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UNIVERSITE DE MONTREAL

ECOLE POLYTECHNIQUE

Ce mémoire intitulé:

A CAD/CAM WIDEBAND MICROWAVE SIX-PORT JUNCTION

présenté par: Sining Wang

en vue de l'obtention du grade de: maître es sciences appliquées (M.Sc.A.) a
été dûment accepté par le jury d'examen constitué de:

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Sommaire

Depuis l'introduction de la technologie à six-port au début des années soixante-dix, plusieurs méthodes et formalismes ont été utilisés avec succès pour l'étalonnage du reflectometre six-port aussi bien que pour la procedure de mesure entre $1 \sim 100GHz$. Néanmoins, le recours à la technique six-port s'avère toujours nécessaire pour des mesures en balayage de fréquence sur une bande de $100MHz$ et pour des mesures pulsés avec une resolution d'environ $1\mu s$. Afin d'atteindre cet objectif, l'auteur de ce mémoire a recouru à la CAO/FAO pour concevoir et construire une jonction six-port ayant des points q_i quasi-invariables avec la fréquence. Les contributions principales de l'auteur sont les suivantes:

- Des coupleurs large bande, couvrant la bande de fréquence $2 \sim 18 GHz$ et ayant des niveaux de couplage très élevés de $1.76 dB$ et $3 dB$, ont été conçus, construits et mesurés avec succès.
- Trois différents diviseurs de puissance de type Wilkinson, opérant à la

bande de fréquence $2 \sim 15 \text{ GHz}$, ont été conçus, construits et mesurés. Les résultats ont été satisfaisants. L'utilisation de diviseurs de puissance de type Wilkinson à lignes courbées a permis de maintenir une très bonne isolation (meilleur qu'à -25 dB), entre les deux ports de sortie du diviseur de puissance tout au long de la bande de fréquence $2 \sim 15 \text{ GHz}$.

- L'étalonnage du reflectometre six-port qui repose sur l'utilisation d'une charge coulissante pour obtenir différentes terminaisons étalons. La non disponibilité de telle charge coulissante pour des fréquences supérieures à 10 GHz limite le choix et le nombre des terminaisons étalons. Ce problème a été résolu en utilisant la théorie de la ligne longue (long line theory). Des améliorations appropriées ont été apportées à la théorie afin qu'elle réponde à nos besoins. La validité de ces améliorations a été confirmée par l'étalonnage de la jonction six-port entre $2 \sim 12 \text{ GHz}$ et son utilisation pour mesurer des charges étalons.
- Les formules pour calculer les points q_i de la jonction six-port ont été développées en se basant sur la méthode de transformation bilinéaire qui permet de calculer les points q_i à partir des paramètres d'étalonnage de la jonction six-port.

Abstract

Six-port technology was introduced in the early 1970's. Different methods and formalisms to design and build a six-port junction were successfully used for various applications over $1 \sim 100\text{GHz}$. However, there still exists the need to apply six-port techniques in wideband applications, such as swept frequency measurements over 100MHz bandwidth and microwave pulse measurements with time resolutions better than $1\mu\text{s}$. A *CAD/CAM* wideband six-port junction design with frequency invariant q_i points is carried out in this thesis in order to advance toward the above goals. The main contributions of the author in this thesis are the following: 1) Wideband couplers which cover the frequency range from $2 \sim 18\text{GHz}$ with very tight coupling levels (1.76dB and 3dB respectively) have been designed and measured successfully. 2) Three different Wilkinson power dividers over the frequency range of $2 \sim 15\text{GHz}$ have been designed and measured with satisfactory results. A very good isolation (better than -25dB) between the two output ports of a power divider over the frequency range of $2 \sim 15\text{GHz}$ has been achieved by using a curved line Wilkinson power divider. 3) Most calibrations at microwave frequencies (up

to 10 GHz) depend on the use of a sliding short circuit to obtain different impedance terminations. However, a commercial sliding short circuit operating above 10 GHz is not yet available. This problem has been solved by using the long line theory with appropriate improvements. The improvements have been confirmed by measuring a known standard using the designed six-port junction over the frequency range of 2 ~ 12 GHz. 4) Expressions to calculate q_i points of the designed six-port reflectometer were developed according to a published calibration method. The calculation is based on a bilinear transformation concept, which derives q_i point calculation procedures from the calibration parameters.

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Chapter 1

Introduction

The behaviour of microwave devices and circuits is currently evaluated by their scattering matrices [S] at each operating frequency. The S parameters of a microwave device can be measured quantitatively, either in the frequency domain or in the time domain. The technique which corresponds to microwave measurements in the time domain is known as Time-Domain Reflectometry (TDR) [1,2,3]. The current techniques which represent the development tendency of microwave measurements in the frequency domain are based on the use of Automatic Network Analysers (ANA) [4,5] and Six-Port Automatic Network Analysers (SPANNA) [6,7,8]. The research work in this thesis will concentrate on the design of a wide band six-port junction, a fundamental component of a Six-Port Automatic Network Analyser.

1.1 Automatic Network Analysers

Automatic network analysers (ANA) are available in two types: scalar automatic network analysers (SANA) and vector automatic network analysers (VANA). A schematic diagram of a more versatile VANA is shown in figure (1.1). It can be noted from figure (1.1) that the system is established on the basis of a four port network. With additional switching, multiport networks can be analyzed for both reflection and transmission characteristics [1].

The measurement procedure for ANA is as follows: samples of the input signal (reference) and the reflected (or transmitted) signal are frequency converted to an intermediate frequency (IF), either by coherent sampling or phase locked superheterodyne mixing. The two IF signals are measured by using a vectorial ratio meter. Frequency conversion is unavoidable with a VANA since no phase meter can operate over all the microwave frequency range [4,5].

1.2 Six-Port Reflectometry

The need to measure the phase of the reflection coefficient of a Device Under Test (DUT) by means of ANA can be eliminated by the addition of two detectors to the four-port measurement network mentioned in section (1.1). The intervening network becomes a six-port junction, four ports of which are

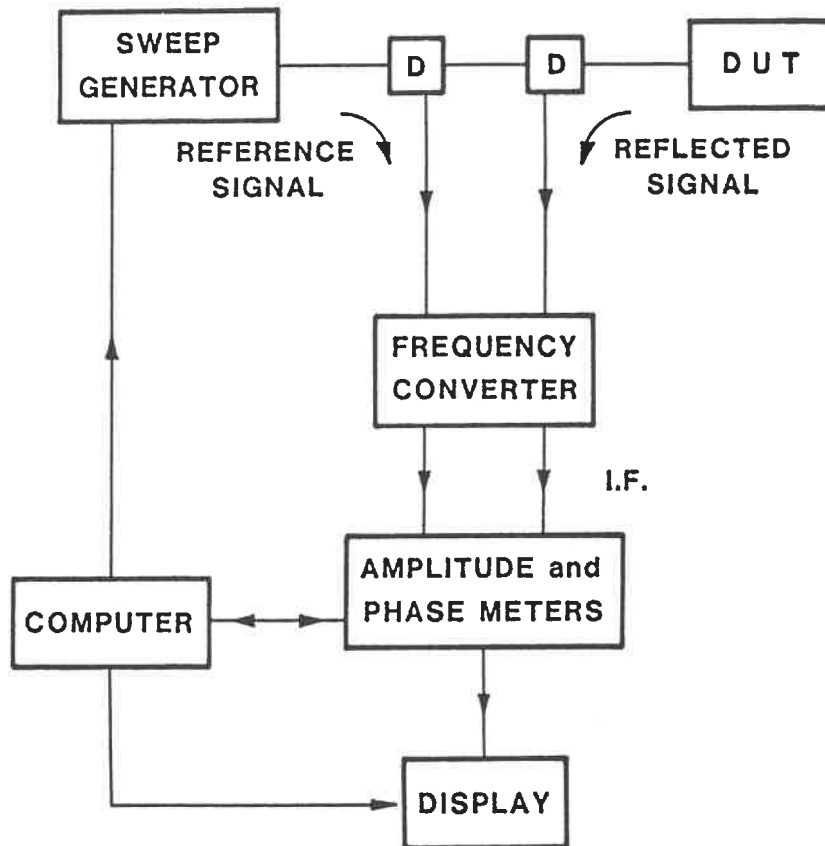


Figure 1.1: A Vector Automatic Network Analyser System

terminated by power detectors, with readings denoted as P_3, P_4, P_5 and P_6 . The four power readings are related to the reflection coefficient of a *DUT* by the following equation (it will be explained in the next chapter) :

$$P_i = |K_i|^2 |b_2|^2 |\Gamma - q_i|^2, \quad i = 3, 4, 5 \text{ and } 6. \quad (1.1)$$

Rewriting Γ and q_i in terms of their real and imaginary components:

$$\Gamma = x + jy,$$

$$q_i = \alpha_i + j\beta_i, \quad i = 3, 4, 5 \text{ and } 6,$$

then, substituting Γ and q_i into equation (1.1) and simplifying the equation, we can express the reflection coefficient of a *DUT* by using the following equations [3,10]:

$$x = \frac{U_0 P_3 + U_1 P_4 + U_2 P_5 + U_3 P_6}{P_3 + C_1 P_4 + C_2 P_5 + C_3 P_6}, \quad (1.2)$$

$$y = \frac{V_0 P_3 + V_1 P_4 + V_2 P_5 + V_3 P_6}{P_3 + C_1 P_4 + C_2 P_5 + C_3 P_6}, \quad (1.3)$$

where U_i, V_i and C_i are complex parameters which characterize a six-port junction and can be determined by calibration [10].

The six-port technique has been developed into a valuable precision microwave measurement tool since it was introduced by Engen and Hoer in early 1970's [6,7,8]. The advantages of this type of reflectometer include:

- the absence of any need for frequency conversion and phase meters;

- the absence of any need to match power detectors to the four output ports of a six-port junction and to calibrate them to measure power in an absolute sense;
- it's capability to measure multi-port network (n port) characteristics by using n six-port junctions;
- it's suitability for high power microwave measurements;
- it's suitability for high frequency applications such as millimeter wave and submillimeter wave bands.

Due to these advantages, the six-port measurement technique has been applied to various kinds of microwave measurements. Many efforts to develop optimal six-port junctions have been done in the past [8,11,12,13,14,15,16,17]. However, there still exists an important need to develop six-port design techniques to improve their performance for swept frequency measurements (100MHz bandwidth) and pulse microwave measurements (resolution $1\mu s$) over a large bandwidth [18].

This thesis will discuss in detail a computer aided design and computer aided manufacture (CAD/CAM) of a wideband six-port junction with quasi-fixed frequency q_i positions in the Γ plane. Simulated and tested results are also presented in this thesis.

Chapter 2

Six-Port Measurement Technique

2.1 Introduction

Six-port reflectometry is strongly supported by a rigorous theory. The measurement accuracy is an important factor to evaluate the viability of such technique. According to different application needs, specific configurations of six-port junctions are required. Many experts have contributed to the development of the technique. G. F. Engen and C. A. Hoer formulated the initial theory and developed the design considerations in early 1970's [7,8,9,19,20]. These fundamental problems of a six-port design will be discussed in this chapter.

2.2 Analysis of a Six-Port Reflectometer

The operation theory of a six-port reflectometer shown in figure (2.1) is based on the four following equations [21],

$$b_i = M_i a_2 + N_i b_2, \quad i = 3, 4, 5 \text{ and } 6 \quad (2.1)$$

where a_2 and b_2 are the incident and the emergent signals respectively at port 2 which is connected to a DUT, b_i is the emergent signal at the detector D_i of port i and M_i , N_i are complex system parameters.

Equations (2.1) can be derived by describing the reflectometer in terms of its 36 S parameters and the Voltage Reflection Coefficients (VRC) which are denoted by $\Gamma_i = a_i/b_i$ and associated to detector D_i . If there is only one mode of microwave present at each port, it is convenient to use the complex incident and emergent wave amplitudes a_i and b_i , ($i = 1, \dots, 6$) as twelve terminal variables. Suppose that all the detectors and the junction itself are linear, then each b_i is simply composed of the linear combinations of a_i which can be represented by the following matrix,

$$[b] = [S] [a] \quad (2.2)$$

where elements of $[S]$ are scattering coefficients normalized to the characteristic impedance of the junction. For each detector connected to port i , the

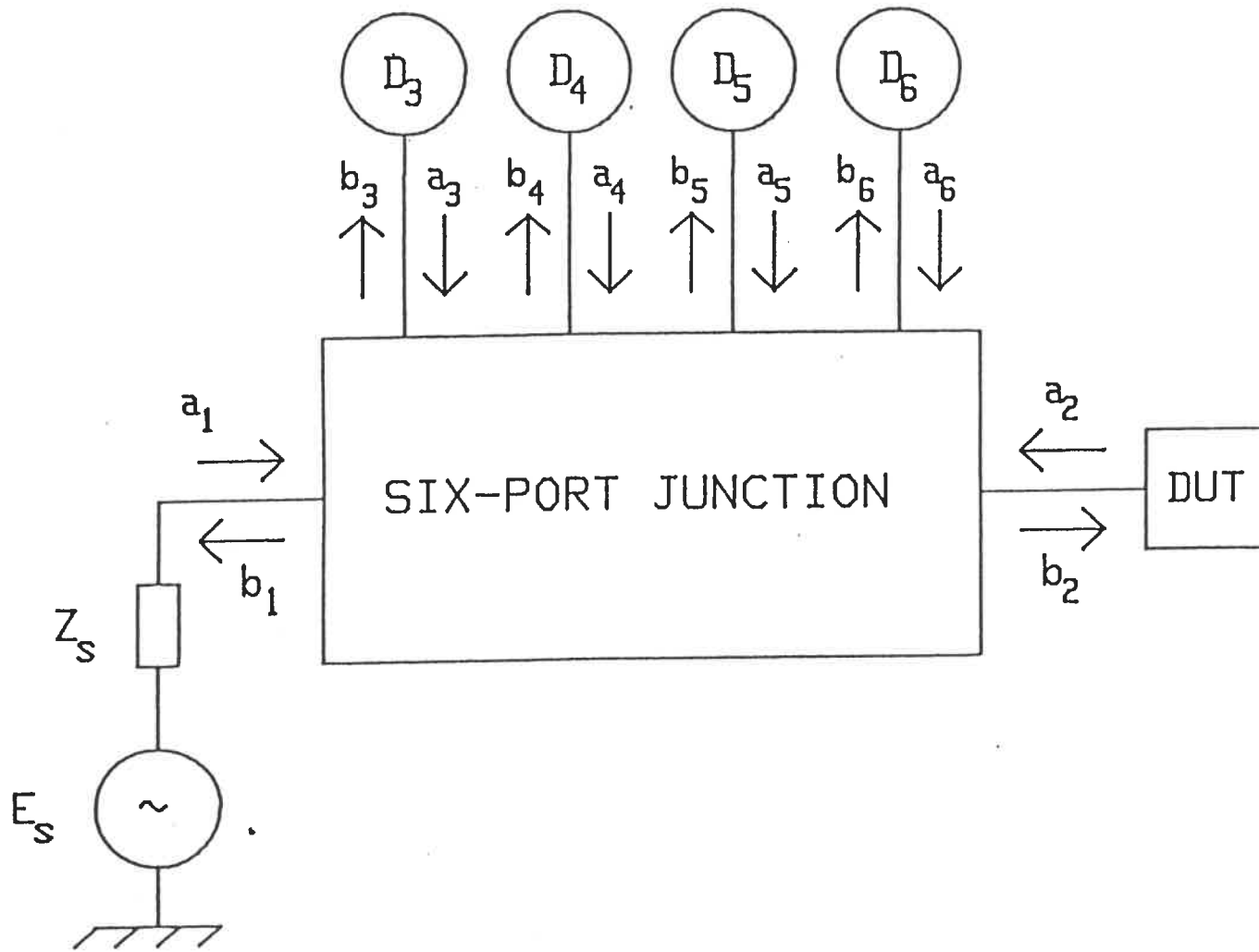


Figure 2.1: Six-port Reflectometer Diagram

substitution of Γ_i into equation (2.2) gives

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_6 \end{bmatrix} = [S] \begin{bmatrix} a_1 \\ a_2 \\ \Gamma_3 b_3 \\ \vdots \\ \Gamma_6 b_6 \end{bmatrix} \quad (2.3)$$

After simplification, equation (2.3) becomes

$$\begin{bmatrix} b_1 \\ b_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13}\Gamma_3 & s_{14}\Gamma_4 & s_{15}\Gamma_5 & s_{16}\Gamma_6 \\ s_{21} & s_{22} & s_{23}\Gamma_3 & s_{24}\Gamma_4 & s_{25}\Gamma_5 & s_{26}\Gamma_6 \\ s_{31} & s_{32} & (s_{33}\Gamma_3 - 1) & s_{34}\Gamma_4 & s_{35}\Gamma_5 & s_{36}\Gamma_6 \\ s_{41} & s_{42} & s_{43}\Gamma_3 & (s_{44}\Gamma_4 - 1) & s_{45}\Gamma_5 & s_{46}\Gamma_6 \\ s_{51} & s_{52} & s_{53}\Gamma_3 & s_{54}\Gamma_4 & (s_{55}\Gamma_5 - 1) & s_{56}\Gamma_6 \\ s_{61} & s_{62} & s_{63}\Gamma_3 & s_{64}\Gamma_4 & s_{65}\Gamma_5 & (s_{66}\Gamma_6 - 1) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{bmatrix} \quad (2.4)$$

Denoting the coefficient matrix in equation (2.4) by $[Sc]$, it can be proved that $\det [Sc] \neq 0$ [21]. By denoting $[Sc]^{-1} = [M]$

$$\begin{bmatrix} a_1 \\ a_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{bmatrix} = [M] \begin{bmatrix} b_1 \\ b_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2.5)$$

the emergent wave at each detector port can be expressed as follows:

$$b_i = m_{i1}b_1 + m_{i2}b_2 \quad (2.6)$$

where

$$b_1 = \frac{1}{m_{21}}(a_2 - m_{22}b_2) \quad (2.7)$$

$$a_2 = m_{21}b_1 + m_{22}b_2$$

Equation (2.1) can be obtained by solving (2.6) and (2.7), where $M_i = m_{i1}/m_{21}$ and $N_i = m_{i2} - m_{22}m_{i1}/m_{21}$. This equation can also be written in terms of b_2 and the reflection coefficient of the DUT - Γ

$$b_i = (\Gamma M_i + N_i) b_2 \quad (2.8)$$

The power reading at each detector D_i can be expressed as follows:

$$P_i = G_i (|b_i|^2 - |a_i|^2) = G_i (1 - |\Gamma_i|^2) |b_i|^2, \quad i = 3, 4, 5 \text{ and } 6 \quad (2.9)$$

Substituting (2.8) into (2.9), we obtain

$$P_i = |K_i|^2 |b_2|^2 |\Gamma - q_i|^2, \quad i = 3, 4, 5 \text{ and } 6 \quad (2.10)$$

where $|K_i|^2 = G_i |M_i|^2 (1 - |\Gamma_i|^2)$ and $q_i = -N_i/M_i$.

This is the fundamental equation to analyse any six-port junction. All design discussions carried out later are based on it.

2.3 Design Criterion of a Six-Port Junction

The first step to design a six-port junction is to choose scalar values $|K_i|^2$ and complex coefficients q_i in equation (2.10) according to a given configuration. Moreover, a reference port is usually needed to monitor the input incident power level. For this purpose, a directional coupler is used to sample the incident wave amplitude $|b_2|$. In our six-port configuration, port 3 performs this function, consequently equation (2.10) become:

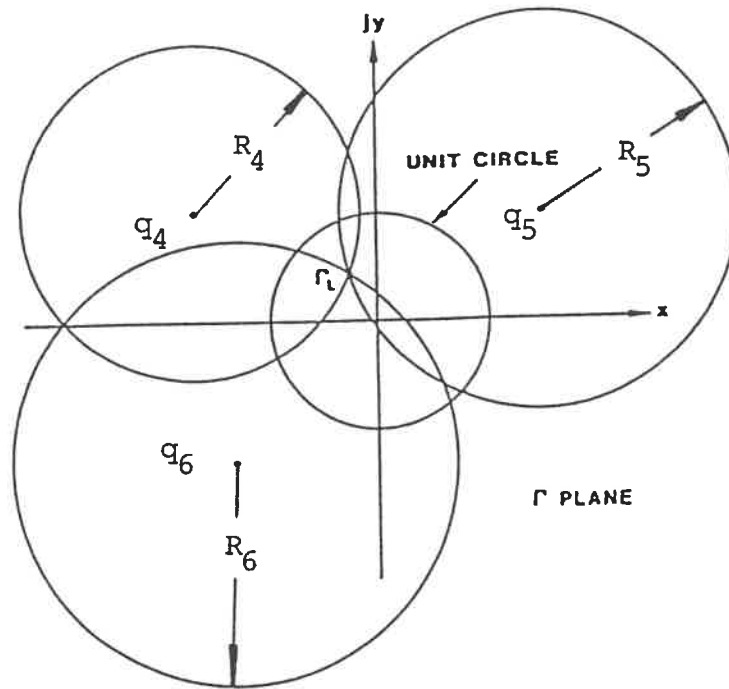
$$P_3 = |K_3|^2 |b_2|^2. \quad (2.11)$$

Eliminating $|b_2|^2$ from (2.10) by dividing (2.11), we have

$$\frac{P_i}{P_3} = \frac{|K_i|^2}{|K_3|^2} |\Gamma - q_i|^2, \quad i = 4, 5 \text{ and } 6. \quad (2.12)$$

Assuming q_i and $|K_i|^2$ are known from calibration and the measurement results P_i ($i = 4, 5$ and 6) are given, it is clear that equation (2.12) represents three circles which are centered at q_i and have radii $\sqrt{P_i}|K_3|/\sqrt{P_3}|K_i|$ respectively in the Γ plane as shown in figure (2.2). Suppose that three q_i points are neither on the same line nor located at the same point, the intersection of the three circles will determine the complex reflection coefficient Γ of the DUT port (both magnitude and phase angle). The design problem then becomes how to select all of the coefficients q_i and $|K_i|^2$ in equation (2.12).

It should be noted that all of the above discussions and mathematical deduc-



q_i ($i = 4, 5$ and 6) describe the centers of the three circles.
 R_i ($i = 4, 5$ and 6) stand for the radii of the three circles, where

$$R_i = \sqrt{P_i} |K_3| / \sqrt{P_3} |K_i|.$$

Figure 2.2: Geometrical Explanation of a Six-port Reflectometer Principle

tions are based on the situation of measurement at a single frequency. This kind of six-port reflectometer can also be used for multifrequency measurements to characterize nonlinear device such as a transistor operated in a nonlinear mode [55]. In these cases, some filters and matching networks should be added between the power detectors and the output ports of the six-port junction in order to separate the signal of each required frequency.

It is evident from inspection of (2.12) that $|K_i|^2$ are scale factors which determine the power levels at the relevant power detectors. Usually these parameters are chosen such that the measured levels are compatible with the dynamic range of power detectors. The major design task, therefore, centers around the choice of q_4, q_5 and q_6 . The prospect of achieving a direct measurement of the reflection coefficient magnitude is quite attractive. By choosing q_4 , for example, at the center of the unit circle, we can measure directly the reflected wave $|a_2|$ by P_4 . There are several considerations, however, which argue against this choice for q_4 . The expected deviations of q_4 from zero will eliminate the potential advantages of the six-port junction. A more serious objection arises from the limitation of the power detector dynamic range [9].

From symmetry considerations, the points q_4, q_5 and q_6 of a preferred six-port junction should be located at the vertices of an equilateral triangle, having its center at the origin in the Γ plane. In such case $|q_4| = |q_5| = |q_6|$ while the

relative phase differences between them are 120° . Therefore, the only choice remained is the magnitude of $|q_i|$ ($i = 4, 5$ and 6). Since Γ is determined from the intersection of the three circles, it is evident that an ill-conditioned situation will result when the radii of these circles become too large in comparison with the unit circle for the case of $|\Gamma| < 1$. On the other hand, the choice of $|q_i| < 0.5$ will result in similar problems as q_i is very near to the origin. Therefore, it appears that an optimum value for $|q_i|$ should be expected to lie in the range $0.5 \sim 1.5$. Computer simulations [9] show that the calibration techniques become less accurate if $|q_i| \cong 1$ and a decrease in the measurement accuracy has been verified when $|\Gamma| \cong |q_i|$.

2.4 Measurement Accuracy Estimation

It is convenient to visualize the six-port operation by means of a diagram in the complex plane as explained in section (2.2), where three circles are constructed and their intersection point gives the value of the measured reflection coefficient. The centers of the circles are primarily determined by the six-port characteristics and nominally independent of the reflection coefficient being measured. The circle radii, on the other hand, are proportional to the three normalized power readings P_6/P_3 , P_5/P_3 and P_4/P_3 .

In practice, due to measurement errors and detector noises, the three circles usually do not intersect at a common point. Their intersection will fall inside a triangle area as shown in figure (2.3). Therefore, how to assign the value of Γ from this triangle becomes the main task to enhance the measurement accuracy of the six-port technology.

For a wide-spread general utility, the preceding picture is only approximate. In fact, the centers of the three circles also have some functional dependence upon the detector readings. To evaluate the accuracy of a six-port junction, the reflection coefficient under test is expressed by the following equation (it will be proved in section (4.1)):

$$\Gamma = \frac{e - w}{cw - d} \quad (2.13)$$

where c, d and e are calibration parameters which are dependent on the six-port junction and power detectors, and w satisfies the following equations [22]:

$$|w|^2 = \frac{P_4}{P_3} \quad (2.14)$$

$$|w - m'|^2 = A'^2 \frac{P_5}{P_3} \quad (2.15)$$

and

$$|w - n'|^2 = B'^2 \frac{P_6}{P_3} \quad (2.16)$$

where m', n', A'^2 and B'^2 are also coefficients related to the calibration parameters of a six-port reflectometer.

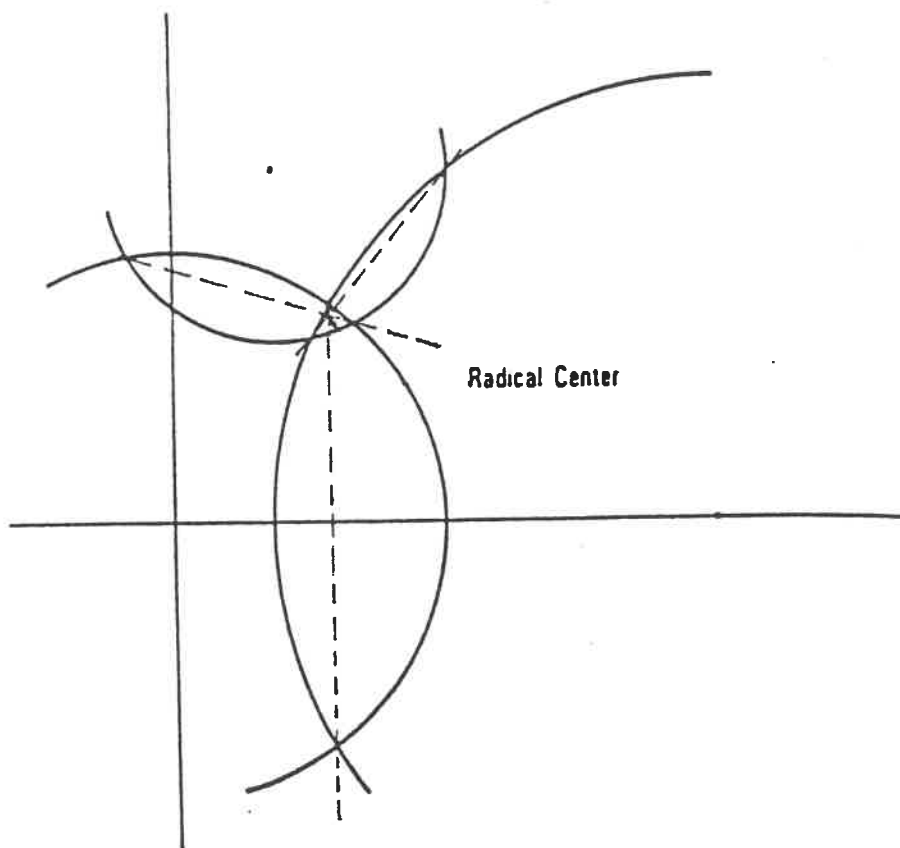


Figure 2.3: Confidence Area of Six-Port Reflectometry Measurements

In order to solve equations (2.14) ~ (2.16), let

$$w = x + jy \quad (2.17)$$

$$m' = x_1 + jy_1 \quad (2.18)$$

$$n' = x_2 + jy_2 \quad (2.19)$$

thus, equations (2.14), (2.15) and (2.16) become

$$x^2 + y^2 = r_0^2 \quad (2.20)$$

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2 \quad (2.21)$$

$$(x - x_2)^2 + (y - y_2)^2 = r_2^2 \quad (2.22)$$

where $r_0^2 = P_4/P_3$, $r_1^2 = A'^2 P_5/P_3$ and $r_2^2 = B'^2 P_6/P_3$. Subtracting (2.20) from (2.21) and (2.22) respectively, we can obtain a set of linear equations in terms of x and y . A solution of the above linear system gives

$$x = \frac{y_2 (r_0^2 - r_1^2 + x_1^2 + y_1^2) - y_1 (r_0^2 - r_2^2 + x_2^2 + y_2^2)}{2 (x_1 y_2 - x_2 y_1)} \quad (2.23)$$

$$y = \frac{x_1 (r_0^2 - r_2^2 + x_2^2 + y_2^2) - x_2 (r_0^2 - r_1^2 + x_1^2 + y_1^2)}{2 (x_1 y_2 - x_2 y_1)} \quad (2.24)$$

Assume that the values of parameters c, d, e, m', n', A'^2 and B'^2 are known from calibration. Generally speaking, power detector readings P_3, P_4, P_5 and P_6 will differ from their true values. A maximum likelihood estimation of w

via a least square procedure is introduced to find a best estimator of Γ [24]. If the power meter error is assumed to be of Gaussian distribution, it can be shown [22] that the maximum likelihood estimations of P_3, P_4, P_5 and P_6 are minimizing the error function F as follows:

$$F = \sum_{i=3}^6 \left(\frac{P_i - P_{it}}{\sigma_i} \right)^2 \quad (2.25)$$

where σ_i is the standard variance of the observed values of P_i and P_{it} is the assumed true power reading values which must satisfy equations (2.14), (2.15) and (2.16). In order to impose this constraint, it is convenient to retain P_{3t} as one of the independent variables and then eliminate P_{4t}, P_{5t} and P_{6t} from equation (2.25). The error related to these power detectors is:

$$\varepsilon_3 = P_3 - P_{3t} . \quad (2.26)$$

Substituting (2.26) into (2.14) ~ (2.16), we obtain

$$\varepsilon_4 = P_4 - P_{3t} |w|^2 \quad (2.27)$$

$$\varepsilon_5 = P_5 - \frac{P_{3t} |w - m'|^2}{A'^2} \quad (2.28)$$

$$\varepsilon_6 = P_6 - \frac{P_{3t} |w - n'|^2}{B'^2} . \quad (2.29)$$

Therefore, equation (2.25) can be expressed in the following form

$$F = \sum_{i=3}^6 \left(\frac{\varepsilon_i}{\sigma_i} \right)^2 . \quad (2.30)$$

At this point, it is only necessary to determine the value of P_{3t} , and then P_{4t}, P_{5t} and P_{6t} are easily deduced from P_{3t} and equations (2.27), (2.28) and

(2.29). The complete solution of this problem is given in [22].

It is noticed that the selection of the function to be minimized is only appropriate when the power meter error is assumed to have a Gaussian distribution. Sometimes the distribution of measurement errors or detector noises show a strong departure from Gaussianity. In this case, the maximum likelihood estimation will be not suitable and a nonlinear minimization is required, which will be difficult to apply in practice. A statistically based method to construct estimators of the reflection coefficient and to compare different six-port designs provides new development to analyse the accuracy of a six-port junction. The details of the method have been introduced in reference [23].

2.5 Conclusion

Basic principles of the six-port technique have been reported in this chapter. Analysis of a six-port reflectometer is developed to emphasize the importance of q_i point positions in designing six-port junction. Based on the significance of the q_i points, the design criterion of a six-port junction has been discussed. Finally, a method to increase the measurement accuracy of a six-port reflectometer is presented.

Chapter 3

Design of the Wideband Six-Port Junction

3.1 Introduction

The fundamental characteristics of any microwave six-port reflectometer that determine the performance of the reflectometer in measurements are represented by the positions of the four q_i points in the complex plane. In the case of a six-port junction incorporating a reference port to monitor the incident power level, only three q_i points remain pertinent in designing this kind of six-port junctions.

Various proposed microwave six-port circuit configurations are based on the interconnection of several standard four port networks which enable broadband frequency coverage [11,24]. Nevertheless, these six-port circuit configurations

do not satisfy the optimal design goals suggested by Engen as we discussed in section (2.3) [11]. Some efforts have been focused to find simple six-port structures with an optimal q_i point distribution. Successful results have been obtained only in narrow frequency band [25,26,27].

3.2 Configuration of the Six-Port Junction

An integrated preferred six-port configuration with non-standard components is used in this design as shown in figure (3.1), where $PD1$ and $PD2$ are two-way equal power dividers, and Q_1, Q_2, Q_3 are hybrid bidirectional couplers with different coupling levels. It will be shown that an optimal distribution of the three q_i points is obtained by using two nonstandard directional couplers and one 3 dB hybrid directional coupler. The phase compensation with frequency variations is provided by carefully choosing the lengths of the interconnections of transmission lines used in the six-port circuit. For analysis convenience, all of the components in this discussion are assumed to be lossless.

It is noticed that the port 3 is used to sample and to monitor the incident signal in the above six-port junction design. The relations between emergent waves at the four ports and the parameters of the six-port junction shown in figure (3.1) can be deduced by analysing the wave propagation inside the junc-

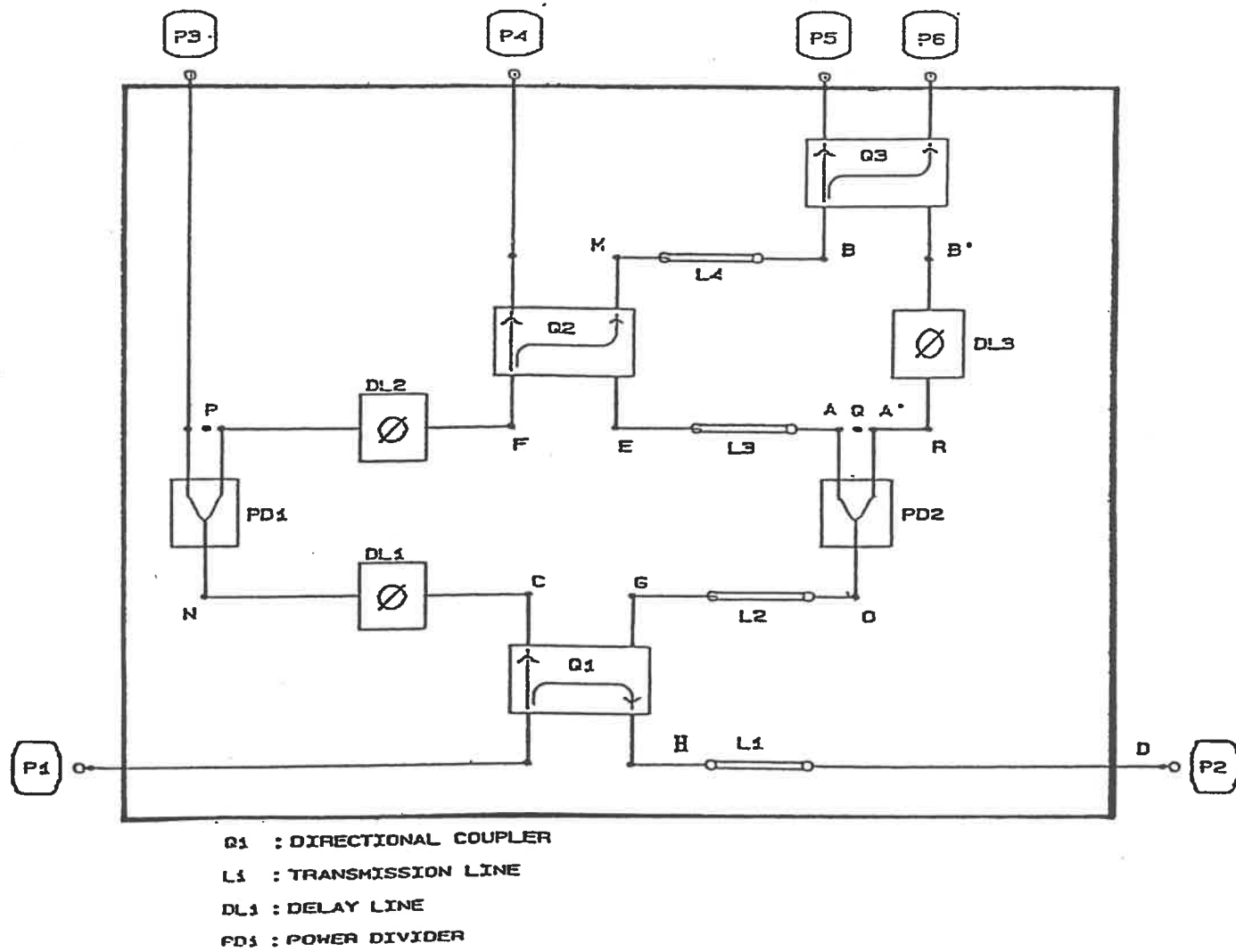


Figure 3.1: A Diagram of Designed Six-Port Junction

tion. The emergent waves at the four detecting ports are:

$$b_3 = \frac{t_1}{j\sqrt{2}c_1} b_2 e^{j(-\phi_2 + \phi_3 + \phi_5 + \theta_p)} \quad (3.1)$$

$$b_4 = \frac{jt_1c_2}{\sqrt{2}} b_2 e^{j(\phi_2 + 2\theta + \phi_4 + \phi_7 + \phi_9 + \theta_p)} \left[\Gamma - \frac{t_2}{c_1c_2} e^{j(-2\phi_2 - \theta - \phi_4 - \phi_7 + \phi_3 + \phi_6)} \right] \quad (3.2)$$

$$b_5 = \frac{t_1}{\sqrt{2}} b_2 e^{j(\phi_2 + 2\theta + \phi_4 + \theta_p + \phi_{11} + \phi_8)} [t_2t_3 e^{j(\phi_7 + \theta + \phi_{10} - \phi_8)} + jc_3] \cdot \left\{ \Gamma + \frac{c_2t_3 e^{j(-2\phi_2 + \phi_3 + \phi_6 + \phi_{10} - \phi_4 - \phi_8)}}{c_1[t_2t_3 e^{j(\phi_7 + \theta + \phi_{10} - \phi_8)} + jc_3]} \right\} \quad (3.3)$$

$$b_6 = \frac{t_1}{\sqrt{2}} b_2 e^{j(\phi_2 + 2\theta + \phi_4 + \theta_p + \phi_{12} + \phi_8)} [t_3 + jt_2c_3 e^{j(\phi_7 + \phi_{10} + \theta - \phi_8)}] \cdot \left\{ \Gamma + \frac{jc_2c_3 e^{j(-2\phi_2 + \phi_3 + \phi_6 + \phi_{10} - \phi_4 - \phi_8)}}{c_1[t_3 + jt_2c_3 e^{j(\phi_7 + \phi_{10} + \theta - \phi_8)}]} \right\} \quad (3.4)$$

where $\Gamma = a_2/b_2$, a_2 and b_2 are the incident and reflected waves at the *DUT* port, θ represents the phase shift through a directional coupler, similarly θ_p is the phase shift through a power divider, c_1 , c_2 , c_3 and t_1 , t_2 , t_3 illustrate the coupling levels and transmitting levels of three directional couplers Q_1 , Q_2 , Q_3 respectively. Under ideal assumption, $c_i^2 + t_i^2 = 1$, ($i = 1, 2$ and 3) and ϕ_j ($j = 1, \dots, 12$) represent effective electrical lengths of delay lines *HD*, *CN*, *GO*, *PF*, *AE*, *A'B'*, and *MB* as shown in figure (3.1) .

Comparing above equations with the basic six-port relation in formula (2.10), q_i points can be found as follows:

$$q_4 = \frac{t_2}{c_1 c_2} e^{j(-2\phi_2 - \theta - \phi_4 - \phi_7 + \phi_3 + \phi_6)} \quad (3.5)$$

$$q_5 = -\frac{c_2 t_3 e^{j(-2\phi_2 - \phi_4 - \phi_8 + \phi_3 + \phi_6 + \phi_{10})}}{c_1 [t_2 t_3 e^{j(\phi_7 + \phi_{10} + \theta - \phi_8)} + j c_3]} \quad (3.6)$$

$$q_6 = -\frac{j c_2 c_3 e^{j(-2\phi_2 - \phi_4 - \phi_8 + \phi_3 + \phi_6 + \phi_{10})}}{c_1 [t_3 + j t_2 c_3 e^{j(\phi_7 + \phi_{10} + \theta - \phi_8)}]} \quad (3.7)$$

Equations (3.5), (3.6) and (3.7) demonstrate that q_i points will be frequency invariant when the following equations are satisfied

$$\phi_3 + \phi_6 = 2\phi_2 + \phi_4 + \phi_7 + \theta \quad (3.8)$$

$$\phi_8 = \phi_7 + \phi_{10} + \theta \quad (3.9)$$

Substituting equations (3.8) and (3.9) into equations (3.5), (3.6) and (3.7), we can express q_i simply as follows:

$$q_4 = \frac{t_2}{c_1 c_2} \quad (3.10)$$

$$q_5 = -\frac{c_2}{c_1 (t_2 + j c_3 / t_3)} \quad (3.11)$$

$$q_6 = -\frac{c_2}{c_1 (t_2 - j t_3 / c_3)} \quad (3.12)$$

The three q_i points, therefore, depend entirely on the choice of the circuit components. Once the coupling levels of the three directional couplers are determined, the three q_i points will be fixed also. Considering the optimum design criterion : $|q_4| = |q_5| = |q_6|$, which are expected to lie within the range of $0.5 \sim 1.5$ and their arguments should differ by 120° . The latter condition can be achieved, if

$$c_2 = \frac{\sqrt{2}}{\sqrt{3}} = 1.76 \text{ dB} \quad (3.13)$$

$$c_3 = \frac{1}{\sqrt{2}} = 3 \text{ dB} . \quad (3.14)$$

Now the magnitudes of q_i can be adjusted by the choice of c_1 . It is clear from equation (3.10), (3.11) and (3.12) that the magnitudes of q_i points are inversely proportional to the coupling level of the first main directional coupler. That means the magnitudes of q_i points will be reduced as the coupling level c_1 increases. As mentioned in section (2.3), if $|q| \cong 1$ or $|q| \cong |\Gamma|$, a decrease in the measurement accuracy will occur. To avoid this problem, the three q_i points are pushed out of the unit circle in Γ plane in this six-port junction design. There are a number of possible variants of the value c_1 to keep the three q_i points out of the unit circle. Not apart from the optimum distribution suggested by Engen, the magnitudes of the q_i points become 1.54, when c_1 is chosen to be

$$c_1 = 0.45 = 6.75 \text{ dB} \quad (3.15)$$

Having determined all values of components based on the requirements of the q_i point distribution, the set of values of $|K_i|$ in equation (2.10), which in turn determine the relative power levels of the four signals at the four power detectors should be discussed to complete the design. Returning to equations (3.1) ~ (3.4), it is found out that

$$|K_3| = \frac{t_1}{\sqrt{2} c_1} = 1.1 \quad (3.16)$$

$$|K_4| = \frac{t_1 c_2}{\sqrt{2}} = 0.51 \quad (3.17)$$

$$|K_5| = \frac{t_1}{\sqrt{2}} |t_2 t_3 + j c_3| = 0.51 \quad (3.18)$$

$$|K_6| = \frac{t_1}{\sqrt{2}} |t_3 + j t_2 c_3| = 0.51 . \quad (3.19)$$

The equality of $|K_4| = |K_5| = |K_6|$ displays the advantage obtained by the consideration of phase compensation of q_i points which minimize the requirement to the dynamic range of the four detectors. In such case the same quality power detectors with acceptable dynamic range (50 dB) can be used at the four output ports. This circuit, therefore, provides also an optimal set of the values $|K_i|$ in terms of the power detector dynamic range.

So far, an optimum integrated six-port junction has been described attentively. It is noted that the operating frequency range of the six-port junction

depends mainly on the working bandwidth of the components, i.e. power dividers and directional couplers. In this design, the expected frequency range should cover $2 \sim 18 \text{ GHz}$.

3.3 Directional Coupler Designs and Measurements

In order to construct a preferred wideband integrated six-port junction, as described in section (3.1), three hybrid directional couplers and two equal power dividers which cover a wide frequency range from 2 to 18 GHz should be designed as the first step in designing a complete six-port circuit.

3.3.1 Wideband Directional Couplers with Tight Coupling Levels

A variety of physical configurations for directional couplers with tight coupling levels have been proposed and are used in microwave integrated circuits [28,29,30,31,32,33]. The common used types are branch-line hybrids, re-entrant structures [34], Lange couplers [30,35] and broadside coupled parallel lines or overlap coupled line configurations [33,36,37].

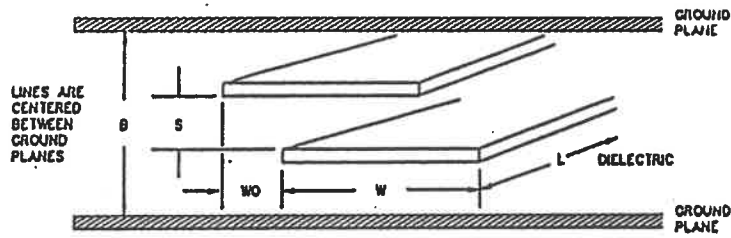
For increasing bandwidth and flatness of frequency responses, a single section of parallel lines should be expanded by cascading multi-sections

[29,30,34,38,39]. Whenever multi-section couplers are fabricated for broad-band applications, a significant factor controlling their practical realization is the physical dimensions (i.e. the spacing between two coupling lines) of the middle coupling section. A method to solve this problem has been presented by Shelton in 1965 [29], namely tandem connection technique. It consists of several couplers with lower coupling values which are tandemly connected together in order to design the final coupler with a tight coupling level.

A wide band directional coupler with a slightly tighter coupling level (i.e. 6 *dB* coupler) can be obtained by suitably cascading broad-side coupled striplines (middle section) and overlap coupled parallel striplines (remaining sections) as shown in figure (3.2). For a 3 *dB* hybrid or an even more tighter coupler (e.g. 1.76 *dB* coupler) tandem connection technique must be applied.

3.3.2 Directional Coupler Designs

The 6.75 *dB* directional coupler can be achieved by using the configuration shown in figure (3.2). The 3 *dB* directional coupler is obtained by tandemly connecting two 8.34 *dB* directional couplers as shown in figure (3.4). The same configuration is used to obtain the 1.76 *dB* coupler from two 6.75 *dB* directional couplers.



port1
(input)

$\epsilon_r = 2.2$, $B = 70$, $s = 10.1$

$w_1 = 53.2$,	$w_{01} = 0$
$w_2 = 55.9$,	$w_{02} = 46.9$
$w_3 = 57.5$,	$w_{03} = 58.5$
$w_4 = 58.9$,	$w_{04} = 88.2$
$w_5 = 60$,	$w_{05} = 140$
$l_1 = 176.6$	
$l_2 = 32.7$	
$l_3 = 173.8$	
$l_4 = 191.9$	
$l_5 = 220.8$	

port3
(isolating)

(all dimensions are in mil)

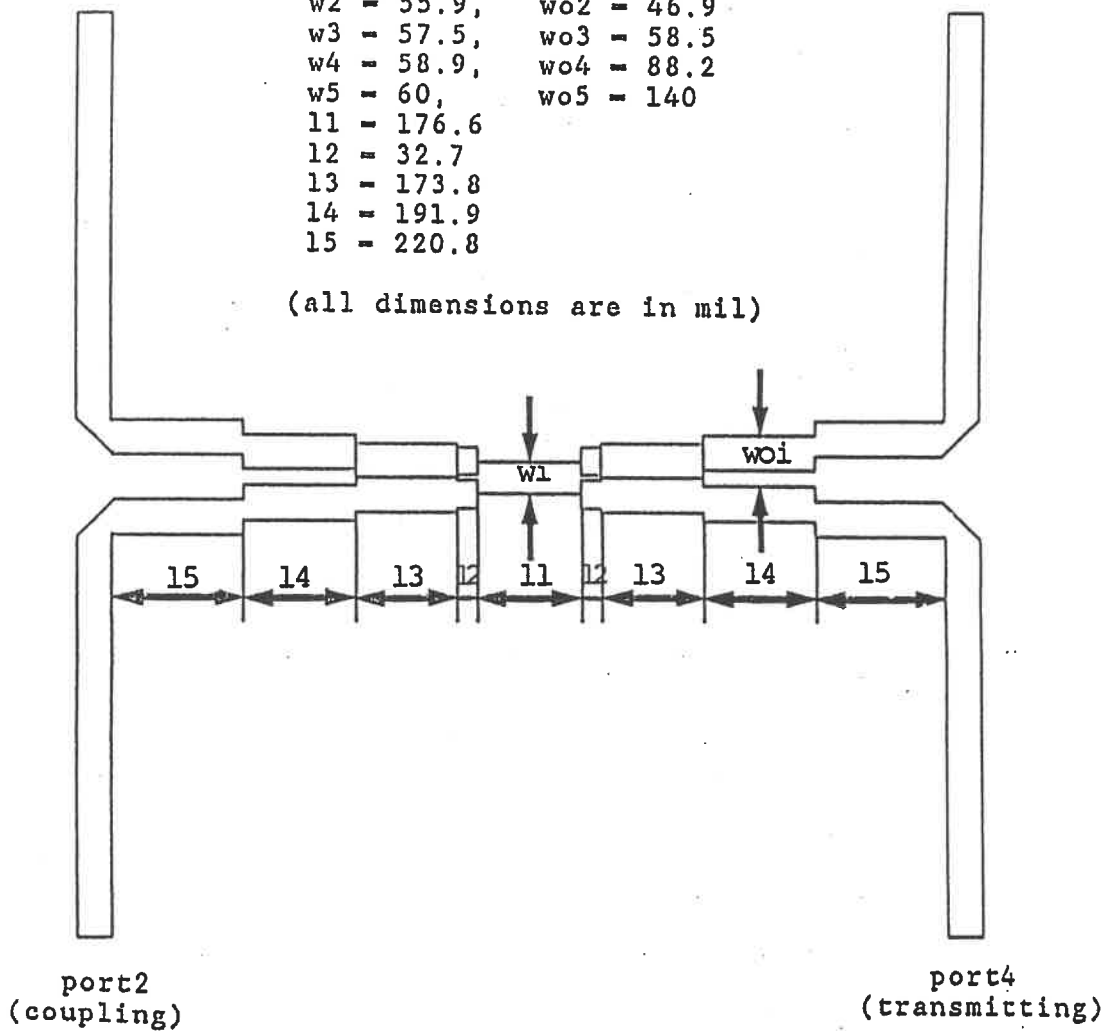


Figure 3.2: The Layout of the 6.75 dB Directional Coupler

For this kind of symmetrical multisection directional couplers, the design procedure is

1. Determine the required number of sections to cover frequency bandwidth ($2 \sim 18GHz$) [40].
2. According to the coupling level required and the number of sections chosen, synthesize the even- and odd-mode impedances of the individual sections of the coupler by using a commercial software 'Linecalc'¹ [41].
3. Choose appropriately the substrate and its thickness in order to obtain a good performance at high frequency.
4. Based on the special configuration shown in figure (3.2) and the parameters of the substrate selected, calculate the dimensions of the individual sections by means of the even- and odd-mode impedances obtained above.
5. After all of sections connected together, adjust the final dimensions of the complete junction by 'trial and error' so that optimum characteristics, such as coupling level, reflection coefficient and directivity are achieved.

The substrate material is teflon with a dielectric constant of 2.30. The distance between the ground plates B is 1.778 millimeters (see figure (3.2)). The spacing of the center gap of the broad side coupling stripline configuration

¹Linecalc : trade mark of ESSOF

should be as small as possible to minimize the effect caused by the nonsymmetrical location of the conductor strip lines with respect to the ground planes in the design of the power dividers. The power dividers which will be built up on the same substrate board contain resistors which are soldered on two branches of the power dividers. The thickness of such resistors available in our labs is 0.254 mm. Therefore, the thickness of the middle layer substrate should be no less than 0.254 mm. In our design, this value is chosen to be 0.254 mm exactly.

After many iterations by using a ' Touchstone² ', a good performance directional coupler with coupling level 6.75 dB has been obtained. The dimensions of the coupler have also been shown in figure (3.2). The simulation results of the coupler are shown in figure (3.3), where s_{11} represents the reflection coefficient, s_{21} stands for the coupling coefficient, s_{41} is the transmitting coefficient and s_{31} expresses the isolation coefficient.

The 3 dB coupler is obtained by two suitably tandem connected 8.34 dB couplers as illustrated in figure (3.4). The 8.34 dB coupler is designed following the previous procedure. To meet the needs of the tandem connection, some stripline miters and transmission striplines with 50 Ω characteristic impedance must be added between the two less tight couplers. The final dimensions of the optimized 3 dB coupler is also illustrated in figure (3.4). Figure (3.5) shows the

²Touchstone : trade mark of ESSOF

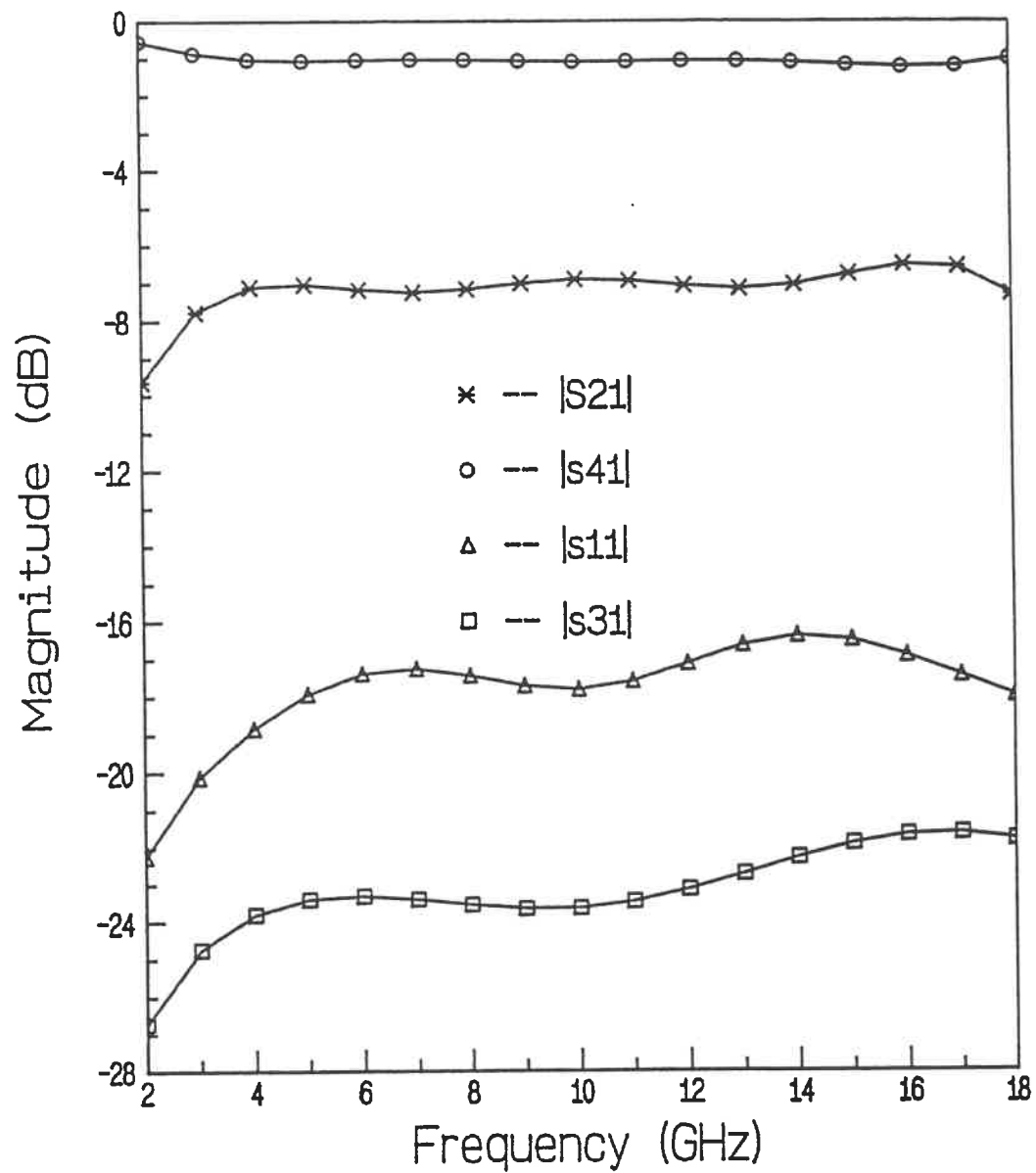
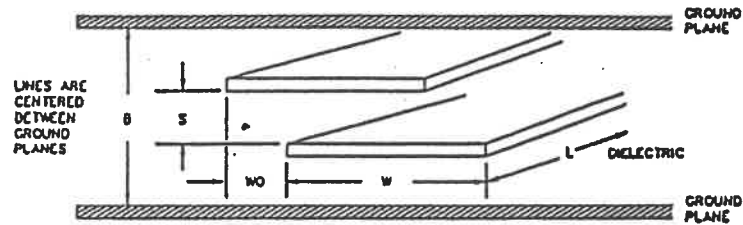


Figure 3.3: Simulation Results of the 6.75 dB Directional Coupler



$\epsilon_r = 2.2, B = 70, s = 10.1$

port1
(input)

port4
(isolating)

- w1 - 53.2, w01 - 0
- w2 - 56.9, w02 - 48
- w3 - 58, w03 - 60
- w4 - 59, w04 - 82.5
- w5 - 59.1, w05 - 129.6
- l1 - 145.4
- l2 - 62.2
- l3 - 149.5
- l4 - 179.8
- l5 - 264.9

(all dimensions are in mil)

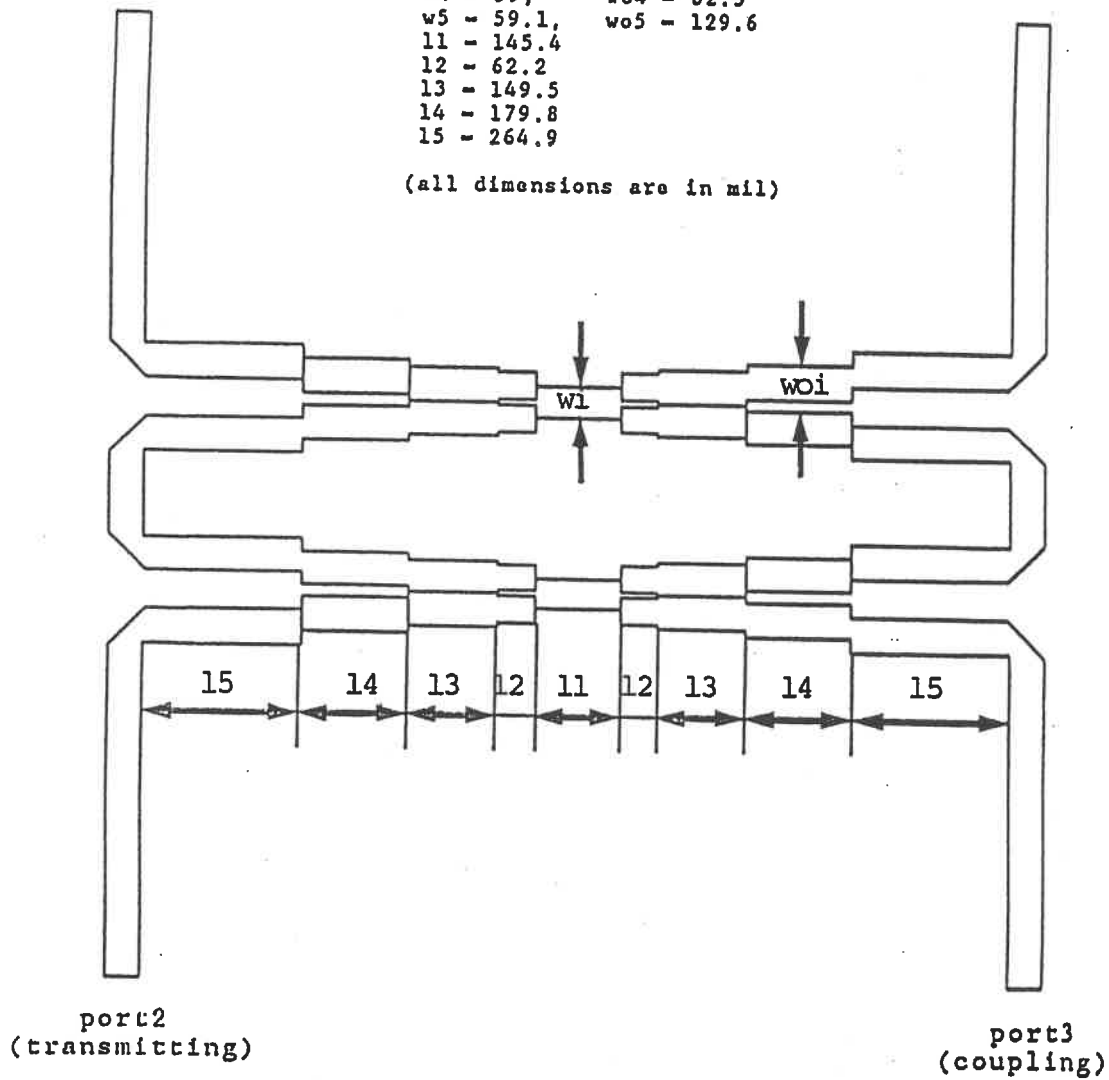


Figure 3.4: The Layout of the 3 dB Directional Coupler

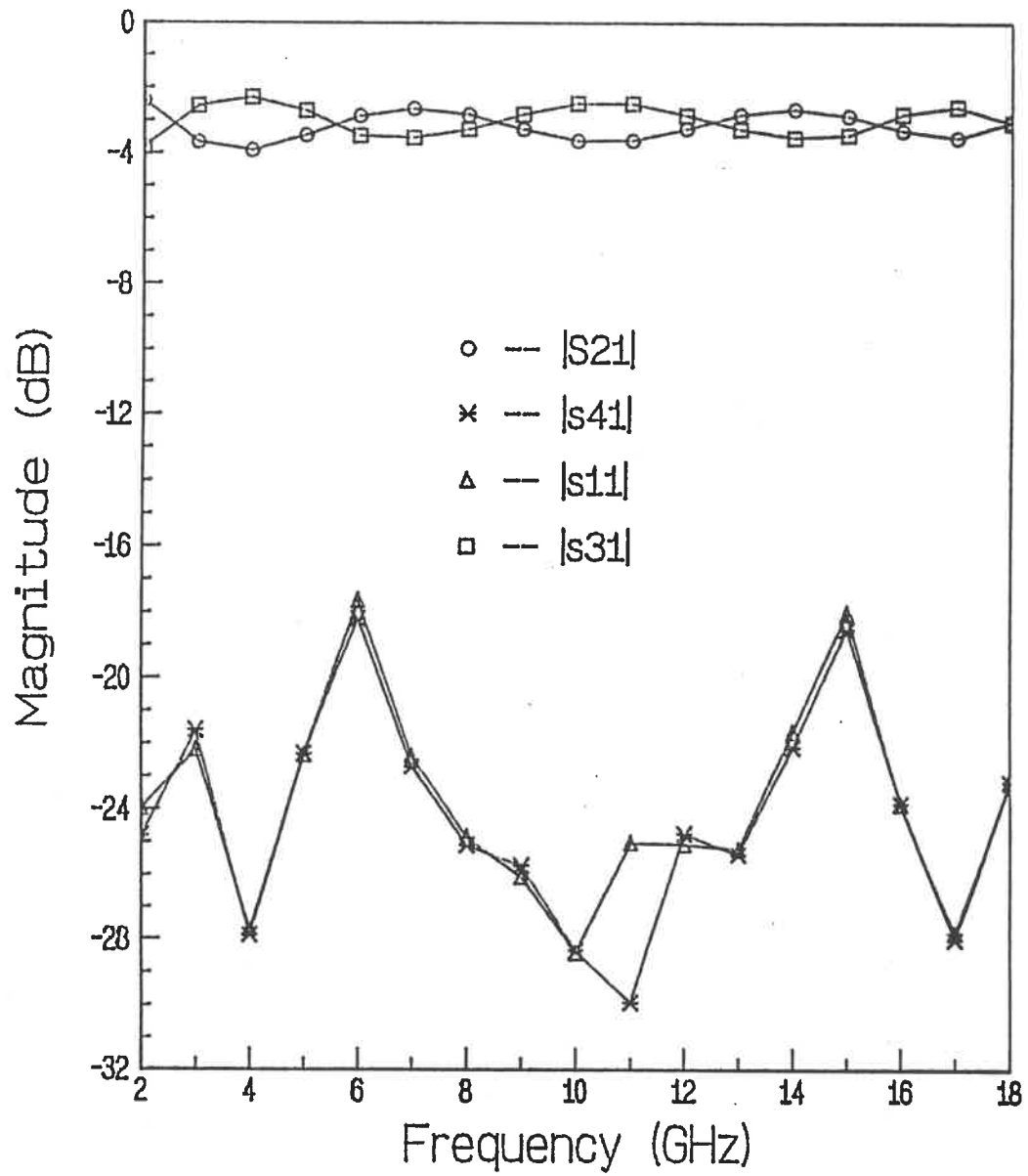


Figure 3.5: Simulation Results of the 3 dB Directional Coupler

simulation results of the 3 *dB* coupler.

A similar approach can be taken to design a 1.76 *dB* coupler which is composed of the same configuration as in figure (3.4). A single coupler with a little tighter coupling, i.e. 6.75 *dB* in stead of 8.34 *dB*, should be designed first. The design procedure has been discussed before. The dimensions of each coupler in tandem section of the 1.76 *dB* coupler are the same as that of the 6.75 *dB* coupler as shown in figure (3.2). The simulation results of the designed 1.76 *dB* coupler by using ' Touchstone ' is given in figure (3.6).

3.3.3 Manufacture and Test of *CAD* couplers

A block diagram of the measurement system used to test the designed six-port junction and its components is illustrated in figure (3.7). All of the instruments shown in figure (3.7) have wide operating frequency range which covers 2 ~ 18 *GHz*. A simple program has been made to establish the relations between these power ratios and to calculate the *S* parameter magnitudes of the tested coupler.

The measured magnitudes of *S* parameters of the 6.75 *dB*, 3 *dB* and 1.76 *dB* couplers are shown in figures (3.8), (3.9) and (3.10) respectively. Comparing with simulated results shown in figures (3.3), (3.5) and (3.6), it is obvious that,

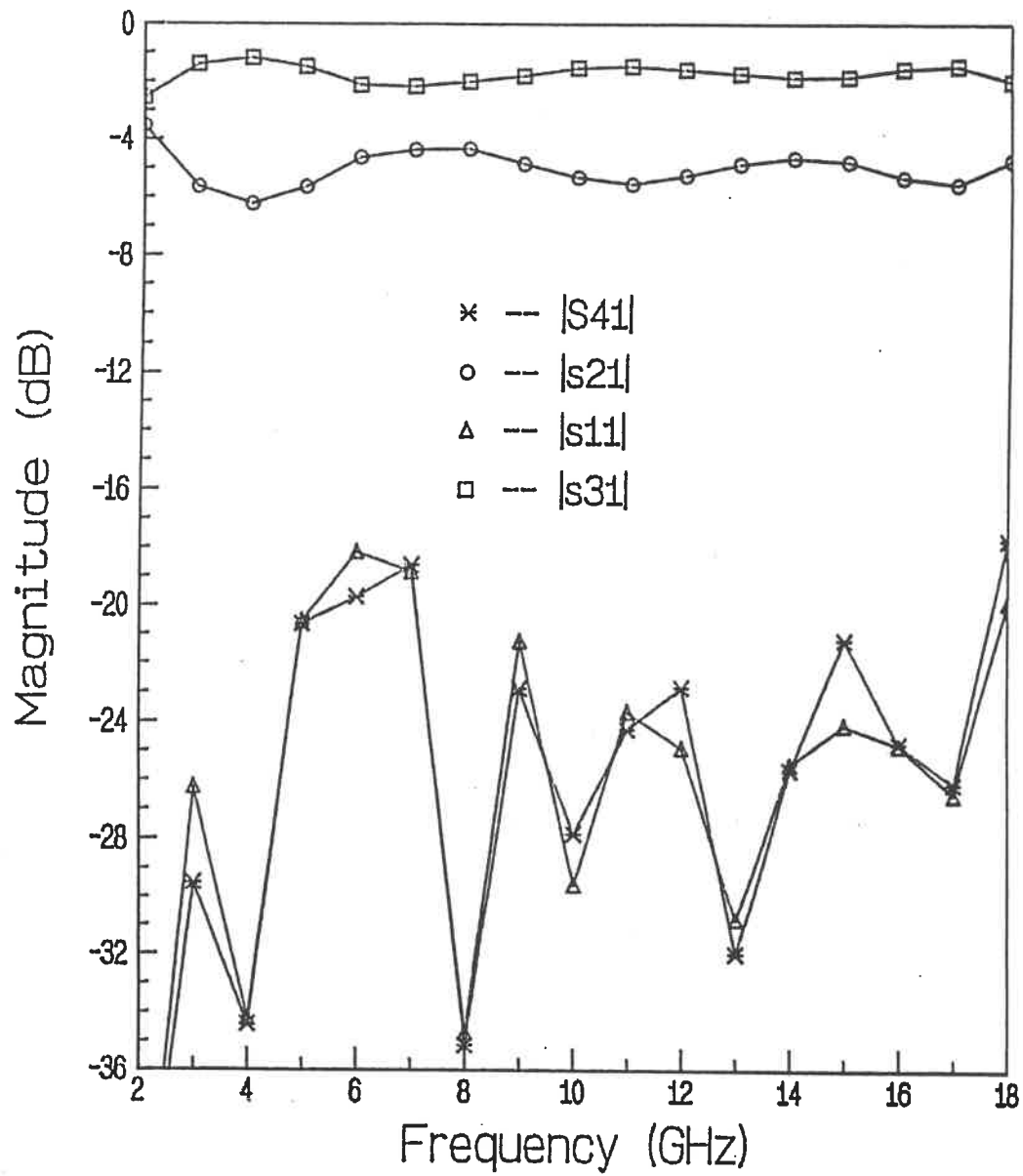


Figure 3.6: Simulation Results of the 1.76 dB Directional Coupler

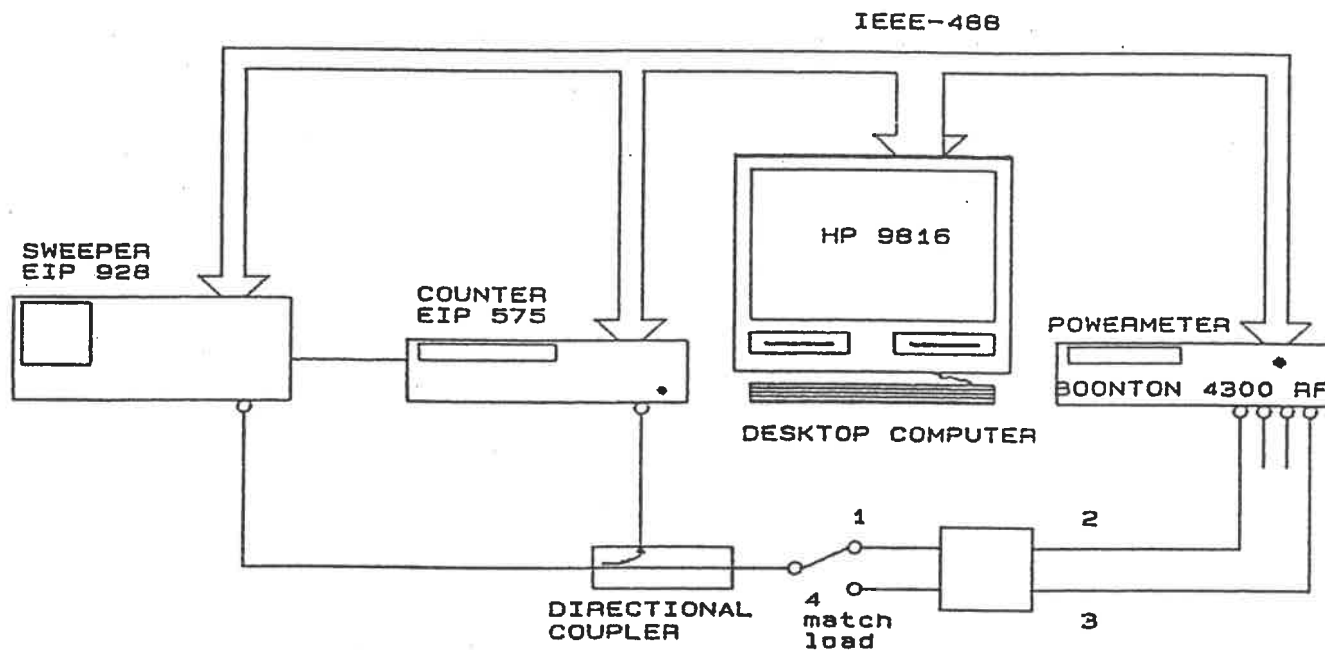


Figure 3.7: The Block Diagram of the Measurement System

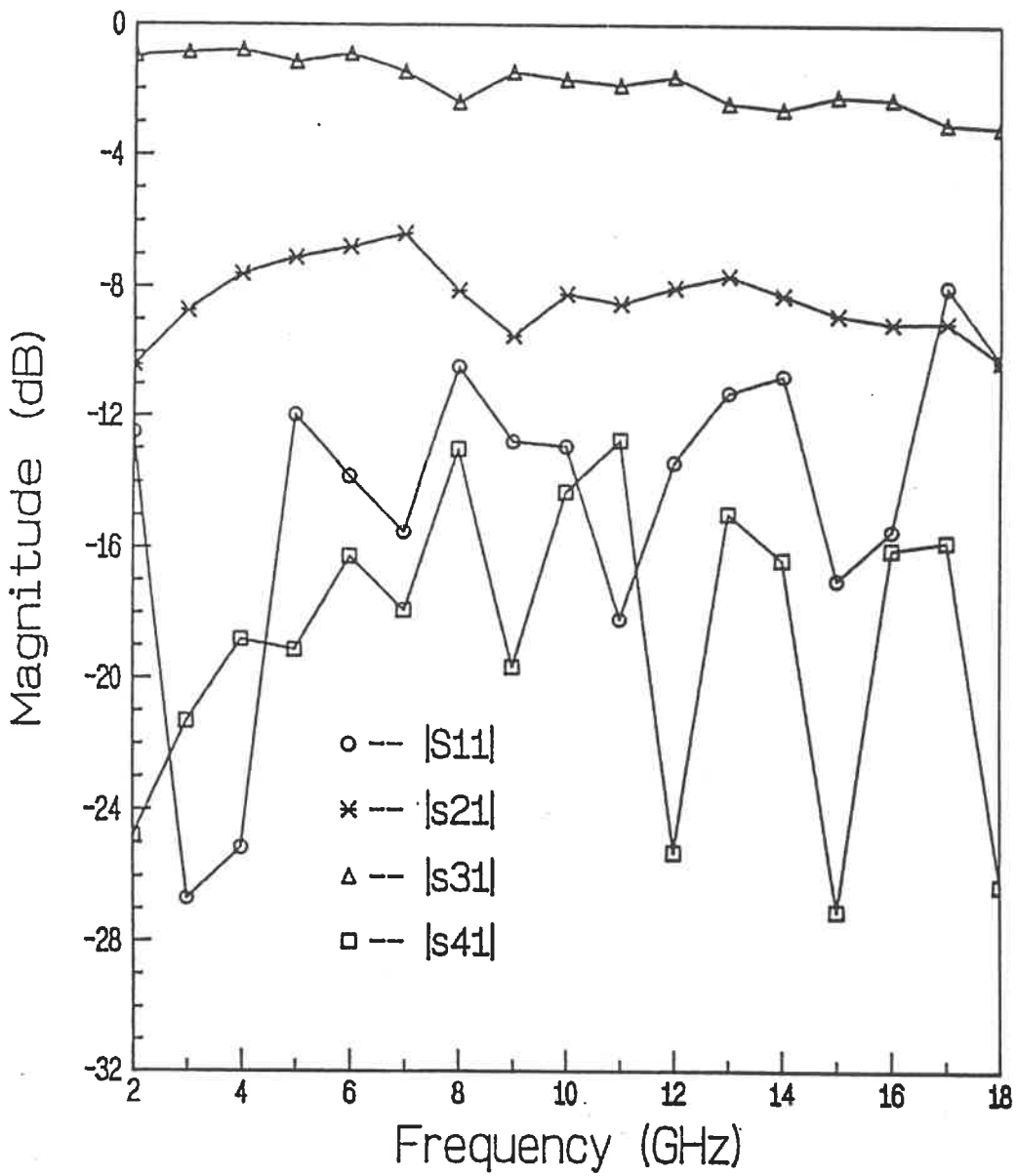


Figure 3.8: Measurement Results of the 6.75 dB Directional Coupler

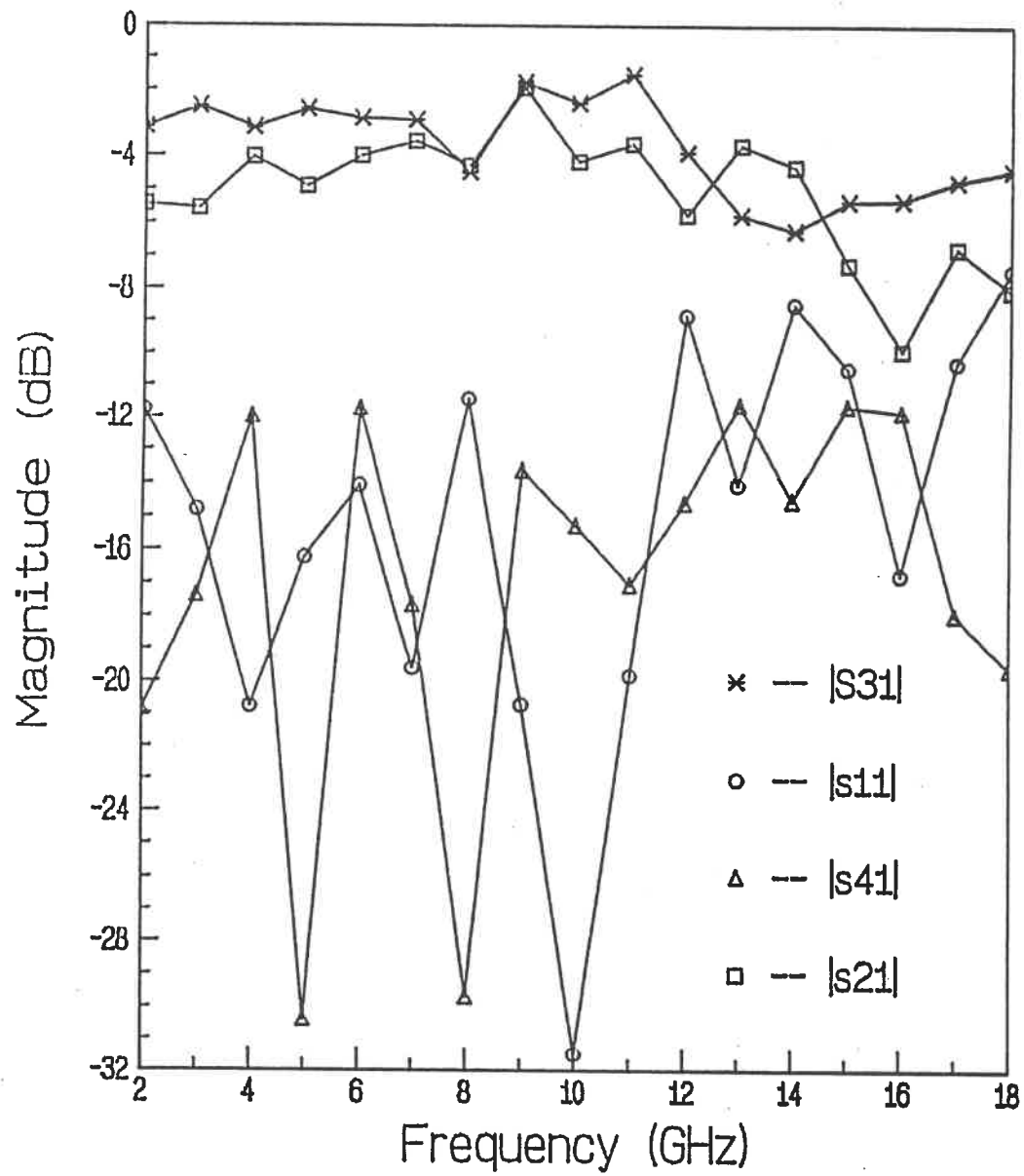


Figure 3.9: Measurement Results of the 3 dB Directional Coupler

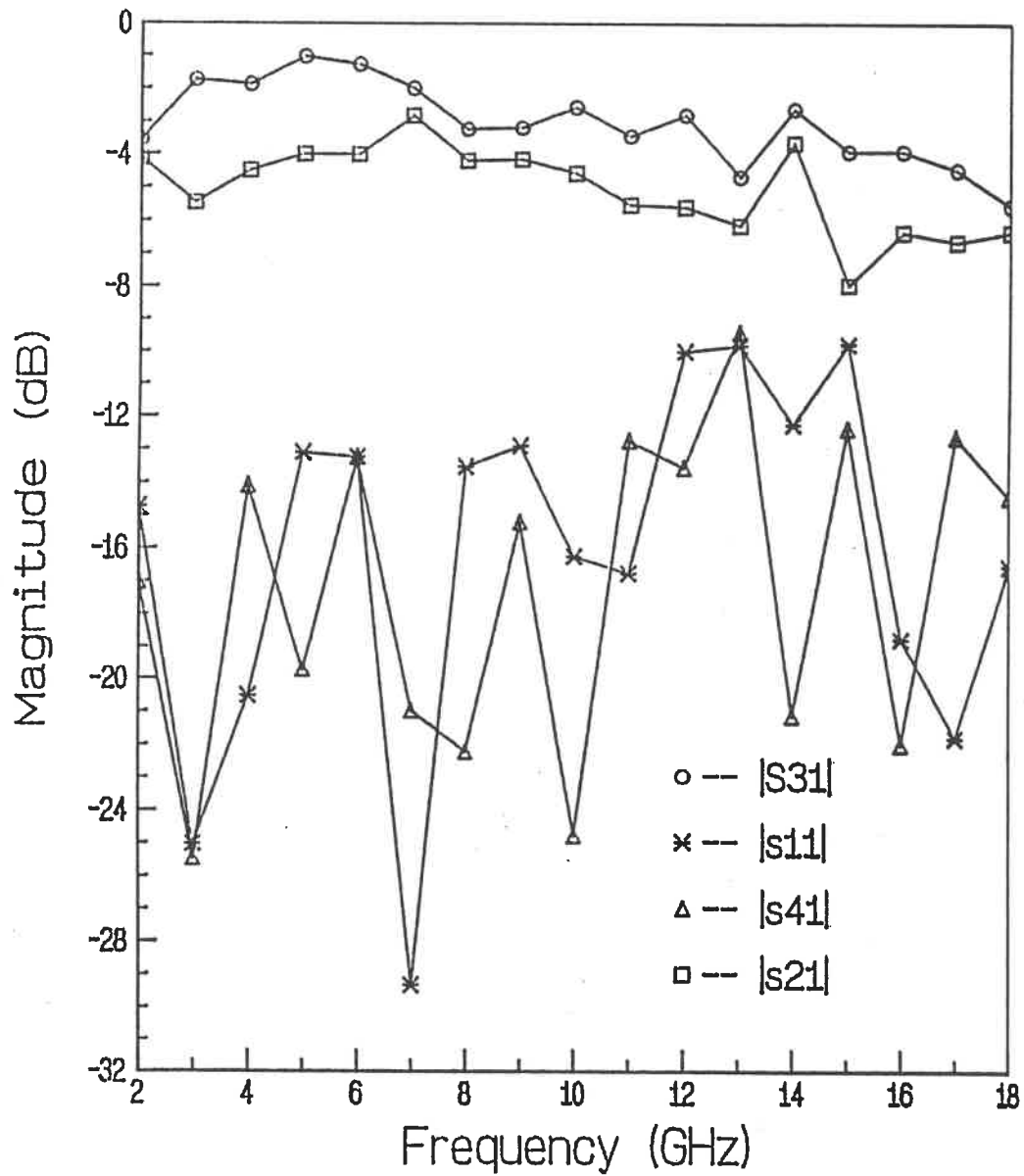


Figure 3.10: Measurement Results of the 1.76 dB Directional Coupler

at low frequencies the measured results are in excellent agreement with the simulated results obtained from ' Touchstone '. At high frequencies, especially above $15GHz$, the coupling level decreases gradually as the reflection coefficient increases. This can be explained by the fact that the radiation loss, the conductor loss and the dielectrical loss of an actual coupler increase with frequency and these effects are more serious above $15GHz$.

3.4 Designs and Measurements of Power Dividers

There are various kinds of microwave power dividers [42,43,44]. A useful broadband circuit for power division with equal phase characteristics at each of the output ports, as well as good isolation between the output ports, may be achieved through use of the series terminated, three port in-line power dividers first introduced by Wilkinson [42]. It consists of pairs of quarter-wave transmission lines terminated by resistors as illustrated in figure (3.11). As the number of individual sections increases, the bandwidth of the device increases also.

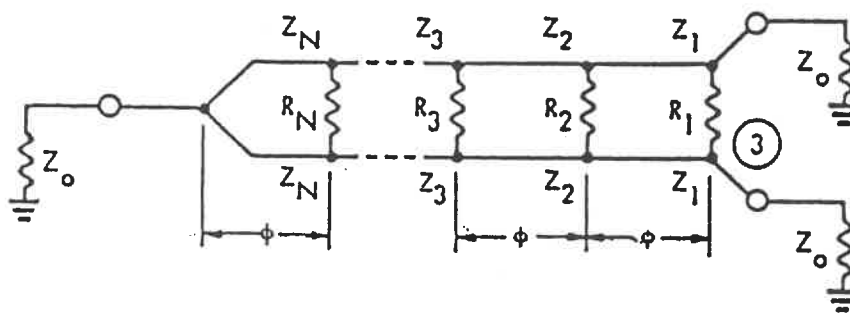


Figure 3.11: Electrical Configuration of a Multi-Section Wilkinson Two-Way

Equal Power Divider

3.4.1 Design and Measurement of Stright Branch Line Wilkinson Power Dividers

The procedure of designing a Wilkinson power divider is quite similar to that of the coupler design. The first step is to decide the number of sections of the power divider. A seven-section with seven pairs of quarter-wavelength transmission lines is considered in this design. The impedances and the associated resistors of the individual sections should be determined according to reference [43]. Finally, the software ' Touchstone ' is used to optimize the power dividers in order to satisfy the design objectives.

Two kinds of power dividers are analysed in this thesis. The first kind consists of seven sections with quarter-wave length transmission lines and a right angle splitting as shown in figure (3.12). The second kind possesses the same configuration except that a 30° angle is used instead of the right angle splitting as illustrated in figure (3.13). The latter structure is expected to improve the input match. Measurements show that the characteristics of the structure with 30° angle splitting are improved comparing with the right angle one. Nevertheless, another problem arises. To achieve a high isolation between the output ports over the whole operating frequency range, the resistors must be very small, and the dimensions of resistors available in our labs are 1.52×1.27 mm. This means that the two branches of the power divider must be placed

$w50 = 55.19, \quad wr = 50, \quad lr = 70$

$w1 = 10,$	$l1 = 79.5,$	$r1 = 100$
$w2 = 20.9,$	$l2 = 137.4,$	$r2 = 142$
$w3 = 28.1,$	$l3 = 118.7,$	$r3 = 220$
$w4 = 35.2,$	$l4 = 167.5,$	$r4 = 250$
$w5 = 37.7,$	$l5 = 121.9,$	$r5 = 308$
$w6 = 46.2,$	$l6 = 153.6,$	$r6 = 400$
$w7 = 49.2,$	$l7 = 120.1,$	$r7 = 450$

(all of dimensions are in mil)

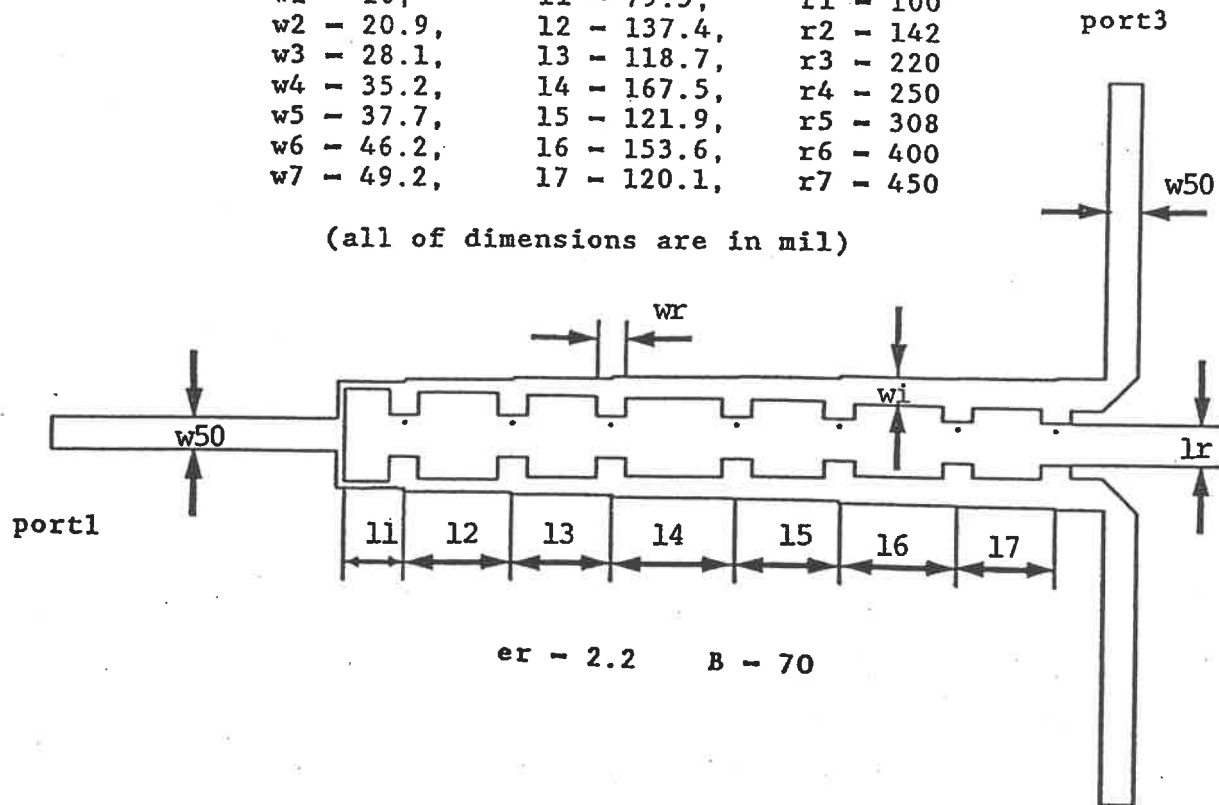


Figure 3.12: The Layout of the Wilkinson Power Divider with Input Right port2

Angle Splitting

w50 - 55.19,	wr - 50,	lr - 70
w1 - 10.4,	l1 - 81.2,	r1 - 100
w2 - 18.1,	l2 - 119.7,	r2 - 142
w3 - 24.6,	l3 - 138.2,	r3 - 220
w4 - 34.2,	l4 - 174.2,	r4 - 250
w5 - 37.2,	l5 - 124.1,	r5 - 308
w6 - 44.4,	l6 - 169.2,	r6 - 400
w7 - 50.3,	l7 - 119.6,	r7 - 450

(all of dimensions are in mil)

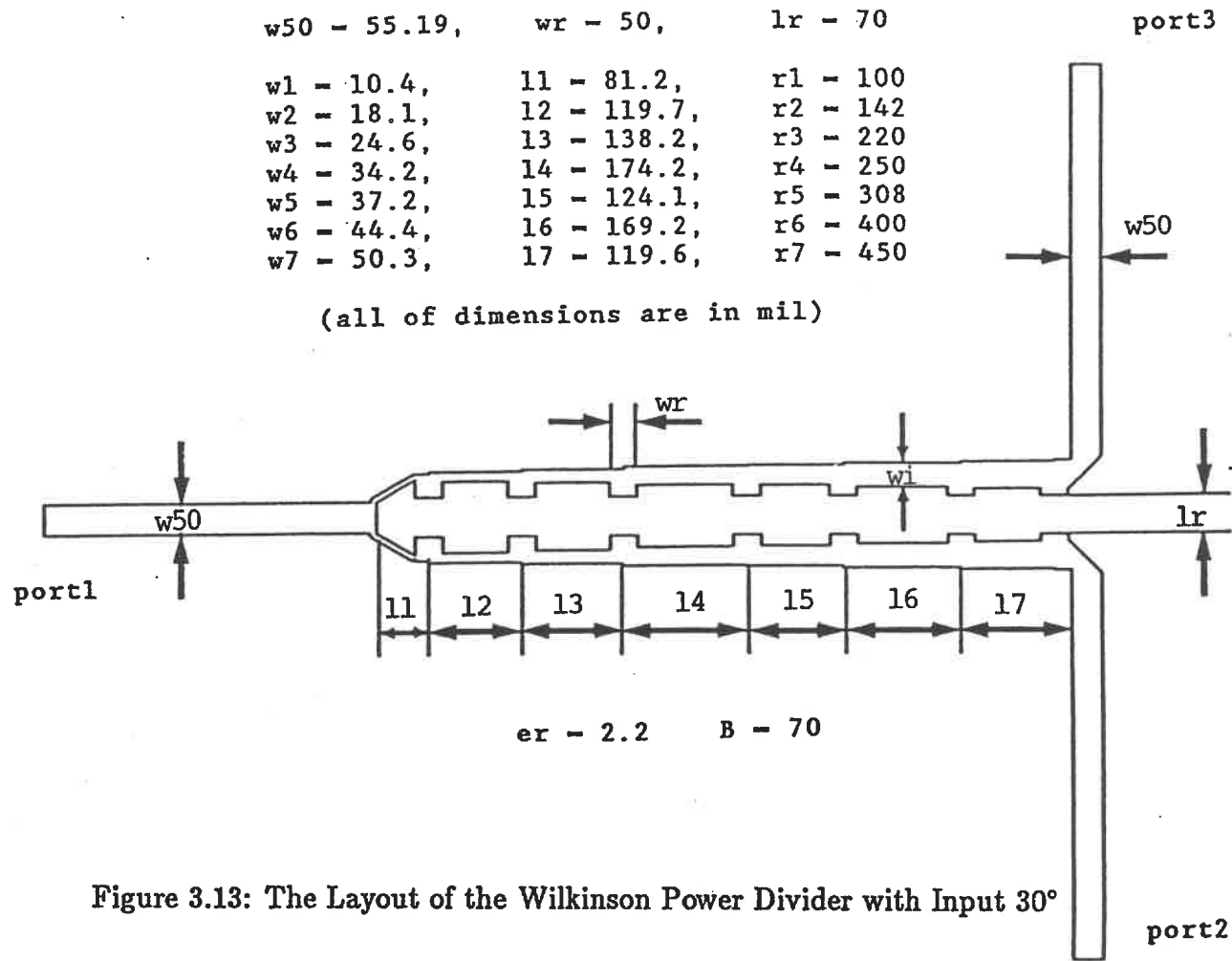


Figure 3.13: The Layout of the Wilkinson Power Divider with Input 30°

Angle Splitting

closely to each other in order to be connected to the resistors, and consequently the mutual couplings between the two branches arise. To avoid these unexpected couplings, the bridging transmission lines have been added between the parallel branches as shown in figure (3.13) to hold the resistors. The negative effects of such bridging lines are the degradation of the isolation between the two output ports. The S parameter amplitudes calculated by using ' Touchstone ' for these two configurations are presented in figure (3.14) and figure (3.15) respectively, where s_{32} represents the isolation between port 2 and 3 which is higher than 20 dB over the whole frequency band, s_{11} is the reflection coefficient at the input port (port 1), s_{21} and s_{31} stand for emergent waves from port 2 and 3 respectively.

Both power dividers have been built using the same manufacturing technique as that used to build the directional couplers. The measurement system used to characterize the directional couplers is also kept for testing power dividers. The measured S parameter amplitudes of the two kinds of power dividers are given in figure (3.16) and (3.17). Comparing these two responses, it can be deduced that 30° angle splitting power divider presents more flat responses over almost the whole frequency band and shows less reflection at high frequencies than the right angle splitting one. It is also noted that, the reflection coefficient $|s_{11}|$ and isolation between two output ports $|s_{32}|$ increase sharply after 15 GHz. The reasons of this problem are probably: the effects of resistor dimensions (re-

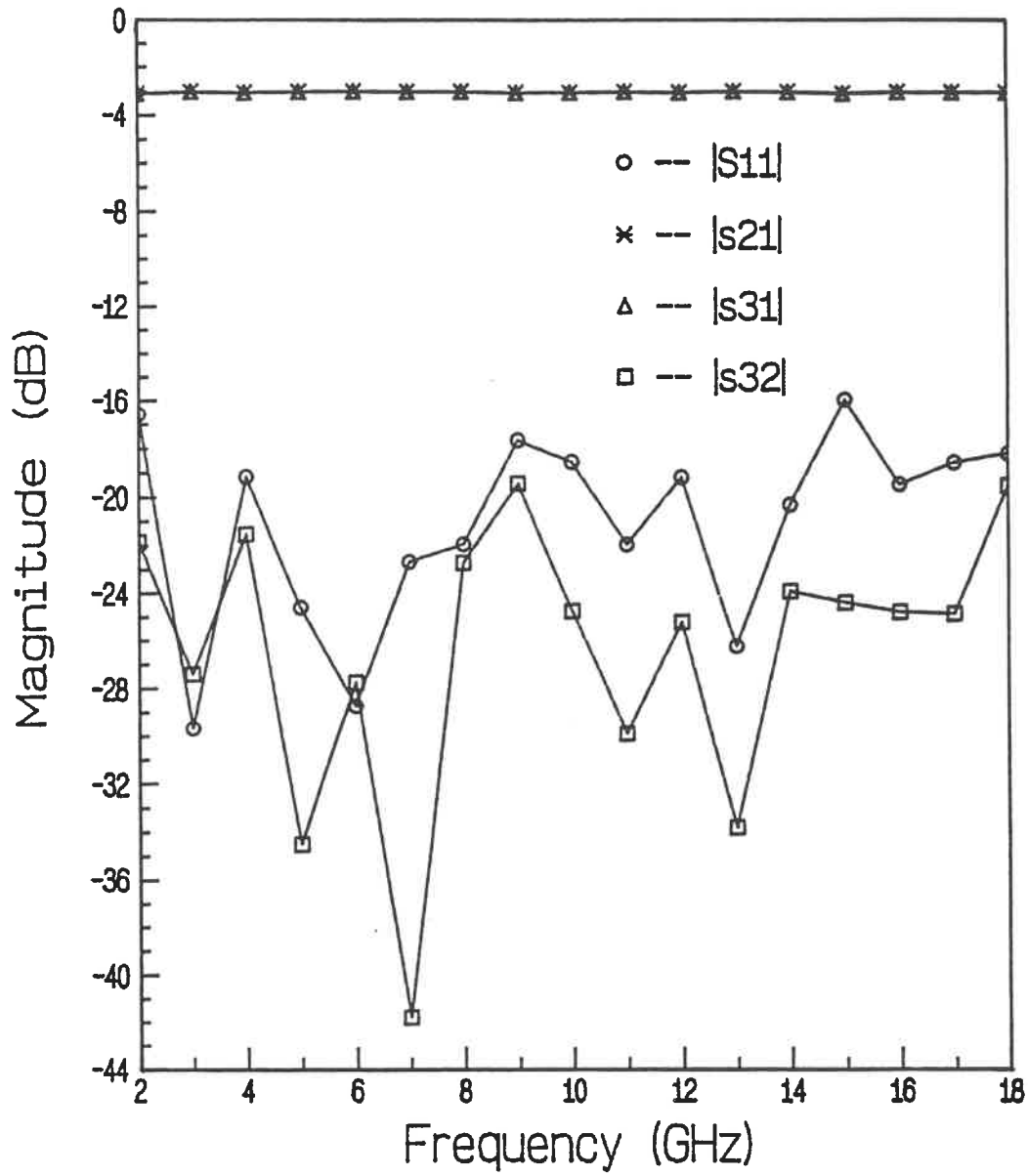


Figure 3.14: Simulation Results of the Right Angle Splitting Power Divider

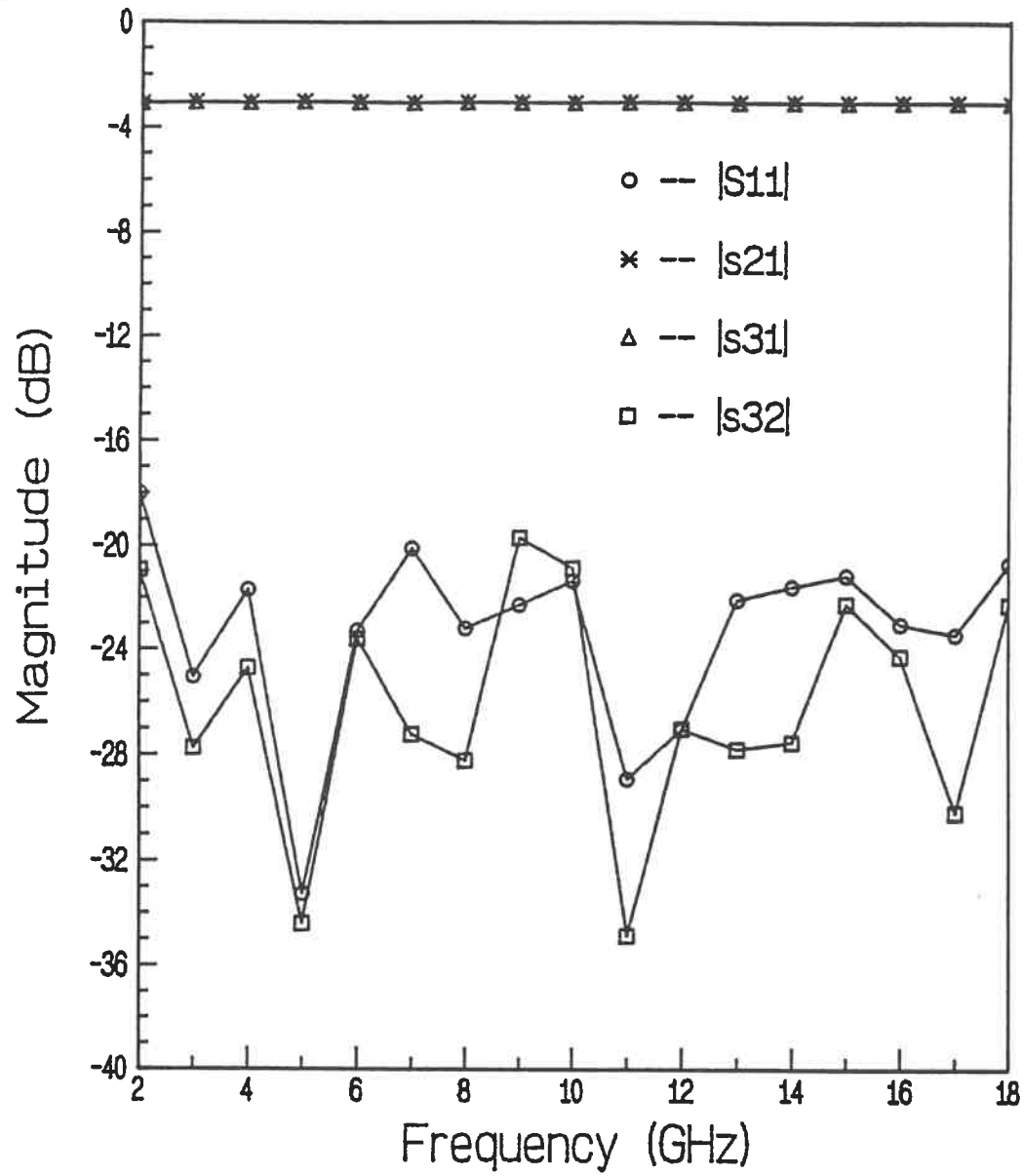


Figure 3.15: Simulation Results of the 30° Angle Splitting Power Divider

sistors should not be considered as lumped elements at high frequencies); the operating frequency range of the resistors; the length of bridging transmission lines for soldering the resistors and the effects of discontinuities introduced by T junctions between each section.

3.4.2 Design and Measurement of a Curved line Power Divider

The step discontinuities between each section of the branch transmission lines and the effects of the bridging lines at the end of each section in a common Wilkinson straight line power divider induce a degradation on its performance, specially at high frequency (i.e. higher than 15 GHz). A solution of this problem will be very attractive if the short bridging lines can be removed away, meanwhile the distances between the two branches of each section can be made large enough to neglect the couplings between them. Fortunately, this solution can be realized when the straight branch lines of each section are bent into half-circles [45,46]. Consequently, bridging lines disappear as shown in figure (3.18). We shall see that in this configuration the bridging lines for soldering the terminating resistors are replaced by the intersection of the two adjacent curved lines, the distances between the two branches of each section are increased and the discontinuity between each section is reduced also.

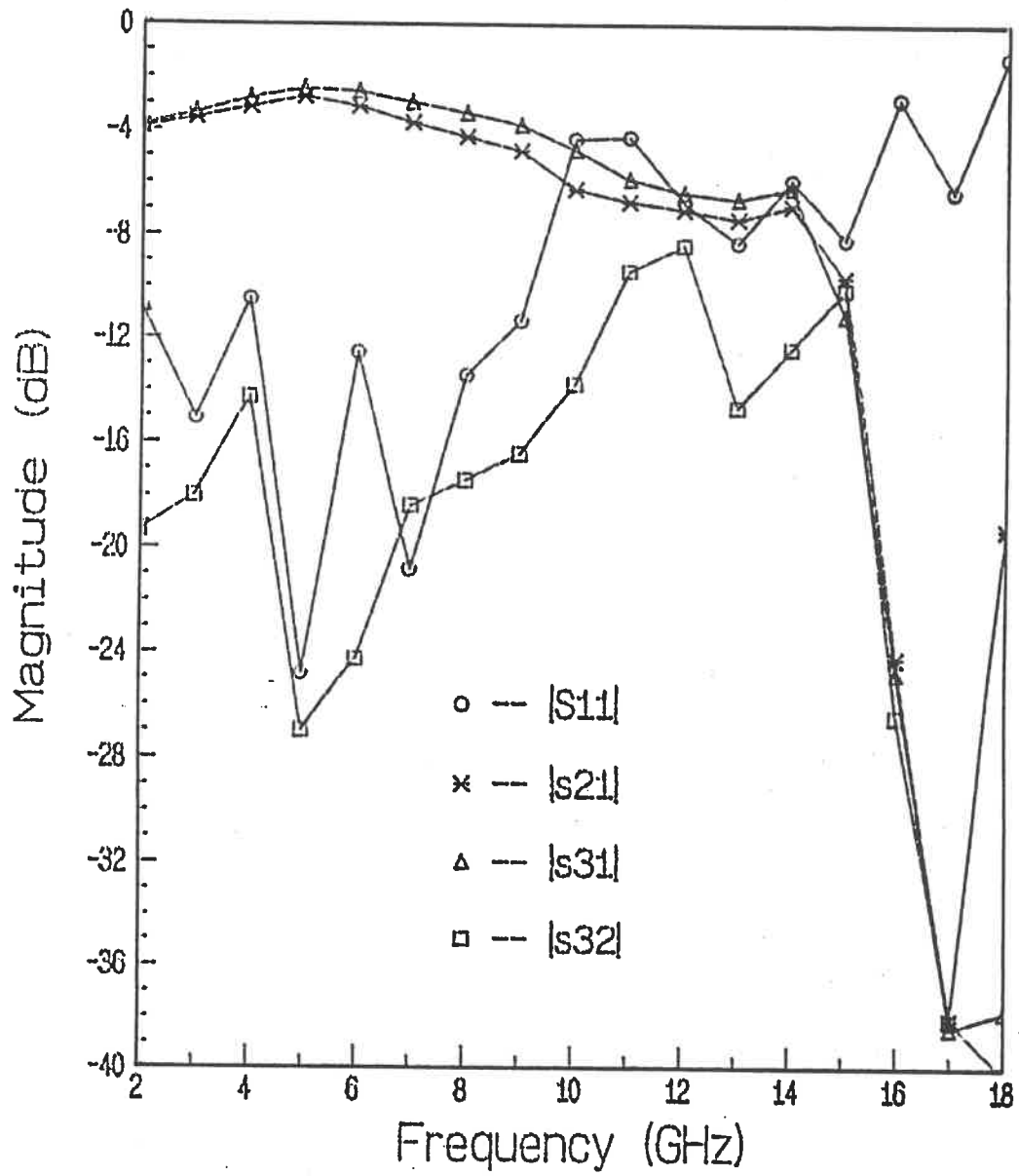


Figure 3.16: Measurement Results of the Right Angle Splitting Power Divider

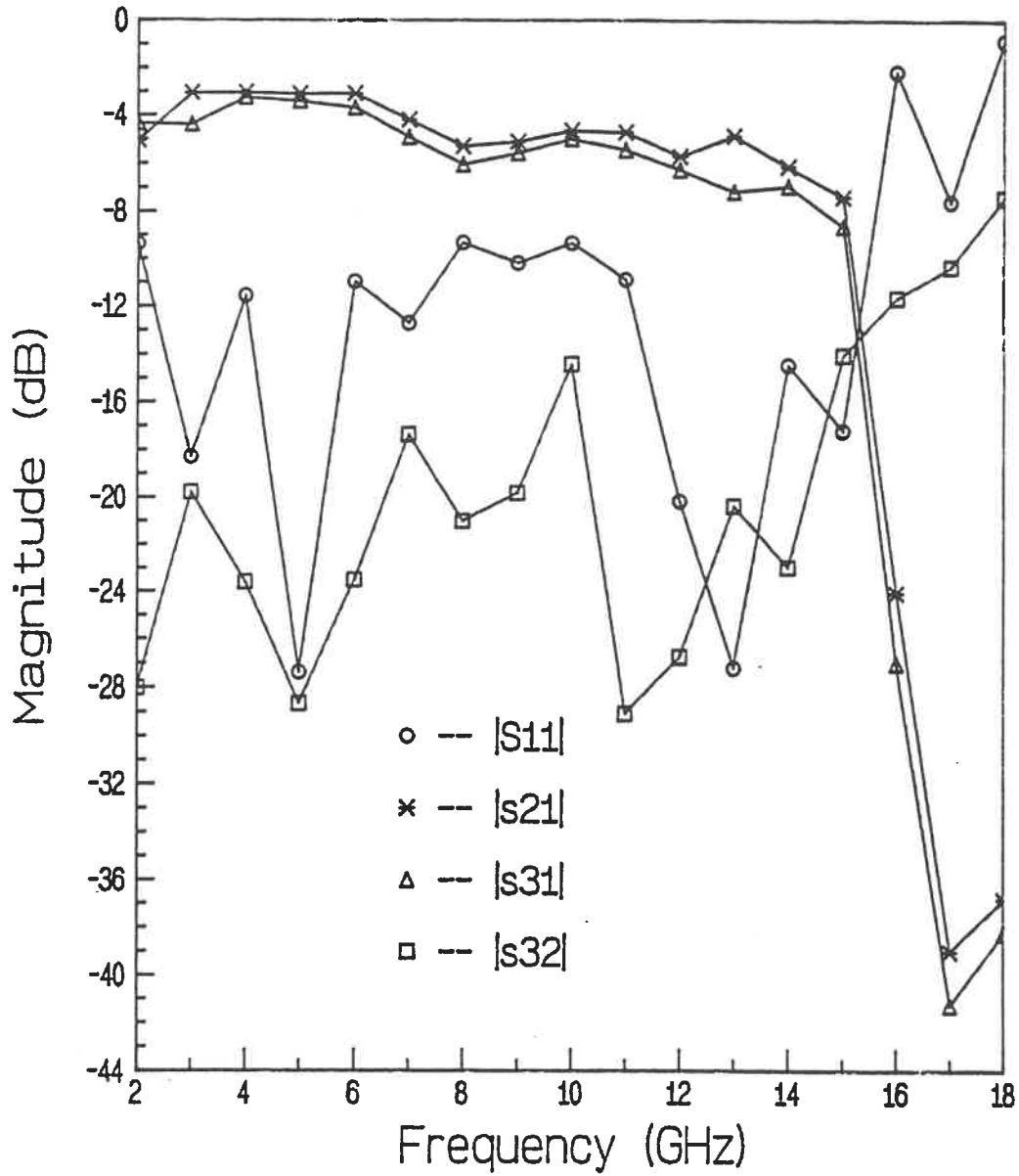


Figure 3.17: Measurement Results of the 30° Angle Splitting Power Divider

er - 2.2 B - 70

w1 - 18.8,	r1 - 189.4,	a1 - 155.1
w2 - 24.1,	r2 - 192.0,	a2 - 147.7
w3 - 29.1,	r3 - 194.5,	a3 - 147.7
w4 - 34.2,	r4 - 197.1,	a4 - 147.7
w5 - 38.1,	r5 - 199.0,	a5 - 147.7
w6 - 40.4,	r6 - 200.2,	a6 - 147.7
w7 - 43.2,	r7 - 201.6,	a7 - 147.7

(all of dimensions are in mil)

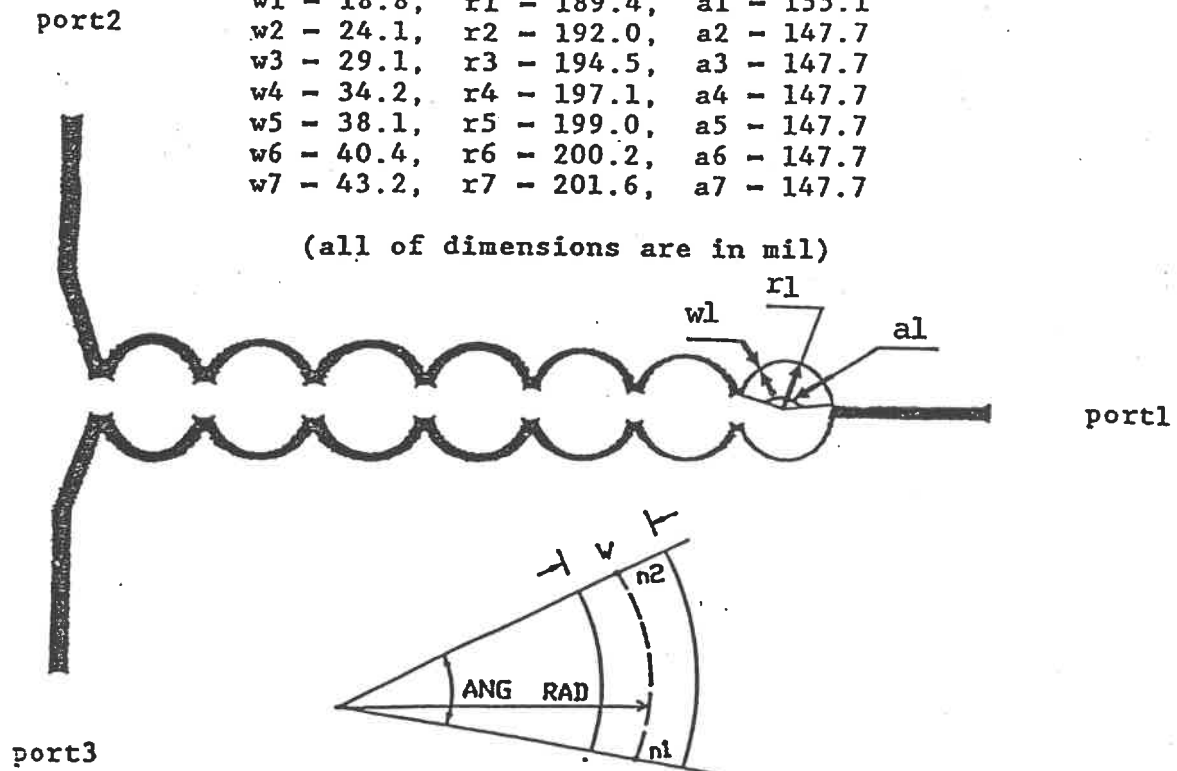


Figure 3.18: The Layout of the Curved Line Wilkinson Power Divider

The values of the impedances and resistors for each section of the curved line power divider are selected to be the same as the values of the straight line power dividers recommended in reference [43]. The physical length of a curved branch in the *CAD* model is taken to be equal to the median path of the half-circle as shown in figure (3.18). The electrical lengths of the curved line configuration remain initially the same as the straight line configuration because there is no special means to calculate the physical dimensions of the curved stripline by 'Linecalc'. First analysed results of this structure by 'Touchstone' shows that it is not as well as expected in broadband performances. Optimization techniques are applied again to obtain a good performance. The simulation of *S* parameter amplitudes after numerous optimizations and the corresponding measurement results are illustrated in figures (3.19) and (3.20) respectively.

Comparing the measured *S* parameter amplitudes of the straight line power divider with 30° angle splitting in figure (3.17) with that of the curved line one in figure (3.20), it is noted that the reflection coefficient of the curved line structure is not improved much more than the configuration of straight lines, but the isolation between the two output ports of the curved line power divider is much better than the straight line one, and it is even better than the *CAD* simulated results. This indicates that the simulation models are not effective enough. This result is reasonable since the short soldering lines are eliminated so that the terminating resistors can be connected to the branches directly.

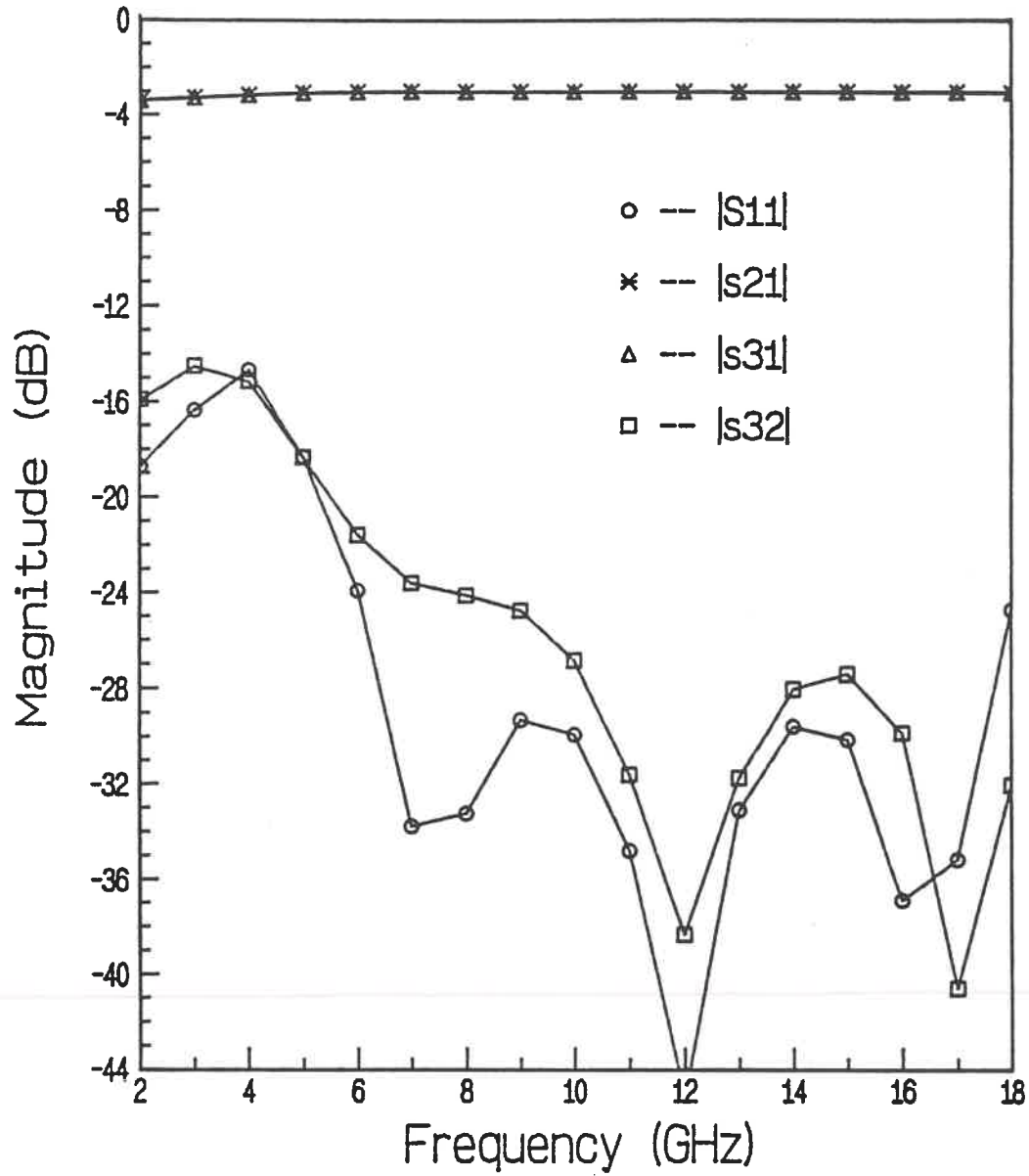


Figure 3.19: Simulation Results of the Curved Line Power Divider

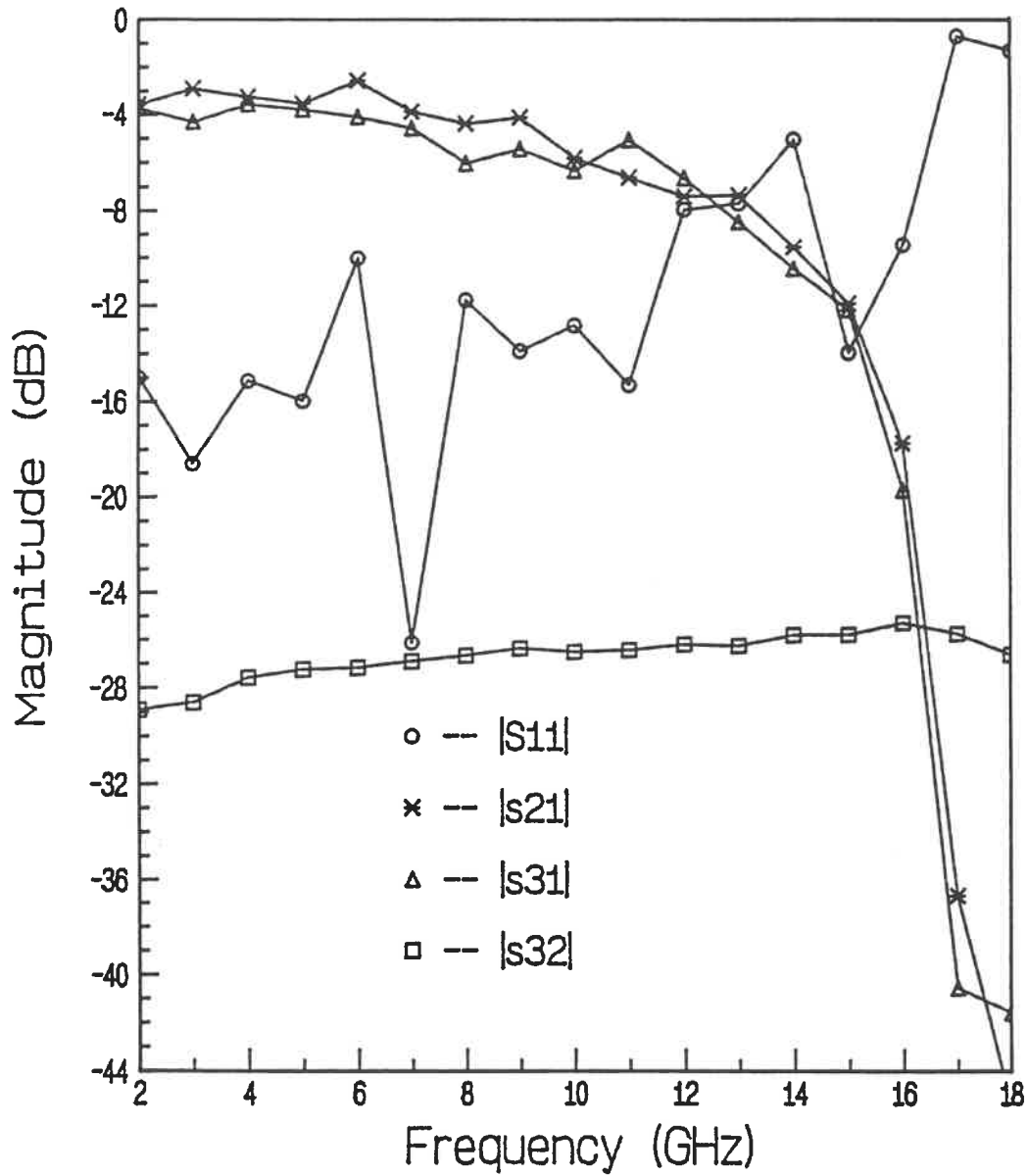


Figure 3.20: Measurement Results of the Curved Line Power Divider

The high reflection coefficients of Wilkinson power dividers with both straight branches and curved branches at high frequencies are caused by many factors. The dimensions of the resistors available are not small enough so that they no longer behave like lumped resistors (their physical lengths are comparable with the wave length of the signal at high frequencies above 15 GHz) [45].

3.5 The Complete Integrated Six-Port Junction

In the last two sections , three directional couplers and two power dividers required to build the optimal six-port junction are designed and tested. In this section, we will discuss the interconnection of these components according to the optimal topology shown in figure (3.1) by using $50\ \Omega$ transmission lines and bends.

To make the q_i points fixed with frequency variations and distributed symmetrically in the complex plane by 120° , two important conceptual equations which involve the lengths of several transmission lines must be satisfied in terms of electrical length requirements as illustrated in figure (3.1)

$$CNPF = HD + DHGOAE \quad (3.20)$$

$$A'B' = AEMB . \quad (3.21)$$

In addition to the above two equations, the following three equations must be taken into account to deal with the physical connections of the different components constituting the six-port junction shown in figure (3.1)

$$NCGO = PFEQ \quad (3.22)$$

$$EAA'R = MBB' \quad (3.23)$$

$$ME = B'R . \quad (3.24)$$

Since the coupled lines of the three couplers locate in two different layers, the positions of all components and transmission lines at each layer must be determined carefully to avoid the unexpected intercross between top and bottom layers. The layout of the six-port junction is illustrated in figure (3.21). The layouts of the top and bottom layers are shown in figures (3.22) and (3.23) respectively. The important dimensions of the six-port junction which determine the characteristics of the phase compensations are included in six equations as shown in figure (3.22). The meaning of the symbols used in these equations are explained in the following:

l_{abcd} : physical length in mil of the fraction line $abcd$

$$l_{3031} = 600$$

$$l_{1112} = 580$$

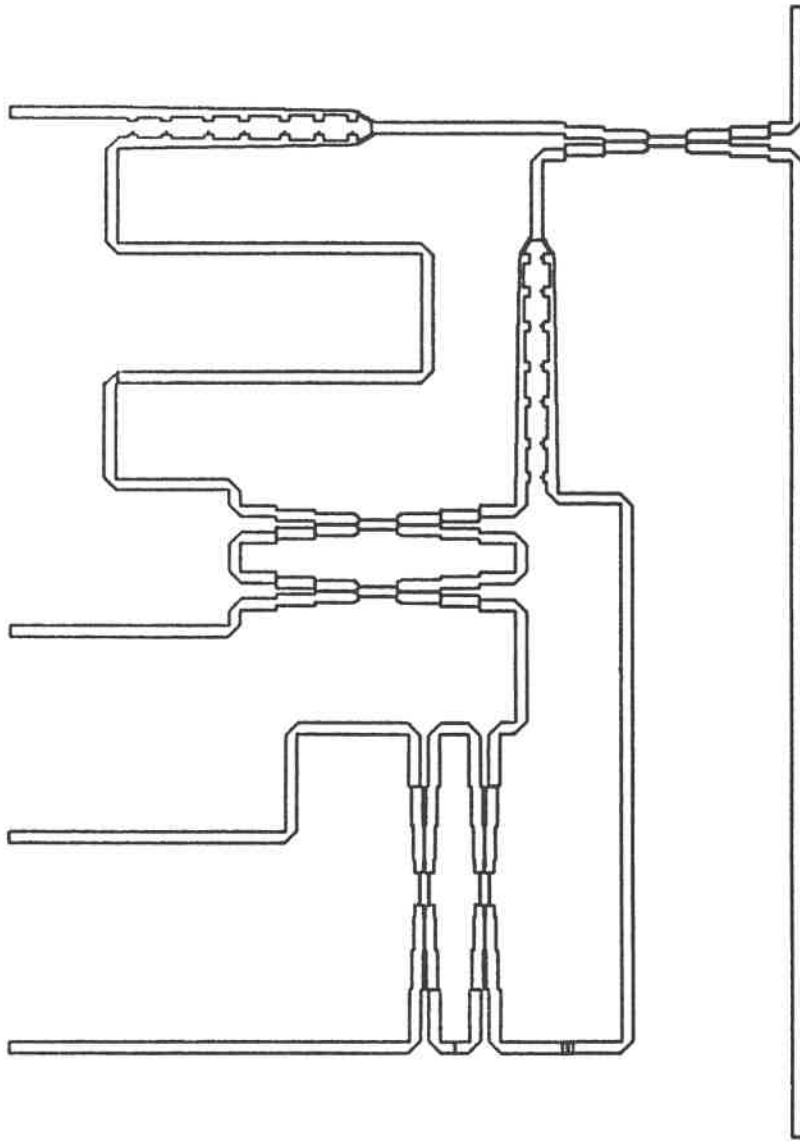


Figure 3.21: The Layout of the *CAD* Six-Port Junction

$$l_{3435} = 400$$

$$l_{0920} = 500$$

$$l_{3940} = 500$$

$l_{econ} = 1756$: effective electrical length of the connector at the port

DUT

$l_{eb} = 43.9$: effective electrical length of the stright angle bend

$l_{ecoui}, (i = 1, 2)$: effective electrical length of the i^{th} coupler

$$l_{ecou1} = 1278$$

$$l_{ecou2} = 3252$$

$w_{50} = 55.2$: width of the 50Ω transmission line

$w_{o5} = 140$: offset width of the 5^{th} section for the first coupler

$l_{couj}, (j = 2, 3)$: physical length of the j^{th} coupler

$$l_{cou2} = 1546$$

$$l_{cou3} = 1730$$

$l_{pdv} = 1363$: physical length of the power divider

$w_{pdv} = 98.6$: width of the inner outline of the power divider

$$\begin{aligned}
 12122 &= 13031 + lecon - 11112 - 2 * leb + (lecou1 + 3 * w50 - wo5 - lcou2) / 2 \\
 10405 &= 11112 + lcou2 - lpdv + (w50 + wpdv) / 2 \\
 12324 &= lpdv + 13435 + wo5 - 2 * 10920 - (7 * w50 + wpdv) / 2 \\
 14748 &= (lecou2 - 2 * leb - wcou2 - lcou3 - wpdv) / 2 \\
 14950 &= wcou2 + 13940 - 2 * w50 + lcou3 \\
 15152 &= (14748 + wpdv + 2 * w50) / 2
 \end{aligned}$$

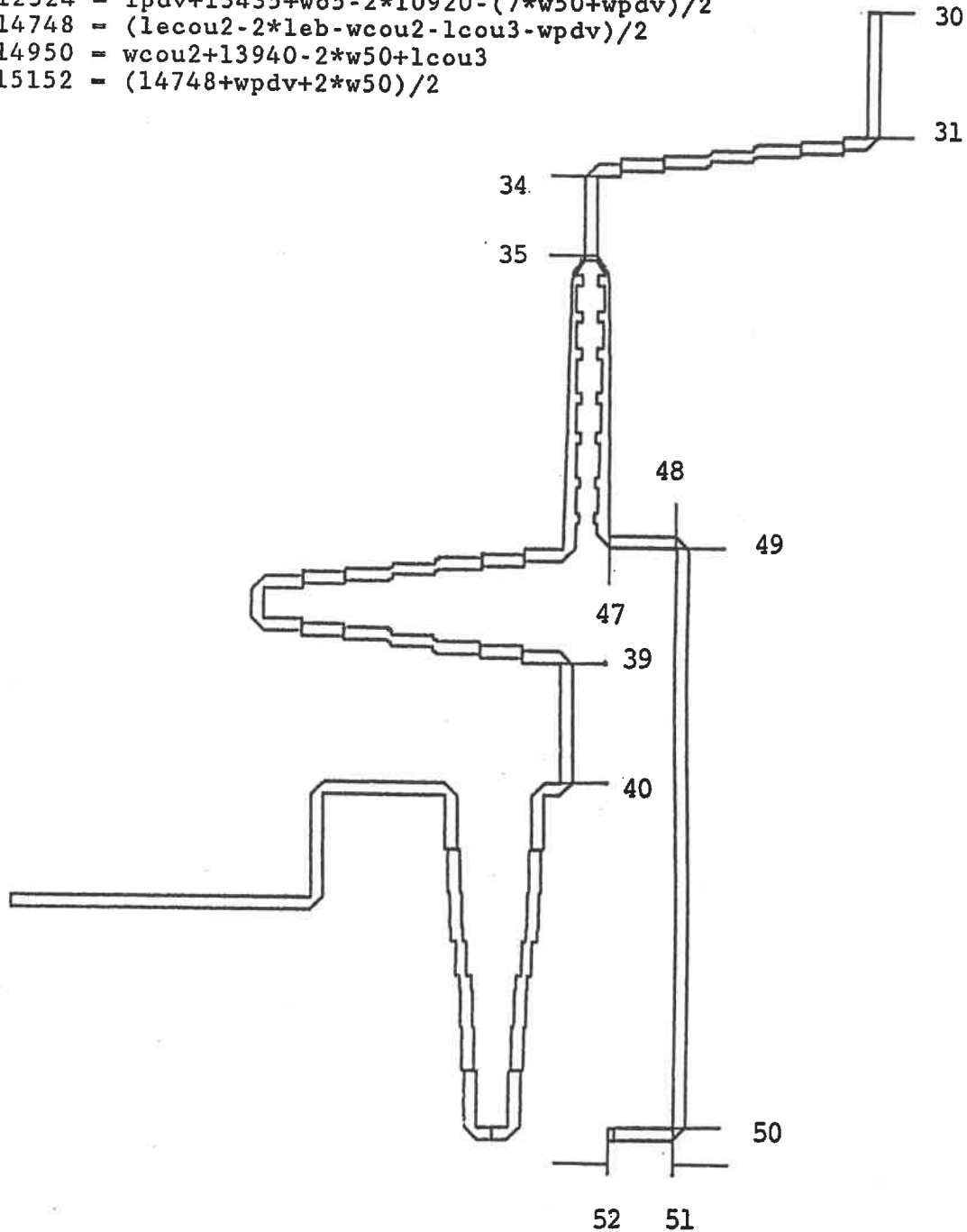


Figure 3.22: The Layout of the Top Layer of the Six-Port Junction

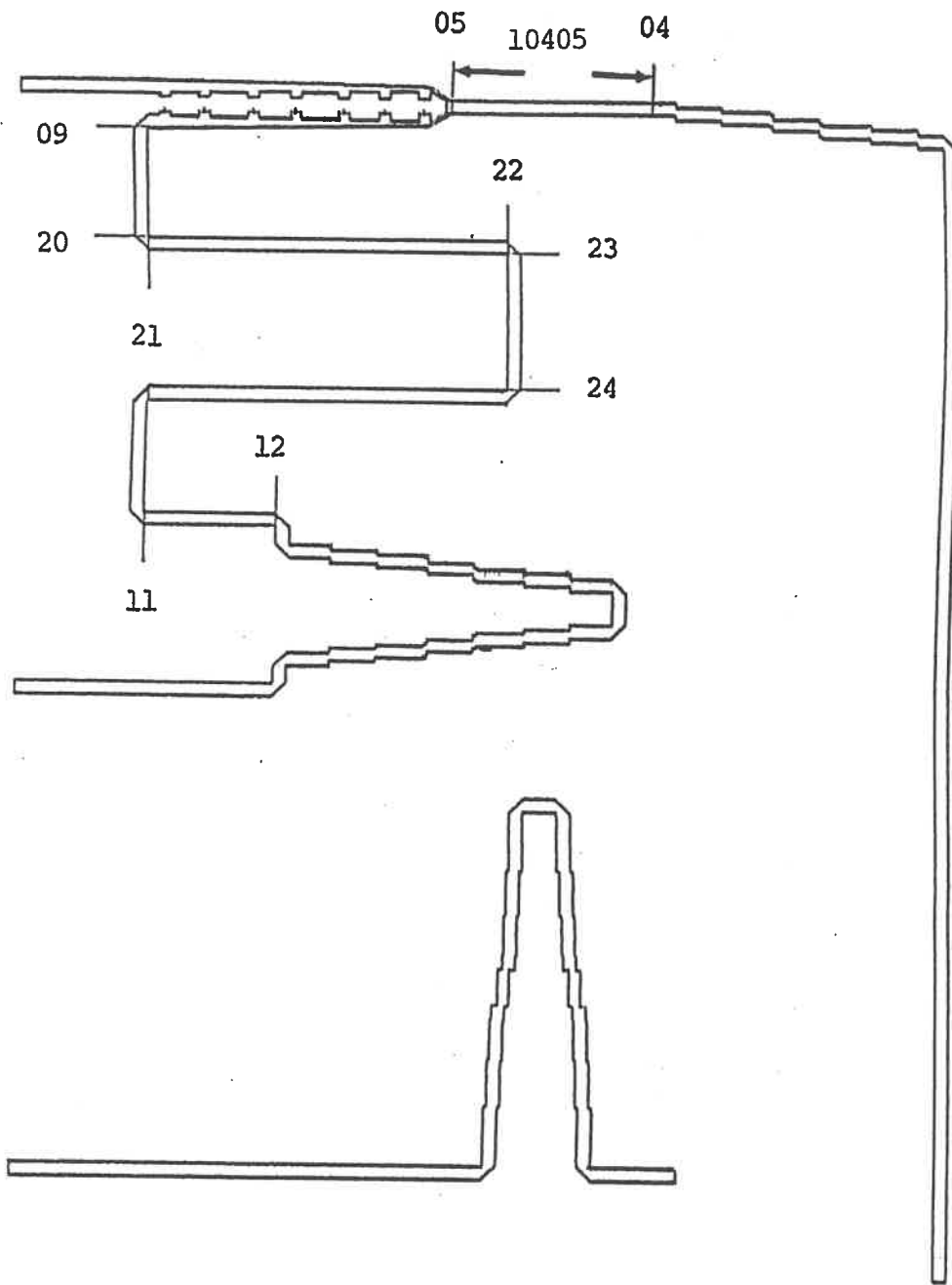


Figure 3.23: The Layout of the Bottom Layer of the Six-Port Junction

$w_{\text{cou}2} = 694.4$: width of the outer outline of the second coupler

A tapered via hole with finite metal thickness is unavoidable and must be used to transmit a RF signal from the bottom to the upper layers as shown in figure (3.21). The dimensions of the hole should be as small as possible in order to push its intrinsic resonance frequency higher than 18 GHz .

The complete junction can be simulated by ' Touchstone '. As it will be explained later that there is a disagreement between the theoretical analysis and practical measurement of the six-port above 12 GHz . For the convenience of comparing these two results, the frequency range of our six-port junction is cut down below 12 GHz . The final characteristics of the junction in terms of S parameters are obtained through optimizations. The variations of the q_i point positions with frequency are mostly concerned for our design objective. When output ports of the six-port junction are matched to each power detector, it is shown [47] that the q_i points can be expressed as a function of the six-port scattering parameters as follows:

$$q_i = \frac{s_{i1}}{s_{22}s_{i1} - s_{21}s_{i2}}, \text{ for } i = 3, 4, 5 \text{ and } 6 .$$

If the junction incorporates a reference port (in our case, it is port 3) to monitor the forward signal ($s_{32} \cong 0$), and the measuring port mismatch is not excessive ($s_{22} \cong 0$), then q_3 becomes infinite as discussed before.

The amplitudes and phases of three q_i points are calculated in terms of a $APC - 7$ to N type connector by using the above equations over frequency range $2 \sim 12 GHz$ and are illustrated in figures (3.24) and (3.25). It is clear that there are some small ripples of the three q_i point positions with frequency variations. This perturbation is caused by many reasons, such as

1. fluctuations of the coupling factors and power dividing levels with frequency;
2. the mismatch of different components at the input and the output ports;
3. the phase unbalance at the output of the couplers and power dividers;
4. the finite directivity of the couplers and the finite isolation between the two branches of the power dividers.

3.6 Conclusion

Three directional couplers ($1.76 dB$, $3 dB$ and $6.75 dB$) and two power dividers have been designed, built and tested. The optimal six-port junction is obtained by connecting the above components and using 50Ω transmission lines. Simulation results show that this six-port junction has the following important advantages: the three q_i points are distributed symmetrically in the complex plane and their positions change little with signal frequency variations

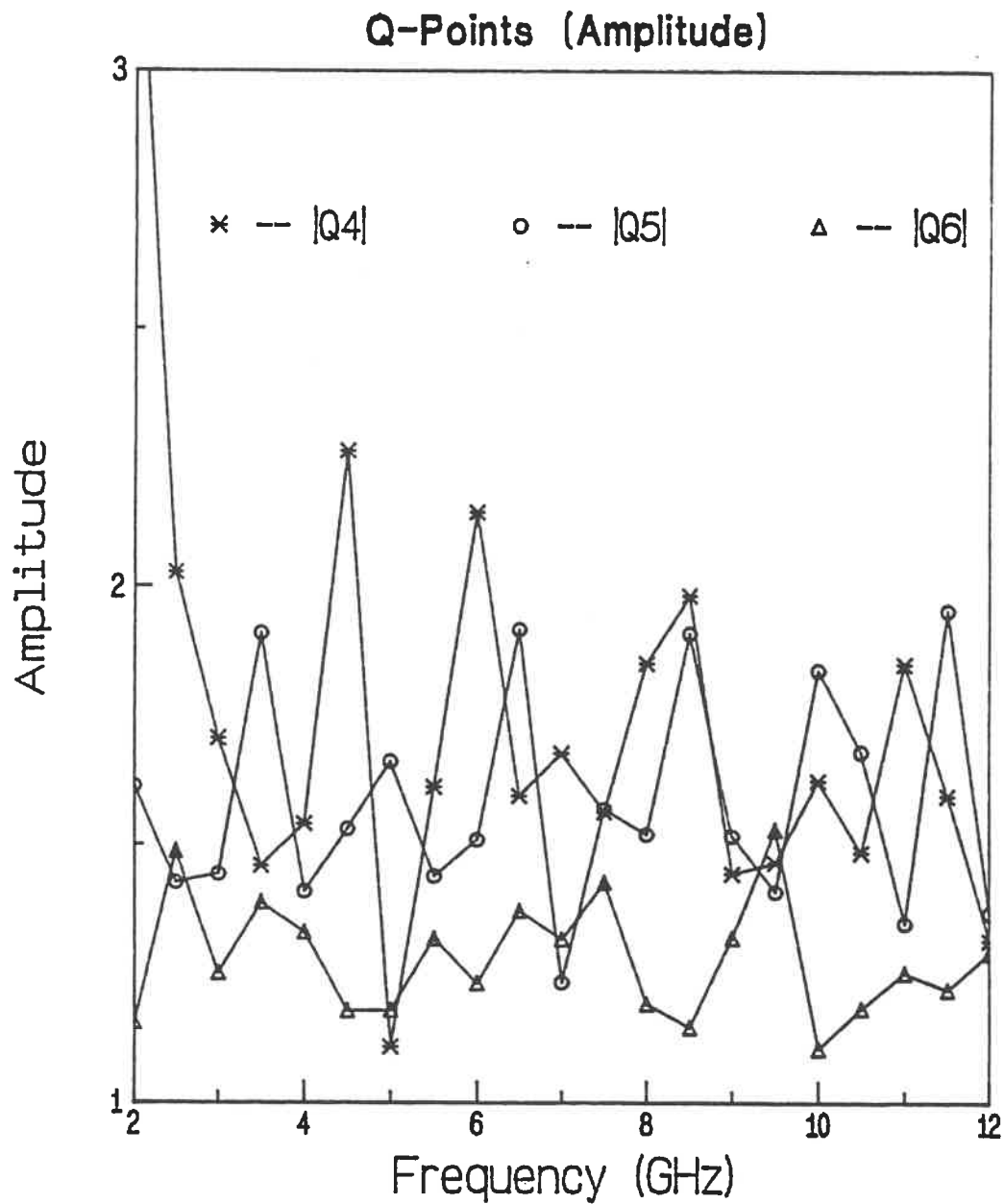


Figure 3.24: Simulation Amplitude Results of the Q_i Point Variations over

2 ~ 12GHz Frequency Band with a APC-7 to N Connector

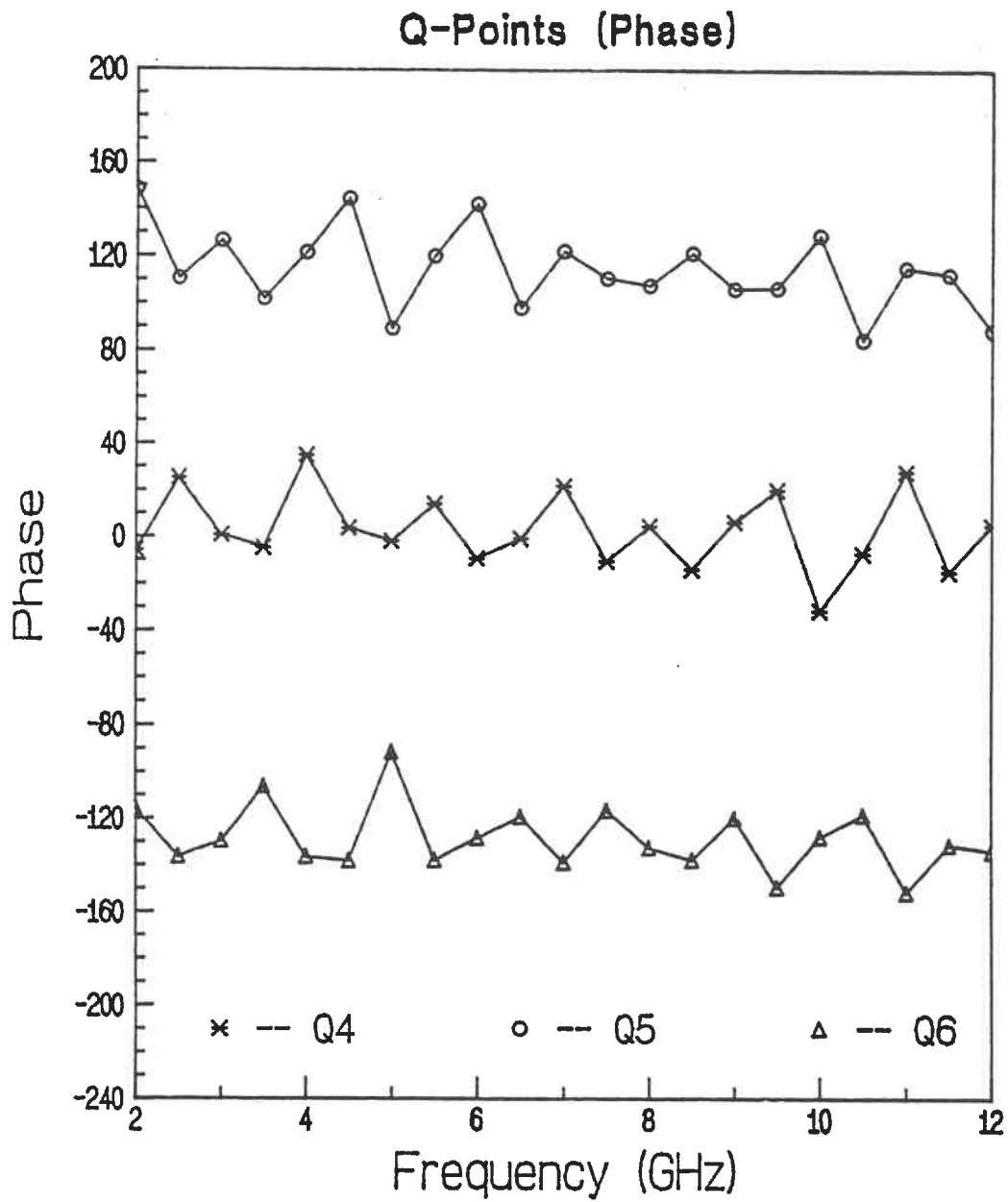


Figure 3.25: Simulated Results of the Phase of the Q_i Point Variations over
 2 ~ 12GHz Frequency Band with a APC-7 to N Connector

over very large bandwidth ($2 \sim 12\text{GHz}$). This feature minimizes the number of frequency points at which the reflectometer must be calibrated, it also reduces the effect of the frequency instability of the signal source on calibration and measurement results.

Chapter 4

Calibration of Six-Port Reflectometers

4.1 Introduction

Various methods for calibrating a six-port reflectometer have been presented in the past [10,48,49,50,51,52]. The most important differences between these methods are the number of calibrating standards required, the restrictions on the type of standards and the amount of computational effort needed to find the calibrating parameters.

Each method has its own advantages and drawbacks. For example, the calibration using four offset short circuits [10] assumes that in each case $|\Gamma| = 1$. In practice there is loss associated with the short-circuit element (with its offsetting line), but the calibration procedure does not include this information.

Moreover, the use of only reactive calibrating standards leads to reduced confidence in measurements of Γ near the center of the Smith Chart.

4.2 Calibration of the Wide-band Six-Port Reflectometer

To calibrate the designed six-port junction, the method first proposed by Engen [53] and later developed in details by Hodgetts and Griffin [21] is chosen. This method is based on the use of sliding terminations [22] and permits the calibration problem to be separated into two distinct steps. In the first, the six-port is reduced to an equivalent nominal four port reflectometer. This requires the determination of five of the eleven constants which describe the nominal four-port reflectometer. The second part of the problem is to determine the six real (or three complex) parameters, which define the reference plane (error box). This approach has several advantages, i.e.

1. it is not necessary to determine all eleven constants simultaneously;
2. only $3\frac{1}{2}$ known standard impedances are required. In addition, a number of different unknown impedances (at least 10) are needed;
3. it provides a convenient method of exploiting the redundancy which is inherent in this method.

Details about the algorithm can be found in reference [21]. For the convenience of discussion about the calculations of q_i point positions in the next section, some equations are repeated in the following. The relation between power detector readings and the reflection coefficient of the DUT has been deduced in section (2.1). After the normalization of equation (2.10) by P_3 , it gives

$$w_i^2 = \frac{P_i}{P_3} = \frac{|d_i \Gamma + e_i|^2}{|c \Gamma + 1|^2}, \quad i = 4, 5 \text{ and } 6 \quad (4.1)$$

where

$$c = -\frac{1}{q_3}, \quad d_i = -\frac{K_i}{K_3 q_3}, \quad e_i = \frac{K_i q_i}{K_3 q_3}.$$

Equation (4.1) can be rewritten as follows:

$$w_K = \frac{d_K \Gamma + e_K}{c \Gamma + 1}, \quad K = i - 3 \quad (4.2)$$

Solving Γ from these equations, we have

$$\Gamma = \frac{e_1 - w_1}{c w_1 - d_1} = \frac{e_2 - w_2}{c w_2 - d_2} = \frac{e_3 - w_3}{c w_3 - d_3}. \quad (4.3)$$

Writing $Q_K = |w_K|^2$ and eliminating Γ from equation (4.3), the following three equations are obtained:

$$Q_1 = |w_1|^2, \quad A^2 Q_2 = |w_1 - m|^2, \quad B^2 Q_3 = |w_1 - n|^2 \quad (4.4)$$

with

$$A = \left| \frac{c e_1 - d_1}{c e_2 - d_2} \right|, \quad B = \left| \frac{c e_1 - d_1}{c e_3 - d_3} \right|$$

$$m = \frac{d_1 e_2 - d_2 e_1}{c e_2 - d_2}, \quad n = \frac{d_1 e_3 - d_3 e_1}{c e_3 - d_3}$$

where complex numbers m and n can be written as follows:

$$m = M \cos \mu + j M \sin \mu, \quad n = N \cos \nu + j N \sin \nu, \quad M, N > 0. \quad (4.5)$$

Using equation (4.5), one can define

$$p \equiv |m - n|^2, \quad q \equiv |n|^2 = N^2, \quad r \equiv |m|^2 = M^2. \quad (4.6)$$

The embedded reflection coefficient w is related to the reflection coefficient Γ as follows:

$$w = \frac{d \Gamma + e}{c \Gamma + 1} \quad (4.7)$$

where c , d and e are the error box parameters. These parameters are functions of Q_K^S and Γ_K^S . Q_K^S are ratios of the power readings P_K/P_3 corresponding to the reflection coefficients of standard impedances Γ_K^S used in error box calibration procedures. The vector w can be calculated from the five real parameters A^2 , B^2 , p , q , r and three power ratios Q_K observed for any subsequently connected load. The relation between w and w_1 can be expressed as follows [21],

$$w = w_1(\cos \mu - j \sin \mu). \quad (4.8)$$

Substituting equation (4.8) into equation (4.2), one can obtain that $d = d_1(\cos \mu - j \sin \mu)$ and $e = e_1(\cos \mu - j \sin \mu)$.

However, the five real parameters A^2 , B^2 , p , q and r which characterize a nominal four port reflectometer can be found by observing the power ratios corresponding to ten (or more) impedances. The VRC of such impedance must be different and not need to be explicitly known [21]. The procedure to obtain the five real parameters is to solve a set of equations by the standard least square method. It is not necessary to display every details of this procedure, since it has been explained very clearly in reference [21].

At low frequency measurements, the ten different impedance loads can be easily provided by a sliding short circuit and some known standards, i.e. a match load, a short circuit and an open circuit [53]. However, for high frequency applications, there is no sliding short circuit available above 10 GHz. In order to obtain the required number of load terminations at high frequency range, the long line theory [54] is applied. The idea of the theory is that various different impedances along a circle in the Γ plane with its radius equal to or less than unity over the operating frequency range can be obtained by means of a section of delay transmission line, an attenuator and an open / a short circuit termination. A key problem of this theory is to avoid each impedance value from coinciding with another over the whole operating frequency range. The theory originally presented by Hoer [54] serves for ' Thru-Reflect-Line ' (TRL) or ' Thru-Short-Delay ' (TSD) calibration methods. The phase shift caused by

a transmission line (through) is $e^{-j\beta l}$, where l is the physical length of the line. The length of the transmission line should be chosen so that the value of its electrical length must not be or not near multiples of 180° , otherwise the system used to solve the parameters characterizing the six-port reflectometer becomes ill-conditioned. In our case, we expect that the section of delay transmission line plays a role as a phase shifter to replace a sliding short circuit over frequency range $2 \sim 18 \text{ GHz}$. The phase shift caused by the line is $e^{-j2\beta l}$ instead of $e^{-j\beta l}$ in the ' through ' situation. Therefore, some equations proved by Hoer in [54] to calculate the length of the transmission line and the phase shift resulted from this line must be modified correspondingly.

Let the calibration frequency step be Δf , the phase shift over each Δf through the transmission line is,

$$\Delta\phi = 2\beta l = 24l \Delta f \sqrt{\epsilon_r} \quad (4.9)$$

where l represents the length of the line in centimeter, Δf is the calibration frequency step in gigahertz, $\Delta\phi$ expresses the phase shift in degree caused by the delay line at each frequency step, ϵ_r stands for the dielectrical constant of the medium in the transmission line.

If the line length is chosen so that the phase shifts nearest to 180° (denoted by ϕ_{min}) satisfy the following relation,

$$\Delta\phi = 2\phi_{min} \quad (4.10)$$

where

$$\phi_{min} = 90^\circ / (1 + n) , \quad n = 0, 1, 2 \dots \quad (4.11)$$

and selecting the starting frequency f_1 for the calibration to be one of the following points

$$f_1 = \frac{\Delta f}{2} + n_1 \Delta f , \quad n_1 = 0, 1, \dots \quad (4.12)$$

It can be proved that the effective phase shifts nearest to 180° at all frequencies of measurement will be equal to or greater than ϕ_{min} [54]. From equations (4.9) and (4.10) we can obtain:

$$\Delta f = \frac{\phi_{min}}{12 l \sqrt{\epsilon_r}} \quad (4.13)$$

Hence, the length of the transmission line can be determined by

$$l = \frac{\phi_{min}}{12 \Delta f \sqrt{\epsilon_r}} . \quad (4.14)$$

There are several available values of ϕ_{min} and their relevant lengths of the transmission line from equations (4.11) and (4.14), when n is an integer ($n = 0, 1, 2 \dots$). In our calibration procedure, $\phi_{min} = 90^\circ$ and the corresponding length of the transmission line $l \cong 6.6$ cm have been chosen.

By adopting this technique, thirteen standards have been obtained and are grouped as following:

1. A match load, an open circuit and a short circuit.
2. An open circuit and a short circuit plus this delay line, which produces two values along the unit circle in the Γ plane with 90° phase different from open circuit and the short circuit as shown in figure (4.1).
3. An open circuit and a short circuit with a 3 dB attenuator, which provides two points on the circle $|\Gamma| = 0.707$.
4. An open circuit and a short circuit with a 3 dB attenuator plus the delay line, the situation is the same as case 2 except that the two points are located on the circle $|\Gamma| = 0.707$.
5. An open circuit and a short circuit with a 6 dB attenuator.
6. An open circuit and a short circuit with a 6 dB attenuator plus the delay line.

The choice of the standards according to the above method ensures that the calibration system to be solved is well-conditioned. Consequently no singularity over the whole operating frequency band is expected. The distribution of the impedances on the complex plane obtained from the thirteen standards is shown in figure (4.1).

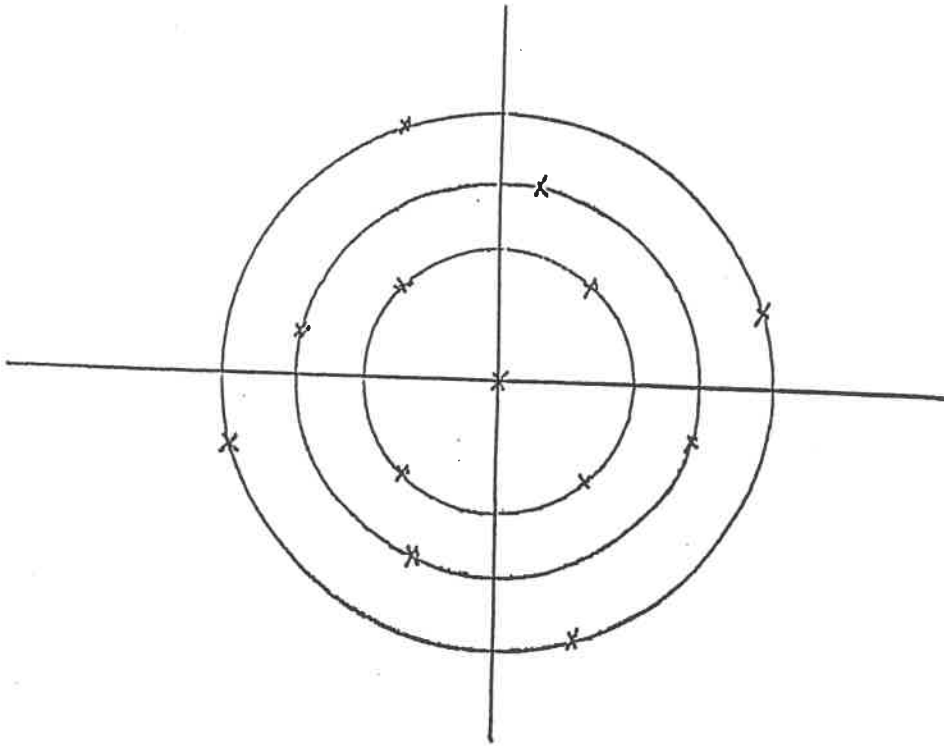


Figure 4.1: Impedance Distribution of Thirteen Calibration Standards on the
Complex Plane

The six-port reflectometer discussed before is calibrated by means of this method over frequency range of $2 \sim 12 \text{ GHz}$. After the calibration, the designed six-port junction is used to measure an open/short circuit (Wiltron Co. model 22A50). The measurement results of this open/short circuit by using the six-port junction are compared with the calculation result as shown in figure (4.2) and (4.3). The measurement result of the six-port circuit displays a very good agreement with the numerical calculation.

4.3 Calculation of q_i Points

The variations of the q_i point positions with frequency are most concerned in this design. An interesting result from a computer simulation has been discussed in section (3.4). After the calibration of a six-port junction, its q_i point positions over the operating frequency range can be calculated from the calibration parameters.

It is noticed that equations (4.4) express three circles in w_1 plane, their centers are 0, m and n respectively. The solution for these equations of w_1 is given geometrically by the intersection of the three circles. That means, in fact, it is w_1 not Γ that will be determined by the intersection of three circles. However, w is related to Γ via a bilinear transformation. Solving Γ from equation

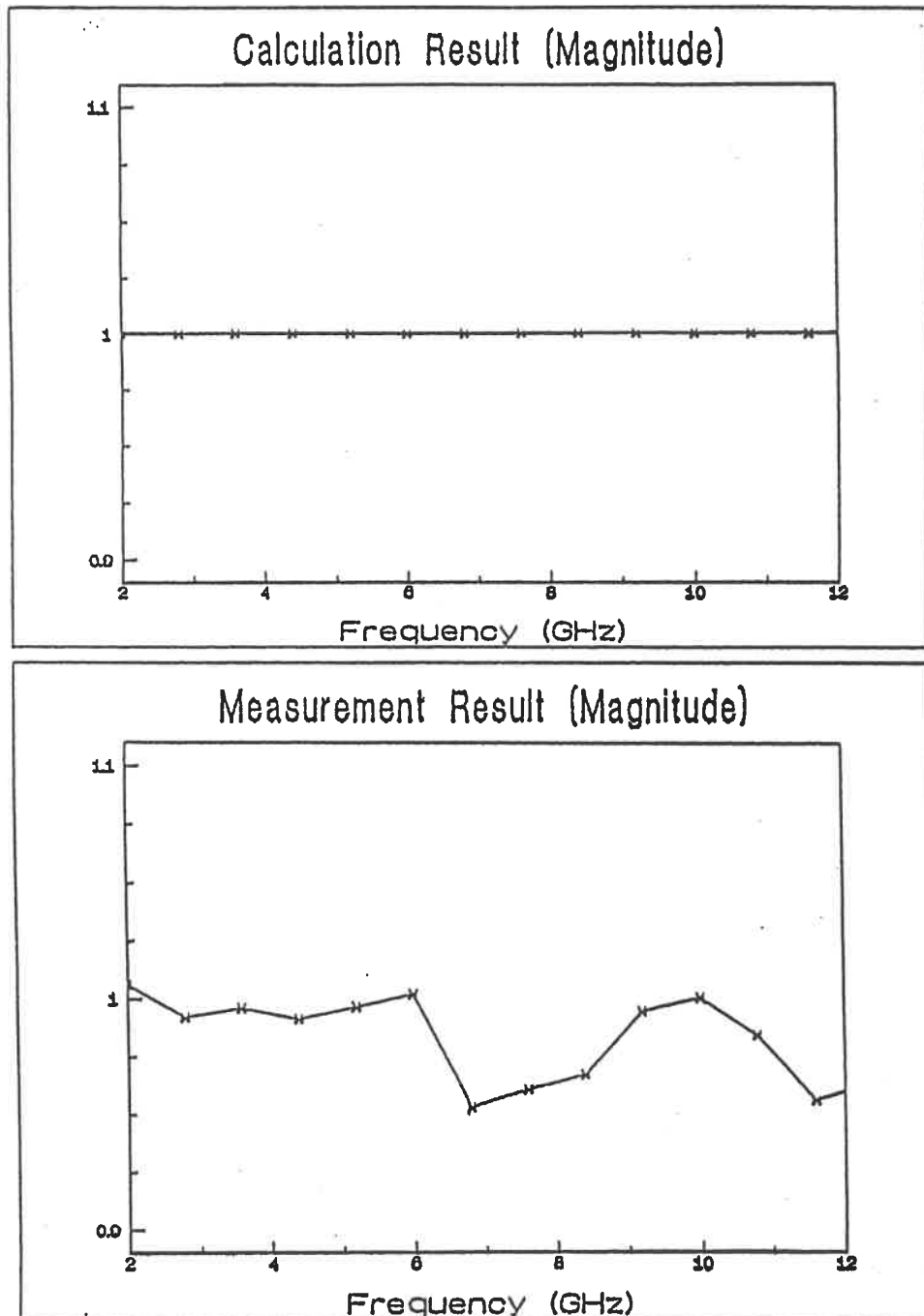


Figure 4.2: Measurement and Calculation Results of an Offset Short Circuit

(Wiltron Co. Model: 22A50) over 2 ~ 12GHz (Amplitude)

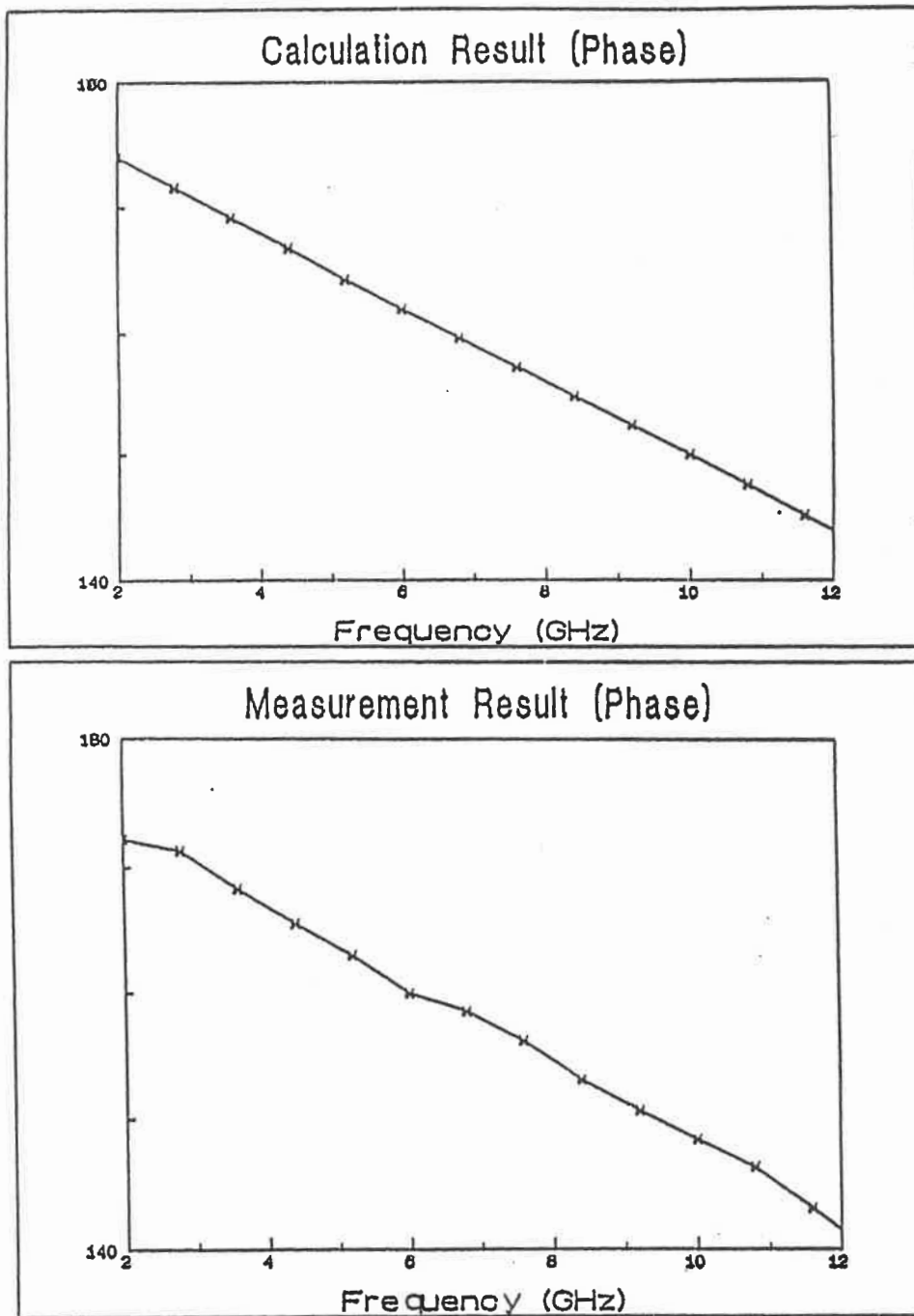


Figure 4.3: Measurement and Calculation Results of an Offset Short Circuit

(Wiltron Co. Model: 22A50) over 2 ~ 12GHz (Phase)

(4.8), we can get

$$\Gamma = \frac{e - w}{cw - d} \quad (4.15)$$

A well known property of any bilinear transformation is that circles are mapped into circles, which indicates that any point on w plane can be mapped into an unique position on Γ plane by the equation (4.14). It gives an hint that the three q_i points on Γ plane can be obtained from the centers of the three circles on w plane by means of the bilinear transformation.

The w plane is achieved by rotating the w_1 plane with an angle μ degree along the counterclockwise direction as shown in equation (4.7). So the centers of the three circles denoted by cc_1 , cc_2 and cc_3 respectively on w plane will be obtained easily by multiplying 0, m , n to the rotating factor $(\cos\mu - j\sin\mu)$, therefore

$$cc_1 = 0 \quad (4.16)$$

$$cc_2 = m(\cos\mu - j\sin\mu) = M \quad (4.17)$$

$$cc_3 = n(\cos\mu - j\sin\mu) = N\cos(\mu - \nu) + jN\sin(\mu - \nu) \quad (4.18)$$

$$\cos(\mu - \nu) = -\frac{(p - q - r)}{2\sqrt{qr}}$$

$$\sin(\mu - \nu) = \pm\sqrt{1 - \cos^2(\mu - \nu)}$$

The sign in the last equation can be determined according to reference [21] by using a $\frac{1}{2}$ standard load. It should be noted that cc_1 , cc_2 and cc_3 represent the q_i points in w plane. By mapping the w plane to Γ plane using equation (4.14), three q_i points in Γ plane can be calculated from the measured values

$$q_4 = -\frac{e}{d} \quad (4.19)$$

$$q_5 = \frac{e - M}{cM - d} \quad (4.20)$$

$$q_6 = \frac{e - N [\cos(\mu - \nu) + j \sin(\mu - \nu)]}{cN [\cos(\mu - \nu) + j \sin(\mu - \nu)] - d} \quad (4.21)$$

The variations of q_i points of the designed six-port junction over frequency range $2 \sim 12 \text{ GHz}$ calculated by equations (4.18) \sim (4.20) are given in figures (4.5) and (4.6) respectively. It is noticed that the phase of the measured q_i points of the six-port junction shown in figure (4.6) is not compensated so well as the result from the computer analysis in figure (3.25). This deviation is caused by the different types of connectors used in measurements and in analysis. A connector from *APC - 7* to *N* type is taken into account in computer analysis. However, connector from *APC - 7* to *SMA* type is utilized in the manufacture and in measurements. The two types of connectors have different electrical lengths, therefore, they will produce different phase shifts

in the circuit. A section of lossless transmission line with the same length as the difference between the two connectors can be added in measurements so that the same compensated condition as in the computer analysis can be achieved. To avoid this accurate manufacture, the equivalent electrical length of the connector (*APC – 7* to *SMA*) used in measurements is exchanged with that (*APC – 7* to *N*) used in computer analyses to verify the identity between measurements and computer analyses. New simulation results using *APC – 7* to *SMA* connector are illustrated in figure (4.4). Comparing figure (4.4) and (4.6), similar responses are obtained. This confirms the success in designing the six-port junction according to the objective goals.

The magnitudes of the q_i points of the designed six-port junction shown in figure (4.5) mainly concentrate between 1 and 2. At a few exceptional frequencies, the measured magnitudes of q_i exceed 2 and this might result from the via hole in the circuit. However, these points of large magnitudes will not influence the measurement properties of the six-port because they can be corrected by the calibration.

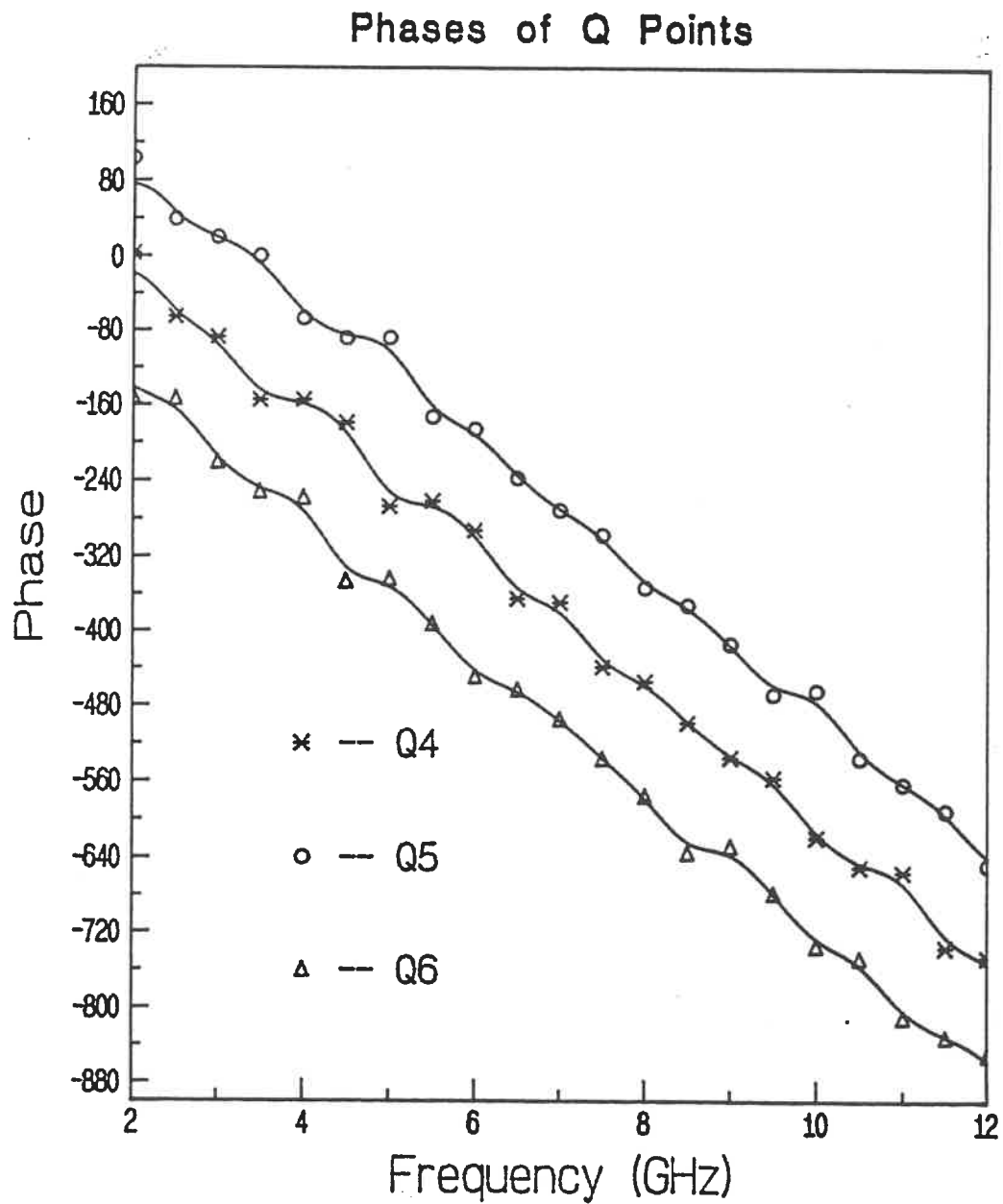


Figure 4.4: Simulated Results of the Phase of the Q_i Point Variations over

2 ~ 12GHz Frequency Range with a APC-7 to SMA Connector

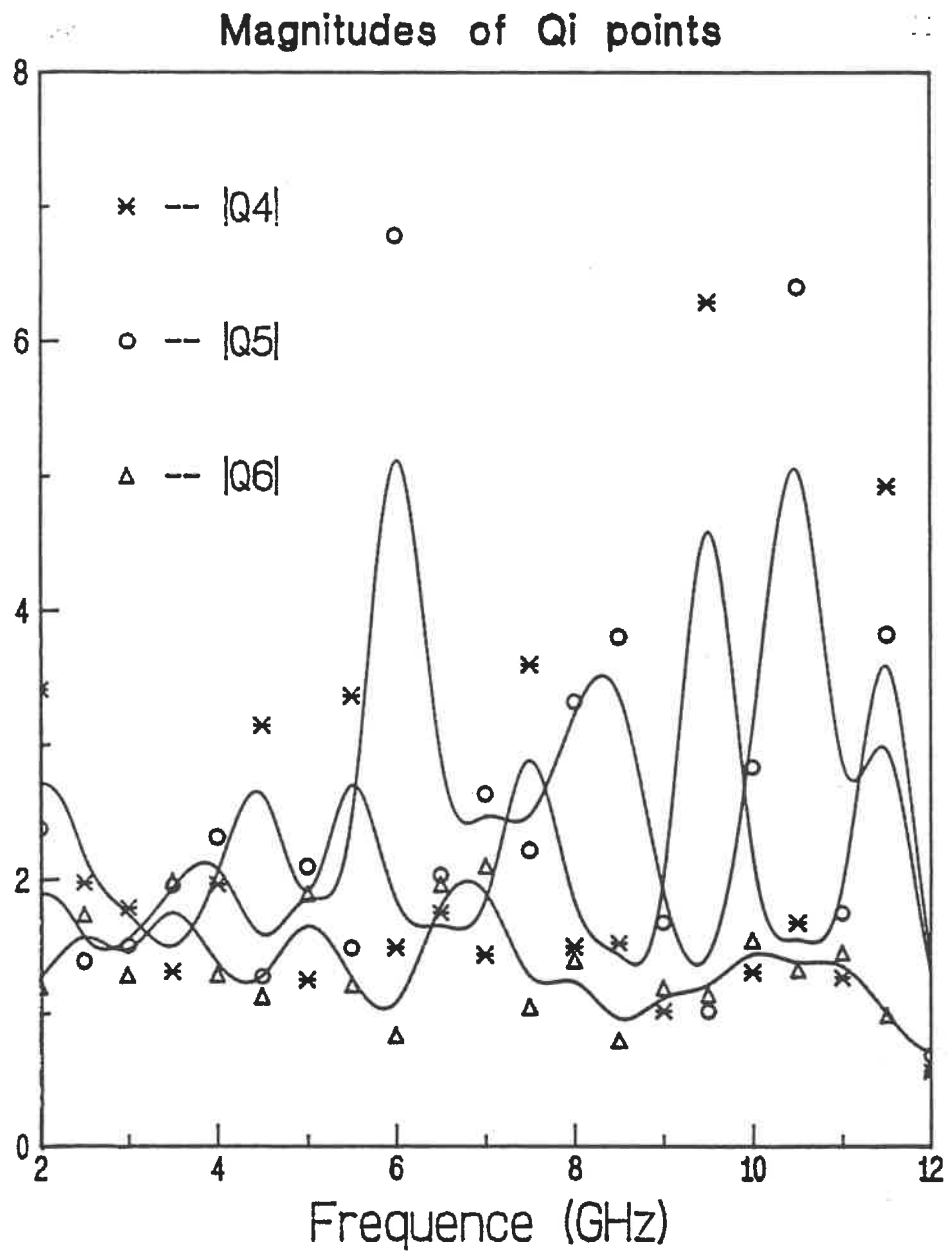


Figure 4.5: Measured Results of the Amplitude of the Q_i Point Variations over
 2 ~ 12GHz Frequency Range with a APC-7 to SMA Connector

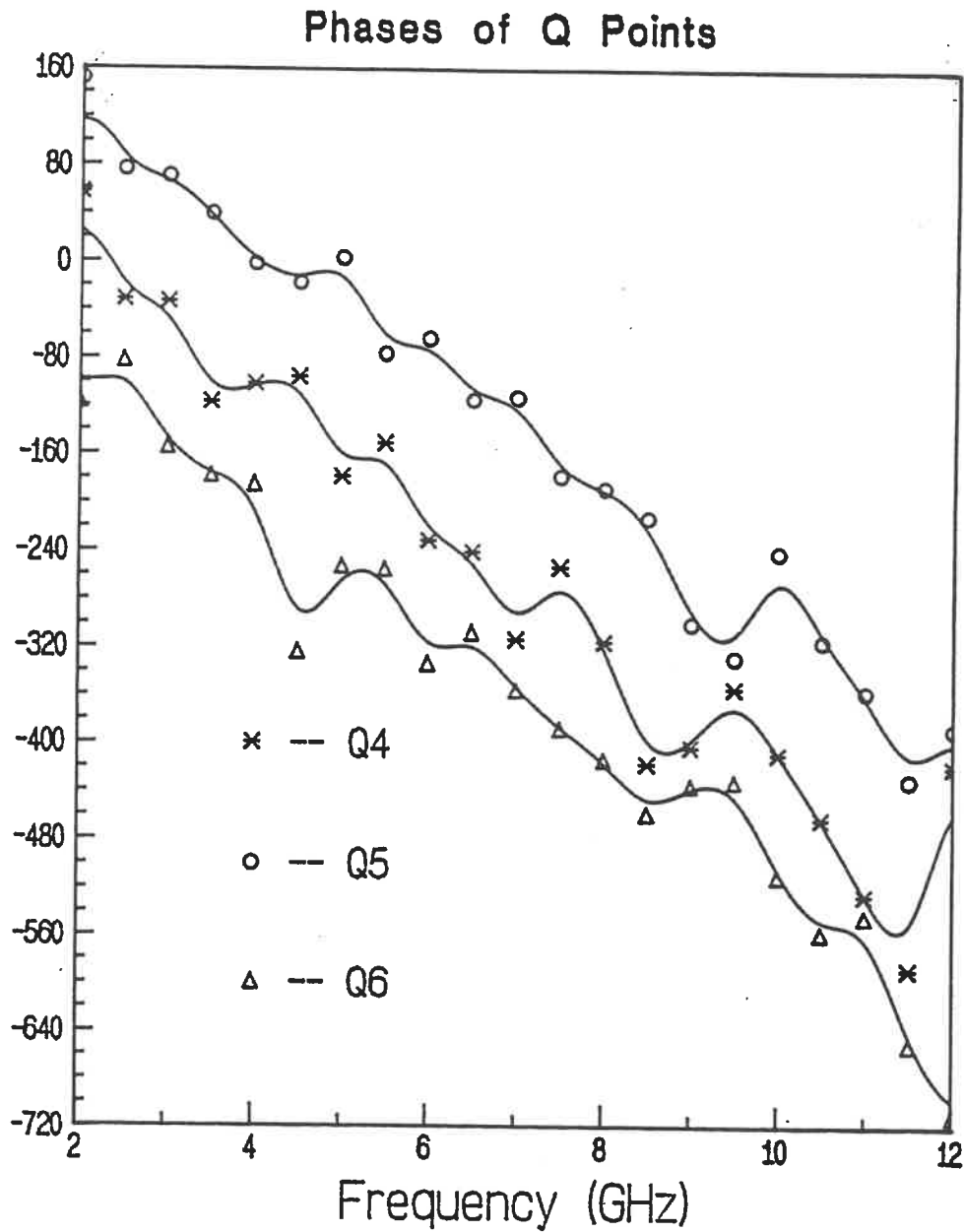


Figure 4.6: Measured Results of the Phase of the Q_i Point Variations over

2 ~ 12GHz Frequency Range with a APC-7 to SMA Connector

4.4 Conclusion

It is concluded that a compensated six-port junction has been designed, fabricated and tested. By applying the long line theory and mapping principles, the agreement between computer analysis results and measurement results has been verified. In order to reduce the deviations between the analysis and measurement, a better manufacture technology is required.

Chapter 5

Conclusion

This thesis describes the procedures for the design, the manufacture, the measurement and the calibration of a wideband six-port junction over a wide frequency band. Solutions to the problems encountered in the designing procedure are discussed in detail. The main contributions of this thesis can be summarized as follows:

1. Wideband couplers covering a frequency range of $2 \sim 18 \text{ GHz}$ with very tight coupling levels (1.76 dB and 3 dB respectively) have been designed, built and measured successfully. The small deviations between *CAD* results and measurement data are explained.
2. Three different Wilkinson power dividers, i.e. a right angle splitting power divider, a 30° angle splitting power divider and a curved line power divider, operating in a frequency range of $2 \sim 15 \text{ GHz}$ have been designed,

built and measured with satisfactory results. It has been found out that the 30° angle splitting power divider presents a better input match than the right angle one. In addition, the curved line power divider gives a very good isolation between its two output ports (better than -25 dB over a frequency range of $2 \sim 15\text{ GHz}$). Due to this property, the curved line power divider could be very useful for certain special applications, such as balanced amplifier designs.

3. Since there is no available effective sliding short circuit above 10 GHz to provide the required number of impedance loads for the calibration over the frequency range of $2 \sim 18\text{ GHz}$, the long line theory [54] has been modified to solve this problem. The designed six-port junction operating over the frequency range of $2 \sim 12\text{ GHz}$ was calibrated by using this improved theory. The final calibration results have confirmed the improvements.
4. Mathematical expressions to calculate q_i points of a six-port junction based on Hodgetts and Griffin's calibration method has been found. These formulas (obtained by the bilinear transformation concept) derive the q_i point calculation procedure from calibration parameters. The q_i point positions of the designed six-port junction have been calculated by using the above expressions. The results are comparable to those obtained by

computer simulations.

Finally, it was found that the designed six-port junction presents very little phase sensitivity to the frequency variations over $2 \sim 12GHz$. Computer simulation results and experimental measurement analysis display a very good agreement over the complete frequency band. This kind of six-port junction is suitable for swept frequency measurements and microwave pulse measurements.

Recommendations

We have already discussed different configurations of Wilkinson power dividers in section 3.4. The measurement results for three kinds of Wilkinson power dividers have shown large reflections above 15 GHz. This phenomenon is caused by many factors. Two of them are very important and further work might worth to be done in these respects.

Firstly, the resistors with smaller dimensions or integrated stripline resistors should be used. If the dimensions of resistors are not small enough in comparison to the wave length, the resistors will no longer behave like lumped components. Their resonance frequencies may be comparable to the signal frequency, therefore, give rise to some problems at high frequencies.

Secondly, an input signal is transmitted to the two branches of a Wilkinson power divider by a $50\ \Omega$ transmission line via a symmetrical T junction. Both the discontinuity of the T junction and mismatching between the transmission line ($50\ \Omega$) and the first branch ($95\ \Omega$) contribute the negative responses to such power dividers at the high frequency range. The following efforts could provide improvements to the problems. 1) Design a special matching network which will compensate the reflections at high frequency range and remain the good performances of the power divider under 12 GHz. 2) Develop a better model

of T junction at high frequency by advanced methods, i.e. various numerical methods, in stead of the available model in ' Touchstone '.

In addition, the connection between two layers of the six-port junction should be payed much attention to obtain good behaviour. The diameter of the hole for the connection should be as small as possible. If both problems of the discontinuity of power dividers and the connection between the two layers of the junction can be solved well, the designed six-port reflectometer can be expected to operate over the frequency range of $2 \sim 18 \text{ GHz}$.

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Appendix A

There are many programs have been made by the author in different softwares in order to simulate, optimize, calibrate and calculate required parameters of components of the six-port junction. All programs used in the above research work are enclosed and explained in this appendix.

The programs listed in this appendix will organize the same order as they appeared in the previous chapters. The files of these programs will be displayed after their names and short explanations about their locations, their functions and their utilizations in the following pages.

Touchstone File No. 1 — scou69.ckt (page A 5)

The purpose of this file is to simulate a 6.75 dB stripline hybrid coupler by using broadside and cascaded offside structures over $2 \sim 18$ GHz. The substrate is made by teflon. The definition of all dimensions and layout of the

coupler in this file have been shown in figure 3.2.

Touchstone File No. 2 — scou39.ckt (page A 6)

This file is used to simulate a 3 dB stripline hybrid coupler by tandemly connected two 8.34 *dB* hybrid couplers. The detailed dimensions and the layout of the coupler have been given in figure 3.4.

Touchstone File No. 3 — scou19.ckt (page A 8)

This file is used to simulate a 1.76 dB stripline hybrid coupler by the same configuration as 3 dB hybrid explained above.

Touchstone File No. 4 — pdvs.ckt (page A 10)

The file is used to simulate a two-way stripline Wilkinson equal power divider with seven sections and right angle splitting input over frequency range 2-18 GHz. The dimensions and the layout of this kind of power divider are shown in figure 3.12.

Touchstone File No. 5 — pdvs2.ckt (page A 12)

This file is used to simulate a two-way stripline Wilkinson equal power divider with seven sections and 30° angle splitting input over frequency range 2-18 GHz. The dimensions and the layout of this kind of power divider are shown in figure 3.13.

Touchstone File No. 6 — pdvs13.ckt (page A 15)

This file allows to simulate a two-way stripline Wilkinson equal power divider with seven sections and curved line branch over frequency range 2-18 GHz. The dimensions and the layout of this kind of power divider are shown in figure 3.18.

Touchstone File No. 7 — spjw9.ckt (page A 19)

The file is used to simulate the complete six-port junction with phase compensation over $2 \sim 12$ GHz. The final dimensions and the layout of this six-port junction are shown in figures 3.21, 3.22 and 3.23 respectively.

Program No. 8 — q_simu (page A 24)

This program is used to calculate the distribution of three complex q_i points from simulation results.

Program No. 9 — circle.sin (page A 25)

This program is designed to plot the distribution curves of three q_i points of the six-port junction by simulation results on Smith Chart.

Program No. 10 — calibrat.for (page A 36)

The objective of this program is to calibrate the six-port reflectometer by using thirteen standards.

Program No. 11 — qpnts.w (page A 42)

This program proceeds the calculation of the q_i points from calibration parameters obtained by program 10.

All of the programs presented here are stored in directories /users/wang/ or /eesof/users/wang/ of HP-300. The MICAD files which give the layouts of all components and the six-port junction are also stored in these directories with the same names as TOUCHSTONE files except the extension is .dwg in stead of .ckt.

TOUCHSTONE FILE No. 1

```

!name: /users/wang/scou69.ckt
!purpose: Simulate a 6.75 dB hybrid coupler with stripline.
var
  w1# 5    53.17566    55
  w2# 10   55.94775    57
  w3# 25   57.54633    59
  w4# 30   58.89824    60
  w5# 40   59.99735    61
  w6# 15   46.98273    48
  w7# 20   58.54716    85
  w8# 40   88.21836    120
  w9# 80   139.99373   140
  l1# 100  176.58426   600
  l2# 30   32.71959    400
  l3# 100  173.77057   400
  l4# 30   191.89558   400
  l5# 100  220.87592   400
  s1=10.1

eqn
  w50=58.16
  x11=w6/2
  x12=-x11
  x21=(w7-w6)/2
  x22=-x21
  x31=(w8-w7)/2
  x32=-x31
  x41=(w9-w8)/2
  x42=-x41

ckt
  ssub er=2.30    b=71.1    t=1.0    rho=0
  soclin 45 46 36 35 w^w5 wo^w9 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
  soclin 35 36 32 31 w^w4 wo^w8 s^s1 l^14 w1^x41 w2^x42 w3=0 w4=0
  soclin 31 32 02 01 w^w3 wo^w7 s^s1 l^13 w1^x31 w2^x32 w3=0 w4=0
  soclin 01 02 03 04 w^w2 wo^w6 s^s1 l^12 w1^x21 w2^x22 w3=0 w4=0
  sbclin 04 03 05 06 w^w1 s^s1 l^11 w1^x11 w2^x12 w3^x12 w4^x11
  soclin 06 05 07 08 w^w2 wo^w6 s^s1 l^12 w1=0 w2=0 w3^x22 w4^x21
  soclin 08 07 09 10 w^w3 wo^w7 s^s1 l^13 w1=0 w2=0 w3^x32 w4^x31
  soclin 10 09 37 38 w^w4 wo^w8 s^s1 l^14 w1=0 w2=0 w3^x42 w4^x41
  soclin 38 37 47 48 w^w5 wo^w9 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
  def4p 45 46 47 48 amp

freq
  sweep 2 18 1

grid
  range 2 18 1

opt
  range 2 18 1
  couple db[s31]=-1.76 2
!
  couple db[s11]<-18
  couple db[s41]<-18

```

TOUCHSTONE FILE No. 2

```
!name: /users/wang/scou39.ckt
!purpose: Simulate a 3 dB hybrid coupler with stripline by tandem
! connection technique.
```

```
var
```

```
w1# 5 53.17566 55
w2# 10 56.89228 57
w3# 25 57.98434 59
w4# 30 58.97050 60
w5# 40 59.07040 61
w6# 15 47.99568 48
w7# 20 60.03483 85
w8# 40 82.52119 120
w9# 80 129.62764 140
l1# 100 145.45259 600
l2# 30 62.17291 400
l3# 100 149.48808 400
l4# 30 179.84398 400
l5# 100 194.90436 400
s1=10.1
```

```
eqn
```

```
w50=58.16
x11=w6/2
x12=-x11
x21=(w7-w6)/2
x22=-x21
x31=(w8-w7)/2
x32=-x31
x41=(w9-w8)/2
x42=-x41
w61=-w6
w71=-w7
w81=-w8
w91=-w9
```

```
ckt
```

```
ssub er=2.30 b=71.1 t=1.0 rho=0
soclin 45 46 36 35 w^w5 wo^w9 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
soclin 35 36 32 31 w^w4 wo^w8 s^s1 l^14 w1^x41 w2^x42 w3=0 w4=0
soclin 31 32 02 01 w^w3 wo^w7 s^s1 l^13 w1^x31 w2^x32 w3=0 w4=0
soclin 01 02 03 04 w^w2 wo^w6 s^s1 l^12 w1^x21 w2^x22 w3=0 w4=0
sbclin 04 03 05 06 w^w1 s^s1 l^11 w1^x11 w2^x12 w3^x11 w4^x12
soclin 06 05 07 08 w^w2 wo^w61 s^s1 l^12 w1=0 w2=0 w3^x21 w4^x22
soclin 08 07 09 10 w^w3 wo^w71 s^s1 l^13 w1=0 w2=0 w3^x31 w4^x32
soclin 10 09 37 38 w^w4 wo^w81 s^s1 l^14 w1=0 w2=0 w3^x41 w4^x42
soclin 38 37 47 48 w^w5 wo^w91 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
def4p 45 46 47 48 amp
```

```
slin 10 11 w^w50 l=70
smiter 11 12 w^w50
slin 12 13 w^w50 l=70
def2p 10 13 conc
```

```
amp 01 02 03 04
conc 11 01
conc 02 12
conc 03 13
conc 14 04
def4p 11 12 14 13 part
```

```
part 01 02 03 04
```

```

part 03 05 06 02 flip
slin 11      01 w^w50 1=500
slin 05      55 w^w50 1=500
slin 06      66 w^w50 1=500
slin 04      44 w^w50 1=500
def4p 11 55 66 44 couple

out
couple db[s21] gr1
couple db[s41] gr1
couple db[s11] gr1
couple db[s31] gr1
couple ang[s21] gr2
couple ang[s41] gr2
couple ang[s31] gr2

freq
sweep 2 18 1

grid
range 2 18 1

opt
range 2 18 1
couple db[s31]==-1.76 2
! couple db[s11]<-18
couple db[s41]<-18

```


TOUCHSTONE FILE No. 3

```
!name: /users/wang/scou19.ckt
!purpose: Simulate a 1.76 dB hybrid coupler with stripline by tandem
! connection technique.
```

```
var
```

```
w1# 5 53.17566 55
w2# 10 55.94775 57
w3# 25 57.54633 59
w4# 30 58.89824 60
w5# 40 59.99735 61
w6# 15 46.98273 48
w7# 20 58.54716 85
w8# 40 88.21836 120
w9# 80 139.99373 140
l1# 100 176.58426 600
l2# 30 32.71959 400
l3# 100 173.77057 400
l4# 30 191.89558 400
l5# 100 220.87592 400
s1=10.1
```

```
eqn
```

```
w50=58.16
x11=w6/2
x12=-x11
x21=(w7-w6)/2
x22=-x21
x31=(w8-w7)/2
x32=-x31
x41=(w9-w8)/2
x42=-x41
w61=-w6
w71=-w7
w81=-w8
w91=-w9
```

```
ckt
```

```
ssub er=2.30 b=71.1 t=1.0 rho=0
soclin 45 46 36 35 w^w5 wo^w9 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
soclin 35 36 32 31 w^w4 wo^w8 s^s1 l^14 w1^x41 w2^x42 w3=0 w4=0
soclin 31 32 02 01 w^w3 wo^w7 s^s1 l^13 w1^x31 w2^x32 w3=0 w4=0
soclin 01 02 03 04 w^w2 wo^w6 s^s1 l^12 w1^x21 w2^x22 w3=0 w4=0
sbclin 04 03 05 06 w^w1 s^s1 l^11 w1^x11 w2^x12 w3^x11 w4^x12
soclin 06 05 07 08 w^w2 wo^w61 s^s1 l^12 w1=0 w2=0 w3^x21 w4^x22
soclin 08 07 09 10 w^w3 wo^w71 s^s1 l^13 w1=0 w2=0 w3^x31 w4^x32
soclin 10 09 37 38 w^w4 wo^w81 s^s1 l^14 w1=0 w2=0 w3^x41 w4^x42
soclin 38 37 47 48 w^w5 wo^w91 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
def4p 45 46 47 48 amp
```

```
slin 10 11 w^w50 l=70
smiter 11 12 w^w50
slin 12 13 w^w50 l=70
def2p 10 13 conc
```

```
amp 01 02 03 04
conc 11 01
conc 02 12
conc 03 13
conc 14 04
def4p 11 12 14 13 part
```

```
part 01 02 03 04
```

```

part  03 05 06 02 flip
slin  11      01 w^w50  l=500
slin  05      55 w^w50  l=500
slin  06      66 w^w50  l=500
slin  04      44 w^w50  l=500
def4p 11 55 66 44 couple

out
couple db[s21] gr1
couple db[s41] gr1
couple db[s11] gr1
couple db[s31] gr1
couple ang[s21] gr2
couple ang[s41] gr2
couple ang[s31] gr2

freq
sweep  2  18  1

grid
range  2  18  1

opt
range  2  18  1
couple db[s31]=-1.76  2
! couple db[s11]<-18
couple db[s41]<-18

```

TOUCHSTONE FILE No. 4

!name: /eesof/users/wang/pdvs.ckt
 !purpose: Simulate an two-way equal Wilkinson power divider in stripline with
 !seven section and right angle splitting over frequency range 2-18 GHz.

var

```

111# 60 79.53388 700
122# 100 137.44058 600
w11# 10 10.00320 60
w22# 15 20.89998 45
w33# 20 28.10320 45
w44# 30 35.22472 50
w55# 35 37.69623 50
w66# 40 46.21544 53
w77# 40 49.18617 53
l33# 100 118.68668 600
l44# 100 167.50681 700
l55# 100 121.90446 600
l66# 100 153.64542 600
l77# 100 120.12370 600
l2# 50 50.01918 300
r1=100
r2=142
r3=220
r4=250
r5=308
r6=400
r7=450

```

eqn

```

w50=54.16
s=(w50+w11)/2+12
l3=s-35-w22/2
l4=s-35-w33/2
l5=s-35-w44/2
l6=s-35-w55/2
l7=s-35-w66/2
l8=s-35-w77/2
l9=s-35-w50/2

```

ckt

```

ssub er=2.30 b=71.1 t=1.0 rho=0.0
slin 1 2 w^w50 l=50
stee 3 14 2 w1^w11 w2^w11 w3^w50
slin 3 4 w^w11 l^l2
sbend 5 4 w^w11 ang=90
slin 5 6 w^w11 l^l11
stee 6 7 8 w1^w11 w2^w22 w3=50
slin 8 11 w=50 l^l3
res 11 12 r^r1
slin 12 13 w=50 l^l3
slin 14 15 w^w11 l^l2
sbend 15 16 w^w11 ang=90
slin 16 17 w^w11 l^l11
stee 18 17 13 w1^w22 w2^w11 w3=50

slin 7 19 w^w22 l^l22
stee 19 20 21 w1^w22 w2^w33 w3=50
slin 21 24 w=50 l^l4
res 24 25 r^r2
slin 25 26 w=50 l^l4
slin 18 27 w^w22 l^l22

```

```

ste  28 27 26 w1^w33    w2^w22    w3=50
slin 20 29      w^w33    1^133
ste  29 30 31 w1^w33    w2^w44    w3=50
slin 31 34      w=50      1^15
res  34 35      r^r3
slin 35 36      w=50      1^15
slin 28 37      w^w33    1^133
ste  38 37 36 w1^w44    w2^w33    w3=50

slin 30 39      w^w44    1^144
ste  39 40 41 w1^w44    w2^w55    w3=50
slin 41 44      w=50      1^16
res  44 45      r^r4
slin 45 46      w=50      1^16
slin 38 47      w^w44    1^144
ste  48 47 46 w1^w55    w2^w44    w3=50

slin 40 49      w^w55    1^155
ste  49 50 51 w1^w55    w2^w66    w3=50
slin 51 54      w=50      1^17
res  54 55      r^r5
slin 55 56      w=50      1^17
slin 48 57      w^w55    1^155
ste  58 57 56 w1^w66    w2^w55    w3=50

slin 50 59      w^w66    1^166
ste  59 60 61 w1^w66    w2^w77    w3=50
slin 61 64      w=50      1^18
res  64 65      r^r6
slin 65 66      w=50      1^18
slin 58 67      w^w66    1^166
ste  68 67 66 w1^w77    w2^w66    w3=50

slin 60 69      w^w77    1^177
ste  69 70 71 w1^w77    w2^w50    w3=50
slin 71 74      w=50      1^19
res  74 75      r^r7
slin 75 76      w=50      1^19
slin 68 77      w^w77    1^177
ste  78 77 76 w1^w50    w2^w77    w3=50
def3p 1 70 78 amp

out
amp  db[s32]  gr1
amp  db[s11]  gr1
amp  db[s22]  gr1
amp  db[s31]  gr1

freq
sweep  2  18  1

grid
range  2  18  1

opt
range  2  18  1
amp  db[s32] <-20
amp  db[s11] <-18
amp  db[s22] <-18
amp  db[s31] =-3.01  2

```

TOUCHSTONE FILE No. 5

!name: /eesof/users/wang/pdvs2.ckt
 !purpose: Simulate an two-way equal Wilkinson power divider in stripline with
 !seven section and 30 degree angle splitting over frequency range 2-18 GHz.

var

```
lm # 80 81.22088 700
l22# 100 119.74888 600
w11# 10 10.42927 70
w22# 15 18.10150 45
w33# 20 24.59375 45
w44# 30 34.23678 50
w55# 35 37.17457 55
w66# 40 44.42837 60
w77# 40 50.34691 65
l33# 80 138.21889 600
l44# 100 174.20088 700
l55# 100 124.08887 600
l66# 100 169.23085 600
l77# 100 119.60981 600
r1=230
r2=130
r3=230
r4=300
r5=460
r6=600
r7=460
```

eqn

```
w50=55.19
! lm=111+50
s=(w50+w11)/2+0.500*lm
l3=s-35-w22/2
l4=s-35-w33/2
l5=s-35-w44/2
l6=s-35-w55/2
l7=s-35-w66/2
l8=s-35-w77/2
l9=s-35-w50/2
```

ckt

```
ssub er=2.20 b=70.1 t=1.0 rho=0.0
slin 1 2 w^w50 l=50
stee 3 14 2 w1^w11 w2^w11 w3^w50
sbend 90 3 w^w11 ang=30
sbend 4 90 w^w11 ang=30
slin 4 5 w^w11 l^lm
sbend 6 5 w^w11 ang=30
stee 6 7 8 w1^w11 w2^w22 w3=50
slin 8 11 w=50 l^l3
res 11 12 r^r1
slin 12 13 w=50 l^l3
sbend 14 91 w^w11 ang=30
sbend 91 15 w^w11 ang=30
slin 15 16 w^w11 l^lm
sbend 16 17 w^w11 ang=30
stee 18 17 13 w1^w22 w2^w11 w3=50

slin 7 19 w^w22 l^l22
stee 19 20 21 w1^w22 w2^w33 w3=50
slin 21 24 w=50 l^l4
res 24 25 r^r2
```

```

slin 25 26 w=50 1^14
slin 18 27 w^w22 1^122
stee 28 27 26 w1^w33 w2^w22 w3=50

slin 20 29 w^w33 1^133
stee 29 30 31 w1^w33 w2^w44 w3=50
slin 31 34 w=50 1^15
res 34 35 r^r3
slin 35 36 w=50 1^15
slin 28 37 w^w33 1^133
stee 38 37 36 w1^w44 w2^w33 w3=50

slin 30 39 w^w44 1^144
stee 39 40 41 w1^w44 w2^w55 w3=50
slin 41 44 w=50 1^16
res 44 45 r^r4
slin 45 46 w=50 1^16
slin 38 47 w^w44 1^144
stee 48 47 46 w1^w55 w2^w44 w3=50

slin 40 49 w^w55 1^155
stee 49 50 51 w1^w55 w2^w66 w3=50
slin 51 54 w=50 1^17
res 54 55 r^r5
slin 55 56 w=50 1^17
slin 48 57 w^w55 1^155
stee 58 57 56 w1^w66 w2^w55 w3=50

slin 50 59 w^w66 1^166
stee 59 60 61 w1^w66 w2^w77 w3=50
slin 61 64 w=50 1^18
res 64 65 r^r6
slin 65 66 w=50 1^18
slin 58 67 w^w66 1^166
stee 68 67 66 w1^w77 w2^w66 w3=50

slin 60 69 w^w77 1^177
stee 69 70 71 w1^w77 w2^w50 w3=50
slin 71 74 w=50 1^19
res 74 75 r^r7
slin 75 76 w=50 1^19
slin 68 77 w^w77 1^177
stee 78 77 76 w1^w50 w2^w77 w3=50
def3p 1 70 78 amp

out
amp db[s32] gr1
amp db[s11] gr1
amp db[s22] gr1
amp db[s31] gr1

freq
sweep 2 18 1

grid
range 2 18 1

opt
range 2 8 1
amp db[s32]<-20
amp db[s11]<-18
amp db[s22]<-18
amp db[s31]==-3.01 2
range 8 14 1
amp db[s32]<-20 2

```

```
amp db[s11]<-20 2
amp db[s22]<-20 2
amp db[s31]=-3.01 4
range 14 18 1
amp db[s32]<-20 3
amp db[s11]<-20 3
amp db[s22]<-20 3
amp db[s31]=-3.01 6
```

TOUCHSTONE FILE No. 6

!name: /eesof/users/wang/pdvs13.ckt
 !purpose: Simulate an two-way equal Wilkinson power divider in stripline with
 !seven section and curve line branch over frequency range 2-18 GHz.

dim

ang deg

var

w11 # 10 18.84462 35
 w22 # 15 24.07305 35
 w33 # 20 29.05625 40
 w44 # 25 34.23674 45
 w55 # 30 38.08396 50
 w66 # 35 40.36448 55
 w77 # 40 43.16020 60
 r0 # 50 179.99767 250
 w50= 55.19
 wres=100
 r11 = 350
 r22 = 300
 r33 = 250
 r44 = 400
 r55 # 200 328.10034 500
 r66 # 200 253.21495 500
 r77 # 300 405.40640 500
 r88 # 300 463.87314 500
 r99 # 300 421.74271 500

eqn

!

r0=300/pi
 ww0= wres/2
 w01= wres/2
 w02= wres/2
 w03= wres/2
 w04= wres/2
 w05= wres/2
 w06= wres/2
 w07= wres/2
 w08= wres/2
 w011=w50/2
 l50= (w50-59.05511)/2
 r1= r0 +w11/2
 r2= r0 +w22/2
 r3= r0 +w33/2
 r4= r0 +w44/2
 r5= r0 +w55/2
 r6= r0 +w66/2
 r7= r0 +w77/2
 r8= r0 +w88/2
 r9= r0 +w99/2
 r10=r0 +w50/2
 c=(w50/2)/(r1-w11/2)
 a10=(c+c^3/6+3*c^5/40+15*c^7/336)*180/pi
 a=ww0/(r0)
 a0=(a+a^3/6+3*a^5/40+15*a^7/336)*180/pi
 a1=180-a10-a0
 a2=180-2*a0
 a3=180-2*a0
 a4=180-2*a0
 a5=180-2*a0


```

a6=180-2*a0
a7=180-2*a0
a8=180-2*a0
a9=180-2*a0
a11= a1+a10
w110=r1-(r1-w11/2)*cos((180-a1)/2)
w120=r2-(r2-w22/2)*cos((180-a2)/2)
w130=r3-(r3-w33/2)*cos((180-a3)/2)
w140=r4-(r4-w44/2)*cos((180-a4)/2)
w150=r5-(r5-w55/2)*cos((180-a5)/2)
w160=r6-(r6-w66/2)*cos((180-a6)/2)
w170=r7-(r7-w77/2)*cos((180-a7)/2)
w180=r8-(r8-w88/2)*cos((180-a8)/2)
w11=w110+w120
w12=w120+w130
w13=w130+w140
w14=w140+w150
w15=w150+w160
w16=w160+w170
w17=w170+w180
ww01=0!(wres-50)/2

ckt
      ssub      er=2.20      b=70.1      t=1.0      rho=0.0
      slin      1      2      w^w50      l^r1
      stee 102 101 2 w1^w11 w2^w11 w3^w50
      sbend      101      103      w^w11      ang^a9
      sbend      104      102      w^w11      ang^a9
      scurve 103 13      w^w11      ang^a1      rad^r1
      scurve 21 23 w^w22 ang^a2 rad^r2
      scurve 31 33 w^w33 ang^a3 rad^r3
      scurve 41 43 w^w44 ang^a4 rad^r4
      scurve 51 53 w^w55 ang^a5 rad^r5
      scurve 61 63 w^w66 ang^a6 rad^r6
      scurve 71 73 w^w77 ang^a7 rad^r7
      scurve 81 83 w^w88 ang^a8 rad^r8
      scurve 91 93 w^w99 ang^a9 rad^r9
      stee 21 13 15 w1^w22 w2^w11 w3=50      a1^a0 a2^a0
      stee 31 23 25 w1^w33 w2^w22 w3=50      a1^a0 a2^a0
      stee 41 33 35 w1^w44 w2^w33 w3=50      a1^a0 a2^a0
      stee 51 43 45 w1^w55 w2^w66 w3=50      a1^a0 a2^a0
      stee 61 53 55 w1^w66 w2^w55 w3=50      a1^a0 a2^a0
      stee 71 63 65 w1^w77 w2^w66 w3=50      a1^a0 a2^a0
      stee 81 73 75 w1^w88 w2^w77 w3=50      a1^a0 a2^a0
      stee 91 83 85 w1^w99 w2^w88 w3=50      a1^a0 a2^a0
      stee 111 93 95 w1^w50 w2^w99 w3=50      a1^a0 a2^a0
      slin 111 113 w^w50 l^r10
      scurve 14 104      w^w11      ang^a1      rad^r1
      scurve 24 22 w^w22 ang^a2 rad^r2
      scurve 34 32 w^w33 ang^a3 rad^r3
      scurve 44 42 w^w44 ang^a4 rad^r4
      scurve 54 52 w^w55 ang^a5 rad^r5
      scurve 64 62 w^w66 ang^a6 rad^r6
      scurve 74 72 w^w77 ang^a7 rad^r7
      scurve 84 82 w^w88 ang^a8 rad^r8
      scurve 94 92 w^w99 ang^a9 rad^r9
      stee 14 22 16 w1^w11 w2^w22 w3=50      a1^a0 a2^a0
      stee 24 32 26 w1^w22 w2^w33 w3=50      a1^a0 a2^a0
      stee 34 42 36 w1^w33 w2^w44 w3=50      a1^a0 a2^a0
      stee 44 52 46 w1^w44 w2^w55 w3=50      a1^a0 a2^a0
      stee 54 62 56 w1^w55 w2^w66 w3=50      a1^a0 a2^a0
      stee 64 72 66 w1^w66 w2^w77 w3=50      a1^a0 a2^a0

```

```

steep 74 82 76 w1^w77 w2^w88 w3=50      a1^a0 a2^a0
steep 84 92 86 w1^w88 w2^w99 w3=50      a1^a0 a2^a0
steep 94 112 96 w1^w99 w2^w50 w3=50     a1^a0 a2^a0
slin 114 112 w^w50 l^r10
slin 15 19 w=50 l^ww01
slin 25 29 w=50 l^ww01
slin 35 39 w=50 l^ww01
slin 45 49 w=50 l^ww01
slin 55 59 w=50 l^ww01
slin 65 69 w=50 l^ww01
slin 75 79 w=50 l^ww01
slin 85 89 w=50 l^ww01
slin 95 99 w=50 l^ww01
slin 16 18 w=50 l^ww01
slin 26 28 w=50 l^ww01
slin 36 38 w=50 l^ww01
slin 46 48 w=50 l^ww01
slin 56 58 w=50 l^ww01
slin 66 68 w=50 l^ww01
slin 76 78 w=50 l^ww01
slin 86 88 w=50 l^ww01
slin 96 98 w=50 l^ww01
! res 15 16 r^r11 spac l=50
! res 25 26 r^r22 spac l=50
! res 35 36 r^r33 spac l=50
! res 45 46 r^r44 spac l=50
! res 55 56 r^r55 spac l=50
! res 65 66 r^r66 spac l=50
! res 75 76 r^r77 spac l=50
res 18 19 r^r11 spac l=50
res 28 29 r^r22 spac l=50
res 38 39 r^r33 spac l=50
res 48 49 r^r44 spac l=50
res 58 59 r^r55 spac l=50
res 68 69 r^r66 spac l=50
res 78 79 r^r77 spac l=50
res 88 89 r^r88 spac l=50
res 98 99 r^r99 spac l=50
def3p 1 113 114 amp
out
amp db[s32] gri
amp db[s11] gri
amp db[s22] gri
amp db[s13] gri
freq
sweep 2 18 1
grid
range 2 18 1
opt
range 2 18 1
amp db[s32]<-20 1
amp db[s11]<-25 1
amp db[s22]<-20 1
amp db[s31]==-3.01 5
range 8 14 1
amp db[s32]<-25 3
amp db[s11]<-30 2
amp db[s22]<-20 2
! amp db[s31]==-3.01 6
! range 14 18 1
! amp db[s32]<-18 4

```

```
amp db[s11]<-25 3  
amp db[s22]<-20 3  
! amp db[s31]=-3.01 6
```

TOUCHSTONE FILE No. 7

```
!name: /eesof/users/wang/spjw9.ckt
!purpose: Simulate a complete six-port junction with phase compensation over
!      2-12 GHz.
```

var

```
w50 = 55.19
wp1 = 10.2
wp2 = 18.4
wp3 = 25.5
wp4 = 34.2
wp5 = 37.0
wp6 = 44.4
wp7 = 50.3
lp1 = 85.4
lp2 = 125.1
lp3 = 129.0
lp4 = 159.8
lp5 = 136.7
lp6 = 168.8
lp7 = 123.9
w1 = 47.8
w2 = 52.5
w3 = 54.0
w4 = 55.0
w5 = 55.3
wo2 = 42.6
wo3 = 60.8
wo4 = 93.9
wo5 = 140.0
l1 = 201.1
l2 = 17.0
l3 = 209.6
l4 = 201.8
l5 = 110.1
s1 = 10.1
w11 = 45.2
w22 = 52.6
w33 = 53.4
w44 = 55.0
w55 = 55.9
wo22 = 45
wo33 = 57.2
wo44 = 76.2
wo55 = 101.7
l11 = 169.7
l22 = 66.2
l33 = 177.5
l44 = 205.4
l55 = 197.2
l3031# 400 600.00096 700
l3435# 300 400.85773 600
l3940# 200 495.10242 700
l1112# 450 578.23846 800
l0920# 300 487.96359 700
```

eqn

```
sp = (w50+wp1)/2+0.5*lp1
lp11 = sp-35-wp2/2
lp22 = sp-35-wp3/2
lp33 = sp-35-wp4/2
```

```

lp44 = sp-35-wp5/2
lp55 = sp-35-wp6/2
lp66 = sp-35-wp7/2
lp77 = sp-35-w50/2
lecon = 1756
leb = 43.9
lpdv = lp1+lp2+lp3+lp4+lp5+lp6+lp7+wp1+400
wpdv = 2*sp-w50
wcou2 = (wo5+w50)*2+280+24
lcou2 = 11+2*(12+13+14+15)+140+2*w50+12
lcou3 = 111+2*(122+133+144+155)+140+2*w50+12
lecou1 = 11+2*(12+13+14+15)
lecou2 = 3252
x11 = wo2/2
x12 = -x11
x21 = (wo3-wo2)/2
x22 = -x21
x31 = (wo4-wo3)/2
x32 = -x31
x41 = (wo5-wo4)/2
x42 = -x41
wo21 = -wo2
wo31 = -wo3
wo41 = -wo4
wo51 = -wo5
x311 = wo22/2
x312 = -x311
x321 = (wo33-wo22)/2
x322 = -x321
x331 = (wo44-wo33)/2
x332 = -x331
x441 = (wo55-wo44)/2
x442 = -x441
wo221 = -wo22
wo331 = -wo33
wo441 = -wo44
wo551 = -wo55
l1394 = 11112+550
l2122 = 13031+lecon-11112-2*leb+(lecou1+3*w50-wo5-lcou2)/2+9
l0405 = 11112+lcou2-lpdv+(w50+wpdv)/2+5
l2324 = lpdv+13435+wo5-2*10920-(7*w50+wpdv)/2-5
l4748 = (lecou2-2*leb-wcou2-lcou3-wpdv)/2
l4950 = wcou2+13940-2*w50+lcou3+15
l5152 = (l4748+wpdv+2*w50)/2+6

```

ckt

```

ssub er=2.20 b=70.1 t=1.0 rho=0.0
steer 3 14 1 w1^wp1 w2^wp1 w3^w50 !power divider
sbend 90 3 w^wp1 ang=30
sbend 4 90 w^wp1 ang=30
slin 4 5 w^wp1 l^lp1
sbend 6 5 w^wp1 ang=30
steer 6 7 8 w1^wp1 w2^wp2 w3=50
slin 8 11 w=50 l^lp11
res 11 12 r=100 spac l=60
slin 12 13 w=50 l^lp11
sbend 14 91 w^wp1 ang=30
sbend 91 15 w^wp1 ang=30
slin 15 16 w^wp1 l^lp1
sbend 16 17 w^wp1 ang=30
steer 18 17 13 w1^wp2 w2^wp1 w3=50
slin 7 19 w^wp2 l^lp2 !the second one

```

```

stee 19 20 21 w1^wp2 w2^wp3 w3=50
slin 21 24 w=50 l^lp22
res 24 25 r=142 spac l=60
slin 25 26 w=50 l^lp22
slin 18 27 w^wp2 l^lp2
stee 28 27 26 w1^wp3 w2^wp2 w3=50
slin 20 29 w^wp3 l^lp3 !the third one
stee 29 30 31 w1^wp3 w2^wp4 w3=50
slin 31 34 w=50 l^lp33
res 34 35 r=200 spac l=60
slin 35 36 w=50 l^lp33
slin 28 37 w^wp3 l^lp3
stee 38 37 36 w1^wp4 w2^wp3 w3=50
slin 30 39 w^wp4 l^lp4 !the fourth one
stee 39 40 41 w1^wp4 w2^wp5 w3=50
slin 41 44 w=50 l^lp44
res 44 45 r=230 spac l=60
slin 45 46 w=50 l^lp44
slin 38 47 w^wp4 l^lp4
stee 48 47 46 w1^wp5 w2^wp4 w3=50
slin 40 49 w^wp5 l^lp5 !the fifth one
stee 49 50 51 w1^wp5 w2^wp6 w3=50
slin 51 54 w=50 l^lp55
res 54 55 r=300 spac l=60
slin 55 56 w=50 l^lp55
slin 48 57 w^wp5 l^lp5
stee 58 57 56 w1^wp6 w2^wp5 w3=50
slin 50 59 w^wp6 l^lp6 !the sixth one
stee 59 60 61 w1^wp6 w2^wp7 w3=50
slin 61 64 w=50 l^lp66
res 64 65 r=400 spac l=60
slin 65 66 w=50 l^lp66
slin 58 67 w^wp6 l^lp6
stee 68 67 66 w1^wp7 w2^wp6 w3=50
slin 60 69 w^wp7 l^lp7 !the seventh
stee 69 70 71 w1^wp7 w2^w50 w3=50
slin 71 74 w=50 l^lp77
res 74 75 r=450 spac l=60
slin 75 76 w=50 l^lp77
slin 68 77 w^wp7 l^lp7
stee 78 77 76 w1^w50 w2^wp7 w3=50
slin 70 80 w^w50 l=50
slin 78 79 w^w50 l=50
def3p 1 80 79 pdv

soclin 45 46 36 35 w^w5 wo^wo5 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
soclin 35 36 32 31 w^w4 wo^wo4 s^s1 l^14 w1^x41 w2^x42 w3=0 w4=0 !coupler1
soclin 31 32 02 01 w^w3 wo^wo3 s^s1 l^13 w1^x31 w2^x32 w3=0 w4=0
soclin 01 02 03 04 w^w2 wo^wo2 s^s1 l^12 w1^x21 w2^x22 w3=0 w4=0
sbclin 04 03 05 06 w^w1 s^s1 l^11 w1^x11 w2^x12 w3^x11 w4^x12
soclin 06 05 07 08 w^w2 wo^wo2 s^s1 l^12 w1=0 w2=0 w3^x21 w4^x22
soclin 08 07 09 10 w^w3 wo^wo3 s^s1 l^13 w1=0 w2=0 w3^x31 w4^x32
soclin 10 09 37 38 w^w4 wo^wo4 s^s1 l^14 w1=0 w2=0 w3^x41 w4^x42
soclin 38 37 47 48 w^w5 wo^wo5 s^s1 l^15 w1=0 w2=0 w3=0 w4=0
def4p 45 46 47 48 coupl1
slin 10 11 w^w50 l=70 !coupler2
smiter 11 12 w^w50
slin 12 13 w^w50 l=70
def2p 10 13 conc !bend for tendam connection
coupl1 01 02 03 04
conc 11 01

```

```

      conc 02      12
      conc 03      13
      conc 14      04
      def4p 11 12 14 13 part
      part 01 02 03 04
      part 03 05 06 02 flip
      def4p 01 05 06 04 coupl2
soclin 45 46 36 35 w^w55 wo^wo55 s^s1 l^155 w1=0 w2=0 w3=0 w4=0 !coupler3
soclin 35 36 32 31 w^w44 wo^wo44 s^s1 l^144 w1^x441 w2^x442 w3=0 w4=0
soclin 31 32 02 01 w^w33 wo^wo33 s^s1 l^133 w1^x331 w2^x332 w3=0 w4=0
soclin 01 02 03 04 w^w22 wo^wo22 s^s1 l^122 w1^x321 w2^x322 w3=0 w4=0
sbclin 04 03 05 06 w^w11      s^s1 l^111 w1^x311 w2^x312 w3^x311 w4^x312
soclin 06 05 07 08 w^w22 wo^wo22 s^s1 l^122 w1=0 w2=0 w3^x321 w4^x322
soclin 08 07 09 10 w^w33 wo^wo33 s^s1 l^133 w1=0 w2=0 w3^x331 w4^x332
soclin 10 09 37 38 w^w44 wo^wo44 s^s1 l^144 w1=0 w2=0 w3^x441 w4^x442
soclin 38 37 47 48 w^w55 wo^wo55 s^s1 l^155 w1=0 w2=0 w3=0 w4=0
      def4p 45 46 47 48 amp2
      amp2 01 02 03 04
      conc 11      01
      conc 02      12
      conc 03      13
      conc 14      04
      def4p 11 12 14 13 part2
      part2 01 02 03 04
      part2 03 05 06 02 flip
      def4p 01 05 06 04 coupl3

      slin 91      02 w^w50 l=5100      !six-port circuit
      smiter 02      03 w^w50
      slin 30      92 w^w50 l^lecon
      slin 31      30 w^w50 l^13031
      smiter 32      31 w^w50 l^13031
      coupl1 03 32 33 04
      slin 04      05 w^w50 l^10405
      pdv 05 08 06
      slin 06      93 w^w50 l=550
      smiter 08      09 w^w50
      slin 09      20 w^w50 l^10920
      smiter 20      21 w^w50
      slin 21      22 w^w50 l^12122
      smiter 23      22 w^w50
      slin 23      24 w^w50 l^12324
      smiter 25      24 w^w50
      slin 25      26 w^w50 l^12122
      smiter 26      27 w^w50
      slin 27      10 w^w50 l^10920
      smiter 10      11 w^w50
      slin 11      12 w^w50 l^11112
      smiter 28      12 w^w50
      smiter 13      29 w^w50
      slin 13      94 w^w50 l^11394
      smiter 33      34 w^w50
      slin 34      35 w^w50 l^13435
      pdv 35 46 36
      coupl2 28 39 29 36
      slin 39      40 w^w50 l^13940
      smiter 41      40 w^w50
      coupl3 19 41 18 45
      slin 45      55 w^w50 l=500
      smiter 55      56 w^w50
      slin 56      57 w^w50 l=500

```

```

smiter 58      57 w^w50
slin  58      95 w^w50 l=1440
smiter 46      47 w^w50
slin  47      48 w^w50 l^14748
smiter 49      48 w^w50
slin  49      50 w^w50 l^14950
smiter 51      50 w^w50
slin  51      52 w^w50 l^15152
via   52      53 d1=10 d2=10 h=10.1 t=1 w^w50
slin  18      53 w^w50 l^15152
slin  19      96 w^w50 l=2000
match 93
match 94
match 95
def3p 91 92 96      spout

out
spout mag[s31] gr1
spout mag[s32] gr1
spout mag[s22] gr1
spout mag[s21] gr1
spout ang[s31] gr2
spout ang[s32] gr2
spout ang[s22] gr2
spout ang[s21] gr2

freq
sweep  2  12  0.5

grid
range  2  12  0.5

opt
range  2  12  0.5
spout  db[s22]<-18

```


PROGRAM No. 8

```
% Name: q_simu
% This program is to calculate the distribution of three qi points from
% simulation results.

./q_calc <$1 >q_p
./q_calc <$2 >>q_p
./q_calc <$3 >>q_p
./q_separe <q_p
rm q_p
DIR=$4
if test $# -lt 4
then
    DIR="t"
fi
if test $DIR = c
then
    ./tgraph /dev/crt hp300h <mag.cmd
    echo "Hit RETURN to continue"
    read ANS
    ./tgraph /dev/crt hp300h <ang.cmd
    echo "Hit RETURN to continue"
    read ANS
else
    if test $DIR = p
    then
        echo "Load paper in the plotter    and hit RETURN"
        read ANS
        ./tgraph /dev/rplotter hpgl <mag.cmd
        echo "Load paper in the plotter    and hit RETURN"
        read ANS
        ./tgraph /dev/rplotter hpgl <ang.cmd
    else
        ./tgraph <mag.cmd
        echo "Hit RETURN to continue"
        read ANS
        ./tgraph <ang.cmd
        echo "Hit RETURN to continue"
        read ANS
    fi
fi
clear
```

PROGRAM No. 9

```

1!NAME: "CIRCLE_SIN:,700,0"
2  GINIT
3  OPTION BASE 1
4  !
5  COM /Centre/ Qim(4),Qip(4),Aim(4),Aip(4),Rs(4),Bi(4)
6  COM /Gamma/ Gam(201),Pha(201)
7  COM /Wind/ Wxi,Wxa,Wyi,Wya,Facteur
8  COM /Quad/ Result(8,8),Racine(4,4,4),M
9  COM /Frequence/ Freq_debut,Freq_fin,Freq_step,Fact,Direct$[20]
10 F1=0
11 Arret=1
12 Medium=CRT
13 ! PARAMETRES SIX-PORTS DE LI
14 Fadhel=1
15 SELECT Fadhel
16 CASE 0
17   ! SIX-PORTS DE LI PROPUREMENT DIT
18   C1nom=3/8*SQR(3)/SQR(2)! .459  6.76 DB
19   C2nom=SQR(2)/SQR(3)  ! .816  1.76 DB= 2x6.76 dB
20   C3nom=1/SQR(2)*1.00  ! .707  3.00 DB
21 CASE 1
22   ! SIX-PORTS DE LI FACTEUR DE COUPLAGE MODIFIE
23   C1nom=.316!1/SQR(2)          ! 6.00 DB
24   C2nom=SQR(2)/SQR(3)!1/SQR(2)  ! 3.00 DB
25   C3nom=1/SQR(2)*1.00! 3.00 DB
26 END SELECT
27 C2=C2nom
28 C3=C3nom
29 T2=SQR(1-C2^2)
30 T3=SQR(1-C3^2)
31 C1nom_db=20*LGT(C1nom)
32 Er=2.17
33 FO=5
34 Theta=-3*PI/2
35 Freq_step=.02
36 Freq_debut=2
37 Freq_fin=3
38 Ff=Freq_fin+Freq_step/10
39 FOR Freq=Freq_debut TO Ff STEP Freq_step
40   L=Theta/(2*PI*FO*1.E+9/2.997925E+8*SQR(Er))
41   L=1.E-3*10.2
42   L1=L*5
43   L2=L*5*2+L*1
44   L3=L*5*2+L*1
45   Ld2=L*5
46   ! Ld1=0*Ld2+L          ! Ld1=l1+Ld2
47   Ld1=L*5
48   Fact=1.00
49   Ligne=(L*10+L)*Fact
50   ~=-2*PI*Freq*1.E+9/2.997925E+8*SQR(Er)
51   Philigne=~*Ligne
52   Directivity=10.0
53   Direct$=VAL$(-Directivity)
54   Dir_deb=40
55   Dir_fin=10!C1nom_db
56   ! FOR Directivity=Dir_deb TO Dir_fin STEP -1
57   Dir1=10^(-Directivity/20)
58   Dir1=0
59   IF Dir1=0 THEN Direct$=""

```

```

60      A=1.      ! 0<A< 1
61      E1=SQR(C1nom^2*Dir1^2/(1+(1-A)*Dir1^2))
62      C1=SQR(C1nom^2-(1-A)*E1^2)
63      T1=SQR((1-C1nom^2)-A*E1^2)
64      Y=PI/2
65      Phaset1=^*L1
66      Phasec1=^*L1
67      Phasee1=0
68      Jk=0
69      IF Dir1 THEN Phasee1=^*L1+^*L1*Jk+Y
70      !
71      ! LIGNE INETR COMPOSANTES
72      Co=.085
73      Pha1=^*(.0782+Co)
74      ^1=-2*PI*Freq*1.E+9/2.997925E+8*SQR(1.10)
75      Pha2=2*^*(.0660)+2*^1*(.060)
76      Pha3=^*0
77      Pha4=^*0
78      Pha5=^*(.1175+Co)
79      Pha6=^*(4*L)*1.0
80      Pha7=^*(1*L)
81      Pha8=^*(1*L)
82      Pha9=^*((4*L)+Co)
83      Pha10=^*(1*L)
84      Pha11=^*(1*L)
85      Pha12=^*((1.5*L)+Co)
86      Pha13=^*((1.5*L)+Co)
87      ! COMPENSATION
88      Pha6=(Pha2+Pha7+Phasec1)*1      ! 360 ->17/28      ! 120 ->25/28      ! 28-3.5
89      !POWER DIVIDERS 1,2
90      D1=1/SQR(2)
91      D2=1/SQR(2)
92      Aa1=.500
93      Aa2=.500
94      D11=SQR(1-Aa1)
95      D12=SQR(1-(1-Aa1))
96      D21=SQR(1-Aa2)
97      D22=SQR(1-(1-Aa2))
98      Pd1=^*Ld1
99      Pd2=^*Ld2
100     ! COUPLEURS 2,3
101     Phaset2=^*L2
102     Phasec2=^*L2
103     Phasee2=^*L2+^*L2*Jk*Y
104     Phaset3=^*L3*1.00
105     Phasec3=^*L3*1.00
106     Phasee3=^*L3+^*L3*Jk+Y
107     IF Freq=Fd THEN GOSUB Sortie
108     !=====
109     ! PRINT T1,C1,E1,T1^2+C1^2+E1^2
110     ! CALCUL DE Q3
111     Mx7=D11
112     Px7=Pd1
113     Mx8=0
114     Px8=0
115     IF Dir1 THEN CALL Cf1(Mx7,Px7,Mx8,Px8,E1,Phasee1,T1,Phaset1,C1,
116     Phasec1,Qim(1),Qip(1),Pha2)
117     ! PRINT "Q3: ",Qim(1),Qip(1)*180/PI
118     ! PRINT USING "K,2X,4D.3D,2X,4D.2D";"Q3:",Qim(1),Qip(1)*180/PI
119     ! CALCUL DE Q4
120     Mx5=D12*T2

```

```

120 Px5=Pd1+Phaset2+Pha3+Pha6
121 Mx6=D21*C2
122 Px6=Pd2+Phasec2+(+1)*PI/2+Pha4+Pha7
123 Cf1(Mx5,Px5,Mx6,Px6,E1,Phasee1,T1,Phaset1,C1,Phasec1,Qim(2),Qip(2),Pha2)
124 OUTPUT Medium USING "X,2D.2D,#";Freq
125 OUTPUT Medium USING "X,K,2D.3D,X,4D.2D,#";"Q4:",Qim(2),Qip(2)*180/PI
126 !=====
127 Q5: !
128 ! CALCUL DE Q5
129 Mx1=D12*C2*T3
130 Px1=Pd1+Phasec2+Phaset3+(+1)*PI/2+Pha3+Pha6+Pha10
131 Mx222=D21*T2*T3
132 Px222=Pd2+Phasec2+Phaset3+Pha4+Pha7+Pha10
133 Mx233=D22*C3
134 Px233=Pd2+Phasec3+Pha4+Pha8+Pha11
135 Rmx2=Mx222*COS(Px222)+Mx233*COS(Px233)
136 Imx2=Mx222*SIN(Px222)+Mx233*SIN(Px233)
137 Rmx2=PROUND(Rmx2,-10)
138 Imx2=PROUND(Imx2,-10)
139 Mx2=SQR(Rmx2^2+Imx2^2)
140 Ppp=PI/2*(1-SGN(Rmx2))
141 Pp=SGN(Imx2)*Ppp
142 Px2=Pp
143 IF Rmx2 THEN Px2=ATN(Imx2/Rmx2)+Pp+Ppp-SGN(Rmx2)*Pp
144 Cf1(Mx1,Px1,Mx2,Px2,E1,Phasee1,T1,Phaset1,C1,Phasec1,Qim(3),Qip(3),Pha2)
145 OUTPUT Medium USING "X,K,2D.3D,X,4D.2D,#";"Q5:",Qim(3),Qip(3)*180/PI
146 Q6: !
147 ! CALCUL DE Q6
148 Mx3=Mx1*C3/T3
149 Px3=Px1+Phasec3-Phaset3+(+1)*PI/2
150 Mx322=Mx222*C3/T3
151 Px322=Px222+Phasec3-Phaset3+(+1)*PI/2
152 Mx333=Mx233*T3/C3
153 Px333=Px233+Phasec3-Phaset3-(+1)*PI/2
154 Rmx3=Mx322*COS(Px322)+Mx333*COS(Px333)
155 Imx3=Mx322*SIN(Px322)+Mx333*SIN(Px333)
156 Rmx3=PROUND(Rmx3,-10)
157 Imx3=PROUND(Imx3,-10)
158 Mx4=SQR(Rmx3^2+Imx3^2)
159 Ppp=PI/2*(1-SGN(Rmx3))
160 Pp=SGN(Imx3)*Ppp
161 Px4=Pp
162 IF Rmx3 THEN Px4=ATN(Imx3/Rmx3)+Pp+Ppp-SGN(Rmx3)*Pp
163 Cf1(Mx3,Px3,Mx4,Px4,E1,Phasee1,T1,Phaset1,C1,Phasec1,Qim(4),Qip(4),Pha2)
164 OUTPUT Medium USING "X,K,2D.3D,X,4D.2D,#";"Q6:",Qim(4),Qip(4)*180/PI
165 Center=1
166 FOR I=2 TO 4
167 ! Resultats(Qim(*),Qip(*),Fl,I,Center)
168 NEXT I
169 PRINT
170 IF Dir1 THEN CALL Cf1_modifie(Mx7,Px7,Mx8,Px8,E1,Phasee1,T1,
    Phaset1,C1,Phasec1,Aim(1),Aip(1))
171 Cf1_modifie(Mx5,Px5,Mx6,Px6,E1,Phasee1,T1,Phaset1,C1,Phasec1,Aim(2),
    Aip(2))
172 Cf1_modifie(Mx1,Px1,Mx2,Px2,E1,Phasee1,T1,Phaset1,C1,Phasec1,Aim(3),
    Aip(3))
173 Cf1_modifie(Mx3,Px3,Mx4,Px4,E1,Phasee1,T1,Phaset1,C1,Phasec1,Aim(4),
    Aip(4))
174 !=====
175 !CALCUL DES PUISSANCES
176 GOTO Frequence

```

```

177 Fr=1
178 Ga=Gam(Fr)
179 Ph=Pha(Fr)
180 IF NOT Center THEN
181   OUTPUT KBD USING "2D.3D,K,4D.2D,#";Gam(Fr),",",Pha(Fr)*180/PI
182   INPUT "GAMMA",Gam(Fr),Pha(Fr)
183 END IF
184 Pha(Fr)=Pha(Fr)*PI/180
185 IF Ga<>Gam(Fr) OR Ph<>Pha(Fr) THEN Fl=0
186 I1=2
187 IF Dir1 THEN I1=1 ! DIRECTIVITE NON NULLE
188 FOR I=I1 TO 4
189   Reel=Gam(Fr)*COS(Pha(Fr))-Qim(I)*COS(Qip(I))
190   Imag=Gam(Fr)*SIN(Pha(Fr))-Qim(I)*SIN(Qip(I))
191   Fx=SQR(Reel^2+Imag^2)
192   IF I=1 THEN Fx3=Fx
193   Bi(I)=Fx*Aim(I)*C1
194 NEXT I
195 IF NOT Dir1 THEN
196   Bi(1)=D1*T1/SQR(2)
197   Aim(1)=1
198   Fx3=1
199 END IF
200 Random=1
201 FOR I=2 TO 4
202   Rs(I)=Bi(I)/Bi(1)*Aim(1)/Aim(I)*Fx3*(1.00+.03*(2*RND-1))
203 NEXT I
204 ! PRINT Bi(*)
205 ! PRINT Rs(*)
206 Center=1 !0> CENTRE ET CERCLE 1> CENTRE
207 Frequence: !
208 Resultats(Qim(*),Qip(*),Fl,I,Center,Rs(*),Arret)
209 NEXT Freq
210 GOTO Fgh
211 OUTPUT KBD USING "K,#";"N"
212 Direct$=VAL$(Directivity)
213 IF Dir1=0 THEN Direct$=""
214 OUTPUT PRT USING "K,#";"Directivity: ",Direct$," dB Phase shift: ",Fact
215 ! NEXT Directivity
216 Fgh: !
217 OUTPUT Medium
218 BEEP
219 STOP
220 Sortie: !
221 ^=~/1000
222 OUTPUT Medium;"Directivity: "&VAL$(Directivity)
223 OUTPUT Medium USING "2X,K,4D,#";"L1= ",-Pha1/^,"L2= ",-Pha2/^,"L3= ",
  -Pha3/^,"L4= ",-Pha4/^,"L4= ",-Pha4/^
224 OUTPUT Medium
225 OUTPUT Medium USING "2X,K,4D,#";"L5= ",-Pha5/^,"L5= ",-Pha5/^,"L6= ",
  -Pha6/^,"L7= ",-Pha7/^,"L8= ",-Pha8/^
226 OUTPUT Medium
227 OUTPUT Medium USING "2X,K,4D,#";"L9= ",-Pha9/^,"L10= ",-Pha10/^,"L11= ",
  -Pha11/^,"L12= ",-Pha12/^,"L13= ",-Pha13/^
228 OUTPUT Medium
229 OUTPUT Medium USING "2X,K,4D,#";"L1 Coupleur #1= ",L1*1000,"L2 Coupleur
  #2= ",L2*1000,"L3 Coupleur #3= ",L3*1000
230 OUTPUT Medium
231 OUTPUT Medium USING "2X,K,4D,#";"L1 Diviseur #1= ",Ld1*1000,"L2 Diviseur
  #2= ",Ld2*1000,"L DEphaseur= ",Ligne*1000
232 OUTPUT Medium

```

```

233  OUTPUT Medium USING "2X,K,2D.2D,#";"BALANCEMENT DE PHASE: ",Fact,"
      % Energie au port IsolE";A
234  OUTPUT Medium
235  OUTPUT Medium
236  ^--^*1000
237  RETURN
238  END
239  SUB Cf1(Mx1,Px1,Mx2,Px2,Me1,Pe1,Mt1,Pt1,Cm,Cp,Qim,Qip,Pha2)
240  !      t1x1 + e1x2
241  !      -----
242  !      t1x2 + e1x1
243  ! DENOMINATEUR
244  Ma1=Me1*Mx1
245  Pa1=Pe1+Px1
246  Ma2=Mt1*Mx2
247  Pa2=Pt1+Px2
248  Ma3=Me1*Mx2
249  Pa3=Pe1+Px2
250  Ma4=Mt1*Mx1
251  Pa4=Pt1+Px1
252  Prn=Ma1*COS(Pa1)+Ma2*COS(Pa2)
253  Pin=Ma1*SIN(Pa1)+Ma2*SIN(Pa2)
254  Prn=PROUND(Prn,-10)
255  Pin=PROUND(Pin,-10)
256  Md=SQR(Prn^2+Pin^2)
257  Ppp=PI/2*(1-SGN(Prn))
258  Pp=SGN(Pin)*Ppp
259  Pd=Pp
260  IF Prn THEN Pd=ATN(Pin/Prn)+Pp+Ppp-SGN(Pin)*Pp
261  ! PRINT Prn,Pin,Md,Pd
262  ! NUMERATEUR
263  Prn=Ma3*COS(Pa3)+Ma4*COS(Pa4)
264  Pin=Ma3*SIN(Pa3)+Ma4*SIN(Pa4)
265  Prn=PROUND(Prn,-10)
266  Pin=PROUND(Pin,-10)
267  Mn=SQR(Prn^2+Pin^2)
268  Ppp=PI/2*(1-SGN(Prn))
269  Pp=SGN(Pin)*Ppp
270  Pn=Pp
271  IF Prn THEN Pn=ATN(Pin/Prn)+Pp+Ppp-SGN(Pin)*Pp
272  ! PRINT Prn,Pin,Md,Pd
273  Qim=Mn/Md/Cm
274  Qip=Pn-Pd-Cp+(+1)*PI/2-Pha2    !-PI/3
275  GOTO Sd
276  Boucle:Qip=Qip-SGN(Qip)*2*PI
277  Sd: IF ABS(Qip)>PI THEN Boucle
278  SUBEND
279  !
280  SUB Cf1_modifie(Mx1,Px1,Mx2,Px2,Me1,Pe1,Mt1,Pt1,Cm,Cp,Qim,Qip)
281  !      t1x1 + e1x2
282  Ma1=Me1*Mx1
283  Pa1=Pe1+Px1
284  Ma2=Mt1*Mx2
285  Pa2=Pt1+Px2
286  Prn=Ma1*COS(Pa1)+Ma2*COS(Pa2)
287  Pin=Ma1*SIN(Pa1)+Ma2*SIN(Pa2)
288  Prn=PROUND(Prn,-10)
289  Pin=PROUND(Pin,-10)
290  Qim=SQR(Prn^2+Pin^2)
291  Ppp=PI/2*(1-SGN(Prn))
292  Pp=SGN(Pin)*Ppp

```

```

293   Qip=Pp
294   IF Prn THEN Qip=ATN(Pin/Prn)+Pp+Ppp-SGN(Pin)*Pp
295   GOTO Sd
296 Boucle:Qip=Qip-SGN(Qip)*2*PI
297 Sd: IF ABS(Qip)>PI THEN Boucle
298   ! PRINT Prn,Pin,Qim,Qip
299   SUBEND
300   !*****!
301   SUB Resultats(Ampl(*),Qip(*),F1,I,Center,OPTIONAL Rs(*),Arret)
302   COM /Wind/ Wxi,Wxa,Wyi,Wya,Facteur
303   COM /Gamma/ Gam(*),Pha(*)
304   COM /Quad/ Result(*),Racine(*),M
305   COM /Frequence/ Freq_debut,Freq_fin,Freq_step,Fact,Direct$
306   GRAPHICS ON
307   Theta_debut=0
308   Theta_fin=2*PI
309   Theta_step=(Theta_fin-Theta_debut)/36
310   No_change=1
311   Passe=0
312   VIEWPORT 25,95,15,85
313   IF Arret THEN
314     IF F1 THEN Saut
315     OUTPUT KBD USING "K,#";0,"<"
316     INPUT " O>CRT 1> PLOTTER",Unit
317     IF Unit THEN
318       PLOTTER IS 705,"HPGL"
319       OUTPUT 705;"IN;DF;"
320     ELSE
321       PLOTTER IS CRT,"INTERNAL"
322       GINIT
323     END IF
324   Saut: VIEWPORT 25,95,15,85
325     Wxi=-3
326     Wxa=3
327     Wyi=-3
328     Wya=3
329     Passe=1
330     IF NOT F1 THEN Suite
331     IF F1 THEN Point
332   END IF
333   !IF F1 THEN Point
334   ON KEY 1 LABEL "ZOOM",2 CALL Curseur
335   ON KEY 2 LABEL "CONT",2 GOSUB Suite
336   ON KEY 3 LABEL "NO_CHANGE",2 GOSUB Av_suite
337   ON KEY 4 LABEL "PASSE",2 GOTO Passe
338   ON KEY 5 LABEL "FINI",2 GOTO Final
339   LOOP
340   END LOOP
341   Passe:   !
342     Passe=1
343     GOTO Suite
344   Av_suite:No_change=0
345   Suite:   !
346     GCLEAR
347     Pyi=.8
348     ALPHA OFF
349     ! OUTPUT KBD USING "K,#";Wxi,"",Wxa,"",Wyi,"",Wya
350     ! INPUT "Window",Wxi,Wxa,Wyi,Wya
351     CLIP ON
352     SHOW Wxi,Wxa,Wyi,Wya
353     CLIP Wxi,Wxa,Wyi,Wya

```

```

354 Wx_moy=(Wxi+Wxa)/2
355 Wy_moy=(Wyi+Wya)/2
356 Px=(Wxa-Wxi)/10
357 Py=(Wya-Wyi)/10
358 Facteur=Px1/Px
359 !PEN 2
360 AXES Px,Py,Wxi,Wyi,2,2
361 AXES Px,Py,Wxa,Wya,2,2
362 IF SGN(Wyi)<>SGN(Wya) THEN
363     MOVE 0,Wyi
364     DRAW 0,Wya
365 END IF
366 IF SGN(Wxi)<>SGN(Wxa) THEN
367     MOVE Wxi,0
368     DRAW Wxa,0
369 END IF
370 CLIP OFF
371 CSIZE 2.50
372 LORG 6
373 FOR G=Wxi TO Wxa+Px/10 STEP Px
374     MOVE G,Wyi
375     LABEL PROUND(G,-2)
376 NEXT G
377 LORG 8
378 FOR G=Wyi TO Wya+Py/10 STEP Py
379     MOVE Wxi,G
380     LABEL PROUND(G,-2)
381 NEXT G
382 LORG 4
383 CSIZE 2.5
384 MOVE (Wxi+Wxa)/2,Wya+2/2*Py
385 LABEL "Directivity: "&Direct$&" dB"
386 MOVE (Wxi+Wxa)/2,Wya+Py*2/4
387 LABEL "Phase balance: "&VAL$(ABS(Fact-1)*100)&" %"
388 MOVE (Wxi+Wxa)/2,Wya
389 LABEL "Frequency band: "&VAL$(Freq_debut)&" - "&VAL$(Freq_fin)&" GHz
steps: "&VAL$(Freq_step*1000)&" MHz"
390 CSIZE 2
391 LORG 2
392 MOVE Wxi+Px/2,Wyi+3/2*Py
393 LABEL "q4 *****"
394 MOVE Wxi+Px/2,Wyi+Py*2/2
395 LABEL "q5 00000"
396 MOVE Wxi+Px/2,Wyi+Py/2
397 LABEL "q6 +++++"
398 ! LABEL "q6 ....."
399 LORG 5
400 CSIZE 5.0
401 PEN 1
402 Point: !
403 IF F1 THEN CSIZE 2.0
404 IF Center THEN
405     FOR I=2 TO 4
406         MOVE Ampl(I)*COS(Qip(I)),Ampl(I)*SIN(Qip(I))
407         DRAW Ampl(I)*COS(Qip(I)),Ampl(I)*SIN(Qip(I))
408         !IF I=4 AND F1=0 THEN LABEL "|"
409         IF I=4 THEN LABEL "+"
410         IF I=2 THEN LABEL "*"
411         IF I=3 THEN LABEL 0
412     NEXT I
413 ELSE

```



```

414     FOR I=2 TO 4
415         IF No_change THEN Dessin
416         Quadratique(Ampl(*),Qip(*),I,Rs(*))
417         Xc=Ampl(I)*COS(Qip(I))
418         Yc=Ampl(I)*SIN(Qip(I))
419         Xi=Racine(I,1,1)
420         Xa=Racine(I,2,1)
421         Yi=Racine(I,1,2)
422         Ya=Racine(I,2,2)
423         IF Xi=0 AND Yi=0 AND Xa=0 AND Ya=0 AND M>2 THEN
424             Theta_debut=0
425             Theta_fin=2*PI
426             GOTO Bn
427         END IF
428         Rei=PROUND((Xc-Xi)*(-1),-4)
429         Imi=PROUND((Yc-Yi)*(-1),-4)
430         Rea=PROUND((Xc-Xa)*(-1),-4)
431         Ima=PROUND((Yc-Ya)*(-1),-4)
432         Ppp=PI/2*(1-SGN(Rei))
433         Pp=SGN(Imi)*Ppp
434         Theta_debut=Pp
435         IF Rei THEN Theta_debut=ATN(Imi/Rei)+Pp+Ppp-SGN(Imi)*Pp
436         GOTO Sdi
437 Bouclei:Theta_debut=Theta_debut-SGN(Theta_debut)*2*PI
438 Sdi:     IF ABS(Theta_debut)>PI THEN Bouclei
439         Ppp=PI/2*(1-SGN(Rea))
440         Pp=SGN(Ima)*Ppp
441         Theta_fin=Pp
442         IF Rea THEN Theta_fin=ATN(Ima/Rea)+Pp+Ppp-SGN(Ima)*Pp
443         GOTO Sda
444 Bouclea:Theta_fin=Theta_fin-SGN(Theta_fin)*2*PI
445 Sda:     IF ABS(Theta_fin)>PI THEN Bouclea
446         IF Theta_debut=Theta_fin THEN Theta_debut=Theta_debut+2*PI
447         ! IF Xc>0 THEN Theta_debut=Theta_debut+2*PI
448 Bn:     !
449         ! IF ABS(Theta_debut)>PI/2 THEN Theta_debut=Theta_debut+2*PI
450         ! *SGN(Theta_debut)
451         ! IF ABS(Theta_fin)>PI/2 THEN Theta_fin=Theta_fin+2*PI
452         ! *SGN(Theta_fin)
453         A1=SQR((Racine(I,1,1)-Wx_moy)^2+(Racine(I,1,2)-Wy_moy)^2)
454         Ac=SQR((Xc-Wx_moy)^2+(Yc-Wy_moy)^2)
455         IF Ac<A1 THEN
456             Theta_debut=Theta_debut-2*PI*SGN(Theta_debut)
457         END IF
458         IF Xc>Wxa AND (Racine(I,1,1)<=Wxa OR Racine(I,2,1)<=Wxa) THEN
459             Theta_debut=Theta_debut-2*PI*SGN(Theta_debut)
460             IF Theta_debut=-PI THEN Theta_debut=PI
461         END IF
462         Theta_step=(Theta_fin-Theta_debut)/50
463 Dessin: !
464         MOVE Xc,Yc
465         LABEL "O"
466         ! CLIP ON
467         ALPHA OFF
468         FOR Angle=Theta_debut TO Theta_fin STEP Theta_step
469             MOVE Xc+Rs(I)*COS(Angle),Yc+Rs(I)*SIN(Angle)
470             DRAW Xc+Rs(I)*COS(Angle),Yc+Rs(I)*SIN(Angle)
471         NEXT Angle
472     NEXT I
473 END IF
474 IF NOT Passe THEN RETURN

```

```

473 Final:      !
474     ALPHA ON
475     Fl=1
476     OFF KEY
477     SUBEND
478     SUB Curseur
479     VIEWPORT 25,95,20,90
480     COM /Wind/ Wxi,Wxa,Wyi,Wya,Facteur
481     GRAPHICS INPUT IS KBD,"ARROW KEYS"
482     PLOTTER IS CRT,"INTERNAL"
483     SET LOCATOR X,Y
484     TRACK 3 IS ON
485     DIGITIZE X,Y
486     TRACK 3 IS OFF
487     Xi=Wxi
488     Xa=Wxa
489     Yi=Wyi
490     Ya=Wya
491     Q=1
492     LOOP
493     ON KEY 1 LABEL "POIDS: "&VAL$(Q),3 GOSUB Poids_aug
494     ON KEY 11,3 GOSUB Poids_dim
495     ON KEY 6 LABEL "FRAME",3 GOSUB Clipping
496     ON KEY 5 LABEL "CORRECT",3 GOTO Fsd
497     ON KEY 7 LABEL "INCXI: "&VAL$(Incx),3 GOSUB Increment_xi
498     ON KEY 17,3 GOSUB Decrement_xi
499     ON KEY 8 LABEL "INCYI: "&VAL$(Incy),3 GOSUB Increment_yi
500     ON KEY 18,3 GOSUB Decrement_yi
501     ON KEY 9 LABEL "INCXA: "&VAL$(Incx),3 GOSUB Increment_xa
502     ON KEY 19,3 GOSUB Decrement_xa
503     ON KEY 4 LABEL "INCYA: "&VAL$(Incy),3 GOSUB Increment_ya
504     ON KEY 14,3 GOSUB Decrement_ya
505     END LOOP
506 Fsd:      !
507     OFF KNOB
508     Facteur=MAX((Wxa-Wxi)/(Xa-Xi),(Wya-Wyi)/(Yi-Ya))
509     OUTPUT KBD USING "K,#";Facteur
510     INPUT "FACTEUR",Facteur
511     Wxi=Xi
512     Wxa=Xa
513     Wyi=Yi
514     Wya=Ya
515     SUBEXIT
516 Clipping:  !
517     WAIT 1
518     PEN -1
519     FRAME
520     PEN 1
521     Prox=Wxa-Wxi
522     Proy=Wya-Wyi
523     Xi=(X-Wxi)/Prox*Incx/Q+Wxi
524     Xa=(Wxa-X)/Prox*Incx/Q+Wxa
525     Yi=(Y-Wyi)/Proy*Incy/Q+Wyi
526     Ya=(Wya-Y)/Proy*Incy/Q+Wya
527     CLIP Xi,Xa,Yi,Ya
528     FRAME
529     RETURN
530 Poids_aug:  !
531     Q=Q*10
532     RETURN
533 Poids_dim:  !

```

```

534     Q=Q/10
535     RETURN
536 Increment_xi:  !
537     Incxi=Incxi+1
538     RETURN
539 Decrement_xi:  !
540     Incxi=Incxi-1
541     RETURN
542 Increment_yi:  !
543     Incyi=Incyi+1
544     RETURN
545 Decrement_yi:  !
546     Incyi=Incyi-1
547     RETURN
548 Increment_xa:  !
549     Incxa=Incxa+1
550     RETURN
551 Decrement_xa:  !
552     Incxa=Incxa-1
553     RETURN
554 Increment_ya:  !
555     Incya=Incyi+1
556     RETURN
557 Decrement_ya:  !
558     Incya=Incyi-1
559     RETURN
560 SUBEND
561 !#####
562 SUB Quadratique(Ampl(*),Qip(*),K,Rs(*))
563     OPTION BASE 1
564     COM /Wind/ Wxi,Wxa,Wyi,Wya,Facteur
565     COM /Quad/ Result(*),Racine(*),M
566     MAT Result= (0)
567     MAT Racine= (0)
568     Reim(1)=Ampl(K)*COS(Qip(K))
569     Reim(2)=Ampl(K)*SIN(Qip(K))
570     Wind(1,1)=Wxi
571     Wind(1,2)=Wxa
572     Wind(2,1)=Wyi
573     Wind(2,2)=Wya
574     M=0
575     FOR I=1 TO 2
576         M1=I
577         M2=3-I
578         FOR J=1 TO 2
579             B=-2*Reim(I)
580             Ac=(-B/2)^2+(Wind(3-I,J)-Reim(3-I))^2-Rs(K)^2
581             Radical=B^2-4*Ac
582             IF Radical>=0 THEN
583                 Ra=SQR(Radical)
584                 Te=-(B+Ra)/2
585                 Result(2*(I-1)+J,1)=Te
586                 IF Wind(I,1)<=Te AND Te<=Wind(I,2) THEN
587                     M=M+1
588                     Racine(K,M,M1)=Te
589                     Racine(K,M,M2)=Wind(3-I,J)
590                 END IF
591                 Tee=-(B-Ra)/2
592                 Result(2*(I-1)+J,2)=Tee
593                 IF Wind(I,1)<=Tee AND Tee<=Wind(I,2) THEN
594                     M=M+1

```

```
595         Racine(K,M,M1)=Tee
596         Racine(K,M,M2)=Wind(3-I,J)
597     END IF
598 ELSE
599     Ra=SQR(-Radical)
600     Result(2*(I-1)+J,3)=-B/2
601     Result(2*(I-1)+J,4)=Ra/2
602 END IF
603     ! PRINT USING "4(3D.3D,X)";Result(2*(I-1)+J,1),
        Result(2*(I-1)+J,2),Result(2*(I-1)+J,3),Result(2*(I-1)+J,4)
604 NEXT J
605 NEXT I
606 ! PRINT USING "4(3D.3D,X)";Racine(*)
607 PRINT
608 PAUSE
609 SUBEND
```

```

PROGRAM No. 10

PROGRA CALIBRATION

C
C NUMBER OF STANDARDS, POINTS OF FREQUENCIES, THE STEP OF POINTS
C OF FREQUENCIES, NUMBER OF RESAUSES,
C MAX DIMENSION OF MATRICES
C
C RESOLUTION OF NON LINEAIRE SYSTEME BY OPTIMIZATION
C IMPLICIT REAL (A-H)
C IMPLICIT REAL (O-Z)
C
C Modification for read format P
C
C PARAMETER(NSTD=13, NFREQ= 201, NPAS=1, NLIN=9)
C PARAMETER(NMAX=20, NNLIN=5)
C EXTERNAL FCN
C EXTERNAL LSJAC
C
C VARIABLES GENERALES
C INTEGER I, J, K
C INTEGER FR, NFR
C FICHER DE PUISSANCE
C REAL PSTD(NSTD, NFREQ, 4)
C MATRICE LINEARISEE
C INTEGER STDVEC(NMAX)
C REAL ALIN(NMAX, NMAX), BLIN(NMAX), X(NMAX), X1(NMAX)
C SOLUTION DU SYSTEME SURDETERMINE
C REAL TOL, RES(NMAX), FAC(NMAX, NMAX), RCOND
C INTEGER KBASIS, IPVT(NMAX)
C COEFFICIENTS DE CALIBRATION
C 1=P, 2=Q, 3=R, 4=A2, 5=B2
C REAL SOL(NNLIN), SOL1(NNLIN)
C PUISSANCES NORMALISEES POUR EQUATION NON-LINEAIRE
C REAL FCNQ
C COMMON /FCOEF/FCNQ(NSTD, 3)
C CHOIX DES EQUATION QUI FONT PARTIE DU SYS D'EQ NON-LIN
C INTEGER EQSYS(NSTD), NBSTD
C SOLUTION DU SYSTEME NON-LINEAIRE
C NORME DE L'ERREUR APRES SOLUTION
C REAL FNORM, XSCALE(NNLIN), FSCALE(NSTD), FVEC(NSTD), FJAC(NSTD, NNLIN)
C INTEGER ERRCOD, ERRSOL, INDEQ
C PARAMETRES D'OPTIMISATION
C REAL RPARAM(7)
C INTEGER IPARAM(6), ELIM
C DATA XSCALE/NNLIN*1.0/, FSCALE/NSTD*1.0/
C
C OPEN(7, FILE='w.dat')
C ELIM=0
C WRITE(7, *) NFR
C PARAMETRES STANDARDS P.843 IMSL
C IPARAM(1)=0
C LECTURE DE LA MATRICE DE PUISSANCE
C READ(5, *) (((PSTD(I, K, J), J=1, 4), K=1, NFREQ), I=1, NSTD)
C DO 100 FR=1, NFREQ, NPAS
C IF (PSTD(1, FR, 1).NE.0.0) THEN
C WRITE(6, '(//, A, I4, 2X, F5.2, /)') ' FREQUENCE: ', FR
C CONSTRUCTION DU SYSTEME LINEAIRE .
C CHOISIR LES EQUATION QUI FERONT PARTIE DU SYSTEME
C BOUCLE D'ESSAI DE 9 EQUATIONS PARMIS 13
C DO 111 J1=1, NSTD-8

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```

DO 111 J2=J1+1,NSTD-7
DO 111 J3=J2+1,NSTD-6
DO 111 J4=J3+1,NSTD-5
DO 111 J5=J4+1,NSTD-4
DO 111 J6=J5+1,NSTD-3
DO 111 J7=J6+1,NSTD-2
DO 111 J8=J7+1,NSTD-1
DO 111 J9=J8+1,NSTD
STDVEC(1)=J1
STDVEC(2)=J2
STDVEC(3)=J3
STDVEC(4)=J4
STDVEC(5)=J5
STDVEC(6)=J6
STDVEC(7)=J7
STDVEC(8)=J8
STDVEC(9)=J9
CALL SYSLIN(PSTD, NSTD, NFREQ, FR, STDVEC, ALIN,
& BLIN, NMAX)
C
C SOLUTION DU SYSTEME LINEAIRE
C
C CALL LSQRR(9, NLIN, ALIN, NMAX, BLIN, TOL, X, RES, KBASIS)
C
C CALCULS DES COEFFICIENTS. PREMIERE APROXIMATION
C 1=P, 2=Q, 3=R, 4=A2, 5=B2
ERRSOL=0
IF ((X(2).LT.0.).OR.(X(3).LT.0.).OR.(X(1).EQ.0)) THEN
WRITE(6,*) '----- PAS DE SOLUTION LINEAIRE'
C WRITE(7,'(1X,F5.2,A,/)') FR,
C & k '----- PAS DE SOLUTION LINEAIRE'
C
C UTILISATION D'UNE ANCIENNE SOLUTION SI POSSIBLE
C
ERRSOL=1
ELSE
SOL(3)=(2*X(5)-X(7)*X(9))/(2*X(1)*X(9)-X(5)*X(7))
SOL(2)=(2*X(4)-X(7)*X(8))/(2*X(1)*X(8)-X(4)*X(7))
SOL(1)=SOL(2)+SOL(3)+(X(7)/X(1))
IF((SOL(1).LT.0.).OR.(SOL(2).LT.0.).OR.(SOL(3).LT.0)) THEN
WRITE(6,'(A,/)') '----- SOLUTION LINEAIRE NON VALIDE'
C
C UTILISATION D'UNE ANCIENNE SOLUTION SI POSSIBLE
C
ERRSOL=2
ENDIF
ENDIF
C
C RECUPERATION D'UNE VIEILLE SOLUTION
C
IF ( ERRSOL.NE.0) THEN
DO 125 I=1,NNLIN
SOL(I)=X1(I)
125 CONTINUE
ELSE
SOL(4)=SQRT(SOL(1)*SOL(3)*X(2))
SOL(5)=SQRT(SOL(1)*SOL(2)*X(3))
C DO 127 I=1,NNLIN
C X1(I)=SOL(I)
C127 CONTINUE
ENDIF

```

```

WRITE(6, '(A,5(2X,F14.5),/)' ) ' PQRAB APROX: ', (SOL(I), I=1,5)
DO 170 I=1,NNLIN
  SOL1(I)=SOL(I)
170 CONTINUE
C
C EQUATIONS QUI CONSTITUENT LE SYSTEME NON-LINEAIRE
DO 180 I=1,NSTD
  EQSYS(I)=I
180 CONTINUE
C COEFFICIENTS
CALL CALCQ(PSTD, NSTD, NFREQ, FR, EQSYS)
C VALEUR DE DEPART DE L'EQUATION
CALL FCN(NSTD,NNLIN,SOL,X)
FNORM=0.
IF (ELIM.EQ.1) THEN
C ELIMINATION D'UNE EQUATION
DO 130 I=1,NSTD
  IF (FNORM.LT.ABS(X(I))) THEN
    FNORM=ABS(X(I))
    NEQU=I
  ENDIF
  WRITE(6, '(A,I3,2X,F10.7)' ) ' EQUATION NO.', I, X(I)
130 CONTINUE
  WRITE(6, '(A,I4)' ) ' EQUATION ELIMINEE: ', NEQU
  NBSTD=NSTD-1
  DO 135 I=NEQU,NBSTD
    EQSYS(I)=EQSYS(I+1)
135 CONTINUE
  ELSE
    NBSTD=NSTD
  ENDIF
C CALCUL DES NOUVELLES VALEURS DE DEPART
CALL CALCQ(PSTD, NSTD, NFREQ, FR, EQSYS)
CALL FCN(NBSTD,NNLIN,SOL,X)
C
C PARAMETRES DE DEPART STANDARDS P.843
C IPARAM(1)=0
C IPARAM(1)=0
C
CALL U4LSF(IPARAM, RPARAM)
C
C AUGMENTATION DES CRITERES D'OPTIMISATION
C
C IPARAM(2)=8
C RPARAM(1)=RPARAM(1)/1000.0
C RPARAM(2)=RPARAM(2)/1000.0
C RPARAM(4)=RPARAM(4)/1000.0
C
C
C SOLUTION DE L'EQUATION NON-LINEAIRE
C
C EMPECHER LES ERREURS D'INTERROMPRE LE PROG
CALL ERSET(4,0,0)
CALL UNLSJ(FCN,LSJAC,NBSTD,NNLIN,SOL,XSCALE,FSCALE,IPARAM,
& RPARAM,X,FVEC,FJAC,NBSTD)
ERRCOD=IERCD()
CALL ERSET(0,2,2)
C WRITE(6, '(A,6(I6,2X))' ) ' IPARAM', (IPARAM(I), I=1,6)
C WRITE(6, '(A,7(F10.6,2X))' ) ' RPARAM', (RPARAM(I), I=1,7)

```

```

IF (ERRCOD .GT. 0) THEN
  WRITE(6,*) ' *** ERREUR SUB UNLSJ, CODE: ',ERRCOD,' ***'
END IF
WRITE(6,'(/,A,5(2X,F14.5),/)' ) ' PQRAB ITERATIF:',
& (X(I),I=1,NNLIN)
IF(X(1).LE.0.01 .OR. X(2).LE.0.01 .OR. X(3).LE.0.01 .OR.
& X(4).LE.0.01 .OR. X(5).LE.0.01) THEN
  GOTO 111
ELSE
WRITE(7,'(1X,I3,5(A,F12.7))' ) FR,',',X(1),',',X(2),',',X(3),
& ',',X(4),',',X(5)
CALL FCN(NBSTD,NNLIN,X,SOL)
FNORM=0.
DO 161 I=1,NNLIN
  X1(I)=X(I)
161 CONTINUE
DO 160 I=1,NBSTD
  WRITE(6,'(A,I3,2X,F10.7)' ) ' EQUATION NO.',I,SOL(I)
  FNORM=FNORM+SOL(I)*SOL(I)
160 CONTINUE
WRITE(6,'(A,E10.3)' ) ' ERREUR FIN FCN: ',SQRT(FNORM)
GOTO 112
ENDIF
111 CONTINUE
112 CONTINUE
ENDIF
100 CONTINUE
CLOSE(7)
STOP
END

```

```

C
C CONSTRUCTION DU SYSTEME LINEAIRE SELON L'EQUATION
C 3.11, P14.
C NBSTD: NOMBRE DE STANDARDS UTILISES
C STDVEC: CONTIENT LES NUMEROS DES STANDARDS A UTILISER

```

```

SUBROUTINE SYSLIN(PSTD, NSTD, NFREQ, FR, STDVEC, ALIN,
& BLIN, NMAX)
REAL PSTD(NSTD, NFREQ, 4)
REAL ALIN(NMAX, NMAX)
REAL BLIN(NMAX)
INTEGER FR, STDVEC(NMAX)
INTEGER I
REAL Q1, Q2, Q3

```

```

DO 100 I=1,9
C PUISSANCES NORMALISEES
C DES STD DESIGNES PAR STDVEC
Q1=PSTD(STDVEC(I),FR,2)/PSTD(STDVEC(I),FR,1)
Q2=PSTD(STDVEC(I),FR,3)/PSTD(STDVEC(I),FR,1)
Q3=PSTD(STDVEC(I),FR,4)/PSTD(STDVEC(I),FR,1)
C MATRICE A
ALIN(I,1)=Q1*Q1
ALIN(I,2)=Q2*Q2
ALIN(I,3)=Q3*Q3
ALIN(I,4)=Q1*Q2
ALIN(I,5)=Q1*Q3
ALIN(I,6)=Q2*Q3
ALIN(I,7)=Q1

```



```

      ALIN(I,8)=Q2
      ALIN(I,9)=Q3
C      MATRICE B
      BLIN(I)=-1.
100    CONTINUE
      RETURN
      END

C      CALCUL DES COEFFICIENTS NORMALISES Q1,Q2,Q3 POUR LES EQ NON-LIN
      SUBROUTINE CALCQ(PSTD, NSTD, NFREQ, FR, EQSYS)
      INTEGER NSTD, NFREQ, EQSYS(NSTD), I, FR
      REAL PSTD(NSTD, NFREQ, 4), FCNQ
      COMMON /FCOEF/FCNQ(13,3)

      DO 100 I=1,NSTD
        FCNQ(I,1)=PSTD(EQSYS(I), FR, 2)/PSTD(EQSYS(I), FR, 1)
        FCNQ(I,2)=PSTD(EQSYS(I), FR, 3)/PSTD(EQSYS(I), FR, 1)
        FCNQ(I,3)=PSTD(EQSYS(I), FR, 4)/PSTD(EQSYS(I), FR, 1)
100    CONTINUE
      RETURN
      END

C      FONCTION NON-LINEAIRE A RESOUDRE
      SUBROUTINE FCN(M,N,X,F)
      INTEGER N,M,I
      REAL X(N), F(M)
      REAL FCNQ
      COMMON /FCOEF/FCNQ(13,3)

      DO 100 I=1,M
        F(I)=X(1)*FCNQ(I,1)*FCNQ(I,1)
        &      +X(2)*X(4)*X(4)*FCNQ(I,2)*FCNQ(I,2)
        &      +X(3)*X(5)*X(5)*FCNQ(I,3)*FCNQ(I,3)
        &      +(X(3)-X(1)-X(2))*X(4)*FCNQ(I,1)*FCNQ(I,2)
        &      +(X(2)-X(1)-X(3))*X(5)*FCNQ(I,1)*FCNQ(I,3)
        &      +(X(1)-X(2)-X(3))*X(4)*X(5)*FCNQ(I,2)*FCNQ(I,3)
        &      +X(1)*(X(1)-X(2)-X(3))*FCNQ(I,1)
        &      +X(2)*(X(2)-X(1)-X(3))*X(4)*FCNQ(I,2)
        &      +X(3)*(X(3)-X(1)-X(2))*X(5)*FCNQ(I,3)
        &      +X(1)*X(2)*X(3)
100    CONTINUE
      RETURN
      END

C      CALCUL DU JACOBIEN DE FCN
      SUBROUTINE LSJAC(M,N,X,FJAC,LDFJAC)
      INTEGER N,M,LDFJAC,I
      REAL X(N),FJAC(LDFJAC,N),Q
      COMMON /FCOEF/Q(13,3)

      DO 100 I=1,M
        FJAC(I,1)=Q(I,1)*Q(I,1) - X(4)*Q(I,1)*Q(I,2)
        &      -X(5)*Q(I,1)*Q(I,3)
        &      +X(4)*X(5)*Q(I,2)*Q(I,3) + (2*X(1)-X(2)-X(3))*Q(I,1)
        &      -X(2)*X(4)*Q(I,2) - X(3)*X(5)*Q(I,3) + X(2)*X(3)
        FJAC(I,2)=X(4)*X(4)*Q(I,2)*Q(I,2) - X(4)*Q(I,1)*Q(I,2)
        &      +X(5)*Q(I,1)*Q(I,3) - X(4)*X(5)*Q(I,2)*Q(I,3)
        &      -X(1)*Q(I,1) + (2*X(2)-X(1)-X(3))*X(4)*Q(I,2)
        &      -X(3)*X(5)*Q(I,3) + X(1)*X(3)
        FJAC(I,3)=X(5)*X(5)*Q(I,3)*Q(I,3) + X(4)*Q(I,1)*Q(I,2)
        &      -X(5)*Q(I,1)*Q(I,3) - X(4)*X(5)*Q(I,2)*Q(I,3)

```

```
&          -X(1)*Q(I,1) -      X(2)*X(4)*Q(I,2)
&          +(2*X(3)-X(1)-X(2))*X(5)*Q(I,3) + X(1)*X(2)
FJAC(I,4)=X(2)*2*X(4)*Q(I,2)*Q(I,2)
&          +(X(3)-X(1)-X(2))*Q(I,1)*Q(I,2)
&          +(X(1)-X(2)-X(3))*X(5)*Q(I,2)*Q(I,3)
&          +X(2)*(X(2)-X(1)-X(3))*Q(I,2)
FJAC(I,5)=2*X(5)*X(3)*Q(I,3)*Q(I,3)
&          +(X(2)-X(1)-X(3))*Q(I,1)*Q(I,3)
&          +(X(1)-X(2)-X(3))*X(4)*Q(I,2)*Q(I,3)
&          +X(3)*(X(3)-X(1)-X(2))*Q(I,3)
100  CONTINUE
      RETURN
      END
```

PROGRAM No. 11

```

1!  NOM:  "QPNTS_W"
2    !
4    !
5    !   Program to calculate Qi points from parameters of calibration
6    !   C, D, E and P, Q, R, A2, B2
7    !
8    !   Ajout des rapports dans le calcul des points (standard #1)
9 !   FIND " SUB Home"
10   !
11  OPTION BASE 1
12  DEG
13  COM /Boite/ COMPLEX C(201),D(201),E(201),INTEGER Sgn(201),Max_points,
REAL P(201),Q(201),R(201),A2(201),B2(201),Pmes(13,201,4)
14  COM /Point/ COMPLEX Q4(201),Q5(201),Q6(201)
15  COM /File/ REAL Npas,F_q$[20],F_puiss$[20],F_bte_b$[20],F_cal$[20]
16  !
17  REAL M,N,Alp,Alp1,X1,X2,X3,X4,E5,E6,F4,G4,F5,G5,F6,G6
18  REAL Dr,Di,Cr,Ci,Er,Ei
19  INTEGER F,I,J,K,Rapp,L
20  DIM Fichier$[20],A$[80]
21  REDIM C(28),D(28),E(28),Sgn(28),P(28),Q(28),R(28),A2(28),B2(28),
Pmes(13,28,4)
23  !
24  Med=CRT
25  Rapp=1
26  Max_points=28   ! Grosseur des matrices de donnees
27  Npas=1         ! Pas dans la boucle de frequences
28  IF Sgn(1)=0 THEN
29    F_bte_b$="B3HP24:,700,1"
30    F_cal$="W3HP24:,700,1"
31    F_puis$="P3HP24:,700,1"
32    F_q$="Q4HP:,700,1"
33    MAT Sgn= (1)
34  END IF
35  ON KEY 5 GOSUB Lis_bte_b
36  ON KEY 6 GOSUB Lis_cal
37  ON KEY 16 GOSUB Lis_puiss
38  ON KEY 7 GOSUB Calcul_q
39  ON KEY 8 GOSUB Print_q
40  ON KEY 18 GOSUB Sauve_q
41 Menu:  !
42  Home
43  LOOP
44    PRINT TABXY(1,2);"Programme de calcul des points Qi"
45    PRINT TABXY(1,9);"Cle 5:   Lire Boite d'erreur format B"
46    PRINT TABXY(1,10);"Cle 6/16: Lire Calibration (w)/ Lire puissance
(format P)"
47    PRINT TABXY(1,11);"Cle 7:   Calcul des points Qi"
48    PRINT TABXY(1,12);"Cle 8/18: Impression des points Qi/Sauve points q"
49  END LOOP
50  !
51 Lis_bte_b: !
52  Home
53 Aab:OUTPUT KBD USING "K,#";F_bte_b$
54  LINPUT "Fichier de boite d'erreur a lire: ",Fichier$
55  IF Fichier$="" THEN
56    GOTO Menu
57  ELSE
58    F_bte_b$=Fichier$

```

```

59   END IF
60   ON ERROR GOTO Lbtebug_b
61   ASSIGN @Ff TO F_bte$
62   ENTER @Ff;Fd,Ff,Fp,Max_point
63   ENTER @Ff;C(*),D(*),E(*),Sgn(*)
64   ASSIGN @Ff TO *
65   OFF ERROR
66   RETURN
67 Lbtebug_b:  !
68   SELECT ERRN
69   CASE 56  ! File name is undefined
70     BEEP
71     PRINT TABXY(1,18);ERRM$
72     GOTO Aab
73   CASE ELSE
74     DISP ERRM$
75     BEEP
76     PAUSE
77   END SELECT
78   OFF ERROR
79   RETURN
80   !
81   !
82 Lis_cal:  !
83   Home
84 Aag:OUTPUT KBD USING "K,#";F_cal$
85   LINPUT "Fichier de calibration a lire: ",Fichier$
86   IF Fichier$="" THEN
87     GOTO Menu
88   ELSE
89     F_bte$=Fichier$
90   END IF
91   ON ERROR GOTO Lcalbug
92   ASSIGN @Ff TO F_bte$
93   ENTER @Ff;Fd,Ff,Fp,Sp,Puissance_cal
94   ENTER @Ff;P(*),Q(*),R(*),A2(*),B2(*)
95   ASSIGN @Ff TO *
96   OFF ERROR
97   RETURN
98   RETURN
99 Lcalbug:  !
100  SELECT ERRN
101  CASE 56  ! File name is undefined
102    BEEP
103    PRINT TABXY(1,18);ERRM$
104    GOTO Aag
105  CASE ELSE
106    DISP ERRM$
107    BEEP
108    PAUSE
109  END SELECT
110  OFF ERROR
111  RETURN
112  !
113 Lis_puiss:  !
114   Home
115 Aah:OUTPUT KBD USING "K,#";F_puis$
116   LINPUT "Fichier de puissance a lire: ",Fichier$
117   IF Fichier$="" THEN
118     GOTO Menu
119   ELSE
120     F_puis$=Fichier$

```

```

121 END IF
122 ON ERROR GOTO Lpuibug
123 ASSIGN @Ff TO F_puis$
124 ENTER @Ff;Fd,Ff,Fp,Max_point
126 ENTER @Ff;Pmes(*)
127 ASSIGN @Ff TO *
128 OFF ERROR
129 RETURN
130 Lpuibug: !
131 SELECT ERRN
132 CASE 56 ! File name is undefined
133 BEEP
134 PRINT TABXY(1,18);ERRM$
135 GOTO Aah
136 CASE ELSE
137 DISP ERRM$
138 BEEP
139 PAUSE
140 END SELECT
141 OFF ERROR
142 RETURN
143 !
144 Sauve_q: !
145 Home
146 Aaq:OUTPUT KBD USING "K,#";F_q$
147 LINPUT "Fichier de points Qi a sauver: ",Fichier$
148 IF Fichier$="" THEN
149 GOTO Menu
150 ELSE
151 F_q$=Fichier$
152 END IF
153 ON ERROR GOTO Lqbug
154 Aaq1: !
155 CREATE ASCII F_q$,Max_points/Npas+1
156 ASSIGN @Ff TO F_q$
157 FOR I=1 TO Max_points STEP Npas
158 A$=VAL$(PROND(I,0))&" "&VAL$(PROND(ABS(Q4(I)),-4))&" "&VAL
$(PROND(ARG(Q4(I)),-2))&" "&VAL$(PROND(ABS(Q5(I)),-4))&" "&
VAL$(PROND(ARG(Q5(I)),-2))
159 A$=A$&" "&VAL$(PROND(ABS(Q6(I)),-4))&" "&VAL$(PROND(ARG(Q6(I)),-2))
160 OUTPUT @Ff;A$
161 NEXT I
162 ASSIGN @Ff TO *
163 OFF ERROR
164 RETURN
165 Lqbug: !
166 SELECT ERRN
167 CASE 56 ! File name is undefined
168 BEEP
169 PRINT TABXY(1,18);ERRM$
170 GOTO Aaq
171 CASE 54 ! Duplicate file name
172 PURGE F_q$
173 GOTO Aaq1
174 CASE ELSE
175 DISP ERRM$
176 BEEP
177 PAUSE
178 END SELECT
179 OFF ERROR
180 RETURN

```

```

181      !
182 Calcul_q:  !
183          L=13
184      FOR I=1 TO Max_points STEP Npas
185      IF P(I)<>0 THEN !AND I<>151 THEN
186          IF Rapp=1 THEN
187              W4=Pmes(L,I,2)/Pmes(L,I,1)
188              W5=Pmes(L,I,3)/Pmes(L,I,1)
189              W6=Pmes(L,I,4)/Pmes(L,I,1)
190          ELSE
191              W4=0
192              W5=0
193              W6=0
194          END IF
195          !
196          M=SQR(R(I))
197          N=SQR(Q(I))
198          Alp=(P(I)-Q(I)-R(I))/(2*SQR(Q(I)*R(I)))
199          Alp1=SQR(1-PROUND(Alp,-3)^2)*Sgn(I)
200          !
201          ! POINT Q4
202          Q4(I)=-E(I)/D(I)
203          !
204          ! POINT Q5
205          Q5(I)=(E(I)-M)/(C(I)*M-D(I))
206          !
207          ! POINT Q6
208          Q6(I)=(E(I)-N*CMLX(-Alp,Alp1))/(C(I)*N*CMLX(-Alp,Alp1)-D(I))
209          !
210          END IF
211      NEXT I
212      !
213      BEEP 3000,1
214      RETURN
215      !
216      !
217 Print_q:  !
218      Home
219      FOR I=1 TO Max_points STEP Npas
220      IF (P(I)<>0) THEN
221          OUTPUT Med USING "X,3D,4X,3(4D.4D,X,4D.2D,2X)";I,ABS(Q4(I)),
                ARG(Q4(I)),ABS(Q5(I)),ARG(Q5(I)),ABS(Q6(I)),ARG(Q6(I))
222      END IF
223      NEXT I
224      PAUSE
225      Home
226      RETURN
227      !
228      END
229      !
230      SUB Home
231          GCLEAR
232          OUTPUT 2 USING "K,#";"K"
233      SUBEND
234      !

```

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