW) technology. Such a concept enables us to achieve an antenna with the capabilities of being single beam, multi-beam, multi-band, dual-mode and dual-polarization in addition to the fixed beam and scanning beam operation from a single aperture which can satisfy the requirements of 5G communication and their related applications. A full analytical design procedure is presented with verifications through full-wave simulations and prototypes measurement.

To begin with, the fundamental behavior of HSH in a periodic SIW structure is theoretically analyzed. Equations for the excitation conditions of HSH and their related propagation constant of both fundamental and higher order modes within a periodic SIW unit-cell is investigated and studied. Besides the contribution of HSH as fast wave associated with the substrate selection, permittivity, periodicity, effective width of an SIW unit-cell and mode cutoff frequencies is studied, analyzed and demonstrated. Furthermore, the differences between fundamental and HSH

are also investigated and their contribution to different antenna characteristic are highlighted and their trades off are explained.

Furthermore, most periodic LWAs usually operate in their first pass band frequencies. However, the operation of periodic LWAs at their higher pass band frequencies remains unknown. In this regard, here the behavior of fundamental and HSH of a periodic structure at their higher pass band operation for different antenna features are investigated. In addition, most of recent 5G communication systems are required to operate in different operating band frequencies. In this regard, we introduce a guideline for designing LWA with the capability of operating in dual-band and triple band by utilizing the HSH concept along with different combination set of pass band frequencies where different antenna performances such as the propagation constant behavior, scanning range, bandwidth, radiated power, and radiation efficiency are studied. Furthermore, the tradeoff performance of different HSH at different frequencies are highlighted and studied.

In addition, periodic LWAs usually suffer from the stop band issue when their beam crosses the broadside angle. Here the band edge issue of different HSH at different stop band frequencies is investigated and a solution is provided to overcome the matching issue which allows the antenna to keep its performance in an acceptable range while it is operating at stop band frequencies.

Taking advantage of HSH features and applying them to the concept of polarization diversity could be highly beneficial as an essential factor of 5G wireless system applications. In this work, the concept of HSH is applied to a hybrid form of nonradiative dielectric (NRD) waveguide and SIW of two orthogonal oriented modes. The effect of mode coupling to the different antenna characteristics such as propagation constant, leakage ratio, scanning range variation of each polarization are studied, and analyzed. A major point to consider here is that most of DP-LWAs are amenable of providing a fixed beam operation. Hence, in this work and for the first time a multi-functional DP-LWA with the capability of providing simultaneous fixed and scanning beam operation is demonstrated. Such a topology and design is novel because different tasks are defined to be assigned to each antenna polarization through a common aperture which can sufficiently reduce the volume and size of wireless communication systems and present an alternative solution for future broadcasting designs. Several prototypes of LWAs are demonstrated as proofs of concept, and the obtained experimental results show a very good agreement with their simulation and analysis counterparts.

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LIST OF SYMBOLS AND ABBREVIATIONS

BFN	Beam Forming Network
CST	Computer Simulation Technology
CRLH	Component Right Left Hand
CRLH-LWA	Component Right Left Hand Leaky-Wave Antenna
DGS	Defected Ground Structure
DMC-MS	dual-mode composite microstrip-line
DPA	Dual-Polarized Antenna
DP-LWA	Dual-Polarized Leaky-Wave Antenna
DOA	Direction Of Arrival
FR2	Frequency Range 2
FMCW	Frequency Modulated Continuous Wave
FWR	Fast Wave Region
HEMT	High Electron-Mobility Transistor
HSR	Higher-Order Space Harmonics
LWA	Leaky-Wave Antenna
MBA	Multi-Beam Antennas
MB-LWA	Multi-Beam Leaky-Wave Antenna
MBMBA	Multi-Band and Multi-Beam Antenna
MIMO	Multiple Input Multiple Output
MNG	Mu-Negative
MWA	Millimeter-Wave Antenna
NRD	Nonradiative Dielectric
OMT	Orthomode Transducer
PRS	Partially Reflected Surface
PSC	Polarization-Selective Coupling
RF	Radio Frequency
SIW	Substrate Integrated Waveguide
SIW-LWA	Substrate Integrated Waveguide Leaky-Wave Antenna
SOC	Smartphone System On-Chip

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CHAPTER 1 INTRODUCTION

5G Radio communication has been dramatically expanding due to the significant demand of data transferring from multi-users streaming. One of the key elements for designing 5G communication systems is a high gain narrow beam millimeter-wave antenna (MWA). Such antennas are widely used in a variety of applications such as aerospace communications [1], biomedical sensing and health monitoring [2], smartphone system on-chip (SOC) [3], autonomous car radars [4], synthetic aperture radar [5], etc. The spatial coverage of most MWA is usually limited to specific angles which brings them as a suitable choice for point to point communication system. Such a performance is amenable of supporting multiuser streaming in which the beam needs to be steer mechanically or electrically to find reliable substitute link. Hence, it may not be consider as a good fit for future requirements of 5G system communication in which the antenna beam needs to be tracking the user plan location to provide an acceptable communication link. On the contrary, multi-beam antennas (MBA) [1] achieve wider scanning ranges by generating directive beams which makes them a more suitable candidate for multi-user streaming. Such a performance of MBA is usually achieved through feeding networks such as butler matrix, Luneburg lens, R-KR and Rotman lenses which can generate only predefined beam angles and they do not hold the feature of continuous beam steering. Besides, due to the high data demand of multi-user bandwidth consumption has become a major issue for system engineering where polarization diversity and multi-band operation could potentially contribute to solve such issue. However, most of the current MBA feeding networks not only have their own complexity and bulkiness but can only operate in one frequency band. Applying polarization diversity feature to them required to use of none planar orthomode transducer which result in a bulkiness of whole system. Nevertheless, a low profile MBA with the capability to provide multi-band operation or polarization diversity along with the scanning feature can be highly attractive for future 5G communication systems.

CHAPTER 2 LITERATURE REVIEW

2.1. Leaky-Wave Antenna

Leaky wave antenna (LWA) as a family member of travelling-wave antenna has recently captivated the attention of most antenna designers due to their specific features of being a simple low profile single layer structure with wide beam steering capabilities without resorting to any feeding networks or phase shifters compared to the phased array antenna, which usually require complex and bulky feeding networks [6] and [7]. This type of antenna usually has a narrow fan beam type of radiation pattern which is widely used in various kind of applications such as microwave image processing [8], direction of arrival (DOA) of radar sensing human tracking [9], feed of high gain reflector antennas in satellite communications [10] and frequency modulated continuous wave (FMCW) radar [11], fading mitigation in multipoint communications [12]-[13].

One-dimensional LWA (1D-LWA) based on their radiation mechanism and geometry is divided into uniform [14], quasi-uniform [15]-18] and periodic [19]-[21]. The geometry of the one-dimensional uniform LWA is shown in Figure 2.1, in which a long slot allows the power to leak through a rectangular waveguide. In most of the uniform LWA the width of the slot is usually narrower compared to the height of the waveguide and it causes only a small perturbation of the fast-wave TE_{10} dominant mode with propagation constant $\beta_{10}^{TE} = \sqrt{k_0^2 - \pi^2/a^2}$. The structure of Figure. 2.1 assumed as a uniform structure since the geometry of slot does not change in the longitudinal (z axes). However, a lower sidelobe level can be achieved by tapering the slot ends. The corresponding radiation pattern of uniform LWA is restricted to the forward quadrant excluding broadside due to the positive and nonzero value of propagating phase ($\beta > 0$) for all operating frequency range.

The second type of LWA is a periodic LWA consisting of periodic modulation (in the form of periodic discontinuity) along the axis of propagation. Figure 2.2 shows an example of a periodic LWA in which the structure consists of a rectangular waveguide filled with dielectric material and has a periodic array of radiating holes in the narrow wall of the waveguide [22]. According to

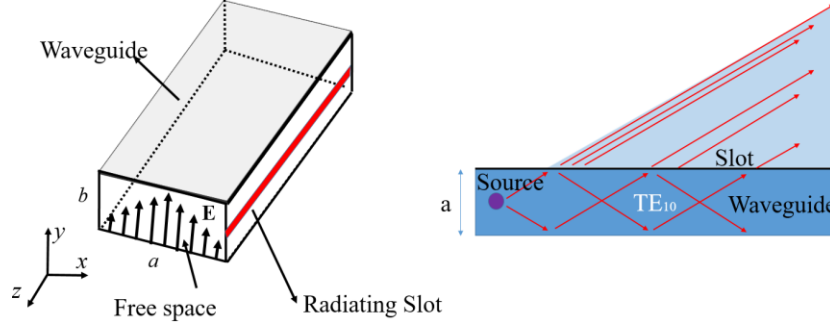


Figure 2.1 One-dimensional uniform LWA

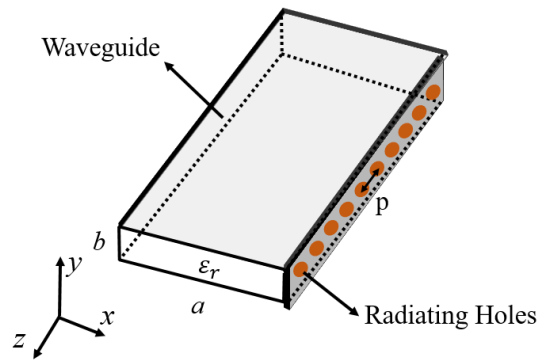


Figure 2.2 Dielectric filled rectangular waveguide with a periodic array of holes in the narrow wall of the waveguide and ground plane baffle

Bloch-Floquet theory, periodic LWA supports an infinite number of space harmonics (Floquet waves) due to their periodicity [23] where the relation between the space harmonics is represented as $\beta_n = \beta_0 + 2n\pi/p$ where p is the periodicity of unit cell and n is an integer. In most of the periodic LWAs the periodicity is usually considered to be larger than half wavelength which result $n = -1$ space harmonic as fast wave for a specific frequency range. The $n = 0$ space harmonic in most of the periodic LWA is usually slow wave (for specific frequency range) and it does not contribute to the radiation of the antenna. Compared to the uniform LWA, the scanning range of periodic LWA is not limited to the forward quadrant and they scan in backward quadrant due to the negative value of propagation constant of $n = -1$ space harmonic ($\beta_{-1} < 0$, for specific frequency range). One of main drawback of periodic LWAs related to the broadside radiation. In most of the periodic LWAs the matching will be degrading since their scanning beam reaches through broadside. Usually, at this point, all the radiating element are excited in phase and most of the power backed

to source which deteriorated antenna performances at the related frequency. This frequency range usually refers as open stop band [24]-[25]. This effect will be investigated in the next section.

Another type of LWA is quasi-uniform LWA. The topology of this antenna is similar to the periodic LWA. However, they are electromagnetically similar to the uniform LWA. Usually in most of the quasi-uniform LWA, the periodicity is considered to be very small compared to the guided wavelength of travelling wave ($p \ll \lambda_g$) [26] in which the radiation mechanism is not related to the $n = -1$ space harmonic anymore and it is related to the fundamental space harmonic ($n = 0$). The radiation mechanism of this antenna is usually limited to the forward quadrant and it is similar to the uniform LWA.

2.2. Field Behavior of LWA

In a uniform LWA, the guided mode represents itself as fast wave ($0 < \beta < k_0$) and having complex number $k_z = \beta - j\alpha$. In periodic LWA, the guided mode consists of an infinite number of space harmonics with the wave number of $k_z = \beta_n - j\alpha$ where the relation between space harmonics represents as $\beta_n = \beta_0 + 2n\pi/p$. In most of the periodic LWA, the $n = -1$ space harmonics is usually the one that causes radiation through specific frequencies ($|\beta_{-1}/k_0| < 1$). In periodic LWA, when the phase and group velocity of radiating space harmonic are in the opposite direction of each other we have a backward wave ($\beta_{-1} < 0$) and a forward wave ($\beta_{-1} > 0$) is achieved when the group and phase velocity are in the same direction. If we model the LWA of Figure. 2.1 as a magnetic line source, then the radial wave number (vertical wavenumber) is given by $k_p = (k_0^2 - k_z^2)^{1/2}$. Therefore, due to the complex value of k_z there are two possible solutions for the value of k_p :

$$k_p^2 = k_0^2 - k_z^2 \quad (2.1)$$

$$(\beta_p - j\alpha_p)^2 = k_0^2 - (\beta_z - j\alpha_z)^2$$

$$\beta_p^2 - \alpha_p^2 - j2\beta_p\alpha_p = k_0^2 - \beta_z^2 + \alpha_z^2 + j2\alpha_z\beta_z$$

Now if we take the imaginary part, then we have $\beta_p\alpha_p = -\beta_z\alpha_z$. If the $\text{Im}(k_p) > 0$ and $\text{Re}(k_p) > 0$ then the field will exponentially increase in the radial direction and the power radially outward so we have an improper field. For the proper field the $\text{Im}(k_p) < 0$ and the field will be exponentially decaying in the radial direction and the power is radially inward. The condition of proper and

improper wave is more used in periodic LWA compared to the uniform LWA since the antenna can scan in backward or forward due to the value of the propagating space harmonic (β_{-1}).

2.3. Elimination of Open Stop Band in LWA

Several methods and techniques can be used for eliminating the open stop band of LWA. With the emergence of metamaterials, a new kind of LWA as component right left hand (CRLH) LWA has been proposed which has the capability of suppressing the open stop band issue. This antenna is fundamentally different compared to the conventional periodic LWAs since it radiates through the fundamental harmonic ($n = 0$). In fact, it maybe considered as a quasi-uniform LWA even though it is structurally periodic. In most of the CRLH-LWA the open stop band elimination is achieved through utilizing a specific transmission line, which is known as balanced transmission line. In the balanced condition, the antenna has acceptable performance when its beam reaches through the broadside. This kind of LWAs is not very suitable for millimeter-wave frequency due to the condition of $p \ll \lambda_g$ which causes many limitations for the prototype of antenna especially for THz frequency bands.

Another technique that used to suppress the open stop band is a quarter-wave transformer or alternatively a matching stub inside a unit cell of a LWA, which force the Bloch impedance to be real in broadside frequency. However, this method has a limitation in term of bandwidth due to the frequency of its transformer. In order to solve the size problem, we can use a matching stub and a delay line near the radiating stub instead of impedance transformer [27]. However, the scanning range in [27] is not wide and the antenna has narrow scanning. Therefore, this method is not a suitable candidate for wideband applications.

In [28], more general studies of open stop band were reported with respect to the transverse asymmetry, longitudinal asymmetry and double asymmetry of a unit cell. In [29] a unit cell with respect to the transverse axis leveraged is used for suppressing the open stopband. However, this methodology involved a lot of complexity requiring an equivalent circuit composed of a series resonator, a shunt resonator, and the transformation ratio. In this methodology, not only we need to balance the series and shunt radiating elements for frequency balancing but also we have to adjust the degree of asymmetry for quality factor balancing. The design parameters of this method required the periodicity of $p \ll \lambda_g$, which may not be a good candidate for millimeter-wave frequencis due to the of fabrication tolerance limitations.

In [30]-[31] another method to suppress the open stop band were presented in which a periodic LWA is realized by periodically loading shunt radiating element in a microstrip transmission line. Each of these shunt elements have capacitive and inductive behavior. Therefore, we can have a pure real input impedance in which the susceptance of shunt radiating element cancel each other, Therefore, at open stop frequency band, we have real input impedance and the open stop band is eliminated. This technique is more useful with microstrip line technology. For millimeter-wave frequencies, it is difficult to implant this method to the unit cell of periodic LWA. In addition, this methodology suffer from a very low radiation efficiency.

Jackson [32] introduced a pair of identical radiating element in which the distance between the pair element are set to be a quarter of the period of each unit cell to eliminate the open stop band. This technique has the advantage in terms of simplicity and can be easily applied to various periodic LWAs especially for low cost substrate integrated waveguide (SIW) LWAs. This method was further developed in [33] in which two similar but not identical pair radiating elements of a unit cell used to eliminate the open stop band. This technique has advantages in terms of wide bandwidth, high radiation efficiency and it can be easily applied to the conventional low loss waveguide at millimeter-wave frequencies compared to the previous methods. In the next chapter of this thesis, we aims to tackle the current limitations of 1D-periodic LWAs.

CHAPTER 3 APPROACH OF THE WHOLE RESEARCH

3.1. Objectives

The main objective of this thesis is to overcome the current limitations of periodic LWAs, such as those mentioned in the previous sections. Here we want to overcome such issues by presenting the novel utilization of higher-order space harmonics (HSH). Such a concept will give us the flexibility of targeting the limitation of periodic LWAs from different perspectives. Here, we tackle the main common disadvantages of LWAs in which they only can produce one beam within their operating frequency band. We propose a methodology to design and analyze periodic LWA as MBA to be able to control the number and position of different radiated beams. Moreover, we investigate the limitation of LWAs in terms of single band operation and we demonstrate a methodology for designing LWAs as single beam multi-band or multi-beam multi-band antennas. Furthermore, the limitation of HSH at different pass band and stop band frequencies is studied, analyzed and a solution is demonstrated to solve the mismatch issue of HSH at different stop band frequencies. Besides, most of LWAs usually are limited to operate with single polarization. Hence, this thesis aims to demonstrate a dual-polarized LWA (DP-LWA). In addition, most of LWAs usually steer the beam within their operation frequency. Such a feature may not be desirable for point-to-point communication systems. Here, our objective is to overcome such a limitation by demonstrating a LWA with fixed beam capability. Besides, a combination of fixed beam operation and beam steering (through different frequencies) along with polarization diversity can sufficiently reduce the volume and size of wireless communication systems and present an alternative solution for future broadcasting designs. In this regard, as a final objective, we demonstrated a novel LWA with the capability of supporting the polarization diversity feature along with beam steering and fixed capability through a planar geometry that can enhance the integrity feature of it.

3.2. Thesis Organization

This thesis focuses on proposing the concept of applying and implementing HSH to the periodic LWAs, which aims to overcome the current limitation of periodic LWAs where different

methodologies and solutions are theoretically studied, analyzed and examined through different fabricated antenna. The thesis is organized as follows:

Chapter 4 presents the fundamental behavior of HSH as fast waves for different modes of an SIW structure where we were analyzed the effect of permittivity, periodicity, and parametric effect of unit-cell geometrical structures to the excitation condition of different HSH. In addition, the behavior and response of HSH is also compared to the fundamental ones so that their effect on the different antenna characteristics are highlighted, and their tradeoff are studied and explained.

Chapter 5 investigates the limitations of periodic LWAs in terms of single beam and single band operation. Here we demonstrate a methodology of designing periodic LWA as MBAs by utilizing the HSH concept. The behavior of HSH for different passband frequencies are studied and analyzed where we investigate the flexibility of applying HSH for different combination set of different pass band frequencies. Besides, the effect of unit-cell geometrical structures on the propagation constant, scanning range variation, radiation efficiency, and radiated power response for different frequency bands are studied, and analyzed. Such an evaluation of HSH gives us the flexibility of proposing different LWAs with distinguished features of dual-band single beam, dual-band multi-beam, triple band multi-beam operation. Such a concept is examined by showing a prototype of a periodic LWA.

Chapter 6 tackles the mismatching issues of periodic LWAs for the case of HSH operation. We investigate the behavior of propagation constant response of different stopband frequencies related to the different HSHs. A solution is proposed here in which it has the flexibility to be applied and implemented on different band edges of a periodic LWA in order to overcome the reflected power back issue. In addition, the phase distribution of the radiating element is also analyzed, which gives us the flexibility of forcing the antenna to have single beam or multi-beam operation through its stop band frequencies which is validated by a periodic LWA prototype.

Chapter 7 presents a novel approach for the design of periodic LWAs in which we tackle several LWA's limitations by demonstrating a multi-functional LWA. Several methodologies are applied and implemented to the presented LWA. First, we investigate the limitation of applying the polarization diversity through a dual-mode operation for a periodic SIW-LWA where different characteristics of LWA such as propagation constant, leakage ratio, and beam steering features for different HSHs are investigated. It is shown that the HSH enable us to achieve a DP-LWA with the capability of wide beam steering and wide bandwidth features through a single antenna aperture

in which we can get the benefit of having single or multi-beam operation for each antenna polarization. In addition, we also tackle the limitation of LWA for point-to-point communication by presenting a DP-LWA with the capability of generating fixed beam operation through a single aperture by utilizing the HSH concept. It should be mentioned that a combination of continuous beam steering feature and fixed beam operation in addition to the multi-beam features can sufficiently reduce the volume and size of wireless communication systems. Here for the first time, we demonstrate a multi-functional LWA with the capability of simultaneous fixed and scanning beams operation which can be considered as an alternative solution for future broadcasting designs. Experimental results show a good agreement between the simulation, analysis, and measurements.

Chapter 8 presents the general discussion and investigates how the HSH benefits the LWAs.

Chapter 9 provides a summary of the thesis as well as conclusions and remarks the novel approaches presented. It also provides guidance and tracks to be followed in the future based on the new ideas introduced in this dissertation.

CHAPTER 4 ARTICLE 1: HIGHER-ORDER SPACE HARMONICS IN SUBSTRATE INTEGRATED WAVEGUIDE LEAKY-WAVE ANTENNAS

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Most of the periodic LWAs usually operate within their fundamental space harmonic ($n = -1$). However, the behavior and response of periodic LWAs for their HSH is not investigated and their responses and effect on the antenna performances remains unknown. In this regard, this chapter demonstrates a novel concept, and fundamental behavior analysis of HSH as fast wave for an SIW structure. Such a concept will give us the flexibility of targeting the limitation of periodic LWAs from different perspectives which are highlighted in different chapters of this thesis. In this chapter, we specifically studied the effect of permittivity, periodicity and parametric effect of unit-cell geometrical structures to the excitation condition of different HSH. In addition, the behavior and response of HSH are also compared to the fundamental ones where their effect to the different antenna characteristics are highlighted, and their tradeoff are studied and explained.

4.1. Operation and Topology of One-Dimensional Periodic LWA (1D-Periodic LWA)

A 1D-periodic LWA is a structure that consists of periodic modulation, in the form of a periodic discontinuity, for one of its geometric features (slot, section, metallization, etc.) along the axis of propagation. According to the Bloch-Floquet theory, this type of structure supports an infinite number of space harmonics due to their periodicity in which the relation between space harmonics is represented as $\beta_n(\omega) = \beta_0(\omega) + 2n\pi/p$, where p is the periodicity and n is an integer. The wave number of this structure is represented as $k_{zn} = k_0 + 2n\pi/p$, in which the fundamental ($n = 0$) wave is given by $k_0 = \beta - j\alpha$. In most of 1D-periodic LWAs, the periodicity is usually set to be bigger than a half wavelength in order to generate the $n = -1$ space harmonic as a physical fast wave ($|\beta_{-1}/k_0| \leq 1$). Usually in this type of structure, the fundamental ($n = 0$) Floquet mode is a slow wave ($k_{z0} > k_0$), and it does not contribute to radiation. One of the tools that has been used in the analysis of LWAs is the Brillouin diagram which is a graphical representation of the dispersion relation of space harmonic axial phase constants [34]. Figure. 4.1 shows the schematic of a Brillouin diagram.

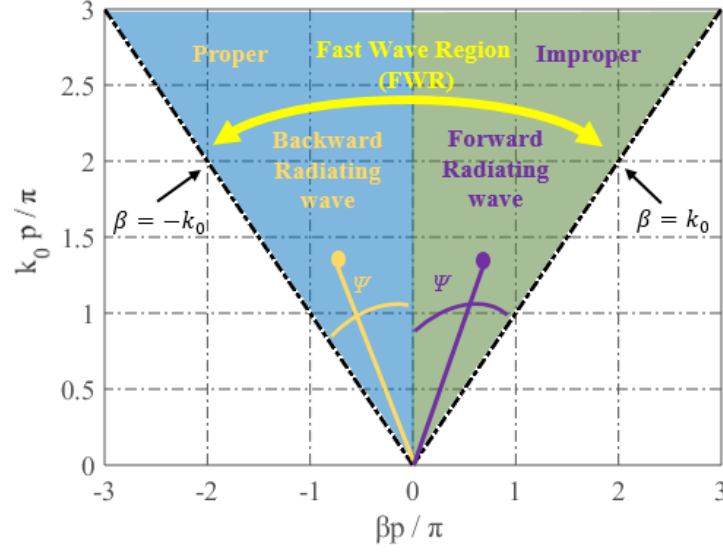


Figure 4.1 Schematic view of Brillouin diagram

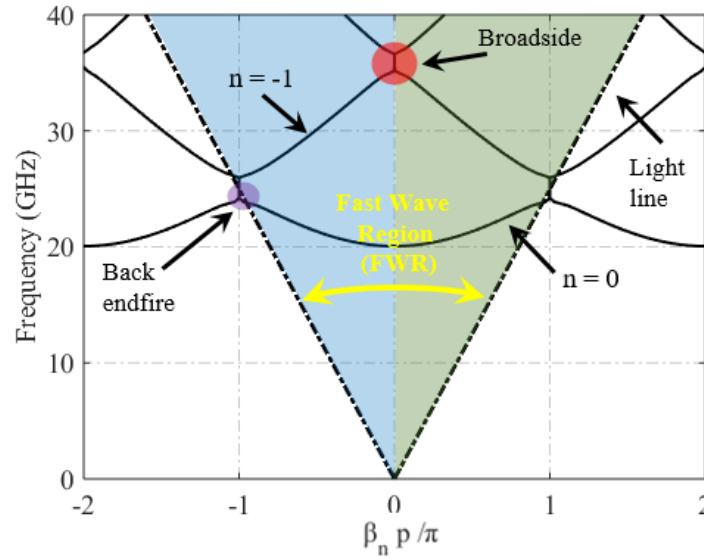


Figure 4.2 Brillouin diagram for an 1D-periodic reciprocal SIW-LWA with periodicity of 6mm on a dielectric propagating medium with dielectric constant of $\epsilon_r = 2.94$

By using this diagram, we are able to analyze information about the behavior of waves in terms of the slow and fast waves (proper and improper waves). Figure 4.2 shows the Brillouin diagram for a 1D-periodic reciprocal LWA ($\beta_n \leftrightarrow -\beta_n$) with periodicity of 6mm on a propagating medium with a dielectric constant of 2.94. Here we studied the case of a substrate integrated waveguide (SIW) with single mode operating of TE_{10} in the frequency range of $20 < f_{GHz} < 40$ (the width and thickness of SIW are considered to be 0.762mm and 4.36mm, respectively). In Figure 4.2, in order

to simplify the analysis, we plot the y-axis in terms of frequency (GHz). For frequencies above 25 GHz (up to 35.1 GHz), the condition for propagation of the $n = -1$ space harmonic is $-k_0 \leq \beta_{-1} < 0$ or $-k_0 \leq \beta_0 - 2\pi/p < 0$, where we have a physical proper fast wave (backward leaky wave). The open stop band happens between $35.1 < f_{\text{GHz}} < 36.6$ in which the propagation constant of the $n = -1$ space harmonic is equal to zero ($\beta_{-1} = 0$). For frequencies above 36.6 GHz, the condition for the propagation constant of the $n = -1$ space harmonic changes to $0 < \beta_{-1} \leq k_0$ or $0 < \beta_0 - 2\pi/p \leq k_0$, and thus we have a physical improper fast wave (forward leaky wave) for a specific frequency range, in which its beam angle can be achieved from $\sin\theta_{-1} = \beta_{-1}/k_0$ or $\sin\theta_{-1} = \tan \Psi_0$ (consider Ψ with respect to the k_{0p}/π axis in the Brillouin diagram of Figure. 4. 1).

As previously mentioned in the radiation mechanism for most of the 1D-periodic LWA is usually related to the $n = -1$ space harmonic which can act as a fast wave for specific frequency ranges. In the next sections, we will investigate the conditions of excitation of HSH ($n < -1$) and a method will also be demonstrated which will show how HSH ($n < -1$) can constructively contribute to the radiation pattern of a 1D-periodic LWA without disturbing or deteriorating the other space harmonics.

4.2. Higher-Order Space Harmonics (HSH)

The $n = -1$ space harmonic can act as a physical fast wave for a specific frequency range in most of 1D-periodic LWAs. However, there is a possibility of exciting HSHs, such as $n = -2$, as a leaky wave for a specific frequency range by increasing the periodicity between the radiating elements (or increasing the frequency range of interest). The coupling and interdependency of the $n = -2$ space harmonic was partially discussed in [35]-[38], and the focus was on providing a detailed analysis of the propagation constant behavior of the $n = -1$ space harmonic and its complete spectrum analysis of 1D-periodic LWA. Hence, several aspects of HSH characteristics such as radiation properties, amplitude variation, scanning range limitation and propagation constant behavior (β_n) were missing in the references which are studied and analyzed in detail in this work. In order to get the constructive contribution of the $n = -2$ space harmonic to the radiation of a periodic LWA, this space harmonic must behave as a physical fast wave and has to penetrate the fast wave region (FWR). In other terms, the absolute value of the propagation constant of the $n = -2$ space harmonic (β_{-2}) should be less than the free-space wavenumber ($|\beta_{-2}/k_0| \leq 1$). The interdependency and characteristic behavior of the $n = -2$ space harmonic with other space

harmonics ($n \leq -1$) remains unknown. Thus, as a first step, we analyze the behavior of the propagation constant of four HSH ($n \in [-1, -2, -3, -4]$), which includes of two higher-order even space harmonics ($n \in [-2, -4]$) and two higher-order odd space harmonic ($n \in [-1, -3]$), to examine the consequences on the radiation properties of each. In the 1D-periodic LWA, for each of the HSHs ($n \leq -1$) to act like a fast wave in a specific frequency range, the value of propagation constants of each HSH ($n \leq -1$) must penetrate the FWR. Stated otherwise, if the absolute value of propagation constants (β_n) of HSH ($n \leq -1$) obeys $|\beta_{n<-1}/k_0| \leq 1$, then the wave behavior of the related space harmonic can be represented as a physical fast wave for a specific frequency range, and hence it acts like a radiating wave (if suitable radiating elements are used). For 1D-periodic LWA to satisfy the condition of $|\beta_{n<-1}/k_0| \leq 1$ for a specific frequency range of $n \in [-1, -2, -3, -4]$ space harmonics, we must have the conditions for (β_n) as:

$$\beta_{-1} = \beta_0 - 2\pi/p \quad \rightarrow \quad |\beta_{-1}/k_0| \leq 1 \quad (4.1)$$

$$\beta_{-2} = \beta_0 - 4\pi/p \quad \rightarrow \quad |\beta_{-2}/k_0| \leq 1 \quad (4.2)$$

$$\beta_{-3} = \beta_0 - 6\pi/p \quad \rightarrow \quad |\beta_{-3}/k_0| \leq 1 \quad (4.3)$$

$$\beta_{-4} = \beta_0 - 8\pi/p \quad \rightarrow \quad |\beta_{-4}/k_0| \leq 1 \quad (4.4)$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ \beta_n = \beta_0 + 2n\pi/p & \rightarrow & |\beta_{-n}/k_0| \leq 1 \end{array}$$

To have a better comparison between the excitation conditions of HSHs ($n \leq -1$) of an SIW-LWA, we plot the Brillouin diagram for each of these HSH separately. Figures. 4.3-4.6 show the behavior of the $n \in [-1, -2, -3, -4]$ space harmonics in a Brillouin diagram, respectively. Here we investigated the effect of the permittivity variation on the HSH behavior in the FWR. In all, we assume to have propagating media with different dielectric constant values based on commercial substrates (RT6002 with $\epsilon_r = 2.94$, RT6035 with $\epsilon_r = 3.66$, RT6006 with $\epsilon_r = 6.45$ and RT6010 with $\epsilon_r = 10.7$) with a fixed-periodicity and thickness of $p = 8\text{mm}$ and 0.762mm , respectively. In addition, the SIW width of RT6002, RT6035, RT6006 and RT6010 in Figures. 4.3-4.6 is considered to be 2.94, 3.95, 2.95 and 2.28 (all in mm), respectively in order to have single mode operation (TE_{10}) for the frequency range of $20 < f_{\text{GHz}} < 40$. The analysis from Figures. 4.3-4.6 shows that by increasing the permittivity value, the contribution of the space harmonics in the FWR region decreases. For instance, in Figure. 4.3, for $\epsilon_r = 2.94$ and $\epsilon_r = 10.7$, the $n = -1$ space

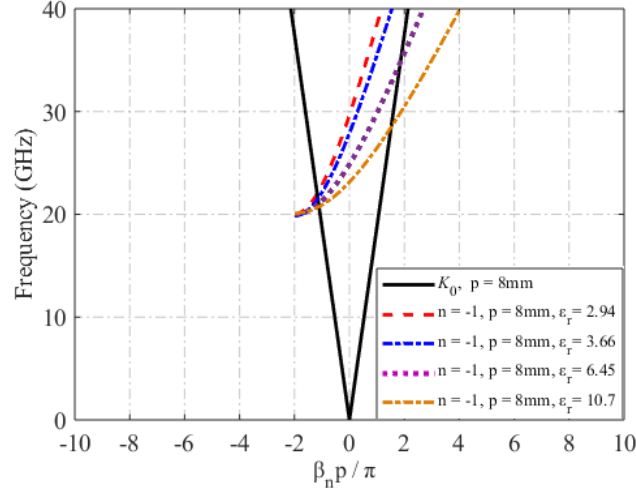


Figure 4.3 Effect of dielectric constant on the excitation of the $n = -1$ space harmonic

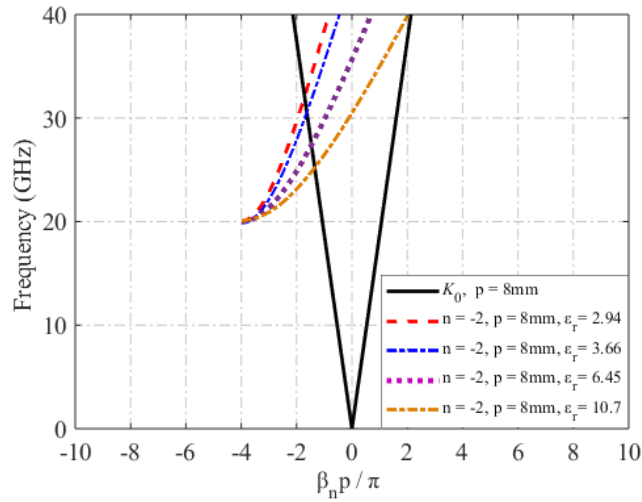


Figure 4.4 Effect of dielectric constant on the excitation of the $n = -2$ space harmonic

harmonic remains as fast wave in the FWR for the frequency range of $22 < f_{\text{GHz}} < 40$ and $20.7 < f_{\text{GHz}} < 28.4$, respectively. The same behavior is observed for the $n \in [-2, -3, -4]$ space harmonics in Figs. 2.4-2.6, respectively. Another conclusion that can be drawn out from the analysis of Figures. 4.3-4.6 is that for the same value of permittivity, the contributions of HSH such as $n = -4$ space harmonic in the FWR are more than the lower space harmonic such as $n = -1$. For instance, in Figure. 4.3 the frequency variation of the $n = -1$ space harmonic for $\epsilon_r = 10.7$ in the FWR are $20.7 < f_{\text{GHz}} < 28.4$ but for the $n = -2$ space harmonic in Figure. 4.4 this variation is from $25.2 < f_{\text{GHz}} < 40$. In addition, the analysis of Figures. 4.3-4.6 shows that the variation of permittivity has more effect on the excitation frequency of HSH such as $n = -4$ compared to the lower space harmonic such as $n = -1$. For instance, in Figure. 4.3, the cross section between the FWR and β_{-1} varies from

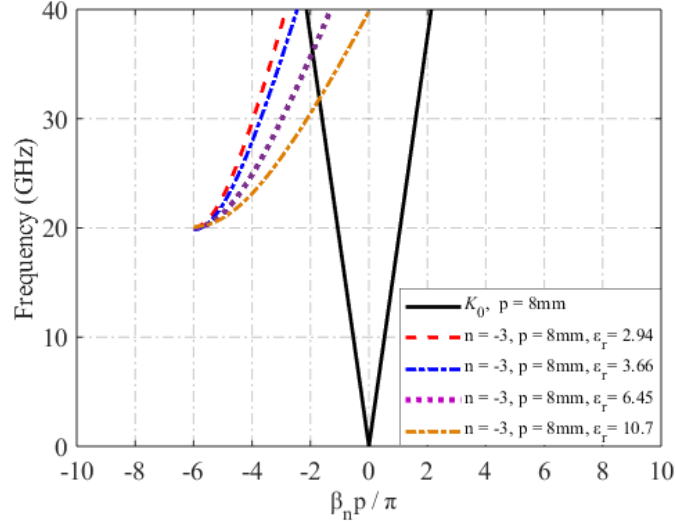


Figure 4.5 Effect of dielectric constant on the excitation of the $n = -3$ space harmonic

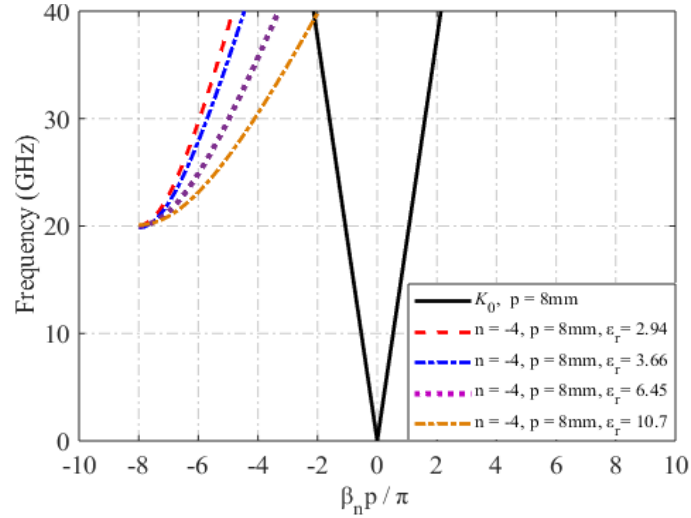


Figure 4.6 Effect of dielectric constant on the excitation of the $n = -4$ space harmonic

$20.7 < f_{\text{GHz}} < 22$, but for HSH such as $n = -2$ in Figure. 4.4, the variation range is from $25.2 < f_{\text{GHz}} < 32$. Thereby, HSH such as $n = -4$ are more sensitive to the permittivity variation compared to the lower ones in terms of the frequency range.

Another factor that has a major effect on designing 1D-periodic LWA is periodicity (radiating element separation), which needs to be investigated for the excitation of HSH ($n \leq -1$). As mentioned in section 2.1, there is a possibility of exciting HSH ($n \leq -1$) by increasing the periodicity. In order to investigate the effect of a periodicity variation on the excitation of HSH ($n \in [-1, -2, -3, -4]$), we plot the Brillouin diagram for each of the HSH separately as shown in Figures. 4.7-4.10, respectively, in which we assume to have a constant value for the dielectric

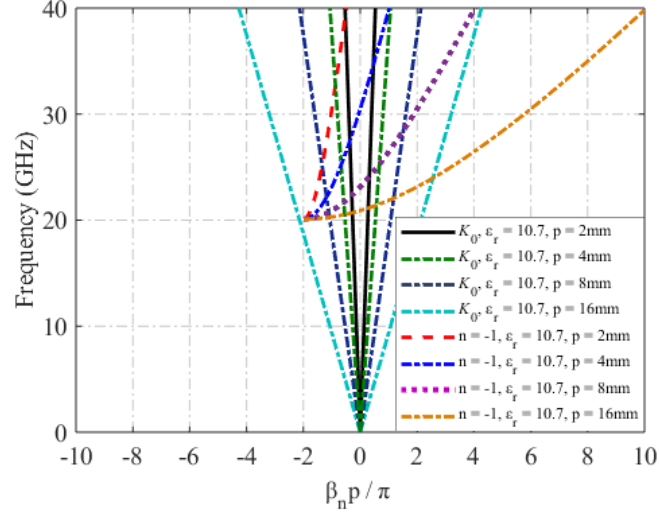


Figure 4.7 Effect of periodicity on the excitation of the $n = -1$ space harmonic

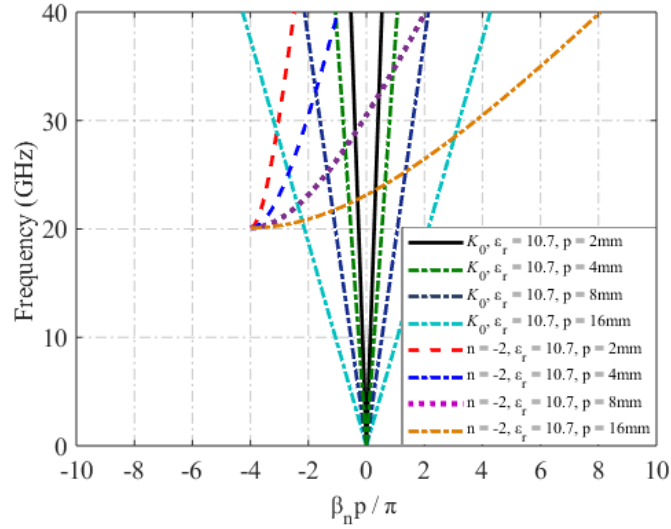


Figure 4.8 Effect of periodicity on the excitation of the $n = -2$ space harmonic

propagating medium ($\epsilon_r = 10.7$) with different periodicities ($p = 2\text{mm}$, $p = 4\text{mm}$, $p = 8\text{mm}$ and $p = 16\text{mm}$, respectively). In order to have a single operation mode (TE_{10}) for the frequency range of $20 < f_{\text{GHz}} < 40$, the SIW width is considered to be 2.28mm. The observation from Figure. 4.7 shows that the excitation frequency of the $n = -1$ space harmonic is around 39.4 GHz for the periodicity of 2mm and around 20.7 GHz for the periodicity of 8mm. This indicates that increasing the periodicity has an inverse relation with the value of excitation frequency of the $n = -1$ space harmonic (lower excitation frequency achieved by higher periodicity). The same phenomena happens for the $n \in [-2, -3, -4]$ space harmonics in Figures. 4.8-4.10. However, the comparison between the variations of the excitation frequency of HSH such as $n = -4$ space harmonic and the

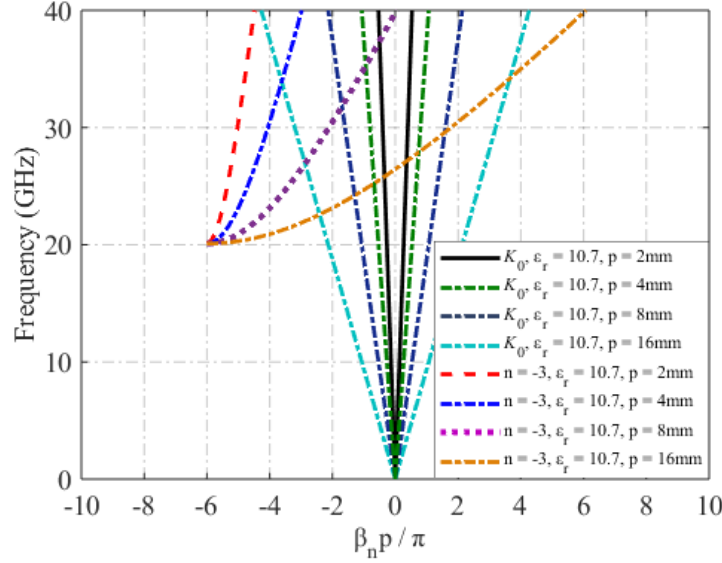


Figure 4.9 Effect of periodicity on the excitation of the $n = -3$ space harmonic

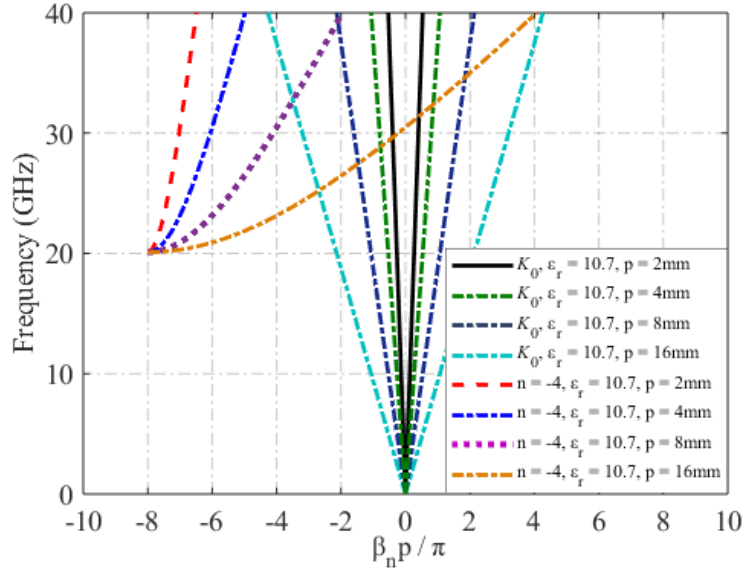


Figure 4.10 Effect of periodicity on the excitation of the $n = -4$ space harmonic

lower space harmonics such as $n = -1$ space harmonic, for the same variation of periodicity, suggests that the sensitivity of HSH is more compared to the lower ones in terms of the variation of frequency (for the two periodicities of $p = 8\text{mm}$ and $p = 16\text{mm}$, the variation of excitation frequency of $n = -2$ is around 4.5 GHz and around 14.1 GHz for $n = -4$).

To have a better understanding of the excitation frequency of HSH and its relationship with the periodicity, we plot the propagation constant for each in Figures. 4.11-4.14 (here we consider $\epsilon_r = 10.7$ for the propagating medium with different values of periodicity where the width of the SIW

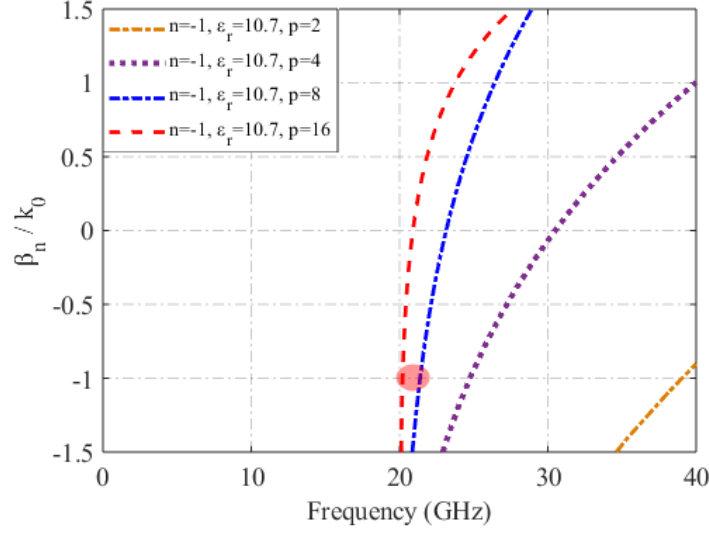


Figure 4.11 Propagation constant of the $n = -1$ space harmonic for different periodicity

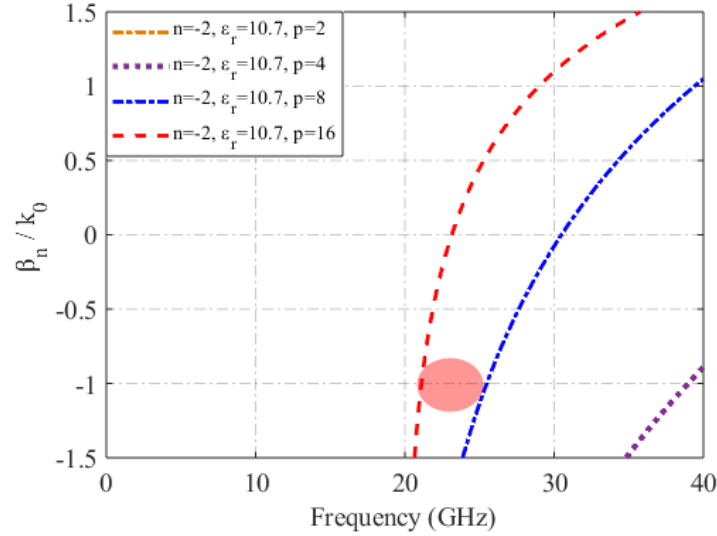


Figure 4.12 Propagation constant of the $n = -2$ space harmonic for different periodicity

is 2.28mm, to have the single operation mode of TE₁₀ for the frequency range of $20 < f_{\text{GHz}} < 40$). The red circles in Figures. 4.11-4.14 demonstrate that the excitation frequency of HSH such as $n = -4$ space harmonic are more sensitive to the variation of the periodicity compared to the lower ones showing a good agreement with the analysis of Figures. 4.7-4.10. The graphs demonstrate some common frequency range operation for each of HSH ($n \in [-1, -2, -3, -4]$). The comparison between the propagation constant of the $n = -1$ space harmonic for the periodicity of $p = 8$ mm and the propagation constant of the $n = -2$ space harmonic with the same periodicity shows that between

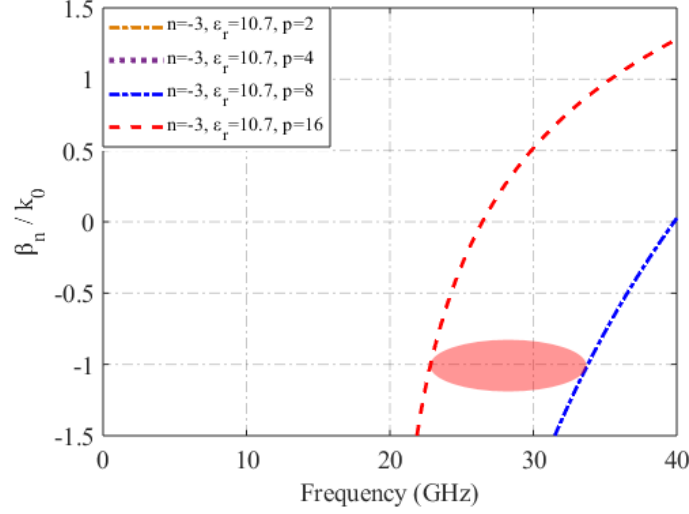


Figure 4.13 Propagation constant of the $n = -3$ space harmonic for different periodicity

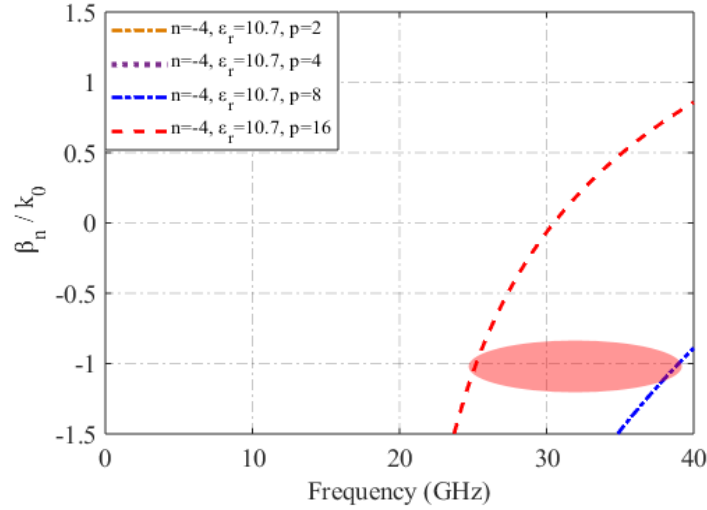
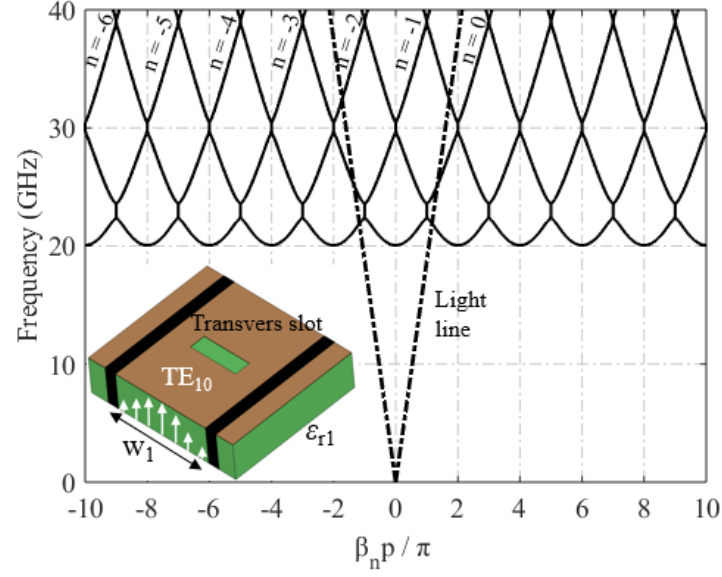


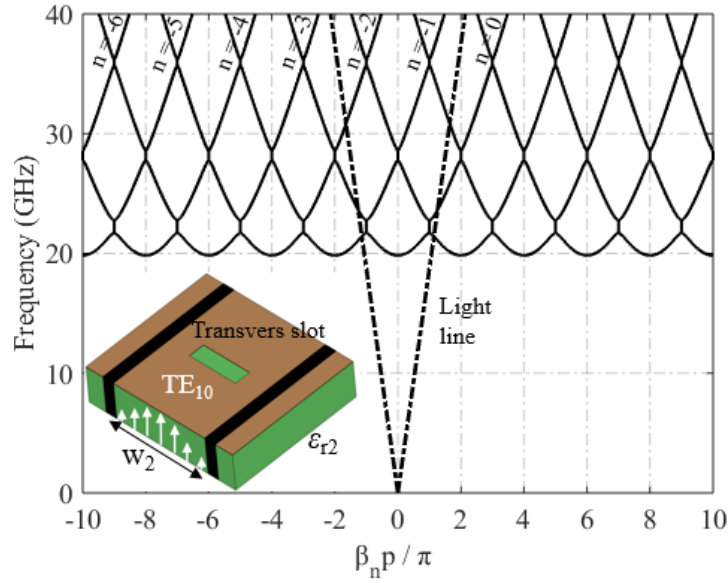
Figure 4.14 Propagation constant of the $n = -4$ space harmonic for different periodicity

the approximate frequency range of $25.5 < f_{\text{GHz}} < 26.5$ GHz, we have two space harmonics ($n \in [1, -2]$) which can penetrate to the FWR and behave like fast waves. However, the observation shows also that the behavior of the propagation constants (β_{-1} and β_{-2}) of the space harmonics ($n \in [-1, -2]$) is not the same in the proper and improper wave analysis; also, the slope variation of each HSH ($n \in [-1, -2]$) is not the same (Figs. 2.11-2.12, respectively). The effects of slope variations of HSH ($n \in [-1, -2, -3, -4]$) and their radiation properties are further addressed in section 4.4.

Another factor that has a crucial effect on the analysis of periodic LWA is the propagating mode operation of periodic unit cell. This needs to be investigated for the excitation of HSH ($n \leq -1$).



(a)



(b)

Figure 4.15 Unit cell analysis of HSH of TE_{10} mode of an SIW with $p = 8$, (a) $w_1 = 4.366$, $\epsilon_{r1} = 2.94$, (b) $w_2 = 3.95$, and $\epsilon_{r2} = 3.66$, (dimensions are in mm)

The geometry and permittivity of unit cell usually cause different types of mode operation in different structures. In this work, we focus on the HSH analysis of an SIW structure. Figure. 4.15 shows the Brillouin diagram analysis for different unit cells of an SIW structure. All the geometries of the unit cells were chosen to have a single mode operation of TE_{10} for the frequency range of $20 < f_{\text{GHz}} < 40$. The comparison between Figures. 4.15 (a) and (d) shows that the capability

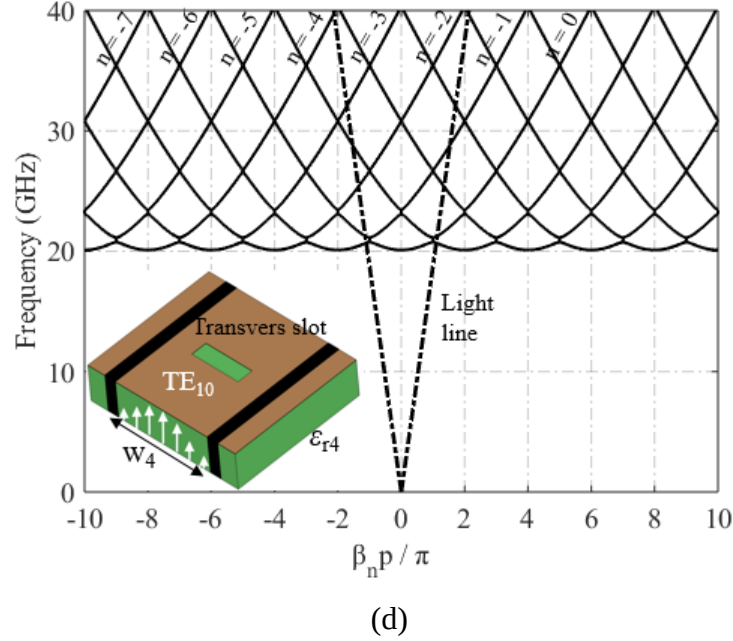
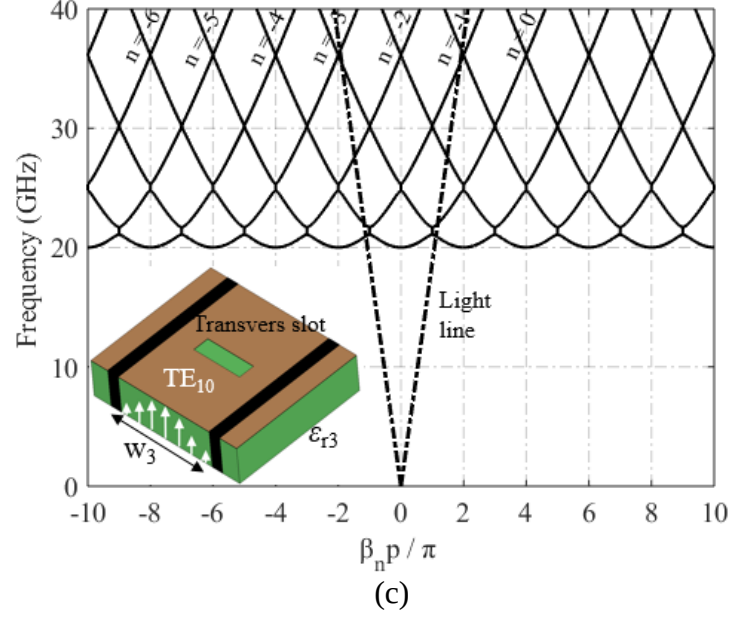


Figure 4.15 Unit cell analysis of HSH of TE_{10} mode of an SIW with, (c) $w_3 = 2.95$, $\epsilon_{r3} = 6.45$ and (d) $w_4 = 2.28$, $\epsilon_{r4} = 10.7$ (dimensions are in mm)

of contribution of HSH in the FWR as a single space harmonic (only one) decreases (in terms of frequency range) by decreasing the geometry and increasing the permittivity value of substrate. For instance, in Figures. 4.15 (a) and (d) the contribution of the $n = -1$ space harmonic in the FWR as single space harmonic are 7.3 GHz ($25.1 < f_{GHz} < 32.4$) and 4.15 GHz ($21.2 < f_{GHz} < 25.35$), respectively. In addition, the observation even shows that the unit cell of Figure. 4.15 (d) has

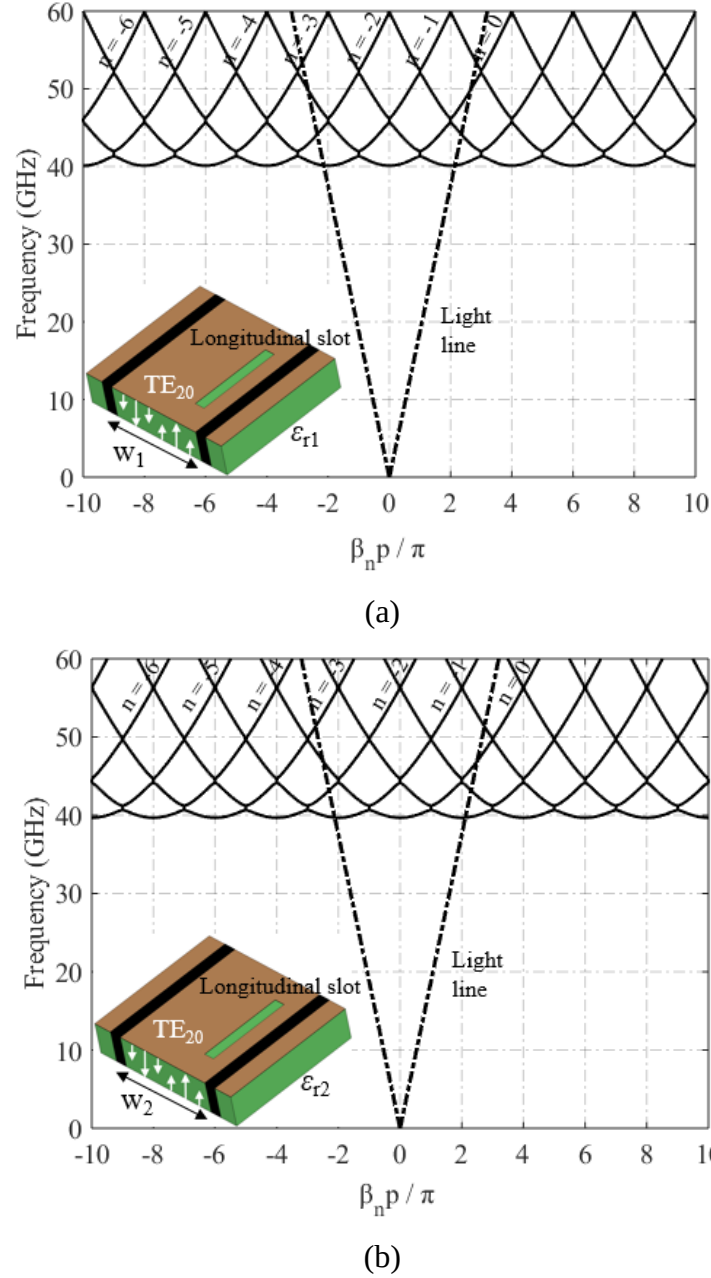


Figure 4.16 Unit cell analysis of HSH of TE_{20} mode of an SIW with $p = 8$, (a) $w_1 = 4.366$, $\epsilon_{r1} = 2.94$, and (b) $w_2 = 3.95$, $\epsilon_{r2} = 3.66$, (dimensions are in mm)

the capability of getting contribution of the $n = -2$ space harmonic as a single space harmonic for the specific frequency range ($28.85 < f_{GHz} < 32.1$) in the FWR. However, the unit cell of the Fig. 2.15 (a) does not show such a behavior. It should be mentioned that each of the unit cells has different capabilities for involving different kinds of HSH in the FWR region based on the propagating mode operation of the transmission line and geometry of the unit cell. To have a better

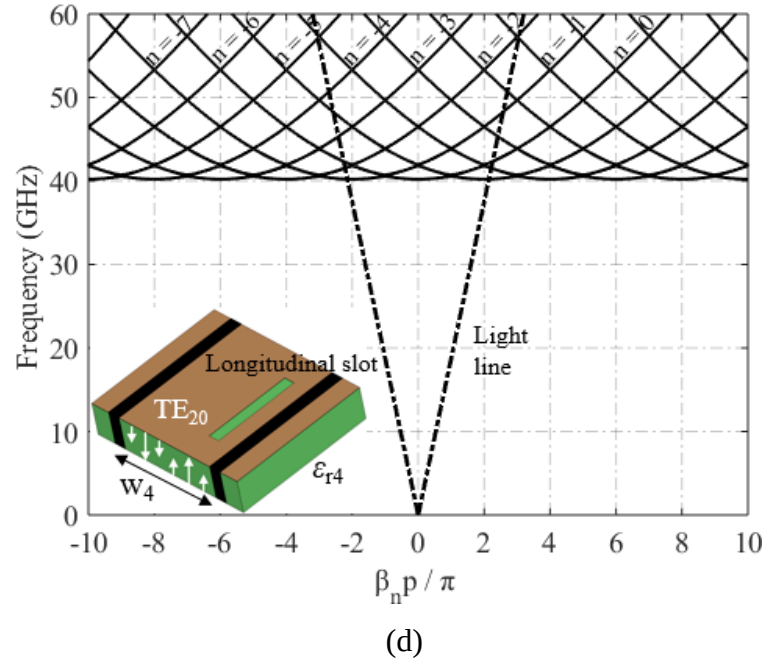
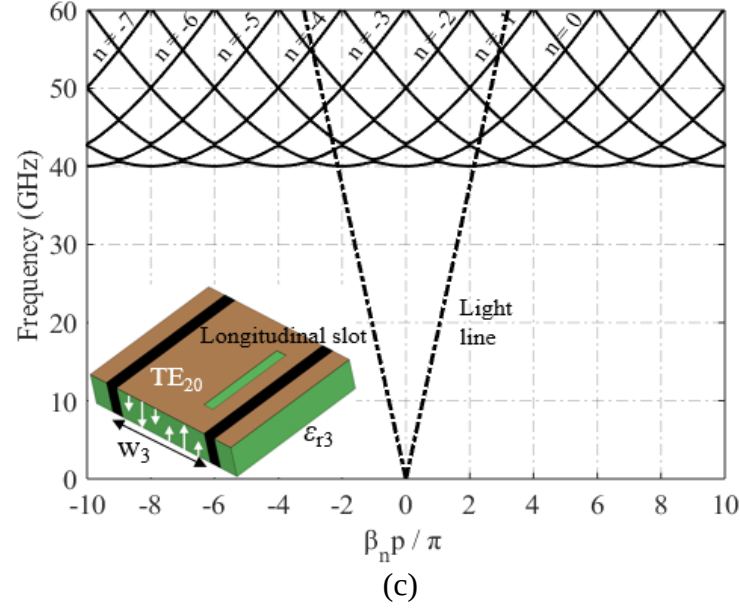


Figure 4.16 Unit cell analysis of HSH of TE_{20} mode of an SIW with $p = 8$, (c) $w_3 = 2.95$, $\epsilon_{r3} = 6.45$ and (d) $w_4 = 2.28$, $\epsilon_{r4} = 10.7$ (dimensions are in mm)

comparison of HSH behavior and its relation to the propagating mode, we also plot the Brillouin diagram for the TE_{20} mode of an SIW in Figure.4.16 (the geometry of the unit cell is similar to the unit cell of Figure. 4.15 and we get the contribution of TE_{20} for the frequency range of $40 < f_{GHz} < 60$). The observation from Figures. 4.15-4.16 show that by using the higher mode of an SIW, the capability of unit cell in terms of involving different HSH in the FWR can increase. Here the unit

cells of Figures. 4.15 (a) and (d) have capabilities of involving 3 ($n \in [0, -1, -2]$) and 4 ($n \in [0, -1, -2, -3]$) space harmonics respectively for the case of TE_{10} mode. However, for the case of TE_{20} mode in Figures. 4.16 (a) and (d) we can get the contribution of 4 ($n \in [0, -1, -2, -3]$) and 6 ($n \in [0, -1, -2, -3, -4, -5]$) space harmonics, respectively. Therefore, the effect of geometrical shape of the unit-cell is highlighted and the contribution response of different HSH as fast wave to the frequency range of our interest is investigated. Hence, the geometrical shape of unit-cell must be chosen based on application requirements and the performance of the antenna. In addition, to the excitation condition of the HSH we also need to dig the contribution of them to the different antenna characteristics. This analysis is carried out analyses studied in the next section of this chapter.

4.3. Radiation Properties of Higher-Order Space Harmonics (HSH)

In the previous section, we studied the effect of periodicity and permittivity variation and geometrical SIW unit-cell on the excitation frequency of HSH. In addition, we analyzed the capability of involving different HSH in the FWR for different unit cell-geometries for two propagating modes (TE_{10} and TE_{20}) of an SIW structure. The analysis of Figures. 4.3-4.16 shows that the HSH can remain as fast wave in a wider frequency range when we use a unit cell with lower permittivity by increasing the periodicity we should get the contribution of different HSH simultaneously for a specific frequency range. In this section, we want to study the SIW unit-cells with capability of simultaneously generating different HSH in which we are interested to evaluate the antenna radiation performance for each of HSH along each other. Figure. 4.17 shows the Brillouin diagram analysis of an SIW unit-cell which can excite 4 HSH of $n \in [-1, -2, -3, -4]$ of a TE_{10} mode. The width of the SIW unit-cell is considered to be 4.36 mm where we have a single-mode operation of TE_{10} in the frequency range of $20 < f_{GHz} < 40$ (the cutoff of TE_{10} and TE_{20} modes are 20 and 40 GHz, respectively), and we assume that the radiating element of the periodic structure is a transverse slot. Therefore, it is expected that this radiating element only works with the TE_{10} mode of a SIW due to its field distribution and the contribution of the second mode of the SIW (TE_{20}) is negligible since it has a different field distribution.

As a first step, we analyze the $n = -1$ space harmonic. From Figure. 4.17 and (1), the excitation condition of $n = -1$ space harmonic ($|\beta_{-1}/k_0| \leq 1$) is satisfied for frequencies above 21.5 GHz, and its wave appears in the FWR and behaves like a fast wave in which $\beta_{-1} = \beta_0 - 2\pi/p$. At this

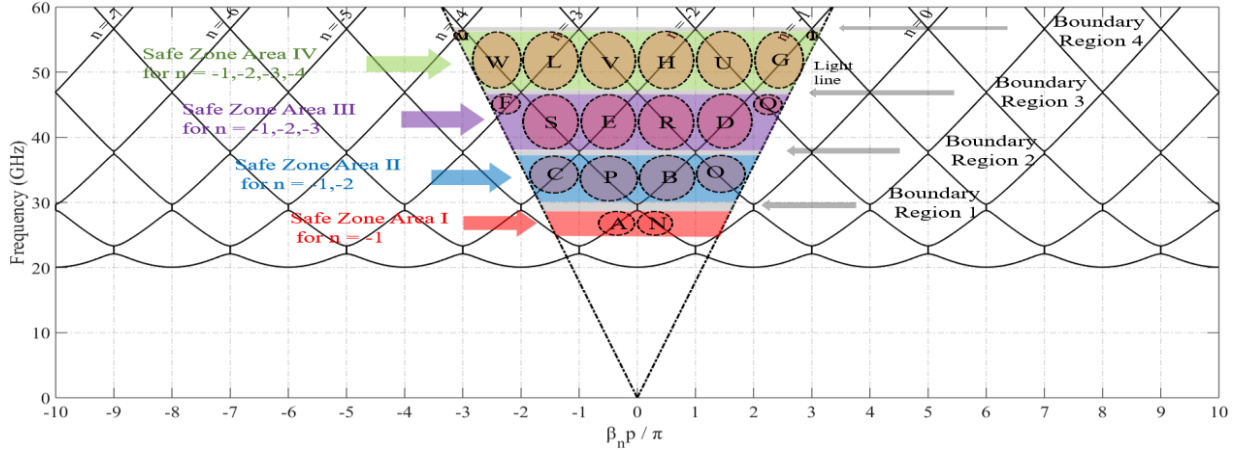


Figure 4.17 Brillouin diagram for a 1D-periodic SIW-LWA with periodicity of $p = 8.4\text{mm}$ on dielectric propagating medium with $\epsilon_r = 2.94$

frequency, the value of $|\beta_{-1}/k_0| = 1$. Thereby, it is expected that the beam of $n = -1$ space harmonic appears near backward endfire as a result of the negative value of its propagation constant ($\beta_{-1} < 0$) while the beam of $n = 0$ is in the forward quadrant. For frequencies of $22 < f_{\text{GHz}} < 23.3$ the $n \in [0, -1]$ space harmonics encounter with the stop band. For frequencies above 25.1 GHz, the beam of $n = -1$ space harmonic continues to scan in the backward quadrant as single beam since the $n = 0$ space harmonic appears outside the FWR. This situation is continued until the propagation constant of $n = -1$ space harmonic reaches zero ($\beta_{-1} = 0$). This condition happens in the frequency range of $28.75 < f_{\text{GHz}} < 29.75$, where we have a stop band for the $n = -1$ space harmonic and the beam of the $n = -1$ is at broadside. Similarly, at the frequency of 31.2 GHz the excitation condition of the $n = -2$ space harmonic is satisfied ($|\beta_{-2}/k_0| \leq 1$). Above this frequency the propagation constant of $n = -2$ space harmonic appears in the FWR and behaves like a fast wave, in which $\beta_{-2} = \beta_0 - 4\pi/p$. In addition, at this frequency $|\beta_{-2}/k_0| = 1$ and it is expected that the beam related to the $n = -2$ space harmonic appears near backward endfire quadrant. Thus, at 31.2 GHz we have two space harmonics ($n \in [-1, -2]$) that can simultaneously behave like fast waves ($|\beta_{-1}/k_0| \leq 1$ and $|\beta_{-2}/k_0| = 1$). For the frequency range of $29.75 < f_{\text{GHz}} < 31.2$ the beam related to the $n = -1$ space harmonic contributes to the radiation without involving by the $n = -2$ space harmonic. However, for frequency above 31.2 GHz, the condition of excitation frequency for $n = -2$ space harmonic satisfies ($|\beta_{-2}/k_0| \leq 1$) and we can get a constructive contribution of two space harmonics simultaneously. Thereby, the frequency range of $28.75 < f_{\text{GHz}} < 29.75$ can act as the boundary region between the $n = -1$ space harmonic and $n = -2$ space harmonic (when both space harmonics are in the FWR), that is shown in Figure. 4.17 as boundary region 1, in which the value of the

propagation constant of $n \in [-1, -2]$ is set to be $\beta_{-1}p/\pi = 0$ and $\beta_{-2}p/\pi = -2$, respectively. It should be mentioned that the excitation frequency related to the $n = -2$ space harmonic can get closer to boundary region 1 by choosing a lower permittivity value or higher periodicity. For the frequency range below boundary region 1, i.e. $25.1 < f_{\text{GHz}} < 28.75$, we have only one space harmonic ($n = -1$) as a fast wave, which has the capability of scanning from in the backward quadrant ($\beta_{-1} < 0$) to near broadside ($\beta_{-1} = 0$). Here, we refer to this frequency range ($25.1 < f_{\text{GHz}} < 28.75$) as safe zone area I, in which the beam related to the $n = -1$ space harmonic scans without involving and distributing any HSH ($n \leq -2$). Circle A represents the variation of the propagation constant of the $n = -1$ space harmonic in the safe zone area I where $-1 < \beta_{-1}p/\pi < 0$. For frequencies above boundary region 1, we have two space harmonics ($n \in [-1, -2]$) as fast waves. However, the conditions for the propagation constants of each space harmonic are different. Above boundary region 1, the value of the propagation constant of $n = -1$ space harmonic is no longer negative and becomes positive ($\beta_{-1} > 0$). However, the value of the propagation constant of $n = -2$ is negative ($\beta_{-2} < 0$, for a specific frequency range). Thus, according to the values of their propagation constants we have one beam in the forward quadrant which is related to the $n = -1$ space harmonic and the second beam in the backward quadrant (appears with delay) which is related to the $n = -2$ space harmonic for a specific frequency range. In Figure. 4.17, we refer to the frequency range of $29.75 < f_{\text{GHz}} < 37.4$ as the safe zone area II in which we can get constructive contribution of $n \in [-1, -2]$ space harmonics simultaneously, where their beams can scan in the forward and backward quadrants respectively. Circles B and C represent the variation of the propagation constant of $n \in [-1, -2]$ space harmonics in safe zone area II, where $0 < \beta_{-1}p/\pi < 1$ and $-2 < \beta_{-2}p/\pi < -1$.

The beams of $n \in [-1, -2]$ space harmonics scan in both quadrants until they reach the frequency of 37.4 GHz in which the next stop band occurs. Here we refer to this frequency range $37.4 < f_{\text{GHz}} < 37.9$ as boundary region 2 in which we have the condition of $\beta_{-1}p/\pi = 1$, $\beta_{-2}p/\pi = -1$ and $\beta_{-3}p/\pi = -3$ for the $n \in [-1, -2, -3]$ space harmonics, respectively. In boundary region 2 the conditions for the propagation constants of $n \in [-1, -2, -3]$ space harmonics are different compared to one another. The propagation constant of $n = -1$ space harmonic at boundary region 2 has the value of $\beta_{-1}p/\pi = 1$. Thus, it is expected that its beam appears in the forward quadrant due to the positive value of its propagation constant ($\beta_{-1} > 0$, if suitable radiating element is used). In addition, at boundary region 2 for $n \in [-2, -3]$ space harmonics, we have $\beta_{-2}p/\pi = -1$ and $\beta_{-3}p/\pi = -3$, respectively. However, only $n = -2$ space harmonic contributes to the radiation pattern since the condition of $|\beta_{-2}/k_0| \leq 1$ is

satisfied. Thereby, it is expected that its beam will appear in the backward quadrant due to the negative value of its propagation constant ($\beta_{-2} < 0$, if suitable radiating element is used). In boundary region 2, the condition of $|\beta_{-3}/k_0| \leq 1$ is not satisfied and the $n = -3$ space harmonic does not appear at the FWR. Hence, we can get contribution of only two space harmonics ($n \in [-1, -2]$) in the boundary region 2.

In Figure. 4.17, for frequencies above boundary region 2, the beams of $n \in [-1, -2]$ space harmonics simultaneously scan in both quadrants until they reach the frequency of 43 GHz ($n = -1$ in forward and $n = -2$ in backward quadrant since we have the condition of $\beta_{-1} > 0$ and $\beta_{-2} < 0$ for a specific frequency range). At this frequency the excitation condition of $n = -3$ space harmonic ($|\beta_{-3}/k_0| \leq 1$) is also satisfied and its beam must appear near the backward endfire due to the condition of $|\beta_{-3}/k_0| = 1$. Thereby, for frequencies above 43 GHz, we have three space harmonics ($n \in [-1, -2, -3]$) as fast waves in which their propagation constants condition are different. In Figure. 4.17, we refer to the frequency range of $37.9 < f_{\text{GHz}} < 46.8$ as the safe zone area III in which we can get constructive contribution of $n \in [-1, -2, -3]$ space harmonics simultaneously, where their beams can scan in the forward and backward quadrants respectively. At safe zone area III the value of the propagation constant of $n = -1$ is positive ($\beta_{-1} > 0$), and its beam appears in the forward quadrant. Besides, the propagation constants of $n \in [-2, -3]$ have negative value ($\beta_{-2} < 0$ and $\beta_{-3} < 0$), and their beams appear in the backward quadrant. Circles D, E and F represent the variation of the propagation constant of $n \in [-1, -2, -3]$ in safe zone area III where we have $1 < \beta_{-1}p/\pi < 2$, $-1 < \beta_{-2}p/\pi < 0$ and $-3 < \beta_{-3}p/\pi < -2$, respectively.

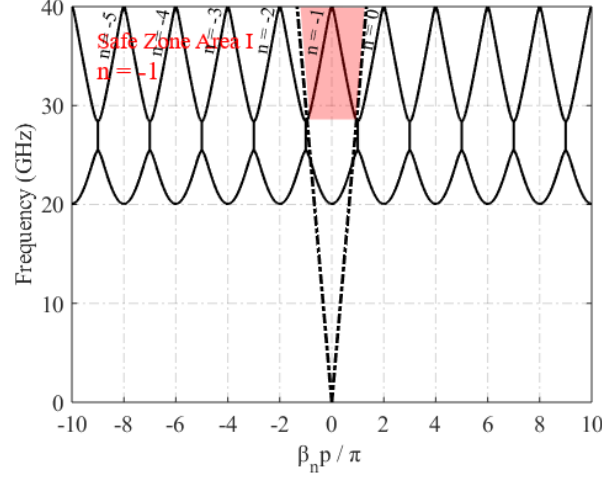
In Figure. 4.17, for frequencies above safe zone area III, the $n \in [-1, -2, -3]$ space harmonics encounter a stop band. Here we refer to the frequency range between $46.8 < f_{\text{GHz}} < 47.2$ as boundary region 3 in which the propagation constants of the $n \in [-1, -2, -3, -4]$ space harmonics are $\beta_{-1}p/\pi = 2$, $\beta_{-2}p/\pi = 0$, $\beta_{-3}p/\pi = -2$ and $\beta_{-4}p/\pi = -4$, respectively. It should be mentioned that the condition of HSH in boundary region III is different compared to boundary region II. In boundary region 3 we have 3 space harmonics as fast waves in the FWR ($n \in [-1, -2, -3]$). In addition, the $n = -2$ space harmonic appears as broadside at this frequency range since its propagation constant equals to zero ($\beta_{-2} = 0$) and the beams related to the $n \in [-1, -3]$ must appear at forward and backward quadrants since their propagation constants are positive and negative, respectively at this frequency range ($\beta_{-1} > 0$, $\beta_{-3} < 0$). For frequencies above boundary region 3 the excitation condition of $n = -4$ space harmonic is satisfied at $f = 55.9$ GHz in which we have $|\beta_{-4}/k_0| \leq 1$. Hence, it is expected that its

Table 4.1 Behavior of the propagation constants of $n \in [-1, -2, -3, -4]$ space harmonics in FWR based on the analysis of Figure 4.17

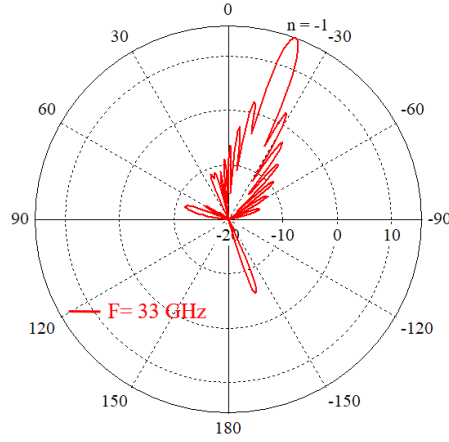
	Safe zone area I $25.1 < f < 28.75$ (GHz)	Boundary region 1 $28.75 < f < 29.75$ (GHz)	Safe zone area II $29.75 < f < 37.4$ (GHz)	Boundary region 2 $37.4 < f < 37.9$ (GHz)	Safe zone area III $37.9 < f < 46.8$ (GHz)	Boundary region 3 $46.8 < f < 47.2$ (GHz)	Safe zone area IV $47.2 < f < 56.7$ (GHz)
$n = -1$ space harmonic (β_{-1})	Proper $-1 < \beta_{-1}p/\pi < 0$ Circle A	Broadside $\beta_{-1}p/\pi = 0$	Improper $0 < \beta_{-1}p/\pi < 1$ Circle B	Improper $\beta_{-1}p/\pi = 1$	Improper $1 < \beta_{-1}p/\pi < 2$ Circle D	Improper $\beta_{-1}p/\pi = 2$	Improper $2 < \beta_{-1}p/\pi < 3$ Circle G
$n = -2$ space harmonic (β_{-2})	-	-	Proper $-2 < \beta_{-2}p/\pi < -1$ Circle C	Proper $\beta_{-2}p/\pi = -1$	Proper $-1 < \beta_{-2}p/\pi < 0$ Circle E	Broadside $\beta_{-2}p/\pi = 0$	Improper $0 < \beta_{-2}p/\pi < 1$ Circle H
$n = -3$ space harmonic (β_{-3})	-	-	-	-	Proper $-3 < \beta_{-3}p/\pi < -2$ Circle F	Proper $\beta_{-3}p/\pi = -2$	Proper $-2 < \beta_{-3}p/\pi < -1$ Circle L
$n = -4$ space harmonic (β_{-4})	-	-	-	-	-	-	Proper $-4 < \beta_{-4}p/\pi < -3$ Circle M

beam appears near backward endfire due to the condition of $|\beta_{-4}/k_0| = 1$. Thereby, for frequencies above 55.9 GHz, we have four space harmonics ($n \in [-1, -2, -3, -4]$) as fast waves in which their propagation constant conditions are different compared to one another. In Figure. 4.17, we refer to the frequency range between $47.2 < f_{\text{GHz}} < 56.7$ as safe zone area IV in which we can get constructive contribution of $n \in [-1, -2, -3, -4]$ space harmonics simultaneously, where their beams can scan in the both quadrants. Circle G represents the variation of the propagation constant of the $n = -1$ in safe zone area IV where $2 < \beta_{-1}p/\pi < 3$. The beam of the $n = -1$ space harmonic in safe zone area IV is expected to appear in the forward quadrant due to the positive value of its propagation constant ($\beta_{-1} > 0$). Circle H represents the variation of the propagation constant of $n = -2$ in safe zone area IV where $0 < \beta_{-2}p/\pi < 1$. The condition of the propagation constant of $n = -2$ space harmonic changes in safe zone area IV, as compared to the safe zone area III where we have a positive value for its propagation constant ($\beta_{-2} > 0$), and the beam related to this space harmonic is expected to appear in the forward quadrant. Circles L and M represent the variation of the propagation constants of $n \in [-3, -4]$ in safe zone area IV where we have $-2 < \beta_{-3}p/\pi < -1$ and $-4 < \beta_{-4}p/\pi < -3$, respectively. Hence, it is expected that their beams appear in the backward quadrant due to the negative value of their propagation constant ($\beta_{-3} < 0$ and $\beta_{-4} < 0$). This kind of analysis can be extended to use other HSH ($n \leq 5$) which are not investigated in this paper. A summary of the behavior of HSH ($n \in [-1, -2, -3, -4]$) is shown in Table 4.1. The significance of regions (Circles) N, O, P, Q, R, S, T, U, V and W will be highlighted in section 4.4.

The analyses of Table 4.1 shows the total response of propagation constant behavior of TE_{10} mode and its related HSH. Here is that the behavior of HSH can be manipulated based on the



(a)



(b)

Figure 4.18 (a) Brillouin diagram for a periodicity of $\epsilon_r = 2.94$, (a) $p = 5\text{mm}$, and (b) corresponding E-plane co-polar radiation pattern

excitation condition of them and their related contribution factors such as a permittivity, periodicity, effective width of SIW structure, and propagating mode. Such factors give us the flexibility of shifting different safe zone areas and boundary regions to the frequency range we are interested. Hence, as first step, we define our frequency range of interest as $26.5 < f_{\text{GHz}} < 40$ in which we would like to analyze the periodicity of the unit-cell as a contribution factor for generating different HSH behavioral models. Figure. 4.18(a) shows the Brillouin diagram analysis of HSH for the case of TE_{10} mode of an SIW structure. The geometry of the unit cell is similar to Figure. 4.15 (a) where we have single mode operation. Here we consider having a propagating medium with a dielectric constant of $\epsilon_r = 2.94$ with different periodicities. Figure. 4.18(a) shows

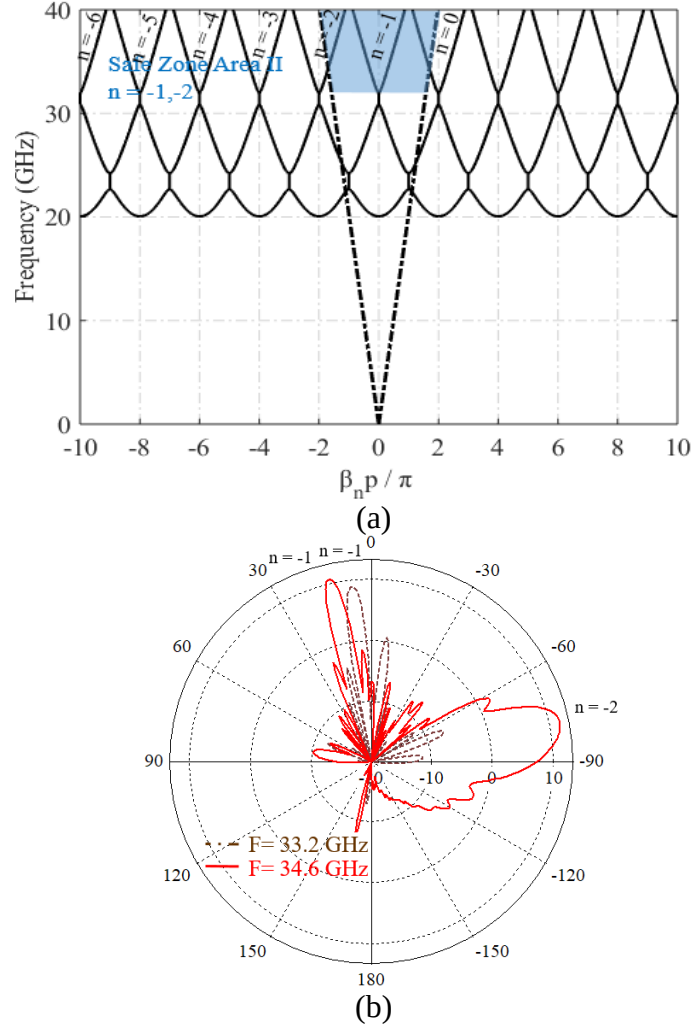


Figure 4.19 (a) Brillouin diagram for a periodicity of $\epsilon_r = 2.94$, (a) $p = 5$ mm, and (b) corresponding E-plane co-polar radiation pattern

the Brillouin diagram analysis for a periodicity of $p = 5$ mm in which we have only $n = -1$ space harmonic as a fast wave in safe zone area I. Based on the analysis of the Brillouin diagram in Figure. 4.17 and Table 4.1, it is expected to have only one proper beam in safe zone area I. To prove this, the simulation result related to the Brillouin diagram analysis of Figure. 4.18(a) is shown in Figure. 4.18(b) where we consider the width of the SIW as 4.36mm with thickness of 0.765mm in order to have single mode operation (TE_{10}) for our frequency range of interest (the length of antenna considered is $12\lambda_0$). In the simulation model, we used a series of transverse slots in which the slot length and width were 2.2mm and 0.7mm, respectively. Figure. 4.18(b) demonstrates that the radiation beam of $n = -1$ space harmonic at 33 GHz in safe zone area I is in the backward quadrant which shows good agreement with the prediction of our analysis.

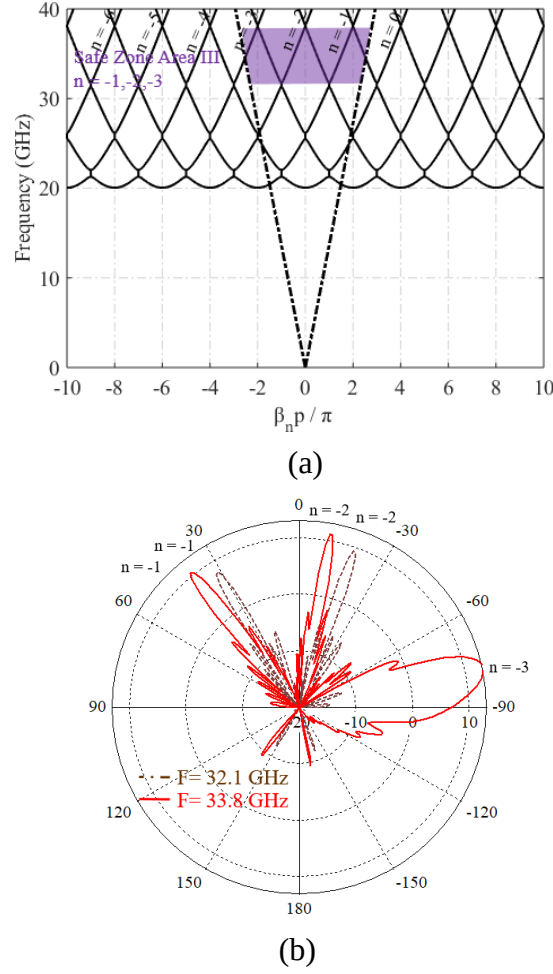
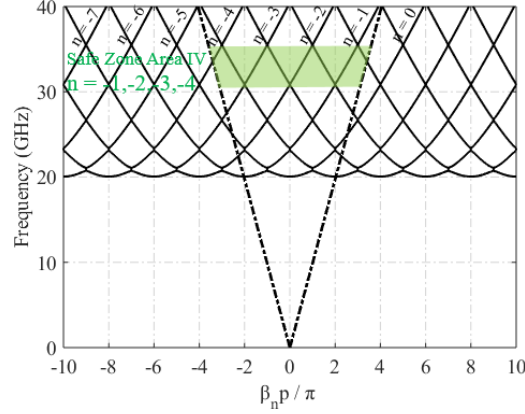


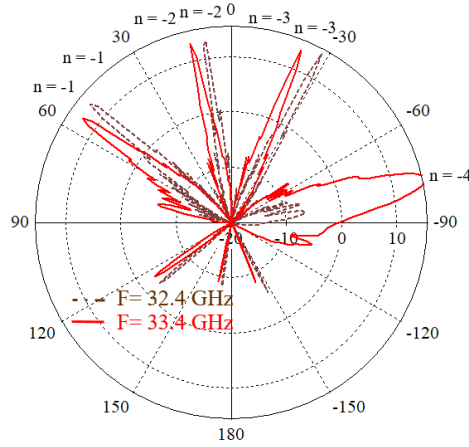
Figure 4.20 (a) Brillouin diagram for a periodicity of $\epsilon_r = 2.94$, (a) $p = 11$ mm, and (b) corresponding E-plane co-polar radiation pattern

Figure.4.19(a) shows the Brillouin diagram analysis for a periodicity of $p = 7$ mm. Similarly, it is expected to have an improper beam and a proper beam in safe zone area II of this figure, where the propagation constant value of $n \in [-1, -2]$ space harmonics are in the FWR. Figure. 4.19(b) shows the simulated radiation behavior based on the analysis of Figure. 4.19(a). We only have one beam in the forward quadrant (related to $n = -1$) at $f = 33.2$ GHz and we have one beam in the forward quadrant (related to $n = -1$) with another beam in the backward quadrant (related to $n = -2$) at $f = 34.6$ GHz in safe zone area II. This shows good agreement with the analysis prediction of Figure. 4.17 and Table I in which the second space harmonic ($n = -2$) appears with a delay in safe zone area II compared to the $n = -1$ space harmonic.

Figure. 4.20(a) shows the Brillouin diagram analysis for a periodicity of $p = 11$ mm. It is expected to have an improper beam and two proper beams in safe zone area III where the $n \in [-1,$



(a)



(b)

Figure 4.21 (a) Brillouin diagram for a periodicity of $\epsilon_r = 2.94$, (a) $p = 15\text{mm}$, and (b) corresponding E-plane co-polar radiation pattern

-2, -3] space harmonics behave like fast waves in the FWR. Figure. 4.20(b) shows the related simulation of the radiation properties based on analysis of Figure. 4.20(a). We have one beam in the forward quadrant ($n = -1$) and one beam in the backward quadrant ($n = -2$) at $f = 32.1\text{ GHz}$ and at $f = 33.8\text{ GHz}$ we have one beam in the forward quadrant ($n = -1$) with two beams in the backward quadrant $n \in [-2, -3]$ which shows good agreement with the analysis prediction.

Finally, Figure. 4.21(a) shows the Brillouin diagram analysis for a periodicity of $p = 15\text{mm}$. Based on our analysis, it is expected to have two improper beams and two proper beams in safe zone area IV where the $n \in [-1, -2, -3, -4]$ space harmonics penetrate FWR. Figure. 4.21 (b) shows the simulation result in which two beams are observed in the forward quadrant ($n \in [-1, -2]$) and one beam in the backward quadrant ($n = -3$) at $f = 32.4\text{ GHz}$ and at $f = 33.4\text{ GHz}$ we have two beams in the forward quadrant ($n = -1, -2$) and two beams in the backward quadrant $n \in [-3, -4]$.

This shows good agreement with the theory and analysis of Figure. 4.17 and Table 4.1. The analysis and radiation features of HSH at different boundary region frequencies are further investigated in chapter 6 of this thesis where we propose a solution for suppressing the stop band issue of HSH. It should be mentioned that the propagation constant response of different HSH do not have the same response for each HSH at the same safe zone area or different safe zone areas. Such behavior response needs to be studied and investigated since it directly affects the beam steering response of the antenna. Hence, in the next section we evaluate the beam steering capability of the antenna for different HSHs.

4.4. Beam Steering Features of Higher-Order Space Harmonics (HSH)

The comparison between the scanning ranges of HSH ($n \in [-1, -2, -3, -4]$) for different safe zone areas of FWR is another point that needs to be investigated. Here we want to study the beam steering capability of different HSH related to different SIW unit-cell with the capability of generating different safe zones and boundary regions. As first step, we compare the scanning range of SIW unit-cell with the capability of generating lower number of passband frequency. Here and as our first analysis, we want to evaluate beam steering feature of the $n \in [-1, -2]$ space harmonics in safe zone area II of Figure. 4.19. (a) in which we have to check the values and variation of $|\beta_{-1}/k_0|$ and $|\beta_{-2}/k_0|$ when the values of the propagation constants related to the $n \in [-1, -2]$ space harmonics are in safe zone area II of FWR. Figure. 4.22 shows the variation of $|\beta_n/k_0|$ based on Figure 4.19. (a) analysis. By considering the equation of $\sin^{-1}(\beta_n/k_0)$, in safe zone area II of Figure. 4.22, the $n \in [-1, -2]$ space harmonics approximately varies from 0 to 0.44 and 1 to 0.57, respectively which correspond to the angles of 0° to 27° and -90° to -35° , respectively. Hence, according to the values and variation of $|\beta_n/k_0|$, it is expected that the beam related to the $n = -2$ space harmonics varies faster and scans more angles compared to the beam of $n = -1$ space harmonic in safe zone area II of Figure 4.19. (a).

In the next step, we compare the scanning range of SIW unit-cell with the capability of generating more pass band frequency such as one in Figure. 4.20(a) where we have $n \in [-1, -2, -3]$ space harmonics in safe zone area III. To compare the scanning range variation of $n \in [-1, -2, -3]$ space harmonics, we need to check the values and variation of $|\beta_{-1}/k_0|$, $|\beta_{-2}/k_0|$ and $|\beta_{-3}/k_0|$ in safe

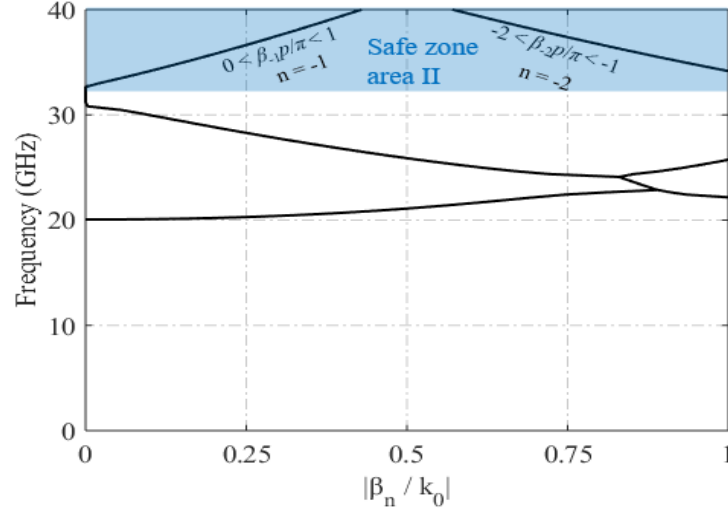


Figure 4.22 Behavior response of $|\beta_n/k_0|$ variation based on the analysis of the Figure 2.19 (a)

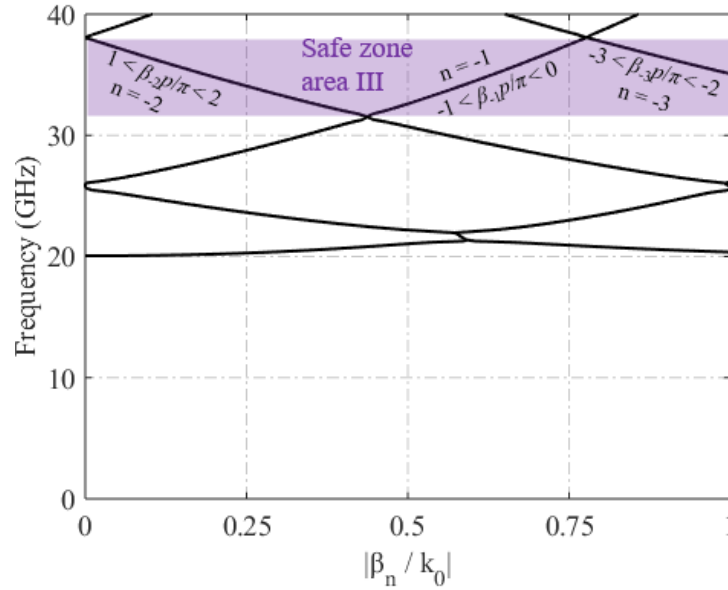


Figure 4.23 Behavior response of $|\beta_n/k_0|$ variation based on the analysis of the Figure 2.20 (a)

zone area III of FWR. Figure. 4.23 shows the behavior of $|\beta_n/k_0|$ based on the analysis of Figure 4.20. (a). In Figure. 4.23 in safe zone area III, the $n \in [-1, -2, -3]$ space harmonics approximately varies from 0.4 to 0.77, 0.4 to 0 and 1 to 0.77, respectively, which correspond to the angles of 23° to 50° , -23° to 0° and -90° to -50° , respectively. Thus, it is expected that the radiated beam related to the $n = -3$ space harmonic varies faster and scans more angles than the beams of $n \in [-1, -2]$.

Finally, we compare the scanning ranges of $n \in [-1, -2, -3, -4]$ in safe zone area IV of Figure. 4.21. (a). Figure. 4.24 shows the behavior of $|\beta_n/k_0|$ based on the analysis of Figure. 4.21. (a).

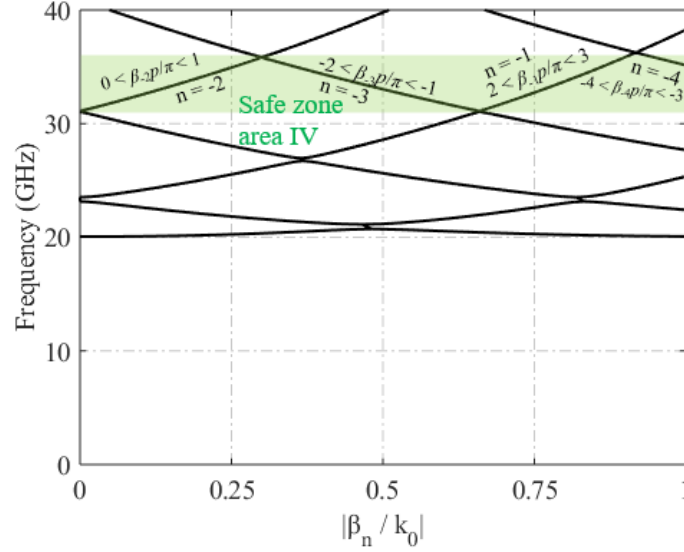


Figure 4.24 Behavior response of $|\beta_n/k_0|$ variation based on the analysis of the Figure 2.21 (a)

Comparing with $|\beta_{-2}/k_0|$, $|\beta_{-3}/k_0|$ and $|\beta_{-4}/k_0|$ needs to be studied in safe zone area IV of FWR. In Figure. 4.24 in safe zone area IV, the $n \in [-1, -2, -3, -4]$ space harmonics approximately vary from 0.69 to 0.88, 0 to 0.29, 0.69 to 0.29 and 1 to 0.87, respectively which correspond to the angles of 44° to 62° , 0° to 16° , -44° to -17° and -90° to -60° , respectively. Thus, it is expected that the radiated beam of the $n = -4$ space harmonic varies faster and scans more angles compared to the others.

For a proof of this concept, the simulation results related to the Brillouin diagram analysis of Figure. 4.22-4.24 are shown in Figure. 4.25 where we consider the width of the SIW unit-cell as 4.36mm in order to have single mode operation (TE_{10}) for our frequency range of $20 < f_{GHz} < 40$ with thickness of 0.765mm (the length of antenna is $12\lambda_0$). For the simulation model, we used a series of transvers slots in which the slot length and width were considered to be 2.2mm and 0.7mm, respectively. Figure. 4.25(a) shows the simulation results based on the analysis of the Brillouin diagram of Figure. 4.19(a) for two different frequencies, $f_1 = 34.6GHz$ and $f_2 = 37 GHz$, of safe zone area II. In this safe zone, the beam related to the $n = -2$ space harmonic scans faster in the backward quadrant and covers more angles compared to the beam of $n = -1$ space harmonic in the forward quadrant. Figure. 4.25(b) shows the simulation result based on the analysis of the Brillouin diagram of Figure. 4.20 for two different frequencies, $f_1 = 33.8 GHz$ and $f_2 = 35 GHz$, of safe zone area III in which the beam related to the $n = -3$ scans faster in the backward quadrant than others. Figure. 4.25(c) shows the simulation results based on analysis of Brillouin diagram of Figure. 4.21 for two different frequencies, $f_1 = 33.4 GHz$ and $f_2 = 33.8 GHz$, of safe zone area IV,

Table 4.2 Scanning angle variation of HSH in different safe zone area

Space Harmonic	Safe zone area II of Fig. 2.19		Safe zone area III of Fig. 2.20		Safe zone area IV of Fig. 2.21	
	Theory	Sim	Theory	Sim	Theory	Sim
n= -1	0_27	4_26	23_50	25_47	44_60	45_57
n= -2	-90_-35	-85_-39	-23_0	-22_-3	0_17	4_16
n= -3	-	-	-90_-50	-85_-55	-44_-17	-40_-20
n= -4	-	-	-	-	-90_-60	-85_-63

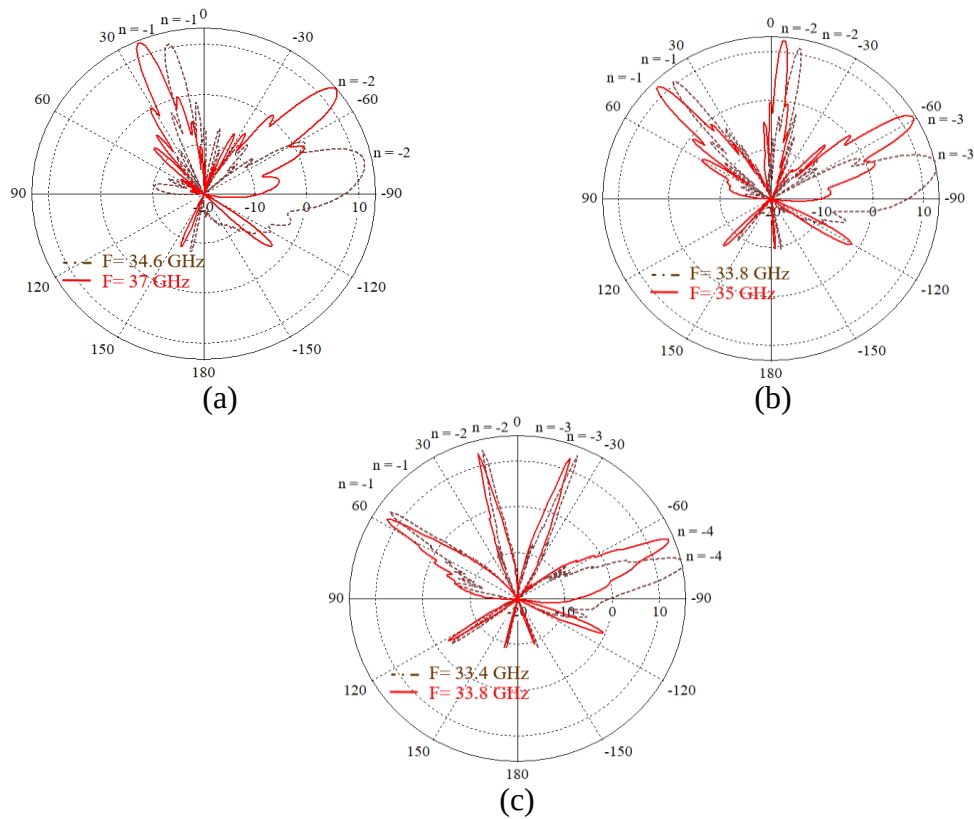


Figure 4.25 (a) E-plane co-polar radiation pattern based on the analysis of the Brillouin diagram of (a), Figure 4.21, (b) Figure 4.20, and (c) Figure 4.21

in which the observation about scanning is verified. Table II shows the comparison between the theory and simulation results of scanning angle behavior of HSH based on analysis of Figures. 4.19-4.25.

Another point that needs to be highlighted here is the scanning angle behavior of HSH in different boundary regions. The beams of each HSH appear at broadside since the value of its propagation constant reaches zero ($\beta_{-n} = 0$) in which the $|\beta_{-n}/k_0| = 0$. In Figure. 4.17, this condition

is satisfied for the $n = -1$ space harmonic over the frequency range of boundary region 1 since its propagation constant value remains zero ($\beta_{-1} = 0$). Hence, the scanning angle of $n = -1$ space harmonic sticks to 0° angle for this frequency range. In boundary region 2 of Figure. 4.17, we have two space harmonics as fast waves ($n \in [-1, -2]$). The values of $|\beta_{-n}/k_0|$ of these two space harmonics ($n \in [-1, -2]$) does not equal to zero at this frequency range since their propagation constants are not zero ($\beta_{-1} \neq 0, \beta_{-2} \neq 0$). Thereby, the scanning angles of these two space harmonics ($n \in [-1, -2]$) varies within the frequency range of boundary region 2. In addition, the variation of scanning angles of these two space harmonics ($n \in [-1, -2]$) are similar to each other in boundary region 2 since their absolute value and variation of their propagation constant are similar within these frequency range in which the $n \in [-1, -2]$ space harmonics scan in the forward and backward quadrants, respectively, due to their positive and negative values of their propagation constant ($\beta_{-1} > 0, \beta_{-2} < 0$).

In boundary region 3 of Figure. 4.17, we have three space harmonics as fast waves ($n \in [-1, -2, -3]$). The $n = -2$ space harmonic appears at broadside since the value of its propagation constant reaches zero ($\beta_{-2} = 0$) in which the $|\beta_{-2}/k_0| = 0$. So the scanning angle of $n = -2$ space harmonic stays at 0° . However, since the value of the propagation constant related to the $n \in [-1, -3]$ space harmonics are not zero in this frequency range ($\beta_{-1} \neq 0, \beta_{-3} \neq 0$), their scanning angles change compared to the $n = -2$ space harmonic which remains constant at 0° . Besides, since the absolute value and variation of $|\beta_{-1}/k_0|$ and $|\beta_{-3}/k_0|$ are similar. Hence, their beams scanning angle variation are same. In addition, their beams scan in the forward and backward quadrants, respectively, since we have the condition of $\beta_{-1} > 0, \beta_{-3} < 0$ for $n \in [-1, -3]$ space harmonics, respectively. Finally, in boundary region 4 of Figure. 4.17, we have four space harmonics ($n \in [-1, -2, -3, -4]$) in the FWR. None of these HSH appear at broadside since their propagation constant values are not zero. Thereby, the scanning angles of these HSH ($n \in [-1, -2, -3, -4]$) change within this frequency range. In this boundary region the absolute value and variation of $|\beta_{-1}/k_0|$ and $|\beta_{-4}/k_0|$ are the same compared so their beams scanning angle variation in the backward and forward quadrant are same since we have the condition of $\beta_{-1} > 0, \beta_{-4} < 0$ for $n \in [-1, -4]$ space harmonics, respectively. Besides, the absolute values and variations of $|\beta_{-2}/k_0|$ and $|\beta_{-3}/k_0|$ are the same thus their beams scanning angle variation are similar and their beams scan in the forward and backward quadrants, respectively, since we have the condition of $\beta_{-2} > 0, \beta_{-3} < 0$ for $n \in [-2, -3]$ space harmonics, respectively. Thus, the above analysis indicates that the HSH enables the antenna to have the

capability of generating multiple beams through their operation frequency range where we were able to predict and control the number and position of the antenna beams by careful analysis of their unit-cell. Besides, it should be noted that many applications satisfy their system requirements through having a single beam operation within their frequency band of interest. This thesis also aims to demonstrate and investigate the contribution of HSH to the antenna as a single beam operation and we highlight the trade-off between different HSH contribution for different antenna characteristics.

As previously mentioned, most of the periodic LWAs operate with their fundamental fast wave ($n = -1$ space harmonic). Here we want to study the possibility of applying HSH to the case of periodic LWA where we want to highlight the difference between fundamental and HSH contributions to different antenna features. The analysis of Figures. 4.3-4.6 indicate that the contribution of different space harmonics in the FWR region has a reverse relationship with the permittivity values of the SIW unit-cell where increasing the value of permittivity will result in decreasing the slope variation of different HSH in the FWR. Therefore, such a behavior will reduce the frequency range contribution of HSH as fast wave. Thus, we should expect that the intersection between the HSH should be reduced when choosing the higher value of permittivity. It should be considered here that other contribution factor to the fast wave behavior of HSH can also affect the HSH performances (such as SIW effective width, and geometrical shape of unit-cell as discussed in previous section). However, their effect is negligible compared to the permittivity variation to the cross section of HSH in FWR region. For further investigation, Here we want to study and analyze the behavior of HSH on the high permittivity material for different periodicity of SIW unit-cell. As a first step, we identify the frequency range of our interest as $35 < f_{\text{GHz}} < 39$. In order to have single mode operation (TE_{10}) for this frequency range of interest, we consider the effective width, permittivity, and thickness of the SIW unit-cell as 2mm, 10.7, and 0.767mm, respectively. In the next step, we have analyzed and compared the behavior of two space harmonics as $n = -1$ and $n = -2$ where we want to identify the differences between the contribution of these two space harmonic as proper single fast wave. Such a behavior response is achievable by choosing the SIW unit-cell periodicity of $n = -1$ and $n = -2$ space harmonic as 2.5mm, and 5.8mm, respectively. Figure 4.26 shows the Brillouin diagram of two SIW unit-cells in this regard. The analyses of Figure. 4.26(a) indicates that the $n = -1$ space harmonic can penetrate through the FWR region and becomes a proper fast wave for the frequency range of $33.8 < f_{\text{GHz}} < 40$ while the $n = -2$ space

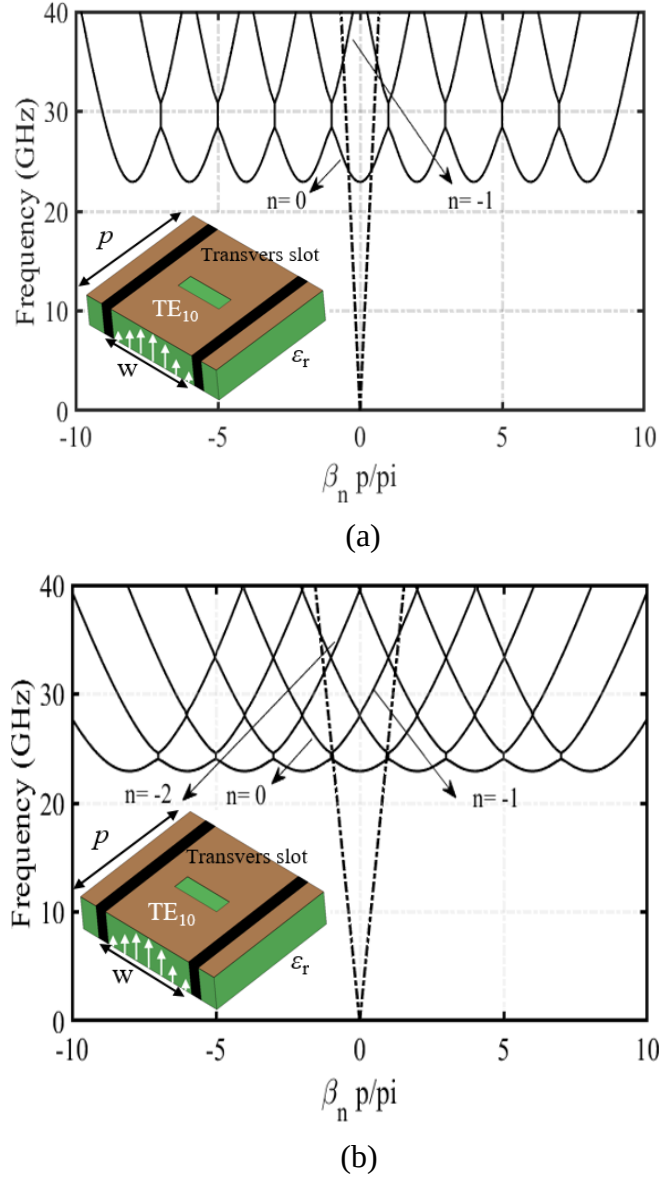


Figure 4.26 Brillouin diagram of SIW unit-cell for a permittivity of 10.7 and periodicity of (a) $p = 2.5\text{mm}$, and (b) $p = 5.8\text{mm}$

harmonic remains a slow wave for this frequency range. In Figure. 4.26(a) since there is no cross section between $n = -1$ space harmonic and other space harmonic in the FWR for the frequency range of $35 < f_{\text{GHz}} < 40$. Hence, we should expect to have a single backward beam operation for this specific frequency range. Besides, the analysis of Figure. 4.26(b) indicates that the $n = -2$ space harmonic can penetrate through the FWR region and becomes a proper fast wave for the frequency range of $33 < f_{\text{GHz}} < 40$ while the $n = -1$ space harmonic remains a fast wave for this frequency range of $24 < f_{\text{GHz}} < 35$. Therefore, for the frequency range of $35 < f_{\text{GHz}} < 40$, we are able to get

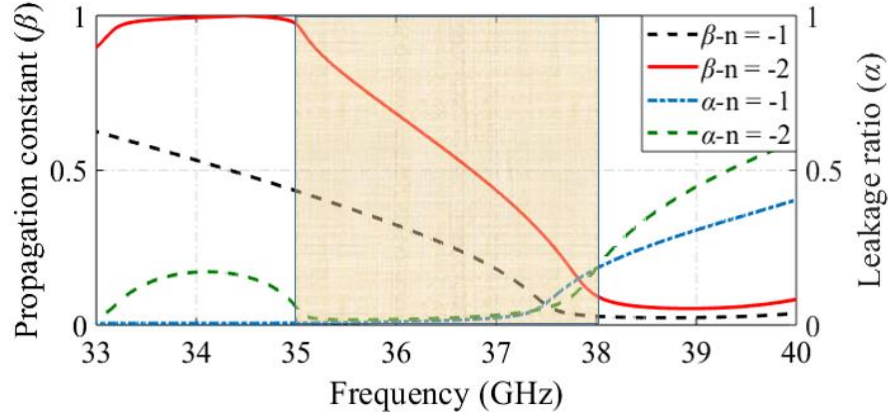


Figure 4.27 Propagation constant and leakage ratio behavior of SIW unit-cells of Figure 2.26

the contribution of the $n = -2$ space harmonic as a single backward beam. It should be mentioned that, in addition to the Brillouin diagram analysis, we must evaluate the effect of radiating elements on the propagation constant and leakage ratio response. Figure. 4.27 shows the Propagation constant and leakage ratio behavior of SIW unit-cell of Figure. 4.26 which can be obtained through the following equation [39]:

$$\beta = \text{Im}[\cosh^{-1}((A + D) / 2)] / p \quad (4.5)$$

$$\alpha = \text{Re}[\cosh^{-1}((A + D) / 2)] / p \quad (4.6)$$

Here A and D are two components of the ABCD matrix and they can be found from the Z and Y matrices. In the above analysis, the radiating element which applied to our SIW unit-cells is a transverse slot where the slot length and width consider to be $0.5\lambda_g$ (2.2mm) and $0.1\lambda_g$ (0.7mm), respectively. The analysis of Figure. 4.27 indicate that the $n = -2$ space harmonic related to the SIW unit-cell of Figure. 4.26(b) has a sharper propagation constant variation (slop) compared to the $n = -1$ space harmonic related to the SIW unit-cell of Figure. 4.26(a) for the frequency range of our interest. It should be mentioned that in addition to the propagation constant analyses we also need to evaluate the variation of β_n/k_0 to recognize the scanning range variation of that specific space harmonic. Dividing the β_{-1} values of Figure. 4.27 by k_0 of for the frequency range of $35 < f_{\text{GHz}} < 40$ will give us the ratio variation of -0.87 to 0. Such a value corresponds to the angle variation of -60° to 0° . Besides, Dividing the β_{-2} values of Figure. 4.27 by k_0 of for the frequency range of $35 < f_{\text{GHz}} < 40$ will give us the ratio variation of -0.85 to 0. Such a variation is corresponding to the angle variation of -58° to 0° . Therefore, from the theatrical Brillouin diagram, and simulated SIW

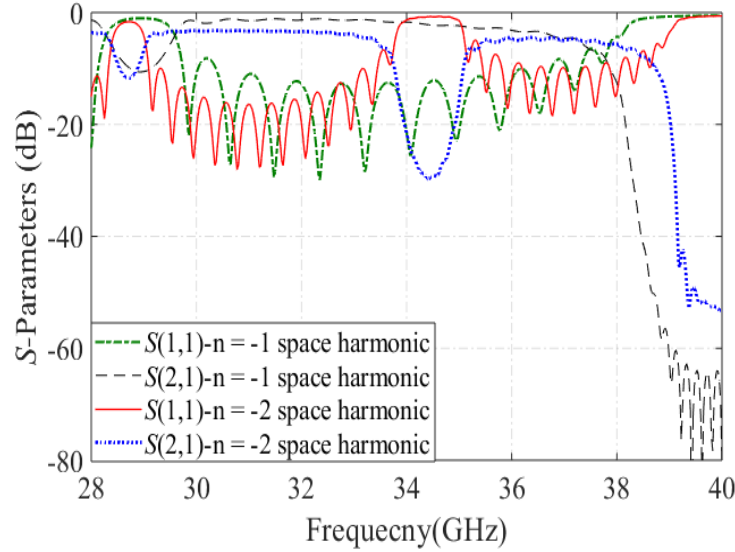


Figure 4.28 S-parameter response of the SIW-LWA based on the SIW unit-cell of Figure 4.26

unit-cell, we should expect to have a single backward beam for our antenna for the frequency range of our interest. In addition, we must analyze the S-parameter response of the antenna. Figure. 4.28 shows the S-parameter response of two LWAs based on the analysis of Figure. 4.26 (to have a fair comparison the number of radiating elements consider to be 20 for both LWAs). In Figure. 4.28 and as an initial evaluation, it seems that the LWA which works with $n = -1$ space harmonic has a larger bandwidth compared to the LWA which works with $n = -2$. This is a tricky observation. Considering fact that the actual useful bandwidth of the $n = -1$ starts from 33GHz since its related space harmonic becomes fast wave (based on analyses of Figure. 4.26(a)). Thus, we should have an acceptable gain level of LWA (based on $n = -1$ space harmonic) for the frequency above 33GHz (even considering 10dB antenna beam sidelobe level can shrink the actual useful bandwidth of the antenna). Besides, for the frequency range of our interest ($35 < f_{\text{GHz}} < 39$), the LWA (based on the $n = -2$ space harmonic) enjoys the benefit of having the $n = -2$ space harmonic as a fast wave (based on analyses of Figure. 4.26(b)). Therefore, we are expected to get the contribution of its related single backward beam for our frequency range of our interest. Another point which needs to consider in the analyses of Figure. 4.28 is that the $S(2,1)$ level of the LWA based on the $n = -2$ space harmonic is lower than the LWA based on the $n = -1$ space harmonic. Thus, we should expect that the more energy leaks out for the case $n = -2$ space harmonic compared to the $n = -1$ space harmonic. It should be mentioned that in addition to the above analysis we always

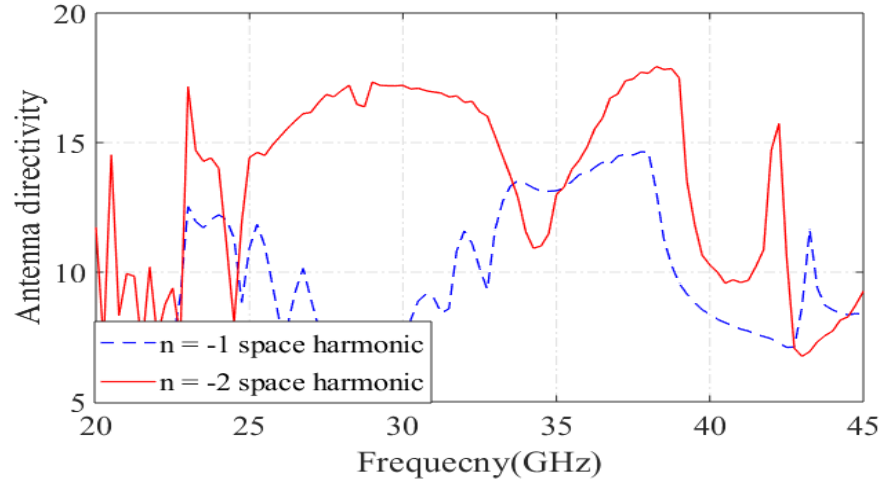


Figure 4.29 LWAs directivity based on unit-cell analysis of Figure 4.26

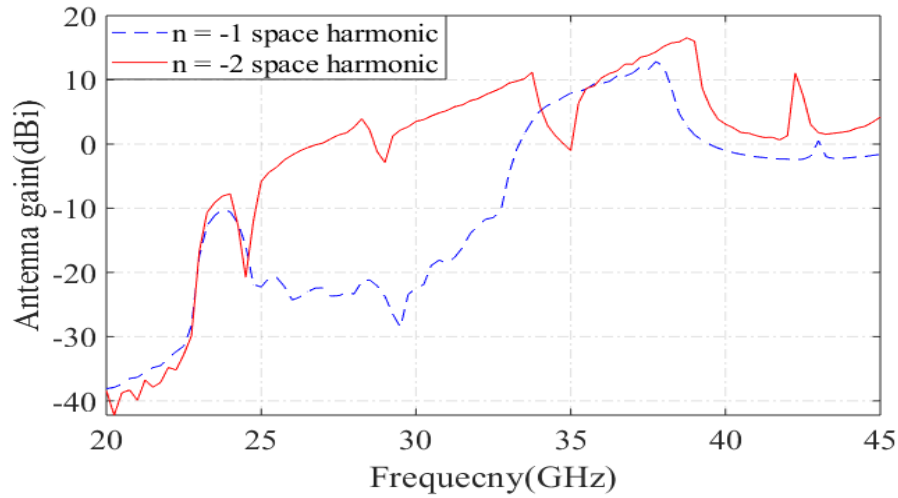


Figure 4.30 LWAs gain based on unit-cell analysis of Figure 4.26

need to evaluate other antenna characteristics such as directivity, gain, and radiation efficiency in order to have a comprehensive analysis about the antenna performances. Figure. 4.29 shows the two LWAs directivity based on LWA's unit-cell analyses of Figure. 4.26. The analysis of Figure. 4.29 indicates that the LWA based on the $n = -2$ space harmonic achieves a higher directivity compared to the LWA based on the $n = -1$ space harmonic for the frequency range of our interest ($35 < f_{\text{GHz}} < 39$). Also for the $34 < f_{\text{GHz}} < 35$ the antenna directivity of $n = -2$ space harmonic is lower due to the band edge issue). Besides, as expected, the directivity of $n = -1$ achieves higher directivity for the frequency range of $33 < f_{\text{GHz}} < 38$ since it becomes a fast wave. This shows a good agreement with the analysis of Figure. 4.26. Figure. 4.30 illustrates two LWAs gain behavior responses based on LWA's unit-cell analyses of Figure. 4.26. As expected, the gain of LWA based

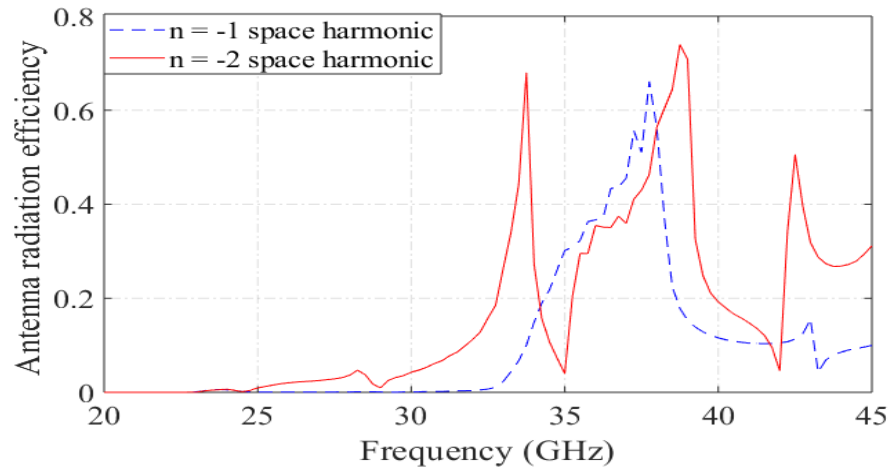


Figure 4.31 LWAs radiation efficiency based on unit-cell analyses of Figure 4.26

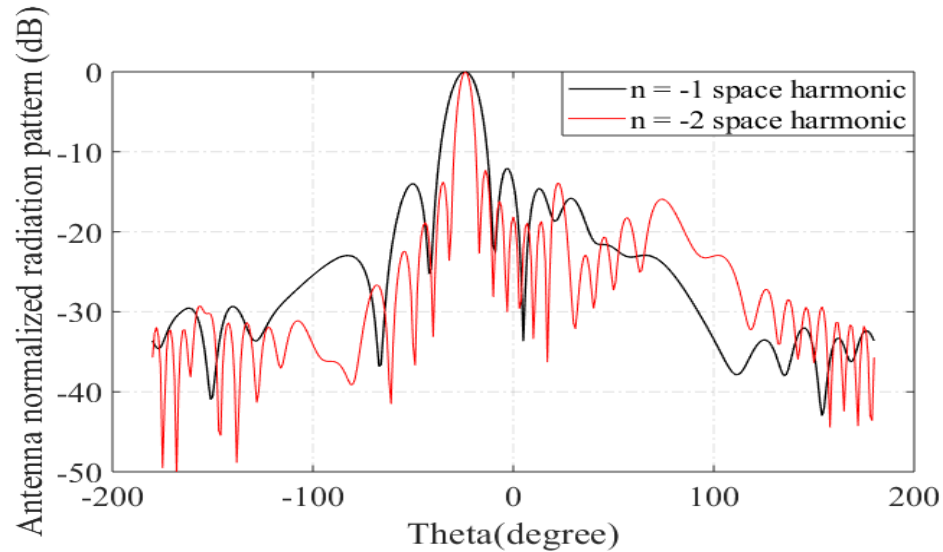


Figure 4.32 Normalized radiation pattern (E-plane) response of two LWAs based on the analyses of Figures 4.26-4.31

on the $n = -1$ space gradually increases for the frequency range above 33GHz since its related space harmonic becomes a fast wave. On the other hand, the LWA based on the $n = -2$ space harmonic gradually increases for the frequency range above 35GHz where we are able to get a single fast wave response of it. Figure. 4.31 also compares the radiation efficiency response of these two LWAs. The analyses of Figure. 4.31 indicates that the LWA based on the $n = -2$ space harmonic achieves a higher radiation efficiency compared to the LWA based on the $n = -1$ space harmonic for the frequency range of our interest. Figure. 4.32 demonstrates the normalized radiation pattern (E-plane) response of two LWAs based on the analysis of Figures. 4.26-4.31 at their scanning

Table 4.3 Comparison between the antenna performances based on the $n = -1$ and $n = -2$ space harmonic based on the analyses of Figure 4.25-4.30

Antenna Type	Antenna bandwidths consider 10dB side lobe level (dB)	Maximum gain (dB)	Maximum directivity (dB)	Maximum radiation efficiency (%)	Antenna beam 3dB beam width at -24°	Scanning range consider 10dB side lobe level (degree)	Antenna average side lobe level (dB)
$n = -1$ space harmonic	34.2-37.4	12.8	14.6	0.63	13.9	-58 to -27	-10.5
$n = -2$ space harmonic	35.2-38.1	16.5	17.9	0.74	6.5	-55 to -11	-11.5

angle of 27° . The LWA based on the $n = -2$ space harmonic has a higher gain compared to the LWA based on the $n = -1$ space harmonic. Hence, we should expect to have a narrower beam for the LWA based on the $n = -2$ space harmonic. The analyses of Figure. 4.30 indicate the same behavior in which the beam related to the $n = -2$ space harmonic has a narrower beam compared to the beam of $n = -1$. This shows a good agreement with the analyses of Figures. 4.25-4.29. Here the 3dB beamwidth of the LWA based on the $n = -1$ and $n = -2$ space harmonics are 13.2° and 6.5° , respectively. The analysis of Figure. 4.30 shows that the side lobe level of the beams related to the $n = -1$ and $n = -2$ space harmonics are -12.4 and -13.7 respectively. It should be noted that in our analysis, we considered the acceptable beam with 10 dB sidelobe level. In this regard, the actual useful bandwidth of the antenna for the $n = [-1, -2]$ space harmonics are $34.2 < f_{\text{GHz}} < 37.4$ and $35.2 < f_{\text{GHz}} < 38.1$, respectively. The analyses of Figure. 4.25-4.30 indicate that the $n = -2$ space harmonic can achieve higher directivity, gain, radiation efficiency, and side lobe level while the antenna with the $n = -1$ space harmonic can provide slightly wider bandwidth. Thus, a comparison between the LWA performance between the $n = -1$ and the $n = -2$ space harmonic for different antenna parameters are studied, analyzed and investigated where we highlighted the tradeoff of the LWA characteristics based on different configurations of single space harmonic.

Considering the analyses of Figure. 4.25-4.30 will give use an antenna with a single beam operation. However, such performance may not be able to satisfy the requirements of other applications in which we need to use a multi-beam for our antenna. Recently, a novel code

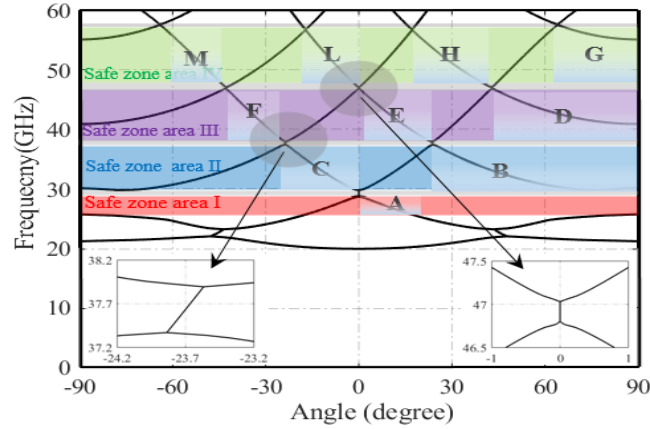


Figure 4.33 Frequency versus scanning angle variation of HSH ($-4 \leq n \leq -1$) based on the analysis of the Brillouin diagram of Figure 4.17

Book was introduced in [40]-[43], it enables a common source MBA to be used for communication purposes. In this thesis, we also investigate how utilizing the different space harmonic enables us to achieve a common source MBA. Figure. 4.33 shows the behavior of the scanning range of HSH ($n \in [-1, -2, -3, -4]$) based on analysis of Figure. 4.17 for different safe zone areas and boundary regions. The analysis of Figure. 4.17 and Figure.4.33 shows that the scanning angles of the lower space harmonics (such as $n = -2$) decreases when they are appearing in the higher safe zone areas (such as safe zone area IV). In addition, the analysis of Figure. 4.17 and Figure. 4.33 show that the scanning range of HSH $n \in [-1, -2, -3, -4]$ decreases when the width of the FWR region increases in terms of $\beta_n p / \pi$. In Figure. 4.17, the width of FWR in safe zone areas II and IV are $-3 < \text{FWR}_{\text{width}} < 3$ and $-5 < \text{FWR}_{\text{width}} < 5$ (in terms of $\beta_n p / \pi$), respectively. The scanning angle of $n \in [-1, -2]$ space harmonics decreases when they are penetrating the safe zone area IV. The scanning angle behavior of HSH in different boundary regions is highlighted in Figure. 4.33 which shows good agreement with analysis of Figure. 4.17. The band edge issue of HSH is further investigated in chapter 6 of this Thesis.

Rectangle A in Figure. 4.33 shows the non-scanning range area of safe zone area I, where the beams related to the $n = -1$ space harmonic cannot scan. Square A of Figure. 4.33 and the missing scanning range are related to Circle N of safe zone area I of Figure. 4.17, in which the $n = -1$ space harmonic cannot penetrate the region of $0 < \beta_n p / \pi < 1$ (the excitation considered to be from one side only). Squares B and C of Figure. 4.33 show the non-scanning range area of safe zone area II where the beams related to the $n = -1, n = -2$ space harmonics cannot scan. Squares B and C of

Table 4.4 Relation between scanning region and non-scanning region based on the analysis of the Brillouin diagram of Figure 4.17

Space harmonic	Propagation constant of the scanning region		Signal of interest and related circle		Signal of not interest and related circle		Propagation constant of the nonscanning region	Safe zone area
$n = -1$	$-1 < \beta_{-1}p/\pi < 0$	$\rightarrow$	Improper Backward Circle A	$\leftrightarrow$	Proper Forward Circle N	$\leftarrow$	$0 < \beta_{-n}p/\pi < -1$	Safe zone area I
$n = -1$	$0 < \beta_{-1}p/\pi < 1$	$\rightarrow$	Proper Forward Circle B	$\leftrightarrow$	Improper Backward Circle P	$\leftarrow$	$-1 < \beta_{-n}p/\pi < 0$	Safe zone area II
$n = -2$	$-2 < \beta_{-2}p/\pi < -1$	$\rightarrow$	Improper Backward Circle C	$\leftrightarrow$	Proper Forward Circle O	$\leftarrow$	$1 < \beta_{-n}p/\pi < 2$	Safe zone area II
$n = -1$	$1 < \beta_{-1}p/\pi < 2$	$\rightarrow$	Proper Forward Circle D	$\leftrightarrow$	Improper Backward Circle S	$\leftarrow$	$-2 < \beta_{-n}p/\pi < -1$	Safe zone area III
$n = -2$	$-1 < \beta_{-2}p/\pi < 0$	$\rightarrow$	Improper Backward Circle E	$\leftrightarrow$	Proper Forward Circle R	$\leftarrow$	$0 < \beta_{-n}p/\pi < 1$	Safe zone area III
$n = -3$	$-3 < \beta_{-3}p/\pi < -2$	$\rightarrow$	Improper Backward Circle F	$\leftrightarrow$	Proper Forward Circle Q	$\leftarrow$	$2 < \beta_{-n}p/\pi < 3$	Safe zone area III
$n = -1$	$2 < \beta_{-1}p/\pi < 3$	$\rightarrow$	Proper Forward Circle G	$\leftrightarrow$	Improper Backward Circle W	$\leftarrow$	$-3 < \beta_{-n}p/\pi < -2$	Safe zone area IV
$n = -2$	$0 < \beta_{-2}p/\pi < 1$	$\rightarrow$	Proper Forward Circle H	$\leftrightarrow$	Improper Backward Circle V	$\leftarrow$	$-1 < \beta_{-n}p/\pi < 0$	Safe zone area IV
$n = -3$	$-2 < \beta_{-3}p/\pi < -1$	$\rightarrow$	Improper Backward Circle L	$\leftrightarrow$	Proper Forward Circle U	$\leftarrow$	$1 < \beta_{-n}p/\pi < 2$	Safe zone area IV
$n = -4$	$-4 < \beta_{-4}p/\pi < -3$	$\rightarrow$	Improper Backward Circle M	$\leftrightarrow$	Proper Forward Circle T	$\leftarrow$	$3 < \beta_{-n}p/\pi < 4$	Safe zone area IV

Figure. 4.33 (missing scanning range) are related to Circles O and P, respectively, of safe zone area II of Figure.4.17 where $n \in [-1, -2]$ space harmonics cannot penetrate the regions of $-1 < \beta_{-n}p/\pi < 0$ and $1 < \beta_{-n}p/\pi < 2$. Squares D, E and F in Figure. 4.33 shows the non-scanning range area of safe zone area III where the beams related to $n \in [-1, -2, -3]$ cannot scan. Squares D, E and F of Figure. 4.33 (missing scanning range) are related to Circles Q, R and S, respectively, of Figure. 4.17 in safe zone area III, where $n \in [-1, -2, -3]$ space harmonics cannot penetrate the region of $2 < \beta_{-n}p/\pi < 3$, $0 < \beta_{-n}p/\pi < 1$ and $-2 < \beta_{-n}p/\pi < -1$. Squares G, H, L and M in Figure. 4.33 show the non-scanning range area of safe zone area IV where the beams related to the $n \in [-1, -2, -3, -4]$ cannot scan. Squares G, H, L and M of Figure. 4.33 (missing scanning range) are related to the Circles W, V, U and T of Figure. 4.17 in safe zone area IV, respectively, where none of the $n \in [-1, -2, -3, -4]$ cannot penetrate the regions of $3 < \beta_{-n}p/\pi < 4$, $1 < \beta_{-n}p/\pi < 2$, $-1 < \beta_{-n}p/\pi < 0$ and $-3 <$

$\beta_{-n}p/\pi < -2$. Table 4.4 shows the relations between the scanning and non-scanning regions of Figure. 4.33 and Figure. 4.17. If we assume to have a simple radiating element, such as a transverse slot, while considering the stop bands, then based on the analysis of Figure. 4.17 and Figure. 4.33. and Table 4.4, for frequencies below boundary regions II and IV in safe zone areas II and IV, we have an approximate equal absolute value of the propagation constants of $|\beta_{-1}| \approx |\beta_{-2}|$ and $|\beta_{-1}| \approx |\beta_{-2}| \approx |\beta_{-3}| \approx |\beta_{-4}|$, respectively. This can give us approximate symmetrical beams. However, it is not possible to have exact symmetric beams due to the band edge issue of frequencies related to boundary regions 2 and 4, in which $|\beta_{-1}| = |\beta_{-2}|$ and $|\beta_{-1}| = |\beta_{-2}| = |\beta_{-3}| = |\beta_{-4}|$ (if a simple radiating element is used). The band edge issue of HSH is further investigated in chapter 6 of this paper. Here we are solely focusing on the HSH behavior of different safe zone areas. Thus, based on the analysis of Figure. 4.17 and Figure. 4.33. and Table 4.4, it is not possible to have exact symmetric beams by using one antenna with a simple radiating element (simple transverse slot). However, in order to have exact symmetric beams, two 1D-periodic LWAs with the same periodicity and same radiating elements can be used as an array with two subarrays in which we feed simultaneously each of the subarrays from different sides (one from left side another from right side) without any phase difference. A wider scanning range can be achieved compared to a single 1D-periodic LWA due to the use of non-scanning regions as scanning regions. The symmetric beam radiation of an array is achieved due to the symmetric relationship between the scanning and non-scanning regions as explained in Figure. 4.17 and Figure. 4.33. and Table 4. 4, in which the propagation constants of space harmonics of Circles A, B, C, D, E, f, G, H, L and M have negative values compared to Circles N, P, O, S, R, Q, W, V, U and T, respectively. Thus, in the case of an array, we use non-scanning regions of one subarray as scanning regions of another subarray to achieve a wider scanning range. In addition, the beams in each of the safe zone areas are symmetric (for array case) since the absolute value of the propagation constants related to each space harmonic of each subarray are equal. Figure. 4.34 shows an example of the behavior of the array radiation pattern based on the analysis of Figure. 4.19, in which we have four beams in safe zone area II (we used matched loads in all un-excited ports in order to avoid unwanted reflected waves which create mirrored beams). The beams of the red circles are related to one subarray (fed from the right), and beams with the green circles are related to the other subarray (fed from the left). The beams of Circles A and B of Figure. 4.34 are related to the $n \in [-1, -2]$ space harmonics, respectively, in which $\beta_{-2R} < 0$ and $\beta_{-1R} > 0$ (feed subarray from the right side). For the other subarray (fed from

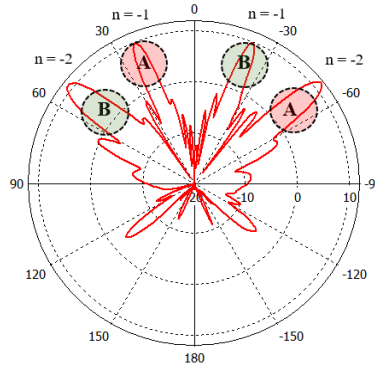


Figure 4.34 E-plane co-polar radiation pattern for the frequency of $f = 37$ GHz of an array based on the analysis of the Brillouin diagram of Figure 4.19

the other side), the beams of Circles C and D of Figure. 4.34 are related to the $n \in [-1, -2]$ space harmonics, respectively, in which $\beta_{-2L} < 0$ and $\beta_{-1L} > 0$. In Figure. 4.34, the absolute value of the propagation constant related to the $n \in [-1, -2]$ space harmonics of each subarray are equal ($|\beta_{-1R}| = |\beta_{-1L}|$, $|\beta_{-2R}| = |\beta_{-2L}|$) which results in having symmetric beams for the radiation pattern of antenna. In the next section, we validate our analyses by showing an antenna prototype.

4.5. Antenna Prototype and Experimental Validation

Figure. 4.35 shows the design prototype of an SIW-LWA and the measurement setup of anechoic chamber room. The material which used here is the RT6010 with permittivity and thickness of 10.7 and 25mil, respectively. The width of SIW structure consider to be 2mm in order to have a single mode operation (TE_{10}) for the frequency range of interest ($35 < f_{GHz} < 39$). The end launch connector is utilized here to excite the antenna and 3D plastic holder is used to hold the antenna in the anechoic chamber room. In the proposed design, we use a series of transverse slots as our radiating element. The slot width and slot length consider to set as $0.5\lambda_g$ (2.2mm) and $0.35\lambda_g$ (1.54mm), respectively. The periodicity of radiating element choose based on the analyses of Fig. 6 as 5.6mm. Figure. 4.36 shows that the measured antenna reflection coefficient is below -10 dB, between $35.1 < f_{GHz} < 39$, corresponding to a bandwidth of 10.8%. There is a small discrepancy between the measured and simulated results is observed due to fabrication tolerances. According to the analyses of Figure. 4.26, it is expected to have a single proper beam of the $n = -2$ space harmonic for the frequency range of interest. Figure. 4.37 shows the measured and simulated normalized radiation patterns of the antenna at for two different angles of -55° and -14° .

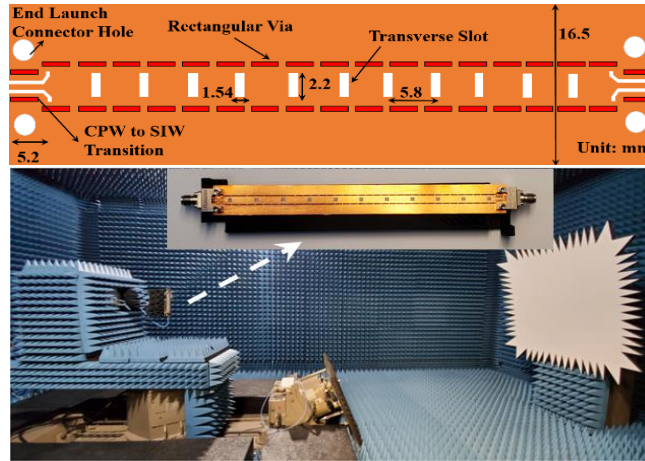


Figure 4.35 Prototype of the SIW-LWA with series of transvers slots (port number indicates at the up-left and bottom-right of the array antenna)

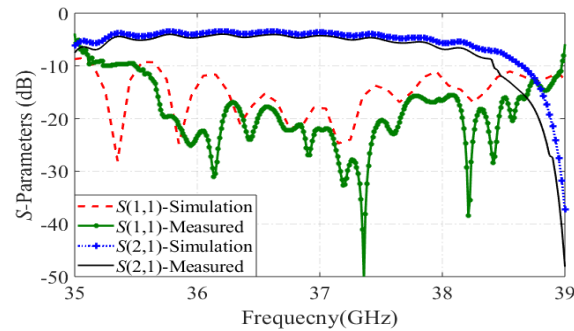


Figure 4.36 Simulated and measured S-parameters of SIW-LWA of Figure 4.35

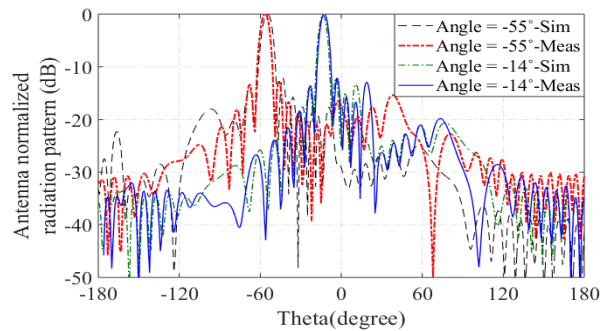


Figure 4.37 Normalized radiation pattern (E-plane) response of antenna prototype of Figure 4.35 for two different beam angles

The analyses of Figure. 4.36 indicates that we can get the benefit of the $n = -2$ space harmonic as a single backward beam through the antenna acceptable operation bandwidth. Here the antenna beam have an average of 12.5dB side lobe level with the 3dB beam width of 6.4° . Figure. 4.38 shows the antenna gain and radiation efficiency. The peak gain of the antenna is 12dB and the maximum radiation efficiency is 0.73. The proposed antenna can achieve scanning range from

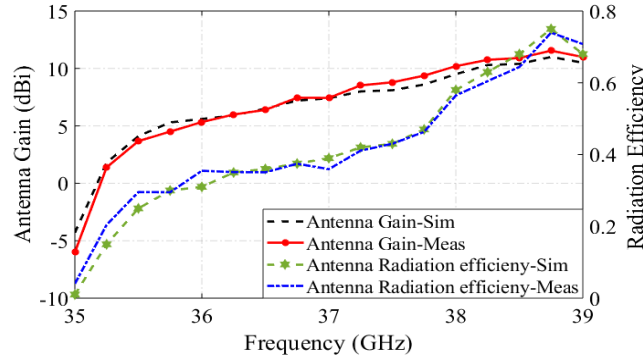


Figure 4.38 Antenna gain and radiation efficiency of the antenna prototype of Figure 4.35

-57° to -11° which shows a good agreement with analyses of Figure. 4.26. Thus, a good agreement is observed between the analyses, simulation, and measurement for validation the proof of SIW-LWA based on HSH concept.

4.6. Conclusion

The concept of HSH ($n \in [-1, -2, -3, -4]$) in a 1D-periodic SIW-LWA was studied, analyzed and applied to the theoretical analyses and experimental validation in this chapter of this thesis. The conditions of excitation of even and odd HSH ($n \in [-1, -2, -3, -4]$) for different unit-cell were studied and analyzed. The propagation constant behavior of even and odd HSH ($n \in [-1, -2, -3, -4]$) and their sensitivity to the permittivity (dielectric constant of propagating media) variation for different periodicities were studied and the behavior of HSH contribution to the FWR are highlighted. Besides, effect of propagating SIW modes of TE_{10} and TE_{20} to the excitation condition of even and odd HSH was studied and their differences was highlighted. Furthermore, the radiation properties of HSH for different frequency ranges in different safe zone areas and boundary regions were studied and demonstrated. Moreover, the behavior response of fundamental space harmonic of a periodic structure related to the fundamental mode of the SIW structure was compared to the HSH of the related mode in which different antenna performances such as directivity, gain, radiation efficiency, beam width, side lobe level, and bandwidth are investigated and their tradeoff are highlighted. Furthermore, the scanning ranges variation of HSH ($n \in [-1, -2, -3, -4]$) for different stop band and pass band were studied and analyzed. The proposed analysis and methodology demonstrated in this thesis can also be extended to explain and predict the behavior of other HSH ($n \leq -5$). A prototype of 1D-periodic SIW-LWA were shown in this chapter as a proof of concept and experimental validation of the analysis and conclusions put forward for the HSH concept.

CHAPTER 5 ARTICLE 2: MULTI-BAND MULTI-BEAM HIGHER-ORDER SPACE HARMONICS-ENABLED LEAKY-WAVE ANTENNAS

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In recent years, considerable efforts have been made in realizing multi-band and multi-beam antennas (MBMBAs). These types of antennas have widely been used in wireless communication systems [44] due to their capability of providing better channel capacity and wider scanning range especially for base station applications. Several methods were proposed to realize dual-band LWAs, such as the dual-mode composite microstrip-line (DMC-MS) [45], back-to-back slotted array substrate integrated waveguide LWA (SIW-LWA) [46], Mu-negative (MNG) transmission line [47], ultra-broadband radiating element [48], and composite right-/left-hand (CRLH) transmission line [49]. However, most of these design techniques generally steer only one beam through their operating frequency band. Thus, they cannot be used as MBAs. It should be mentioned that MBAs based on the operation mechanism of their beams are divided into two different categories. The first category belongs to MBAs that are not capable of switching between the differently generated beams [50]-[54]. The second category belongs to MBAs featuring the capability of beam switching or beam selection. Several beam forming network (BFN) methods, such as Nolen [55], Butler matrices [56]-[57], Luneburg lens system [58], R-KR [59], and Rotman lenses [60], can be used in this type of MBAs for beam switching. However, all these BFNs methods have some disadvantages in terms of design complexity, size, bulkiness, and/or cost. In addition, most of the MBAs (beam switchable) are usually limited to one frequency band operation due to their dependency of their structure on wavelength and they can only produce a predefined beam angle which makes them amenable for the case of continuous beam steering.

On the contrary, an LWA enjoys the benefits of being simple, wide band and low cost in beam steering applications. Most of the current 1D-periodic LWAs only steer one beam within their operating frequency range [61]-[63]. However, some methods can be used with LWA to achieve a common source multi-beam LWA (MB-LWA), such as aperture coupled feeding [64]-[65], defected ground structure (DGS) with CRLH [66], holographic synthesizing method [67]-[68], utilizing IF and LO frequency in a high electron-mobility transistor (HEMT) resistive up converter

[69] and dual mode transition line (used as dual-polarized antenna) [70]. A dual-beam LWA with the capability of beam switching using orthogonal-polarization concept was developed in [71]-[72] at the expense of adding orthomode transducer (OMT) as the feeding network to the antenna which increases the size and complexity of overall structure. Nevertheless, a combination of multi-band and multi-beam features for beam steering of LWAs with a simple feeding mechanism, sufficiently reduces the volume of the wireless communication system and its complexity where as a coding technique can be utilized to resolve the signals from different beams [40]-[43]. In this regard, this thesis aims to tackle the above limitations of LWA by utilizing the HSH concept in which we demonstrate a methodology for design the LWA as MBMBA where we are able to have the flexibility of choosing the number of antenna band and also the number and position of the antenna beam for each frequency band of operation. In this work, we introduce a method for designing and analyzing 1D-periodic LWAs as common source multi-band multi-beam radiators utilizing the feasibility and stability of HSHs ($n \leq -1$) to manipulate them as physical fast waves in different passband of our proposed antenna. This work is different from [73] where they focus on the development of a relation between the number of stop bands and the periodicity for a multiple periodic structure of CRLH-LWA. Although the second space harmonic ($n = -2$) was used in [74]-[75] to achieve a dual-beam LWA, several aspects of the fundamental analysis using HSH ($n \leq -1$), such as radiation properties, scanning range limitations, unit cell geometries, effect of propagation modes and propagation constant behaviors (β_n) for different passband and stopband cases were not discussed or were missing. Hence, we demonstrate in this work a comprehensive analysis of HSHs ($n \in [-1, -2, -3, -4]$) which cover all the missing points and explanations in previous works. In addition, we make use of a combination of $n \in [-1, -2]$ space harmonics to simultaneously achieve a dual-band multi-beam LWA. Moreover, in this work, a triple-band multi-beam LWA is demonstrated to show how the concept of HSH ($n \leq -1$) can be used to design multi-band and multi-beam LWA for current and future developments of wireless communications. This contribution is different from [70] where each space harmonic of $n \in [0, -1]$ is separately used for each band of the antenna and two kinds of periodic structures were used to excite two $n = -1$ spatial harmonic waves for dual-beam operation through two antenna apertures. The authors of [70] used different radiating elements with different periodicities for achieving a dual-beam triple band operation. However, in our proposed work the multi-beam and multi-band operation are achieved

by using only one radiating element and one periodicity which can significantly reduce the design complexity and antenna size which could be good candidate for future wireless applications.

5.1. HSH Unit-Cell Analysis In 1D-Periodic LWA

The $n = -1$ space harmonic can act as a physical fast wave over a specific frequency range in most of 1D-periodic LWAs. However, there is a possibility of exciting HSHs, such as $n = -2$, as a leaky wave over a specific frequency range by increasing the periodicity between the radiating elements and/or increasing the permittivity of the propagating media (or increasing the frequency range of interest). The coupling and interdependency of the $n = -2$ space harmonic was partially discussed in [35]-[38], and the focus was on providing a detailed analysis of the propagation constant behavior of the $n = -1$ space harmonic and its complete spectrum analysis of 1D-periodic LWA. Hence, several aspects of HSH characteristics such as radiation properties, scanning range limitations and propagation constant behaviors (β_n) were missing in these references which we will study and analyze in details in this thesis.

In order to get a constructive contribution of the $n = -2$ space harmonic to the radiation of a periodic LWA, this space harmonic must behave as a physical fast wave and has to penetrate the FWR. In other terms, the absolute value of the propagation constant of the $n = -2$ space harmonic (β_{-2}) should be less than the free-space wavenumber ($|\beta_{-2}/k_0| \leq 1$). Thus, in order to investigate the interdependency and characteristic behavior of the $n = -2$ space harmonic with respect to other space harmonics ($n \leq -1$), we analyze the behavior of the propagation constant of the 4 HSHs ($n \in [-1, -2, -3, -4]$), which consists of two higher-order even space harmonics ($n \in [-2, -4]$) and two higher-order odd space harmonics ($n \in [-1, -3]$) to examine the consequences on the radiation properties of each of them. In the 1D-periodic LWA, for each of the HSHs ($n \leq -1$) to act like a fast wave in a specific frequency range. Stated otherwise, if the absolute value of propagation constants (β_n) of HSHs ($n \leq -1$) obeys $|\beta_{n<-1}/k_0| \leq 1$, then the wave behavior of a related space harmonic can be represented as a physical fast wave over a specific frequency range, and hence it acts like a radiating wave. For 1D-periodic LWA to satisfy the condition of $|\beta_{n<-1}/k_0| \leq 1$ for a specific frequency range of $n \in [-1, -2, -3, -4]$ space harmonics, we must have the conditions for (β_n) as:

$$\beta_n = \beta_0 + 2n\pi/p \quad \rightarrow \quad |\beta_{-n}/k_0| \leq 1 \quad (5.1)$$

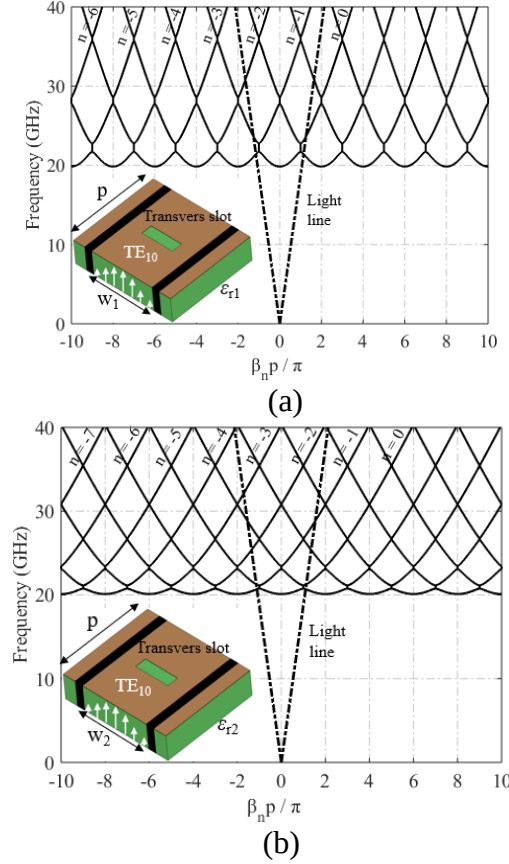


Figure 5.1 Unit-cell analysis of HSHs of TE₁₀ mode of an SIW with $p = 8$, (a) $w_1 = 3.95$, $\epsilon_{r1} = 3.66$, (b) $w_2 = 2.28$, $\epsilon_{r2} = 10.7$ (dimensions are in mm)

in 1D-periodic SIW-LWA. In this case, the phase constant (β_0) of the propagating media in the SIW structure can be written as:

$$\beta_0 = \sqrt{\epsilon_r k_0^2 - \left(\frac{\pi}{w_{eff}}\right)^2} \quad (5.2)$$

As seen from equation (1) the HSH excitation depends on β_0 of the propagating media, where n is an integer and p is the periodicity. In this work, we focus on the analysis of HSHs of the TE₁₀ mode where ϵ_r is the permittivity and w_{eff} is considered to be the effective width of the transmission line. As such, the HSH excitation for the case of TE₁₀ mode of the SIW structure also depends on the geometry of the SIW unit-cell. To have a better perspective of the excitation conditions of HSHs of the TE₁₀ mode, we make use of equations (1)-(2) to plot the Brillouin diagram for two different unit-cells of the SIW structure to examine and illustrate the behavior of HSHs in connection with each one. Figure. 5.1 shows the Brillouin diagram analysis for two different unit-cells of the TE₁₀ mode of the SIW structures. The materials used in this analysis are commercial substrates RT6035

and RT6010 with $\epsilon_r = 3.66$ and $\epsilon_r = 10.7$, respectively. The periodicity and thickness of the unit-cells are considered as $p = 8\text{mm}$ and 0.762mm , respectively. Here, we are interested in analyzing the behavior of HSHs in the Ka-band. For this purpose, the SIW width of RT6035, and RT6010 in Figure. 5.1 are considered to be 3.95 and 2.28 (all in mm), respectively, in order to have single mode operation (TE_{10}) for the frequency range $20 < f_{\text{GHz}} < 40$ and the cutoff of the TE_{20} mode (higher mode) is set to be 40 GHz in both cases to avoid hybrid-mode coupling [77]-[78] in the frequency range of interest. The periodicity is the same in both unit-cells in order to have a fair comparison between HSH behaviors.

The comparison between Figures. 5.1(a) and 5.1(b) shows that the capability of contribution of HSHs in the FWR as a single space harmonic is reduced (in terms of frequency range) by decreasing the geometry and increasing the permittivity value of the unit cell. For instance, in Figures. 5.1(a) and 5.1(b), the contributions of the $n = -1$ space harmonic in the FWR as a single space harmonic are 7.2 GHz ($23.6 < f_{\text{GHz}} < 30.8$) and 4.15 GHz ($21.2 < f_{\text{GHz}} < 25.35$), respectively. On the other hand, the stability of the space harmonics in the FWR of the unit-cell with lower permittivity is more than the unit-cell with higher permittivity. For instance, the $n = -1$ space harmonic in Figure. 5.1(a) can remain as a fast wave for the frequency range of $21.4 < f_{\text{GHz}} < 40$ while in Figure. 5.1(b), the contribution of this space harmonic decreases to the frequency range of $20.7 < f_{\text{GHz}} < 28.8$. In addition, the observation of Figure. 5.1 shows that using materials with high permittivity can involve more HSHs within the frequency operation of the transmission line mode. Here the unit cells of Figures. 5.1(a) and 5.1(b) have capabilities of involving 3 ($n \in [0, -1, -2]$) and 4 ($n \in [0, -1, -2, -3]$) space harmonics, respectively, for the case of TE_{10} mode. However, the slope variation of HSHs in the SIW unit-cell with high permittivity is more than the SIW unit-cell with low permittivity. Thus, we can say that the SIW unit-cell with low permittivity can provide more dispersion linearity for the HSHs in which it allows them to remain as fast waves for wider frequency ranges in the FWR of the transmission line mode (this TE_{10} mode case). It should be mentioned that besides the analysis of HSHs for the unit-cell geometry and its relation to the propagation mode of the transmission line, we also need to analyze the effect of the radiating element on the performance of LWAs, which is discussed in the following section.

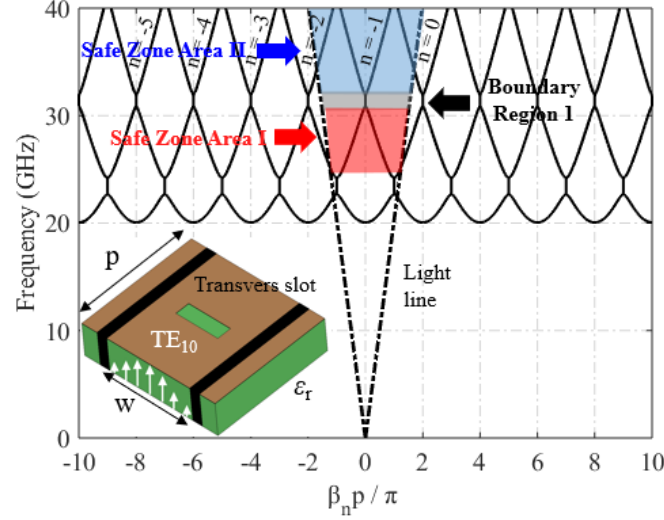


Figure 5.2 Brillouin diagram for a 1D-periodic LWA with periodicity of $p = 7\text{mm}$ on a dielectric propagating medium of $\epsilon_r = 2.94$ and $w = 4.36\text{mm}$

5.2. Unit-Cell Analyses of Multi-Band Multi-Beam 1D-periodic LWA (MBMB-1D-LWA)

In the previous section, we showed that a material with low permittivity can provide more dispersion linearity for HSHs. Here we want to take advantage of this feature in the design of an 1D-periodic LWA in order to achieve a common source multi-band and multi-beam LWA (MBMB-LWA). As a first step, we define our frequency range of interest as Ka-band frequency ($26.5 < f_{\text{GHz}} < 40$). In order to support this frequency range, we need to choose the dimensions and material of our SIW unit-cell. Figure. 5.2 shows a Brillouin diagram for an SIW unit-cell with a propagating medium with a dielectric constant of $\epsilon_r = 2.94$ and thickness of 0.765mm . To support this frequency range we consider the width of the SIW to be 4.36mm in order to have single mode operation (TE_{10}) for our frequency range of interest (the cut-off of TE_{10} and TE_{20} modes are 20GHz and 40GHz , respectively). The parameters of the waveguide structure are chosen in a suitable way in order to avoid hybrid-mode coupling [77]-[78] for the frequency range of interest. It should be mentioned that in this work we mainly focus on analyzing the behavior of HSHs ($n \leq -1$). Thus, the geometry of the SIW unit-cell in Figure. 5.2 is chosen in order not to have the $n = 0$ space harmonic as a fast wave for the frequency range of our interest. Here the condition of $|\beta_0/k_0| \leq 1$ is satisfied for the frequency range of $20 < f_{\text{GHz}} < 25.26$.

As mentioned in the previous section, the stability of HSHs in the FWR for a material with lower permittivity is more than a material with higher permittivity. Therefore, it should be expected that choosing a suitable periodicity value gives us the benefit of using more than one HSH as fast wave in the FWR within the frequency range of our transmission line mode (this work TE₁₀ mode). The analysis of equations (5.1)-(5.2) shows that for the value of $p = 7\text{mm}$ we are able to obtain HSHs of $n \in [-1, -2]$ as fast waves in which we are able to satisfy the condition of $|\beta_{-1}/k_0| \leq 1$ and $|\beta_{-2}/k_0| \leq 1$. In Figure. 5.2, for frequencies of $f \geq 22.4\text{ GHz}$, the excitation condition of $n = -1$ space harmonic is satisfied ($|\beta_{-1}/k_0| \leq 1$) and its beam appears near backward endfire in the FWR where $\beta_{-1} = \beta_0 - 2\pi/p$. For the frequency range of $22.4 < f_{\text{GHz}} < 25.26$, we have $n \in [0, -1]$ space harmonic in FWR in forward and backward quadrants, respectively (the $n = 0$ space harmonic becomes a slow wave for $f > 25.26\text{ GHz}$). Hence, For the frequency range of $25.26 < f_{\text{GHz}} < 30.9$, we have only one proper (backward) beam ($n = -1$) where we denote this frequency range as safe zone area I in which the $n = -1$ space harmonic can contribute to the radiation pattern of the antenna without involving any lower or HSH.

In Figure. 5.2, for the frequency range of $30.9 < f_{\text{GHz}} < 31.8$, we have a stopband (here we refer it as boundary region 1) where $\beta_{-1} = 0$ and $\beta_{-2}p/\pi = -2$. Thus, it is expected that the beam of $n = -1$ sticks to 0° at boundary region 1. For frequencies above $f = 34.6\text{ GHz}$ the excitation condition of $n = -2$ space harmonic is satisfied ($|\beta_{-2}/k_0| \leq 1$) and we have one improper beam ($n = -1$) with one proper beam ($n = -2$). Here we refer to the frequency range of $31.8 < f_{\text{GHz}} < 40$ as safe zone area II in which the $n \in [-1, -2]$ space harmonics can behave as fast waves without involving lower or HSH. The excitation frequency of $n = -2$ space harmonic can get closer or move away from boundary region 1 by choosing different values for the periodicity. In Figure. 5.2, it is expected to have issues in the performance of the antenna in boundary region 1 (if a simple radiating element such as transverse slot is used). Thereby, if we choose a suitable radiating element to get a radiation contribution from frequencies in safe zone areas I and II of Figure. 5.1, then it is possible to create a dual-band LWA for our frequency range of interest i.e. Ka-band. This is due to the open stopband frequencies at which the antenna performance deteriorates. Hence, we need to analyze the radiation stability of a radiating element for both bands of the antenna in order to achieve an acceptable performance. To accomplish this goal, we analyze the admittance/impedance behavior of the radiating element to examine the stability of it for both bands. Figure. 5.3 (a) and Figure 5.3(b) show the impedance behavior of a transverse slot for

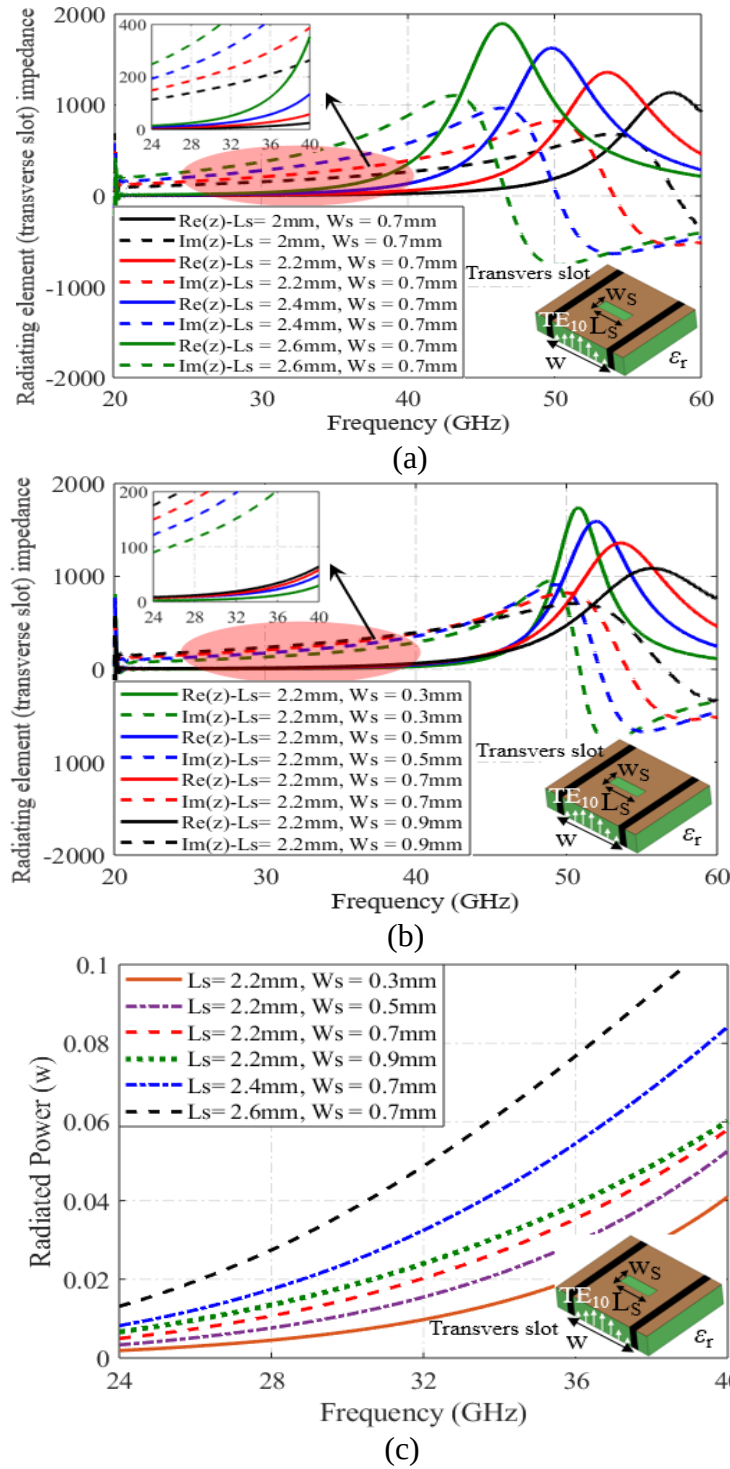


Figure 5.3 Impedance behavior of geometrical variation of radiating elements (transverse slot). (a) for slot length variation, and (b) for slot width variation (periodicity sets based on analysis of Figure 5.2 for both radiating elements), and (c) radiated power behavior of radiating element geometrical variation (transverse slot)

different slot dimensions. The periodicity and effective width of the SIW unit-cell in Figure. 5.3 are set based on the analysis of Figure. 5.2. The analysis of Figures. 5.3(a) and Figure. 5.3(b) show that the transverse slot with longer length and wider width can have more contribution to the real part of the radiating element impedance within the frequency operation of safe zone areas I and II compared to other dimensions. Since the radiated power in the far field is proportional to the real part of the input impedance [78]-[79], we should expect the transverse slot with wider geometry to radiate more power compared to other geometries. The radiated power behavior of the transverse slot geometrical variation also shows in Figure. 5.3(c) where the same behavior is observed for the geometrical variation of the radiating element compared to the Figures. 5.3(a) and Figure. 5.3(b). The analysis of Figure. 5.3 shows that the slope variation of the impedance radiating element (this transverse slot case) with wider geometry is sharper compared to other geometries and it causes more variation in the radiated power when it operates in safe zone areas I and II, which is not desirable for the dual-band or multi-band antenna. Therefore, we need to choose the radiating element in order to have more stability (flat) of the real part of the impedance or its radiated power behavior within the frequency range of our interest. The analysis of Figure. 5.3 shows that the transverse slot with dimensions of $L_s = 2.2\text{mm}$ and $W_s = 0.7\text{mm}$ can provide a suitable tradeoff between the slope variation and real part of the radiating element impedance (or radiated power) for the frequency range of interest. In the next section, we analyze and demonstrate a LWA based on the above unit-cell analyses.

5.3. Antenna Performance Analyses of Multi-Band Multi-Beam 1D-Periodic LWA (MBMB-1D-LWA)

In order to have a dual-band LWA, a wide band transmission line is required. Figure. 5.4 shows the schematic and simulated S-parameters of a back-to-back transmission line in which a transition between coplanar waveguide (CPW) to SIW is used. The width and thickness of the SIW are set to 4.36mm and 0.762mm, respectively, in order to have only one propagating mode (TE_{10}) in the frequency range of interest (Ka-band). Figure. 5.5 shows the model diagram of antenna and results of the simulated S-parameters for different slot lengths of the 1D-periodic SIW-LWA. The periodicity and dielectric constant values are selected based on an analysis of Figure. 5.2 where the antenna length is considered to be $14\lambda_0$. We also used a tapered slot in our design in order to

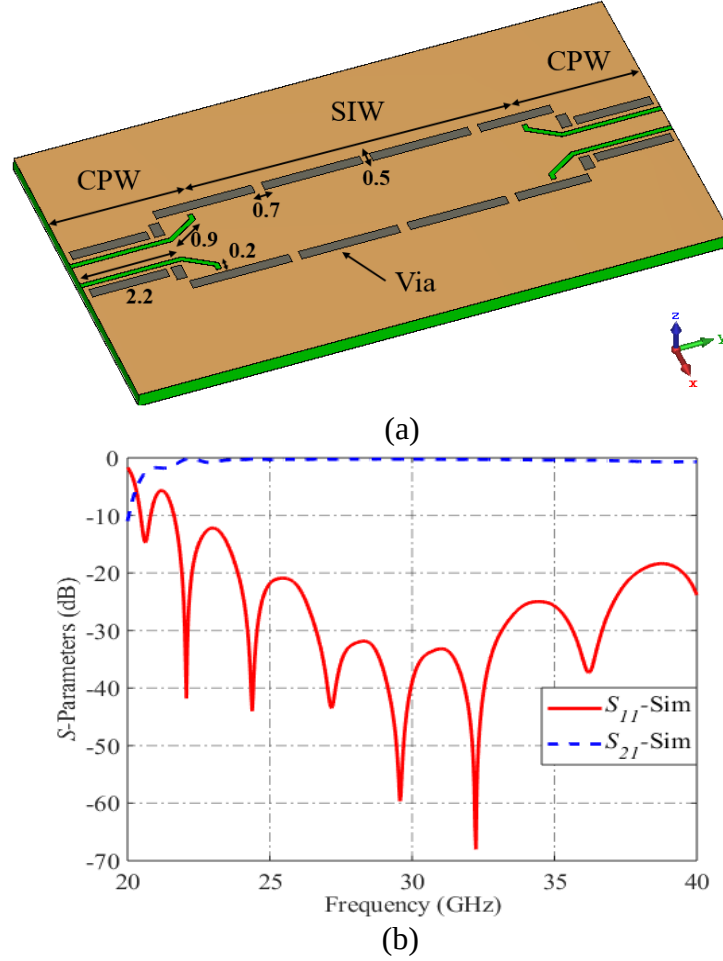


Figure 5.4 (a) Geometry of the proposed SIW with wide-band transition and (b) simulated S-parameters of back-to back transition

minimize unwanted end reflections. The methodology for tapering slots is explained in [80]-[81]. The analysis of Figure. 5.5 shows that a slot length with dimensions of 2.2mm and 0.7mm can provide suitable performance for the antenna in the lower and upper bands of the proposed dual-band LWA which shows a good agreement with the radiating element analysis of Figure. 5.3 and is chosen for fabrication. It should be mentioned that beside analyzing the Brillouin diagrams and the effect of the transmission line modes we also need to check the radiating element effect on the performance of the antenna for achieving an acceptable performance for our LWA.

Another point that needs to be investigated is the scanning range variation of HSHs. According to the Brillouin diagram theory analysis of Figure. 5.2, in safe zone area 1 the variation of β_{-1} is $-1 < \beta_{-1}p/\pi < 0$; and, in safe zone area II for $n \in [-1, -2]$ we have $0 < \beta_{-1}p/\pi < 1$ and $-2 < \beta_{-2}p/\pi < -1$. Comparing the two, it is expected that the missing scanning range of safe zone area II is

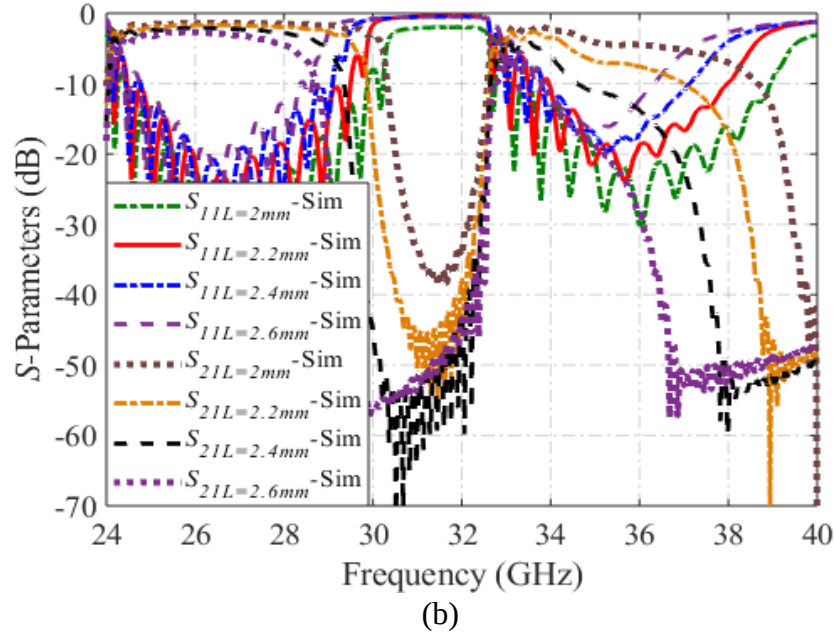
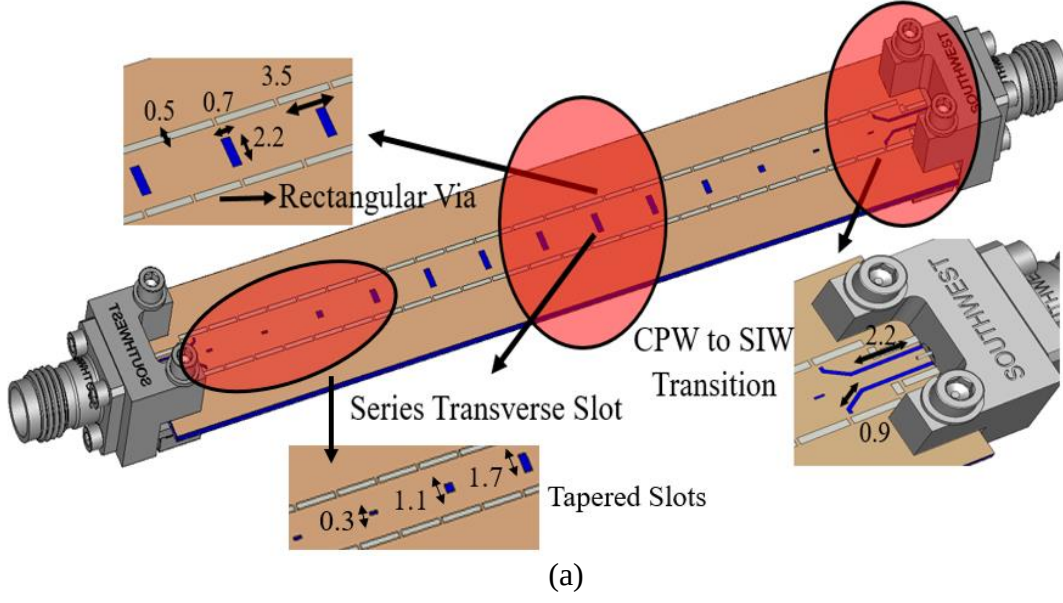


Figure 5.5 (a) Schematic design of the SIW-LWA with series of transverse slots (dimensions in mm) and (b) simulated S-parameters of different slot lengths

compensated by $n = -1$ space harmonic in safe zone area I. By considering the equation $\sin^{-1}(\beta_n/k_0)$ in safe zone area II of Figure. 5.2, the $|\beta_n/k_0|$ value of $n \in [-1, -2]$ space harmonics approximately varies from 0 to 0.44 and 1 to 0.57, respectively, which corresponds to the angles of 0° to 27° and -90° to -35° , respectively. The missing scanning range of the upper-band is compensated by $n = -1$ space harmonic in the lower-band where the variation of $|\beta_{-1}/k_0|$ is from 0.61 to 0 which

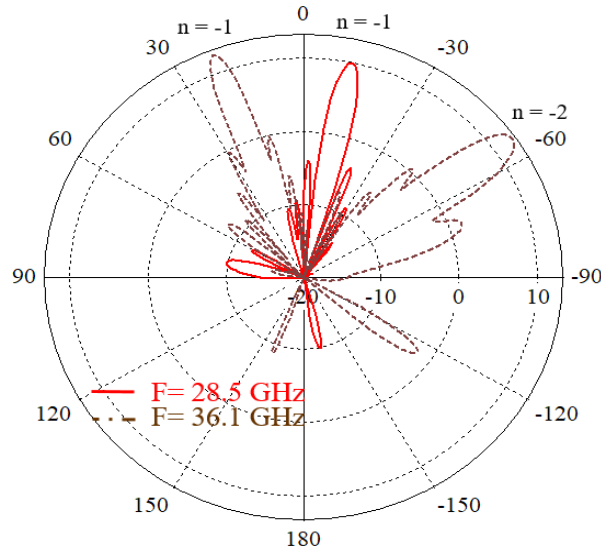


Figure 5.6 Simulated E-plane co-polar radiation pattern (in dB) of the dual-band multi-beam SIW-LWA for two different frequencies of $f_1 = 28.5$ GHz and $f_2 = 36.1$ GHz

correspond to the angles of -38° to 0° . Figure. 5.6 shows the simulated E-plane co-polar radiation pattern of the dual band LWA for two different frequencies of the lower band (safe zone I) and the upper band (safe zone II), namely $f_1 = 28.5$ GHz and $f_2 = 36.1$ GHz respectively. From the theoretical analysis of Figure. 5.2, the values of $|\beta_{-1}/k_0|$ for these two frequencies ($f_1 = 28.5$ GHz and $f_2 = 36.1$ GHz) are 0.21 and 0.35, respectively which correspond to the angles of 12° and 21° , respectively. In addition, the value of $|\beta_{-2}/k_0|$ in Fig. 3.2 at $f_2 = 36.1$ GHz is 0.83 which corresponds to the angle of 56° . These values are well matched with the beam angles simulated in Figure. 5.6. In addition, we expect (Figure. 5.3) the beam levels of the antenna in safe zone area II to be higher than safe zone area I and that is due to the higher real part impedance values which is proportional to the radiated power. This shows a good agreement with the simulation analysis of Figures. 5.5-5.6. The analysis of Figure. 5.6 also shows the antenna beams in the lower band compensate the missing scanning range of the upper band. Table 5.1 also shows the comparison between theoretical and simulation results of scanning ranges related to the $n \in [-1, -2]$ space harmonics in safe zone areas I and II of Figure. 5.2 where a good agreement is also observed.

It should be mentioned that the proposed concept can be used for the combination of different safe zone areas in order to achieve MBMBAs. Figure. 5.7 shows a Brillouin diagram for a periodicity $p = 12.75$ mm in a propagating media with a dielectric constant $\epsilon_r = 2.94$. Based on the analyses of Figure. 5.7, we have three different safe zone areas (II, III and IV) in our frequency

Table 5.1 Scanning angle variation of HSH in different safe zone area

Space Harmonics	Safe zone area I of Fig.2		Safe zone area II of Fig.2		-	
	Theory	Sim	Theory	Sim	Theory	Sim
n= -1	-38_0	-36_-6	0_27	4_26	-	-
n= -2	-	-	-90_-35	-85_-39	-	-
Space Harmonics	Safe zone area II of Fig.7		Safe zone area III of Fig.7		Safe zone area IV of Fig.7	
	Theory	Sim	Theory	Sim	Theory	Sim
n= -1	2_25	3_21	27_46	30_45	47_63	51_62
n= -2	-65_-25	-62_-28	-23_0	-22_-3	0_19	3_17
n= -3	-	-	-90_-46	-85_-45	-45_-19	-40_-22
n= -4	-	-	-	-	-90_-63	-85_-67

range of interest i.e. Ka-band. Thus, due to the band edge issue of frequencies in boundary regions 3 and 4, it is expected to have a triple-band operation for this proposed antenna. Figure. 5.8 shows the simulated results of the S-parameters of a triple-band SIW-LWA with a series of transverse slots based on the analyses of Figure. 5.7. The slot length and width were chosen based on the analysis of Figure. 5.3 as 2.2mm and 0.7mm, respectively, where the antenna length is set to $14\lambda_0$ as well. Based on the analysis of Figure. 5.7, it is expected to have one proper and one improper beams for the first band operating frequencies (safe zone II) where $0 < \beta_{-1}p/\pi < 1$ and $-2 < \beta_{-2}p/\pi < -1$. For middle band frequencies (safe zone III), it is expected to have one improper and two proper beams due to the condition of $1 < \beta_{-1}p/\pi < 2$, $-1 < \beta_{-2}p/\pi < 0$ and $-3 < \beta_{-3}p/\pi < -2$. Finally, for the

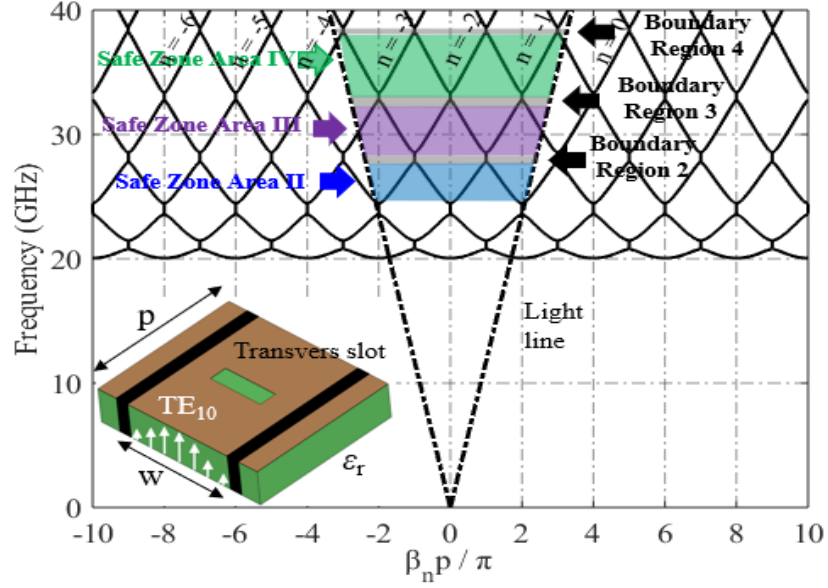


Figure 5.7 Brillouin diagram for a 1D-periodic LWA with periodicity of $p = 12.75\text{mm}$ in a dielectric propagating medium of $\epsilon_r = 2.94$ and $w = 4.36\text{mm}$

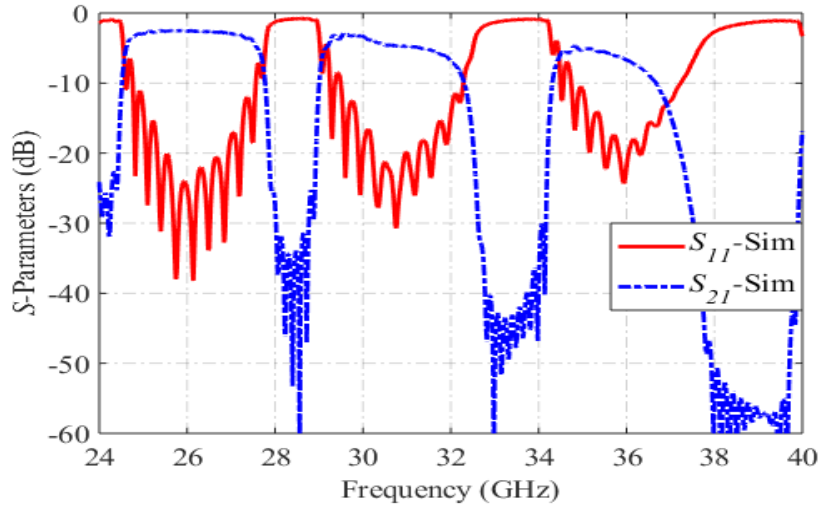


Figure 5.8 Simulated S-parameters of the triple-band SIW-LWA with a series of transverse slots based on analyses of Figure 5.7

third band it is expected to have two improper beams and two proper beams due to the conditions of $2 < \beta_1 p / \pi < 3$, $0 < \beta_2 p / \pi < 1$, $-2 < \beta_3 p / \pi < -1$, and $-4 < \beta_2 p / \pi < -3$. Thus, due to the complementary condition of the propagation constant value (β_n) of the HSH in different safe zone areas, it is expected that the missing scanning ranges of each band are compensated by the other bands.

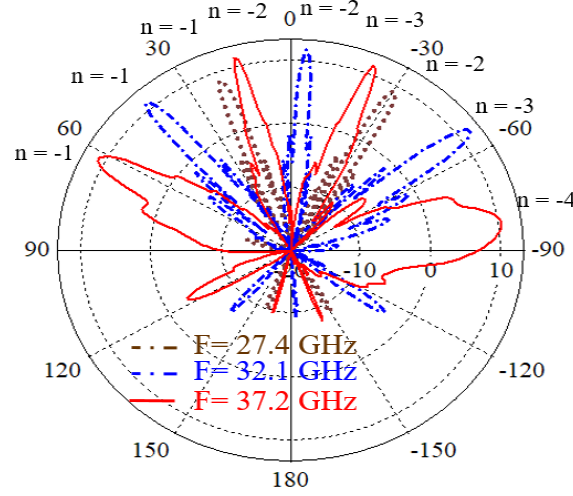


Figure 5.9 Simulated E-plane co-polar radiation pattern (in dB) of the triple-band multi-beam SIW-LWA for three different frequencies: $f_1 = 27.4$ GHz, $f_2 = 32.1$ GHz and $f_3 = 37.2$ GHz

Figure. 5.9 shows the simulation results of radiation patterns (E-plane co-pol) of the proposed triple-band SIW-LWA with a series of transverse slots for three different frequencies of the lower, middle and upper bands ($f_1 = 27.4$ GHz, $f_2 = 32.1$ GHz and $f_3 = 37.2$ GHz). It is clear that we have one forward beam ($n = -1$) and one backward beam ($n = -2$) in the lower band. We also have one forward beam ($n = -1$) with two backward beams ($n \in [-2, -3]$) in the middle band and two forward beams ($n \in [-1, -2]$) with two backward beams ($n \in [-3, -4]$) in the upper band. From Figure. 5.7, the values of $|\beta_n/k_0|$ for $n \in [-1, -2, -3, -4]$ space harmonics for $f_1 = 27.4$ GHz, $f_2 = 32.1$ GHz and $f_3 = 37.2$ GHz are $n_{-1} = [0.35, 0.68, 0.89]$, $n_{-2} = [0.51, 0.11, 0.24]$, $n_{-3} = [-, 0.81, 0.36]$ and $n_{-4} = [-, -, 0.99]$, respectively, which correspond to the angles of $n_{-1} = [20^\circ, 42^\circ, 63^\circ]$, $n_{-2} = [30^\circ, 6^\circ, 14^\circ]$, $n_{-3} = [54^\circ, 21^\circ]$ and $n_{-4} = [81^\circ]$, respectively. These values are well correlated with the beam angles simulated in Fig. 3.9. In addition, based on the analysis of Figure. 5.3, we expect the beam levels of the antenna in safe zone area IV to be higher compared to the lower bands that shows a good agreement with the simulation analysis of Figure. 5.9. The analysis of Figure. 5.9 also shows the antenna beams in each band compensate the missing scanning range of the other bands which allows us to achieve a wide scanning range. Besides, the analysis of the Brillouin diagram in Figure. 5.7 shows that the scanning range variation of HSHs in the vicinity of the light line is more than the HSH which is located near the center. That is due to the arcsine function in which its slope variation is higher when its magnitude is closer to 1 when compared to 0. For instance, in safe zone area 4 of Figure. 5.7 we should expect that the $n = -4$ space harmonic

scans faster compared to other HSHs since the ratio of $|\beta_{-4}/k_0|$ is closer to 1 compared to the other HSHs. Table 5.1 shows the comparison between the theory (based on analysis of $|\beta_n/k_0|$ variation) and simulation results (Full wave simulations) of the scanning range related to the $n \in [-1, -2, -3, -4]$ space harmonics in safe zone areas II, III and IV of Figure. 5.7 where a good agreement is observed.

The proposed method can also be used for designing multi-band LWAs with single-beam operation in each band by using the singularity behavior of HSHs in materials of high permittivity where we can get the benefit of high slope variations of space harmonics. For instance, the SIW unit-cell of Figure. 5.1(b) can benefit from dual-band single-beam operation of the $n = -2$ space harmonic for the frequency range of $28.5 < f_{\text{GHz}} < 30.5$ and $31.5 < f_{\text{GHz}} < 33$. The dual-band single-beam operation can also be applied for the case of the $n = -1$ space harmonic in the SIW-unit-cell of Figure. 5.1(b) for the $28 < f_{\text{GHz}} < 33$. Comparing this feature (dual-band single beam operation) of these two space harmonics ($n \in [-1, -2]$) behavior in Figure. 5.1(b) shows that the beam related to the $n = -2$ space harmonic has less scanning range variation compared to the $n = -1$ space harmonic and that is due to the ratio of β_n/k_0 which is closer to zero for the case of the $n = -2$ space harmonic which can provide us narrower scanning range compared to the wider scanning of the $n = -1$ space harmonic for the same frequency range variations. In addition, it is also possible to have the dual-band single-beam operation of the antenna in which each band have the same behavior response of the beam scanning range such as one in Figure 5.1(b) where the $n \in [-1, -2]$ space harmonic can act as backward fast wave for the frequency range of $21.3 < f_{\text{GHz}} < 24.5$ and $28 < f_{\text{GHz}} < 30.5$, respectively. Thus, by careful analysis of the HSHs of the transmission line mode, we are able to design LWAs with different features such as single-band single-beam, dual-band single-beam and multi-band multi-beam where we can get the benefit of HSH characteristics for achieving different scanning range variations (narrow or wide) for our antenna. Besides, we also need to analyze the radiating element effect on the performance of the antenna especially when we deal with multi-band LWAs to achieve an acceptable performance for each band of the antenna. In the next section, we validate our methodology by showing an antenna prototype to prove this concept.

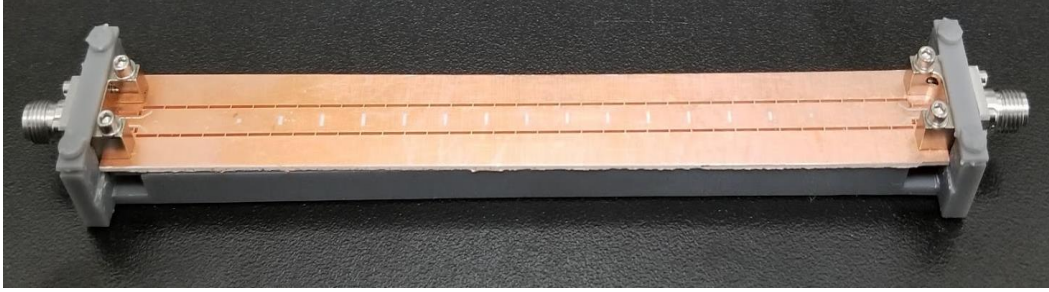


Figure 5.10 Prototype of the dual-band multi-beam SIW 1D-periodic LWA

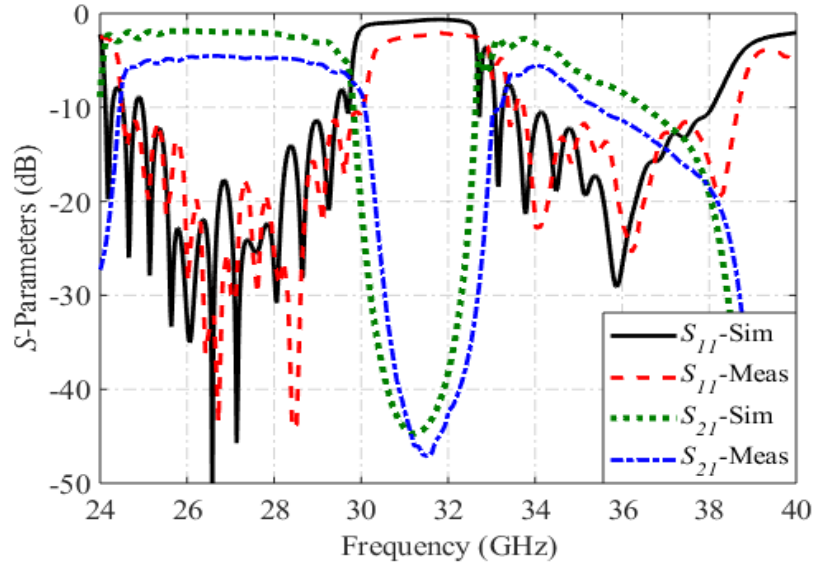


Figure 5.11 Simulated and measured S-parameters of the dual-band multi-beam SIW-LWA with a series of transverse slots of Figure 5.10

5.4. Experimental validation of dual-band multi-beam 1D-periodic SIW-LWA

Figure. 5.10 shows the fabricated prototype of a 1D-periodic dual-band multi-beam SIW-LWA with a series of transverse slots. The proposed antenna is a single layer antenna based on SIW technology. The dielectric material used in this design is RT6002 with a dielectric constant of $\epsilon_r = 2.94$ and a thickness of 0.762 mm. The width of the SIW is set to 4.36mm in order to have single mode operation (TE_{10}) for the frequency of interest. The radiating element is chosen based on the analysis of Figures. 5.2-5.3. Thus, a simple transverse slot with a length of $0.39\lambda_g$ (2.2mm) and a width of $0.12\lambda_g$ (0.7mm) with a periodicity $p = 7\text{mm}$ is used. The antenna length is $14\lambda_0$ and

Table 5.2 Comparison between the proposed dual-band multi-beam HSH based SIW-LWA with other LWAs

Structure	Antenna type	Frequency (GHz)	Scanning angle (degree)	Involved space harmonic
[46]	SIW-LWA	8.2-9.4 13.2-15.2	19 to 78 24 to 84	$n = 0$ $n = 0$
[47]	MS+MNG LWA	3.7-5.5 6.7-10	-43 to 73 -80 to 83	$n = -1$ $n = -2$
[82]	SIW-LWA	9-10.7 13.4-16.2	107 to 167 -41 to -114	$n = 0$ $n = -1$
[45]	DMC-MS LWA	5.75-8.5 35-41.5	-64 to 0 11 to 70	$n = -1$ $n = 0$
This work	SIW-LWA	24.5-29.9	-36 to -6	$n = -1$
		33.5-38.5	5 to 27 -84 to -39	$n = -1$ $n = -2$

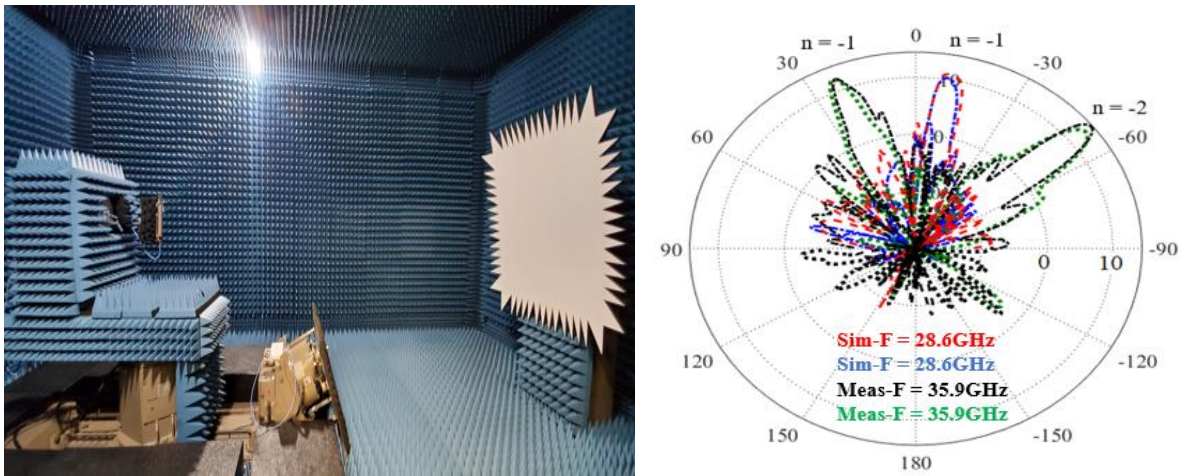


Figure 5.12 Simulated and measured E-plane co-polar radiation patterns (in dB) of the dual-band SIW-LWA at $f_1 = 28.6$ GHz (blue line is simulation and red dash line is measurement results) and $f_2 = 35.9$ GHz (black line is simulation and green dash line is measurement results)

it is excited by an end launch connector. In addition, a 3D-printer plastic holder is designed to hold the antenna during measurements. Figure. 5.11 shows simulated and measured S-parameters of the dual-band SIW-LWA. The measured reflection coefficient of the antenna is below -10dB for two frequency ranges covering $24.5 < f_{\text{GHz}} < 29.9$ and $33.5 < f_{\text{GHz}} < 38.8$. This shows a bandwidth of 18.5% and 14.6% for the lower and upper band frequencies of the proposed dual-band SIW-LWA, respectively. There is a small misalignment between the measured and simulated results due to

fabrication tolerances. Figure. 5.12 shows the antenna radiation patterns for two frequencies covering the lower and upper bands, namely $f_1 = 28.6$ GHz and $f_2 = 35.9$ GHz respectively. The measured peak gain of $n = -1$ space harmonic for the lower and upper bands is 12.6 dB and 13.8 dB, respectively, and is 14.3 dB in the upper band for $n = -2$ space harmonic. The scanning ranges of $n = -1$ space harmonic for the lower and upper band are -36° to -6° and 5° to 27° , respectively, and for the $n = -2$ space harmonic it is -84° to -39° for the upper band. An agreement is observed between the analysis, simulations, and measurement results of the proposed dual-band multi-beam SIW-LWA. Table 5.2 shows a brief comparison between this work and other LWAs.

5.5. Conclusion

The concept of HSHs in 1D-periodic LWAs is studied, analyzed, and applied to several theoretical and an experimental prototype in this chapter of the thesis to tackle the limitation of LWA single-band operation. The feasibility of even and odd HSHs for different geometries of SIW unit-cell are studied and their fast wave behavior response in the FWR are investigated. Besides, the effect of permittivity variation to the excitation condition of HSH for different pass bands are analyzed and studied. It is shown that HSHs and antenna parameters can be integrated to provide design flexibility regarding different number of beams in connection with different number of frequency bands to achieve different features for LWAs such as single-band single-beam, dual-band single-beam and multi-band multi-beam operation. In addition, the scanning range limitation of HSH for different pass band operation are investigated in which we show that wide scanning can also be achieved due to the complementary behavior of HSH in different frequency band operation of the antenna where the missing scanning ranges of one band can be compensated by another. Furthermore, it is shown that the HSH could enable the antenna to have same response of their beam steering for different frequency band operation where the HSH enable the antenna to have the same response for each frequency band. A prototype of 1D-periodic SIW-LWA is shown in this chapter for the proof of concept and experimental validation of the analysis and conclusions put forward for the HSH concept.

CHAPTER 6 ARTICLE 3: STOP-BAND RADIATION PROPERTIES OF HIGHER-ORDER SPACE HARMONICS-ENABLED BROADSIDE MULTI-BEAM LEAKY-WAVE ANTENNA

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In this chapter of this thesis, we tackle another limitation of 1D-periodic LWA in terms of their degradation performance at their stop band frequency operation. As explained in the introduction section, a drawback of the 1D-periodic LWAs is their open stopband issue, in which the antenna performance deteriorates when the beam of the $n = -1$ space harmonic scans through broadside [13,83]. Usually at this point, all radiating elements are excited in phase, and the power is reflected to the source, which results in an unacceptable reflection coefficient. Several methods have been suggested to suppress the open stop band problem, such as reflection cancelation [70], [73], phase reversal technique [84], balanced transmission line of CRLH [85], and impedance matched unit cells [30],[86]-[87]. However, all these methods only provide a solution limited to the broadside radiation of $n \in [0, -1]$ space harmonics as a single beam antenna, and the band edge issue of higher-order space harmonics (HSHs) ($n < -1$) and their conditions and limitations have not been studied or investigated to date. In this regard, this thesis aims to demonstrate a solution which can be used and applied to all HSH at their stop band to achieve an acceptable antenna performance.

6.1. Broadside condition analyses of Higher Order Space Harmonics in 1D-Periodic LWA

In this section, we investigate the behavior of HSH ($n \in [-1, -2, -3, -4]$) in a 1D-periodic SIW-LWA for different stop-band frequencies. The open stopband is one of the common problems in most of 1D-periodic LWAs. The antenna properties deteriorate when the scanning beam of $n = -1$ space harmonic reaches broadside (when simple radiating elements such as transverse slots are used [16]). This is explained by all the radiating elements becoming in phase and the power reflected to the source at point $\beta_{-1} = 0$. Several methods were suggested to alleviate this issue. However, the analysis of the broadside radiation issue of HSH ($n \leq -2$) does not exist in literatures.

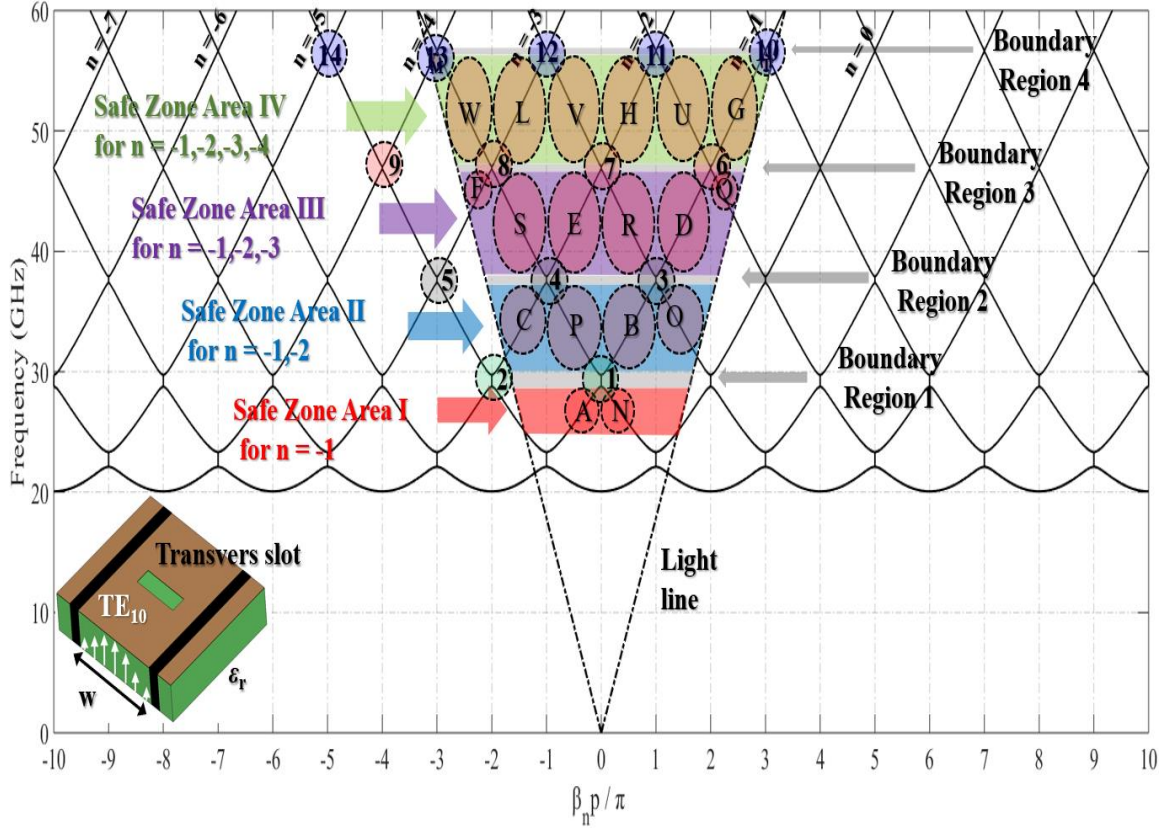


Figure 6.1 Brillouin diagram for a 1D-periodic LWA with periodicity of $p = 8.4\text{mm}$ on a dielectric propagating medium of $\epsilon_r=2.94$, $w=4.3\text{mm}$

Here, we introduce a method to overcome the band edge issue of HSH ($n \leq -1$) by careful analysis of the Brillouin diagram. Figure. 6.1 shows a Brillouin diagram for a 1D-periodic reciprocal LWA with periodicity $p = 8.4\text{mm}$ and $\epsilon_r = 2.94$. The width of the SIW unit-cell is considered to be 4.36mm where we have a single mode operation of TE_{10} in the frequency range of $20 < f_{\text{GHz}} < 40$ (the cutoff of TE_{10} and TE_{20} modes are 20 GHz and 40 GHz , respectively) and we assume that the radiating element of the periodic structure is a transverse slot [6]. Therefore, it is expected that this radiating element only works with the TE_{10} mode of an SIW due to its field distribution and the contribution of the second mode of the SIW (TE_{20}) is negligible since it has a different field distribution. In Figure. 6.1, circles A-L and N-W represent the scanning and out of scanning regions of the proposed SIW unit-cell, respectively, where we should expect to have a symmetric relation between the scanning and out of scanning angles. Here we refer to the passband and stop-band as safe zone areas and boundary

regions, respectively. This categorization helps us have a vivid analysis of HSH. The beam of each HSH ($n \leq -1$) appears at broadside only if the condition of $\beta_n = 0$ is satisfied. According to Figure. 6.1, the broadside beams of HSH appear only in the odd number boundary regions where the relation between related boundary region and their space harmonics is:

$$\beta_{-1} = 0 \quad \rightarrow \quad \text{Boundary region 1} \quad (6.1)$$

$$\beta_{-2} = 0 \quad \rightarrow \quad \text{Boundary region 3} \quad (6.2)$$

$$\beta_{-3} = 0 \quad \rightarrow \quad \text{Boundary region 5} \quad (6.3)$$

$$\beta_{-4} = 0 \quad \rightarrow \quad \text{Boundary region 7} \quad (6.4)$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ \beta_n = 0 & \rightarrow & \text{Boundary region } (n \times 2) - 1 \end{array}$$

Considering fact that the HSH has different phase and propagation constant response where we have to identify the response of them at their stop band frequency and also their excitation condition of them as:

$$n = -1 \quad \rightarrow \quad \Delta\Phi = \beta_0 p = \beta_{-1} p + 2\pi \quad (6.5)$$

$$n = -2 \quad \rightarrow \quad \Delta\Phi = \beta_0 p = \beta_{-2} p + 4\pi \quad (6.6)$$

$$n = -3 \quad \rightarrow \quad \Delta\Phi = \beta_0 p = \beta_{-3} p + 6\pi \quad (6.7)$$

$$n = -4 \quad \rightarrow \quad \Delta\Phi = \beta_0 p = \beta_{-4} p + 8\pi \quad (6.8)$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ n = n & \rightarrow & \Delta\Phi = \beta_0 p = \beta_{-n} p + 2n\pi \end{array}$$

Considering that the HSH at their broadside frequencies have their own specific behavior where their propagation constants values approaching zero. Thereby, such a condition must be applied to the HSH in order to check their performance. By

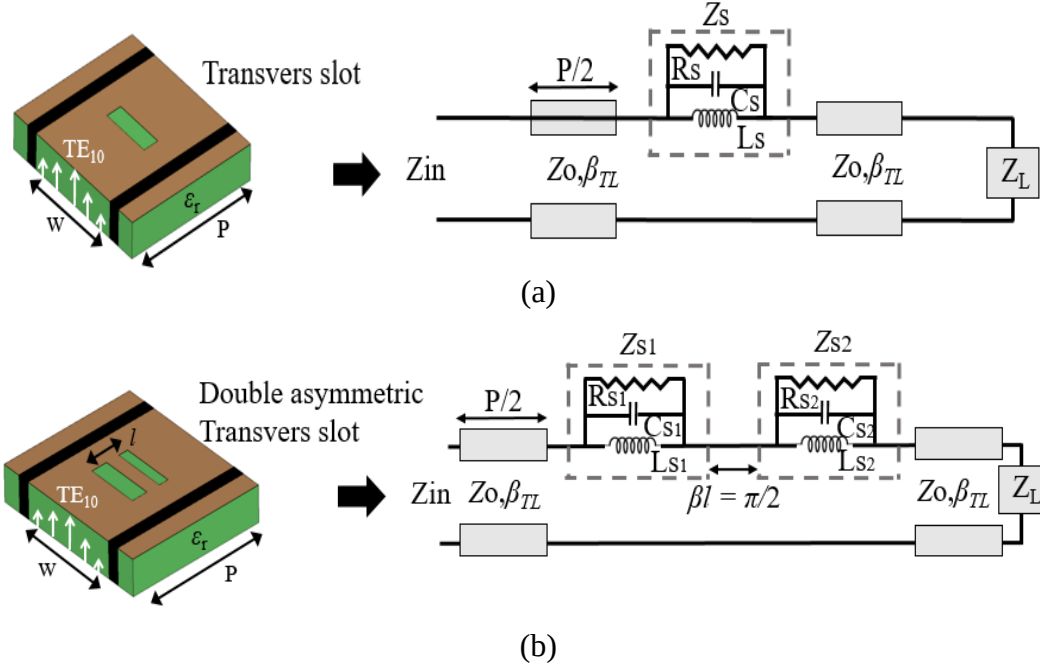


Figure 6.2 (a) SIW-LWA with simple transverse slots and (b) SIW-LWA with double asymmetric transverse slots

implementing the condition of propagation constants (β_n) of HSH of (6.1)-(6.4) to (6.5)-(6.8) we have:

$$n = -1 \quad \rightarrow \quad \Delta\Phi = 2\pi \quad (6.9)$$

$$n = -2 \quad \rightarrow \quad \Delta\Phi = 4\pi \quad (6.10)$$

$$n = -3 \quad \rightarrow \quad \Delta\Phi = 6\pi \quad (6.11)$$

$$n = -4 \quad \rightarrow \quad \Delta\Phi = 8\pi \quad (6.13)$$

$$\vdots \quad \quad \quad \vdots \quad \quad \quad \vdots$$

$$n = n \quad \rightarrow \quad \Delta\Phi = \beta_0 p = 2n\pi$$

Equations (6.9)-(6.13) correspond to broadside frequencies of HSH where band edge issues at related frequencies will occur; it is expected that the antenna properties will deteriorate due to the phase difference between the radiating elements.

A quarter wavelength technique can be used to overcome the band edge issue of HSH in which double asymmetric slots are used, instead of a single slot, as the radiating element. Figure. 6.2

shows the approximate equivalent network for a 1D-periodic LWA with double asymmetric slots in which Z_1 and Z_2 represent the impedance of each slot. Since the condition of $\beta l = \pi/2$ (quarter wavelength) is satisfied, then the impedance of each slot would be equal, and the wave does not reflect back to the source. The phase difference between the radiating elements (double asymmetric slots) has different conditions for each HSH ($n \leq -1$). Thus, by comparison between $\beta l = \pi/2$ and (6.9)-(6.13), we have:

$$\beta_{-1} = 0 \quad \rightarrow \quad l/p = 1/4 \quad (6.14)$$

$$\beta_{-2} = 0 \quad \rightarrow \quad l/p = 1/8 \quad (6.15)$$

$$\beta_{-3} = 0 \quad \rightarrow \quad l/p = 1/12 \quad (6.16)$$

$$\beta_{-4} = 0 \quad \rightarrow \quad l/p = 1/16 \quad (6.17)$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ \beta_n = 0 & \rightarrow & l/p = 1/(n \times 4) \end{array}$$

The equations (6.14)-(6.17),) represent the relations between the periodicity and radiating element distance (double asymmetric slot) to overcome the matching issue of HSH since their related beams are scanning through broadside.

6.2. Stop band analysis of Higher Order Space Harmonics in 1D-Periodic SIW-LWA

The equations (6.14)-(6.17) represent the relations between the periodicity and radiating element distance (double asymmetric slot) to overcome the matching issue of HSH since their related beams are scanning through broadside. According to Figure. 6.1, the matching issue is not only limited to frequencies of broadside radiation of HSH (odd number of boundary regions) but also to frequencies related to the even number of boundary regions where we have a mismatch due to the band edge issue. However, the quarter wavelength technique with double asymmetric slots can be used to solve the mismatch issue of frequencies related to even number of boundary regions. Table 6.1 shows the analysis of boundary regions 1-4 where the phase difference of the radiating element related to the space harmonic of boundary region n is given by $(n+1) \times \pi$. In boundary region 1, it is expected to have one beam as a fast wave in the FWR. Hence, it is expected that the

Table 6.1 Analysis of different boundary regions

Boundary Region	Space Harmonic condition and related circle	Phase difference of radiating element (double slot)	Ratio of l/p
1	$\beta_{-1}p/\pi = 0$, circle 1	$\Delta\Phi = 2\pi$	1/4
1	$\beta_{-2}p/\pi = -2$, circle 2	$\Delta\Phi = 2\pi$	1/4
2	$\beta_{-1}p/\pi = 1$, circle 3	$\Delta\Phi = 3\pi$	1/6
2	$\beta_{-2}p/\pi = -1$, circle 4	$\Delta\Phi = 3\pi$	1/6
2	$\beta_{-3}p/\pi = -3$, circle 5	$\Delta\Phi = 3\pi$	1/6
3	$\beta_{-1}p/\pi = 2$, circle 6	$\Delta\Phi = 4\pi$	1/8
3	$\beta_{-2}p/\pi = 0$, circle 7	$\Delta\Phi = 4\pi$	1/8
3	$\beta_{-3}p/\pi = -2$, circle 8	$\Delta\Phi = 4\pi$	1/8
3	$\beta_{-4}p/\pi = -4$, circle 9	$\Delta\Phi = 4\pi$	1/8
4	$\beta_{-1}p/\pi = 3$, circle 10	$\Delta\Phi = 5\pi$	1/10
4	$\beta_{-2}p/\pi = 1$, circle 11	$\Delta\Phi = 5\pi$	1/10
4	$\beta_{-3}p/\pi = -1$, circle 12	$\Delta\Phi = 5\pi$	1/10
4	$\beta_{-4}p/\pi = -3$, circle 13	$\Delta\Phi = 5\pi$	1/10
4	$\beta_{-5}p/\pi = -5$, circle 14	$\Delta\Phi = 5\pi$	1/10

beam related to $n = -1$ is scanning through broadside at boundary region 1. The $n = -2$ does not appear at boundary region 1 since the condition of $|\beta_{-2}/k_0| \leq 1$ is not satisfied. The beam related to the $n = -2$ space harmonic appears near backward end-fire for frequencies above boundary region 1. We have the same condition for other boundary regions where the beam related to the $n+1$ space harmonic does not appear at boundary region n since the condition of $|\beta_n/k_0| \leq 1$ is not satisfied for the $n+1$ space harmonic at boundary region n .

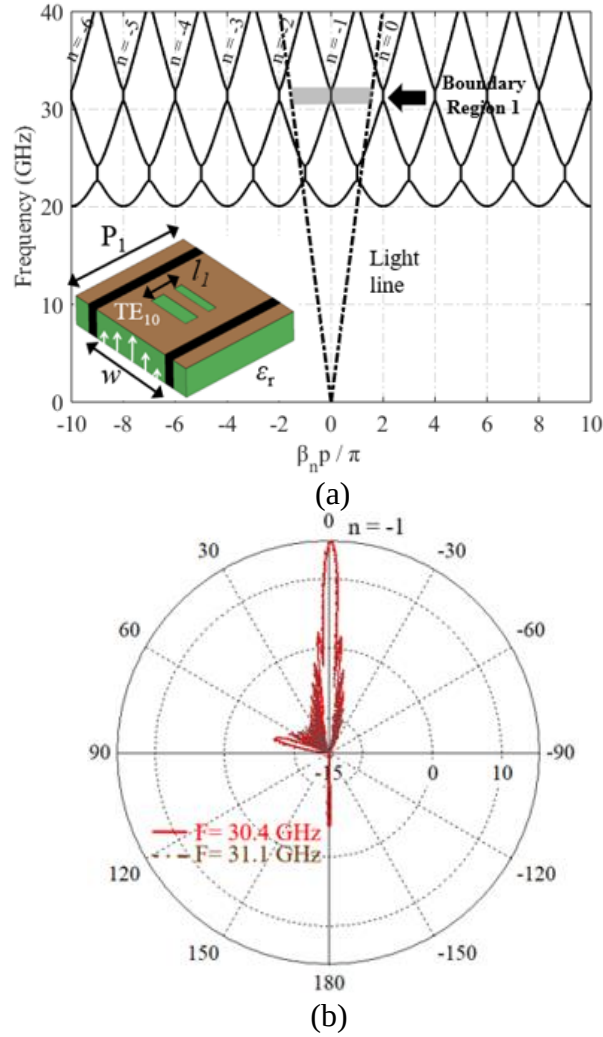


Figure 6.3 (a). Brillouin diagram for different periodicities of $\epsilon_r = 2.94$ and $w = 4.36\text{mm}$, of $p = 7\text{mm}$, and (b) corresponding E-plane co-polar radiation patterns (in dB) at $f = 30.4\text{ GHz}$ and $f = 31.1\text{ GHz}$ for $p = 7\text{mm}$

6.3. Stop Band Radiation Properties of Higher Order Space Harmonics in 1D-Periodic LWA

Figures. 6.3-6.6 show the comparison between the simulation results and analysis of HSH for different boundary regions. In Figures. 6.3-6.6, we consider a medium with $\epsilon_r = 2.94$ and different periodicities (the simulation is done based on an SIW-LWA with a series of double asymmetric transverse slots). In addition, we define our frequency range of interest to be between 26.5-40 GHz (Ka-band) where the SIW width is 4.36mm. Figure. 6.3(a) shows the Brillouin diagram analysis for $p = 7\text{mm}$. It is expected that the beam related to the $n = -1$ space harmonic at the frequency of

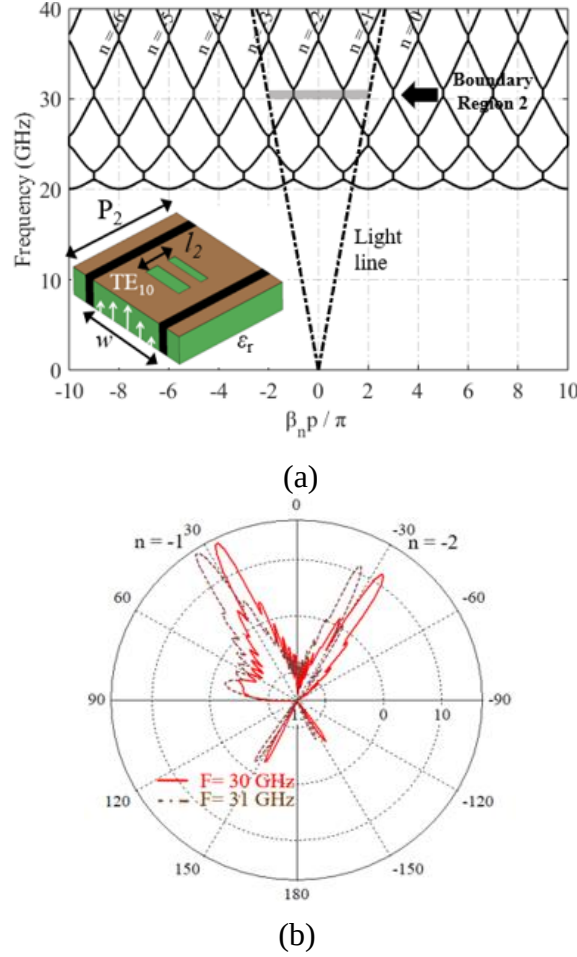


Figure 6.4 (a). Brillouin diagram for different periodicities of $\epsilon_r = 2.94$ and $w = 4.36$ mm, of $p = 10$ mm, and (b) corresponding E-plane co-polar radiation patterns (in dB) at $f = 30$ GHz and $f = 31$ GHz for $p = 10$ mm

boundary region 1 appears at the broadside where $\beta_{-1} = 0$. The simulated radiation pattern result related to Figure. 6.3(a) is shown in Figure. 6.3(b) ($l/p = 0.22$ mm $\approx 1/4$), in which the radiation beam of $n = -1$ space harmonic at $f = 30.4$ GHz and $f = 31.1$ GHz of the boundary region 1 is at broadside. The beam of $n = -2$ space harmonic does not appear at this frequency since the condition of $|\beta_{-2}/k_0| \leq 1$ is not satisfied. In addition, the beam of $n = -1$ space harmonic sticks to 0° at boundary region 1 since its propagation constant value remains zero at this frequency range.

Figure. 6.4(a) shows the Brillouin diagram for $p = 10$ mm. Similarly, it is expected to have an improper beam ($\beta_{-1} > 0$) and a proper beam ($\beta_{-2} < 0$) in boundary region 2. The beam related to the $n = -3$ space harmonic does not appear at this frequency range since the condition of $|\beta_{-3}/k_0| \leq 1$ is not satisfied. In addition, it is expected that the scanning range variation related to the $n \in [-1, -2]$

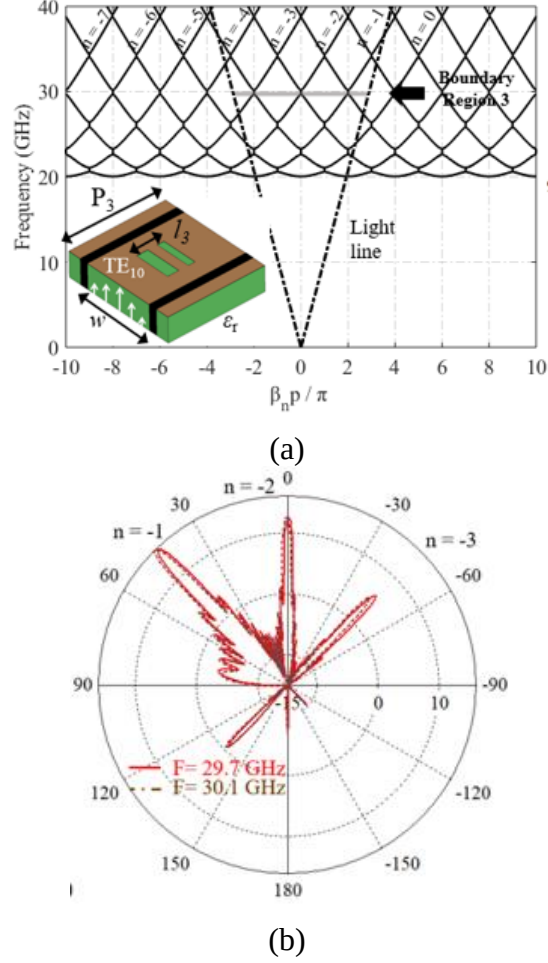


Figure 6.5 (a). Brillouin diagram for different periodicities of $\epsilon_r = 2.94$ and $w = 4.36$ mm, of $p = 14.5$ mm, and (b) corresponding E-plane co-polar radiation patterns (in dB) at $f = 29.7$ GHz and $f = 30.1$ GHz for $p = 14.5$ mm

space harmonics must be the same since the value and variation of $|\beta_{-1}/k_0|$ and $|\beta_{-2}/k_0|$ are similar in boundary region 2. Figure. 6.4(b) shows the simulated radiation pattern results ($l/p = 0.14$ mm $\approx 1/66$) for two different frequencies of boundary region 2 ($f_1 = 30$ GHz and $f_2 = 31$ GHz) where we have one beam in the forward quadrant (related to $n = -1$), another beam in the backward quadrant (related to $n = -2$) at each of these frequencies. In addition, the scanning range variations related to $n \in [-1, -2]$ space harmonics are similar at boundary region 2 which shows a good agreement with theory analysis of HSH.

Figure. 6.5(a) shows the analysis of periodicity, $p = 14.5$ mm. This time, it is expected to have three beams at the frequency of boundary region 3. The beam related to $n = -1$ space harmonic is an improper beam ($\beta_{-1} > 0$), and the beam of $n = -3$ space harmonic is a proper beam ($\beta_{-3} < 0$). In

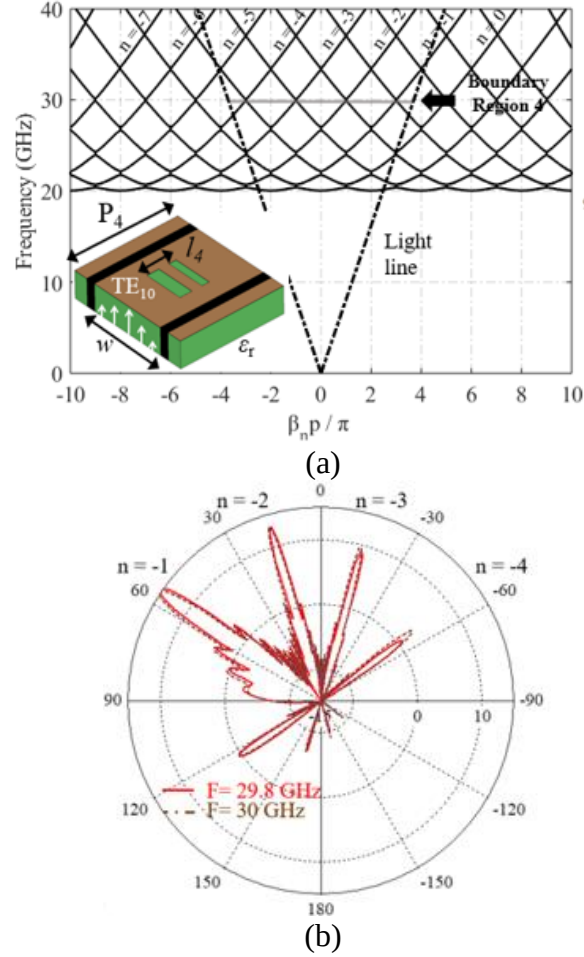


Figure 6.6 (a). Brillouin diagram for different periodicities of $\epsilon_r = 2.94$ and $w = 4.36\text{mm}$, of $p = 18.5\text{mm}$, and (b) corresponding E-plane co-polar radiation patterns (in dB) at $f = 29.8\text{GHz}$ and $f = 30\text{ GHz}$ for $p = 18.5\text{mm}$

addition, the beam of $n = -2$ space harmonic must appear at broadside since $\beta_{-2} = 0$, and the beam of $n = -4$ space harmonic should not appear. According to Figure. 6.5(a), it is expected that the scanning range variation related to the $n \in [-1, -3]$ space harmonics must be the same since the value and variation of $|\beta_{-1}/k_0|$ and $|\beta_{-3}/k_0|$ are similar in boundary region 3. Figure. 6.5(b) shows the simulated radiation pattern ($l/p = 1.12\text{mm} \approx 1/8$) for two different frequencies of boundary region 3 ($f_1 = 29.7\text{ GHz}$ and $f_2 = 30.1\text{ GHz}$) where the beam of $n = -2$ sticks to 0° angle and the scanning angle variations of the $n \in [-1, -3]$ space harmonics are similar compared to each other.

Finally, Figure. 6.6(a) shows the analysis of $p = 18.5\text{mm}$. It is predicted to have two improper beams and two proper beams at the frequency of boundary region 4 where the β_n values for $n \in [-1, -2, -3, -4]$ are in the FWR with the condition of $\beta_{-1} > 0$, $\beta_{-2} > 0$, $\beta_{-3} < 0$ and $\beta_{-4} < 0$. In addition, at

the frequency of boundary region 4, the beam angle variations of $n \in [-1, -4]$ and $n \in [-2, -3]$ must be the same due to similar variations of $|\beta_n/k_0|$. Figure. 6.6(b) shows the simulated radiation pattern result ($l/p = 0.09\text{mm} \approx 1/10$) for two different frequencies in boundary region 4 ($f_1 = 29.8$ GHz and $f_2 = 30$ GHz) where the scanning range variation related of $n \in [-1, -4]$ and $n \in [-2, -3]$ space harmonics are similar to one another as predicted.

It should be mentioned that using the unit cell of Figure. 6.2(b) has some consequences on the radiation performance of the antenna. If the condition of $k_0 l \sin \theta_n - \beta_0 l = \pm(2m+1)\pi$ (where $\sin \theta_n = \beta_n / k_0$, and $m = [0, 1, 2, \dots]$) is satisfied in this unit cell then it is expected that the beam related to the n^{th} space harmonic will be eliminated due to the appearing of a null in the array factor [73]. In other terms, if the condition of $l/p = \pm (2m+1)/2n$ (for $m = [0, 1, 2, \dots]$ and $n = [-1, -2, -3, \dots]$) is satisfied then the $n \in [-1, -2, -3, -4 \dots]$ space harmonics must be suppressed for the ratio of $l/p = [1/2, 1/4, 1/6, 1/8 \dots]$, respectively. Comparing these ratios with the analysis of l/p ratios regarding different boundary regions in Table 6.1, it can be shown that by applying the condition of boundary region n to boundary region $n+1$, we should expect that the beam of the n^{th} space harmonic in boundary region $n+1$ to disappear. Figure. 6.7 shows the comparison of the simulated radiation patterns of an SIW-LWA (based on analysis of Figure. 6.4 at 30 GHz for two different ratios of l/p ($1/4$ and $1/6$)). As expected, the beam related to the $n = -2$ space harmonic in boundary region 2 for the ratio of $l/p = 1/4$ is suppressed. However, using the ratio of $l/p = 1/4$ cannot satisfy the performance of the antenna in terms of the S -parameters response based on the analysis of (15)-(18) and Table 6.1. Thus, since the ratio of l/p of boundary region 2 (in table 4.I) are very close to the ratio of space harmonic suppressing ($1/6 \rightarrow 1/4$) then we should expect observing a drop in the beam of $n = -2$ space harmonic in the antenna radiation pattern due to dependency of the unit cell on λ . The same behavior is observed for other HSH in other boundary regions. From Table 6.1, the ratio of l/p in boundary region 3 ($l/p = 1/8$) is closer to the ratio of $l/p = 1/6$ (for suppressing $n = -3$ space harmonic) compared to the ratio of $l/p = 1/4$ (for suppressing $n = -2$ space harmonic). Therefore, we should expect that the beam related to the $n = -3$ space harmonic has more drop compared to the $n = -2$ space harmonic. Similarly, in boundary region 4, the beams related to the HSH has more drop compared to the lower space harmonic since the ratio of their l/p is closer to their suppression ratio. It should be mentioned that the work in [88] is more focused on eliminating the HSH for achieving a single beam operation of the antenna at a fixed frequency. Instead in our work, we analyzed the 1D-periodic SIW-LWA to achieve a common source multi-beam operation

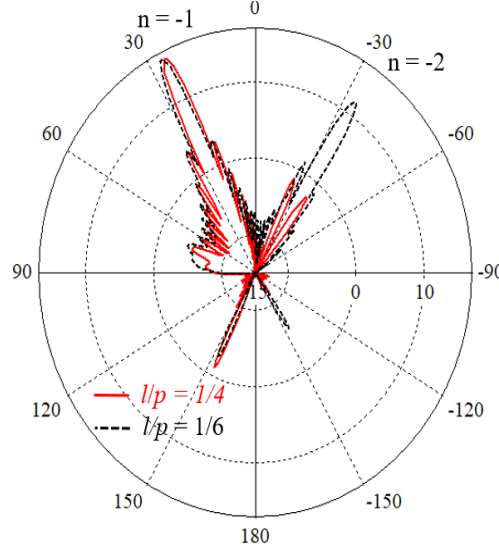


Figure 6.7 Radiation pattern (in dB) of an SIW-LWA for different ratio of l/p based on analysis of Figure 6.2(b) and Figure 6.4

in a wide band frequency range by using different HSH. In addition, the methodology that was used in [88] cannot be applied in this work because the performance of the antenna cannot be satisfied at different boundary regions (stop band) frequencies. However, here we demonstrate a new methodology based on the analysis of (6.14)-(6.17) and Table 6.1 that can be used in the design and understanding of 1D-periodic SIW-LWA which allows us to have common source multi- beam operation at different boundary region (stop band) frequencies while keeping the antenna performance acceptable. In the next section, we validate our methodology by showing an antenna prototype to prove this concept.

6.4. Experimental Validation of 1D-periodic SIW-LWA with Broadside Scanning

The prototype of a single layer 1D-periodic SIW-LWA with a series of double asymmetric transverse slots is shown in Figure. 6.8. RT6002 with $\epsilon_r = 2.94$ and thickness of 0.762 mm. The width of the SIW is set to 4.36mm in order to have single mode operation (TE_{10}) for the frequency of interest. The radiating element dimensions and periodicity are chosen based on Figure. 6.9, in which the slot length and two slot widths are set to $0.39\lambda_g$ (2.2mm), $0.14\lambda_g$ (0.8mm) and $0.12\lambda_g$ (0.7mm), respectively. The distance between the double asymmetric slots is $1.52\text{mm} \approx 1/8 \approx l/p$.

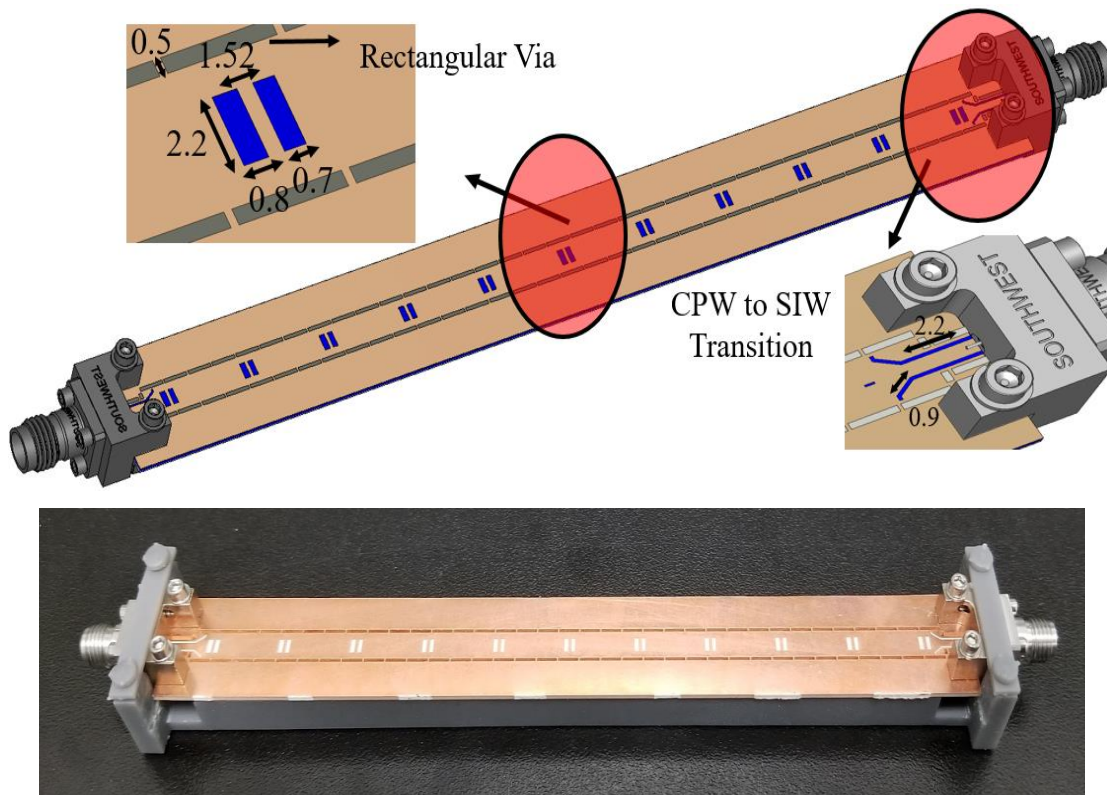


Figure 6.8 Prototype of SIW-LWA with series double asymmetric transverse slots mounted on a plastic holder (dimensions are in mm)

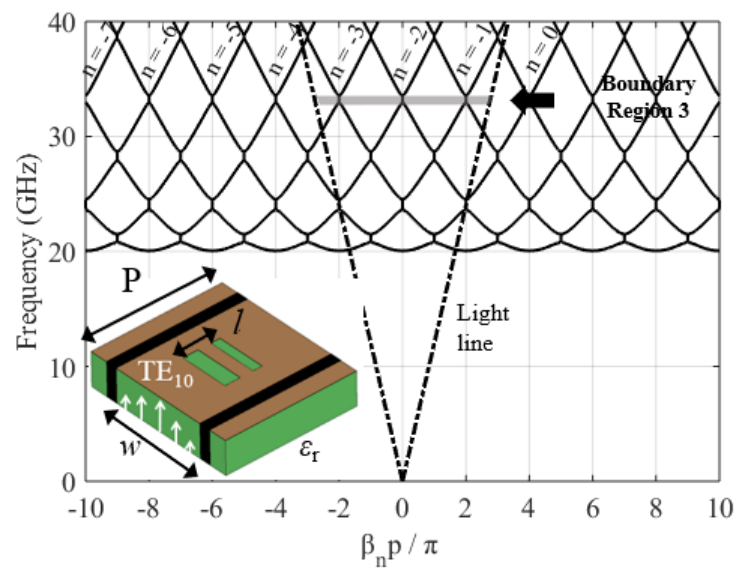


Figure 6.9 Brillouin diagram for a 1D-periodic LWA with periodicity of $p = 12.5\text{mm}$ in a dielectric propagating medium of $\epsilon_r = 2.94$ and $w = 4.36\text{mm}$

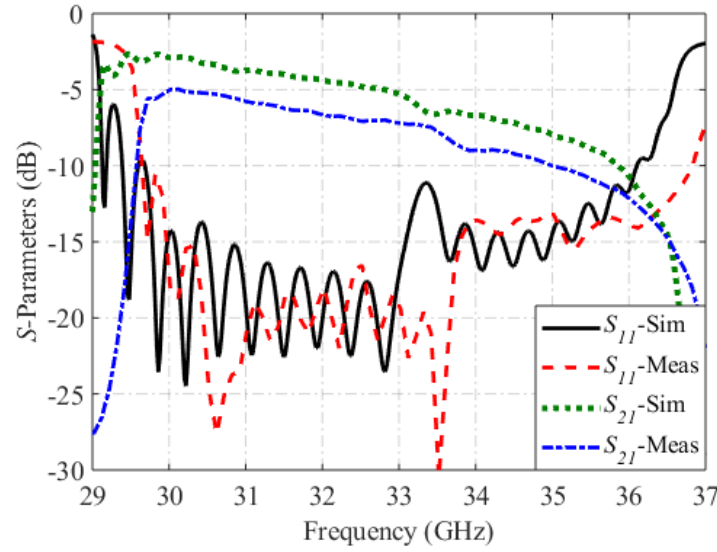


Figure 6.10 Simulated and measured S -parameters of SIW-LWA with a series of double asymmetric transverse slots

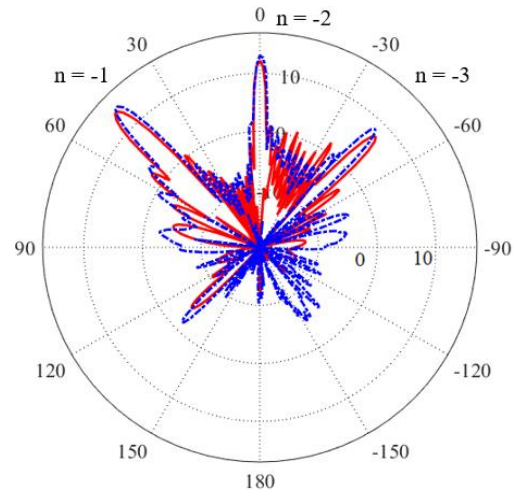
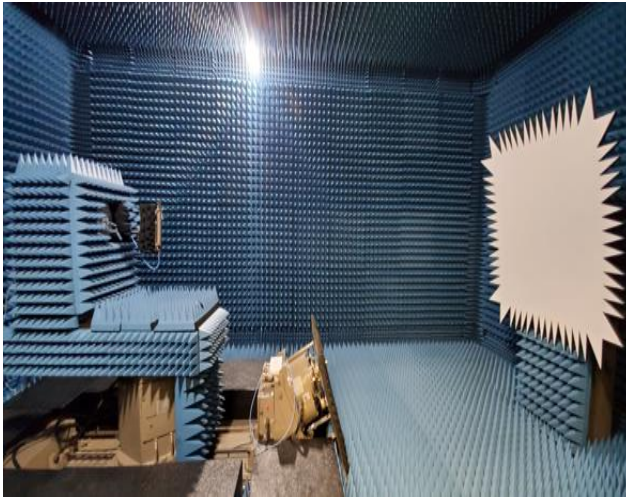


Figure 6.11 Simulated and measured E-plane co-polar radiation patterns (in dB) of SIW-LWA with series double asymmetric transverse slots of broadside frequencies of $f_1 = 33.4$ GHz (red line-simulated) and $f_2 = 33.7$ GHz (blue dash line-measurement)

The proposed antenna is held by a 3D-printed plastic and is excited by an end launch connector. Figure. 6.10 shows simulated and measured results of the S -parameters. The measured reflection coefficient of the antenna is below -10dB, between $29.6 < f_{\text{GHz}} < 36.8$, showing a bandwidth of 21.6%. There is a small discrepancy between the measured and simulated results due to fabrication tolerances. According to the analysis of Figure. 6.9, it is expected to have broadside radiation for the $n = -2$ space harmonic for the frequency at boundary region 3 where $\beta_{-2} = 0$. In

Table 6.2 Comparison of the proposed HSH based SIW-LWA with open stopband solution with other LWAs

Reference	Antenna type	Frequency (GHz)	Scanning angle (degree)	Involved space harmonic
[85]	CRLH-LWA	3.9-6.2	-42 to 47	n = 0 broadside
[84]	MS-LWA	3-6.5	-15 to 50	n = -1 broadside
[33]	SIW-LWA	12.1-16	-78 to 45	n = -1 broadside
[86]	MS-LWA	20-29	-50 to -50	n = -1 broadside
[30]	MS-LWA	12.1-20	-40 to 40	n = -1 broadside
This work	SIW-LWA	29.6-36.8	32 to 59 -21 to 13 -84 to -31	n = -1 n = -2 broadside n = -3

addition, it is expected that the beams of $n \in [-1, -3]$ space harmonics appear as improper and proper waves due to $\beta_{-1} > 0$ and $\beta_{-3} < 0$, respectively. Figure. 6.11 shows the measured and simulated radiation patterns of the antenna at broadside related to the $n = -2$ space harmonic in which we have one proper ($n = -3$) and one improper ($n = -1$) beams. The peak gains related to the $n \in [-1, -2, -3]$ are 15.8 dB, 12.7 dB and 8 dB, respectively, with an approximate -12 dB sidelobe level for all beams. In addition, it is predicted that the beam related to the $n = -3$ space harmonic scans faster than the $n \in [-1, -2]$ space harmonics due to the ratio of $|\beta_n/k_0|$. Here the scanning range of $n \in [-1, -2, -3]$ space harmonics are 32° to 59° , -21° to 13° and -84° to -31° , respectively, showing an agreement with the analysis and method provided.

Table 6.II shows a brief comparison between this work and others. It is clear that this work is the first to address the broadside issue of $n = -2$ space harmonic and provides detailed methods for its utilization of HSH to obtain common source multi-beam antenna system. It should be mentioned that the proposed methodology can also be applicable for achieving a single beam at broadside without the appearance of another HSH. The analysis of previous chapters shows that the dispersion singularity behavior of HSHs in materials with high ϵ_r is more than those with low ϵ_r where we can get the benefit of a high slope variation of space harmonics to achieve single beam operation. For instance, the SIW unit-cell of Figure.6.1(b) can provide broadside radiation of the $n = -2$ space harmonic as a single beam for the frequency range of $28.5 < f_{\text{GHz}} < 33$. Therefore, we are able to design LWAs with different features such as single-beam or multi-beam over their stop-band frequency range by benefiting HSH characteristics. Here we validated our methodology by showing an antenna prototype to prove this concept.

6.5. Conclusion

In this chapter we investigate the behavior of HSH for different stop bands frequency of a 1D-periodic SIW-LWA. For the first time it is shown that the stop bands behavior of HSH is not restricted to broadside angle, and it can occur at other angles. The phase response behavior of HSH for different stop band frequency for each of HSH is identified and analyzed in detail. A solution is demonstrated to overcome the mismatching issue of different HSH for different stop band frequencies (even and odd boundary regions) that enables the antenna to have an acceptable performance. In this regard, the phase difference of radiating element of different HSH for different stop band frequency is analyzed where a quarter wavelength introduces which can be applied to different HSH to overcome the mismatching issue of their stop band frequency. In addition, it is shown that the HSH can have the flexibility of having symmetric and unsymmetric beam steering response at their related stop band frequencies. Furthermore, it is shown that the HSH give us the flexibility of approaching different number of antenna beam behavior though different stop band frequencies which enables us to achieve a single beam or multi-beam operation for our antenna. In this chapter, 1D-periodic SIW-LWA designs are shown as a proofs of concept of the analysis method proposed; the measured results are in good agreement with the simulated ones, thus validating the proposed method.

CHAPTER 7 ARTICLE 4: A MONOLAYER DUALY POLARIZED HIGH-ORDER SPACE HARMONIC LEAKY-WAVE SIW ANTENNAS WITH FIXED AND SCANNING BEAM CAPABILITY

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7.1. Previous Work

One-dimensional periodic leaky-wave antennas (1D-periodic LWAs) have some distinguishable features such as low profile, single layer, wide bandwidth, and inexpensive beam steering solution compared to phased array antennas which usually require couplers, phase shifters, and complex bulky feeding or beam-forming networks [89]-[92]. Based on their geometrical structures, LWAs are divided into three categories: uniform [14], quasi-uniform [15]-[18], and periodic [19]-[20]. Regardless of this classification, most of the LWAs usually produce a narrow fan beam which finds many potential applications in frequency modulated continuous-wave (FMCW) radars [93], feeding of high gain reflector antennas [10], sparse 3D imaging [94], fading mitigation in multipoint communications [12], and multi-target sensor detection [95].

With the recent and rapid evolutionary growth of wireless communications like 5G networks, bandwidth consumption has become a major concern. Fortunately, deploying FR2 bands (24.2 to 54.6 GHz) in the millimeter-wave (30 to 300 GHz) frequency range with polarization diversity offers a potential solution to fulfill this gap. In this case, orthomode transducer (OMT) is an essential component for polarization diversity. Different methodologies can be used in designing OMT, such as Bøifot [96], turnstile junctions [97]-[98], dual-mode double ridge waveguides [99], and groove gap waveguides [100]. However, most have 3D geometrical structures which make them hard to integrate with other parts. Planar OMT structures were investigated in [101]-[102] at the expense of using multiple layers. Nevertheless, a low profile monolayer planar OMT with integration capability should be highly attractive for 5G applications and beyond.

Additionally, considerable efforts have been made in realizing dually polarized antennas (DPAs) due to the spectrum limitation and high data demand in cellular systems. DPAs judging from their mechanisms and radiation properties are divided into two different categories. The first category belongs to the DPA with the capability of fixed beam operations [103]-[109], where the antenna

beam of each polarization targets a similar angle. These types of DPAs are more suitable for channel capacity improvement especially in dense areas where we encounter user plane (UE) traffic [110]-[111]. The second category is related to DPAs featuring a different beam direction for each polarization [71]-[72]. These types of DPAs provide a wider coverage compared to the first category since the beam of each polarization targets different angles. It should be mentioned that besides this categorization, the features of beam steering and polarization diversity can also be beneficial for multi-user streaming and broadcasting where the use of a multiple input multiple output (MIMO) technology can improve the cell throughput (base station) performances [112]-[113].

Several methods were proposed to realize a dually polarized LWA (DP-LWA), such as the dual-mode transmission line [114], symmetrical spoof surface plasmon polariton lines [115], back to back slot array [116], OMT based LWA [72], partially reflected surface (PRS) LWA [117], metamaterial LWA [118], and lens LWA [119]. However, all those methodologies can only provide a single beam operation for each polarization which makes them unsuitable for multi-beam operations, which are essential in 5G new radio (NR) [120]. A multi-beam mechanism can be used to enhance the spectral efficiency, power delay profile, reduce recovery times [40], and also to provide reduction in computational complexity and access times [43]. Furthermore, a code book technique can be applied to simultaneous multi-beam radiators to achieve faster initial access times [42]. Some methods were also used to achieve common source multi-beam LWAs, such as dual-mode transmission line [121], defected ground structure (DGS) [66] and aperture coupled feeding [64]-[65]. However, applying all these methodologies [121], [64]-[66] to a DPA to achieve a multi-beam operation is challenging, and to the authors' best knowledge, do not yet exist in literature. In addition to multi-beam operation, dual-polarization, and beam steering features, it is also beneficial for the antenna to have a fixed beam operation, especially for point-to-point communications [122]. However, the beam in most LWAs usually steers with frequency which makes them unamenable for fixed beam operations. Besides, using single beam operation there will be a high possibility of link failure due to the blockage effect. This issue can be overcome by using multi-beam operation and assigning a code book to the radiated signals. In this case, if one of the beams fails then the alternative one can still provide a reliable connection [41].

In this work, we introduce a method for designing and analyzing 1D-periodic LWA as a common source dually polarized multi-beam antenna. We try to benefit from the hybrid form of the

nonradiative dielectric (NRD) waveguide and the substrate-integrated square waveguide (SIW) to achieve the polarization diversity for our LWA design. The authors in [123]-[124] demonstrated a planar OMT which has the potential integration capacity with antenna. However, they did not investigate this feature in their work since the focus was on developing the concept and theory of OMT operation. Hence, in this work, we demonstrate a comprehensive analysis in this regard; we analyze the behavior of two OMT modes (TE_{10} and TE_{01}), along with an LWA, for different higher-order space harmonic (HSH) of each OMT operation mode. This work differs from [125] where the authors discussed the HSH behavior for a single polarization LWA and their focus was on the broadside condition of $n = -2$ space harmonic. Here, however, we tackle the HSH behavior with the presence of two orthogonal modes in which the geometrical effect of the LWA's unit cell on the propagation constant, leakage ratio, and stop-band for single and dual-mode operations is investigated and their differences are highlighted. Furthermore, the design flexibility in terms of multi-beam alignment of the HSH for two OMT modes is also investigated.

In the first design reported in this work, we demonstrate a dually polarized multi-beam steering LWA where we use a combination of one even and one odd HSH of $n \in [-1, -2]$ of each OMT mode. The second design presents a dually polarized multi-beam LWA with the capability of a fixed multi-beam operation. In this design, we use a combination of two odd ($n \in [-1, -3]$) and two even ($n \in [-2, -4]$) HSHs. This second design is different compared to [126] where two reflector antennas with 180° phase shift between the reflected waves were used to achieve a single fixed-beam operation for their LWA. While, in this work, we achieve a dually polarized fixed multi-beam LWA by utilizing the HSH concept. This contribution differs from [122] and [127] where the fixed single beam LWA (single polarization) is achieved at the expense of adding a mirror and glide-symmetric prisms to the structure.

A combination of fixed beam operation along with beam steering can sufficiently reduce the volume and size of wireless communication systems and present an alternative solution for future broadcasting designs. This work also demonstrates a dually polarized multi-beam LWA with the capability of providing simultaneous fixed and scanning beam operation. In the third design, we use a combination of polarization-selective coupling (PSC) mechanism and four HSHs belonging to $n \in [-1, -2, -3, -4]$. To the best of our knowledge, this is the first time that an antenna with the capability of simultaneous fixed and scanning beams operation is proposed and demonstrated.

Experimental results show a good agreement between the simulation, analysis, and measurements (CST STUDIO SUITE used in all simulations and analyses).

This chapter is organized as follows. Section II investigates LWA's unit-cell for two oriented modes and shows the analysis and experimental validation of a dually polarized multi-beam steering LWA. Section III presents the operation principle and experimental validation of a DP-LWA with fixed multi-beam operation. Section IV gives the modeling, analysis and experimental validation of a DP-LWA with simultaneous fixed and scanning multi-beam capabilities. Finally, Section V concludes the work and discusses future perspectives.

7.2. Dually Polarized Periodic LWA

7.2.1. Effect of Polarization on Unit-Cell Radiated Power

In this section, we study and analyze the effects of the TE_{10} and TE_{01} polarization diversity in connection to our antenna radiating element for a DP-LWA design based on the PSC concept. The performances of the periodic LWAs are predictable thanks to careful analysis of their unit-cell radiating element [13]. The geometrical shape of the radiating element is usually chosen based on the current distribution of the transmission line propagating mode. Most of the uni-polarized periodic LWAs operate with a single mode to prevent additional modes from any hybrid-mode coupling in their operation band [77]-[78]. However, for dual-polarization (if two modes are used for the antenna operation), it is necessary to examine the coupling effect between the two operating modes and its impact on the antenna performances. In addition, for each polarization, we also need to investigate the geometrical shape of the LWA's unit-cell to make sure we can get an acceptable radiating performance from it.

As a first step, we study and analyze the effect of the SIW-LWA unit-cell for two modes, namely TE_{10} and TE_{01} . Here we are interested in examining the unit-cell in the Ka-band. Therefore, the square section of the SIW-LWA's unit-cell is considered to be 3mm, using an RT6002 substrate. Based on these dimensions, the cutoffs of the TE_{10} and TE_{01} modes are 29 GHz, and the higher mode cutoff starts from 41.2GHz. The behavior of most periodic LWAs is usually predictable thanks to a careful analysis of their Brillouin diagram, where the relation between different space harmonics can be written as $\beta_n = \beta_0 + 2n\pi/p$. In this work (DP-LWA), we want to study the behavior of the propagation constant (β_0) of the two modes TE_{10} and TE_{01} . Here the focus is on the $n = -1$ space harmonic. By choosing the periodicity of the LWA's unit-cell as $p = 6.9\text{mm}$

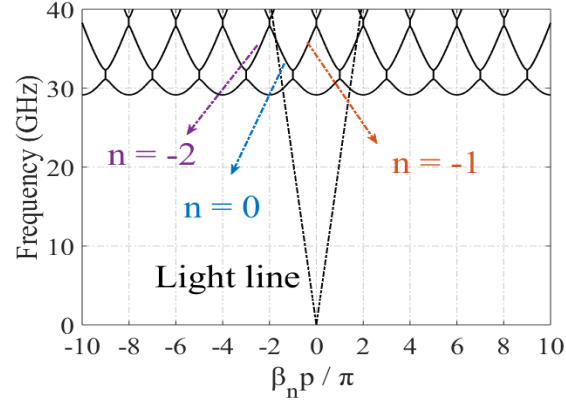


Figure 7.1 Brillouin diagram for 1D-periodic SIW-LWA with periodicity of $p = 6.9\text{mm}$ on a dielectric propagating medium of $\epsilon_r = 2.94$ with an effective width of 3mm

and the square section's length as 3mm , the contribution of the $n = -1$ space harmonic is a single fast wave ($\beta_{-1}/k_0 \leq 1$) for the frequencies above 36GHz where the fundamental and $n = -2$ space harmonics remain as a slow wave due to the condition of $\beta_0/k_0 \leq 1$ and $\beta_{-2}/k_0 \geq 1$, respectively. Figure. 7.1 shows the Brillouin diagram analysis in this case (the propagation model is theoretically calculated). Here we achieve the same Brillouin diagram for the TE_{10} and TE_{01} modes because of the square section unit-cell. It should be mentioned that besides the analysis of the Brillouin diagram, it is also necessary to investigate the radiating element's effect on the performance of the LWA.

Figure. 7.2.(a) shows different radiating geometries that can be used for our LWA's unit-cell. Here the focus is on the upper frequency of the Ka-band, so the length of the cross-slot, X-slot, square-slot and diameter of circle-slot are considered to be $\lambda_g/2$ (2.2mm) and the width of cross-slot, and X-slot are $\lambda_g/10$ (0.44mm). The response of the impedance/admittance behavior of these LWA's unit-cells is demonstrated in Figures. 7.2(b)-(e). In this analysis, we consider modes 1 and 2 of the LWA's unit-cell as TE_{10} and TE_{01} , respectively, where the relation for impedance and admittance behavior based on the Z and Y matrix analysis [60] can be written as:

$$\text{TE}_{10} \rightarrow B_y = -1/ Y_{2(1)1(1)} \quad (7.1)$$

$$\text{TE}_{01} \rightarrow B_y = -1/ Y_{2(2)1(2)} \quad (7.2)$$

$$\text{TE}_{10} \rightarrow C_z = 1/ Z_{2(1)1(1)} \quad (7.3)$$

$$\text{TE}_{01} \rightarrow C_z = 1/ Z_{2(2)1(2)} \quad (7.4)$$

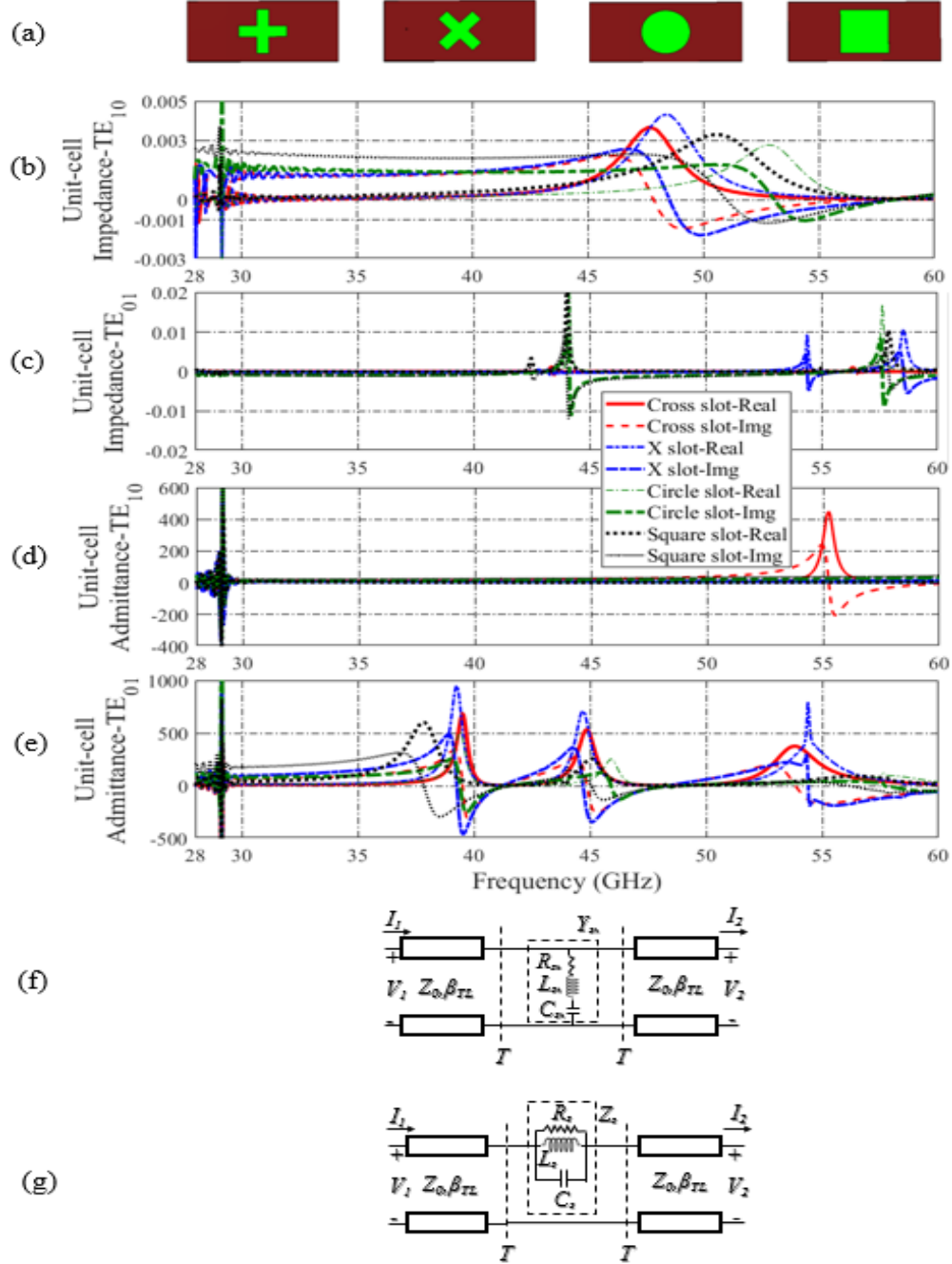


Figure 7.2 (a) LWA's unit-cells, (b) radiating element impedance for TE₁₀ mode, (c) radiating element impedance for TE₀₁ mode, (d) radiating element admittance for TE₁₀ mode, (e) radiating element admittance for TE₀₁ mode, (f) equivalent circuit for TE₀₁, and (g) equivalent circuit for TE₁₀ mode

where B_y and C_z are the parameters of the ABCD matrix of the LWA's unit-cell. The analysis of Figures. 7.1-7.2 shows that the LWA's radiating elements have different responses for each polarization. For instance, comparing Figures. 7.2 (b)-(c) indicates that we can only get the contribution of the real part of the radiating element impedance for the TE_{10} mode for the frequency range of interest ($35 < f_{GHz} < 39$), while we do not have any response for the TE_{01} mode over this frequency range. Besides, comparing Figures. 7.2(d)-(e) also shows that the contribution of the real part of the radiating element admittance only belongs to the TE_{01} mode, and we have no response for the TE_{10} mode in the frequency range of interest. Thus, each polarization has different circuit response. Approximate equivalent circuits for the TE_{01} and TE_{10} modes are illustrated in Figure. 7.2(f)-(g), respectively. Another point that needs to be considered here is related to the radiated power response of LWA's unit-cell. The analysis of Figure. 7.2(b)-(e) shows that the radiating element with a wider geometry (square-slot in this case) radiates more power compared to other LWA's unit-cells. However, the slope variation of the impedance/admittance behavior of the square-slot is sharper compared to other LWA's unit-cells in the frequency range of interest. Thus, we expect to have more gain variation for our LWA, which is not desirable. The analysis of Figure. 7.2(a)-(g) show that the cross-slot can provide a suitable tradeoff between the slope variation and the real part of unit-cell's impedance/admittance behavior for both polarizations (TE_{10} and TE_{01} modes) within the frequency range of interest. Thus, we choose the cross slot as the radiating element for the design of the DP-LWA.

7.2.2. Effect of Polarization on Unit-Cell Propagation Constant and Leakage Ratio

It should be mentioned that most of the periodic LWAs operate with a single polarization. However, adding a second polarization to the LWA will highly affect the performance of the primary one. To address this issue, we investigate the effect of single-and dual-polarization on the performance of our periodic LWA unit-cells. Figure. 7.3 (a)-(b) show the propagation constant and leakage ratio behavior for different LWA's

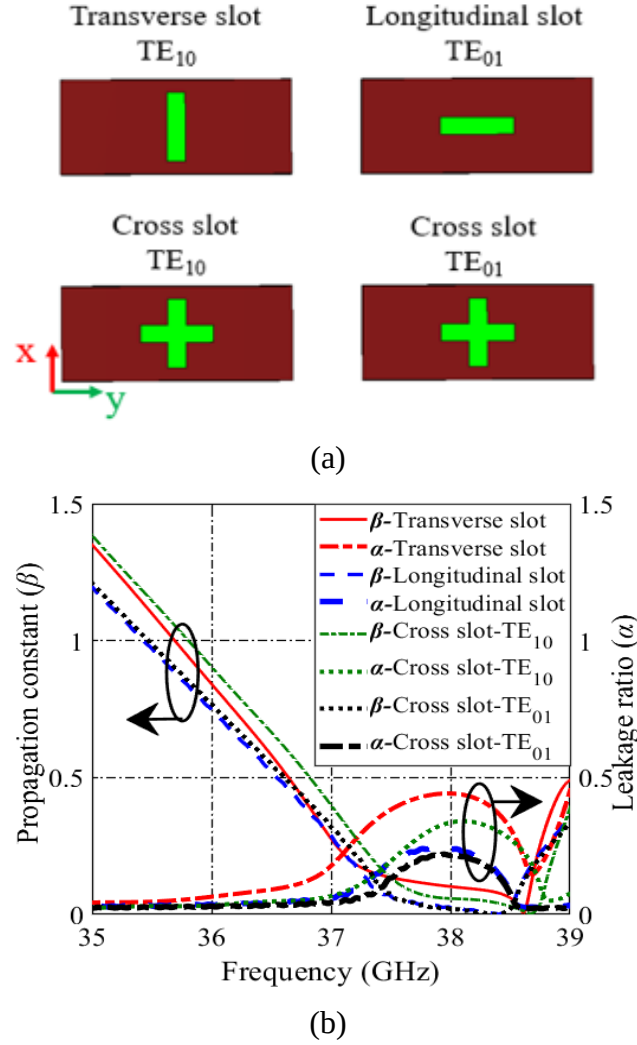


Figure 7.3 (a) LWA's unit-cells, (b) propagation constant and leakage ratio behavior for single and dual-polarization unit-cells for the case of single- and dual-polarization where the phase and attenuation constants can be expressed as [39]:

$$\beta = \text{Im}[\cosh^{-1}((A + D) / 2)] / p \quad (7.5)$$

$$\alpha = \text{Re}[\cosh^{-1}((A + D) / 2)] / p \quad (7.6)$$

Here A and D are two components of the ABCD matrix and they can be found from the Z and Y matrices. In the analysis of Figures. 7.3 (a)-(b), we consider having transverse and longitudinal slots with single polarization and cross-slots for dual-polarization. The periodicity in the unit-cells of Figure.7.3(a) is chosen based on the analysis of Figure. 7.1 and is equal to 6.9mm and the length

and width of all slots are $\lambda_g/2$ (2.2mm) and $\lambda_g/10$ (0.44mm), respectively. Besides, the square section of the SIW-LWA's unit-cell is set to 3mm with the substrate RT6002. Based on these dimensions, the same cutoff is obtained for the two modes as in subsection A. At first, we compare the operation of the TE_{10} mode between the single and dual-polarization of our LWA's unit-cells. The analysis of Figure. 7.3(b) shows that the propagating TE_{10} mode can provide a wider stop-band frequency range for the case of a single polarization (transverse slot) compared to the dual-polarization (cross-slot). In addition, the leakage ratio of propagating TE_{10} mode for the case of a single polarization (transverse slot) has a higher value at the passband and stop-band frequencies compared to the dual-polarization (cross-slot). Hence, we should expect to have more radiated power in the single polarization (transverse slot). Furthermore, the propagation constant behavior of the propagating TE_{10} mode also has different behavior for each case of the single and dual polarization at the passband frequency. It is expected that the propagating TE_{10} mode for the dual-polarization provides more scanning range compared to the single polarization. This is attributed to the higher value and increased variation of its propagation constant (β_{-1}) (over the passband). On the contrary, the propagation constant behavior and leakage ratio variation of the propagating TE_{01} mode has approximately similar behavior in both the single polarization (longitudinal slot) and dual-polarization (cross-slot). Hence, their radiated power and scanning angle variations must be similar. Another notable point from the analysis of Figure. 7.3(b) is that we also have different responses of propagating TE_{01} and TE_{10} modes for dual-polarization cases (cross-slot). Here the TE_{10} mode can provide a wider stop-band frequency compared to the TE_{01} mode scenario while the leakage ratio of these modes has an approximately similar response in their common passband frequency range. In addition, the propagation constant (β_{-1}) of the TE_{01} mode shows more variation as compared to that of the TE_{10} mode (in the common passband) which results in a wider scanning range and angular misalignment.

To overcome the issue of misalignment between propagation constant variations in each polarization, we investigate the geometrical effect of the cross-slot LWA's unit-cell for the two polarizations of our DP-LWA. Figures. 7.4-7.5 show the effect of slot length variation of the cross-slot for the propagating TE_{10} and TE_{01} modes, respectively. The periodicity of unit-cells in Figure. 7.4-7.5 is chosen based on the analysis of Figure. 7.1. The analysis of Figures. 7.4(a)-(b) shows that using a longer slot not only provides a wider stop band, but it also shifts down the lower edge of the stop band to lower frequencies while slightly affecting the upper stop band edge as well. In

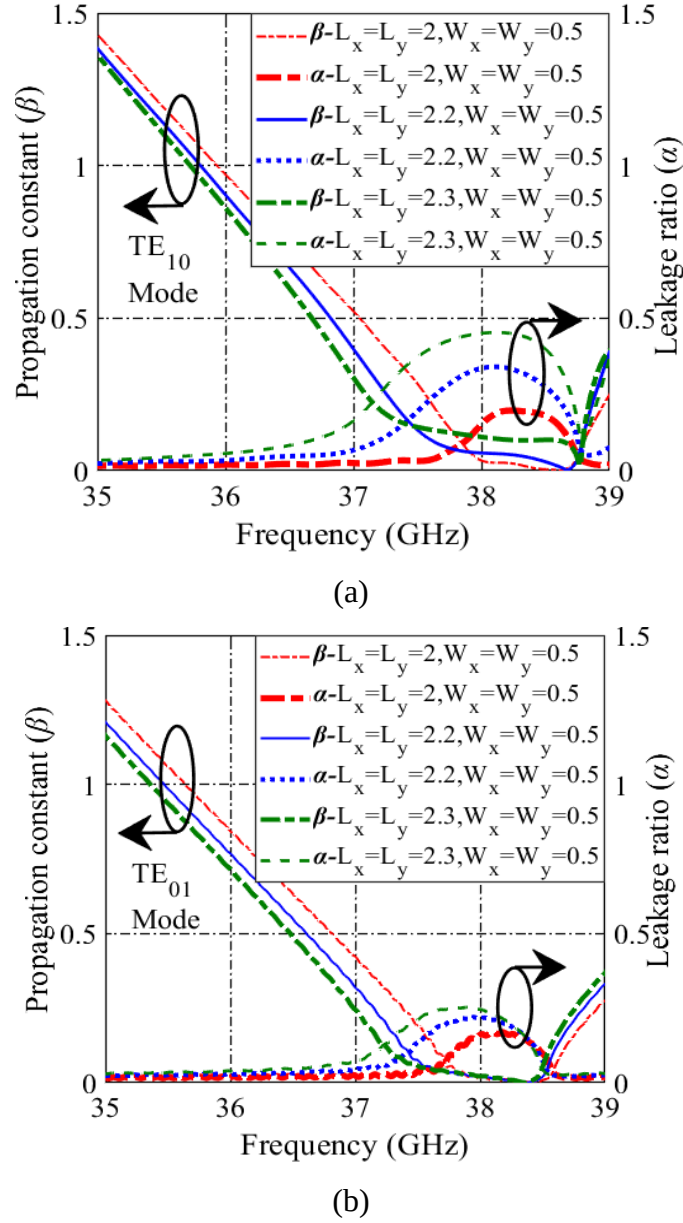
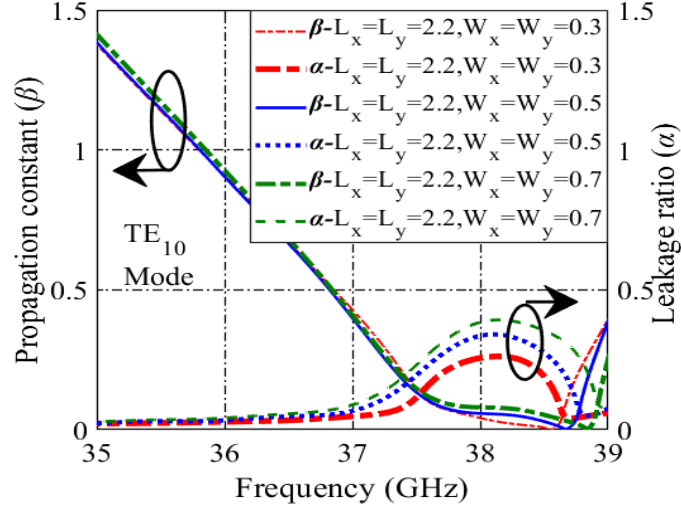
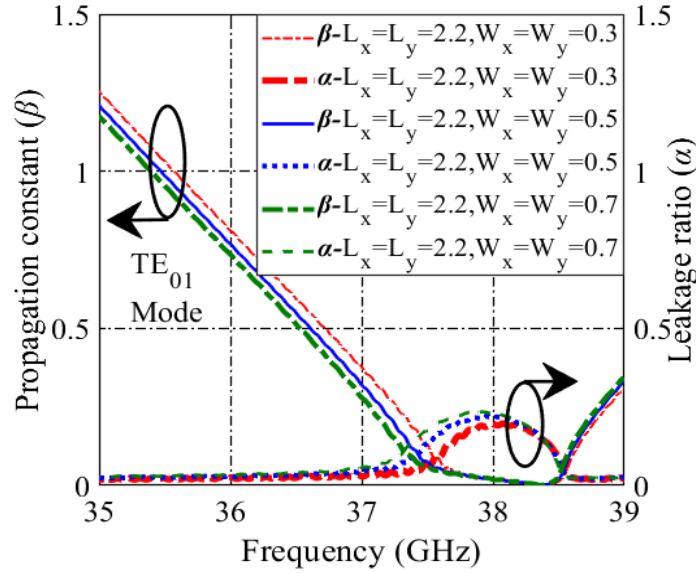


Figure 7.4 Propagation constant and leakage ratio of (a) slot length variation effect of TE_{10} mode, (b) slot length variation effect of TE_{01} mode

addition, using the longer slot decreases the variation and values of the propagation constant (β) in the passband, which results in a lower scanning range. Comparing Figures. 7.4(a)-(b) also shows that a propagating TE_{10} mode is more sensitive to slot length variations compared to the TE_{01} mode. Figure. 7.5 show the effects of slot width variations with the same condition as the length variation. The analysis of Figure. 7.5 shows that a wider slot (for the case of TE_{10}) not only provides a wider stop band, but also it shifts up the upper edge of the stop band to higher



(a)



(b)

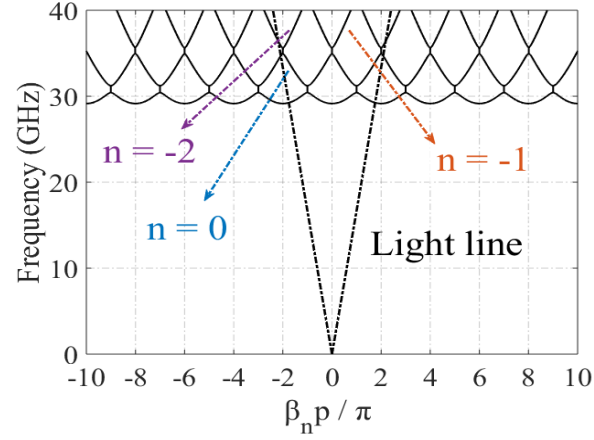
Figure 7.5 Propagation constant and leakage ratio of (a) slot width variation effect of TE_{10} mode, (b) slot width variation effect of TE_{01} mode

frequencies while slightly affecting the lower edge of the stop band. Also, it slightly affects the propagation constant (β_{-1}) in the passband frequency range. While for the TE_{01} mode, using a wider slot decreases the variation and values of the propagation constant (β_{-1}), which results in a shorter scanning range. Besides, using a wider slot for the propagating TE_{01} mode also increases the stop band and shifts down the lower edge of stop band to lower frequencies, while slightly affecting the upper edge of stop band.

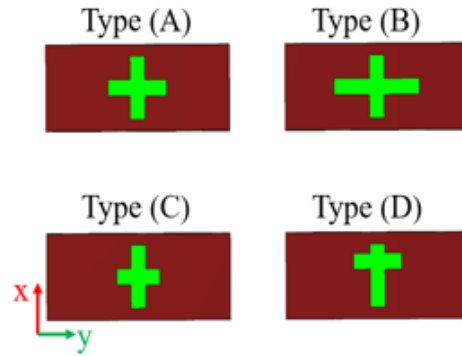
The analysis of Figures. 7.4-7.5 suggests that a symmetric cross slot could provide an approximate similar response of leakage ratio for both TE_{10} and TE_{01} modes in the common passband frequency range. However, the propagation constant (β_{-1}) of these modes has different responses in their common passband frequency ranges. Interestingly, choosing the cross-slot as our LWA's radiating element gives us the flexibility of controlling the propagation constant for each propagating modes of the TE_{10} and TE_{01} since it can be approximately considered as a combination set of a transverse slot and a longitudinal slot. From the analysis of Figures. 7.4-7.5, it is expected that an asymmetric cross-slot can decrease the difference between the propagation constants of each propagating mode, TE_{10} and TE_{01} . This is shown by plotting the $\beta_{-1TE_{10}} - \beta_{-1TE_{01}}$ of the LWA's unit-cell. In addition, if the condition of $\beta_{-1TE_{10}} - \beta_{-1TE_{01}} \approx 0$ is satisfied, we should expect that the phase difference between the two modes also approaches zero ($\Delta\phi_{TE_{01}} - \Delta\phi_{TE_{10}} \approx 0$) and that their related beams must be in alignment. However, the $\beta_{-1TE_{10}} - \beta_{-1TE_{01}}$ condition is only valid and applicable for the single space harmonic (this study case $n = -1$) operation for our DP-LWA. The beam's alignment for a dual-polarized operation (two modes operation in this study) is more complex when we are simultaneously dealing with more than one space harmonic (as fast waves) at the same frequency, since the distinction between the phase operation of each mode and their related HSH becomes more challenging and complicated.

7.2.3. Beam Alignment of HSH

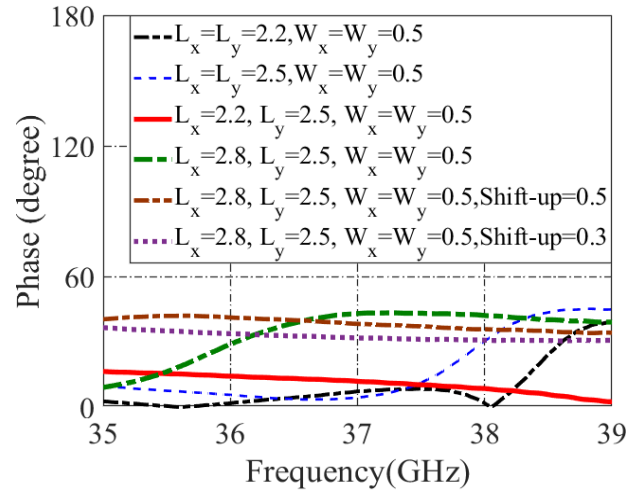
In order to address this issue in a comprehensive manner, first, we analyzed and studied the behavior of phase variation of different unit-cells with the capability of supporting two space harmonics as fast waves at the same frequency. Based on the analysis of $\beta_n = \beta_0 + 2n\pi/p$, we expect to get the contribution of $n \in [-1, -2]$ space harmonics as fast waves by choosing the permittivity, effective width and periodicity of our SIW-LWA's unit-cell as 2.94, 3mm, and 8.5mm, respectively, in the frequency range of $35 < f_{GHz} < 39$. Figure. 7.6 (a) shows its Brillouin diagram analysis, where the $n = 0$ space harmonic remains as slow waves and $n \in [-1, -2]$ space harmonics behave as fast waves for frequencies above 35GHz. The Brillouin diagram of Figure. 7.6 (a) is also applicable to both TE_{10} and TE_{01} modes since the SIW-LWA's unit-cell is designed to have a square section dimension (3mm). Figures. 7.6(b)-(c) show symmetric and asymmetric cross-slot type radiating elements with their phase shift difference response of two propagating modes of



(a)



(b)



(c)

Figures 7.6 (a), Brillouin diagram for a 1D-periodic SIW-LWA with periodicity of $p = 8.5\text{mm}$ on a dielectric propagating medium of $\epsilon_r = 2.94$ with and effective width of 3mm , (b) SIW-LWA's unit-cell, and (c) phase shift difference of two propagating modes of TE_{10} and TE_{01} for different SIW-LWA's unit-cells of Figures 7.6(b)

TE_{10} and TE_{01} ($\Delta\phi_{TE_{01}} - \Delta\phi_{TE_{10}}$), respectively. In the analysis of Figures. 7.6(b)-(c) we try at first to investigate the phase response behavior for two symmetric cross-slots (type A), where the length and width dimensions are set to be $\lambda_g/2$ and $\lambda_g/10$ for $f = 35.5\text{GHz}$ (black line) and $f = 38.5\text{ GHz}$ (blue line), respectively. We chose these two frequencies since they can be set as lower and upper frequencies for the passband of the Brillouin diagram of Figure.7.6(a). The analysis of Figure. 7.6(c) shows that using a symmetric cross-slots (blue and black lines) cannot provide a flat and low response for the phase shift difference of two propagating modes (TE_{10} and TE_{01}). However, based on the analysis of Figures. 7.3-7.5, we should expect to have less difference between two propagating modes' phase shift variations by using an asymmetric cross-slot in which the transverse slot has a shorter length compared to the longitudinal slot (type B). Figure. 7.6(c) shows that a transverse slot with dimensions of 2.2mm, and 0.5mm along with a longitudinal slot with dimensions of 2.5mm, and 0.5mm in a cross slot can provide a low value and flat response for the phase shift difference variations between the two propagating modes (red line). Contrarily, an asymmetric cross-slot with a longer geometrical length for its transverse slot (type C) cannot provide such a flat response (green line). Besides, our analysis also shows that choosing a longer dimension for the transverse slot compared to the longitudinal slot, in addition to shifting up/down the longitudinal slot in an asymmetric cross slot (type D), not only can give us a flat response for the two propagating modes' phase shift difference but also gives us the feasibility of shifting up/down the phase shift difference between them (brown and purple lines).

Comparing the A-D responses of the radiating element in Figure. 7.6 indicates that a better beam alignment must be achieved for type B since it realizes a lower value of phase shift difference between the two propagating modes. It should be mentioned that the beam angle alignment between the two propagating modes in Figure. 7.6 does not comply with the value of the phase shift difference between the two propagating modes. This non-compliance occurs as it shows the total phase response difference between the two propagating modes and their related HSH's phases. In order to find an accurate beam angle difference between the two propagating modes and their related HSH, we investigate the behavior of the propagation constant of each mode along with the propagation constant response of each mode's HSH. Here we are interested in analyzing the unit-cells of Figure. 7.6 for $35 < f_{\text{GHz}} < 39$. Based on $\beta_n = \beta_0 + 2n\pi/p$, the total phase response for each propagating mode in the frequency range of our interest must be the summation of

$\beta_{TE_{10}} (n = -1) + \beta_{TE_{10}} (n = -2)$ for TE_{10} mode and $\beta_{TE_{01}} (n = -1) + \beta_{TE_{01}} (n = -2)$ for TE_{01} mode. They can be written as:

$$\beta_{TE_{10}} l_z = l_z \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_x\right)^2} - \frac{2\pi}{p} \right) + l_z \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_x\right)^2} - \frac{4\pi}{p} \right) \quad (7.7)$$

$$\beta_{TE_{01}} l_z = l_z \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_y\right)^2} - \frac{2\pi}{p} \right) + l_z \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_y\right)^2} - \frac{4\pi}{p} \right) \quad (7.8)$$

where l_z is the length of periodic unit-cell of our LWA. The difference between the two propagating modes is:

$$\beta_{TE_{10}} - \beta_{TE_{01}} = 2 \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_x\right)^2} - \sqrt{\varepsilon_r k_0^2 - \left(\pi/l_y\right)^2} \right) \quad (7.9)$$

It should be mentioned that the factor of 2 in (9) is only applicable when we are dealing with 2 space harmonics simultaneously (this case $n \in [-1, -2]$). However, the conditions in (9) can also be extendable for any set combination of different space harmonics as:

$$\beta_{TE_{10}} - \beta_{TE_{01}} = m \left(\sqrt{\varepsilon_r k_0^2 - \left(\pi/l_x\right)^2} - \sqrt{\varepsilon_r k_0^2 - \left(\pi/l_y\right)^2} \right) \quad (7.10)$$

where m is the number of fast wave space harmonics in the frequency range of interest. One point that needs to be considered here is that the beam angle difference between similarly involved space harmonics of each propagating mode must comply with propagation constant difference value. The difference between their arcsine function can be written as:

$$\sin^{-1} \left(\frac{(\beta_{TE_{10}} - \beta_{TE_{01}})/m}{k_0} \right) \quad (7.11)$$

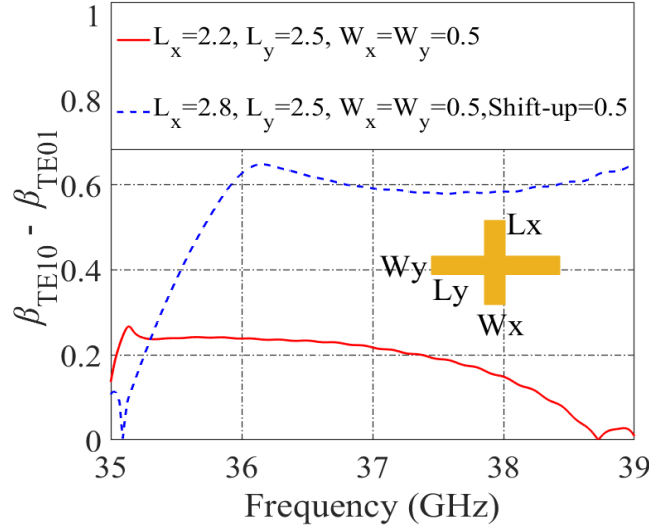


Figure 7.7 Difference between the propagation constant of TE_{10} and TE_{01} modes of two SIW-LWA's unit-cells of Figure 7.6 (types B and D)

To investigate the beam angle difference between the two modes of TE_{10} and TE_{01} and their related HSH, in Figure. 7.7 we plot the propagation constant difference of TE_{10} and TE_{01} modes of the two SIW-LWAs' unit-cells of Figure. 7.6(b) (types B and D). This analysis shows that the value of $\beta_{TE_{10}} - \beta_{TE_{01}}$ in type B of the SIW-LWAs' unit-cell has a lower value compared to type D, which shows a good agreement with the geometrical unit-cell analysis of Figures. 7.3-7.6. To examine the validity of our analysis we choose a random frequency, i.e. 38GHz, to check the beam behavior of the two propagating modes in comparison. Based on Figure. 7.6(a), at $f = 38\text{GHz}$ we have two space harmonics as fast waves, so m in (11) must be set to 2, and the value of k_0 is set to be 2.35. The value of $\beta_{TE_{10}} - \beta_{TE_{01}}$ in Figure. 7.4 at $f = 38\text{GHz}$ for unit-cell types B and D are 0.15 and 0.6, respectively. Dividing these values by 2 and putting them in the arcsine function of (11) give us the angle of 1.82° and 7.73° for SIW-LWAs' unit-cells type B and D, respectively. So, for type B of SIW-LWA's unit-cell in Figure. 7.6, we should expect that the beam angle difference between two $n = -1$ space harmonics related to the TE_{10} and TE_{01} modes must be 1.82° at $f = 38\text{GHz}$. Similar angle difference must be expected for two beams of $n = -2$ space harmonics at $f = 38\text{GHz}$ in a type B unit-cell. On the other hand, for type D unit-cell, the expected angle difference is 7.73° at $f = 38\text{GHz}$ for each pair of $n \in [-1, -2]$ space harmonics. Figure. 7.8 shows the simulated radiation pattern of two SIW-LWAs based on type B and D of SIW-LWA's unit-cells in Figure. 7.6 (the length of the antennas considered to be more than $10\lambda_0$ in this example).

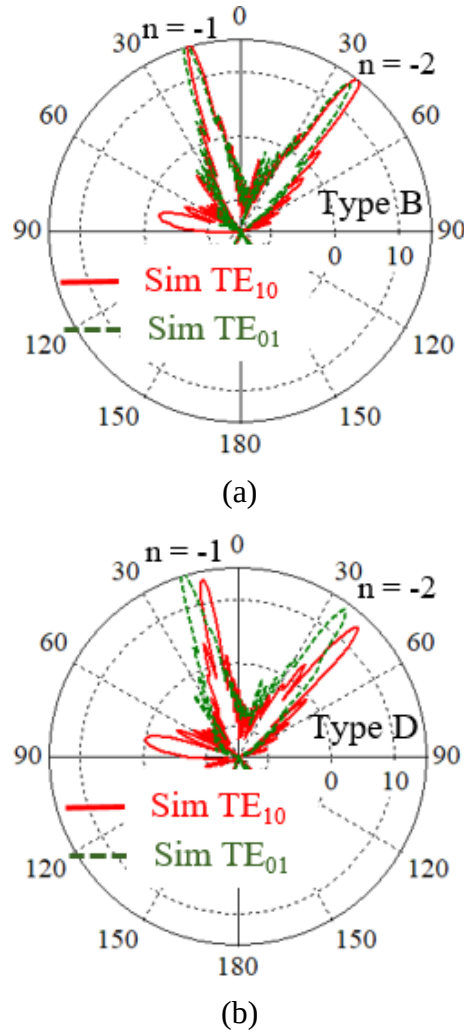
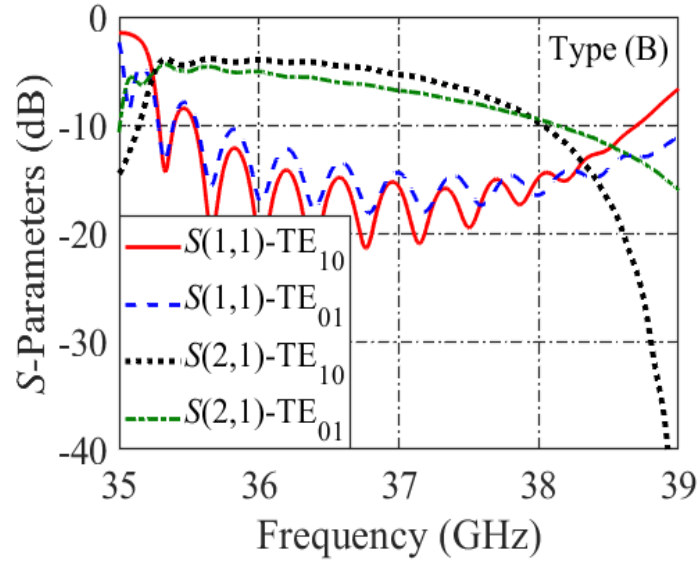


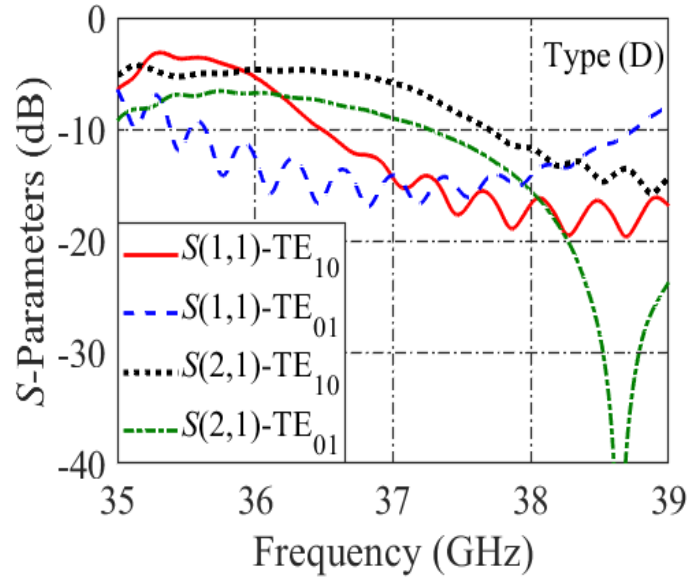
Figure 7.8 Simulated radiation pattern (gain in dB) of two SIW-DP-LWAs based on (a) type B, and (b) type D SIW-LWA's unit-cells of Figure. 7.6 at $f = 38\text{GHz}$

Figure. 7.8 shows a 2° and 7° difference between each pair of beams for our LWAs based on type B and D unit-cells, respectively. This shows a good agreement with our unit-cell analysis of Figures. 7.3-7.6.

The analysis of Figures. 7.6-7.8 also show that we can feasibly shift the beams of each mode by choosing a suitable unit-cell (Type D) for our LWA with a careful analysis of the propagation constant behavior of the LWA's unit-cell. It should be mentioned that besides the study of the DP-LWA's unit-cell behavior, we also need to analyze its effect on the bandwidth for our antenna to make sure that the two propagating modes of our DP-LWA have roughly the same bandwidth operation. Figure. 7.9 shows the simulated S-parameter responses of two LWAs based on type B



(a)



(b)

Figure 7.9 Simulated S-parameters of two SIW-DP-LWAs based on type B and D SIW-LWA's unit-cells of Figure 7.6

and D unit-cells of the previous example (the antenna length is considered to be $10\lambda_0$ in this analysis). The analysis of and. Figure 7.9 shows that the type B DP-LWA can provide a better alignment between the S-parameter responses compared to the type D for the two propagating modes of TE_{10} and TE_{01} . Thus, it is chosen in the fabricated prototype.

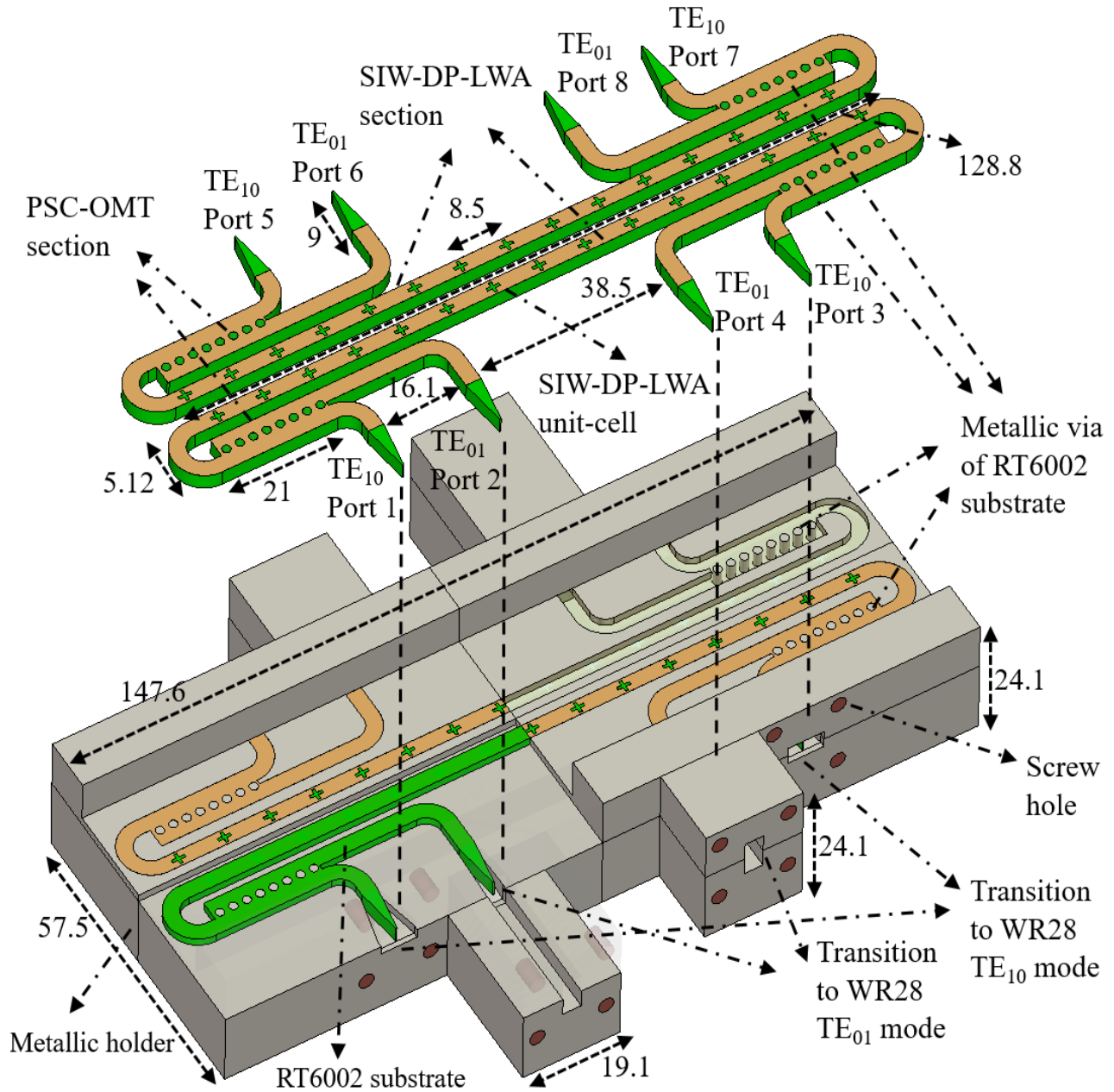


Figure 7.10 Schematic design of SIW-DP-LWA with the PCS-OMT and transition section to WR28 (all dimensions are in mm)

7.2.4. Experimental Validation and Configuration of SIW-DP-LWA

The geometry of the designed SIW-DP-LWA is shown in Figure. 7.10. Here we utilized PSC-OMT as a compact feeding network since it provides two orthogonal modes of TE₁₀ and TE₀₁. The

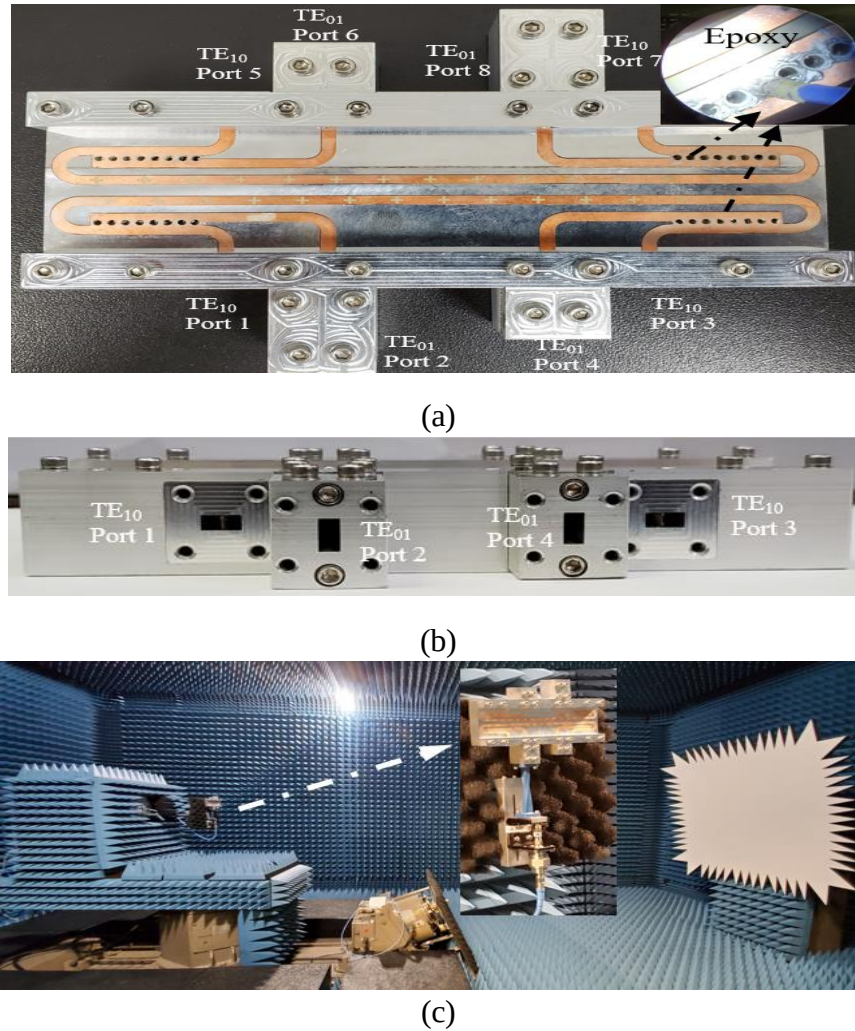


Figure 7.11 (a) Top view of fabricated SIW-DP-LWA prototype with PCS-OMT and transition section to WR28, (b) side view, and (c) measurement setup in a quasi-far-field chamber

dimensions of the PSC-OMT were calculated based on the analysis of [128] and applied to the proposed design. In addition, a transition between the PSC-OMT and the WR28 waveguide is designed to support the operation over the frequency range of interest ($35 < f_{\text{GHz}} < 39$). Here we use a triangular shape for our transition section (taper section) with the length of 9mm where we removed the top and bottom copper layer of the substrate. This transition is used on both ports of the PSC-OMT along its vertical and horizontal axes for the excitation of TE₁₀ and TE₀₁ modes, respectively. For the LWA section, we used a type B cross slot radiating element. The length of the LWA's section is considered to be more than $10\lambda_0$ in this analysis. In addition, due to the reciprocal behavior of HSH in the Brillouin diagram analysis of Figure. 7.6, we used two sets of SIW-DP-LWAs in this design to have a symmetric multi-beam radiation for our antenna.

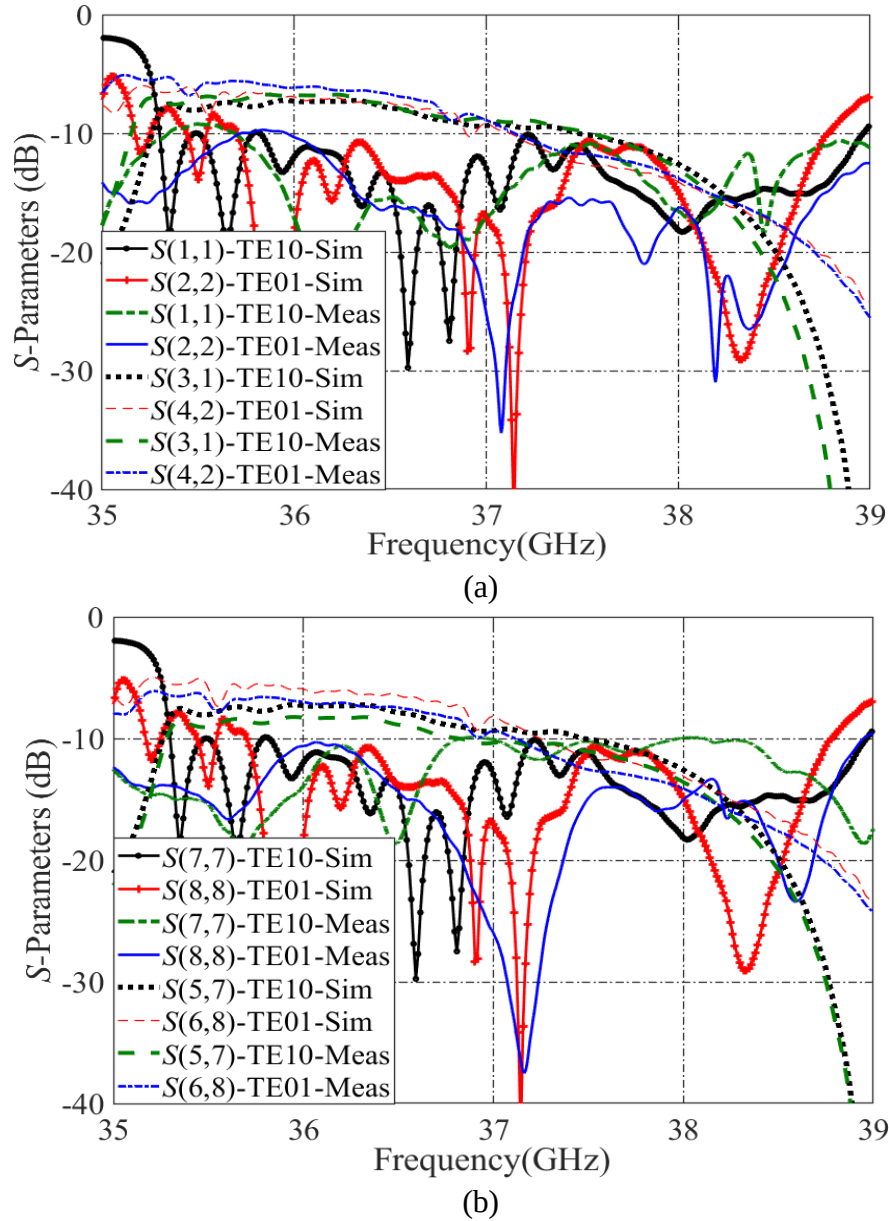


Figure 7.12 Simulated and measured S-parameter response of TE₁₀ and TE₀₁ modes of (a) ports 1 and 2, and (b) ports 7-8

Figure. 7.11 shows the fabricated prototype of the SIW-DP-LWA with the PCS-OMT and transition section to WR28. The dielectric material used in this design is RT6002 with a dielectric constant of $\epsilon_r = 2.94$ and thickness of 3mm. In addition, we also applied a metal epoxy in the via section of the PSC-OMT in order to ensure the via's wall is well covered with metal to keep the antenna performance acceptable. The type B cross slot has transverse and longitudinal slots lengths of 2.2mm and 2.5mm, respectively, with a width of 0.5mm. Figures. 7.12 (a)-(b) show simulated

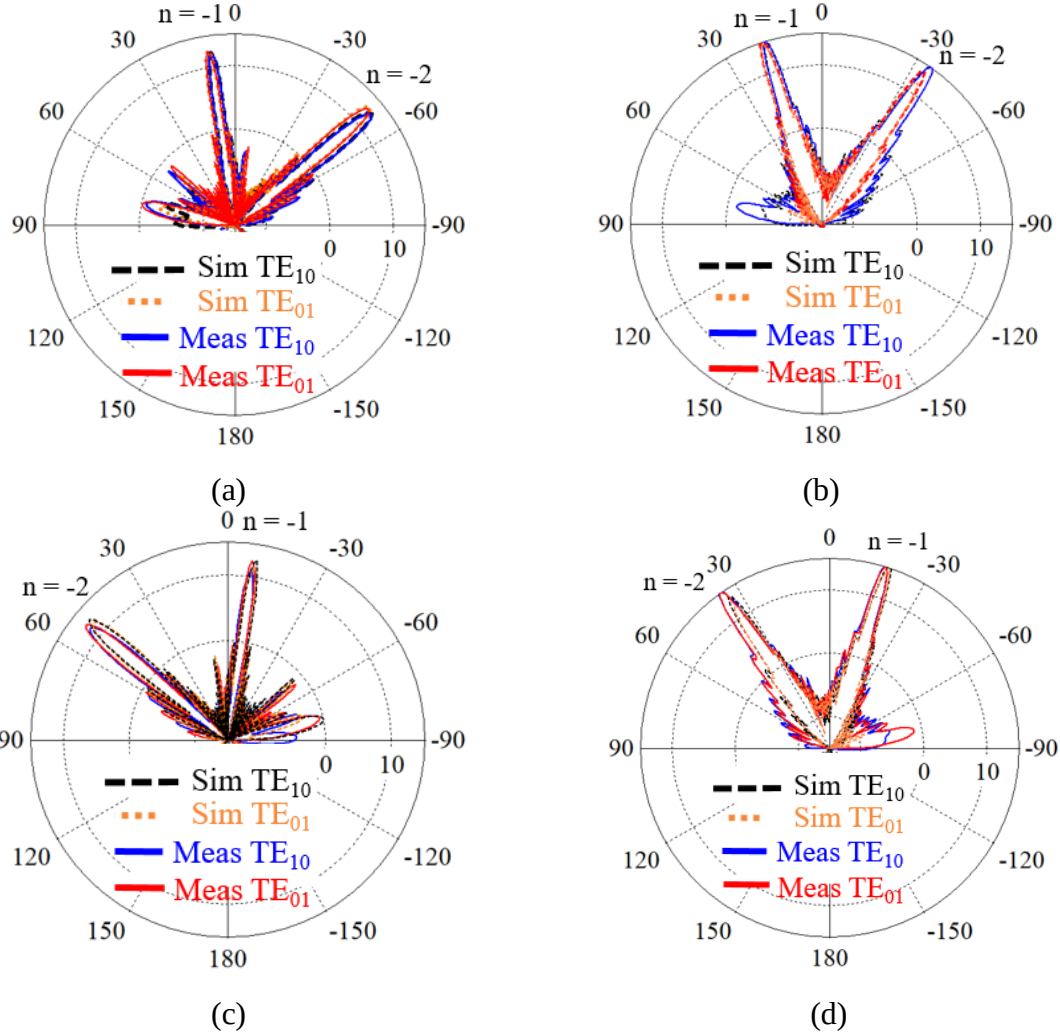


Figure 7.13 Simulated and measured E-plane co-polar radiation patterns (gain in dB) of SIW-DP-LWA of Figure. 7.11 for TE₁₀ and TE₀₁ modes of (a) ports 1 and 2 at $f = 36.5\text{GHz}$, (b) ports 1-2 at $f = 38.4\text{GHz}$, (c) ports 7 and 8 at $f = 36.5\text{GHz}$, and (d) ports 7-8 at $f = 38.4\text{GHz}$

and measured S -parameters of the proposed SIW-DP-LWA for ports 1-2 and ports 7-8, respectively. The measured reflection coefficients of TE₁₀ (port 1 and 7) and TE₀₁ (port 2 and 8) modes for the antenna are below -10dB for the frequency ranges of $35.3 < f_{\text{GHz}} < 38.9$ and $35.7 < f_{\text{GHz}} < 38.7$, respectively. This shows that the two propagating modes have an approximately similar bandwidth behavior for our DP-LWA. In addition, the simulated and measured leakage ratio of the antenna for the two propagating modes has approximately similar behavior. There is a small discrepancy between the measured and simulated results due to fabrication tolerances. According to the analysis of Figure. 7.6, it is expected to have one proper beam ($n = -2$) and one

improper beam ($n = -1$) for our antenna. Figure. 7.13 shows the antenna radiation patterns at two frequencies; $f = 36.5\text{GHz}$ and $f = 38.4\text{GHz}$ for the two propagating modes of TE_{10} and TE_{01} where we have one backward beam and one forward beam through the whole frequency range of the antenna. The peak gains of HSH ($n \in [-1, -2]$) for both modes of TE_{10} and TE_{01} are 15.3dB and 15.1dB, respectively. Besides, based on the analysis of Figure. 7.6(a), we expect that for both modes the beam related to the $n = -2$ space harmonics scans faster than the $n = -1$ space harmonic beam since the arcsine function variation of β_{-2}/k_0 is closer to 1 compared to the β_{-1}/k_0 . This behavior is also validated in Figure. 7.13, in which the beam of $n = -2$ space harmonic covers more angles than the beam of $n = -1$ space harmonic for the same frequency variation. Here the measured scanning ranges of $n \in [-1, -2]$ space harmonics are 4° to 22° and -67° to -33° , respectively, which shows a good agreement with the ratio analysis of arcsine β_{-n}/k_0 of Figure. 7.6(a). In addition, based on the analysis of Figure. 7.7, a misalignment is expected between the beams of TE_{10} and TE_{01} modes for our antenna. Figure. 7.13 also shows that we have a 2° mismatch alignment between the beams of TE_{10} and TE_{01} modes. Thus, a good agreement is observed between the analysis, simulations, and measurement results of the proposed DP-SIW-LWA in which a wide scanning range can be achieved by using the HSH ($n \in [-1, -2]$) concept.

7.3. Dual Polarized LWA with Fixed Beam Capability

7.3.1. Analysis and Modeling

The total behavior of the scanning range in periodic LWAs is predictable based on the arcsine function analysis. This function has two specific features when applied in the analysis of periodic LWAs. First, as long as we keep the ratio of β_n/k_0 close to zero in the frequency range of the antenna, we expect the scanning range variation related to the involved space harmonic not to vary too much due to the specific behavior of the arcsine function. However, periodic LWAs usually encounter the stopband issue when the ratio of β_n/k_0 approaches zero. Therefore, using this feature of the arcsine function to overcome the wide scanning range requires applying methods to suppress the open stopband problem, such as a phase reversal technique [84], impedance matched unit cells [125], [30]-[86], and reflection cancelation [70]. The second feature of the arcsine function, which can be applied to overcome the limitation of a wide scanning range in periodic LWAs is the possibility of decreasing the variation of β_n/k_0 in the passband frequency range operation of the antenna, leading to the decrease in the scanning range variation. Since the scope of this work is

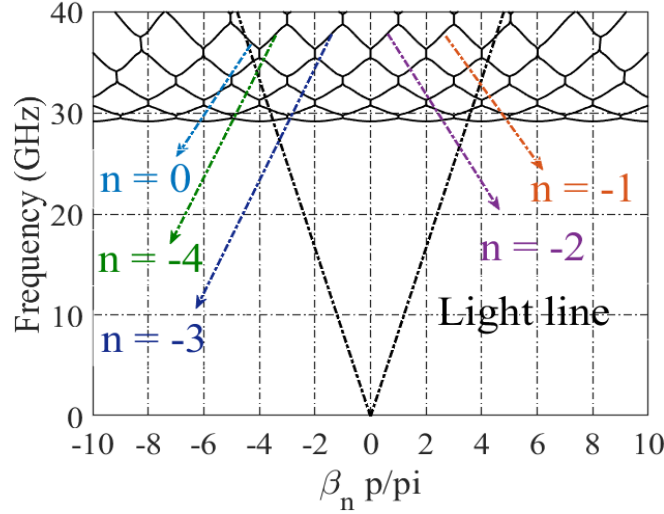


Figure 7.14 Brillouin diagram for a 1D-periodic SIW-LWA with periodicity of $p = 17\text{mm}$ on a dielectric propagating medium of $\epsilon_r = 2.94$ and effective width of 3mm

not focused on the band edge issue of periodic LWAs, we chose to investigate the possibility of applying the second feature to our antenna.

From the analysis of Figure. 7.6(a), the scanning range variation of $n = -1$ space harmonic decrease at the third passband frequencies ($f \geq 35\text{GHz}$) compared to lower ones. This is due to the higher value of k_0 which decrease the variation of β_{-1}/k_0 . On the other hand, the $n = -2$ space harmonic has a wide scanning range variation compared to the $n = -1$ space harmonic in the third passband as the variation of β_{-2}/k_0 is close to 1. Thus, there is a possibility of decreasing the scanning range variation of the $n = -2$ space harmonic by approaching the fourth or higher passband since the ratio of β_{-2}/k_0 will be decreased. Figure. 7.14 shows the Brillouin diagram analysis of a one-dimensional periodic SIW-LWA with 5 passbands (periodicity, dielectric propagating medium, and effective width are 17mm , 2.94 , and 3mm , respectively). Here we are interested in setting our analysis for the upper frequency range of Ka-band ($f \geq 36\text{GHz}$). Therefore, based on the analysis of Figure. 7.14, the fundamental space harmonic ($n = 0$) remains a slow wave, and we have 4 HSHs as fast waves ($n \in [-1, -2, -3, -4]$). The ratio of β_n/k_0 for $n \in [-1, -2, -3, -4]$ space harmonics for $36 < f_{\text{GHz}} < 38$ in the fifth passband are $[-0.54, -0.64]$, $[-0.08, -0.15]$, $[0.41, 0.33]$, $[0.89, 0.84]$, respectively, which correspond to the angles $[-33^\circ, -39^\circ]$, $[-4^\circ, -8^\circ]$, $[24^\circ, 19^\circ]$, $[63^\circ, 57^\circ]$, respectively. Besides, the analysis of Figure. 7.14 also shows that the $n = -2$ space harmonic has the lowest scanning range variation in the fifth passband since its propagation constant is located near the center of the Brillouin diagram, resulting in the lowest value and variation ratio

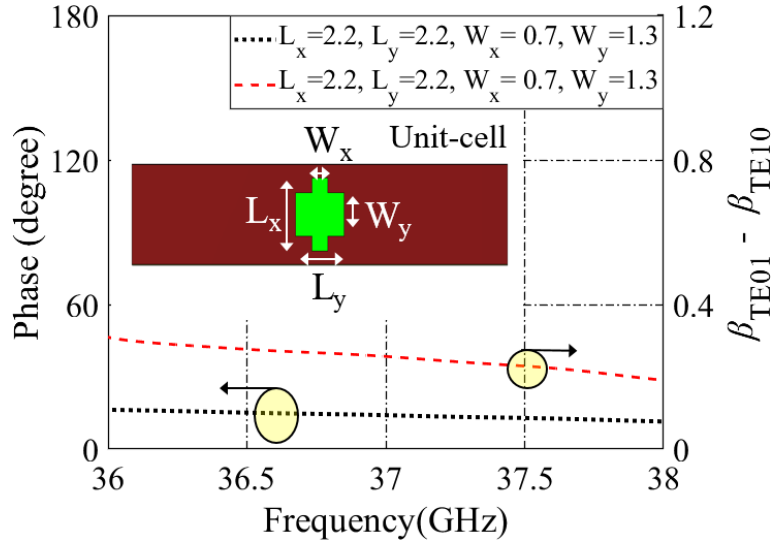


Figure 7.15 Propagation constant and phase difference between TE₁₀ and TE₀₁ modes of SIW-DP-LWA's unit-cell based on analysis of Figure 7.14

of β_n/k_0 . Thus, we expect to have very low scanning range variation (around 5°) for our antenna in the frequency range of interest ($36 < f_{\text{GHz}} < 38$).

On the other hand, since in this work we are dealing with a DP-LWA based on dual-mode operation, it is essential to investigate the effect of the radiating element on the antenna performance for each propagating mode to ensure an acceptable performance yield for each antenna polarization. In this work, the main challenge of using a dual-mode operation for the DP-LWA is related to their beam alignment. However, this issue can be overcome by choosing a suitable radiating element by repeating the analysis of Figures. 7.3-7.9 and applying the conditions of (7)-(11) on the Brillouin diagram in Figure. 7.14. Redoing the analyses shows that using a transverse slot with dimensions of 2.2mm and 0.7mm with a longitudinal slot with dimensions of 2.2mm and 1.3mm in an asymmetric cross slot can provide a suitable response for our DP-LWA. Figure. 7.15 shows the propagation constant and phase shift difference response between the TE₁₀ and TE₀₁ modes of the proposed SIW-DP-LWA's unit-cell. According to Figure. 7.15, the propagation constant and phase shift difference between the two propagating modes of the proposed unit-cell have low values in the frequency range of interest. An acceptable beam alignment between the beams of the two propagating modes is expected. For instance, at $f = 37.5\text{GHz}$ the propagation constant difference between the TE₁₀ and TE₀₁ modes is 0.2 in which we have 4 space harmonics as fast waves. Dividing this value by 4 and placing it in the arcsine function

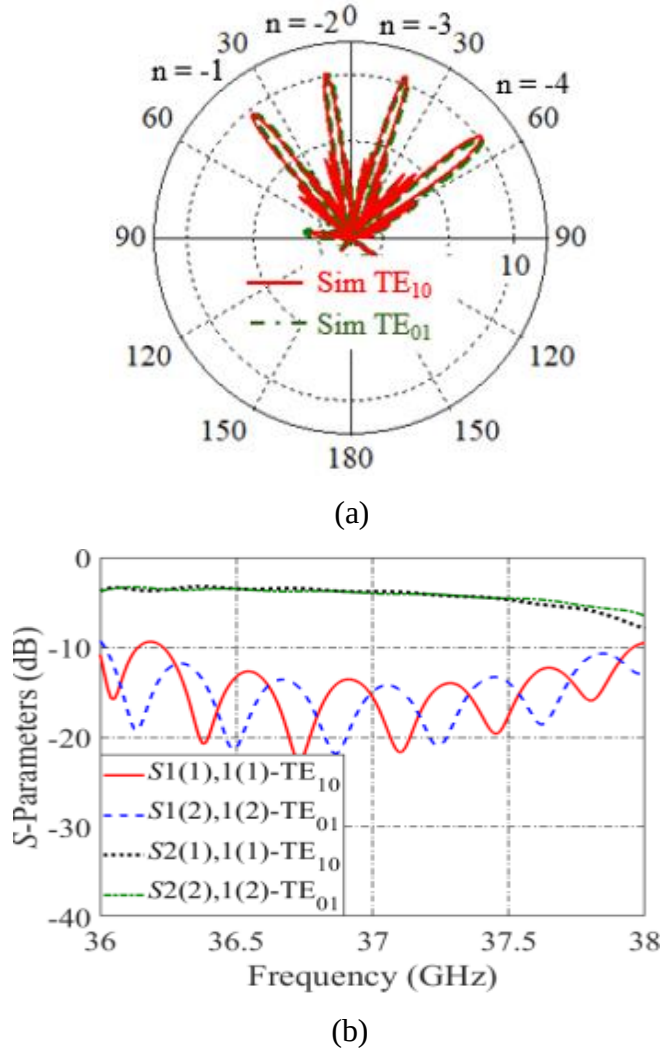


Figure 7.16 (a) Simulated radiation pattern (gain in dB) of SIW-DP-LWA based on unit-cell analysis of Figure 7.12 at $f = 37.5\text{GHz}$, and (b) Simulated S-parameters response of SIW-DP-LWA based on unit-cell of Figure 7.15

of (11) give us the angle of 0.6° which indicates an acceptable beam alignment. Figure. 7.16(a) illustrates the simulated radiation patterns (gain in dB) of SIW-DP-LWA based on the unit-cell analysis of Figure. 7.15 at $f = 37.5\text{GHz}$. It shows an acceptable beam alignment between the two propagating modes of TE_{10} and TE_{01} (the antennas length is considered more than $10\lambda_0$ in this analysis).

Figure. 7.16(b) shows the simulated S-parameter response of an SIW-DP-LWA. The analysis of Figure. 7.16 shows that using an asymmetric cross slot unit-cell, as shown in Figure. 7.15, not

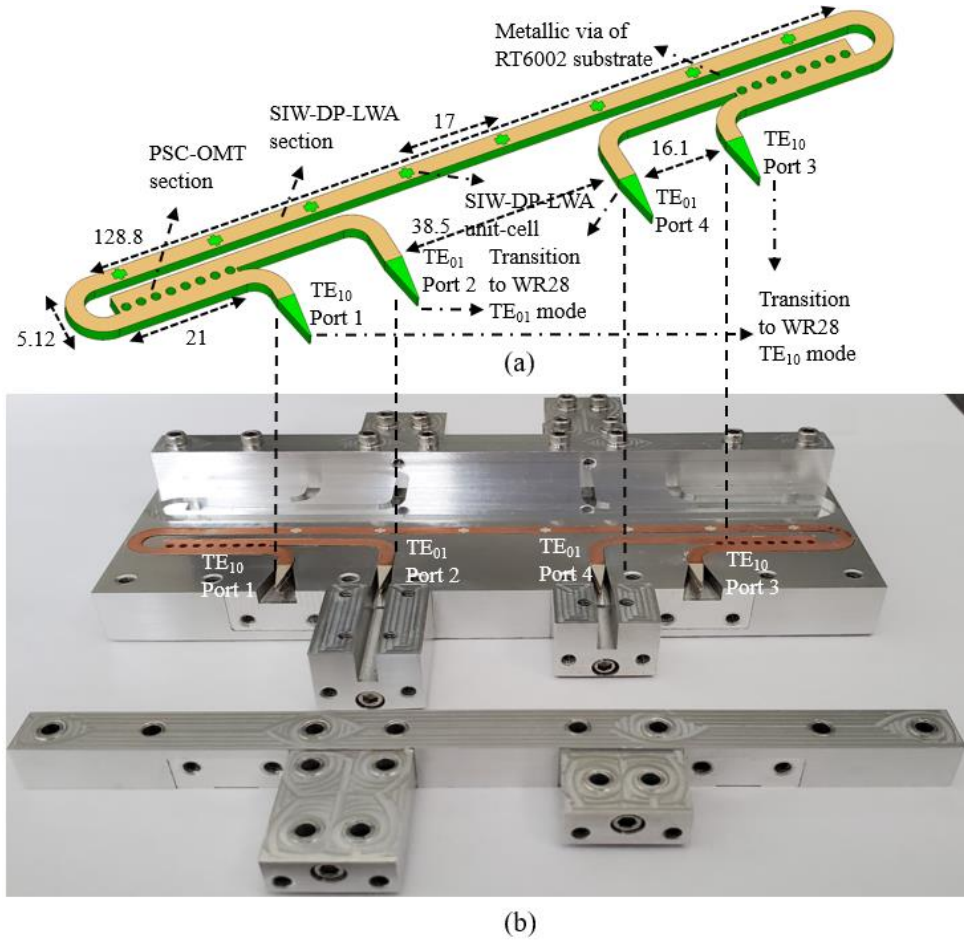


Figure 7.17 (a) Design of SIW-DP-LWA with fixed beam capability (all dimensions are in mm), and (b) fabricated prototype with the PCS-OMT and transition section to WR28

only can provide a similar response of S-parameter for the two propagating modes in the frequency range of interest, but it also provides a suitable beam alignment between the HSHs of each propagating mode. In addition, this unit-cell also has the capability of providing an approximately fixed beam operation for our DP-LWA, since the scanning range variation of related HSH of each mode is low. Thus, we chose this unit-cell for fabricating this design.

7.3.2. Experimental Validation OF SIW-DP-LWA with Fixed Beam Capability

Figure. 7.17 shows the schematic design and prototype of the proposed SIW-DP-LWA with fixed beam operation. The PSC-OMT and its transition are selected. The dielectric material used

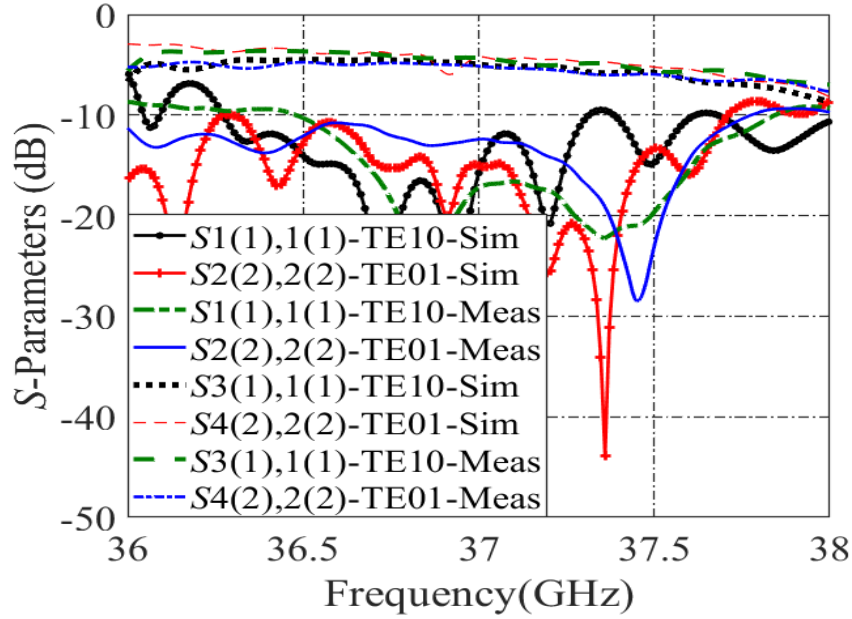


Figure 7.18 Simulated and measured S-parameters response of SIW-DP-LWA of Figure. 7.17 for the TE_{10} and TE_{01} modes

in this design is RT6002 with a dielectric constant of $\epsilon_r = 2.94$ and thickness of 3mm. In this prototype and for the SIW-LWA's section, we use an asymmetric cross slot unit-cell, in which the width of transverse and longitudinal slots are set as 0.7mm and 1.3mm, respectively, with a similar length of 2.2mm. Figure. 7.18 shows the simulated and measured S-parameters response of the proposed DP-LWA for port 1 and port 2. The measured reflection coefficients of TE_{10} (port 1) and TE_{01} (port 2) modes for the proposed DPA are below -10dB for the frequency ranges of $36.25 < f_{GHz} < 38$ and $35.9 < f_{GHz} < 38$, respectively. In addition, the simulation and measured leakage ratio of the antenna for the two propagating modes have similar behavior. Thus, it shows the two propagating modes have an approximately similar bandwidth behavior. There is a small difference between the measured and simulated results due to fabrication tolerances. According to the analysis of Figure. 7.14, it is expected to have two improper beams ($n \in [-1, -2]$) and two proper beams ($n \in [-1, -2]$) for our DPA. Figure. 7.19 (a)-(b) show the simulated and measured E-plane co-polar radiation patterns (gain in dB) of the fabricated prototype at the two frequencies of $f = 36.5\text{GHz}$ and $f = 37.5\text{GHz}$ for the two propagating modes of TE_{10} (port1) and TE_{01} (port2), where we have two backward and two forward beams through the whole frequency range of the antenna. The peak gain of the HSH beams for both modes TE_{10} and TE_{01} are 10.3 dB and 10.1dB,

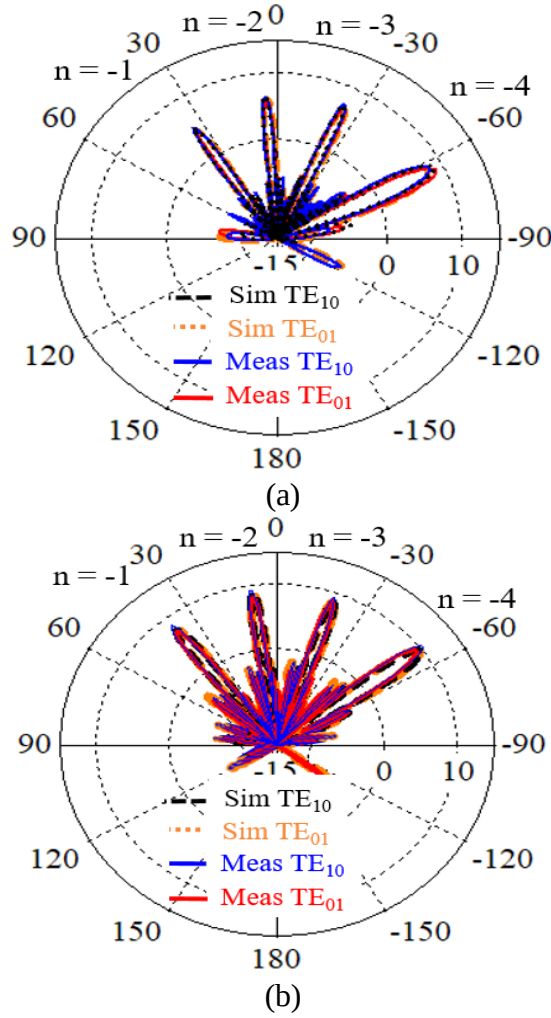


Figure 7.19 Simulated and measured E-plane co-polar radiation patterns (gain in dB) of SIW-DP-LWA of TE₁₀ and TE₀₁ modes (a) at $f = 36.5\text{GHz}$, and (b) $f = 37.5\text{GHz}$

respectively. A very low scanning range variation for each of HSH's beams is expected due to the specific behavior of the arcsine function and the ratio of β_n/k_0 for the two propagating modes of TE₁₀ and TE₀₁ and their related HSHs in the frequency range of interest. Here, the measured scanning range has validated this behavior, in which we have $[5^\circ, 4^\circ, 5^\circ, 6^\circ]$ angle beam's variation for $n \in [-1, -2, -3, -4]$, respectively (through the whole frequency range of the antenna). In addition, based on analysis of the Figure. 7.15, it is expected to have a very low misalignment between the beams of TE₁₀ and TE₀₁ modes for our antenna. The analysis of Figure. 7.19 also shows that we have a 1° degree mismatch alignment between the beams of TE₁₀ and TE₀₁ modes. Thus, a good agreement is observed between the analysis, simulations, and measurement results of the proposed SIW-DP-LWA, in which we utilized the HSH concept for achieving a fixed multi-beam DPA.

7.4. Dual Polarized LWA with Fixed and Scanning Beam Capability

7.4.1. Analysis and Modeling

A DPA based on its radiation mechanism can be divided into two categories: a DPA with fix beam operation and a DPA with scanning beam operation. To the best of the authors' knowledge, a DPA with the capability of both scanning and fixed beam operations does not exist in literature. Therefore, in this section, we demonstrate a DPA with fixed and scanning beam capabilities by using the HSH concept. The core idea of the proposed design is to assign a specific task (scan or fix) to each polarization of the proposed DP-LWA. However, several aspects need to be analyzed and their trade off needs to be investigated. In the proposed design, first, we need to choose the topology of each polarization and decide about their function and operation task. In addition, other antenna characteristics such as gain level alignment and gain stability between each polarization need to be analyzed. In the proposed design and as a first step, we chose to assign the scanning and fixed beam operations to the TE_{01} and TE_{10} modes, respectively.

In the second step, we analyze the Brillouin diagram with the unit-cell geometrical effect (periodicity) on the antenna performances. From that, we can predict the HSH behavior in the fast wave region and evaluate the scanning range variation. A point that needs to be considered here is that the topology of applying scanning and fixed beam operation requires different periodicities (based on Brillouin diagram analysis of Figure. 7.6 and Figure. 7.14). Thus, to avoid modifying the geometrical shape of the antenna radiating element, we should choose the periodicity ratio between both polarizations as $P_{TE_{01}}/P_{TE_{10}} = 0.5$ or $P_{TE_{10}}/P_{TE_{01}} = 2$. Besides, taking the periodicity into the consideration for the proposed DP-LWA has a direct effect on the number of radiating elements for each polarization. Since one polarization has a higher number of radiating elements. Therefore, as a first estimation, we should expect to have a higher gain for one polarization compared to the other (if only we judge based on the radiating element number). A point that needs to be considered is that we also need to evaluate the effect and influence of the radiating elements on the antenna performances for both operating modes of TE_{01} and TE_{10} especially when we are dealing with the dually polarized operation.

To investigate this effect and as a third step, we analyze the geometrical effect of the radiating elements on the radiated power response of each polarization (TE_{10} and TE_{01} modes). First, we

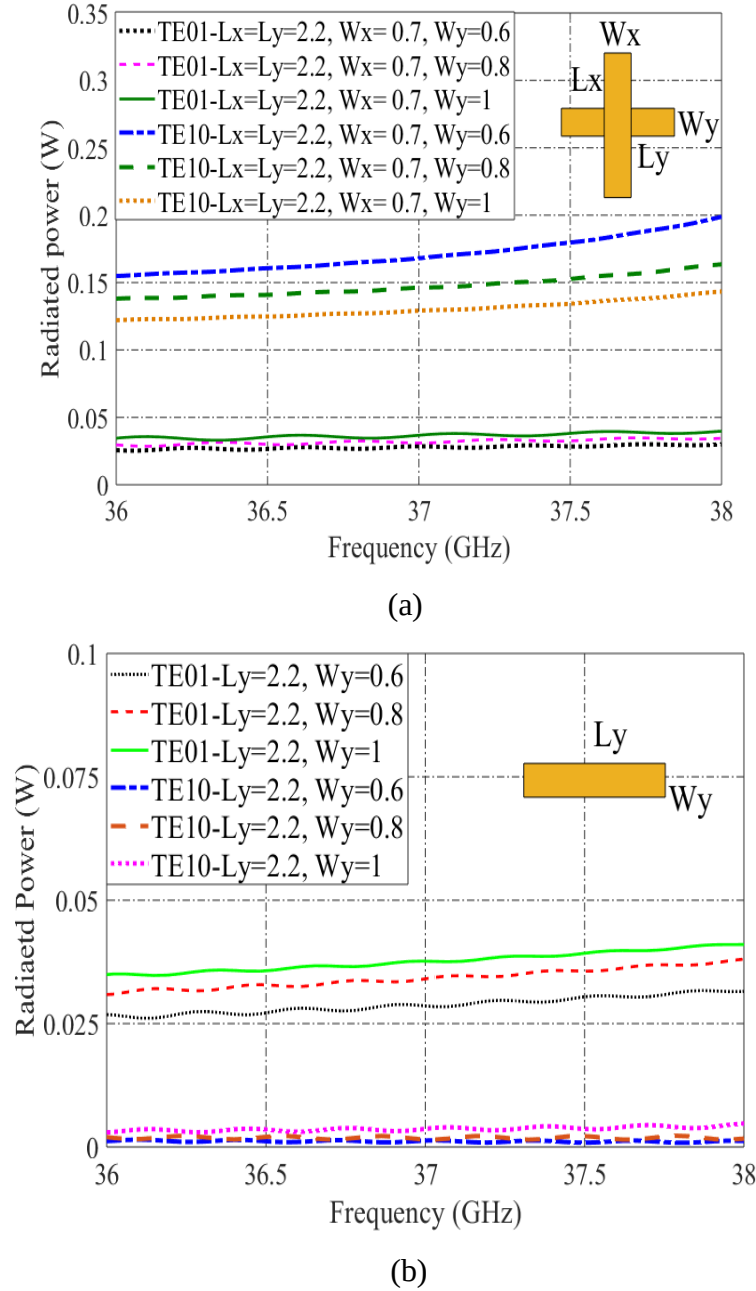
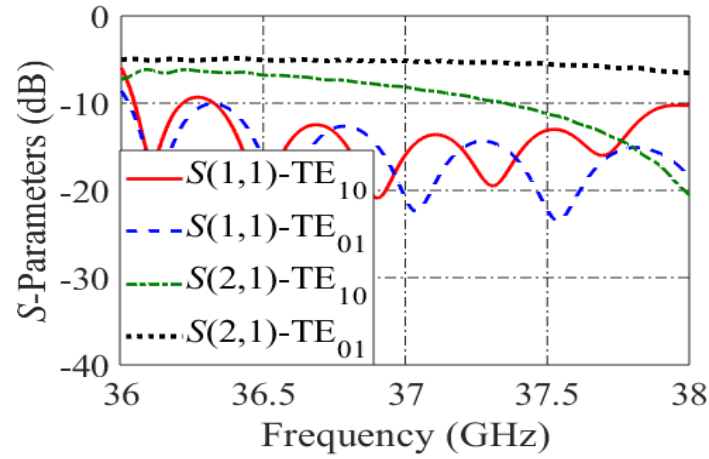


Figure 7.20 Effect of longitudinal slot width variation to the radiated power responses of TE₁₀ and TE₀₁ modes for the case of (a) a cross slot, and (b) a longitudinal slot. Input power is 0.5W

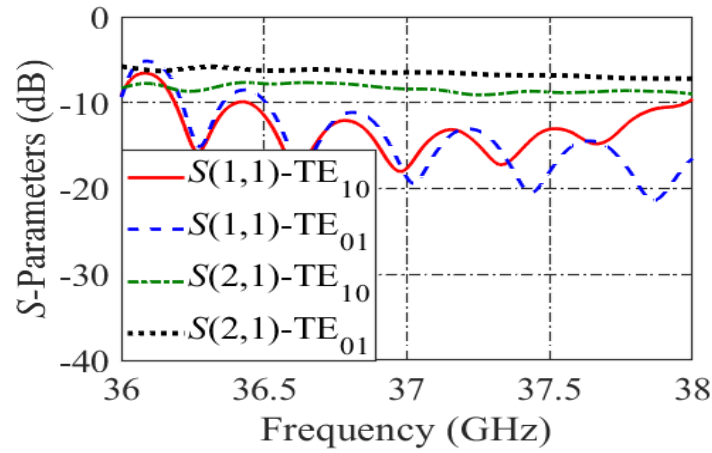
consider a symmetric cross slot and its longitudinal slot as our radiating element where they are assigned to the TE₁₀ and TE₀₁ modes, respectively (TE₀₁ and TE₁₀ modes are assigned to the Brillouin diagram of Figure. 7.6 and Figure. 7.14, respectively). Figure. 7.20 shows the radiated power response of these unit-cells for the frequency range of interest ($36 < f_{\text{GHz}} < 38$). This analysis

shows that the TE_{01} and TE_{10} radiated power responses have different behavior for each of these unit-cells. The TE_{10} mode has a higher radiated power compared to the TE_{01} mode for the case of a symmetric cross slot, while for the case of a longitudinal slot it has much less radiated power compared to the TE_{01} mode. A point that needs to be considered here is that the TE_{01} mode has an approximate similar response for both radiating elements (symmetric cross slot and longitudinal slot) and its slope variation is not sharp, while the slope variation for the TE_{10} has a sharp variation for the case of a symmetric cross slot which results in more gain variation for this antenna polarization (TE_{10} mode). To overcome this issue, we investigated the geometrical effect of our radiating elements on their radiated power response for two polarizations of our DP-LWA. In this regard, we analyzed the effect of slot width variation on the radiated power responses of TE_{10} and TE_{01} modes for the case of a cross-slot and a longitudinal slot. The analysis of Figure. 7.20 shows that the radiated power response of TE_{01} mode is increased by increasing the longitudinal slot width for both cases of cross slot and longitudinal slot. However, for the case of TE_{10} mode, the radiated power response will decrease for the case of the asymmetric cross slot while it remains close to zero for the case of a longitudinal slot and it is much less compared to the TE_{01} mode. It should be mentioned that in addition to the LWA unit-cell analysis, we also need to check the S-parameter response of each antenna polarization to ensure that the DPA has an acceptable performance.

Figures. 7.21 (a)-(b) show the S-parameters responses for the case of DP-LWA with symmetric and asymmetric unit-cells, respectively (dimensions of LWA unit-cells specified in the capture of Figure. 7.21). The analysis of Figure. 7.21 shows that the antenna polarization related to the TE_{10} mode has a narrower bandwidth compared to the TE_{01} mode since it has a narrower passband frequency range. This shows a good agreement with the Brillouin diagram analysis of Figure 7.14 and Figure. 7.6. In addition, S-parameters responses ($S_{-2,1}$) related to the TE_{10} mode for the case of LWA with symmetric unit-cell have a sharper variation compared to the TE_{01} mode, while both modes have smooth variation for the case of LWA with asymmetric unit-cell. In this regard, we should expect to have a mismatch between the gain level of each antenna polarization for the case of LWA with symmetric unit-cell. Besides, From Figure.7.21(b) it is expected that the beam levels of TE_{10} and TE_{01} modes have approximately similar levels since the radiated power of TE_{10} mode (with four beams) is around 3 dB higher than TE_{01} mode (with two beams). Figure. 7.22 shows the simulated radiation pattern response (gain in dB) of the DP-LWA at $f = 37.5\text{GHz}$ based on the



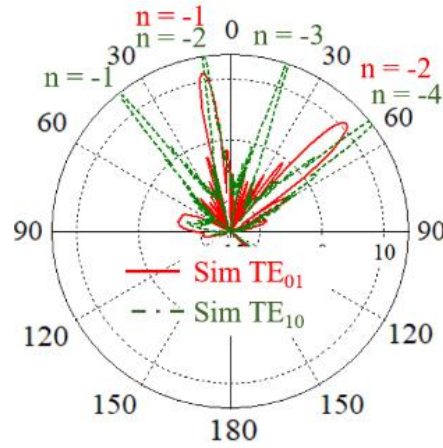
(a)



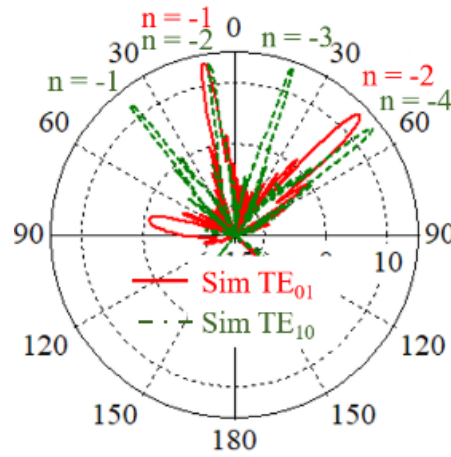
(b)

Figure 7.21 (a) S-parameters responses of a DP-LWA with symmetric cross slot ($L_x = 2.2$, $L_y = 2.2$, $W_x = 0.7$, $W_y = 0.7$) with a longitudinal slot ($L_y = 2.2$, $W_y = 0.7$), and (b) S-parameters responses of a DP-LWA with an asymmetric cross slot ($L_x = 2.2$, $L_y = 2.2$, $W_x = 0.7$, $W_y = 1$) with a longitudinal slot ($L_y = 2.2$, $W_y = 1$). All dimensions are in mm

analysis of Figure 7.21. The analysis of Figure 7.22 shows that for both LWAs cases (with symmetric and asymmetric unit-cell), we have one proper beam ($n = -2$) and one improper beam ($n = -1$) for the TE_{01} mode while we have two proper beams ($n \in [-1, -2]$) and two improper beams ($n \in [-3, -4]$) for the TE_{10} mode. This shows a good agreement with the Brillouin diagram analysis of Figures 7.14 and 7.6. Besides, these analyses show that we have a mismatch between the gain level of each polarization for the case of LWA with symmetric unit-cell (4.2dB difference). However, a good gain alignment is observed between the antenna polarization for the case of



(a)



(b)

Figure 7.22 Simulated radiation pattern of DP-LWA at $f = 37.5\text{GHz}$ based on (a) Figure. 7.21 (a) analysis, and (b) based on Figure 7.21(b) analysis

LWA with asymmetric unit-cell (0.1dB difference). This shows a good agreement with the analysis of Figures. 7.20-7.21. Thus, with a careful analysis of Brillouin diagrams and their related unit-cells, we are able to achieve a DPA with fixed and scanning beam capabilities. We could also assign the features of scanning and fixed beam operations to the TE_{10} and TE_{01} modes, respectively. However, the use different radiation elements will be required for our DPA to find a suitable tradeoff between the antenna characteristics of the two propagating modes. In Section 7.3.2 we validate our analysis by showing a prototype of the proposed DP-SIW-LWA. Such a dual operation can be beneficial in next-generation access points.

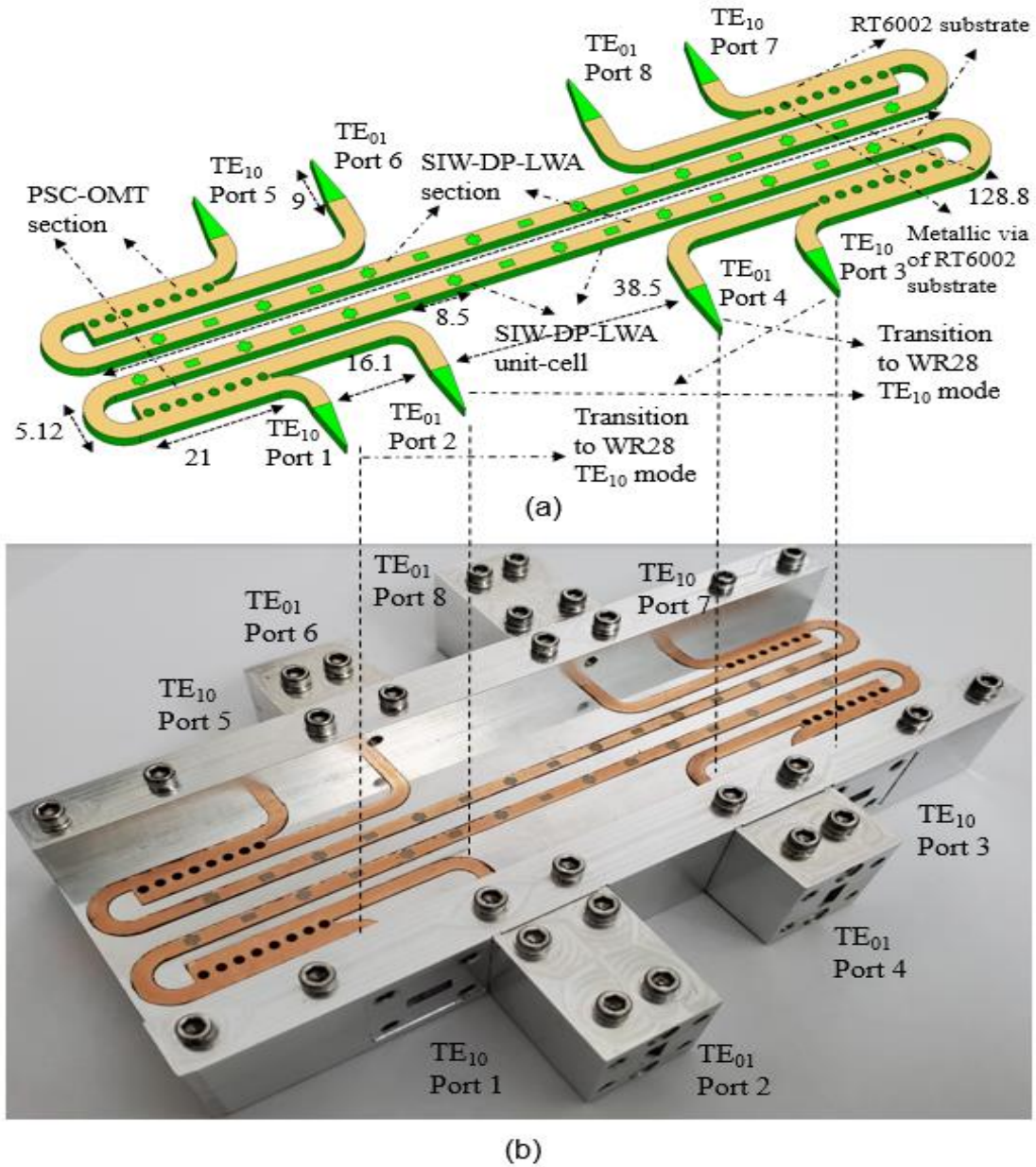


Figure 7.23 (a) Model of SIW-DP-LWA with fixed and scanning beam capabilities with and transition section to WR28, and (b) fabricated prototype

7.4.2. Validation of a DPA-LWA with Fixed and Scanning Beam Capability

Figure. 5.23 shows the design prototype of the proposed SIW-DP-LWA with simultaneous fixed and scanning beam capabilities. Here, we again use a PSC-OMT for our DPA. The dielectric

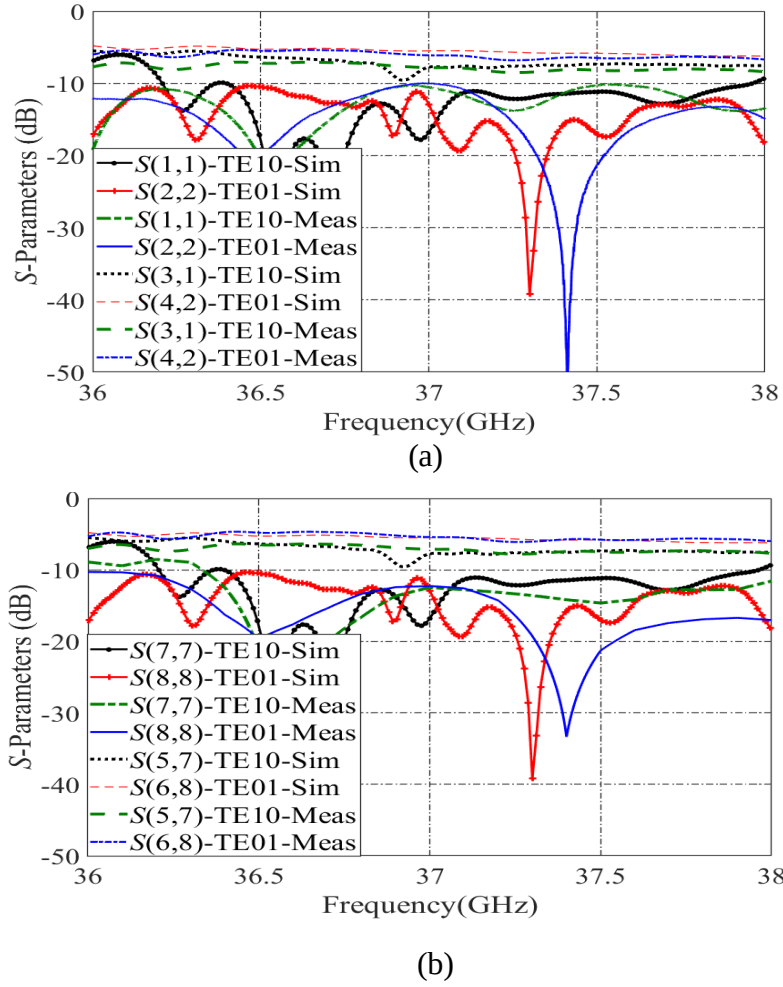


Figure 7.24 Simulated and measured S-parameter response of TE₁₀ and TE₀₁ modes of (a) ports 1 and 2, and (b) ports 7-8

material used in this design is RT6002 with a dielectric constant of $\epsilon_r = 2.94$ and thickness of 3mm. In the proposed DPA's prototype and the SIW-LWA's section, we use two sets of radiating elements in which we assign the periodicity of 17mm and 8.5mm to each. The first radiating element is an asymmetric cross slot in which the length of the transverse and longitudinal slot dimensions are set to 2.2mm, and their widths are set to 0.7mm and 1mm, respectively. The second radiating element is a longitudinal slot with length and width of 2.2mm and 1mm, respectively.

Figures. 7.24 (a)-(b) show the simulated and measured S-parameters response of the proposed SIW-DP-LWA for ports 1-2 and ports 7-8, respectively. The measured reflection coefficients of the TE₁₀ (port 1 and 7) and TE₀₁ (port 2 and 8) modes for the antenna are below -10dB for the frequency ranges of $36.35 < f_{\text{GHz}} < 38$ and $36 < f_{\text{GHz}} < 38$, respectively. There is a small discrepancy

between the measured and simulated results due to fabrication tolerances. According to Figure. 7.6 and Figure. 7.14, it is expected to have two improper beams ($n \in [-1, -2]$) and two proper beams ($n \in [-1, -2]$) for the TE_{10} mode and one proper beam ($n = -2$) with one improper beam ($n = -1$) for the TE_{01} mode of our DP-LWA. In addition, we used two sets of DP-LWA in this design to have a symmetric multi-beam radiation for our antenna. Figure. 7.25 shows the antenna radiation patterns at the two frequencies of $f = 36.5\text{GHz}$ and $f = 37.5\text{GHz}$ for two propagating modes of TE_{10} and TE_{01} . Here we have two forward beams and two backward beams for the TE_{10} mode and one backward beam with one forward beam for the TE_{01} mode of our antenna. Besides, based on Figure. 7.6, we should expect that the beam related to the $n = -2$ space harmonic of the TE_{01} mode scans faster than the $n = -1$ space harmonic beam of this mode since the arcsine function variation of β_{-2}/k_0 is closer to 1 compared to the β_{-1}/k_0 . In addition, Figure. 7.14 predicts to have a very low scanning range variation for each of HSH's beams of the TE_{10} mode since the variation of β_n/k_0 of this mode is very low, and they are not close to 1. Figure. 7.25 also validates this behavior. Here the measured scanning ranges of $n \in [-1, -2]$ space harmonics of the TE_{01} mode are 4° to 22° and -67° to -33° , respectively. For the TE_{10} mode we have $[5^\circ, 4^\circ, 5^\circ, 6^\circ]$ angle beam's variation for $n \in [-1, -2, -3, -4]$, respectively. This shows a good agreement with the ratio analysis of the arcsine β_n/k_0 in Fig. 5.6 and Figure.7.14. In addition, the scanning range variation for the fixed beam operation in this work is in an acceptable range compared to the scanning range variation in [126] and [129], which have around 12° variation. Thus, an agreement observed between the analysis, simulation, and measurement results of the proposed DP-LWA in which the simultaneous fixed and scanning features are achieved by using the PSC mechanism and the HSH concept.

Figure. 7.26 also shows the antenna gain performance for each polarization of the proposed DP-LWA (values are the average gain of different beams related to each polarization). The peak gains for both TE_{10} and TE_{01} modes are 14.8dBi and 14.6dBi, respectively. An acceptable gain alignment is observed between those polarizations. This shows a good agreement with the unit-cell radiated power analyses of Figure. 7.20. The maximum gain difference between the beams related to the TE_{10} and TE_{01} modes are 0.2dB and 0.3dB, respectively (the gain values presented in Figure. 7.25 are the average values of the beams of TE_{10} and TE_{01} modes). Figure. 7.27 provides the side lobe level (SLL) of each polarization where they are operating in an acceptable range better than -12dB over the whole operating frequency range. Figure. 7.28 gives the 3dB beamwidth where a good

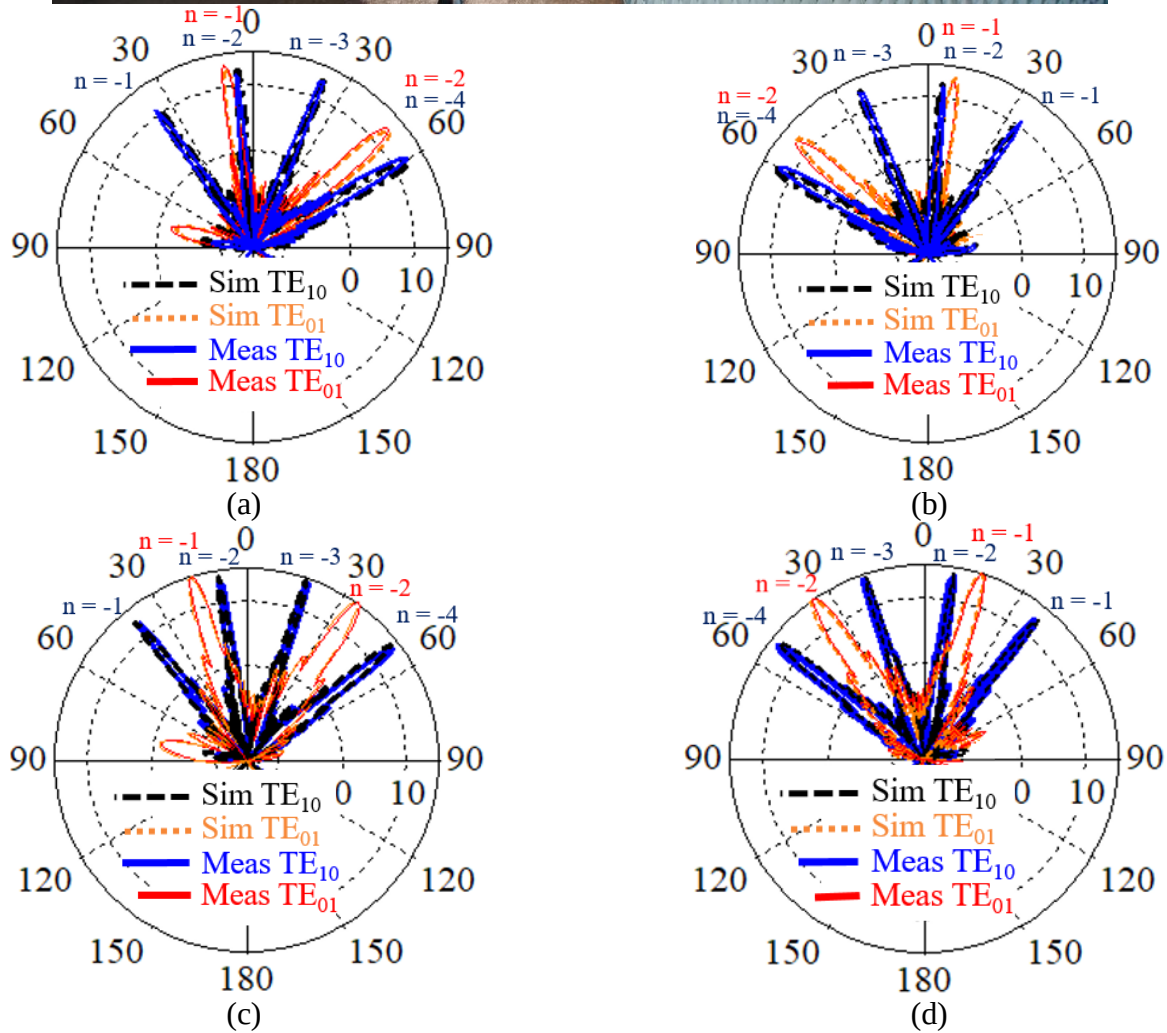
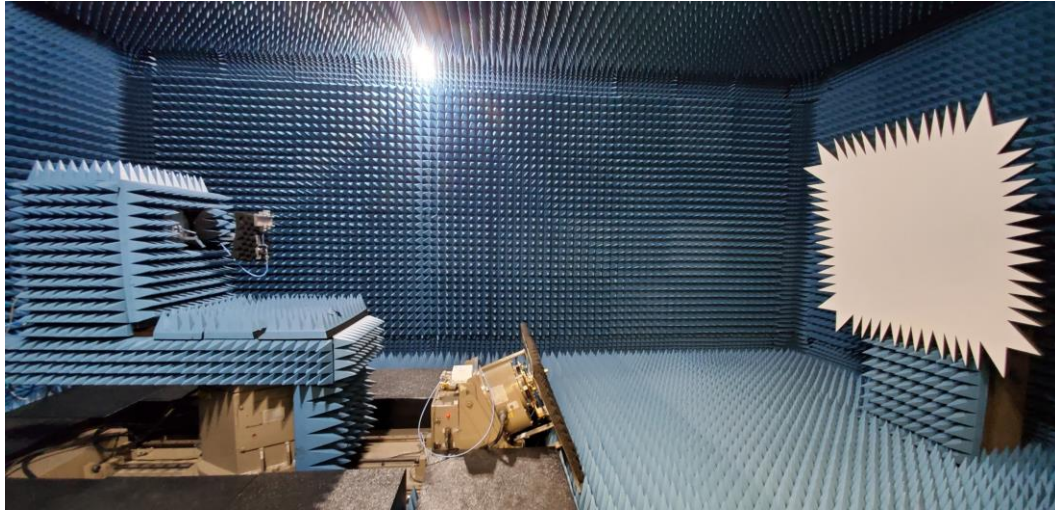


Figure 7.25 Simulated and measured E-plane co-polar radiation patterns (gain in dB) of SIW-DP-LWA of TE_{10} and TE_{01} modes of (a) ports 1 and 2 at $f = 36.5\text{GHz}$, (b) ports 7 and 8 at $f = 36.5\text{GHz}$, (c) ports 1 and 2 at $f = 37.5\text{GHz}$, and (d) ports 7 and 8 at $f = 37.5\text{GHz}$

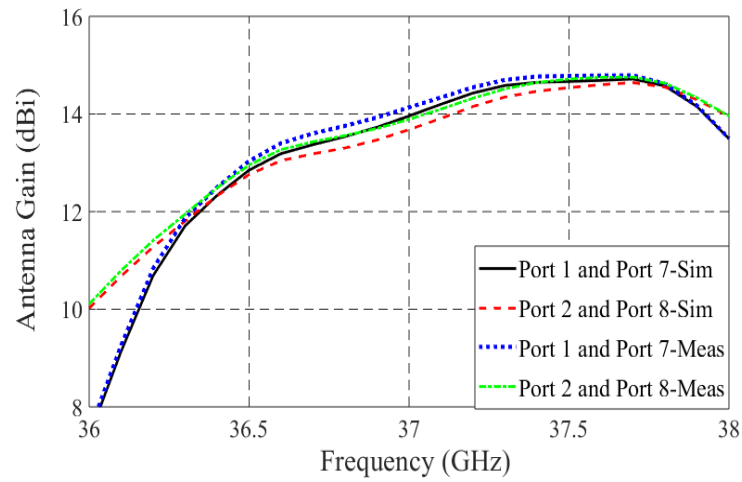


Figure 7.26 Simulated and measured antenna gain (in dBi)

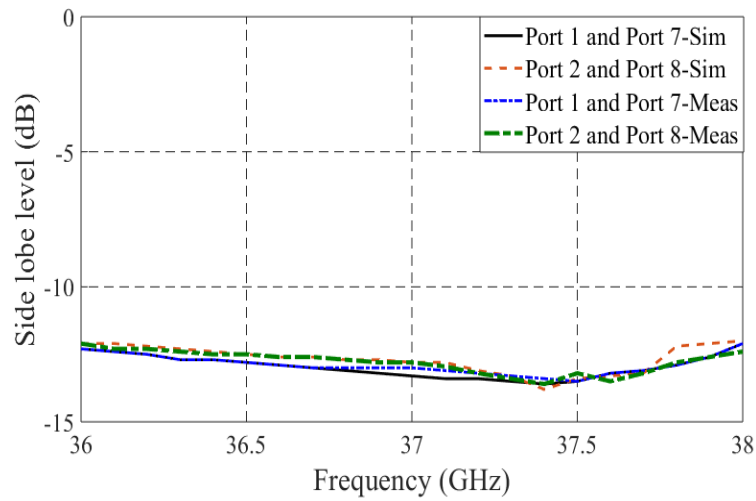


Figure 7.27 Simulated and measured side lobe level

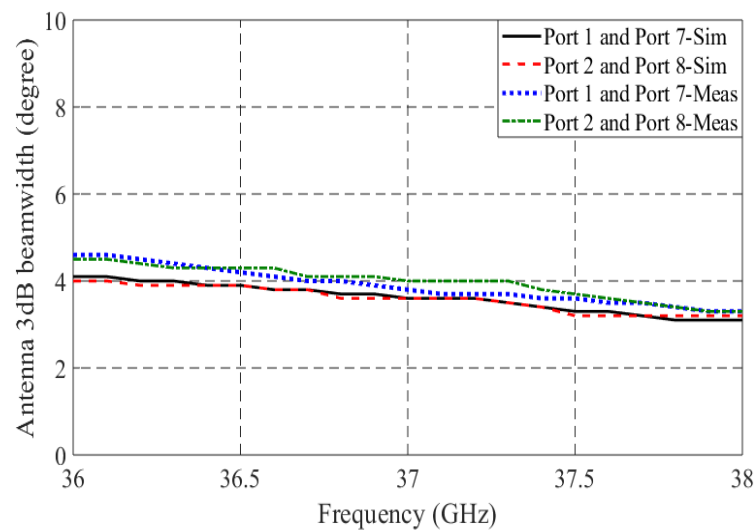


Figure 7.28 Simulated and measured 3dB beamwidth

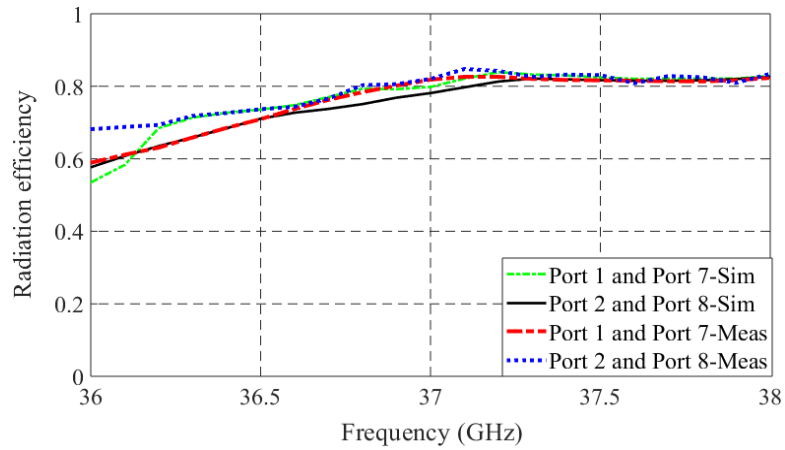


Figure 7.29 Simulated and measured radiation efficiency

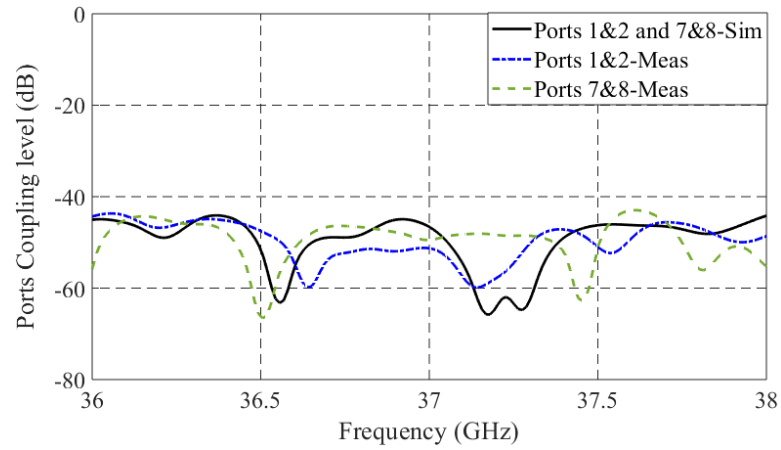


Figure 7.30 Simulated and measured ports coupling level

agreement is observed for both polarizations. Figure. 7.29 presents the antenna radiation efficiency in which a maximum radiation efficiency of 84% is obtained for each polarization. Besides, a high level of coupling between antenna ports could be highly beneficial to reduce the effects of interference. Figure. 7.30 shows the port coupling level of the proposed antenna. A coupling level better than -40dB is observed for the whole operating frequency range. Table 7.1 shows the comparison between proposed work and others LWAs. The work presented in section 7.1 (LWA with scanning feature) achieves more bandwidth and lower scanning range compared to [116] while these features improved in [115] by using a plasmon polariton LWA. The works of [115]-[116] generated a single beam while the work presented here can provide multi-beam operation from

Table 7.1. Comparison of proposed SIW-DP-LWA with other LWAs

Ref.	Antenna Type	Antenna Polarization	Antenna Feature	Max Scanning Variation for each polarization (degree)	Antenna Bandwidth (GHz)	Max Eff (%)
[115]	Plasmon Polariton LWA	Dual-Polarized Single beam	Scanning	49 63	6	-
[116]	SIW LWA	Dual-Polarized Single beam	scanning	60 73	2.8	-
[122]	Glide Symmetric Prism LWA	Single-Polarized Single-Beam	Fixed	2	8	90
[126]	Reflector -LWA	Single-polarized	Fixed	12	2	80
[129]	Reflector -LWA	Dual Polarized Single-Beam	Fixed	11 11	2	94
[127]	Dispersive Symmetric Prism-LWA	Single-Polarized Multi-Beam	Fixed	2	10	90
This Work	SIW-LWA	Dual-Polarized Multi-Beam	Scanning	34 34	4	84
This Work	SIW-LWA	Dual-Polarized Multi-Beam	Fixed	5 5	2	85
This Work	SIW-LWA	Dual-Polarized Multi-Beam	Fixed and Scanning	5 34	2	83

each antenna polarization which can improve the link reliability and availability [53]. Besides, the antenna demonstrated in section 7.2 takes the benefit of shrinking the size and achieving a lower scanning range variation compared to the reflector based LWAs in [126]-[129] for the case of a fixed beam operation. On the other hand, using dispersive symmetric prism [127] and glide symmetric prism [122] can provide a lower scanning range and wider bandwidth at the expense of a larger geometry for the antenna to achieve a fixed beam operation. Finally, this work demonstrates a combination of fixed and scanning beam operations in section 7.3 which can reduce the volume and size of wireless communication systems, thereby presenting an alternative solution for future broadcasting and wireless developments.

7.5. Conclusions

The concept of HSHs in a hybrid form of the NRD waveguide and the square SIW structure for the TE_{10} and TE_{01} modes was proposed and applied to several theoretical and experimental prototypes. The properties of polarization diversity related to the unit-cell geometrical structures for different features of an LWA were investigated. It was shown that the propagation constant of the TE_{10} and TE_{01} modes can be manipulated by the geometrical structure of the LWA's radiating element to achieve the design flexibility of the proposed antenna. In addition, the effect of the difference between the two propagation constants for the two modes TE_{10} and TE_{01} on the beam alignment of their related HSHs was investigated. Besides, the feasibility of even and odd HSHs ($n \in [-1, -2, -3, -4]$) of the two propagating modes (TE_{10} and TE_{01}) in different passbands was studied. We showed that the features of scanning and fixed beam operations are achievable with a careful analysis of the Brillouin diagram and propagation constant variation of each HSH. In this regard, the PSC mechanism along with the HSH concept was used to demonstrate a multi-functional SIW-DP-LWA with the capability of simultaneous fixed and scanning multi-beam operations. In this work, two experimental prototypes of the proposed antennas were shown as proofs of concept to validate the analysis method formulated. The measured results show a good agreement with simulated counterparts, thus validating the proposed LWAs.

CHAPTER 8 GENERAL DISCUSSION

This thesis demonstrates and proposes the concept of applying HSH to the periodic LWAs, which aims to overcome the current limitation of periodic LWAs. Here, we investigate the drawback of periodic LWAs in which they only generate one beam through their operating frequency band. A solution is demonstrated in which we show how a periodic LWA can achieve a multi-beam feature where we are able to control the angle of the different beams and their scanning ranges. Moreover, we investigated the limitation of LWAs in terms of single-band operation where we presented a solution to achieve multi-beam operation for the antenna in which we can control the number and position of different radiated beams for each antenna band.

Furthermore, the limitation of HSH at different pass band and stop band frequencies are studied, and analyzed and a solution is demonstrated to solve the mismatch issue of HSH at different stop band frequencies. It is shown that a periodic LWA can have an acceptable performance at different band edges in which we were able to control the number of antenna beams. In addition, most the LWAs usually steer the beam within their operating frequency. Such a feature may not be desirable for point-to-point communication systems. Here, we were demonstrated how the flexibility of HSH enables LWA to achieve a fixed beam operation which can benefit the antenna to be used in the base station while providing an acceptable link from one sector to another one.

Besides, most the LWAs usually were limited to operating with a single polarization. Here, we are demonstrated how the NDR structure can benefit the LWA to achieve polarization diversity feature where HSH enables the antenna to have multiple beam operation with wide scanning features. moreover, a combination of fixed beam operation and beam steering (through different frequencies) along with polarization diversity can sufficiently reduce the volume and size of wireless communication systems and present an alternative solution for future broadcasting designs. Here, we demonstrated a novel LWA with the capability of supporting the polarization diversity feature along with beam steering and fixed capability through a planar geometry that can enhance its integrity feature of it. Such a feature can be used in the future access point to provide an acceptable communication link for different user planes.

CHAPTER 9 CONCLUSION AND RECOMMENDATIONS

With the rapid growth of wireless communications and high demand for fast data transfer, limited spectrum resources, and bandwidth requirement become more crucial and problematic for system design engineers. Two potential solutions can be applied to overcome such issues like allocating the users to different bands or utilizing polarization diversity. Previously, applying multi-band features required the use of different antenna configurations in which each antenna aperture was responsible for one band. Implementing the polarization diversity features required the use of nonplanar orthomode transducers which resulted in bulky and complex systems. Furthermore, the required coverage of the antenna for each band and even for each polarization based on the application requirements will increase the complexity of the design. Utilizing active phased array antennas not only increases power consumption budgets but also the dependency of their phase shifter to λ brings new design challenges for implementing the features of multi-band or polarization diversity operation. Therefore, the main motivation of this thesis is on the development of planar low profile and low-cost integrated passive antenna at mmW frequency to overcome the above mentioned problems while providing an alternative solution for future (5G) wireless communication and their related applications.

This PhD thesis exploited and proposed a highly original idea based on the utilization of higher-order space harmonic (HSH) which tackles the above mentioned limitations. The novelty presented in this thesis lies in investigating the principle operation of HSH which provides a guideline for the design of LWAs based on SIW with capability of providing novel features and suppress the current limitations where different methodologies and solutions are theoretically studied, analyzed and examined through different antenna fabricated prototypes. It is shown that the proposed concept can satisfy the antenna performance at FR2 frequency range (24.25 GHz to 52.6 GHz). Such topologies can also be extended to other millimeter-wave frequency range to satisfy the future design of wireless communications. The original contributions and highlights of this thesis work are summarized as follows:

- The principle operation and fundamental behavior of HSH for different modes of an SIW structure were studied. We analyzed the sensitivity of propagation constant

- response of different HSH to the variation of permittivity, periodicity, and unit-cell geometrical structures in addition to the response of the HSH in the FWR.
- The behavior and response of HSH was also compared to the fundamental space harmonic in a 1D-periodic SIW-LWA of the fundamental mode operation where different antenna characteristics based on the HSH or fundamental space harmonic were studied and analyzed, and their tradeoffs were explained.
 - The beam steering features of different HSH and fundamental space harmonic for different pass band frequencies were investigated so that the proper and improper characteristic of different HSH were highlighted through the FWR. The trade off between the number of pass band frequency and scanning range variation of each HSH were also studied and analyzed and their limitations were explained.
 - We demonstrated how the topology of HSH can be implemented in order to have the flexibility for our number and position antenna beams through our frequency range of interest. The HSH concept allows us to suppress the current limitation of 1D-periodic LWA in terms of single beam operation in which we are able to achieve single beam, dual-beam, and multi-beam operation for our antenna performances where we are able to predict the exact location of our inserted beam/beams based on the application requirements. A prototype of a dual-beam SIW-LWA is shown for the proof of the concept which shows a good agreement with the simulation analyses.
 - It is shown that the distinguishing features of HSH concept presents to tackle another limitation of 1D-periodic LWA in terms of single band operation. Here we demonstrated how the principle operation of HSH gave us the flexibility to approach an antenna with our desired number of bands, number and positions of beams of each band through different combination sets of pass band frequencies.
 - For the case of multi-band operation here we investigated the impedance, and radiated power response of the LWA radiating element for different frequency range of our interested to achieve an acceptable power level for each antenna band. Besides, it is shown how the geometrical shape of the unit-cell can have an impact on the number of pass band frequency range of antenna operation.
 - The flexibility of HSH and implementation of them through multi-band operation was investigated. Here we demonstrated two dual-band LWAs and one triple-band LWA.

The first dual-band LWA can get the benefit of having single beam operation for each band in which the beam steering and position of each beam of each band are similar compared to each other. The second dual-band antenna had single beam in one band and had two beams in another band. Here we get the benefit of a distinguish feature of HSH to reached wide scanning, based on complementary behavior of HSH in different antenna pass band. It was shown that the missing scanning ranges of one band can be compensated by another (similar response was implemented to the triple-band antenna). A prototype of a dual-band SIW-LWA was shown as a proof of concept which showed a good agreement with the simulation analyses.

- The behavior of HSH at their stop band frequencies was studied. Here we analyzed the contribution of HSH to the different stop band frequencies in the FWR. It shown that the band edge issue of HSH is not limited to the broadside angle and there is a possibility of occurring in another angles. Besides, the symmetric and unsymmetric beam steering behavior of different HSH is studied and investigated.
- A solution was demonstrated to overcome the mismatching issue of HSH at their stop band frequency by careful analyses of the phase distribution between the radiating element which gives us the flexibility of forcing the antenna to have single beam, or multi-beam operation, through its stop band frequencies. Such a response and behavior is validated by showing a periodic LWA prototype in which a good agreement is observed between the theoretical analyses, simulation, and measurement results.
- We applied the polarization diversity feature to our antenna by utilizing a hybrid form of the NRD waveguide and the square SIW structure which enables us to get the benefit of dual-mode operation. Here we investigated the impedance and admittance behavior for each operating mode to identify the radiated power contribution for different radiating elements. Besides, the coupling effect of two operation modes on the propagation constant, leakage ratio, pass band and stop band frequency range were investigated and their tradeoff highlighted. In addition, the geometrical shape of unit-cell to the phase variation response of each mode and their effect on the beam alignment response related to the single and multiple HSH were investigated. It is shown that the HSH can be implemented to the case of a DP-LWA with the capability of wide beam steering and wide bandwidth features through a single antenna aperture where we are

able to control the number and position of beams related to each antenna polarization. A prototype of a DP-SIW-LWA was shown for the proof of concept which shows a good agreement with the simulation analyses.

- We also tackled another limitation of periodic LWAs in terms of their wide beam features. It is shown that the HSH give us the flexibility of shrinking the scanning range operation in a periodic LWA. We applied such an operation to the case of a DP-LWA with the capability of generating fixed beam operation through a single aperture. The beam alignment of each antenna polarization were also investigated and their relation to the phase variation of different antenna propagating mode was highlighted and their tradeoff explained. A prototype of a DP-SIW-LWA was shown for proof of concept, which showed a good agreement with the simulation analyses.
- A combination set of continuous beam steering feature plus a fixed beam operation in addition to the multi-beam function through a single antenna aperture were also investigated in this thesis. Here we demonstrated a DP-LWA by utilizing the HSH concept in which we assigned a specific function to each antenna polarization. The effect of mode coupling on the radiated power response of each antenna polarization was investigated and their tradeoff explained. Here, for the first time, we demonstrate a prototype of multi-functional LWA with the capability of simultaneous fixed and scanning beams operation which can sufficiently reduce the volume and size of wireless communication systems where it can consider as an alternative solution for future broadcasting designs. Experimental results showed a good agreement between the simulation, analysis, and measurements.

The research contributions summarized in this thesis can be further extended in the following mentioned areas:

- The HSH concept can be extended to study the propagating mode of different transmission lines such as a dielectric slab air filled substrate integrated waveguide (SAFSIW), half mode substrate integrated waveguide (HMSIW), substrate integrated image dielectric guide (SIIDG), folded ridge substrate integrated waveguide (FRSIW), and Substrate integrated non-radiative dielectric (SINRD) waveguide.

- The topology of HSH can also be implemented to the fixed frequency beam steering LWA in which we can approach different configurations of a linear array by applying different control voltage through a FPGA. Such a performance will allow us to achieve different configurations for the antenna beam.
- The concept of HSH can also be extended to the sub array sections of a SIW Rotman lens where each sub array can generate a specific function through their related radiated beam to achieve a reconfigurable antenna.

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APPENDICES

Appendix A. LIST OF PUBLICATIONS

1. M. R. Rahimi, M. S. Sharawi and K. Wu, "Higher-Order Space Harmonics in Substrate Integrated Waveguide Leaky-Wave Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 8, pp. 4332-4346, Aug. 2021.
2. M. R. Rahimi, M. S. Sharawi and K. Wu, "Multi-Band Multi-Beam Higher-Order Space Harmonics-Enabled Leaky-Wave Antennas," *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, 2020.
3. M. Reza Rahimi, M. S. Sharawi and K. Wu, "Stop-Band Radiation Properties of Higher-Order Space Harmonics-Enabled Broadside Multi-Beam Leaky-Wave Antenna," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, 2021.
4. M. R. Rahimi, M. S. Sharawi and K. Wu, "A Monolayer Dually Polarized High-Order Space Harmonic Leaky-Wave SIW Antennas With Fixed and Scanning Beam Capability," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 1063-1078, 2022.
5. M. R. Rahimi, M. S. Sharawi and K. Wu, "A Dually-Polarized Leaky-Wave Antenna Based on Polarization-Selective Coupling Mechanisiam with Fixed Beams Capability," *2022 16th European Conference on Antennas and Propagation (EuCAP)*, 2022.
6. M. R. Rahimi, M. S. Sharawi and K. Wu, "Multi-Beam Radiation Properties of Higher-Order Space Harmonics-Enabled Leaky-Wave Antenna," *2020 14th European Conference on Antennas and Propagation (EuCAP)*, 2020.

Appendix B ARTICLE 5

Journal name: 2022 16th European Conference on Antennas and Propagation (EuCAP)

Date of publication: 11/May/2022

A Dually-Polarized Leaky-Wave Antenna Based on Polarization-Selective Coupling Mechanism with Fixed Beams Capability

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Abstract—In this work, we investigate the effect of polarization diversity for the higher-order space harmonics (HSH) of periodically-loaded leaky-wave antennas, i.e., TE_{10} and TE_{01} . A hybrid form of nonradiative dielectric (NRD) waveguide and substrate integrated waveguide (SIW) is used to explore the inherent diversity feature for our antenna. The radiation properties of HSH in different passbands are examined where we investigate the behavior of scanning range variation of different HSH of $n \in [-1, -2, -3, -4]$. Furthermore, the effect of the unit-cell geometry on the propagation constant, and beam alignment of the TE_{10} and TE_{01} modes is studied and we show how the concept of HSH can be utilized for achieving a dually-polarized leaky-wave antenna (DP-LWA) with fixed beam operation. The proposed work is validated by showing an experimental prototype of DP-LWA in which a good agreement is achieved between the simulation, analysis, and measurement results.

Index Terms—one-dimensional periodic leaky-wave antenna (1D-periodic LWA), higher-order space harmonics (HSH), dually-polarized antenna (DPA), multi-beam antenna (MBA).

I. INTRODUCTION

With a rapid growth of 5G networks for wireless services, bandwidth allocations have become a major issue in handling user traffics and interference controls. However, using polarization diversity provides a viable solution that can fulfill this gap specifically over frequency range 2 (FR2) frequency bands where an orthomode transducer (OMT) is usually used for achieving such a feature. Different methodologies can be used for designing the OMT such as groove gap waveguides [1], turnstile junctions [2], and dual-mode ridge waveguides [3]. However, most of them have 3D structures which makes them unsuitable for integrating with common PCB boards or commonly used integrated planar structures. Thus, a planar OMT with integration capability could be highly beneficial for shrinking the size and also improving the total loss of circuits.

Besides, dually-polarized antennas (DPA) are utilized by the system design engineers to compensate the currently limited spectrum bandwidth. Several methods were proposed for achieving dually-polarized LWA (DP-LWA), such as dual-mode transmission line [4], spoof surface plasmon [5], OMT based LWA [6], and metamaterial LWA [7]. In most of DP-LWAs, the beam angle of each polarization usually changes with varying frequency which makes them unsuitable choices for point to point communication where a fixed beam operation is usually required. In [8]–[9] a fixed beam operation

(single polarization) is achieved at the expense of adding prism and reflector to the antenna, respectively, which make the structures bulky and increase the total size. Hence, in the proposed work, we strive to overcome all these limitations by presenting a DP-LWA with the capability of providing a fixed beam operation. Here, we utilized a polarization selective coupling (PSC) mechanism [10] for achieving the required diversity feature for our antenna in which we analyzed the behavior of LWA and related higher-order space harmonics (HSH) for two propagating modes of TE_{10} and TE_{01} to achieve the fixed beam operation. In addition, the methodology used here allows us to come up with an integrated form of DP-LWA with PSC-OMT in monolayer PCB format which could be beneficial for future 5G applications and beyond.

This paper is organized as follows. In Section II, we describe the PSC-OMT and its performances as LWA's feeding section. Section III discusses the LWA's unit cell and the HSH behavior of the two propagating modes of TE_{10} and TE_{01} . Section IV demonstrates the modeling and experimental validation. Finally, conclusions are given in Section V.

II. OMT BASED ON PSC

The basic mechanism and operation of PSC-OMT are explained in [10] where the focus was on developing the theory. However, adding any extra section to the proposed OMT disturbs its performances. Therefore, it is essential to study and analyze this effect on the OMT performance when we are considering it as a feeding network for the antenna. Here we are interested in setting our operating frequency to Ka-band. Hence, the dimensions of the square section of the OMT are selected as 3mm (RT6002 substrate is used) in which the cutoff of the TE_{10} and TE_{01} modes are set as 29 GHz and the higher modes cutoff start at 41 GHz. Fig. 1(a) shows the geometry of the antenna feeding section. Here to achieve a more compact size of the antenna feeding section, a bend phase shifter is used rather than a straight one where the radius dimensions of the antenna feeding section need to be calculated from [10] as $r_{out} = 6\text{mm}$ and $r_{in} = 3\text{mm}$ to achieve a suitable performance response. The S -parameters responses of the antenna feeding section are shown in Fig. 1(b) in which both TE_{10} and TE_{01} modes have an acceptable performance for the frequency range of $32 < f_{GHz} < 40$. It should be mentioned that besides the analysis of OMT's performances, we also need to investigate the effect of polarization diversity on the antenna's radiating element, as an essential step for designing the DPA which is to be discussed in the following section.

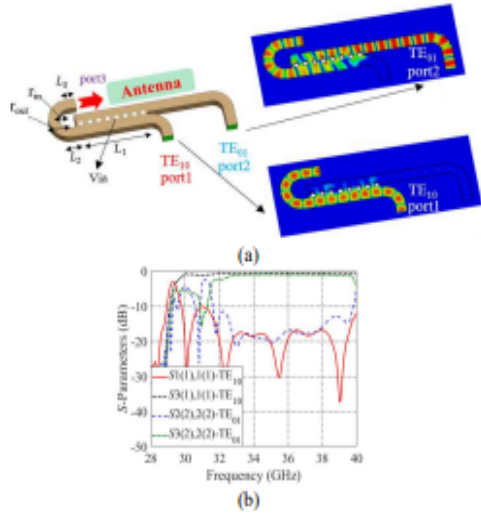


Fig. 1. (a) Geometry of PSC-OMT and electric field distribution of TE₁₀ and TE₀₁ modes at $f=38$ GHz, and (b) PSC-OMT S-parameters response.

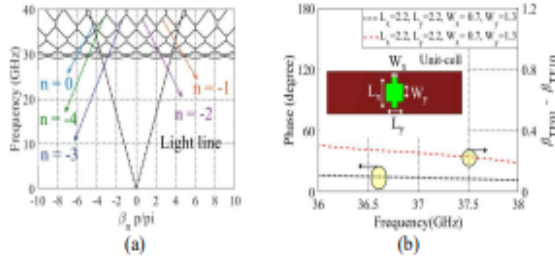


Fig. 2. (a) Brillouin diagram for 1D-periodic SIW-LWA with periodicity of $p = 17$ mm on dielectric propagating medium of $\epsilon_r = 2.94$ with effective width of 3mm, and (b) Propagation constant and phase difference between TE₁₀ and TE₀₁ modes of SIW-DP-LWA's unit-cell based on analysis of Fig. 2(a).

III. POLARIZATION DIVERSITY AND BEAM ALIGNMENT OF LWA'S UNIT-CELL

In most of LWAs, the beam usually steers with varying frequency which may not be considered as a suitable case for point to point communications. Here, we are tackling this limitation by using the HSH concept. In fact, most of periodic LWAs usually operate with their $n \in [0, -1]$ space harmonics in which their scanning range variation is calculated by substituting two values of $\sin^{-1}(\beta_n/k_0)$ related to the upper and lower antenna frequency operation band. In addition, most of periodic LWAs usually operate in their first or second passband frequency where the ratio of the arcsine function related to the related fast wave space harmonic varies around 1 or has a large variation that causes large scanning ranges. However, there is a possibility of decreasing the scanning variation by forcing the ratio β_n/k_0 to approach zero or decreasing the variation of β_n/k_0 within the antenna passband. The point that needs to be considered here is that when the ratio of β_n/k_0 approaches zero, we encounter stopband. Since the scope of this work is not focused on the band edge issue of periodic LWAs, we choose to investigate the possibility of applying the second solution to our antenna.

One of the tools that are usually used in the analysis of LWAs is the Brillouin diagram which is a graphical

representation of space harmonics behavior. Two points should be considered in the HSH analysis based on the Brillouin diagram; first of all, as far as each space harmonic approaches the light line we should expect to have large scanning variations for its beam angle. The other, we should expect that the beam angle variation related to the space harmonic that approaches the center of the Brillouin diagram must be very low due to the specific feature of arcsine function. Considering these features and a close look at the propagation constant equation of TE₁₀ and TE₀₁ modes [10] gives us the flexibility of applying the HSH in different spots of the Brillouin diagram. Fig. 2(a) shows the Brillouin diagram analysis for the two modes of TE₁₀ and TE₀₁ (the dimension and material are chosen based on the square section of the common port of OMT i.e., 3mm and RT6002, respectively, and the periodicity is considered to be 17mm, the same diagram is approached for both modes due to the square cross section). The analysis of Fig. 2(a) shows that the variation and ratio of β_n/k_0 for different HSH are not similar in the different passband frequency range. Here the light line value increases by approaching the higher passband frequency while the variation of β_n/k_0 is decreasing. Hence, by choosing a suitable value for the space harmonic propagating model (such as effective width and periodicity) we are able to set the location of each space harmonic far away from the light line while keeping the variation of β_n/k_0 as low as possible. This condition is satisfied for the TE₁₀ and TE₀₁ Brillouin diagram propagating model of Fig. 2(a) at their fifth passband frequency range as $36 < f_{\text{GHz}} < 38$ where the fundamental space harmonic ($n = 0$) remains a slow wave and we have 4 HSH as fast waves ($n \in [-1, -2, -3, -4]$). The ratio of β_n/k_0 for $n \in [-1, -2, -3, -4]$ space harmonics for $36 < f_{\text{GHz}} < 38$ in the fifth passband frequency are $[-0.56, -0.64]$, $[-0.08, -0.15]$, $[0.41, 0.33]$, $[0.89, 0.84]$, respectively, which correspond to the angles $[-34^\circ, -39^\circ]$, $[-4^\circ, -8^\circ]$, $[24^\circ, 19^\circ]$, $[63^\circ, 57^\circ]$, respectively, thus indicating a very low scanning range variation.

Besides the analysis of the Brillouin diagram, we also need to check the effect of radiating elements on the performance of the antenna. Here we are dealing with two polarizations for our antenna in which we prefer to use a single radiating element with the capability of providing a similar response of each antenna polarization. The point that needs to be considered in this work is that the beam angle alignment between the two polarizations does not follow the phase variation difference between the two modes and it obeys the difference between the summations of all fast wave space harmonics related to each propagating mode which can be calculated from:

$$\sin^{-1}\left(\frac{(\beta_{\text{TE10}} - \beta_{\text{TE01}})}{k_0}\right) = \sin^{-1}\left(\frac{(\beta_{\text{TE10}} - \beta_{\text{TE01}})/m}{k_0}\right) \quad (1)$$

Where the m is the number of fast wave space harmonic in the frequency of our interest ($m \in [1, 2, 3, 4, \dots]$) and n is considered to be the number of space harmonic (such as $n \in [0, -1, -2, -3, -4, \dots]$). Fig. 2(b) shows a cross slot radiating element that is used in this design (periodicity and material

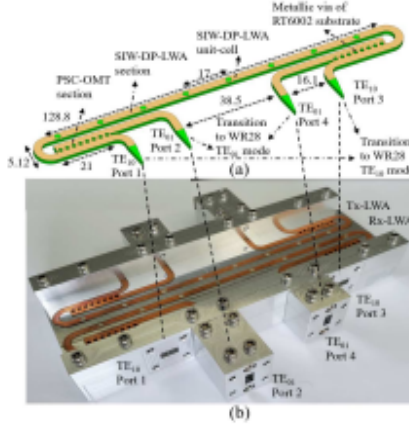


Fig. 3. (a) Design of DP-LWA with fixed beam capability (all dimensions are in mm), and (b) fabricated prototype with the PCS-OMT and transition section to WR28.

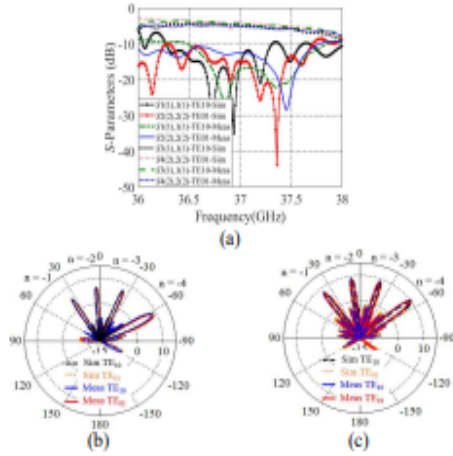


Fig. 4. (a) Simulated and measured S -parameters response of DP-LWA of TE_{10} and TE_{01} modes, and simulated and measured E-plane co-polar radiation patterns (in dB) of SIW-DP-LWA of TE_{10} and TE_{01} modes (b) at $f = 36.5\text{GHz}$, and (c) at $f = 37.5\text{GHz}$.

are chosen based on the analysis in Fig. 2(a)). An acceptable beam alignment between the beams of two propagating modes is expected due to the low value of $\beta_{TE_{10}} - \beta_{TE_{01}}$. For instance, at $f = 37.5\text{GHz}$ the propagation constant difference between the TE_{10} and TE_{01} modes is 0.2 in which we have 4 space harmonics as fast waves. Dividing this value by 4 and placing it in the arcsine function of (1) gives us the angle of 0.6° which indicates an acceptable beam alignment. In the next section, we validate our analysis by showing an experimental antenna prototype.

IV. ANTENNA PROTOTYPE AND EXPERIMENTAL VALIDATION

Fig. 3 shows a complete prototype form of the proposed LWA where we get the benefit of PSC-OMT integration capability to achieve a compact form of DPA. The material used in this design is RT6002 with $\epsilon_r = 2.94$ and thickness of 3mm. The spacing between the radiating element is set to be 17mm. A triangular taper transition between the PSC-OMT to the WR28 waveguide is designed for antenna excitation. Fig. 4(a) shows the simulated and measured results of

Table I. Comparison of the proposed SIW-LWA with other LWAs.

	Antenna type	Frequency (GHz)	Scanning angle variation (degree)	Polarization
[9]	Reflector-LWA	26.5-29.5	12	Single-polarization
[8]	Prism-LWA	54-62	6	Single-polarization
This work	SIW-NRD-LWA	36-38	5	Dual-Polarization

S -parameters for ports 1 and port 2. The measured reflection coefficients of TE_{10} and TE_{01} modes for the proposed DPA are below -10dB over the frequency ranges of $36.25 < f_{\text{GHz}} < 38$ and $35.9 < f_{\text{GHz}} < 38$, respectively. Figs. 4(b)-(c) show the measured and simulated radiation patterns at two different frequencies (36.5 GHz and 37.5GHz) where we have two improper beams ($n \in [-1, -2]$) and two proper beams ($n \in [-3, -4]$) for each antenna polarization. Based on the analysis of Fig. 2, a very low scanning range variation and a low misalignment are expected. Here the beam angle variations of the $n \in [-1, -2, -3, -4]$ are $[5^\circ, 4^\circ, 5^\circ, 6^\circ]$ and we have 1° misalignment between each antenna polarization. Thus, a good agreement is observed between the analysis, simulations, and measurement results of the proposed DP-LWA in which we deployed the HSH concept for achieving a fixed multi-beam DPA. Table I compares the given design with the other designs of LWAs.

V. CONCLUSIONS

The concept of applying HSHs in a hybrid form of NRD and SIW structure for TE_{10} and TE_{01} modes is investigated and detailed. The HSH flexibility based on two propagating modes at different passband frequencies is discussed from which we show that the fixed beam mechanism is achievable by a careful analysis of the Brillouin diagram. Besides, the beam alignment of different polarization is studied and we show that an acceptable beam alignment is achievable by a careful analysis of LWA unit-cell. A DP-LWA prototype is designed and fabricated for the proof of the concept which shows a good agreement between simulation, analysis, and measurement results.

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Appendix C ARTICLE 6

Journal name: 2020 14th European Conference on Antennas and Propagation (EuCAP)

Date of publication: 08/July/2020

Multi-Beam Radiation Properties of Higher-Order Space Harmonics-Enabled Leaky-Wave Antenna

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Abstract—In this work, we investigate the inherent physical behavior of higher-order space harmonics (HSH) along one-dimensional periodic leaky-wave antenna (1D-periodic LWA) structures. The interdependency of even $n \in [-2, -4]$ and odd $n \in [-1, -3]$ HSH on each other is examined in detail and a method is devised and demonstrated for analyzing their radiation properties which allow us to develop a multi-beam antenna (MBA) without using any feeding network. In addition, the scanning range of $n \in [-1, -2, -3, -4]$ space harmonics is studied and their limitation is discussed. The proposed concept is then validated by designing an LWA utilizing the substrate integrated waveguide (SIW) technology in which the $n \in [-1, -2]$ space harmonics are used for achieving a MBA exhibiting wide scanning capability. The experimental results obtained in this work shows a good agreement with the simulation and analysis counterparts.

Index Terms—one-dimensional periodic leaky-wave antenna (1D-periodic LWA), Higher-order space harmonics (HSH), Fast wave region (FWR), safe zone area, boundary region, multi-beam antenna (MBA).

I. INTRODUCTION

Leaky-wave antennas (LWAs) have captured much attention of antenna researchers and designers due to their distinctive characteristics in terms of beam steering, wide bandwidth, low profile and simple feeding network compared to their phased and slot array counterparts. Based on their geometry and radiation mechanism, LWAs have been classified into uniform [1], quasi-uniform [2] and periodic types [3]. One of the common drawbacks with most of LWAs is that they can only steer one beam within their operating frequency band and their beam angle is usually limited to the forward or backward quadrant (if simple radiating element is used and fed from one side only). Besides, most dual-beam LWAs that appeared in the literature rely on the use of active components [4] which result in narrow bandwidth and narrow scanning range.

On the other hand, a significant effort has been invested in the development of multi-beam antennas (MBAs). These types of antenna are widely used in wireless communication systems especially in connection with multiple input and multiple output (MIMO) technology due to a better channel capacity that they can provide. Most of MBA are usually achieved by adding a feeding network such as Butler matrix [5], Luneburg and Rotman lens [6]-[7] integrated into the antenna array. However, all of them can provide only predefined beam angles and they have their own complexity and bulkiness. On the contrary, LWAs enjoy the benefit of

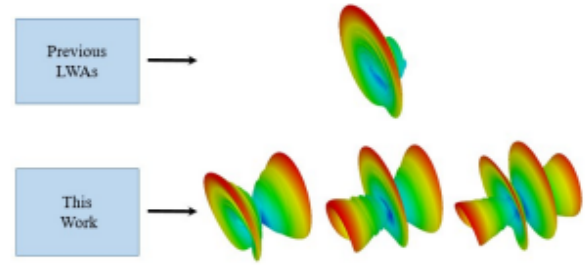


Fig. 1. Comparison between previous LWAs and this work.

a beam steering capability and wide scanning range. However, a combination of LWA and MBA for multiuser mobile streaming is missing and it has not been addressed in the literature. In this work, we demonstrate for the first time a new methodology for designing one-dimensional periodic LWA (1D-periodic LWA) as MBA in which higher-order space harmonics (HSH) can simultaneously act as physical fast waves and contribute to radiation pattern of the antenna. The general idea of this work is depicted in Fig. 1. The proposed concept of utilizing HSH gives us the privilege for designing MBA in terms of selecting a number of beams and eliminating the feeding network.

This paper is organized as follows. In Section II, we describe the fundamental behavior of HSH and a methodology for designing LWA as MBA is demonstrated. Section III discusses the modeling and experimental validation. Finally, conclusions are given in Section IV.

II. ANALYSIS OF HIGHER-ORDER SPACE HARMONICS

In a periodic LWA, the relationship among the propagation constants of space harmonics is described as $\beta_n = \beta_0 + 2n\pi/p$ in which p is the periodicity between the radiating elements and n is an integer. These space harmonics can act as fast or slow waves for a specific frequency range due to the condition of $(|\beta_n/k_0| \leq 1)$. In most of periodic LWAs, the periodicity is usually considered to be $p > \lambda/2$ in order to have only $n = -1$ space harmonic as a leaky wave over a specific frequency range. However, there is a possibility of exciting HSH such as $n = -2$ as a fast wave by increasing the dielectric constant of propagating media or increasing the periodicity. Therefore, as the first step, we derive the excitation condition of HSH as fast waves as follows:

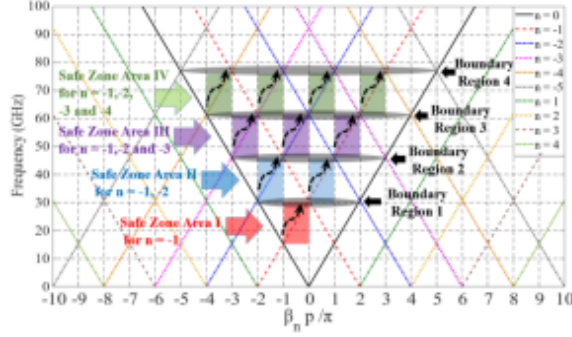


Fig. 2. Brillouin diagram for a 1D-periodic reciprocal LWA with periodicity of $p = 8\text{mm}$ on a dielectric propagating medium with $\epsilon_r = 2.2$.

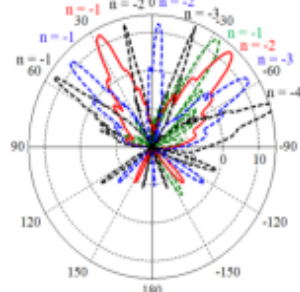


Fig. 3. Simulated result of radiation pattern of HSH for different safe zone areas (the beams behavior related to the safe zone I, II, III and IV show with green, red, blue and black color respectively).

$$\beta_{-1} = \beta_0 - 2\pi/p \rightarrow \beta_{-1} \geq -\pi/p \rightarrow |\beta_{-1}/k_0| \leq 1 \quad (1)$$

$$\beta_{-2} = \beta_0 - 4\pi/p \rightarrow \beta_{-2} \geq -2\pi/p \rightarrow |\beta_{-2}/k_0| \leq 1 \quad (2)$$

$$\beta_{-3} = \beta_0 - 6\pi/p \rightarrow \beta_{-3} \geq -3\pi/p \rightarrow |\beta_{-3}/k_0| \leq 1 \quad (3)$$

$$\beta_{-4} = \beta_0 - 8\pi/p \rightarrow \beta_{-4} \geq -4\pi/p \rightarrow |\beta_{-4}/k_0| \leq 1 \quad (4)$$

$$\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots$$

$$\beta_n = \beta_0 + 2n\pi/p \rightarrow \beta_n \geq -n\pi/p \rightarrow |\beta_n/k_0| \leq 1$$

In order to perform a comprehensive analysis of the global behavior of HSH, we plot the Brillouin diagram for the periodicity of $p = 8\text{mm}$ on a dielectric substrate with $\epsilon_r = 2.2$ as shown in Fig. 2. Based on the analysis of Fig. 2 and (1) for the frequency above 15.4 GHz, the excitation condition of $n = -1$ space harmonic is satisfied ($\beta_{-1} \geq -\pi/p$) and its wave enters the fast wave region (FWR) and thus it behaves as fast wave (leaky wave) where its related beam appears near backward endfire due to the negative value of its propagation constant ($\beta_{-1} < 0$). The beam of $n = -1$ space harmonic continues to scan in the backward quadrant until $f = 30.8\text{GHz}$, where $\beta_{-1} = 0$ and we have an open stop band. In addition, at this frequency, the excitation condition of $n = -2$ space harmonic is satisfied ($\beta_{-2} \geq -2\pi/p$) and it is expected to have two fast waves ($n \in [-1, -2]$) simultaneously. However, due to the contradirectional coupling between $n \in [0, -2]$, the beam related to $n = -2$ space harmonic does not appear at the backward endfire. For frequencies above $f = 30.8\text{GHz}$, the behavior of propagation constant related to the $n = -1$ space harmonic changes and it becomes positive ($\beta_{-1} > 0$). Therefore, it is expected that its beam starts scanning in the forward quadrant. However, the condition for the $n = -2$ space harmonic for frequencies above $f = 30.8\text{GHz}$ is

different compared to the $n = -1$ space harmonics in which its beam is expected to appear in the backward quadrant due to the negative value of its propagation constant ($\beta_{-2} < 0$). Therefore, the frequency of 30.8 GHz can act as the boundary frequency region between the two space harmonics $n \in [-1, -2]$ which we refer to as boundary region I in Fig. 2. In addition, we refer to the frequency range of $15.4 < f_{\text{GHz}} < 30.8$ as safe zone area I in which the $n = -1$ space harmonic can contribute to the radiation pattern of the antenna without being disturbed by HSH ($n \leq -2$).

In Fig. 2, the excitation condition of $n = -3$ space harmonic at 46.2GHz is satisfied based on the propagation constant analysis of (3). However, the beam related to the $n = -3$ space harmonic does not appear in the backward endfire due to the contradirectional coupling between $n \in [0, -3]$ at this frequency. In addition, for frequencies above $f = 46.2\text{GHz}$, we have three space harmonics $n \in [-1, -2, -3]$ acting as fast waves. However, the conditions of propagation constants of these space harmonics are not similar in which we have one improper ($n = -1$) and two proper ($n \in [-2, -3]$) waves in the FWR. Here, we refer to the frequency range between $30.8 < f_{\text{GHz}} < 46.2$ as safe zone area II in which we only have two space harmonics ($n \in [-1, -2]$) considered as fast waves. In addition, the frequency of 46.2 GHz excites the $n = -3$ space harmonic, and marks boundary region 2.

At the frequency of 61.6 GHz, the same is repeated for $n = -4$. The beam related to $n = -4$ does not appear at the backward endfire and it appears as a proper wave for frequencies above 61.6 GHz. Therefore, we mark this frequency (61.6 GHz) as boundary region 3 in which we can categorize the frequency range with 3 or 4 fast space harmonics. Another point that needs to be considered at boundary region 3 is that the propagation constant of $n = -2$ space harmonic becomes zero ($\beta_{-2} = 0$) and its related beam appears at broadside. In addition, at this frequency (61.6 GHz) we have one improper ($n = -1$) and one proper ($n = -3$) waves.

For frequencies above boundary region 3 we have two improper ($n \in [-1, -2]$) and two proper ($n \in [-3, -4]$) waves. Based on this condition, we refer to the frequency range of $46.2 < f_{\text{GHz}} < 61.6$ as safe zone area III in which three space harmonics ($n \in [-1, -2, -3]$) contribute to the radiation pattern without being disturbed by other HSH ($n \leq -4$). Above boundary region 3, 4 space harmonics continue to be scanning in both quadrants until they reach the frequency of 77 GHz at which the excitation condition of $n = -5$ space harmonic is satisfied. Therefore, we can set the frequency of 77 GHz as boundary region 4 where only 4 space harmonics $n \in [-1, -2, -3, -4]$ contribute to the radiation pattern and so on.

Using the concept of boundary regions and safe zone areas in the analysis of HSH allows us to have a methodology for designing LWAs as MBA in which we are able to control the number and position of the beams. Fig. 3 shows the simulated result of a 1D-periodic LWA in which different number of HSH steer simultaneously in both quadrants and provide a wide scanning range.

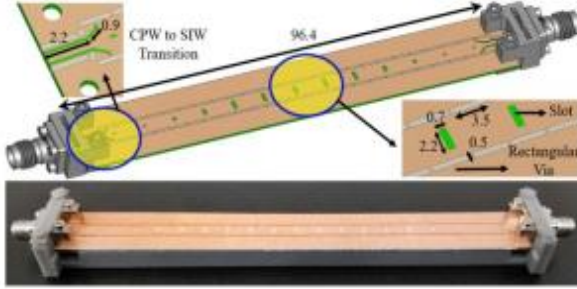


Fig. 4. Schematic and prototype of SIW-LWA, all dimension are in mm.

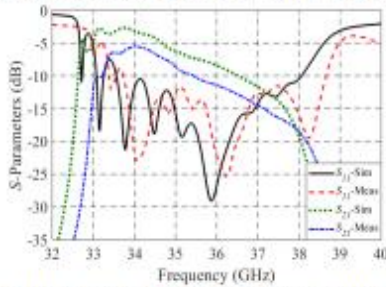


Fig. 5. Simulated and measured S -parameters of SIW-LWA with a series of transverse slots of Fig. 4.

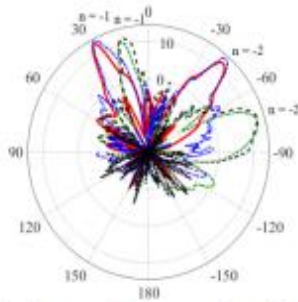


Fig. 6. Simulated and measured E-plane co-polar radiation pattern of SIW-LWA for frequencies of $f_1 = 35$ GHz (green dash line is simulated, black dash line is measurement) and $f_2 = 38$ GHz (red line is simulated, blue dash line is measurement).

III. ANTENNA PROTOTYPE AND EXPERIMENTAL VALIDATION

Fig. 4 shows the prototype of a 1D-periodic LWA based on SIW technology with a series of transverse slots. The material used is a single layer RT6002 with $\epsilon_r = 2.94$ and thickness of 0.762mm. The proposed antenna is excited by an end launch connector where a transition between coplanar waveguide (CPW) and SIW is used to support Ka-band frequency. The conditions of vias are set based on [8]. In addition, a 3D-printer holder is designed to hold the antenna during measurements. Based on the analysis of Fig. 2, the radiating element periodicity considered is set to be 7mm in order to have only two space harmonics as fast waves in the frequency range of interest. Fig. 5 shows simulated and measured S -parameters of the proposed SIW-LWA in which we have 14.6% bandwidth in the range of 33.4-38.6 GHz. Fig. 6 shows simulated and measured radiation patterns of the antenna in which we have one improper ($n = -1$) and one proper ($n = -2$) beam. The peak gain of $n \in [-1, -2]$ is 13.9 dB

Table I. Comparison of the proposed SIW-LWA with other LWAs.

Structure	Antenna type	Bandwidth (%)	Scanning angle (degree)	Involved space harmonic
[2]	Quasi-LWA	16.3	10 to 60	$n = 0$
[3]	Periodic-LWA	11.1	-35 to 7	$n = -1$
This work	Periodic-LWA	15.1	10 to 27 -84 to -42	$n = -1$ $n = -2$

and 14.4 dB, respectively, with an approximate -12 dB sidelobe level. It is expected that the $n = -2$ space harmonic to scan faster compared to the case of $n = -1$ since the variation of $|\beta_{z2}/k_0|$ is more than $|\beta_{z1}/k_0|$ in this frequency range. Here, the scanning range of $n \in [-1, -2]$ is 10° to 27° and -84° to -42°, respectively, showing a good agreement with the analyses and theory of HSH. Table I compares the given design with the other designs of LWA.

IV. CONCLUSIONS

In this work, the concept of HSH in 1D-periodic LWA is studied and analyzed in detail. The radiation properties of each HSH ($n \in [-1, -2, -3, -4]$) based on the behavior of their propagation constants for different frequency ranges of FWR are investigated and a methodology for designing periodic LWAs as MBA is demonstrated where we are able to predict the number and position of beams by using two new concepts, namely safe zone areas and boundary regions. In addition, the proposed design enjoys the benefits of eliminating the feeding network compared to the common MBA that can significantly improve the insertion loss performance and also reduce the size of the whole entire system. The proposed analysis can be extended to explain and predict the behavior of HSH ($n \leq -5$). In addition, a good agreement is observed between simulation and analysis theory of HSH and measurement results.

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