



Titre: Photonic Lantern Engineering for Spatial Mode Control in Fiber-Based Biomedical Imaging
Title:

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Author:

Date: 2026

Type: Mémoire ou thèse / Dissertation or Thesis

Référence: Becerra Deana, R. I. (2026). Photonic Lantern Engineering for Spatial Mode Control in Fiber-Based Biomedical Imaging [Thèse de doctorat, Polytechnique Montréal]. PolyPublie. <https://publications.polymtl.ca/76628/>
Citation:

 **Document en libre accès dans PolyPublie**
Open Access document in PolyPublie

URL de PolyPublie: <https://publications.polymtl.ca/76628/>
PolyPublie URL:

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Programme: Génie biomédical
Program:

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

**Photonic Lantern Engineering for Spatial Mode Control in Fiber-Based
Biomedical Imaging**

RODRIGO ITZAMNA BECERRA DEANA

Institut de génie biomédical

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*
Génie biomédical

Avril 2026

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cette thèse intitulée :

**Photonic Lantern Engineering for Spatial Mode Control in Fiber-Based
Biomedical Imaging**

présentée par **Rodrigo Itzamna BECERRA DEANA**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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DEDICATION

*To Sara, my family and friends,
Ma, Robin, Chel, Hassas, Gabo, Nala, y Drako =)*

ACKNOWLEDGEMENTS

Grateful to have Sara's support in all my adventures, especially on this journey.
 Really thankful to have Stéphane Virally; this project wouldn't have been possible.
 Acknowledgments to Caroline for everything she taught me in every fields and aspects of life.
 Content knowing I have another expert co-supervisor in the area, Nicolas Godbout.
 I appreciate all my mentors in every area who helped me complete this project.
 Appreciation for all the help and support from the incredible team at Castor Optics.
 Surrounded by incredible people, especially all my colleagues at Polytechnique.

Friends on this journey become family.
 Amazing to live in Montréal and enjoy each of the seasons.
 Mom and Dad, I love you.
 In my heart, this project will always remain.
 Loving my family for all their affection and for always being there for me.
 Infinite thanks to all the people who helped me grow into the person I am.
 Award of my PhD.

Thanks to all my colleagues and lab mates for the adventures and help. Special thanks to Raphaël Maltais-Tariant, Martin Poinsinet de Sivry-Houle, Collin Dietrich, Alexis Séguin, Simon Brais Brunet, Sarah Albos, Khaliun Erdenedalai, Xavier Attendu, Valérie Monette, Joseph Lamarre, Édith Ducharme, and to each of the interns who passed through the LFO, LODI, and FemtoQ groups. I want to thank the jury members for taking the time to read my thesis and helping me improve it. Also, I want to thank all my Hispanic community and Montreal family: Sara (again!), Gissel, Salvador, Javier Martínez, Sandra, Eduardo, Adriana, Beto, Lydia, Juanita, Alfredo, Alexa, Javier Bustamante, Marely, Mariana, Matías, and everyone who has been there, even far from Mexico: Anto, Juanpi, Farid, and Sam. Mom, Dad, Chel, Hassas, and Gabo, I am really happy to have you in my life. Sara, thanks =)

RÉSUMÉ

Cette thèse explore le développement, la caractérisation et l'utilisation des lanternes photoniques, en particulier des lanternes photoniques modalement sélectives, afin de relever des défis majeurs en imagerie biomédicale. Cette recherche est motivée par la demande croissante en résolution, en vitesse et en contraste dans des techniques d'imagerie telles que la microscopie confocale et la tomographie par cohérence optique. Bien que les technologies de fibres optiques aient été longuement optimisées pour les télécommunications, leur transposition vers la biophotonique a rencontré des obstacles spécifiques en raison des différences de contraintes opérationnelles, des protocoles de fabrication et des défis d'intégration. Ce travail comble ces lacunes en adaptant et en améliorant les technologies de lanternes photoniques pour une utilisation dans des environnements biomédicaux.

Cette thèse émet l'hypothèse que des coupleurs à fibres spécialisés, appelés lanternes photoniques, peuvent améliorer de manière significative la collecte sélective des signaux optiques dans des configurations à quelques modes, en exploitant des caractéristiques de l'échantillon telles que la rétrodiffusion, les variations de phase et la distribution des vecteurs d'onde, afin d'accroître la résolution et le contraste d'imagerie. En minimisant les pertes excédentaires, ces coupleurs peuvent être intégrés efficacement dans des systèmes d'imagerie pratiques. L'objectif général est de développer des lanternes photoniques compactes et performantes, puis de les intégrer dans des systèmes de microscopie confocale et de tomographie par cohérence optique, permettant ainsi une imagerie multimodale au-delà du mode fondamental.

La thèse débute par l'établissement du cadre scientifique et des principes fondamentaux de l'optique des fibres et des architectures des lanternes photoniques, en s'appuyant sur une revue approfondie de la littérature. Cette revue synthétise l'évolution de la théorie de la propagation de la lumière, des dispositifs de multiplexage et du rôle des composants fibrés dans l'émergence de modalités d'imagerie multimodales. Elle met en évidence les limitations des multiplexeurs optiques traditionnels, telles que leur faible efficacité et leur évolutivité limitée dans des configurations en espace libre ou planaires, et démontre les avantages des lanternes photoniques intégrées en fibre en termes de compacité, de robustesse et d'efficacité de propagation lumineuse. Une attention particulière est accordée à l'émergence des lanternes photoniques dans des domaines dépassant les télécommunications, notamment à leur potentiel transformateur en imagerie biomédicale, où la flexibilité et la miniaturisation sont essentielles.

Une contribution centrale de cette thèse réside dans la conception, la fabrication et la car-

actérisation systématique de lanternes photoniques à trois modes, incluant des dispositifs conventionnels, des lanternes photoniques modalement sélectives et des architectures hybrides. En combinant modélisation théorique, basée sur la théorie des modes couplés et des outils de simulation développés spécifiquement, et validation expérimentale, ce travail met en évidence l’influence de paramètres de conception subtils — tels que la géométrie des fibres, la longueur de l’effilage et le choix des matériaux — sur le couplage modal, les pertes et les performances globales. L’introduction de fibres à double gaine et de techniques optimisées de fusion-étirage permettent la réalisation de lanternes photoniques modalement sélectives présentant à la fois une forte isolation modale, de faibles pertes et une compatibilité avec les systèmes fibrés monomodes standards. Ces avancées sont validées par des protocoles expérimentaux rigoureux, une surveillance en temps réel et des analyses en champ lointain confirmant la génération et la propagation stable de plusieurs modes linéairement polarisés.

La thèse étudie également l’impact de la polarisation et de la longueur d’onde sur les performances des lanternes photoniques, en fournissant un cadre analytique détaillé pour comprendre la réponse de différentes configurations. Les résultats expérimentaux montrent que les dispositifs de lanternes photoniques modalement sélectives conservent des profils de sortie stables sur une large gamme de polarisations et de longueurs d’onde, tandis que les conceptions conventionnelles se révèlent plus sensibles à ces variations. Cette stabilité permet un multiplexage spatial robuste, la génération fidèle de faisceaux vectoriels et de faisceaux à moment angulaire orbital, ainsi que des possibilités avancées de codage, ouvrant la voie à de nouvelles fonctionnalités d’imagerie dans les contextes biomédicaux et du traitement de l’information.

S’appuyant sur ces avancées fondamentales, la recherche présente des implémentations novatrices des lanternes photoniques dans des systèmes de microscopie confocale et de tomographie par cohérence optique. En microscopie confocale, l’intégration d’une lanterne photonique modalement sélective permet une imagerie multiplan simultanée grâce à la génération et à la détection de plusieurs modes linéairement polarisés, chacun correspondant à un plan focal distinct. Cette innovation augmente significativement le débit d’imagerie et permet une analyse volumique d’échantillons biologiques, avec des compromis en résolution et en champ de vision compensés par l’optimisation du système et des techniques de post-traitement. En tomographie par cohérence optique, le développement d’un système à quelques modes intégrant une lanterne photonique modalement sélective autorise une acquisition parallèle sur plusieurs modes spatiaux, ouvrant l’accès à de nouveaux mécanismes de contraste, à une collecte de photons accrue, à la détection des contours et à une réduction efficace du bruit de tavelure. La validation expérimentale inclut l’imagerie de divers spécimens biologiques, démontrant la capacité à résoudre des structures fines et des caractéristiques fonctionnelles

inaccessibles aux systèmes monomodes.

Tout au long de la thèse, une attention particulière est portée aux aspects pratiques de la technologie des lanternes photoniques, tels que la robustesse des dispositifs, leur reproductibilité, leur évolutivité et leur intégration avec les infrastructures fibrées standards, afin de favoriser leur adoption dans des contextes réels de recherche biomédicale et de diagnostic. Ce travail évalue de manière critique les limites et les défis associés à la fabrication avancée des lanternes photoniques, les considérations de coût et la nécessité d’optimisations supplémentaires en vue d’une transposition clinique.

En conclusion, cette thèse établit les lanternes photoniques modalement sélectives comme une plateforme technologique transformative pour l’imagerie biomédicale de nouvelle génération. En comblant le fossé historique entre les technologies fibrées issues des télécommunications et les exigences spécifiques de la biophotonique, cette recherche propose une feuille de route complète pour le développement, l’implémentation et l’optimisation de systèmes d’imagerie fibrés. Les améliorations démontrées en résolution, en vitesse et en polyvalence positionnent les systèmes reposant sur les lanternes photoniques modalement sélectives à l’avant-garde de l’optique biomédicale, jetant ainsi des bases solides pour les futures innovations en imagerie diagnostique, en microscopie à haut contenu et en outils de recherche multimodaux.

ABSTRACT

This thesis explores the development, characterization, and application of photonic lanterns, particularly mode-selective photonic lanterns, to address critical challenges in biomedical imaging. The research is motivated by the growing demand for higher resolution, speed, and contrast in imaging techniques such as confocal microscopy and optical coherence tomography. While optical fiber technologies have long been optimized for telecommunications, their translation to biophotonics has faced unique barriers due to differences in operational requirements, fabrication protocols, and integration challenges. This work bridges these gaps by adapting and enhancing photonic lantern technologies for use in biomedical environments.

This thesis hypothesizes that specialized fiber-couplers, known as photonic lanterns, can markedly improve the selective collection of optical signals in few-mode configurations, leveraging sample features such as backscattering, phase, and k -vector distributions for greater imaging resolution and contrast. Minimizing excess losses, these couplers can be efficiently integrated into practical imaging systems. The overarching goal is to develop compact, efficient photonic lanterns and integrate them into confocal microscopy and optical coherence tomography, ultimately enabling multimodal imaging beyond the fundamental mode.

The thesis begins by establishing the scientific context and fundamental principles of fiber optics and photonic lantern architectures, drawing on a comprehensive literature review. This review synthesizes the evolution of light propagation theory, multiplexing devices, and the role of fiber components in enabling multimodal imaging modalities. It highlights the limitations of traditional fiber multiplexers, such as inefficiency and limited scalability in free-space or planar formats, and demonstrates the advantages of fiber-integrated photonic lanterns for compactness, robustness, and efficient light propagation. Special emphasis is given to the emergence of photonic lanterns in fields beyond telecommunications, particularly their transformative potential in biomedical imaging, where flexibility and compactness are required.

A core contribution of the thesis is the design, fabrication, and systematic characterization of three-mode photonic lanterns—including conventional, mode-selective, and hybrid devices. Leveraging both theoretical modeling (using coupled-mode theory and custom simulation tools) and experimental validation, the research reveals how subtle design parameters—such as fiber geometry, taper length, and material choice—influence modal coupling, loss, and performance. The work introduces double-clad fibers and optimized fusion-tapering techniques, enabling the production of mode-selective photonic lanterns that combine high modal isola-

tion, low loss, and compatibility with standard single-mode fiber systems. These advances are supported by rigorous experimental protocols, real-time monitoring, and far-field imaging that confirm the generation and stable propagation of multiple linearly polarized modes.

The thesis further investigates the impact of polarization and wavelength on photonic lantern performance, providing a detailed analytical framework for understanding the responses of various photonic lantern configurations. Experimental results demonstrate that mode-selective devices maintain stable output profiles across a range of polarizations and wavelengths, while conventional designs are more sensitive to these variations. This enables robust spatial multiplexing, high-fidelity vector beam and orbital angular momentum generation, and advanced encoding possibilities—paving the way for new imaging functionalities in biomedical and information-processing contexts.

Building on these foundational advances, the research presents novel implementations of photonic lanterns in both confocal microscopy and optical coherence tomography systems. In confocal microscopy, the integration of a mode-selective photonic lantern enables simultaneous multiplane imaging through the generation and detection of multiple linearly polarized modes, each corresponding to a distinct focal plane. This innovation significantly increases imaging throughput and enables volumetric analysis of biological samples, with trade-offs in resolution and field-of-view addressed through system optimization and post-processing techniques. In optical coherence tomography, the development of a few-mode system incorporating a mode-selective photonic lantern allows for parallel acquisition from multiple spatial modes, unlocking new contrast mechanisms, enhanced photon collection, edge detection, and effective speckle noise reduction. Experimental validation includes imaging of diverse biological specimens, demonstrating the ability to resolve fine structural and functional features not accessible with single-mode systems.

Throughout the thesis, a strong focus is placed on the practical aspects of photonic lantern technology—such as device robustness, reproducibility, scalability, and integration with standard fiber infrastructure—to facilitate real-world adoption in biomedical research and diagnostic applications. The work critically evaluates the limitations and challenges of advanced photonic lantern fabrication, cost considerations, and the need for further optimization to support clinical translation.

In conclusion, this thesis establishes advanced mode-selective photonic lanterns as a transformative platform for next-generation biomedical imaging. By bridging the longstanding divide between telecommunications-grade fiber technology and the specialized needs of biophotonics, the research offers a comprehensive roadmap for the development, implementation, and optimization of fiber-based imaging systems. The demonstrated enhancements in resolution,

speed, and imaging versatility position mode-selective photonic lantern-enabled systems at the forefront of biomedical optics, laying a solid foundation for future innovation in diagnostic imaging, high-content microscopy, and multimodal research tools.

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LIST OF SYMBOLS AND ABBREVIATIONS

CEM	Computational Electromagnetics
CMT	Coupled-Mode Theory
DCF	Double-Clad Fiber
DOP	Degree of polarization
FDTD	Finite-Difference Time-Domain
FM	Few-Mode
FWHM	Full Width at Half Maximum
ITR	Inverse Taper Ratio
linear PER	Proportion of linearly polarized light to the total light detected
MoM	Method of Moments
MPLC	Multi-Plane Light Conversion
MSPL	Mode-Selective Photonic Lantern
NA	Numerical Aperture
OAM	Orbital–Angular-Momentum
OCT	Optical Coherence Tomography
OS	Optical Switch
PER	Polarization extinction ratio
PL	Photonic Lantern
PM	Polarization-Maintaining
PSF	Point-Spread Function
LP	Linearly Polarized
SLM	Spatial Light Modulator
SS	Swept-Source
STED	STimulated Emission Depletion
μ_0	Vacuum permeability
ε	Permittivity
k	Wavenumber
n	Refractive index
β	Propagation constant
n_{eff}	Effective refractive index
λ	Wavelength
Δ	Relative refractive index difference
a	Core radius

V	V-number
h_1	PSF of illumination
h_2	PSF of detection
O	Object image
I	Intensity image
$\otimes$	convolution operator
e_1	Electric field 1
e_2	Electric field 2
$\bar{\alpha}$	Transverse eigenmodes
Ψ	Normalized amplitude
L_0	Heating length
δz	Elongation of a section
α	α -coefficient
φ	Azimuthal angle

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CHAPTER 1 INTRODUCTION

1.1 Background

Biophotonics is a multidisciplinary field that focuses on the complex interactions between light and biological matter. It leverages a wide range of optical techniques, including free-space optics, waveguides, and advanced photonic devices, to explore and manipulate biological systems at both microscopic and macroscopic scales. By integrating sophisticated optical methodologies into biological samples, biophotonics enhances system capabilities for numerous applications, ranging from medical diagnostics and therapeutic interventions to environmental monitoring and agricultural technologies [1–4].

The analysis of light–matter interactions enables the investigation of cellular dynamics, the elucidation of disease mechanisms, and the development of innovative solutions to critical health challenges [5]. As the demand for high-resolution, minimally invasive, and highly sensitive biomedical tools continues to grow, biophotonics has become increasingly essential in modern biomedical research and clinical practice.

Among the optical technologies employed in biophotonics, optical fibers have emerged as transformative tools in biomedical optics, offering exceptional flexibility, compactness, and portability for the design of clinical and laboratory systems [6–8]. Their intrinsic versatility enables their integration into microscopy and sensing platforms, facilitating detailed investigations of biological processes. Furthermore, the application of biocompatible coatings allows optical fibers to function as minimally invasive probes, capable of accessing deep and otherwise unreachable regions within the human body [9]. This characteristic is particularly advantageous in clinical environments, where diagnostic accuracy, patient safety, and comfort are paramount.

In addition, optical fibers enable the application of diverse optical modalities at the micro- and molecular scales, allowing for high-sensitivity imaging of biological tissues and the delivery of light-based therapeutic treatments [9]. In imaging systems, optical fibers play a crucial role in both illumination and signal collection across various optical configurations. The selection between single-mode and multimode fibers significantly influences overall system performance [5]. Single-mode fibers provide high spatial coherence and resolution, which are essential for discerning fine tissue microstructures, whereas multimode fibers offer superior light throughput, making them well suited for applications requiring efficient signal collection over larger fields of view.

The continuous development of innovative fiber-based components and a deeper understanding of their operational principles are fundamental to advancing biomedical imaging technologies. This knowledge not only refines existing techniques but also enables the emergence of new diagnostic and therapeutic modalities. The integration of advanced optical materials, nano-coatings, and tailored light sources further enhances fiber functionality, improving light management and signal efficiency [4]. For example, fluorescence microscopy benefits substantially from specialized fiber components designed to optimize excitation and emission light collection [5]. Despite these advances, the fabrication and implementation of well-characterized optical devices remain critical challenges, particularly for combining multiple modalities and extracting more detailed information from biological samples. These limitations naturally lead to the central problem addressed in this thesis.

1.2 Problem Statement

Although substantial progress has been made in optical fiber technology, the fabrication and characterization of fiber-based components have historically been driven by the requirements of telecommunications and astrophysics [10–13]. These domains prioritize parameters such as ultra-low attenuation, long-distance transmission, and spectral efficiency, which differ significantly from the constraints encountered in biomedical imaging. Consequently, the translation of advanced fiber components into biophotonic applications remains limited, highlighting the need for targeted design strategies that address biomedical performance requirements [8].

Optical fibers can be broadly classified according to their modal properties into single-mode and multimode fibers, each exhibiting distinct propagation characteristics. In this context, a *mode* refers to a transverse solution of the wave equation that defines a specific electromagnetic field distribution within a guiding structure, such as a waveguide [14]. For cylindrical waveguides, including optical fibers, these solutions are commonly described as transverse linearly polarized (LP) modes under the weakly guiding approximation [15].

The LP modes are characterized by two integer indices, denoted as LP_{lm} , where l and m correspond to the azimuthal and radial mode numbers, respectively [15]. The number of supported modes depends primarily on the refractive index contrast and the geometrical dimensions of the fiber core and cladding. Accordingly, fibers are classified as single-mode when only the fundamental mode propagates, or as multimode or few-mode when multiple transverse modes are supported.

While single-mode operation offers high spatial coherence and resolution, multimode propagation provides enhanced light throughput and collection efficiency. Combining these com-

plementary properties offers considerable advantages for advanced imaging and sensing applications. However, selective excitation and detection of individual modes typically require free-space optical setups involving spatial light modulators or digital micromirror devices, which introduce complexity, alignment sensitivity, and optical losses during fiber-to-free-space transitions [16]. To overcome these limitations, specialized fiber-based components such as mode-selective couplers and photonic lanterns (PLs) have been developed [12, 17]. PLs are fiber-based multiplexers constructed from tapered and fused fiber bundles, which use an adiabatic transformation to convert multimode light into single-mode performance.

Although PLs have been extensively optimized for telecommunications and astrophysical instrumentation, their application in biophotonics remains relatively underexplored. Nevertheless, these devices are particularly promising for biomedical imaging, as they enable efficient and selective coupling between single-mode and multimode regimes, thereby facilitating multimodal imaging strategies. Their integration into confocal microscopy and optical coherence tomography (OCT) systems offers the potential to enhance resolution, contrast, and functional imaging capabilities.

Despite this potential, several challenges limit their widespread adoption in biomedical contexts. In particular, insufficient characterization of fiber components, limited robustness, unclear operational boundaries, and compatibility constraints hinder their effective deployment. Moreover, the fabrication and implementation of fiber-based multiplexers capable of selectively enabling multiple imaging modalities remain underdeveloped. Addressing these limitations requires a systematic investigation into the design, fabrication, and characterization of PLs tailored specifically for biomedical imaging. Accordingly, this thesis focuses on the development, analysis, and implementation of fiber-based (de)-multiplexers, commonly known as PLs, to enhance imaging performance in confocal microscopy and OCT systems.

1.3 Research Objectives

Building upon the challenges and opportunities identified in the previous sections, the objectives of this research are formulated to address the existing technological gaps and to advance fiber-based biomedical imaging systems.

Research Question/Problem

How can novel fiber optic components, particularly PLs, enhance resolution, imaging acquisition speed, and contrast in optical imaging applications?

Hypothesis

Utilizing specialized fiber coupler geometries has the potential to significantly enhance the selective collection of optical signals in few-mode configurations. These advanced designs can exploit multiple sample characteristics, including backscattering intensity, phase variations, and k -vector distributions, thereby improving both imaging resolution and contrast. Moreover, by minimizing excess losses, these couplers can be efficiently integrated into practical imaging systems.

General Objective

The primary objective of this thesis is to design, fabricate, and characterize compact and efficient photonic lanterns, and to investigate their integration into confocal microscopy and optical coherence tomography imaging systems. This research aims to enhance imaging performance by enabling multimodal operation beyond the fundamental mode.

- **Specific Objective 1 (SO1):** To design 3×1 PLs.
 1. To design fiber structures suitable for the effective fabrication of PLs using numerical light propagation simulations based on criteria such as operating wavelength, refractive indices, core and cladding dimensions, number of fibers, and geometrical configuration.
 2. To model the optical fiber configuration of each component while ensuring feasible adiabatic transition criteria.
 3. To conduct detailed experimental characterizations to identify optimal components for biomedical imaging.
- **Specific Objective 2 (SO2):** To develop a fusion-tapering fabrication process for optimized imaging components.
 1. To fabricate compact and robust devices suitable for integration into optical imaging systems.
 2. To obtain components exhibiting appropriate characteristics for imaging, including high modal isolation, controlled polarization response, low overall losses, and stable operational bandwidth.
- **Specific Objective 3 (SO3):** To implement 3×1 PLs in imaging systems.

1. To develop a fiber-based collimation system for illumination and detection using PLs.
2. To demonstrate the performance advantages of PLs in confocal microscopy.
3. To develop a multi-channel OCT system incorporating three parallel illumination and detection paths.
4. To analyze and characterize the performance improvements enabled by the new OCT configuration.

1.4 Thesis Outline

To guide the reader through the logical progression of the research, this thesis is organized into six chapters, grouped into five main parts, as outlined below.

- **Part 1: Introduction.** Chapter 2 provides a comprehensive literature review on the fabrication of optical fiber devices and their current applications. It discusses the fundamental characteristics of these devices and explores two advanced imaging techniques: confocal microscopy and optical coherence microscopy. The chapter also introduces initial efforts toward the integration of PLs into optical imaging systems, establishing the theoretical and technological foundations for the remainder of the thesis.
- **Part 2: Design, characterization, and understanding of PLs.** Chapters 3 and 4 focus on the modeling, fabrication, and characterization of various 3×1 PLs. By systematically analyzing the behavior of these devices, their suitability for biomedical imaging applications is assessed, and key performance parameters are identified. **These chapters correspond to two published scientific articles. The first article provides a detailed explanation of each type of PL (design, theoretical analysis, and simulations) and presents the experimental demonstration of their differences. The second paper demonstrates, for the first time, the response of these devices to changes in their optical profile due to polarization.**
- **Part 3: Mode-selective PLs for optical imaging.** Chapter 5 presents the development and characterization of optimized mode-selective photonic lantern (MSPL), demonstrating high modal selectivity, low excess loss, controlled polarization response, and compact device geometry. These attributes render them particularly suitable for biomedical imaging applications. **This chapter is based on a published scientific paper that demonstrates how double-clad fibers enable the fabrication of more robust, compatible, and efficient structures. These devices**

achieve high isolation, enable real-time monitoring during fabrication, minimize losses, and provide phase-independent optical performance. Furthermore, they offer significant potential for the scalable manipulation of optical modes.

- **Part 4: Implementation of PLs in optical imaging.** Chapters 6 and 7 investigate the integration of PLs into confocal microscopy and OCT systems. The impact of these devices on resolution, contrast, field of view, and system performance is systematically evaluated. **Chapter 6 presents experimental results published in a peer-reviewed journal, while Chapter 7 summarizes key findings introduced at international conferences. Together, these chapters highlight the impact and practical implementation of the fabricated components, demonstrating significant improvements in imaging performance, acquisition speed, and modal contrast.**
- **Part 5: Discussion and conclusion.** This final part provides a comprehensive synthesis of the research outcomes, highlighting the principal contributions, limitations, and perspectives for future developments in fiber-based biomedical imaging.

A complete list of scientific contributions is provided in the appendix.

CHAPTER 2 LITERATURE REVIEW

This section provides an overview of the fundamental physical concepts and technologies underlying this research project, with a focus on relevant prior work.

2.1 Light Propagation in an Optical Fiber

Light propagation in optical fibers is fundamentally governed by Maxwell’s equations, which describe how electric and magnetic fields evolve in space and time [18, 19]. Specifically, when considering linear, isotropic, and non-magnetic media—conditions well-approximated by most glass fibers—these equations can be combined to yield the vector wave equation for the electric field [19]:

$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0, \quad (2.1)$$

where ε is the permittivity of the medium and μ_0 is the vacuum permeability.

In practice, it is common to assume monochromatic electromagnetic fields with harmonic time dependence, which allows the wave equation to simplify further to the Helmholtz equation [19]:

$$\nabla^2 \mathbf{E} + k_0^2 n^2 \mathbf{E} = 0 \quad (2.2)$$

where k_0 is the free-space wavenumber and n is the refractive index profile of the fiber. The solutions to the Helmholtz equation are dictated by the geometry of the medium and the boundary conditions set by discontinuities in the refractive index, such as those at the core–cladding interface in optical fibers [14].

In unbounded media such as free space, solutions like Gaussian or Airy beams are typically used to describe the propagation of light, capturing the natural spread and evolution of the beam profile. However, in bounded systems like optical fibers, the refractive index contrast between the core and the cladding creates transverse confinement, leading to a discrete set of allowed field distributions called guided modes [15]. These guided modes, each with their own propagation constants and field patterns, are the fundamental “channels” along which light can travel within the fiber.

For cylindrical waveguides—the standard geometry for most optical fibers—the symmetry of the structure makes Bessel functions a mathematically convenient choice for construct-

ing modal bases [15]. These modes form a complete and orthogonal set, which means any propagating optical field inside the fiber can be represented as a linear combination of the guided modes. This property is crucial for both theoretical analyses and practical multiplexing strategies, as it enables the systematic management and manipulation of multiple spatial channels within a single fiber.

In optical fibers, the refractive index contrast between the core and the cladding confines light through total internal reflection. Solving the Helmholtz equation with cylindrical symmetry leads to discrete transverse field distributions, each associated with a propagation constant β . The propagation constant is related to the effective refractive index of the mode by [14]

$$\beta = n_{\text{eff}}k_0, \quad (2.3)$$

where $k_0 = 2\pi/\lambda$ is the free-space wavenumber and λ is the operating wavelength. Each guided mode propagates independently with its own effective refractive index.

For this project, the modes of interest are the LP modes obtained under the weak guidance approximation [18]. This approximation is valid when the relative refractive index difference,

$$\Delta = \frac{n_{\text{core}}^2 - n_{\text{clad}}^2}{2n_{\text{core}}^2}, \quad (2.4)$$

is much less than one. In this regime, polarization effects are negligible, allowing the full vector Maxwell equations to be approximated by a scalar formulation. As a result, the fiber's hybrid modes are well described by LP modes.

The mathematical solutions to the Helmholtz equation in cylindrical coordinates form the basis for understanding the modal structure of optical fibers. Among these solutions, the so-called LP modes play a central role in both theory and application. The LP modes are designated as LP_{lm} , where the azimuthal index l corresponds to the number of angular variations (nodes) in the electric field distribution, and the radial index m denotes the number of radial intensity maxima [20]. This notation succinctly captures the symmetry and complexity of each mode's spatial profile. Figure 2.1 illustrates examples of the LP mode profiles, including the fundamental mode and several higher-order modes.

Physically, these indices determine the shape and confinement of the optical field within the fiber core. For instance, the fundamental mode, LP_{01} , exhibits a single central intensity peak and no angular variation, resulting in robust confinement and minimal dispersion. Higher-order modes, such as LP_{11} or LP_{21} , present increasingly intricate patterns, which can be visualized as concentric rings and lobes around the fiber axis. The ability to selectively excite

and manipulate these modes has become a cornerstone of advanced multiplexing schemes, enabling the simultaneous transmission of independent data channels within a single fiber.

A key concept in the study of fiber modes is degeneracy. Certain sets of modes, particularly those with the same total mode order but differing in angular or radial index, may have nearly identical propagation constants. This near-degeneracy allows for the possibility of mode coupling—where energy may transfer between modes due to perturbations in the fiber. Such perturbations can arise from external stresses, bends, twists, or even temperature fluctuations. While uncontrolled mode coupling is generally undesirable, as it leads to signal crosstalk and potential data loss, engineered coupling has been harnessed for novel functionalities such as mode conversion, spatial multiplexing, and optical signal processing.

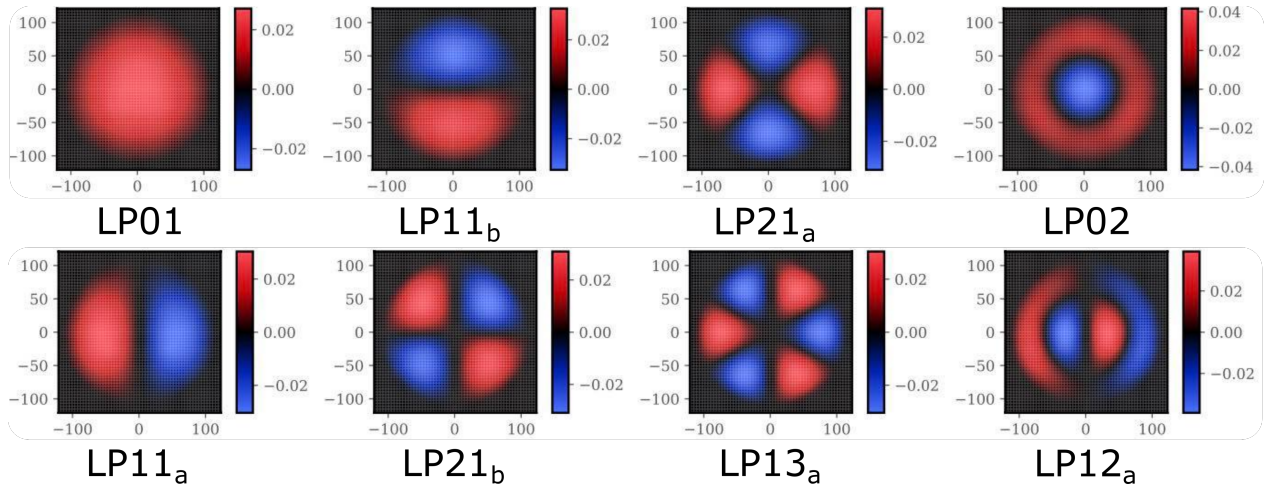


Figure 2.1 LP modes. The LP_{lm} modes are linearly polarized transverse solutions of Maxwell's equations in optical fibers. Their spatial profiles depend on the azimuthal index l and the radial index m . Increasing m increases the number of concentric intensity rings, while increasing l increases the number of angular variations.

The number of modes supported by an optical fiber is determined by the normalized frequency parameter, commonly referred to as the V-number [21],

$$V = \frac{2\pi a}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}, \quad (2.5)$$

where a is the core radius. For step-index fibers, single-mode operation occurs when $V < 2.405$, whereas larger values of V allow the propagation of multiple spatial modes. Consequently, single-mode fibers typically have core diameters of a few micrometers, while multimode fibers can have core diameters ranging from tens to hundreds of micrometers.

Double-clad fibers combine a single-mode or few-mode core with a multimode inner cladding,

enabling simultaneous signal guidance and high-power pumping. Figure 2.2 illustrates a schematic of the composition of an optical fiber and the three types of fibers, emphasizing the core and claddings along with their sizes to scale, highlighting the significant differences between each configuration. In all fiber types, light propagation is governed by the refractive index profile and boundary conditions, which determine modal confinement and dispersion properties.

Modifying the fiber geometry—for example, by tapering or fusing fibers—changes these boundary conditions and enables optical functionalities such as power transfer between modes, wavelength-division multiplexing, and non-reciprocal behavior [15]. In such structures, the adiabatic criterion requires changes in waveguide geometry to occur gradually over distances much longer than the modal coupling length; otherwise, undesired mode coupling and radiation losses can occur. These considerations are especially important for fused fiber devices such as PLs, discussed in the next chapter.

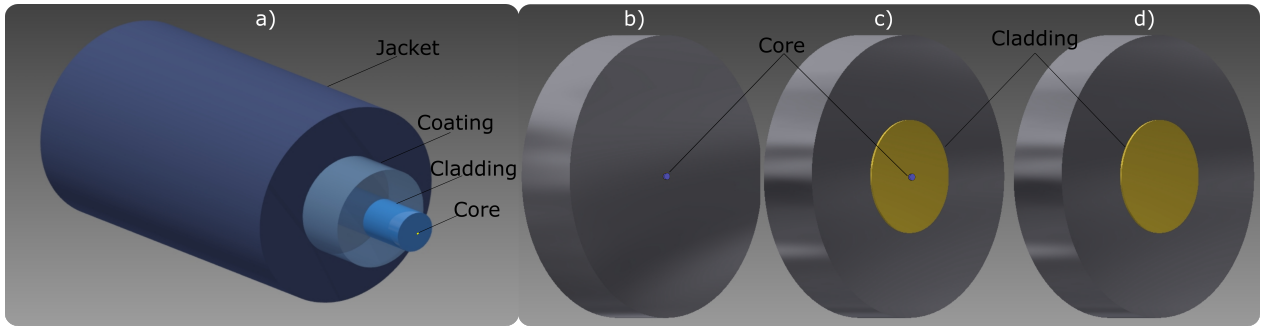


Figure 2.2 Structure and types of optical fibers. (a) The main components of an optical fiber include the core, cladding, coating, and protective jacket. Examples of fiber types include (b) single-mode fibers, (c) double-clad fibers, and (d) multimode fibers with large core diameters.

2.2 Fiber-Based Multiplexers

Fiber-based multiplexers are a cornerstone of modern optical communication and signal processing systems, enabling the simultaneous transmission of multiple data channels and facilitating advanced functionalities in a wide range of applications. The development of multiplexing technologies has paralleled the evolution of fiber optics itself, with early innovations focusing on wavelength-division multiplexing and time-division multiplexing, and more recent efforts directed toward spatial-division multiplexing using distinct fiber modes.

Solutions to Maxwell’s equations yield different families of spatial and vector modes, each corresponding to specific waveguide geometries and boundary conditions. Some modes exhibit

unique properties, making them valuable for advanced applications. As a result, significant research has focused on the controlled generation and manipulation of optical modes for use in telecommunications, astrophysics, turbulent media analysis, biophotonics, and laser systems [3, 22–26].

Multiple technologies have been developed for the generation and conversion of optical modes, each with specific advantages and limitations. Spatial light modulators (SLMs) and digital micromirror devices are commonly employed in free-space optics due to their flexibility, enabling programmable generation of arbitrary holograms and mode profiles. These devices have played a vital role in research laboratories, allowing the rapid prototyping and testing of new modal formats. However, they generally exhibit low power efficiency, with losses between 50% and 60%, which restricts their use in power-sensitive applications such as quantum technologies or high-power laser systems. Their sensitivity to optical alignment and environmental factors further limits their deployment outside controlled settings [16, 27–30].

Multi-Plane Light Conversions (MPLCs) offer an alternative approach by utilizing a sequence of lithographically fabricated phase masks to transform an input Gaussian mode into a desired output mode. MPLCs deliver stable and accurate mode transformations and can be directly integrated into fiber systems. Recent advances in nanofabrication have enabled the production of MPLCs with high mode selectivity and low insertion loss, making them increasingly attractive for network integration. However, they typically exhibit losses of 50% or more and are not reconfigurable after fabrication, which can be a drawback for applications requiring adaptability [31–33].

Among fiber-compatible solutions, mode-selective couplers facilitate efficient excitation of specific higher-order modes in multimode fibers using single-mode inputs. These devices depend on precise control of fiber geometry and refractive index, often involving tapered regions or modified cladding. Although highly efficient for individual-mode generation (with efficiencies ranging from 2% to 50%), mode-selective couplers are inherently limited in scalability, as each device typically supports only one or two modes. Cascading multiple couplers increases both system length and fabrication complexity, presenting practical challenges for large-scale multiplexing [17, 34, 35].

The evolution of multiplexing devices has also been shaped by practical considerations such as fabrication cost, system integration, and reliability. Early demonstrations of mode-multiplexed transmission revealed key limitations in crosstalk and insertion loss, prompting ongoing research into new device architectures and materials. Hybrid systems that combine multiple multiplexing techniques—for example, integrating SLM-based beam shaping with fiber-based couplers—have emerged to address specific application requirements.

PLs represent another class of fiber-based multiplexers and are the primary focus of this work. A PL consists of a bundle of single-mode fibers that are adiabatically fused and tapered into a single multimode fiber, enabling access to multiple spatial modes within a compact device. This architecture provides a robust and efficient solution for mode multiplexing, allowing seamless interfacing between single-mode and multimode systems. Although scalability is limited by fabrication complexity and mode-count matching, PLs offer high efficiency (typical insertion losses of 2% to 10%) and are highly compatible with fiber-based systems. Recent advances in fabrication techniques, including precision tapering and improved fiber alignment, have broadened the scope of PL applications in both laboratory and field settings [12, 33, 36].

Among the available mode-generation techniques, the technologies discussed above are the most established and practical. For the goals of this thesis—efficiently generating and manipulating more than two modes with full fiber compatibility—PLs provide the optimal balance of efficiency, stability, and integration.

2.3 Photonic Lanterns

PLs are a central focus of this thesis, with multiple chapters dedicated to their fabrication, development, and characterization. While this emphasis may result in some repetition across individual publications, a concise and self-contained introduction is essential to clearly define the physical principles, structure, and functionality of PLs. In simple terms, PLs are specialized optical couplers that, like conventional couplers, require both fusion and tapering during fabrication. Their key distinction is that they are cleaved at the narrowest section of the structure, enabling efficient transition between multimode and single-mode light propagation.

A PL is composed of three strongly interdependent sections: the single-mode section, the taper transition, and the (few-)multimode section. Each section plays a critical role in determining the device’s optical performance. Figure 2.3 shows the three main sections of the PLs.

The few-mode (multimode) section. The few-mode section corresponds to the smallest cross-sectional region of the device and is formed by the complete fusion of all single-mode fibers into a single multimode waveguide. The resulting structure supports a discrete set of guided modes whose number matches the number of single-mode inputs. The supported modes are commonly referred to as *super-modes* [37], as they arise from the coherent combination of the fields originating from the individual fibers.

The generation of low-loss and well-defined super-modes requires two key fabrication

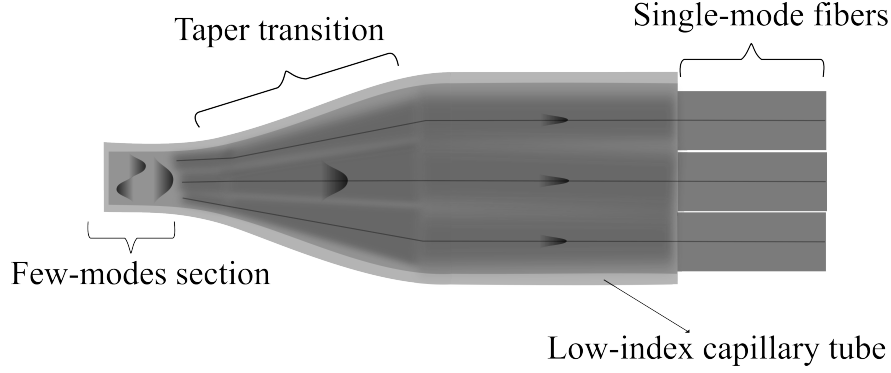


Figure 2.3 PL. The $N \times 1$ (de-)multiplexer consists of three main sections: (1) the few-mode (multimode) section, where super-modes are supported; (2) the taper transition, where the fibers are fused and reduced in diameter under adiabatic conditions; and (3) the single-mode section, formed by N optical fibers arranged inside a capillary tube.

conditions: first, a smooth and complete fusion of the fibers to eliminate scattering losses at residual interfaces; and second, precise control of the relative core positions prior to fusion to ensure the desired modal field distributions [38]. Super-modes can be excited either selectively, by injecting light into a specific single-mode input, or through the coherent excitation of multiple inputs with controlled relative phases and amplitudes [39, 40].

Taper transition. The taper transition connects the single-mode section to the multimode section and is the most critical region for achieving low insertion loss. During this process, the fiber bundle is gradually reduced in diameter while being heated, ensuring that the local waveguide evolution remains adiabatic [41]. Under these conditions, optical power is transferred smoothly from the individual single-mode cores to the corresponding super-modes without inducing unwanted coupling or radiation losses. The taper profile, length, and uniformity directly influence the efficiency, bandwidth, and robustness of the PL.

Single-mode section. The single-mode section consists of N optical fibers operating at the same wavelength, typically arranged inside a capillary tube to maintain mechanical stability and precise spacing. The geometry of this bundle, including the number of fibers, their arrangement, and their optical properties, plays a crucial role in determining the adiabaticity of the taper transition and the overall footprint of the device [42]. Although most PLs employ single-mode fibers in this section, configurations incorporating few-mode or multimode fibers have also been demonstrated for specific applications [12].

A critical aspect linking all three sections is the choice of fiber parameters, including nu-

merical aperture, core and cladding diameters, fiber type, and the total number of fibers. Variations in these parameters strongly affect the supported modal set, mode isolation, adiabatic transition, insertion loss, and final dimensions of the device. Consequently, careful fiber selection and design optimization are essential for tailoring PLs to specific applications.

PLs are typically fabricated using the heat-and-pull technique, which can be implemented on platforms such as fiber drawing towers, plasma arcs, filament heaters, gas torches, or high-power laser stations [43]. This method has enabled the realization of PLs with progressively larger channel counts, including devices with 19 [44], 61 [45], and even 121 single-mode fibers [46]. The PL concept has also been adapted to integrated and planar waveguide platforms, such as laser-ablated three-dimensional waveguides and etched structures, where the taper transition is achieved by gradually reducing the waveguide cross-section. These alternative approaches, however, often exhibit higher insertion losses, sometimes reaching 50%, as well as reduced wavelength flexibility, increased alignment sensitivity, and limited mechanical robustness. Furthermore, changes in boundary conditions in planar geometries result in different modal bases, such as Hermite–Gaussian modes in square waveguides, which further distinguish them from fiber-based lanterns [47].

Several classes of PLs have been developed to address different operational requirements:

- **Standard PLs**, in which all input fibers are identical. In this configuration, individual mode selectivity is not inherent, and the excitation of specific modes relies on coherent illumination of multiple ports with controlled relative phases. Exciting a single port generally results in a superposition of modes at the multimode output [36].
- **MSPLs**, which employ fibers with different effective refractive indices in the single-mode section. This design enables one-to-one mapping between input ports and output modes, resulting in high mode selectivity and minimal inter-modal coupling [48].
- **Semi-MSPLs**, which combine identical and non-identical fibers within the same device. In this case, groups of identical fibers generate superpositions of modes, while distinct fibers excite individual modes selectively [49].

2.4 Super-Modes in Photonic Lanterns

In the context of PLs, the term *super-mode* refers to the guided modes supported by the multimode section that arise from the coherent combination of the fields originating from the individual single-mode inputs [15]. Unlike conventional fiber modes, which are defined solely by the refractive index profile of a single waveguide, super-modes emerge from the collective

behavior of multiple closely spaced cores that are gradually fused into a single multimode structure.

From a physical perspective, super-modes can be understood as the eigenmodes of the coupled system formed by the single-mode fiber array as it transitions into the multimode waveguide. In the single-mode section, light propagates independently in each core. As the fibers approach each other and begin to fuse in the taper region, evanescent coupling between neighboring cores becomes significant. This coupling leads to the formation of collective modes whose field distributions extend across the entire fused region. When the tapering process is adiabatic, each input excitation evolves smoothly into a corresponding super-mode in the multimode section without power transfer to radiation modes [15, 50].

The number of supported super-modes is determined by the number of guided modes supported by the multimode section, which, in an ideal lantern, matches the number of single-mode inputs [12]. This mode-number conservation is a fundamental design principle of PLs and is essential for achieving low-loss and reversible operation. If the multimode section supports fewer modes than the number of input fibers, excess power is inevitably lost through radiation or coupling to unguided modes.

Super-modes are orthogonal solutions of the wave equation within the multimode section and can be expressed as specific linear combinations of the single-mode input fields. Their spatial profiles typically resemble the LP modes of a conventional multimode fiber, provided that the fusion process results in a near-cylindrical refractive index profile. However, the exact form of the super-modes depends on several factors, including the initial arrangement of the fibers, the symmetry of the bundle, the degree of fusion, and the taper geometry [41].

Excitation of super-modes can be achieved in different ways. Selective excitation occurs when light is injected into a specific single-mode input that maps predominantly onto one super-mode, a behavior exploited in MSPLs. Alternatively, coherent excitation of multiple inputs with controlled relative phases and amplitudes enables the generation of arbitrary superpositions of super-modes. This capability allows PLs to function not only as passive multiplexers but also as active mode-shaping elements.

In practical implementations, deviations from perfect symmetry, fabrication tolerances, and non-ideal taper profiles can lead to residual inter-modal coupling and reduced mode purity. Nevertheless, when carefully designed, super-modes exhibit high stability and low cross-talk, making PLs particularly attractive for applications requiring robust and repeatable modal control.

2.5 Early Applications of Photonic Lanterns

PLs were originally developed for astronomical instrumentation, where they enabled efficient coupling between multimode telescope feeds and single-mode photonic devices for spectroscopy, filtering, and modal noise mitigation [12, 51–53]. Owing to their versatility and high efficiency, PLs have since been adopted in optical telecommunications, lidar systems, and quantum optics. More recently, they have attracted growing interest in biophotonics and biomedical imaging.

The first reported biophotonic application appeared in 2019, where a three-mode MSPL was employed in optical tweezers to generate a rotating optical trap using the LP_{11} mode, controlled via polarization modulation at the input [54]. Subsequently, a 7×1 PL was used to collect light from a light-emitting diode (LED) and generate a light-sheet illumination profile for high-resolution microscopy [55]. In 2021, our group further demonstrated the use of PLs in OCT to analyze scattering properties of biological samples [56].

2.6 Optical Reciprocity

The principle of optical reciprocity, also known as the Helmholtz or Lorentz reciprocity theorem, states that in linear, passive, and time-invariant optical systems, the roles of illumination and detection can be interchanged without altering the system’s measured response [57]. In practical terms, this means that light traveling along a specific optical path from point A to point B will experience identical transmission characteristics when propagating from point B to point A—so long as the system does not exhibit gain, nonlinearity, or non-reciprocal elements.

PLs inherently satisfy the fundamental conditions required for reciprocity: they are linear, passive, and reciprocal fiber-based devices when operated within their design bandwidth and under adiabatic conditions. Consequently, the modal transformations performed by a PL are, in principle, reversible. Excitation launched into a specific single-mode port maps onto a defined super-mode in the multimode section. Conversely, exciting that same super-mode at the multimode end will couple back into the corresponding single-mode port when the light propagates in the reverse direction.

While reciprocity is well established for PLs in telecommunications and mode multiplexing, its significance for imaging applications was demonstrated by our research team in [58], using a confocal system. In this study, reciprocity was shown by illuminating the sample with a higher-order spatial mode—such as an annular beam formed by the LP_{11} modes—while detecting through the fundamental LP_{01} mode. This configuration yielded image information

equivalent to the reciprocal arrangement, where illumination was performed with the LP_{01} mode and detection with the LP_{11} modes. As long as the system remained linear and modal coupling and losses were symmetric, both configurations provided access to the same spatial frequency content of the sample.

To quantitatively evaluate the similarity between images obtained in [58] under reciprocal illumination–detection configurations, the Pearson correlation coefficient, r , was employed [59], which is defined as

$$r = \frac{1}{N} \sum_{i=1}^N \left(\frac{x_i - \bar{x}}{\sigma_x} \right) \left(\frac{y_i - \bar{y}}{\sigma_y} \right), \quad (2.6)$$

where x and y represent the intensity distributions of the two images being compared, $\bar{x}$ and $\bar{y}$ are their respective mean values, σ_x and σ_y are the corresponding standard deviations, and N is the total number of pixels. The coefficient r ranges from -1 to 1 , where $r = 1$ indicates perfect positive correlation, $r = 0$ indicates no correlation, and $r = -1$ corresponds to perfect negative correlation.

For a more detailed discussion of optical reciprocity in this context, I recommend consulting [58]—a paper to which I contributed significantly. This work has had a notable impact on several imaging fields, including applications in OCT discussed in the final chapter.

2.7 Confocal Microscopy

Confocal microscopy is an optical imaging technique that achieves optical sectioning and diffraction-limited resolution by selectively rejecting out-of-focus light through spatial filtering [60, 61]. Typically, this is accomplished by employing conjugate pinholes in both the illumination and detection paths, which ensures that only light originating from the focal volume contributes significantly to the detected signal. Consequently, confocal microscopy offers enhanced contrast and depth discrimination relative to wide-field imaging.

Owing to its straightforward yet effective imaging principle, confocal microscopy has been widely adopted in disciplines such as biology, surface metrology, materials science, and industrial inspection [62–69]. Numerous confocal variants have been developed to address specific imaging challenges, including differential contrast confocal microscopy, structured illumination confocal imaging, and dark-field confocal techniques [70–73]. These adaptations increase the versatility of confocal systems by enhancing sensitivity to phase, scattering, or subsurface features.

Figure 2.4 illustrates a schematic representation of a confocal microscope and its operating

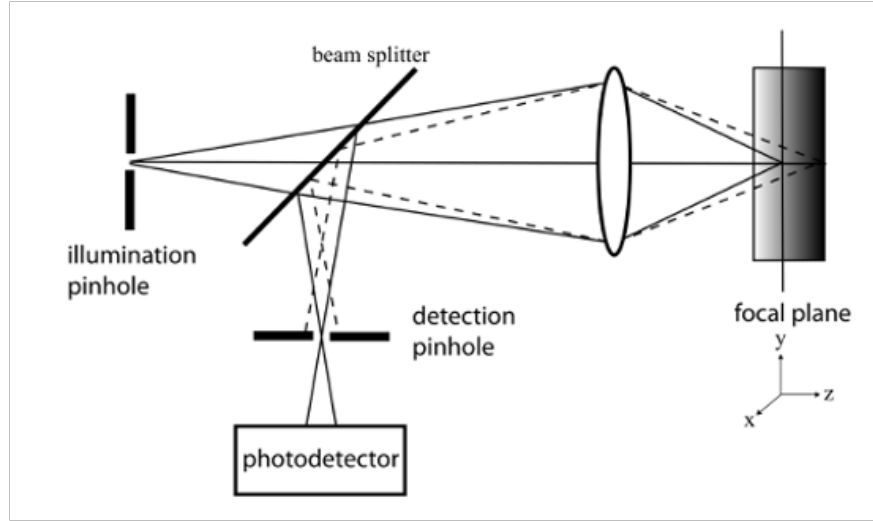


Figure 2.4 Confocal microscope schematic from [61], illustrating a section of a confocal system that uses two pinholes, a beam splitter, and focuses in the focal plane.

principle. Confocal microscopy achieves optical sectioning by employing spatial filtering in both the illumination and detection paths. This is accomplished using two pinholes: an illumination pinhole, which spatially filters the incoming light to produce a well-defined focused beam at the sample, and a detection pinhole, which rejects out-of-focus light returning from the sample.

In configurations such as reflection or scattering microscopy, a beam splitter is used to direct the illumination light toward the sample while simultaneously allowing the backscattered or reflected signal to be collected along the same optical path. The light is focused onto the sample by a lens system, typically a high numerical aperture (NA) objective, which ensures tight focusing and efficient light collection.

As shown in Figure 2.4, only light originating from the focal plane is properly refocused onto the detection pinhole and subsequently reaches the photodetector. In contrast, out-of-focus light is spatially filtered and rejected, resulting in enhanced image contrast and axial resolution. This dual spatial filtering mechanism is the fundamental principle that enables confocal microscopy to achieve depth-resolved imaging.

In recent decades, optical fibers have been increasingly incorporated into confocal microscope architectures, replacing conventional free-space pinholes and enabling compact, flexible, and robust imaging systems [64, 74–77]. Fiber-based confocal microscopy is particularly suitable for endoscopic and in vivo imaging, where alignment stability and system miniaturization are essential. In most fiber-based confocal implementations, the fundamental spatial mode of

the fiber is used for both illumination and detection, thereby serving as a single-mode spatial filter [78].

The imaging performance of a confocal system is determined by the point-spread functions (PSFs) of its illumination and detection optical paths, denoted as h_1 and h_2 , respectively. These PSFs characterize the system's response to a point-like object and are frequently approximated by the response of an ideal diffraction-limited lens [70, 74–76, 78]. For a sample with a spatial distribution of reflectivity coefficients, O , the detected intensity image, I , can be modeled as the coherent interaction between the illumination and detection fields:

$$I = |(h_1 \otimes e_1) \cdot (h_2 \otimes e_2) \otimes O|^2 = |h_{1,\text{eff}} \cdot h_{2,\text{eff}} \otimes O|^2 \quad (2.7)$$

Here, $\otimes$ denotes the convolution operator, e_1 and e_2 are the electric field distributions at the illumination and detection pinholes, and $h_{1,\text{eff}}$ and $h_{2,\text{eff}}$ represent the corresponding effective PSFs. In fiber-based confocal systems, the fields e_1 and e_2 are generally well approximated by Gaussian profiles, which correspond to the fundamental LP_{01} mode of a single-mode fiber [78–80].

A key characteristic of confocal microscopy is that the overall system PSF is determined by the product of the illumination and detection PSFs. This multiplicative relationship results in improved spatial resolution and greater rejection of out-of-focus light compared to conventional wide-field imaging. When considering only lateral resolution, it is typically quantified by the full width at half maximum (FWHM) of the lateral PSF, which can be approximated as

$$\text{FWHM}_{\text{lateral}} = 0.37 \frac{\lambda}{\text{NA}}, \quad (2.8)$$

where λ is the operating wavelength and NA is the numerical aperture on the sample side [81].

The axial resolution of a confocal microscope is also characterized by the FWHM of the axial PSF and is strongly dependent on the numerical aperture. As the NA decreases, the axial response broadens, which reduces depth discrimination [61, 79, 82]. This trade-off among resolution, depth of focus, and signal collection efficiency is central to the design and optimization of confocal imaging systems, especially in fiber-based and multimodal implementations.

2.8 Optical Coherence Tomography

OCT is a non-invasive imaging modality based on low-coherence interferometry, enabling depth-resolved imaging of biological tissues with micrometer-scale resolution [83]. By em-

playing near-infrared light, OCT achieves enhanced penetration depth in scattering media while maintaining high axial and lateral resolutions. OCT provides real-time two- and three-dimensional visualization of tissue microstructure and has become a standard tool in biomedical imaging [5].

OCT systems are commonly implemented using fiber-based architectures, resulting in compact, robust, and flexible platforms that are well suited for clinical translation. In its conventional configuration, OCT relies on single-mode fibers and the fundamental propagation mode, which inherently provides confocal gating in addition to coherence gating. This configuration yields high image contrast and sensitivity, with axial resolution primarily determined by the source coherence length and lateral resolution governed by the numerical aperture.

Several OCT architectures have been developed to optimize performance for specific applications, including time-domain OCT, spectral-domain OCT (SD-OCT), and swept-source (SS)-OCT. Among these, SS-OCT has gained significant attention due to its high imaging speed, extended imaging range, and improved sensitivity at depth [5].

SS-OCT employs a narrowband, rapidly tunable laser that sweeps across a broad optical bandwidth. Depth information is retrieved by measuring the interference signal as a function of optical frequency. The detected interferogram $I(k)$ can be expressed as [5]

$$I(k) \propto |E_r(k) + E_s(k)|^2, \quad (2.9)$$

where $E_r(k)$ and $E_s(k)$ are the reference and sample electric fields, respectively, and k is the wavenumber. The depth-resolved reflectivity profile is obtained by performing a Fourier transform with respect to k , yielding the axial reflectivity as a function of depth.

Compared to spectral-domain OCT, SS-OCT offers several advantages, including reduced sensitivity roll-off with depth, improved signal-to-noise ratio at larger imaging depths, and higher imaging speeds enabled by fast wavelength-swept lasers. Additionally, SS-OCT systems typically operate at longer center wavelengths (e.g., 1.3 μm), further enhancing penetration depth in biological tissues and reducing scattering losses. These characteristics make SS-OCT particularly attractive for applications such as ophthalmology, dermatology, endoscopy, and intravascular imaging [84–86].

Recent developments in OCT have explored alternative illumination and detection strategies to enhance contrast and extract additional sample information. Few-mode (FM)-OCT incorporates higher-order spatial modes to increase photon collection efficiency and to probe angular and modal scattering properties of tissues, as demonstrated in bright-and-dark field (BRAD) OCT [87]. This approach is enabled by fiber-based spatial (de-)multiplexers, such

as PLs, which allow controlled excitation and detection of multiple spatial modes [56].

Integrating PLs into OCT systems enables interference with single-mode performance for both fundamental and higher-order LP modes. This allows for the acquisition of complementary OCT images sensitive to distinct scattering angles, modal coupling mechanisms, and structural characteristics [56, 88]. To further analyze the interactions of single scatterers with higher-order modes, PyMieSim provides valuable simulations that offer new insights into these processes [88]. Figure 2.5 A) illustrates a scattering event as modeled with this software. Additionally, simulations presented in [88], authored by my colleague Martin from our research group, demonstrate how the coupling of certain particles varies between different modes. Figure 2.5 B), also generated with PyMieSim, shows that coupling to LP_{01} and LP_{11} depends on scatterer size [88]. Furthermore, Figure 2.5 C) shows the first experimental results using PLs, where illuminating with LP_{01} and detecting with LP_{11} reveals tissue structures that are not visible with the fundamental mode alone; these differences are highlighted with the red and blue arrows [56].

Additionally, FM-OCT has shown efficiency and potential for angular scattering analysis and flow measurements [89, 90], and even has potential for super-resolution techniques using higher-order modes, such as LP_{02} , or the superposition of both LP_{11} for a depletion beam in stimulated emission depletion (STED) microscopy. Furthermore, PLs enable the generation and detection of vector beams, which have been shown to enhance penetration depth and contrast in scattering media [91].

The combination of PLs with SS OCT presents a promising pathway toward advanced multimodal imaging systems. This architecture preserves the intrinsic advantages of SS-OCT—high speed, sensitivity, and depth range—while extending OCT functionality through spatial-mode multiplexing. Such systems offer a compelling platform for combining OCT with confocal imaging and other single-mode optical techniques in a fully fiber-based, compact, and stable configuration.

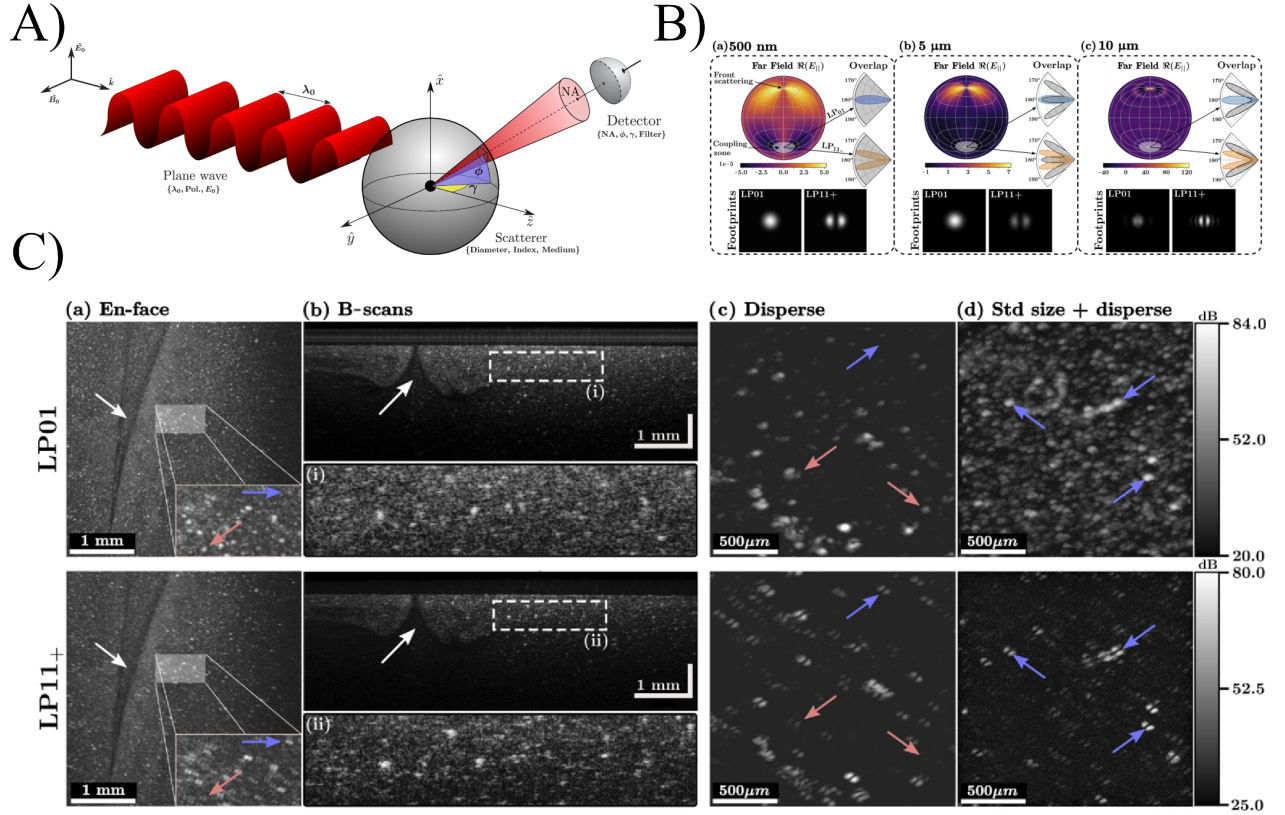


Figure 2.5 PyMieSim and 2 mode FM-OCT. A) A plane wave (wavelength, polarization, electric amplitude, wavevector) strikes a homogeneous sphere (diameter, index) in a medium (index med). The scattered wave is detected by an incoherent detector (NA, angle) through a polarizer, by a coherent or incoherent detector such as a single- or few-mode optical fiber (via LP modes). Reproduce with permission form Optica publishing group [88]. B) (a-c) Lambert projection showing simulated parallel far-field, overlap with LP modes (blue and orange), and modal footprints for scatterers sized 500 nm, 5 μm , and 10 μm [88]. C) FM-OCT scans of a microbead optical phantom with LP (top and bottom). (a) MIP en-face view. (b) B-scans. (c) Oversampled and zoomed C-scan of disperse TiO microbeads. (d) Same for mono-disperse borosilicate glass beads. (d) uses a logarithmic scale bar. Reproduced with permission form Optica Publishing Group [56].

CHAPTER 3 ARTICLE 1: THREE-MODE PHOTONIC LANTERNS: COMPREHENSIVE ANALYSIS FROM THEORY TO EXPERIMENTS

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Published in: Optics Continuum.
Publication date: June 4, 2025.

3.1 Author Contribution

As the first author of the publication, I was responsible for developing the research concept, designing and overseeing the fabrication process, processing and analyzing experimental data, drafting the initial manuscript, preparing the first response to reviewers, creating figures, and conducting the literature review. Raphaël Maltais-Tariant, Guillaume Ramadier, and Martin Poinsinet de Sivry-Houle contributed to the scientific discussions throughout the project. Raphaël Maltais-Tariant also provided detailed feedback and significant revisions to the manuscript. Martin Poinsinet de Sivry-Houle performed the simulations presented in the study. Stéphane Virally offered the development of the research concept, guidance, support, and substantial modifications to the paper. Caroline Boudoux and Nicolas Godbout provided laboratory materials, funding, and access to laboratory facilities. All authors reviewed and approved the final manuscript.

3.2 Chapter Context

This chapter delves into the intricate fabrication process of PLs, categorizing their various types and establishing a comprehensive framework for their characterization. Despite the existence of numerous PL designs, a gap in the literature persists, as no study has offered a complete characterization of these devices, including detailed results on power transfer and operational weight.

Thoroughly characterizing each type of PL is essential for optimizing their performance in various systems. This meticulous approach enables us to discern the most suitable lanterns for specific biomedical applications, particularly in imaging techniques. By gaining a deeper understanding of these devices, we can enhance their efficacy and adaptability in advanced biomedical contexts.

Abstract

The design space for photonic lanterns is large and complex, making it challenging to identify optimal parameters to achieve specific performances, such as coupling, bandwidth, and insertion loss. Effectively navigating this space requires modeling tools capable to extract the most characterizing parameters. This work contrasts theoretical modeling with experimental realizations of the four possible types of 3×1 photonic lanterns using double-clad fibers, covering a spectrum from conventional to hybrid to mode-specific configurations. This work highlights the experimental characteristics of each photonic lantern.

3.3 Introduction

PLs are $N \times 1$ transverse-mode division multiplexers/de-multiplexers composed of N single-mode fibers fused together into a few-mode waveguide [12]. They are typically fabricated by heating and tapering a bundle of N fibers before cleaving the resulting fused section, acting as a few-mode segment. PLs are used in a variety of applications including telecommunications [11, 51, 92–97], lasers [98, 99], astrophysics [52, 53], sensing [100, 101], orbital angular momentum mode generation [102], efficient collection of light [103], and biomedical imaging [56, 89, 104, 105].

The characteristics of PLs vary greatly depending on the fiber configuration and type within the bundle. In general, their behavior can be sorted into three main categories, which we herein call conventional, mode-selective, and hybrid. Conventional PLs are fabricated from N identical single-mode fibers [36, 106, 107] and equally couple each fiber’s fundamental modes to the transverse modes of the multimode section. Conversely, they enable the equipartite collection of the amplitudes of the transverse modes into all N single-mode outputs without distinction between each port. This behavior differs from that of so-called mode-selective photonic lanterns (MSPLs), consisting of N different fibers acting as mode sorters whereby each transverse mode of the few-mode section is selectively coupled to a specific single-mode fiber [48, 56, 108, 109]. MSPLs usually have high modal isolation, and their operation is typically wavelength-independent, up to a bandwidth of 500 nm [33]. The hybrid type—also called semi-selective or group-mode-selective [49, 110, 111]—refers to PLs behaving in between the conventional and mode-selective types.

The plurality of PL designs provides a large design space. Computational electromagnetics (CEM) methods [50, 112] such as finite-difference time-domain (FDTD) and the method of moments (MoM) are often used when no simple closed-form solutions to Maxwell’s equations exist. Recent studies have demonstrated that Coupled-mode theory (CMT) serves as an

effective implementation for simulating guided waves in complex structures [20, 113–115]. This method aptly captures the complexities of electromagnetic field dynamics, transforming it into a more manageable eigenvalue problem. Our group accomplished this through a Python package named SuPyMode [115].

CMT modeling of PLs allows observing the spectrum of behaviors exhibited by various types of PLs, particularly those stemming from symmetry-breaking fiber arrangements, which is well represented by eigenmode decomposition. However, most of the existing simulators operate under ideal conditions. While they provide valuable approximations, fully understanding a device’s performance requires actual fabrication and characterization to ascertain the modal coupling and wavelength response, which are crucial for implementation in various fields.

In this study, we first briefly introduce adiabatic criteria and the logarithmic taper slope associated with a particular fabrication sequence. We combine these two concepts to determine the best parameters for a given component. We then compare theoretical predictions with actual fabricated components of each type of photonic lantern, demonstrating their different performances at each port over a wide bandwidth and their optical profiles. We emphasize the significant differences in the experimental behaviors of components that may seem very similar at first but have distinct internal symmetries.

3.4 Modeling Tools

The main characteristics of PLs can be determined theoretically by comparing the inter-modal adiabatic criteria to the logarithmic slope of the taper. We briefly introduce those two concepts and their relation to the final characteristics of the devices.

3.4.1 Adiabatic Criterion

The design of PLs involves many parameters, including the types of fibers, stacking arrangement, amount of initial fusion, and tapering profile. All of these parameters directly influence the adiabatic criteria, which ultimately determine if and how a device can be fabricated.

In CMT, the adiabatic criterion $\bar{\alpha}_{ij}$ between two transverse eigenmodes i and j is a quantity with units of the inverse of a length. It depends only on two properties of the modes in question: their propagation constants β_i and β_j , and their normalized amplitude profiles Ψ_i and Ψ_j [20, 113, 115]. At any position z along the taper, these can be calculated from the transverse refraction index map $n_0(x, y, z)$ of the fused fiber bundle. The package that we used in this study, SuPyMode [115, 116], determines this map from homotetic transformation of the cross-sectional map $n_0(x, y)$ of the fused fiber bundle before tapering. A typical map

is shown in Fig. 3.1(a). The homotetic ratio $\mathbf{I}(z)$ between the length of any line segment on the fiber cross-section before and after tapering at any particular position z is called the inverse taper ratio (ITR).

3.4.2 Logarithmic Slope

By definition, the logarithmic slope of the taper at any position z is the logarithmic derivative $\frac{1}{\mathbf{I}} \frac{\partial \mathbf{I}}{\partial \mathbf{I}}$ of the ITR at that position. This logarithmic slope, also known as the taper shape, is controlled by the scanning and pulling motors during the fabrication process. The specific shape of the taper is determined by theoretical considerations [117]. Each step of the sequence consists of heating a section of the bundle, at each point increasing or decreasing the length of the heated section to the value $L = L_0 + \alpha \delta z$, where L_0 is the original heating length of the section, and δz is the current elongation of the section. The coefficient α is unitless and ranges from -1 to +1. A positive value of α indicates that the length of the heated section increases as the step progresses. In turn, a negative value of α indicates that the length of the heated section decreases throughout the step. The ITR is fully determined by the ensemble of parameters L_0 and α [117] for each step of the sequence.

3.4.3 Coupling Threshold

The threshold between inter-modal coupling and inter-modal isolation is determined for each pair of modes (i, j) by comparing the adiabatic criterion for the pair to the logarithmic slope determined by the fabrication sequence. Specifically, the condition for inter-modal isolation is $\frac{1}{\mathbf{I}} \frac{\partial \mathbf{I}}{\partial z} \leq \bar{\alpha}_{ij}$ over the full length of the taper.

In addition, a taper is called adiabatic when inter-modal isolation is maintained for all pairs of modes guided by the structure, or

$$\frac{1}{\mathbf{I}(z)} \frac{\partial \mathbf{I}(z)}{\partial z} \leq \min_{(i,j)} \bar{\alpha}_{ij}(z) \quad \forall z. \quad (3.1)$$

Thus, one of the primordial modeling tools for the design of PLs is a graph comparing all relevant adiabatic criteria to the logarithmic slope determined by the fabrication sequence. An example of such a graph is shown in Fig. 3.1(b). This figure shows adiabatic criteria and logarithmic slope values for a specific fabrication sequence as a function of ITR rather than the longitudinal position z of the taper. This improves the readability of the graph, as tapers often feature sections with constant ITRs. The features shown in this particular graph will be reproduced and explained in more details below as it pertains to a case studied in this

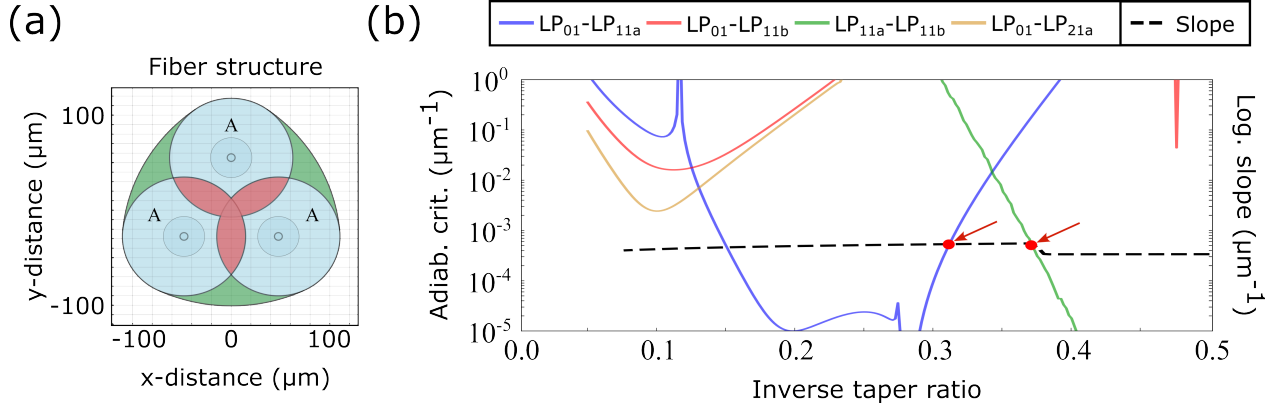


Figure 3.1 Simulation of a three-mode structure using SuPyMode. (a) Cross-sectional map of refractive indices after fusion of the three-fiber bundle. (b) Adiabatic criteria for each mode pair (solid lines) and logarithmic slope of the taper (dashed line) for a given fabrication sequence. The arrows indicate crossings that potentially imply coupling between specific modes, although additional judgment must be applied (see text and supplementary material-Supplement 1).

paper. The supplementary material (Supplement 1) provides a deeper dive into these types of graphs and all the information that can be extracted from them.

3.5 Methodology

In the next section, we highlight the three main fiber configurations and fabrication and characterization of 3×1 components as they already exhibit the full variety of PLs, from conventional to mode-specific and anything in between.

3.5.1 Fiber Configurations

We compare three main types of PLs: devices made of three identical fibers should result in conventional PLs; devices made of three different fibers should result in MSPLs; devices made of two different types of fibers should be hybrids.

Fig. 3.2(a) shows the three main fiber configurations: AAA (three identical fibers), ABC (all different fibers), and ABB (two different types of fibers, each supporting a different mode group). For practicality, we use double-clad fibers with single-mode compatibility at 1550 nm. All fibers feature a 9 μm single-mode core and similar NAs ~ 0.13 . They also feature similar first cladding NAs ~ 0.12 and vary only by first cladding diameters, with respective sizes of 19.6, 32.3, and 42 μm (custom-designed, 2058I1, 2058K1, and 2058J1, Université Laval, Prof. Messaddeq, QC, CA).

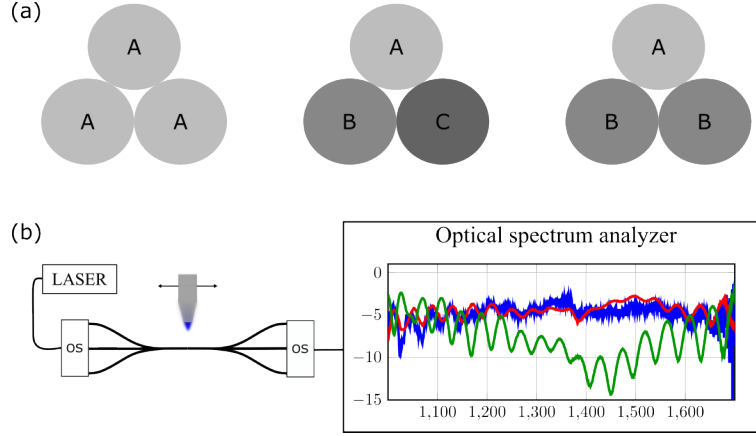


Figure 3.2 Three-mode structures and fabrication process. (a) Three different structures in which each letter represents a type of fiber; AAA uses three identical fibers, ABC uses different fibers, and ABB uses two types of fibers. (b) Schematic diagram of the fusion and tapering station with a heating torch, an illuminating laser, two optical switches (OS), and an optical spectrum analyzer.

3.5.2 Fabrication and Characterization

Before the fusion-taper procedure, all fiber bundles were constrained inside a synthetic fused silica capillary tube (CV1012, Vitrocom, NJ, USA). In-situ, real-time monitoring of the components during fusion and tapering allows to observe and potentially remedy any anomalous loss or coupling between modes [118]. The bundles were clamped to an in-house built setup that allows for fusion and tapering using a mobile torch while pulling on each side. For better comparison, all devices for this study were fabricated using the same sequence, i.e. the same α and L_0 values at all ITRs. In addition, the same characterization setup was used every time. Fig. 3.2(b) shows the in-situ optical characterization system. It starts with a broadband laser source (Energetiq Fiber Coupled Laser-Driven Light Source, model EQ-99, MA, USA) that injects light into a first, in-house built, optical switch (OS) spliced to the input single-mode fibers of the PLs. At the output, a second OS allows the monitoring of each port through an optical spectrum analyzer (OSA, model AQ6317, Ando, Japan). Power transfer is measured by injecting light into one input port and measuring the output across three ports. Additionally, the excess loss is calculated by summing the ratios of all power outputs. After fabrication, the few-mode tapered section was cleaved in the center, producing two identical PLs. Optical far-field profiles were obtained by illuminating each port sequentially with a source operating at 1300 nm (HP 8153ASM, Hewlett-Packard, CA, USA) and capturing the image with an infrared camera (SU320KTS-1.7RT, Goodrich, NJ, USA).

3.6 Results

The following subsections outline the key characteristics of each type of 3-mode PL. This includes a theoretical analysis of the fabrication process, followed by experimental results concerning the final structure's power transfer and the component's optical profile after it has been cleaved. This procedure is consistent across all components, allowing us to identify their main differences.

3.6.1 Conventional Photonic Lanterns

Fig. 3.3 shows the results for a type AAA component, conventional PLs, using three identical fibers (first cladding diameter of 42 μm). Fig. 3.3(a) shows the adiabatic criteria (solid lines) and logarithmic slope (dashed line) calculated by SuPyMode. Two crossings of adiabatic criteria with the logarithmic slope are highlighted by arrows. They show large ranges of ITR for which the adiabatic criteria are below the logarithmic slope: between ~ 0.15 and ~ 0.32 for the LP_{01} - LP_{11a} pair, and above ~ 0.38 for the LP_{11a} - LP_{11b} pair. Those are the three guided modes in the few-mode section, and they are all coupled together via LP_{11a} . Hence, the expected behavior is a split of power between the three modes, independent of the illuminated port. In addition, the model predicts a quasi-lossless device when fabricated without defects because there is no crossing between any guided and unguided modes. This explanation is provided in more detail in Supplement 1. This is witnessed by the fact that the adiabatic criteria coupling the guided modes to the unguided modes of the few-mode section are all above the logarithmic slope curve. Although SuPyMode calculates a large amount of adiabatic criteria, for the sake of clarity, we only show the lowest of the guided-to-unguided pairs (between LP_{01} and LP_{21a}) in Fig. 3.3(a). A more detailed (and more cluttered) example of adiabatic criteria curves is provided as an example in the supplementary material (Supplement 1).

To ascertain the validity of the predictions from the model, we measured the ratio of power in each output, with respect to the power injected at each input, separately. This was done using the in-situ characterization setup at the end of the fusion and tapering process but before cleaving. The results are shown in Figs. 3.3(b–d). The power ratio of each branch with respect to the illumination power is color-coded: branch 1 is blue, 2 is red, and 3 is green). Excess loss at all wavelengths is shown as the black line. Illumination of branch 1 corresponds to Fig. 3.3(b), branch 2 to Fig. 3.3(c), and branch 3 to Fig. 3.3(d).

The three graphs show the expected strong coupling between all the ports. The ratio of power sent to the two non-illuminated branches is about -5 dB, or one-third, as expected.

The strong oscillations on the power ratio of the illuminated branch are expected and are due to interference between the modes. They are highly dependent on the exact length of the tapered section and do not reflect actual coupling values in the final component (which will be cleaved in the middle of the tapered section). Only their average trend is relevant. That trend still shows some imperfections of the device, with slightly higher coupling to the non-illuminated branches and slightly higher excess loss (black line) at ~ 1400 nm. This results in low ratios of power in the illuminating branch (down to less than 10% in two cases). However, the device displays low overall excess loss.

Finally, the far-field images of Fig. 3.3(e) reinforce the fact that the three modes LP_{01} , LP_{11a} and LP_{11b} are well mixed at the output. None of the images features well-defined transverse mode structures.

3.6.2 Mode-Selective Photonic Lanterns

MSPLs are obtained with components that exhibit no coupling between modes. This can be slightly counter-intuitive in the realm of fiber-based components, which often rely on mode-coupling to exhibit interesting behaviors. In this case, however, it should be no real surprise as the idea is to segregate the transverse modes of the few-mode section to selectively direct them into three different single-mode fibers. This can be readily achieved by sufficiently breaking all the symmetries existing in the previous (AAA) configuration. Hence, mode-selectivity is achieved by using three sufficiently different fibers. In this study, we chose three different double-clad fibers (DCFs) with identical single-mode characteristics (see sub-section 3.5.1) and varying first-cladding diameters.

Simulations are displayed in Fig. 3.4(a). They indicate that there should be no coupling between modes. A notable feature, however, seems to suggest otherwise: a crossing of the adiabatic criterion between modes LP_{11a} and LP_{11b} at ~ 0.23 ITR is highlighted by a red arrow in the graph. This is when additional judgment and experience are required in the interpretation. This type of very narrow and very abrupt decrease of an adiabatic criterion is usually spurious. It is an artifact that exists whenever two propagation constants β_i and β_j become equal. A good rule of thumb is to discard very narrow crossings in the graphs. In the end, the simulation suggests that a device fabricated with notable defects should be highly mode-selective and quasi-lossless.

Figs. 3.4 (b–d) show the power transfer for all illumination scenarios where the power remains mainly in the illuminated branch. Power transfers to the non-illuminated branches are minimal, below 10% for most wavelengths. Specifically, in Fig. 3.4 (b), modal isolation between the LP_{01} -like mode and the two LP_{11} -like modes is shown to be above 20 dB for

the range of 1200–1600 nm, and above 12 dB throughout. In Figs. 3.4 (c–d), modal isolation between the two LP_{11} modes is shown to be above 10 dB from 1000–1600 nm. In general, isolation is lower, and excess loss is higher in the measured wavelength range. The effective operational range of these components remains very large, at around 500 nm. In addition, the fabricated device proves to be with low excess loss.

In contrast to the case of the conventional PL, the far-field images of Fig. 3.4 (e) display the well-delineated shapes of the expected transverse modes that look like the LP_{01} , LP_{11a} , and LP_{11b} .

3.6.3 Hybrid Photonic Lanterns

Even with only three fibers in the bundle, devices can be made that will display behaviors between those of conventional and mode-selective components. An obvious way to achieve such behavior with 3×1 PLs is to use two different types of fibers. Here, we introduce two types of hybrid devices, which we call ABB and AAB, where A represents the fiber with the largest first cladding diameter. Interestingly, the two cases display rather different behaviors. A device of type ABB will segregate the LP_{01} -like mode from the twin LP_{11} -like modes, whereas a device of type AAB will hybridize the LP_{01} -like mode with one of the LP_{11} -like modes, while the other one will be segregated. Hence, already with 3 fibers, hybrid PLs components display a variety that can only grow with the number of fibers and can, in principle, be used to tailor devices to desired applications.

Fig. 3.5(a) shows a range of ITRs above ~ 0.38 for which the adiabatic criterion between the twin LP_{11} modes is lower than the logarithmic slope curve. Hence, we can expect a hybridization of those modes and the segregation of the fundamental LP_{01} -like mode. The rapidly oscillating nature of the green adiabatic criterion curve reflects numerical instabilities caused by the degeneracy between the LP_{11} modes. Only the trend is helpful here. In contrast, the model does not predict any coupling between the fundamental mode LP_{01} and the twin LP_{11} modes. Nor does it predict any coupling between guided and unguided modes, which suggests that the particular fabrication sequence, absent defects, can produce a quasi-lossless device.

The experimental results are shown In Fig. 3.5(b–e). In Fig. 3.5 (b), illumination through the first port, corresponding to the lone type A fiber and in principle to the fundamental LP_{01} -like mode, shows high isolation of that mode from the other two guided modes. This is close to the scenario of Fig. 3.4 (b), although in the case of this specific component, higher losses are observed below 1150 nm. In contrast, much higher power transfers exist between the LP_{11} branches, as shown in Figs. 3.5 (c,d). A slow interferometric beating can erroneously

lead to the impression that the coupling is highly dependent on the wavelength. This is not the case: coupling remains high throughout, and only the exact length of the tapered section dictates, through interference, how much power is found in each branch.

The first three images in Fig. 3.5(e) actually show strongly segregated LP_{11} -like modes, akin to the mode-selective case shown in Fig. 3.4(e). This is because the wavelength of the narrow-band illumination laser used for this characterization step, 1300 nm, is very close to a minimum of the hybridization between the LP_{11} -like modes. For this component, we also took a picture with illumination at 1550 nm (last image in Fig. 3.5(e)), which shows hybridization of the LP_{11} -like modes. Interestingly, the interference pattern strongly depends on the polarization state of the illumination laser, a feature that we intend to explore fully in the near future.

A configuration with two A-type fibers (42 μm first cladding diameter) and one B-type (32.3 μm first cladding diameter), or configuration AAB, is not an intuitively straightforward, as the fundamental mode will be hybridized with one of the LP_{11} modes, leaving the other segregated. In other words, the break in the physical symmetry does not correspond to the natural symmetry breaking of the mode structure. The results, shown in Fig. 3.6 are nonetheless enlightening and we include them here for completeness.

As shown in Fig. 3.6(a) there is a large region of ITRs, between ~ 0.15 and ~ 0.3 , where the adiabatic criterion of the LP_{01} - LP_{11a} pair falls below the logarithmic slope curve. We can thus expect power transfers between the two modes while LP_{11b} remains segregated.

Figs. 3.6(b,c) indeed show strong coupling between LP_{01} and LP_{11a} , while LP_{11b} is isolated. The rapid interferometric oscillations observed in these figures are highly dependent on the actual length of the tapered section, and only the average value is relevant. In contrast, illumination of the lone B-type fiber shows modal isolation greater than 10 dB throughout.

The optical profiles in the far field, shown in Fig. 3.6(e), are interesting. In particular, the second profile is clearly a superposition of the LP_{01} mode with one of the LP_{11} modes, while the last profile is purely LP_{11} -like. It is unclear if this feature could easily be exploited in an experiment.

3.7 Discussion

CMT gives rise to very useful modeling tools for the fabrication of complex devices such as PLs, as highlighted by the strong agreement between theory and experiment highlighted in this study. All simulations depict ideal scenarios, assuming no perturbation along the taper axis (dust, micro-bending, uniform fusion) and perfectly homothetic reduction of the

taper. However, imperfections or mechanical flaws may arise during fabrication, leading to excess losses or power transfer in fibers that are supposed to exhibit high modal isolation. Therefore, it is essential to carefully characterize and monitor each PL type. Indeed, we showed that a comparison between adiabatic criteria and logarithmic slopes predicts the behaviors of various types of PLs. As with any modeling tool, however, informed judgment is required to interpret results adequately. For instance, the sudden but very brief plunge of an adiabatic criterion can mislead into thinking that coupling will occur when actual modes remain segregated. Such a spurious signal which occurs only when a criterion lies below the logarithmic slope over a large range of ITRs must be distinguished from actual coupling. The simulations were used as a guideline since achieving ideal scenarios during the fabrication process is impractical. For most of our processes that involve high modal isolation, the coupler is fabricated to operate in a sufficiently adiabatic regime where small variations in L_0 and α become negligible. The parameters L_0 and α each affect the adiabaticity of the coupler in unique ways. Choosing their values involves balancing the need to maintain adiabaticity with the goal of keeping the device compact and durable. Additionally, practical constraints limit the allowable range for L_0 . Since it impacts the overall length of the device, excessively large values of L_0 lead to overly long couplers that are too fragile. On the other hand, there is a minimum value for L_0 , dictated by the length of the heating element (such as a flame, plasma arc, or filament). For each new type of PL, initial values are based on prior experience and are adjusted as needed to optimize the component without compromising its durability.

Modeling tools also present limitations, specifically regarding large wavelength bandwidths. Here, each curve plotting the adiabatic criteria vs logarithmic slope is calculated for a single wavelength, and a study over the whole range of intended performance is necessary before attempting to fabricate the device. In our numerical model, we employ a truncated modal basis consisting of a large number of guided-core and guided-clad eigenmodes. Although the continuous spectrum of leaky modes is not explicitly represented, this discrete set captures the dominant propagation dynamics within the taper. Moreover, the fiber assembly is housed inside a rigid capillary tube, whose boundary conditions further suppress any residual coupling to external leaky modes. Under these conditions, omitting the continuum of leaky modes introduces a negligible error in the predicted device performance. We did not show such an extensive set of curves in the main text, but an example is provided in the supplementary material (Supplement 1). We computed a large ensemble of guided-core and guided-clad eigenmodes (similar but with even more modes than Fig. S2 of supplementary material) but only plotted those exhibiting the strongest coupling to the fundamental mode, since higher-order modes—with diverging effective indices and increasingly orthogonal field symmetries—have overlap integrals that rapidly approach zero and thus contribute negligibly.

Even with simulation tools, the most comprehensive information about a component's performance is obtained by analyzing the full power transfer for each wavelength performance and its optical profile to determine its usefulness in any application. An important consideration when monitoring results is to avoid misinterpreting segregation as an absence of coupling.

Most of the fluctuations in power transfer observed with the same type of fiber (such as AAA, AAB, and ABB configurations) reflect the behavior of standard single-mode splitters or wavelength-division multiplexers. Factors that can influence power transfer include the degree of fusion, coupling length, taper shape, core spacing, effective refractive index, fiber configuration, and, in some cases, the characteristics of the source, such as its polarization. The coupling length needs to be taken into account as the tapered region is subsequently cut in half to make two devices from one fabrication sequence, and no amount of modeling can precisely determine the exact outcome. The performance of each device depends on its coupling efficiency, which is influenced by the effective refractive index of each fiber. Since each fiber has a different first cladding, the effective refractive index changes when the fiber is tapered. This change can break symmetry and selectively generate different modes. Therefore, while simulations provide an initial understanding, experimental characterization of each device is essential to account for any changes that might affect coupling efficiency, operational wavelength, and optical profile.

The far-field optical profiles only provide intensity information. Phase information is important to fully characterize the transverse modes, but its measurement is beyond the scope of this work.

On the other hand, while the AAB configuration demonstrates intriguing behavior, it is crucial to note that it could evolve into a MSPL by increasing the length of the final component. Fig. 3.6(a) illustrates that, by creating a component that reaches values on the order of 10^{-5} , each mode can be individually generated in the few-mode section. Although this configuration may not yield a highly robust component, it does enable the development of a mode-selective component with a reduced number of fibers.

Finally, all PLs fabricated for this study were made with synthetic fused silica capillary tubes, which do not provide the best results in terms of excess loss. Better components can be manufactured using more expensive fluoride capillary tubes. With the exception of excess loss, fused silica capillaries allow reproducing the main outcomes obtained with more expensive capillary tubes.

3.8 Conclusion

This study identifies which of the model’s variables allow predicting the type and specifications of manufactured PLs. Also, implementing double-clad fibers with single-mode compatibility with SMF28 enables optimal and real-time characterization of any PL type. This study paves the way for better reproducibility and manufacturing yields for various PLs. The study describes the properties of the various types of PLs to allow for a better adequacy between a device type and a particular application across various fields. For instance, pure improvements in light collection can be achieved with large bundles of standard PLs [103]. In contrast, purely MSPLs provide additional contrast in some imaging modalities such as optical coherence tomography [56]. Finally, semi-mode selective PLs will prove helpful in telecommunications, where degeneracy of the LP_{11} modes cannot be avoided over long distances in cylindrical symmetries [118].

Fabricating any type of PL for its implementation requires identifying their coupling performance, operational wavelength, and optical profile of the output. Therefore, the simulations and characterizations are critical for its implementation. Simulation tools allow for the determination of the essential ingredients needed for manufacturing devices with specific characteristics. This is particularly relevant when the modeling tool indicates no intersection between the adiabatic criteria and the logarithmic slope of the taper profile.

The existence of reliable models allows for the analysis of numerous new PLs designs without the need for lengthy trial-and-error manufacturing processes. Meanwhile, the fabrication process and characterization provide insights into the coupling performance, operational wavelength, and optical profile. These performance attributes can vary depending on the fiber type, length of the device, and fabrication procedure.

Additionally, ideally, it is possible to categorize PLs into three main types: 1. Conventional PLs, which exhibit strong coupling performance between each port, a high dependence on wavelength, and a superposition of guided modes. 2. Mode-selective devices provide high isolation between all modes, a broadband operational wavelength, and the generation of each mode individually. 3. Hybrid components, which combine the behaviors of the first two types—exhibiting high isolation between certain ports while maintaining strong coupling with others in a large bandwidth with a mixture in the profile of the mode.

The back matter section and supplementary materials appear in Appendix B.

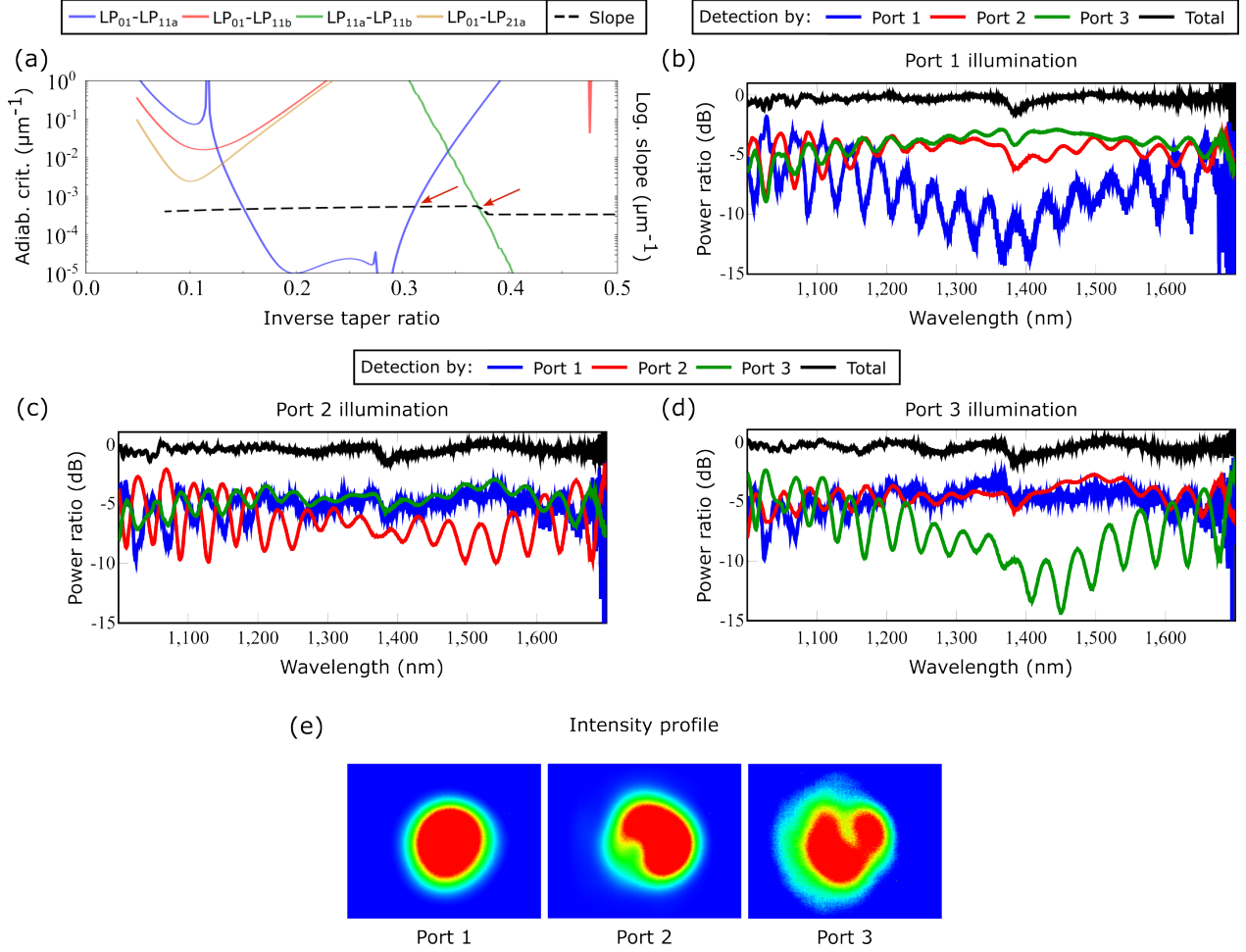


Figure 3.3 AAA fiber configuration. (a) Adiabatic criteria for three identical (AAA) double-clad fibers with a $42\text{ }\mu\text{m}$ -diameter first cladding. The solid blue, red, and green lines show the criteria for each pair of guided modes (LP_{01} , LP_{11a} and LP_{11b} , respectively) in the few-mode tapered section of the device. The lowest adiabatic criterion for coupling between a guided and a non-guided mode (LP_{01} and LP_{21a} in this instance) is also shown. The dashed black curve corresponds to the logarithmic slope for the fabrication sequence. (b–d) Power ratio in each branch, with respect to the input power, after fusion and tapering but before cleaving (branch 1 in blue, 2 in red, 3 in green, total in black) when illuminating input 1 (b), input 2 (c), or input 3 (d), respectively. (e) Far-field optical profile of the few-mode structure after cleaving and illuminating each port.

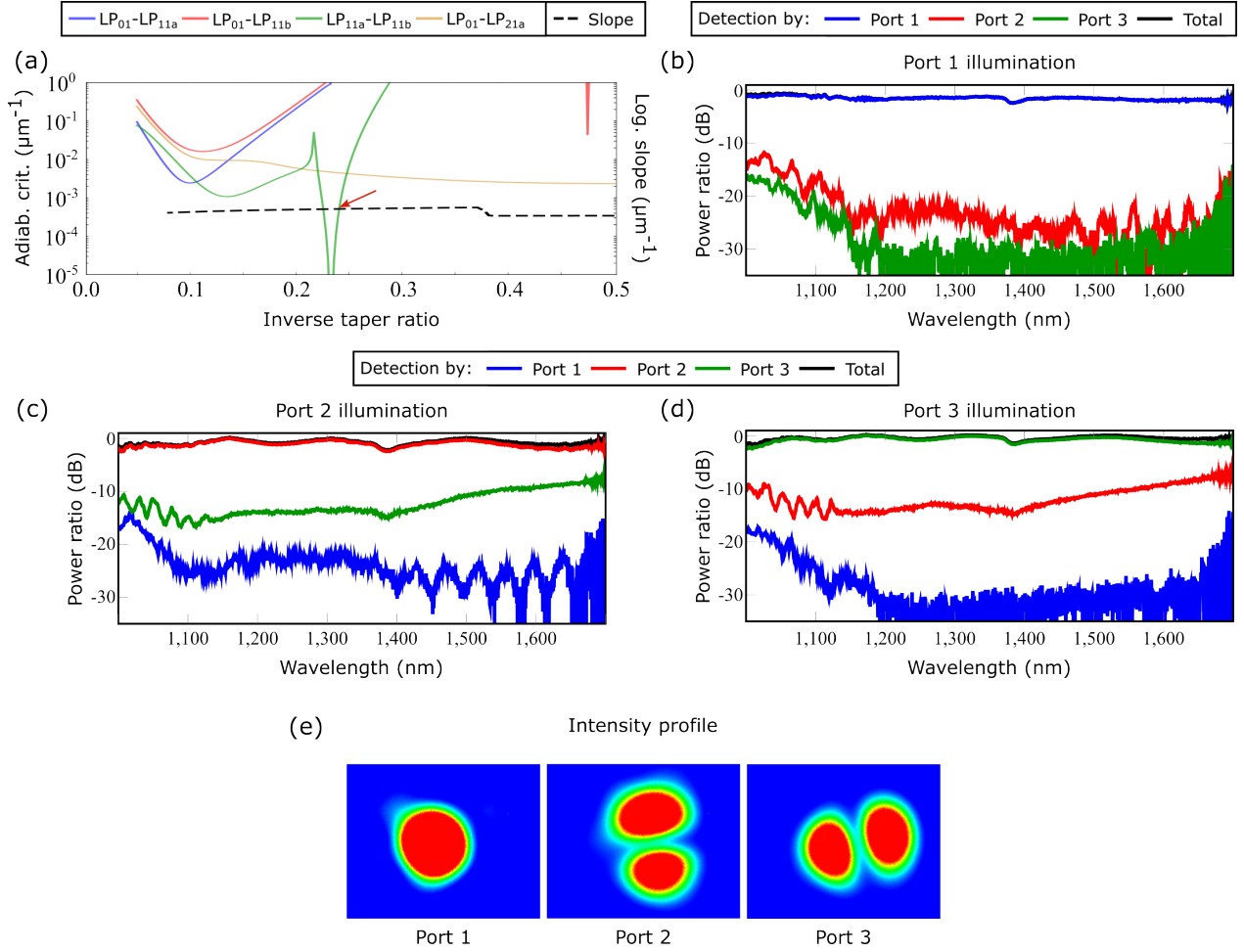


Figure 3.4 ABC fiber configuration. (a) Adiabatic criteria for three different double-clad fibers with 42 (A-branch 1), 32.3 (B-branch 2), and 19.6 μm (C-branch 3) first cladding diameter, respectively. The solid blue, red, and green lines show the criteria for each pair of guided modes (LP_{01} , LP_{11a} , and LP_{11b}) in the few-mode tapered section of the device. The lowest adiabatic criterion for coupling between a guided and a non-guided mode (LP_{01} and LP_{21a} in this instance) is also shown. The dashed black curve corresponds to the logarithmic slope for the fabrication sequence. (b–d) Power ratio in each branch, with respect to the input power, after fusion and tapering but before cleaving (branch 1 in blue, 2 in red, 3 in green, total in black) when illuminating input 1 (b), input 2 (c), or input 3 (d), respectively. (e) Far-field optical profile of the few-mode structure after cleaving and illuminating each port.

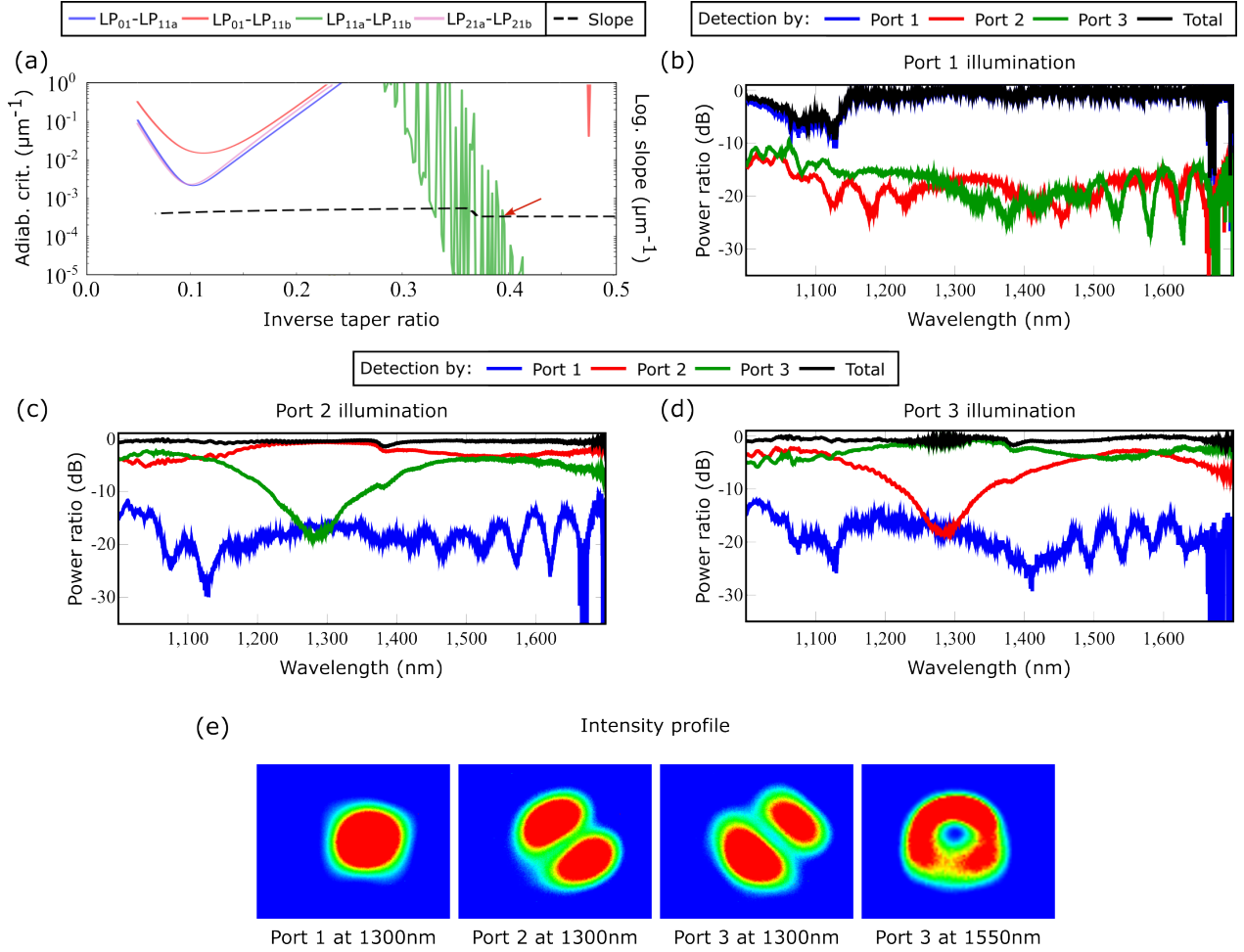


Figure 3.5 ABB fiber configuration. (a) Adiabatic criteria for two different types of double-clad fibers with 42 (A-branch 1) and 32.3 (B-branches 2 and 3) first cladding diameter, respectively. The solid blue, red, and green lines show the criteria for each pair of guided modes (LP_{01} , LP_{11a} , and LP_{11b}) in the few-mode tapered section of the device. The dashed black curve corresponds to the logarithmic slope for the fabrication sequence. (b–d) Power ratio in each branch, with respect to the input power, after fusion and tapering but before cleaving (branch 1 in blue, 2 in red, 3 in green, total in black) when illuminating input 1 (b), input 2 (c), or input 3 (d), respectively. (e) Far-field optical profile of the few-mode structure after cleaving and illuminating each port. The first three images were obtained at 1300 nm. The last one is of port 3 at 1550 nm. It shows mixing between the two LP_{11} -like modes.

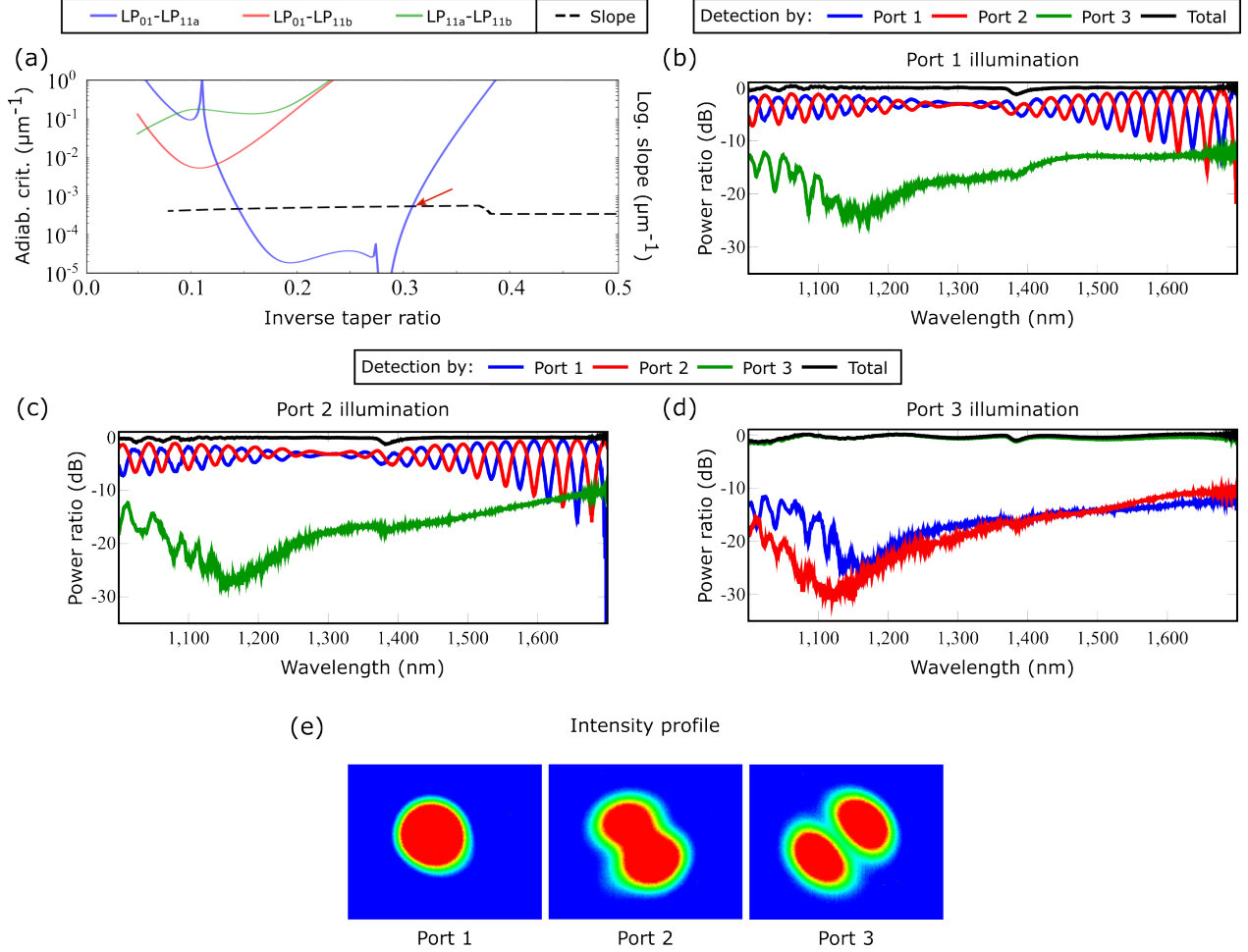


Figure 3.6 AAB fiber configuration. (a) Adiabatic criteria for two different types of double-clad fibers with 42 (A-branches 1 and 2) and 32.3 (B-branch 3) first cladding diameter, respectively. The solid blue, red, and green lines show the criteria for each pair of guided modes (LP₀₁, LP_{11a}, and LP_{11b}) in the few-mode tapered section of the device. The dashed black curve corresponds to the logarithmic slope for the fabrication sequence. (b–d) Power ratio in each branch, with respect to the input power, after fusion and tapering but before cleaving (branch 1 in blue, 2 in red, 3 in green, total in black) when illuminating input 1 (b), input 2 (c), or input 3 (d), respectively. (e) Far-field optical profile of the few-mode structure after cleaving and illuminating each port.

CHAPTER 4 ARTICLE 2: OPTICAL PROFILE RESPONSE TO POLARIZATION AND WAVELENGTHS ACROSS PHOTONIC LANTERNS ARCHITECTURES

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Published in: Optics Express.

Submission date: January 26, 2026.

4.1 Author Contribution

As the first author of the publication, I was responsible for developing the research concept, designing and overseeing the optical system, mounting the optical system, processing and analyzing experimental data, drafting the initial manuscript, preparing the first response to reviewers, creating figures, and conducting the literature review. Joseph Lamarre helped with the literature review and provided some illustrations. Raphaël Maltais-Tariant contributed to the scientific discussions throughout the project and also provided detailed feedback and significant revisions to the manuscript. Adam Zolnai performed measurements of the polarization response. Stéphane Virally offered guidance, support, and substantial modifications to the paper. Caroline Boudoux and Nicolas Godbout provided laboratory materials, funding, and access to laboratory facilities. All authors reviewed and approved the final manuscript.

4.2 Chapter Context

This chapter presents an in-depth exploration of the optical profile response of various types of PLs, focusing on the crucial roles of polarization and wavelength for their effective implementation. Understanding and manipulating these characteristics is essential for optimizing performance across a range of applications. For instance, in optical coherence tomography, precise adjustments to polarization are vital to match it with the reference arms, ensuring interference. Moreover, the physical manipulation of the fiber itself may induce variations in polarization, a phenomenon inherent to many fiber types, particularly when polarization-maintaining fibers are not utilized.

Additionally, the choice of operational wavelength can significantly influence the performance and applicability of these devices. In scenarios where broadband responses are necessary, alterations in optical modes can have profound effects on the outcomes of specific applications.

This chapter seeks to understand the complex dynamics in the optical profile distribution of PLs for optimal use in biomedical imaging.

Abstract

This paper examines the wavelength- and polarization-dependent optical profiles of various types of 3-mode photonic lanterns fabricated using double-clad fibers. By manipulating the input polarization and wavelength, we demonstrate that significant effects can be observed in the modal profile patterns of photonic lanterns with strong coupling between their ports. In contrast, ports with high isolation or low coupling, such as in mode-selective photonic lanterns, show minimal changes in the optical profile. This study also highlights additional potential benefits of photonic lanterns. Specifically, we discuss their use for generating vector beams or as polarization multiplexers.

4.3 Introduction

PLs are waveguide devices that enable adiabatic bidirectional light transfer between a multimode waveguide and a set of single-mode waveguides [41]. Some of these devices, MSPLs, deterministically map a given multimode domain to a tailored set of single-mode outputs [119] and can be used as transverse mode multiplexers/de-multiplexers. Both types of PLs can exhibit broadband performance, up to 500 nm, and small excess loss, less than 1 dB.

Applications of PLs range from their original role in astrophotonics; separating multimode starlight into different single-mode channels to process information in parallel [120], to telecommunications, such as enabling high-dimensional encoding by treating spatial modes as distinct information channels [121], and also biophotonics [91, 122].

Traditionally, the higher-order spatial modes associated with a PL only act as transient carriers, where the chief concern is achieving their combination and separation with minimal loss and crosstalk. However, novel PL-based techniques are emerging with the main objective of studying and implementing the optical properties of higher-order spatial modes [110]. In these emerging applications, performance is governed by the complete optical structure of the beam, not only its modal composition but also its vector degrees of freedom or even its field [123]. For instance, the generation of vector beams and polarization analysis have originally been examined in free-space optics, demonstrating notable impacts across various fields, including telecommunications and biomedical applications [91, 121, 124–130]. Given the significance of vector beams, numerous studies have investigated the generation of higher-order modes and vector beams in fibers, employing various techniques such as fiber gratings, mode-

selective couplers, and offset splicing with few-mode fibers, among others [131–138]. These techniques have led to several applications in laser systems, telecommunications, sensing, and microscopy [139–143]. Owing to their compatibility with optical fibers and their compact designs, PLs present a suitable approach to vector beam manipulation, and generation of structured light. Notably, PLs have demonstrated the capacity to generate structured light more efficiently, where multiple ports can be utilized to generate orbital–angular-momentums (OAMs) [144–150] in a single device. This is achieved by manipulating each port independently in phase and polarization, providing increased flexibility in vector beam generation and polarization control compared to other fiber-based techniques.

Despite these advances, polarization is often an afterthought in the design and use of PLs, or even when considering the wavelength response of the optical profile. The customary scalar LP-mode framework treats each guided mode as having a single, degenerate transverse field component, thereby rendering the lantern nominally polarization-insensitive. Although polarization-maintaining PLs have been demonstrated [151], the optical profile and final polarization orientation of the lobes remain undetermined by the fiber configuration, rotation, fusion, and tapering of several fibers, without even considering their response with wavelength. Consequently, the polarization of light injected into a PL is rarely controlled, and any emerging polarization at the output is usually dismissed as an incoherent mixture. Ignoring polarization, however, can limit performance in several advanced applications. Even if fully polarization-maintaining PLs remain impractical, deliberate manipulation of polarization offers a potent lever for controlling the multimode field and tailoring the polarization properties of higher-order modes. Adjusting the input polarization in the single-mode section can markedly alter, even rotate, the modal pattern delivered at the multimode output, as shown in [54].

In this paper, we experimentally study the influence of wavelength and, more importantly, polarization in the optical profiles of the three types of PLs. We demonstrate how the input polarization determines the mode profile in non-selective devices, opening a new set of possible characteristics for applications. To do so, we use an optical system composed of an infrared camera, a polarization analyzer, polarization controllers, and different sources to allow us to observe and characterize the polarization response for a variety of PLs. This paper also highlights how different PLs, with respect to polarization, can have distinct applications. For example, MSPLs can be designed to be robust against polarization, ensuring that the optical profile remains unaffected while only the polarization of the lobes changes. In contrast, non-selective devices present the novel possibility of spatially encoding information using pure polarization through a single port. Each approach is important for different applications.

4.4 Methodology

We analyzed the optical response of 3×1 PLs, focusing on the coupling between modes under varying injection parameters, including wavelength and polarization state. Figure 2.3 shows a schematic of a three-mode PL and the evolution of three single-mode inputs into the first three modes of the multimode region.

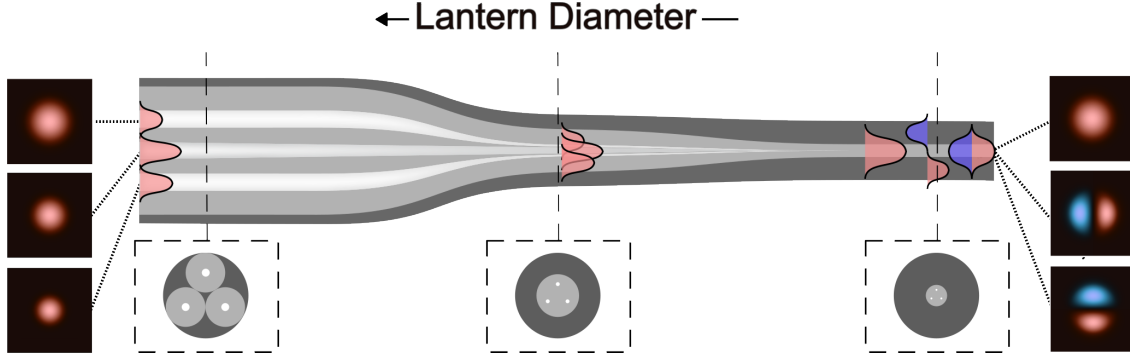


Figure 4.1 Modal evolution in a three-mode photonic lantern. Left: simulated near-field intensity patterns of three input beams in the single-mode fibers. Middle, cross-section of the fusion tapered process. Right: simulated near-field intensity patterns profiles of the multimode output.

The PL is a bundle of three single-mode fibers, fused and adiabatically tapered into a single multimode section that supports the fundamental LP_{01} and the doubly-degenerate LP_{11} set. The figure does not purport to present only the case of an MSPL, where the correspondence between each input fiber and the three modes is one-to-one. In a regular PL each single-mode input contributes to the amplitude to each mode.

The left-hand panel shows the near-field amplitudes of the three single-mode fibers with exaggerated different mode field diameters. The right-hand panel shows the three isolated modes, LP_{01} and even/odd LP_{11} . The middle section shows the adiabatic taper transition region. The vertical dashed lines highlight the geometric transition from the original bundle to the concentric multimode waveguide.

The physical properties of the PLs are, in part, determined by the original fiber bundle configuration. Representing different fiber types with different letters, the typical configurations include AAA or standard PLs with three identical fibers, ABC or an MSPLs, and the hybrid configurations with either AAB or ABB [152].

For this project, all PLs were fabricated using double-clad fibers with single-mode compatibility at 1550 nm with each fiber, labeled A,B, and C, having a $9 \mu\text{m}$ core diameter. The fibers are differentiated by their inner cladding diameters, namely 42, 32.3, and $19.6 \mu\text{m}$ (fibers

2058I1, 2058K1, and 2058J1, Université Laval, Prof. Messaddeq, QC, Canada). The fabrication process is based on the heat and pull method presented in [118]. The three double-clad fibers are inserted into a synthetic fused silica capillary tube (CV1012, Vitrocom, NJ, USA) prior to fusion to maintain the structural alignment of the fiber bundle.

The modal response at the few-mode end of the PL is analyzed under varying single-mode input polarizations and wavelengths, using the setup depicted in fig. 4.2. This setup can accommodate two laser sources: a dual-wavelength narrow band source (HP 8153ASM, Hewlett-Packard, CA, USA) containing two single-mode lasers at 1300 nm and 1550 nm, and a broadband source (SL1310V1-10048, Thorlabs, NJ, USA) with a 100 nm bandwidth centered around 1300 nm. Both lasers are fiber-coupled to polarization controllers (FPC030, Thorlabs, NJ, USA), which are then connected to a specific single-mode input of the PL.

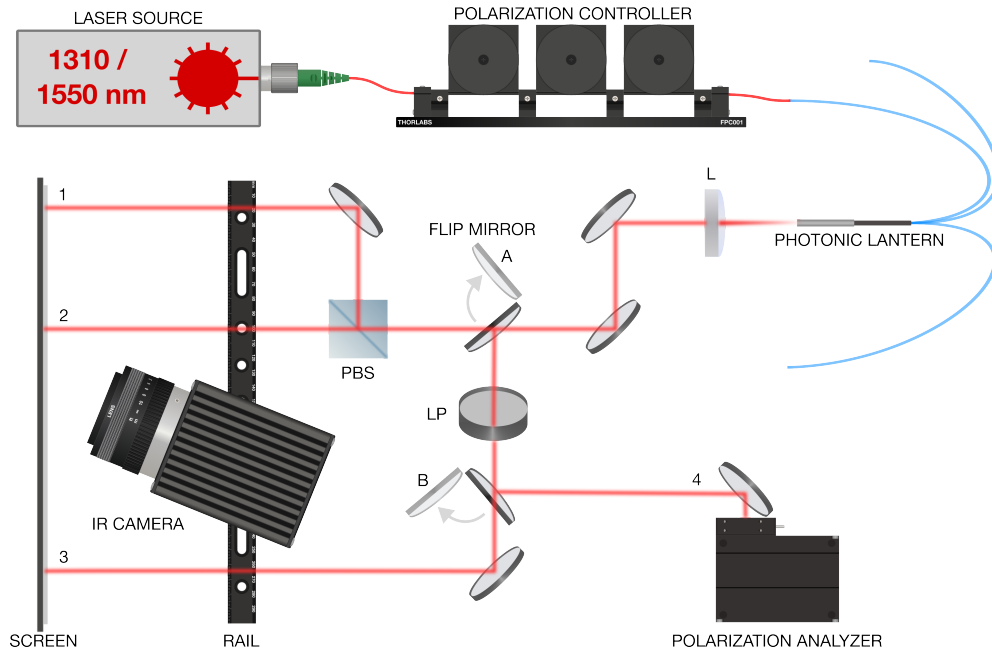


Figure 4.2 Schematic diagram of the optical system for polarization measurements, where PBS denotes a polarization beam splitter, P represents a polarizer, and L is a collimating lens. The two flip mirrors, A and B, lead to four possible paths toward screens 1, 2, and 3, as well as to the polarization analyzer in 4.

Different optical paths allow the observation of the optical profiles for various polarization states. The first two paths are the output of a polarization beam splitter, which separates the optical beam into its horizontal and vertical polarization components. Both outputs are then projected onto screens 1 and 2, where the modes are visualized using an infrared camera (SU320KTS-1.7RT, Goodrich, NJ, USA). This setup allows for the analysis of the polarization components of each optical mode and their evolution over varying input conditions. Flipping

mirror A allows bypassing the polarizing beam splitter to a third optical path, projected onto screen 3 and visualized with the same camera, irrespective of the polarization state. Along this path, flipping mirror B allows for injecting the beam into path 4, which leads to a polarization analyzer (SK010PA-IR, Schäfter + Kirchhoff, HH, DE) that measures the exact polarization state. A linear polarizer is inserted into this path to calibrate the polarization analyzer before acquiring measurements. The polarization analyzer indicates the position of the polarization state on the Poincaré sphere. The two main angles quantify, respectively, the ellipticity (linear polarization on the equator and circular polarization states at the poles) and the orientation of the ellipse's main axis. The radial component corresponds to the degree of polarization (DOP) as a percentage, from depolarized (0%) to fully polarized (100%). In the figures below, the various states are read on the polarization analyzer, and the numbers are converted into 2D pictorial representations (ellipses, circles, or lines).

Such a setup allows for straightforward control of the input parameters (polarization state and wavelength) injected into the PL, as well as accurate measurement of the resulting few-mode output profile. Light is sequentially injected into all three ports across the three types of 3-mode PLs, using five distinct polarization states and three wavelength configurations. The polarization states are: linear horizontal, linear vertical, left- and right-handed circular, and one arbitrary elliptical state. The three wavelength configurations are: narrow-band at 1550 nm, narrow-band at 1300 nm, and broadband, i.e., 100 nm around 1300 nm.

By utilizing this polarization analyzer, it was necessary to have a free space configuration to ensure effective few-mode analysis of the polarization. This approach avoids any performance limitations associated with using only a fiber connector and maintains consistency with the system. The polarization analyzer operates on the principle of a rotating quarter-wave plate positioned in front of a polarization-sensitive detector, which provides raw measurements that are used to calculate the normalized Stokes parameters. All results are presented in the supplementary material, with some representative results in the main text.

4.5 Results and Discussion

4.5.1 Wavelength Response

The responses of each PL depend heavily on its fiber configuration, demonstrating significant differences in their responses to wavelength and power transfer. To examine the behavior of the optical profile based on the wavelength, we focus on the third path of the optical system illustrated in fig. 4.2 by changing the laser source. Figure 4.3 shows the optical profiles of the three ports for each 3-mode PLs configurations (AAA, AAB, ABB, and ABC) and

wavelengths (1550 nm, 1300 nm, and 1300 nm broadband) combinations. Each profile was obtained using a horizontal output polarization.

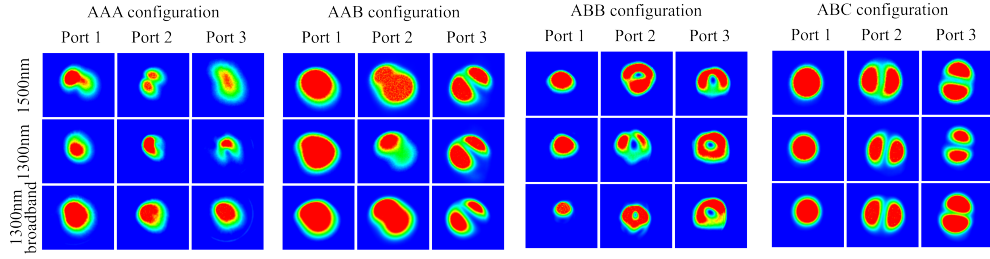


Figure 4.3 Optical profile of each port of the different types of PLs at horizontal polarization state using different wavelengths (1550 nm, 1300 nm, and 1300 nm broadband).

A key observation is the mode selectivity exhibited by each device port. For example, Port 3 of the AAB configuration, Port 1 of the ABB configuration, and all ports of the ABC configuration show a consistent optical profile without notable variations. In contrast, for the AAA configuration's first two rows of three ports and the ABB configuration's ports 2 and 3, the power distribution can change with narrow-band sources depending on wavelength. When using a broadband source, some ports exhibit a quasi-Gaussian profile due to the superposition of all wavelengths at the same spot, such as the three ports of the AAA configuration shown in the last row. This superposition is also observed in the AAB configuration with LP_{01} and LP_{11} . Figure 4.3 ABB displays an optimal response for mode LP_{01} , as there is no coupling with LP_{11} s. Nonetheless, the interaction between the degenerate modes leads to a superposition that generates a donut shape. Using the broadband source in Port three of the ABB configuration, the superposition of those 100 nm does not cover the entire profile, even though one is shown in Port 3 at 1300 nm. Lastly, the ABC configuration shows an indifferent wavelength behavior even with a broadband source (last row of the three ports).

4.5.2 Polarization Response

For the polarization analyses of each mode and profile, the four distinct paths illustrated in fig. 4.2 were used. The first three paths were used to obtain the optical profiles, while the fourth path specifically addressed the polarization response associated with each profile. It is important to note that the experiments were conducted using higher modes and the superposition of them rather than only the fundamental mode. To ensure accurate measurements, it was necessary to examine the output of the polarization analyzer and its behavior with these particular beams to identify any inconsistencies or inaccuracies in the polarization state measurements. Figure 4.4 presents three different cases of polarization measurements

given in the Poincaré sphere by the polarization analyzer, and all the given values (PER [polarization extinction ratio], lin PER [polarization extinction ratio of linearly polarized light], φ [azimuthal angle], rel φ [relative azimuthal angle], DOP [degree of polarization], and Intensity – see supplementary material) are observed in the first yellow square. Figure 4.4(a) represents an example of the calibration measurement done to choose the output polarization, considering the polarizer before the polarization analyzer. The calibration was performed at the beginning of each port measurement, following the procedure described below. The port to be measured was illuminated so that light continued along path number 4. A polarizer was placed between the two flip mirrors (A and B in fig. 4.2) to ensure that only vertical polarization reached the polarization analyzer. The power was maximized by adjusting the polarization controllers to achieve vertical polarization. In some cases, this was further verified by monitoring paths 1 and 2 to confirm that the polarization was predominantly vertical. As mentioned, the calibration was done with the supermode structures.

Additionally, Figure 4.4(a) shows an adequate case measurement at 1300 nm where each measurement in time, represented by a blue dot in the Poincaré sphere, falls into the same targeted polarization (vertical polarization in this case). Although the intensity in this case was low, the polarization was adequately captured, showing a DOP of 98.2.

Figure 4.4(b) displays measurements taken at 1300 nm using an AAA configuration, and Figure 4.4 presents measurements taken at 1300 nm using a broadband source with the same PL. Figure 4.4(b) and (c) illustrate cases where the polarization response varies significantly in time, making it difficult to determine. Even though calibration was performed for each experiment, in some cases, such as Figure 4.4(b) and (c), at the moment of the measurements, the measurements were abrupt, as in these images.

Limitations of the current system demonstrate discrepancies in some aspects of the polarization measurements, as shown in Figure 4.4. A possible explanation for the abrupt polarization measurements is the response of PLs with strong coupling between ports (the repetition of at least one type of fiber AAA, AAB, ABB) where the injection port experiences significant power transfer and interactions with the other ports due to mode superposition, which can be affected by any change in phase. These structures suggest that the superposition of modes could generate partially unpolarized light. This behavior was also observed at 1300 nm, as shown in the supplementary material.

Furthermore, the polarization analyzer has a short-band response (a single wavelength was set for each measurement); however, broadband measurements were still taken and showed satisfactory results, which are detailed in the supplementary material.

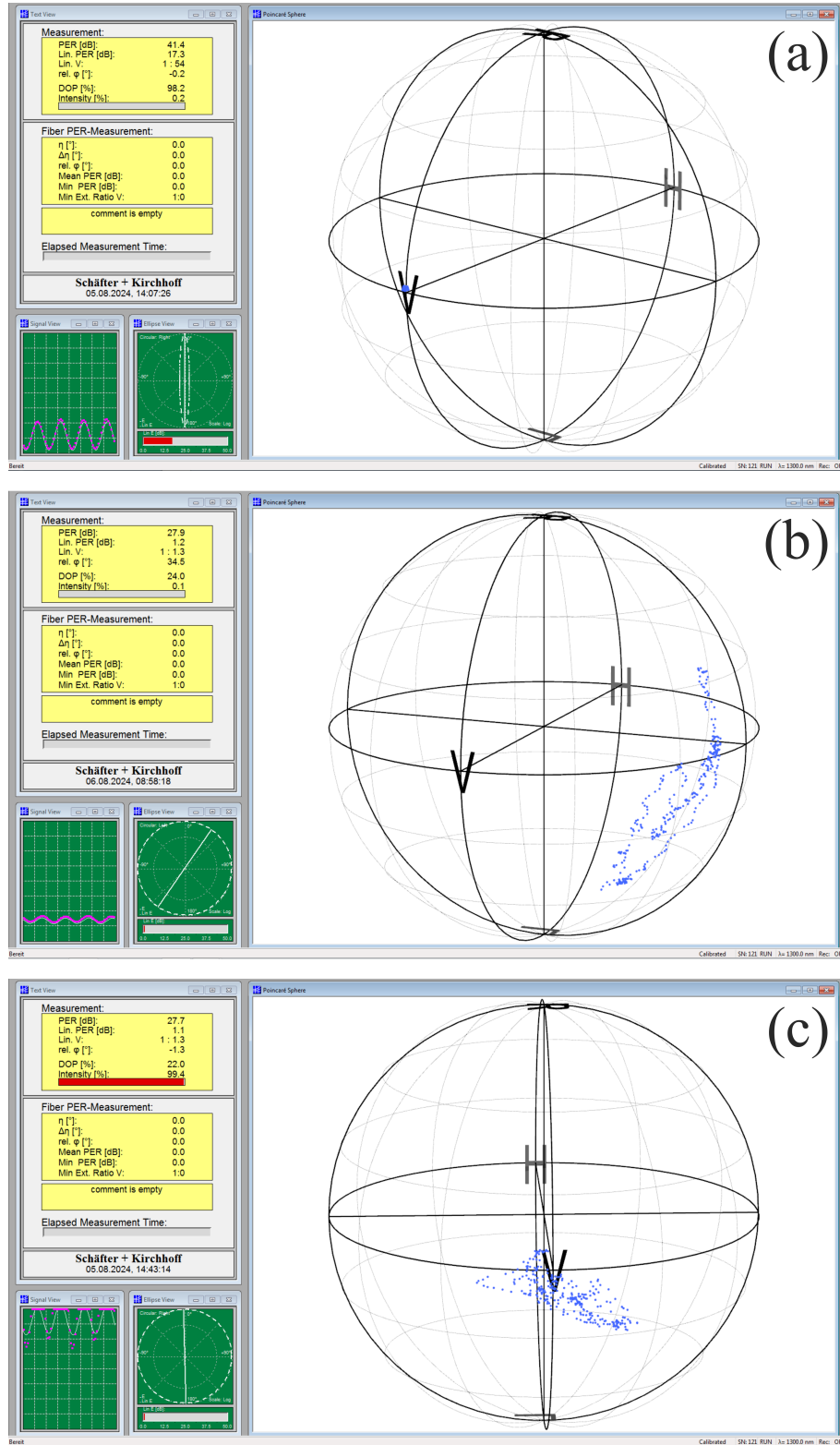


Figure 4.4 Measurements in the polarization analyzer. (a) The measurements done in the calibration, (b) with a AAA configuration at 1300 nm short-band, and (c) AAA configuration at 1300 nm broadband.

AAA Configuration

In all fiber configurations, the polarization state was controlled using the polarization controllers and monitored with the polarization analyzer. In this way, the measurements obtained from the polarization analyzer confirmed the polarization states observed in paths 1 and 2. Once the mode's polarization was fixed, the measurements were taken. Each of the following figures provides all the data from the four paths at different polarizations. However, when the polarization states are inconsistent, the figures display only the optical profiles corresponding to the three reliable paths. Figure 4.5 illustrates the five random polarization states for each port at a wavelength of 1550 nm. Each row corresponds to a type of polarization, while each pair of columns relates to its corresponding injection port, showing three optical profiles. The first column displays the composition power distribution of the polarization, and the second column shows the two orthogonal profiles, horizontal and vertical, respectively represented with the arrows at the top of the first row.

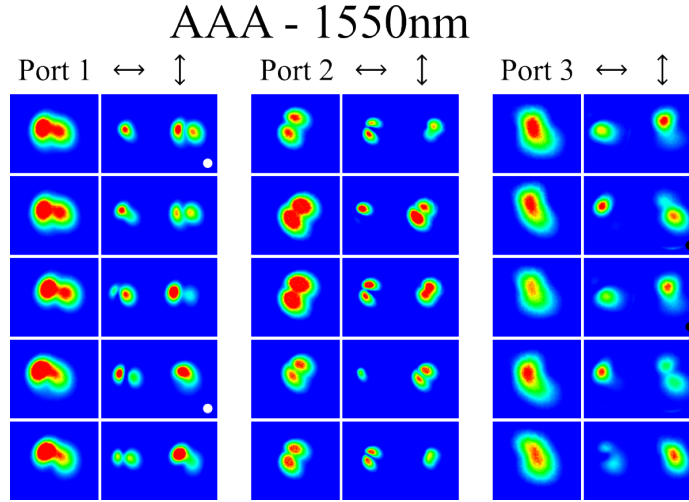


Figure 4.5 Optical intensity profile of each port of a standard 3-mode PL at five tested polarizations. Each row represents a polarization, while each pair of columns corresponds to its associated port, displaying three optical profiles. The first column illustrates the composition of the polarization, and the second column shows the two orthogonal profiles: horizontal and vertical.

The analysis of the optical profiles in Figure 4.5 reveals a power fluctuation between the lobes, with more drastic responses observed in the orthogonal polarization modes view (columns with the horizontal and vertical arrows). Focusing on the first port, particularly in the first and fourth rows (both highlighted with a white dot), it appears that the LP_{01} and LP_{11} modes at those polarizations exhibit a form of degeneration that can be distinguished. This phenomenon is also evident at port 2 across all ports, where, in some cases, the generation of

LP_{11} is separated into horizontal or vertical polarizations, with the remaining power in the opposite polarization. Additionally, power fluctuations in the second and third rows of port 3 of the images of horizontal and vertical responses show significant changes spatially (both highlighted with a black dot). Additional examples of this phenomenon can be found in the supplementary material (Fig. S1, Fig. S2, and Fig. S3).

ABB Configuration

The AAB and ABB configurations have comparable responses, strong coupling with some ports (the one that repeats the letter configuration), and high isolation in the ports that have a different fiber than the others. Their main difference lies in the superposition of modes generated by the few-mode section, which is related to the fiber characteristics and configuration [152]. Their response is a blend of the AAA configuration observed before and the ABC configuration. As a result, this section will solely focus on the ABB configuration for clarity. To maintain consistency in the analysis, the methodology for data acquisition and presentation mirrors that used in the AAA configuration. Figure 4.6a presents the ABB configuration's polarization profile at 1550 nm across its three ports. On the left side of each mode image is a polarization projection of the corresponding mode, obtained using the polarization analyzer's polarization values. Adjacent to that, two optical profiles represent the horizontal and vertical polarization states. On the other hand, Figure 4.6b shows the optical profile for the ABB configuration using a broadband source centered at 1300 nm with the same layout as previously described.

ABB configuration (Figure 4.6a) can support a donut shape through the superposition of the two modes using just a single fiber, as seen in the first row of the third port of Figure 4.6a. In this specific instance, this type of performance can be observed at port 2 in the first and second rows of the images, divided by their polarization (both highlighted with a white dot), or even in port 3 in the third and fifth rows. Clearly, the transition from LP_{11a} to LP_{11b} is not yet complete, but this does not imply that a full transfer could have occurred in a different polarization state. Still, this mode-orthogonality transition suggests a potential method for spatially encoding information via pure polarization, which could occur in devices with strong mode coupling. Furthermore, examining the orthogonal modes in the fourth row of port 2 reveals the generation of two LP_{11} modes with orthogonal polarizations (highlighted with a black dot), yielding results similar to some cases displayed in Figure 4.5 of mode separation throughout polarization.

Additionally, Figure 4.6b shows the response of these devices using a broadband source, where instead of generating a superposition of all the modes into a donut shape or a Gaussian

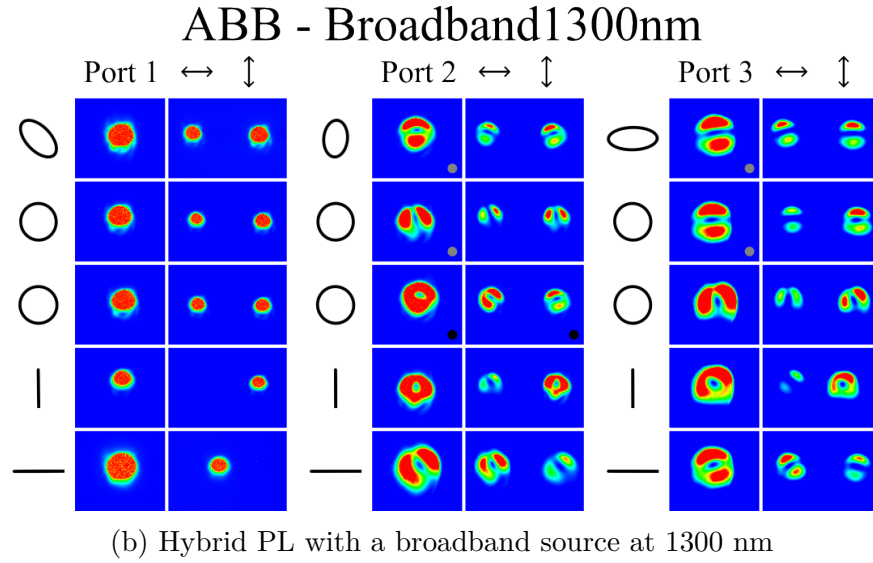
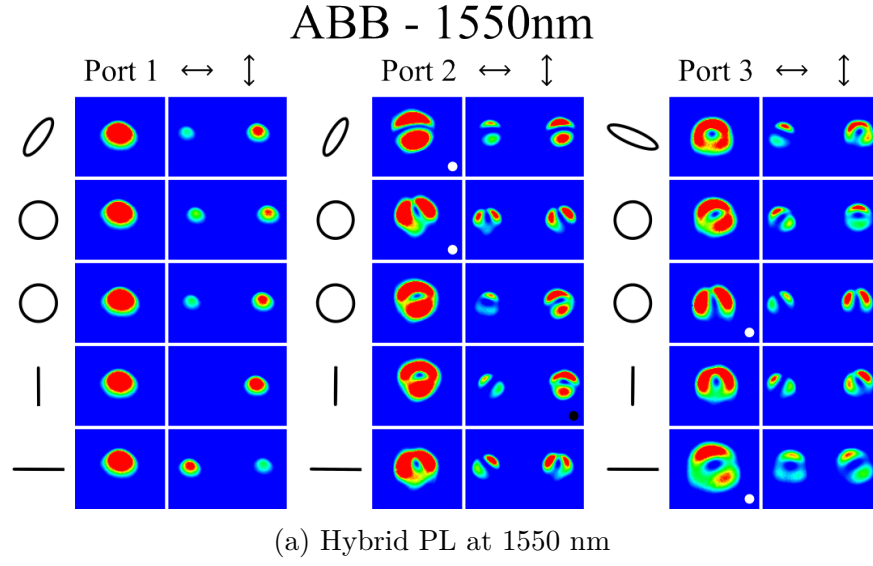


Figure 4.6 The optical intensity profile of each port of the same ABB PL at two wavelengths (a) and (b). Each row represents a specific type of the five polarizations, while each pair of columns corresponds to its associated port, displaying three optical profiles. The first column illustrates the composition of the polarization, and the second column shows the two orthogonal profiles: horizontal and vertical.

profile due to the summation of all optical profiles per wavelength, the response is similar to that in Figure 4.6a, a separation of the modes. It is possible to force all wavelengths to generate a specific mode, enabling the creation of quasi-LP₁₁ modes using one port of a semi-mode-selective PLs, as shown in the first two rows for ports 2 and 3, highlighted with a gray dot. Still, similar to Figure 4.6a, there are cases where the doughnut shape could be generated with only one port, and more interesting to generate the two quasi-LP₁₁ modes with orthogonal polarization for several wavelengths, which is shown in the images with the black dot of Figure 4.6b.

In both scenarios, whether using a single-wavelength source or a broadband source, the response at port 1 is consistent in its profile. This is because port 1 breaks the structure's symmetry and creates a mode with high isolation relative to the others.

ABC Configuration

The last configuration considers the behaviour observed on port 1 of the ABB configuration, as each fiber is different and breaks the symmetry in all directions, generating an optical profile stable and quasi-invariant with respect to polarization. Figure 4.7 shows the polarization profile at 1550 nm for the ABC arrangement across its three ports. A polarization projection of the respective mode is on the left side of every mode image. Next to that, two optical profiles illustrate the horizontal and vertical polarization states.

In contrast with all configurations, the ABC configuration exhibits quasi-spatial invariance to any wavelength and polarization injection, as shown in [118]. Still, there was a case of discrepancy in the polarization that occurred when the polarization did not fully match the response in the optical profile after the beam splitter, as seen in Figure 4.7 for horizontal polarization in the first port. In some cases, these differences could be due to some perturbation caused by the flip mirrors.

The ABC configuration allows a vector beam configuration in which, by simultaneously illuminating the two LP₁₁ ports with different polarizations, radial or azimuthal polarization can be generated. To achieve a superposition of both modes, a 50/50 coupler was incorporated after the laser and before the polarization controllers in the system of Figure 4.2. Figure 4.8 illustrates the intensity profile of the two orthogonal polarization states when the two LP₁₁ ports of an ABC configuration are illuminated with two different light sources, a short-band at 1300 nm (the left column) and broadband at 1300 nm (the right column). This particular configuration had a significant optical path difference, allowing for the generation of a donut shape rather than an LP_{11x} or LP₁₁₊ mode [122, 153–155].

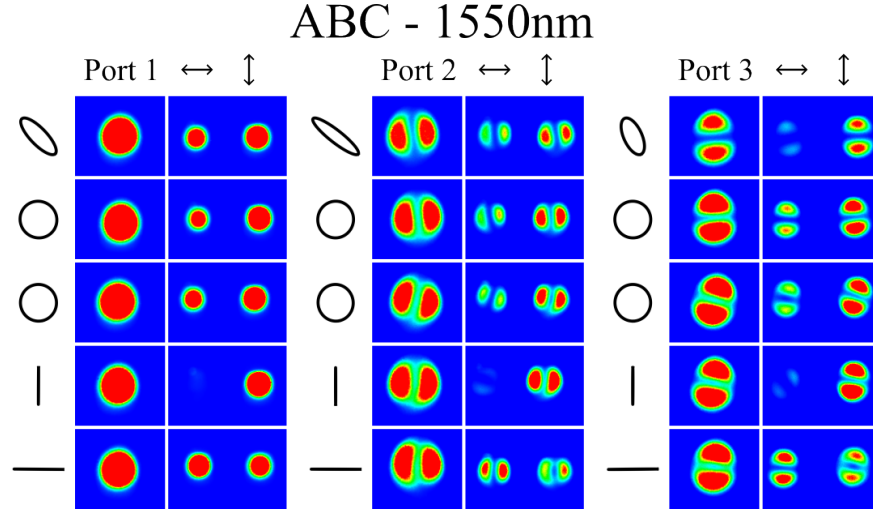


Figure 4.7 The optical intensity distribution for each port of two types of 3-mode PL (a) and (b). Each row corresponds to a particular type of polarization, while each set of columns relates to its respective port, showing three primary optical power distributions. The first column represents the polarization composition, while the second column displays the two orthogonal profiles: horizontal and vertical.

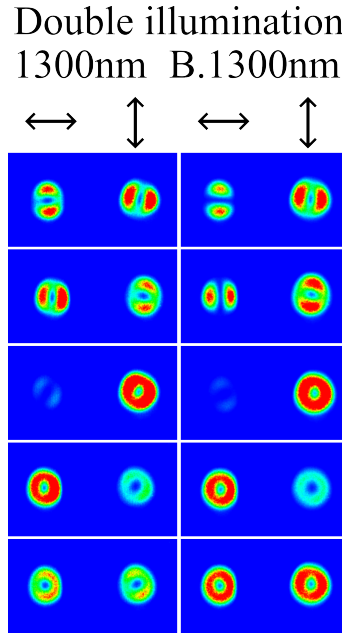


Figure 4.8 Optical intensity profile in a MSPL when the two LP_{11} modes are illuminated at different polarization states. The left column shows the decomposition of the polarization into horizontal and vertical using a short bandwidth, while the right column employs a large bandwidth with the same configuration. Each row illustrates different polarization responses on the donut shape.

In Figure 4.8, polarization measurements were not conducted because the polarization analyzer was designed only for standard polarization and not for vector beams. The configuration used to obtain Figure 4.8 allows controlling the polarization of each mode individually, leading to orthogonal polarizations for each port, as demonstrated in the first two rows of Figure 4.8. This enables the generation of azimuthal and radial polarizations for the first and second rows when the beams are combined, similar to the process used for producing orbital angular momentum [146, 154, 156]. Additionally, it is possible to create the donut shape with horizontal, vertical, and circular polarization, as shown in the third, fourth, and fifth rows of Figure 4.8. Another important aspect is that the circular polarization of the two lobes may be in opposite directions.

It is critical to note that the optical response of each PL is achieved through free-space optical systems. When these devices are spliced to few-mode fibers, the modes could rotate if a standard fiber is implemented, such as in [118], where the two LP_{11} modes share the same propagation, resulting in crosstalk between them.

4.6 Conclusion

We conducted an extended characterization of the polarization of three types of PLs. Understanding how each type of PL responds to variations in polarization states and to broadband sources enables a more refined approach to designing and utilizing these devices for specific applications. The methodologies employed in this study successfully highlighted the differences in response depending on lantern configurations and polarization states, as evidenced by the integration of various laser sources. It was shown that configurations with strong coupling between each port (for instance, AAA, AAB, and ABB) exhibit significant variation in intensity profiles based on wavelength and polarization variations. We further showed that certain polarization states can generate quasi-LP modes for both short-band and broadband responses. Each PL may have distinct applications based on its specific performance. For instance, the AAA configuration is suitable for spatial multiplexing with a single port by changing polarization or wavelength. The ABC configuration, which is independent of wavelength and polarization, shows significant promise for more specialized applications in vector beam generation and biomedical imaging, as it remains unaffected by perturbations in the fibers. Finally, it is important to note that this particular response has a significant impact on free-space configurations, where maintaining a minimally perturbed optical profile is desired. In contrast, when working with optical fibers that have cylindrical symmetry, this effect becomes less pronounced during propagation. For example, modes such as LP_{11} share the same effective refractive index in cylindrical symmetry, which reduces the influence of

these perturbations.

The back matter section and supplementary materials appear in Appendix C.

CHAPTER 5 ARTICLE 3: MODE-SELECTIVE PHOTONIC LANTERNS WITH DOUBLE-CLAD FIBERS

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Published in: Journal of Lightwave Technology.

Publication date: March 25, 2025,

5.1 Author Contribution

As the first author of the publication, I was responsible for designing and overseeing the fabrication process, processing and analyzing experimental data, drafting the initial manuscript, preparing the first response to reviewers, creating figures, and conducting the literature review. Martin Poinsinet de Sivry-Houle contributed to the scientific discussions throughout the project and performed the simulations presented in the study. Stéphane Virally offered guidance, support, and substantial modifications to the paper. Caroline Boudoux and Nicolas Godbout provided the development of the research concept, laboratory materials, funding, and access to laboratory facilities. All authors reviewed and approved the final manuscript.

5.2 Chapter Context

In this chapter, we build upon the insights and findings presented in the previous chapters, focusing on the promising capabilities of MSPLs as a prime candidate for advancing biomedical imaging techniques. We introduce the most advanced MSPL to date, which leverages double-clad fibers to achieve unprecedented performance. This innovative design minimizes excess loss while ensuring exceptional isolation between modes, presenting a broad operational bandwidth that meets the rigorous demands of biomedical applications. Through this exploration, we highlight the robust and practical features of this MSPL, showcasing its potential to significantly enhance imaging methodologies in the biomedical field.

Abstract

We present the design, fabrication, and characterization of mode-selective photonic lanterns using double-clad fibers. Here, we exploited several custom-pulled double-clad fibers to achieve the symmetry break required to excite higher-order modes. The resulting compo-

nents are short and exhibit high modal isolation and low excess loss. They address some of the limitations of existing photonic lanterns in terms of fragility and coupling efficiency. The fabrication process involves the use of lower-index capillary tubes to maintain fiber geometry during fusion and tapering. Through the use of varying first cladding diameters, mode selectivity is achieved without sacrificing single-mode compatibility. This in turn allows proper real-time characterization during the whole fabrication process. Results demonstrate that double-clad fibers stacked inside a fluorine-doped capillary tube feature high modal isolation (above 60 dB) and low excess loss (lower than 0.49 dB), over a broad wavelength range (more than 250 nm) with steeper taper profiles, and more robust components. The use of less expensive synthetic fused silica capillary tubes achieves high modal isolation (above 20 dB) and excess loss lower than 2 dB over the same broad wavelength range.

5.3 Introduction

Fiber-based space-division multiplexers, also known as PLs, were introduced in 2005 as reversible multimode to single-mode multiplexers [36]. These fiber-based devices are designed for streamlined integration into compact, alignment-free optical systems. Three main types of spatial-mode multiplexers/demultiplexers are fully compatible with light injection into and collection from fibers [33]. The MPLC technique generates multiple transverse modes using phase plane masks. MPLC devices are capable of generating up to 1035 modes, and their dimensions are relatively modest (around 100 mm³ to 10 cm³). Their main drawback is higher excess losses (over 3 dB) [157–162]. Additionally, mode-selective couplers can be fabricated using the polished coupler technique [17, 163], with minimal losses around 0.2 dB [34]. One of their limitations is their inability to couple to more than one higher-order mode per device. Several modes can be coupled together, but only in a cascaded configuration, which increases the total length of the system [164]. The final type of transverse mode multiplexer-demultiplexer is the MSPLs, which is the main topic of this paper. In a modest size package of a few centimeters, it offers an efficient conversion and is a potentially lossless device with proper fabrication [12]. Its main drawback so far is the limited number of transverse modes that can be multiplexed, with a reported maximum of 15 modes so far [42]. MSPLs are widely used across multiple disciplines, including astrophysics, telecommunications, and biophotonics, and for many applications such as illumination, spectroscopy, imaging, and efficient scattering collection [38, 52, 54, 56, 89, 103, 165, 166]. They are usually fabricated by fusing and tapering several ($N \geq 2$) fibers to generate a few-mode or multimode guiding structure with a few tens of micrometers diameter. The plurality of design possibilities gives rise to distinct types of PLs. Among them, MSPLs act as mode sorters, allowing the guided

transverse modes of the multimode section to be selectively coupled to a specific single-mode fiber [48]. MSPLs usually feature high modal isolation, and their operation is broadband, up to a bandwidth of 500 nm [33], with excess loss usually lower than 1 dB [12].

Some applications of PLs, such as biomedical imaging and sensing, require sturdy devices capable of being embedded in portable packages. This, in turn, implies the design of shorter components, as long fiber components tend to be much more fragile. The limiting factor in such designs is the adiabatic criterion [115]: a number characterizing the steepest slope at any taper point that allows an adiabatic transfer of modes. A higher adiabatic criterion allows steeper slopes, leading to shorter components. Previous attempts at reducing the length of PLs have included designs at the limit of existing adiabatic criterion graphs with regular single-mode fibers [167]. Unfortunately, this technique is limited by current single-mode fiber technology. Another way is to use graded-index fibers [168] with logarithmic refractive index distributions [169]. This has proven effective in increasing the adiabatic criterion and thus reducing the size of the devices.

Single-mode compatibility (the ability of a fiber to be spliced to a single-mode fiber without any loss due to mode-mismatch) is required for lossless components. Graded-index fibers used to increase adiabatic criteria are multi-mode and thus always generate mode-mismatch losses when spliced to single-mode fibers [170–173]. The same thing actually also occurs with DCFs for which the core diameter is changed. In contrast, changes in the outer diameter of the first cladding can be made without losing single-mode compatibility. This allows for lossless splices and accurate in-situ monitoring of all loss mechanisms, as explained below.

In this paper, we demonstrate the use of DCFs with single-mode cores to design and fabricate MSPLs with increased adiabatic criteria and excellent compatibility with single-mode fibers. The components fabricated using this technique prove to be short and sturdy. They also feature high modal isolation and low excess loss.

5.4 Design and Fabrication

MSPLs are composed of three main sections: a single-mode fiber bundle, a tapered transition, and a few- or multimode structure. Figure 5.1 presents the longitudinal view of a 3×1 MSPL encased inside a fluorine-doped capillary tube to constrain the fiber geometry during the fusion and tapering process.

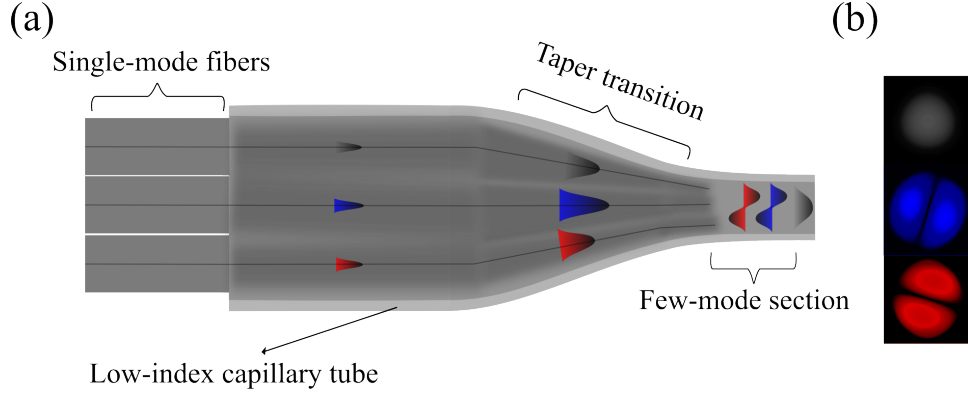


Figure 5.1 Schematic of a 3×1 photonic lantern. (a) From left to right: three single-mode fibers are inserted into a low refractive index capillary tube before being fused and tapered down towards the few-mode section. Image not to scale: the outer diameter of the single-mode fibers is $125 \mu\text{m}$, while the outer diameter of the few-mode structure is approximately $10 \mu\text{m}$. (b) Optical profile of the three output modes akin to LP₁₀ (black), LP_{11a} (blue), and LP_{11b} (red).

5.4.1 Design

The design of PLs involves a large number of degrees of freedom, including the number of fibers, their types, the stacking configuration, the degree of initial fusion, and the tapering profile [33,174–176]. In an MSPL, each fiber in the single-mode bundle must exhibit a distinct refractive index profile to break the symmetry and allow to selectively excite individual transverse modes within the few-mode structure. Given the size of the design parameter space, we use SuPyMode [115], a Python-based simulation tool that uses coupled-mode theory to efficiently compute the adiabatic criterion given the characteristics of the input fiber bundle and the initial degree of fusion. SuPyMode allows rapid iteration and convergence towards adequate fiber parameters for most applications.

DCFs can be designed to offer full compatibility with single-mode fibers. They offer an important advantage over single-mode fibers used in some applications: when DCFs are tapered, the lower-order modes remain contained inside the first cladding even as the core ceases to guide them. In applications such as PLs, this containment mechanism helps to increase the adiabatic criterion [34,115,177,178], albeit to a lesser degree than with graded-index fibers. Containment in DCFs can be achieved with a large variety of first-cladding diameters without changing the diameter of the core. This greatly increases the versatility of designs, while preserving full compatibility with single-mode fibers, a feature difficult to replicate with graded-index fibers. In contrast to [178], we vary the outer diameter of the

first cladding, not the diameter of the core. This enables the devices reported herein to be fully compatible with (i.e., spliced without loss to) single-mode fibers and to monitor in-situ and accurately report all excess losses.

5.4.2 Fabrication

Low-index capillary tubes are used during the fabrication process to constrain the fibers' geometry and provide additional containment in the tapered section. A capillary tube is first tapered in its center using an automated glass processing system (GPX-3000 Vytran, Thorlabs, NJ, USA) with an FTAT4 filament (Thorlabs, NJ, USA). In a 3×1 MSPL, the tube is tapered down to an inner diameter of $270 \mu\text{m}$ to constrain the three-fiber bundle into an equilateral triangle configuration over a length of 20 mm to provide adequate scanning length. Once the proper fiber configuration is obtained, a fusion step is performed, which slightly decreases the bundle size. The tapering process further reduces the few-mode or multimode part of the PL to its final size, around 10 to $20 \mu\text{m}$. The single-mode compatibility of the DCFs fibers with SMF28 allows monitoring the fabrication process in real-time by injecting light into any input and measuring the power at all outputs.

Figure 5.2 shows the in-situ characterization process of a 3×1 MSPL, with inputs connected through an in-house built optical switch to a broadband laser (BBS1550, JDS Uniphase, AZ, USA), centered at 1550 nm with a bandwidth of 50 nm. The component is placed on a heat-and-pull fabrication station, which consists of two holders with homemade clamps mounted on translation stages symmetrically arranged around a moving torch. Outputs are connected to an optical switch (built in-house) to monitor output sequentially on an optical spectrum analyzer (OSA, model AQ6317, Ando, Japan). This setup allows modal isolation and excess loss to be monitored in real-time after establishing a baseline. Any loss due to micro-deformations, dust, and unwanted coupling between modes can be observed in real-time, and the recipe can be altered accordingly, or the process can be halted immediately. We fabricate the devices in a symmetrical manner to produce two lanterns simultaneously. As a result, the losses reported in the figures are, in fact, double the losses expected for a single device, as they comprise both tapered regions.

5.5 Results

Here, we describe the design, fabrication, and characterization of 3×1 MSPLs using DCFs. Three distinct DCFs were custom-designed (2058I1, 2058K1, and 2058J1, Université Laval, Prof. Messaddeq, QC, CA) to offer single-mode operation at 1550 nm, matching the mode-

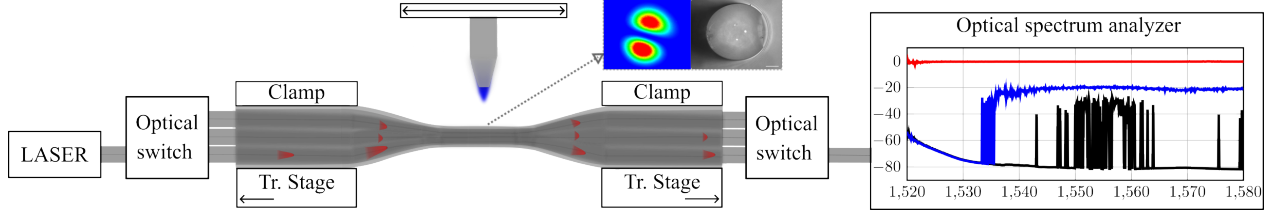


Figure 5.2 Schematic diagram of the fusion tapering station, comprising a flame, clamps, and translation stages, attached to a full *in situ* characterization system comprising a laser, optical switches, and an optical spectrum analyzer. Optical switches allow for all inputs to be illuminated and all outputs to be monitored independently. Inset: one of the LP_{11} modes (left) and image of the few-mode section, both observed post cleave.

field diameter of telecommunication SMF-28 (ITU-T G.657.A1, Corning, NY, USA) fibers. The fibers featured three different first cladding diameters (19.6, 26.8, and 42 μm , respectively) without noticeable differences in their single-mode operation and with a numerical aperture of 0.13 between the core and first cladding. Slight differences in doping concentrations allowed the multimode guiding part (i.e., within the first to second cladding) to feature the same numerical aperture (0.117) for all three fibers.

Figure 5.3 shows the optical power at each output of the 3×1 MSPL for illumination in each input, at the end of the tapering process. The three curves represent the ratio of input power measured at the output when a single input is illuminated. The curve corresponding to the illuminated input remains close to 0 dB and represents insertion loss. The two other curves correspond to the fraction of input power transferred to each other output, i.e., crosstalk or inter-modal isolation. The MSPL characterized in Fig. 5.3 was realized with the DCFs described above, and using a synthetic fused silica capillary tube (CV1012, Vitrocom, NJ, USA). The length of DCF in a device can range from tens of centimeters to several meters. For the devices highlighted herein, during the fabrication process, we kept 1 m of DCF before the taper and 30 cm on the other end. We also spliced both ends of the DCFs to at least one meter of SMF-28 to ensure optimal single-mode performance. The losses at the splices between SMF-28 and DCF were negligible, i.e., comparable to splices between two SMF-28 fibers. Fig. 5.3(a) shows the power transfer for illumination into Input 1 consisting of the DCF with the largest inner cladding, expected to excite a supermode akin to the first linearly-polarized (LP) mode, LP_{01} , in the fused section. Results show power transfer with ≤ 1.84 dB excess loss into Output 1 (black curve), and ≥ 20 dB extinction in Output 2 (blue curve) and Output 3 (red curve) ports, respectively. Similarly, Fig. 5.3(b) shows the power transfer for illumination into Input 2, the DCF with the second largest inner cladding, expected to excite a supermode akin to LP_{11a} in the fused section. Results show quasi-lossless transfer

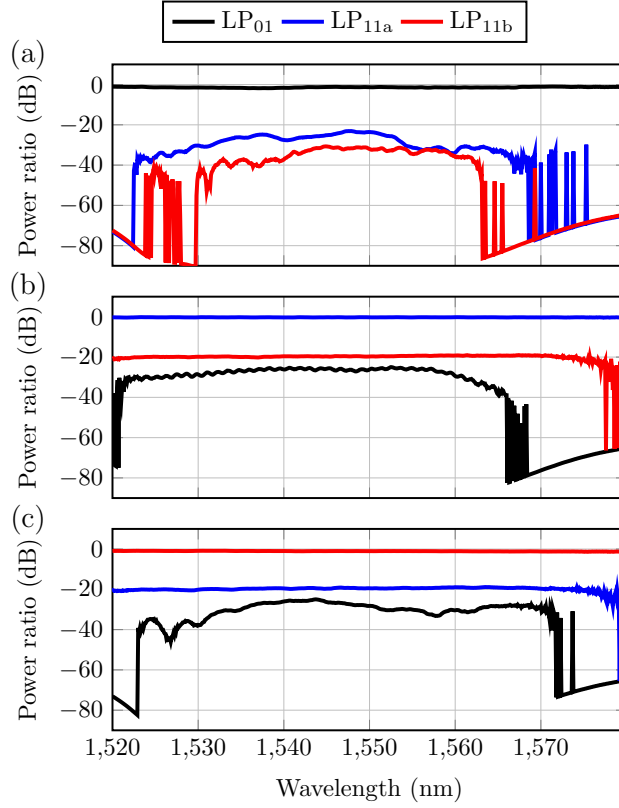


Figure 5.3 Differential power measurements at the output of a 3×1 lantern inside a capillary tube made of synthetic fused silica with a slightly lower index of refraction than that of the outer cladding of the fibers. The measurement is made at the end of the fusion-taper process, before cleaving. (a): core illumination through the fiber with the largest first-cladding diameter, resulting in the fundamental mode, akin to LP_{01} , in the few-mode section. (b): core illumination through the fiber with the second largest first-cladding diameter, which generates the next mode, akin to LP_{11a} . (c): illumination through the fiber with the smallest first-cladding diameter, which generates the last guided mode, akin to LP_{11b} .

(≤ 0.64 dB excess loss) into Output 2 (blue curve), and ≥ 20 dB extinction in Outputs 1 (black curve) and 3 (red curve), respectively. Finally, Fig. 5.3(c) shows the power transfer for illumination into Input 2, the DCF with the smallest inner cladding, expected to excite a supermode akin to LP_{11b} in the fused section. Results show power transfer with ≤ 1.65 dB excess loss into Output 3 (red curve), and ≥ 20 dB extinction in Outputs 1 (black curve) and 3 (red curve), respectively.

Figure 5.4 shows the optical power at each output of the 3×1 MSPL for illumination in two different inputs, right at the end of the tapering step. For this MSPL, the three DCFs were arranged inside a fluorine-doped fused silica capillary tube (FTB03, Thorlabs, NJ, USA). Fig. 5.4(a) shows the power transfer for illumination into Input 1, the DCF with the

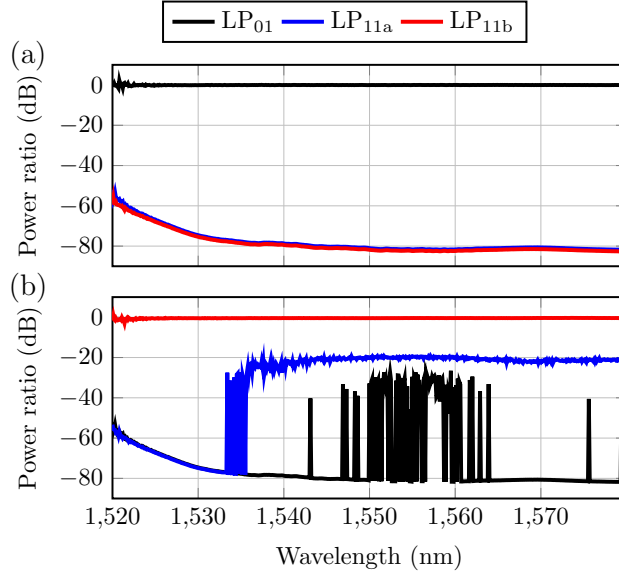


Figure 5.4 Differential power measurements at the output of a 3×1 lantern inside a capillary tube made of fluorine-doped silica, with an even lower index of refraction than that of the outer cladding of the fibers. (a): core illumination through the fiber with the largest first-cladding diameter, resulting in the fundamental mode, akin to LP₀₁, in the few-mode section. (b): illumination through the fiber with the smallest first-cladding diameter, which generates the last guided mode, akin to LP_{11b}. An accidental break of the third fiber resulted in it not being illuminated during that run.

largest inner cladding, expected to excite a supermode akin to LP₀₁ in the fused section. Results show power transfer with ≤ 0.49 dB excess loss into Output 1 (black curve), and ≥ 60 dB extinction in Output 2 (blue curve) and Output 3 (red curve) ports, respectively. Similarly, Fig. 5.4(b) shows the power transfer for illumination into Input 3, the DCFs with the smallest inner cladding, expected to excite a supermode akin to LP_{11b} in the fused section. Results show quasi-lossless transfer (≤ 0.46 dB excess loss) into Output 2 (blue curve), and ≥ 20 dB extinction in Outputs 1 (black curve) and 3 (red curve), respectively. Power transfer for illumination into Input 2 was not recorded for this component. However, the coupling between the two branches is the same in both directions: illuminating Input X and measuring the loss in Output Y gives the same information as illuminating Input Y and measuring the loss in Output X. This can indeed be observed in Fig. 5.3, e.g. comparing the red trace in Fig. 5.3(b) to the blue trace in Fig. 5.3(c). In that respect, apparently anomalous points in the black curve of Fig. 5.4(b), which should follow the red curve of Fig. 5.4(a), and does so most of the time, are probably due to micro stresses (fibers moving) during the fast measurement. In the end, the only information missing from the lack of illumination in Input 2 is the excess loss for the corresponding fiber. It is, however, expected to be in line (≤ 0.5 dB) with that

of the fibers corresponding to Inputs 1 and 3, as is usually the case.

After the fusion and tapering process, both structures were cleaved, and each input port was individually illuminated to capture an optical profile. A fiber polarization controller was used to characterize the component's behavior with respect to input polarization. An image in the far field was obtained by projecting each output onto a screen and recording using an infrared camera (SU320KTS-1.7RT, Goodrich, NJ, USA). Narrow-band illumination at 1300 nm and 1550 nm was achieved with a dual-wavelength source (HP 8153ASM, Hewlett-Packard, CA, USA). A broad source (100 nm wide around 1300 nm) was used for broadband illumination (SL1310V1-10048, Thorlabs, NJ, USA).

Figure 5.5(a) shows the optical profile in the far field of an MSPL based on a synthetic fused silica capillary (left) and based on a fluorine-doped fused silica capillary (right), respectively. For each group, the left column shows the fundamental mode of the structure (akin to LP_{01}) when the largest first-cladding diameter is illuminated. The center and right columns, respectively, show the two other modes (akin to LP_{11a} and LP_{11b} , respectively) in orthogonal orientations when the other two inputs are illuminated. The first two rows correspond to narrow-band illuminations at 1550 nm, with two different polarization states finding the most significant difference between each mode. They show that the behavior of the components is independent of the polarization state of the illumination source. The third row corresponds to narrow-band illumination at 1300 nm. and Figure 5.5(b) shows the optical profile using broadband illumination around 1300 nm for LP_{01} , LP_{11a} , and LP_{11b} , respectively, for the fluorine-doped capillary tube MSPL. On the surface, the response at 1300 nm appears almost identical to that at 1550 nm. Although a good indication, this is not sufficient to claim that the component is broadband. Using broadband sources in the fabrication process and recording isolation and excess losses at all wavelengths will be necessary to characterize the operational bandwidth properly. Figure 5.5 (c) shows a section of the final structure of the MSPL, which is divided into three main parts. From left to right: With a black line above, a 1 cm taper of the capillary tube designed to constrain the DCFs. At this point, no tapering of the three-fiber bundle has taken place yet. With a grey line above, a 1.5 cm taper of the whole structure. And finally, with a white line above, a 0.3 cm section of the few-mode structure. This last section continues further outside of the image, but it is better to cleave it close to the grey-to-white transition, as the grey and white parts are the most fragile sections and should be kept below 2.5 cm to ensure sturdiness.

Figure 5.6 (left) showcases a splice between the few-mode section of an MSPL and a two-mode step-index fiber (FM2010-B, YOFC, CN). On the right of Figure 5.6, various intensity profiles have been captured when the lantern is illuminated in the LP_{11a} input with a broadband

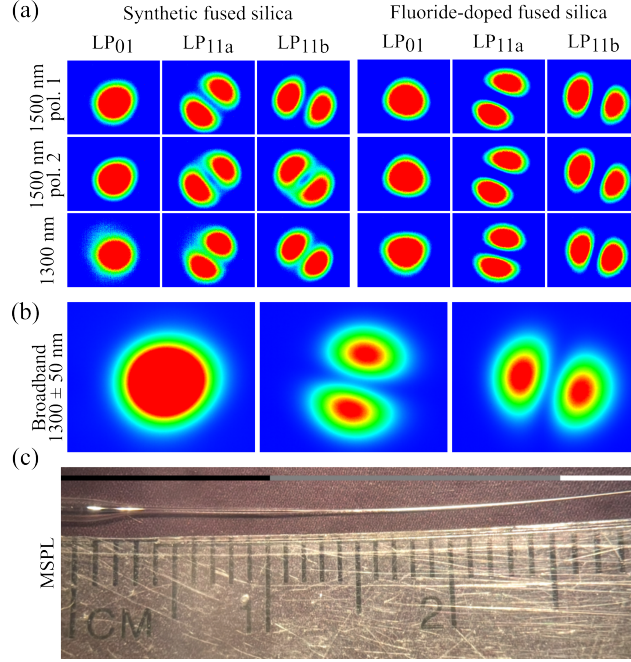


Figure 5.5 Far-field images of the modes at the output of the few-mode section, illuminating through each of the single-mode fiber input to generate a) LP_{01} , b) LP_{11a} , and c) LP_{11b} . d) Picture of the photonic lantern.

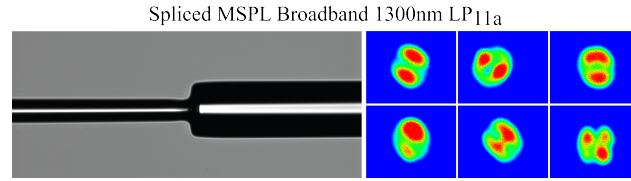


Figure 5.6 Few-mode section of MSPL spliced to a regular few-mode fiber. Left: picture of the splice in the Vytran GPX-30 splicer. Right: optical profiles at the output of the few-mode fiber after injecting light into the LP_{11a} port of the lantern.

source centered around 1300 nm. Since LP_{11a} LP_{11b} are degenerate in the two-mode step-index fiber, they couple and rotate inside that section, and various optical profiles can be obtained by slightly perturbing (e.g., bending or heating) the fiber. In applications requiring mode isolation between the LP_{11} modes, a modified few-mode fiber that is not degenerate for these modes should be spliced instead, or the photonic lantern should be coupled to free space without additional splice [56].

5.6 Discussion

The components fabricated for this study exhibited excess low loss: < 1 dB for the components held in a fluorine-doped capillary tube and < 2 dB for the component held in synthetic fused silica. They also feature large modal isolation above 20 dB, and in the case of the fluorine-doped components above 60 dB, the measurement being limited only by the noise floor of the measuring device.

For both components characterized in Figures 5.3 and 5.4, the operational bandwidth was limited by the bandwidth of the illumination laser (JDS Uniphase 1550 nm). As such components do not rely on mode coupling, they are theoretically as broadband as the guiding properties of the fibers allow.

As shown [115], SuPyMode offers significant insight into the fabrication processes for various optical fiber devices, including MSPLs. It achieves this through the computation of the adiabatic criterion, which dictates the steepest adiabatic taper slope and is thus directly related to the minimum length of the device [115]. Some simulations show that the use of DCFs can offer a decrease in the total length by a factor of 3 compared to standard MSPLs (see Supplementary Material).

A comparison of the results between the two components shows that using a higher index difference between the outer cladding of the fibers and the external capillary tube usually leads to better modal isolation and lower excess losses. Although the fluorine-doped capillary tubes give overall better results, they are much more expensive than those made of synthetic fused silica. In principle, the fabrication process enables two lanterns to be extracted from each fused and tapered bundle, by cleaving exactly in the middle of the tapered section. However, the component is not fully symmetric to start with. Fiber insertion within the capillary tube requires stripping the coating over a distance of at least 20 cm longer than the capillary, on one of its sides. For two lanterns to be made out of the component, re-coating of that section is required to avoid fragility.

In theory, the fabrication of MSPLs should never result in fiber-to-fiber coupling, in contrast to what is expected for couplers. Any such power transfer is thus indicative of a flaw in the device or a non-adiabatic section caused by too steep a transition (e.g., a micro bend) in the device. Real-time monitoring enables these types of flaws to be immediately detected. In-situ monitoring also enables the measurement of actual mode isolation and excess loss, contrary to the cutback method, which measures losses from each input into the few-mode section after cleaving. This method widely underestimates excess losses as it does not measure cladding or coupling losses. For instance, for the component made with a synthetic silica tube, we

measured excess losses of 1.84, 0.64, and 1.65 dB for Inputs 1, 2 and 3, respectively. But the cutback technique, performed after cleaving, gave 0.08, 0.10, and 0.11 dB for the same Inputs, respectively. Note that we did not remove cladding material for the cut-back technique. This could result in underestimating losses as some cladding light could be counted as transmitted. In all cases, we believe the in-situ technique provides a better measurement of losses.

Double-clad fiber-based MSPLs allow for high modal isolation; however, the resulting modes are not quite perfectly matched to the theoretical LP modes. Some mode asymmetry was observed, likely due to the final shape of the few-mode section, which is not perfectly cylindrical.

Lastly, scalability of MSPLs is achieved by varying the characteristics of each individual fiber in the bundle. With single-clad fibers, or indeed with DCFs, this can be achieved by changing the diameter of the core. It has, for instance, been demonstrated that a change in diameter of 3 μm achieves significant mode selectivity [42]. Unfortunately, it comes at the cost of single-mode compatibility. Graded-index fibers can also be used, and their designs vary to achieve some degree of scalability, but again at the cost of single-mode compatibility. DCFs offer another possibility, which is to vary the outer diameter of the first cladding. This can be achieved while maintaining single-mode compatibility. As the first cladding effectively becomes a new core in the tapered structure, and as coupling between modes essentially depends on the distance between cores [12], we expect that changes of 3 μm will be sufficient to introduce selectivity. To maintain single-mode operation, the first cladding outer diameter must fall between 15 and 70 μm . This allows for potentially up to 18 separate modes to be multiplexed. Should more modes be required, additional cladding layers could be added, although systematic research has to be undertaken to verify this. Currently, the main advantage of using DCFs is that they allow for at least equivalent scalability compared to other types of fibers, with the added bonus of single-mode compatibility.

5.7 Conclusion

The use of DCFs in the design of MSPLs provides a versatile means to break symmetries by varying the first-cladding diameter while retaining full compatibility with single-mode fibers. This allows for complete characterization of the devices in real-time during fabrication.

The adiabatic criteria of the DCF-based components is slightly lower than those made of graded-index fibers. However, they are high enough that short ($\simeq 2.5$ cm), sturdy components can be fabricated with relative ease. Our experiments confirm that MSPLs in general keep their characteristics over large bandwidths (at least 250 nm in this study) and are agnostic

to the state of polarization of the illumination.

Components held in synthetic fused silica capillary tube have higher overall excess losses and lower modal isolation figures than those held in fluorine-doped capillary tubes. However, the former are much cheaper than the latter, and they provide a good alternative for components that do not require the best specifications.

The back matter section and supplementary materials appear in Appendix D.

CHAPTER 6 ARTICLE 4: SIMULTANEOUS PLANE ILLUMINATION AND DETECTION IN CONFOCAL MICROSCOPY USING A MODE-SELECTIVE PHOTONIC LANTERN

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Published in: ArXiv.

Submission date: April 2, 2026.

6.1 Author Contribution

As one of the first authors of the publication, I was responsible for developing the research concept, designing and overseeing optical systems, processing and analyzing experimental data, drafting the initial manuscript, preparing the first response to reviewers, creating figures, and conducting the literature review. Simon Desrochers performed the experiments, mounted the system, imaged acquisition, and participated in the literature review. Raphaël Maltais-Tariant, Simon Brais Brunet, Lucien E. Weiss, and Stéphane Virally contributed to the scientific discussions throughout the project. Raphaël Maltais-Tariant also provided detailed feedback and significant revisions to the manuscript and performed the simulations presented in the study, including some sections of the first draft. Guillaume Ramadier checked the manuscript. Caroline Boudoux and Nicolas Godbout provided laboratory materials, funding, and access to laboratory facilities. All authors reviewed and approved the final manuscript.

6.2 Chapter Context

This chapter presents the implementation of the MSPL, fabricated as described in Chapter 3 of this thesis, in confocal microscopy. Each mode generated by these devices has a distinct effective refractive index and spatial mode distribution, resulting in different planes of focus when used with several optics and a microscope objective. One of the main advantages of these devices is their straightforward integration, which enables fast 3D imaging in confocal microscopy.

Importantly, this chapter introduces a new method that can be easily implemented in any confocal system. The approach increases the number of plane scans per mode group, thereby

enhancing acquisition speed in confocal microscopy. Additionally, this opens the opportunity to use other types of multiplexers; we chose to use MSPLs for their simplicity and effectiveness in this context.

These experiments were conducted at the operational wavelength of these devices (1300nm); however, their primary implication lies in applications with biological samples labeled with fluorescent dyes. Fast fluorescence microscopy is essential for in vivo experiments, and this work contributes to this area, potentially having a significant impact.

6.3 Abstract

Confocal microscopy is the cornerstone of cellular biology and biomedical research due to its non-destructive imaging, compatibility with live cells, sensitivity, optical sectioning, and subcellular resolution. To meet the demand for rapid three-dimensional imaging, we propose a novel approach using a MSPL. This fiber-based device transforms single-mode light into multiple linearly polarized modes, allowing simultaneous detection of multiple planes. Using a four-port MSPL to manipulate three group modes (LP_{01} , LP_{11} , and LP_{21}), we demonstrate high-throughput imaging simultaneously with multiple planes. This technique exploits differences in focus sections across modes, enabling individual multi-plane detection via a spatial division multiplexer, with some trade-off in resolution and field of view.

Confocal microscopy is a powerful imaging technique that offers non-destructive analysis, high spatial resolution, and versatility. It is used to study biological and material samples across diverse scientific disciplines. These features make confocal microscopy indispensable in cellular biology, materials science, and biomedical research, as well as in generating high-resolution surface topographies [179–186]

The growing demand for rapid three-dimensional (3D) acquisition and high-resolution imaging has driven significant innovation in optical microscopy. One prominent strategy is the use of simultaneous detection techniques—such as multiple pinholes and beam splitters—to capture several optical planes at once. This parallelized approach increases data throughput and minimizes imaging time, though it can suffer from reduced photon detection when employing more than two beam splitters [187–191]. Another parallelized method is chromatic confocal microscopy, which exploits the chromatic aberration of a lens to focus simultaneously at different planes within a sample [192–196]. Additional multiplane confocal imaging strategies include the use of acoustic tunable lenses [197, 198], z-splitter prisms [199], multiplexed volume holographic gratings [200], and quadratically distorted gratings [201].

In this study, we introduce a novel strategy that enables simultaneous illumination and detec-

tion of multiple planes by leveraging higher-order optical fiber modes. In our approach, each z-position is encoded at a unique spatial location in the detection path using a fiber-based spatial division multiplexer, known as a mode-selective photonic lantern (MSPL). MSPLs are fiber-based spatial mode (de)multiplexers capable of efficiently transforming single-mode light into specific linearly polarized (LP) modes within a few-mode fiber section [12, 49, 118, 202], and vice versa. This modal transformation achieves high efficiency, with insertion losses below 10% over a broadband spectral range of 500 nm [33, 118, 152], making MSPLs particularly useful for biomedical applications such as optical coherence tomography [56, 89, 90] and oblique microscopy Sarah’s paper. MSPLs generate multiple co-aligned beams optimized for simultaneous illumination and detection. By exploiting the intrinsic differences between spatial modes—such as spatial distribution and NA—we show that we can distinguish among imaging planes. This approach accelerates scanning acquisition compared to conventional confocal microscopy but presumably still slower than widefield scanning, by requiring a single x-y scan to capture multiple z planes in parallel using spatial-division multiplexing. Employing a four-port MSPL allows manipulation of three distinct linearly polarized (LP) group modes (LP01, LP11_x and LP11_y, and LP21), enabling concurrent acquisition of three planes (we will show that the degenerate LP11_{x,y} modes generate identical axial shifts), while accepting inherent trade-offs in resolution and field of view. Moreover, this technique is extensible beyond reflective confocal microscopy: the implementation of a visible photonic lantern could readily extend its impact to fluorescence imaging without substantial complications.

6.4 Photonic Lantern and Confocal Microscopy

The mode-selective photonic lantern (MSPL) was fabricated and characterized using four custom double-clad fibers, as described in [118], albeit with an additional fiber to the three presented in the paper. This MSPL exhibits an excess loss of less than -0.5 dB and a high modal isolation of at least 20 dB per group mode. Figure 6.1a) presents a schematic of a MSPL, consisting of several optical fibers arranged within a tapered and fused capillary tube, becoming the new few-mode waveguide. Figure 6.1b) shows the modes that such an MSPL can generate. The top row shows the simulated LP modes while the bottom row shows experimentally observed far-field images. Figure 6.1c) shows the confocal system used with the three group modes of the MSPL. It consists of a laser source (Thorlabs S5FC1021S, USA) connected to a power splitter (JDS Uniphase ACWA104, USA) that directs light to three different circulators, each connected to one ports of the MSPL. The few-mode output from the lantern is collimated and directed through galvanometric mirrors, then passes through

a telescope that matches the back focal plane of the microscope objective (Nikon CFI Plan Apo 20x/0.75 DIC, Japan) to the LP_{21} mode, and finally reaches the sample. Detection is performed through the same optical path as the MSPL demultiplexes the signal to each fiber port, connected to the circulators, and then sent to three photodetectors (Thorlabs PDA10CS, USA) and (Thorlabs PDA20CS2, USA).

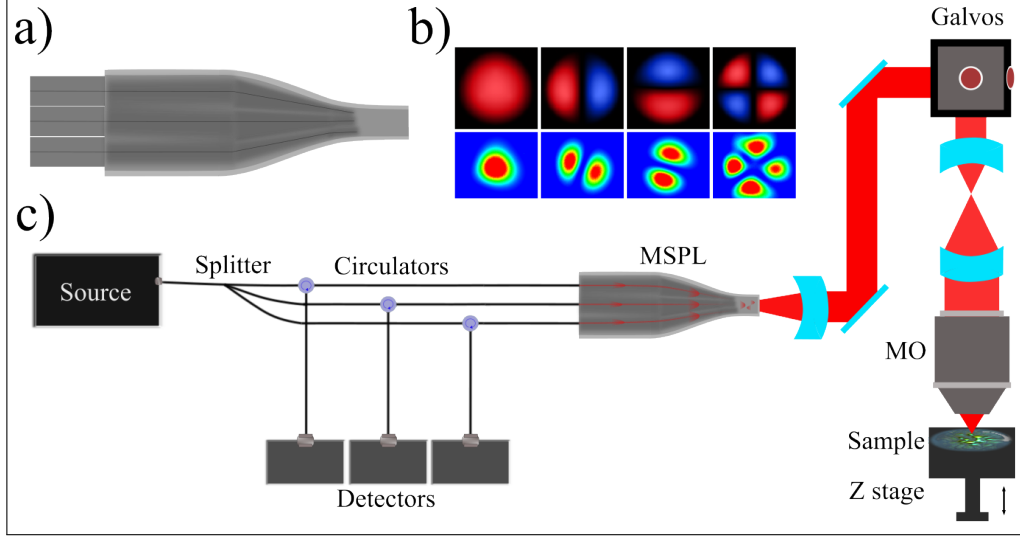


Figure 6.1 Photonic lantern and setup schematics. a) Side view of the fused-tapered fiber bundle, showing the four generated modes. b) A confocal system that implements a MSPL, featuring a splitter designed to illuminate all ports simultaneously, along with three circulators to independently detect light from each plane.

6.5 Plane Shift

Each mode exhibits a distinct beam width that increases with mode number, a consequence of differences in effective refractive index at the output of the MSPL. This leads to unique spatial distributions and NAs for each mode. In the system, the LP_{21} mode was chosen to match the back focal plane of the microscope objective because the LP_{01} mode produces a narrower beam waist. Measurements with the knife-edge method indicate that the beam width of LP_{21} is 1.05 times larger than that of LP_{01} .

This variation in NAs can be leveraged to shift the focal positions of beams from different group modes. Table 6.1 presents simulations using Gaussian beam wave optics [203] for a two-lens optical system, where small differences in initial beam NAs result in distinct waist positions at the conjugated plane. The simulations were conducted at a wavelength of 1300 nm, with collimating and imaging lenses of 4.7 mm and 5.7 mm focal lengths, respectively. The collimating lens was placed 4.7 mm after the initial waist, and the imaging

lens was located 200 mm beyond the collimating lens. These results demonstrate how minor variations in initial divergence can translate into measurable shifts in the focal plane.

To experimentally confirm focal plane shifts, we implemented the setup depicted in Figure 6.1b, placing a mirror at the sample position and performing a z-scan with a motorized stage. Figure 6.2a shows the detected power at each plane, measured by photodetectors when all ports are simultaneously illuminated. The data are grouped by optical mode: LP_{01} (solid red), LP_{11a} (dashed blue), LP_{11b} (solid blue), and LP_{21} (solid black), using a 20X microscope objective. The y-axis represents intensity (arbitrary units), while the x-axis indicates position (mm). For comparison, Figure 6.2b presents the results with a 3X objective, revealing a similar trend. All point-spread functions (PSFs) were smoothed with a Gaussian filter and normalized to their respective amplitude ranges.

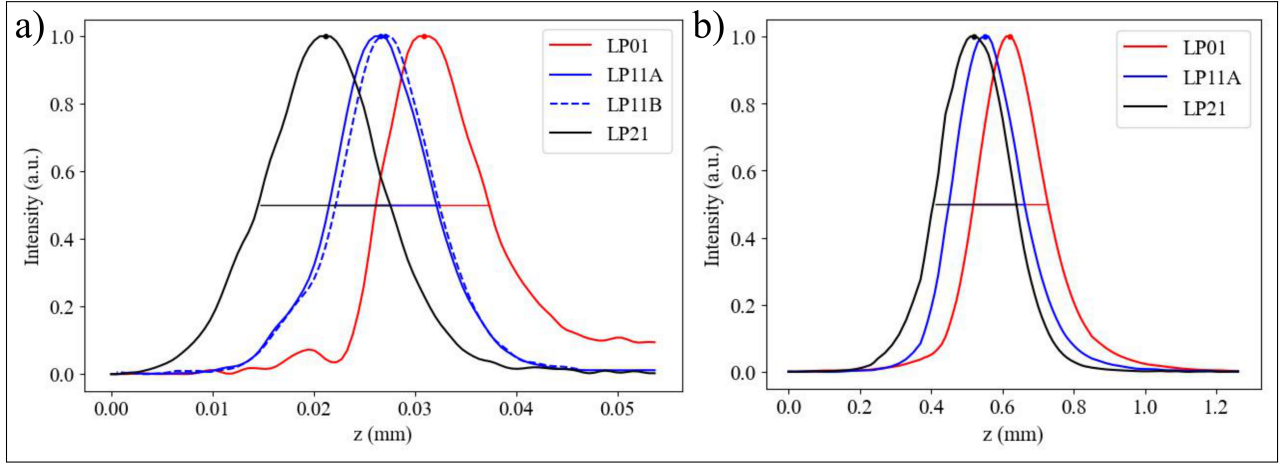


Figure 6.2 Axial resolution utilizing a) 20X and b) 3X microscope objectives for each mode of a MSPL. Each plot represents the LP mode LP_{01} as solid red, LP_{11a} as dashed blue, LP_{11b} as solid blue, and LP_{21} as solid black.

With the 20X microscope objective, the optical shift between LP_{01} and LP_{11a} was measured to be $4.3 \mu\text{m}$, while the shift between LP_{11a} and LP_{21} was $5.4 \mu\text{m}$. In contrast, using the 3X objective, the shift between LP_{01} and LP_{11a} increased to $70.1 \mu\text{m}$, and the shift between LP_{11a} and LP_{21} was $30 \mu\text{m}$. These differences arise because each mode propagates differ-

Initial beam		Beam at sample
Waist size	Divergence	Waist Position
$6 \mu\text{m}$	69.4 mrad	210.416 mm
$5.7 \mu\text{m}$	73.0 mrad	210.456 mm

Table 6.1 Simulation of the same two-lens optical system with a slight variation in the initial beam NA and its impact on the waist position at the system's exit.

ently through the optical system, due to variations in spatial distribution and propagation constants, which impact their interaction with different optical components, especially the microscope objective.

As shown in Figure 6.2, no significant focal plane shift is observed between the degenerate LP_{11} modes. This result is expected, given their nearly identical NA and propagation constants, which lead to negligible differences in focal plane position. Therefore, our analysis focuses on the three distinct groups of modes where clear separation occurs.

Figure 6.3 presents detection results while scanning in the XZ plane for (a) LP_{01} , (b) LP_{11} , and (c) LP_{21} modes using galvanometric mirrors with the 20X microscope objective. This approach enables determination of the field of view, which is reduced to 74% compared to LP_{01} . The calculation is based on the full width at half maximum (FWHM) across the x-axis at the brightest point, comparing the smallest and largest FWHM (with LP_{01} providing the largest). Additionally, the power distribution along the Z axis for LP_{21} reveals a blurrier region, which is consistent with findings in [58], indicating that a higher-order mode experience a 9% lateral and 3% axial resolution loss—limitations that increase with mode number.

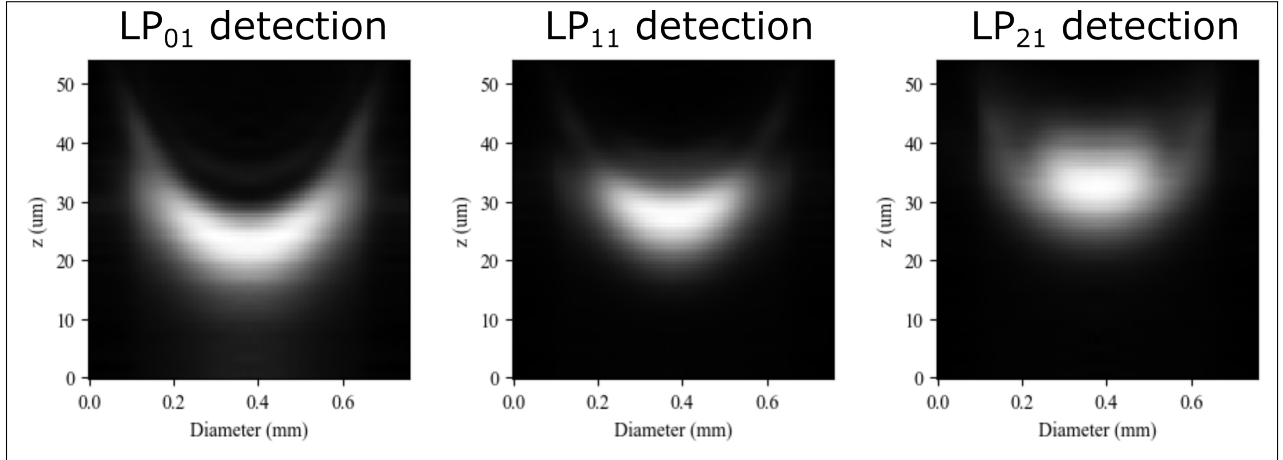


Figure 6.3 Mirror scanned confocal system. Detection performed with LP_{01} , LP_{11} , and LP_{21} ,

6.6 Multiplane Imaging with an MSPL

To experimentally demonstrate the multiplane illumination and detection scheme, we used a nylon custom-made calibration target defined in previous work [204]. This hemispherical target was designed and fabricated with well-defined steps and side sections. Figure 6.4a presents a schematic of the sample, with all dimensions provided in millimeters. In this

work, the lower part of the target was imaged, with the two largest step being the object of focus. Using the 3X microscope objective, we simultaneously illuminated and detected multiple planes within the sample. Figures 6.4b, c, and d display the images corresponding to the LP_{01} , LP_{11} , and LP_{21} modes, each capturing a different focal plane and structural detail. Finally, Figure 6.4e shows a maximum intensity projection, combining information from all three detected planes into a single comprehensive image.

A key advantage of this method is that the demultiplexing process enables both illumination and collection from specific z positions in a single output easily. In contrast, conventional multiplane detection splitting is disconnected from the illumination, leading to additional sample exposure and significantly increasing the complexity of the setup required to align illumination and collection perfectly. Figures 6.4b, c, and d clearly show that each mode provides unique contributions: LP_{01} predominantly images deeper planes (as indicated by the red arrow in Figure 6.4b), with high intensity in the lower steps and minimal response in higher planes such as those captured by LP_{21} . Conversely, LP_{21} excels at imaging higher planes (blue arrow in Figure 6.4d), with enhanced intensity in the upper steps compared to LP_{01} . The LP_{11} mode captures both lower and upper structures, providing a more balanced view of intermediate depths, although its intensity is not sharply peaked in either region or in the middle region (pink arrow in Figure 6.4c). Notably, the structural features are well-resolved in the LP_{01} and LP_{11} images, while the LP_{21} image appears more blurred—reflecting the reduced resolution associated with higher-order modes. This loss in resolution could potentially be mitigated through computational post-processing techniques, such as PSF engineering by further investigating higher-order modes illumination and detection.

Despite the presence of significant speckle contrast in the images, this effect can be minimized by employing a visible MSPL for fluorescence imaging in biological applications or by using a broader bandwidth light source for material analysis, as MSPL has a broadband response. Importantly, the maximum intensity projection (Figure 6.4e) effectively combines information from all three planes, offering a comprehensive view of the sample with a single XY scan. This approach reduces acquisition time by a factor equal to the number of modes used (three in this case), and scaling up to more modes could further accelerate imaging speed—an important advantage for high-throughput applications.

6.7 Conclusion

In this work, we have demonstrated a novel approach to simultaneous multiplane imaging in confocal microscopy using a MSPL. This MSPL, characterized by high modal isolation and low excess loss, enables efficient demultiplexing of three distinct group modes (LP_{01} , LP_{11} ,

and LP_{21}), each corresponding to a different imaging depth within the sample. By exploiting the spatial distribution and NA of the modes, we have shown that focal position differences among LP modes in the few-mode output can be harnessed for concurrent illumination and detection across multiple planes. This results in a significant reduction in acquisition time, which scales with the number of modes used.

Through a combination of simulation and experimental validation, we demonstrated that small differences in the NA of each mode can be used to achieve controlled focal plane separation, with the magnitude of this separation depending on the microscope objective. Multiplane imaging experiments on a structured custom sample confirmed the capability of this technique to resolve different depths simultaneously, with each mode contributing distinct plane information.

The principal limitations of this approach are the reduction of field of view and resolution for higher-order modes, as well as some resolution loss from incomplete back focal plane filling with LP_{01} . However, these challenges can be mitigated through computational post-processing, optimized sample selection, or restricting analysis to regions of interest. The method is also highly versatile, with strong potential for extension to fluorescence imaging and broadband sources. This is particularly impactful for fluorescence microscopy—one of the most widely used techniques for biological samples—and for multichannel applications enabled by the broadband response of MSPLs.

Regarding scalability of the modes, MSPLs have been shown to support up to five group modes [110]. Alternative demultiplexing techniques, such as spatial light modulators or multiplane light conversion, may offer more straightforward scalability at the cost of efficiency, providing flexibility for different experimental requirements.

Overall, our results establish MSPL-enabled multiplane confocal microscopy as a powerful technique for high-throughput, depth-resolved imaging. This advance opens new possibilities for rapid volumetric imaging in biological, biomedical, and materials science applications, paving the way for future developments in multimodal and high-content microscopy.

6.8 Funding

CB and SV acknowledge funding from the Mid-Infrared Quantum Technology for Sensing (MIRAQLS) project, supported by the European Union’s Horizon Europe research and innovation programme under grant agreement 101070700. Natural Sciences and Engineering Research Council (NSERC) of Canada grants #RGPIN-2018-06151 (CB), I2IPJ 590717 - 24 (LEW and CB). LEW acknowledges a salary award from the Fonds de Recherche du Québec—

Santé (FRQS).

6.9 Disclosures

RIBD, GR, LEW, and CB: Peregrine Photon Inc. (I), and Polytechnique Montreal (P).
RIBD: Castor Optics Inc. (E) CB: Castor Optics Inc. (I)

6.10 Data Availability Statement

Data underlying the results presented in this paper is not publicly available at this time but may be obtained from the authors upon reasonable request.

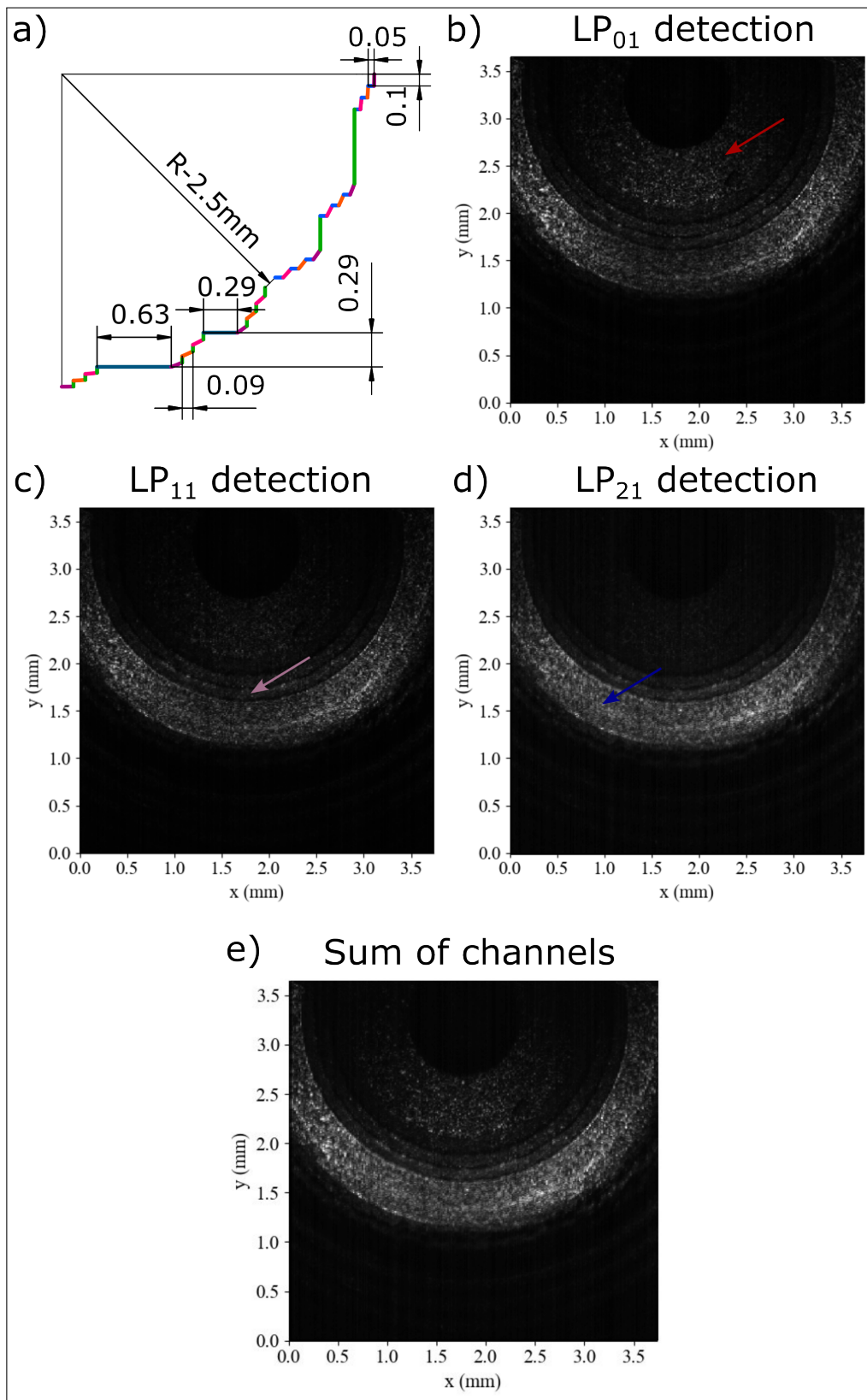


Figure 6.4 Multiplane sample. a) shows a diagram of the custom sample, with the shape of the figure highlighted in green. Simultaneous detection of each plane is exhibited by a) LP_{01} , b) LP_{11} , and c) LP_{21} . d) Maximum intensity projection of the three detected images

CHAPTER 7 FEW-MODE OPTICAL COHERENCE TOMOGRAPHY

This chapter is a compilation of papers submitted to international conferences related to OCT, which implement a MSPL. The conference’s names and dates are listed in the appendix of the contribution list.

For the work presented at the conferences, I was responsible for developing the research concept, designing the mounting, overseeing the optical system, processing and analyzing experimental data, drafting the manuscripts, creating figures, and conducting the literature review. Raphaël Maltais-Tariant, Xavier Attendu, and Martin Poincine de Sivry-Houle contributed to the scientific discussions throughout the project. Raphaël Maltais-Tariant also provided detailed feedback and significant revisions to the manuscripts and to the software for utilizing and controlling the system. Raphaël Maltais-Tariant and Xavier Attendu helped mount the optical system. Stéphane Virally offered guidance, support, and substantial modifications to the manuscripts. Caroline Boudoux and Nicolas Godbout provided laboratory materials, funding, and access to laboratory facilities. Caroline Boudoux, Raphaël Maltais-Tariant, and Martin Poincine de Sivry-Houle participated in developing the research concept.

7.1 Chapter Context

This chapter examines the capabilities that a MSPL can introduce to OCT. Integrating these devices into OCT systems has the potential to enhance several key aspects, such as reducing speckle noise, measuring flow, differentiating scatter, and improving photon detection. Ongoing research continues to explore additional applications and nuances of these capabilities. This thesis focuses on some of the significant impacts of MSPLs in optimizing various OCT modalities.

7.2 Introduction

OCT has emerged as a pivotal imaging technique that primarily utilizes the first-order propagation mode of single-mode fibers. This approach enables confocal gating, which is crucial for achieving exceptional lateral and axial resolutions. The axial resolution, in particular, benefits from enhanced coherence gating, further improving image quality.

An extension of this technology, known as Bright-and-Dark (BRAD) field OCT [87], harnesses higher-order spatial modes to enhance photon-collection efficiency. This advancement introduces a novel contrast mechanism. By capitalizing on the scattering phase functions of

particles with varying size, geometry, and refractive index, BRAD field OCT enables more detailed differentiation of tissue properties, paving the way for improved diagnostic capabilities. Additionally, advanced technologies that utilize higher-order mode detection in OCT, such as multimodal OCT, have shown significant improvements in cancer detection by using multiclad fibers instead of multimode fibers, as demonstrated in BRAD field OCT [205–210].

Additionally, FM-OCT advances these developments by integrating a MSPL, which enables the simultaneous acquisition of OCT data from both fundamental and higher-order modes. This broadens the range of imaging applications and enhances the versatility of the system. A key advantage of MSPLs is their ability to significantly reduce crosstalk, a common source of error in traditional optical fibers. By minimizing mode interference and enabling efficient mode transformation, these lanterns overcome limitations of previous technologies. As a result, they allow for precise identification of higher-order modes and offer greater scalability in a compact form factor, surpassing the capabilities of conventional mode-selective couplers in OCT systems.

For the purpose of this thesis, several PLs were fabricated and implemented in a new FM-OCT system that allows three multiple detections and illumination. The MSPLs were designed to operate within the 1300 ± 100 nm wavelength range, with an excess loss of less than 0.5 dB and an isolation between each mode of over 30 dB, ensuring mode orthogonality and supporting from 2 to 4 different modes. The MSPLs were fabricated according to the third article of this thesis, featuring a short and compact structure of 2 cm to ensure mechanical stability.

The lanterns were fabricated to support the first four LP modes: LP_{01} , the two orthogonal LP_{11} modes, and one LP_{21} mode. The following sections highlight the improvements and capabilities of this new FM-OCT.

7.3 Optical System

Figure 7.1 illustrates the schematic of the FM-OCT system, which features three parallel OCT interferometers. Each channel directs light along a distinct illumination path (swept source laser at 1300 nm), enabling multiple illumination and collection pairs. The setup includes a 90/10 beam splitter that splits light between the sample and reference arms. In the illumination section, one port of the MSPL is connected, while the reference port is connected to a 3-port splitter that splits the power into three separate reference arms. Although the MSPL comprises four channels, the FM-OCT uses only three; however, it is possible to collect data from the fourth port.

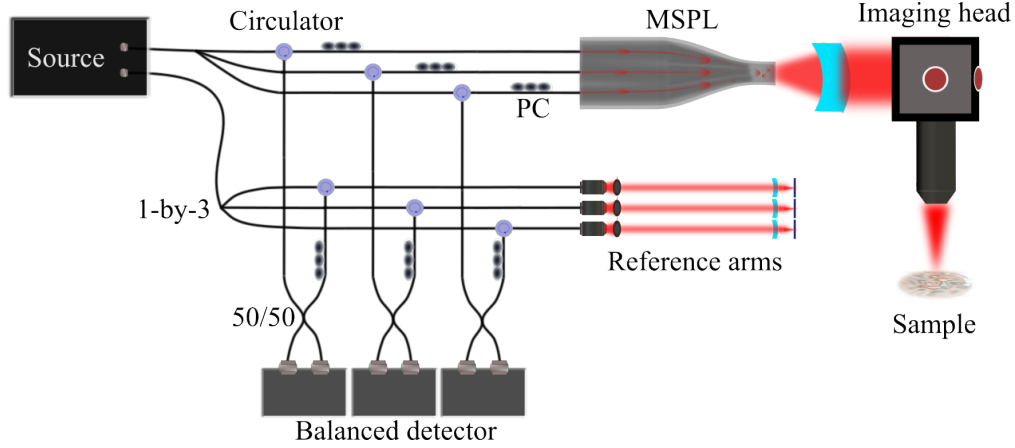


Figure 7.1 FM-OCT schematic. The system features three parallel OCT systems. The laser can be connected to any of the three illumination ports, with each channel equipped with its own circulator and polarization controller (PC). A 3-to-1 coupler enables simultaneous interference detection across all outputs from three reference arms. Additionally, each system includes its own balanced detector along with a separate PC on the reference arm.

After the light interacts with the mirrors and/or the sample, it is routed through a circulator before being combined at the balanced detectors. All ports are matched in length, differing by no more than 1cm in optical path, to facilitate interference with both the reference ports and the ports from the unused sections designated for illumination. While multiple collection modes could be acquired in parallel, each experiment was conducted with a singular illumination mode to mitigate any potential interference between modes at the output of the MSPL. In an interferometric system, the superposition of modes can spatially modify the illumination profile. Additionally, six circulators were implemented to avoid any possible interference along the interferometer's optical paths.

Furthermore, the lantern collects four channels simultaneously using a custom collimation lens and cage system. Each port features a polarization controller to optimize contrast and interference, with the main port dedicated to illumination and polarization alignment. While multiple ports and detectors increase system costs, this setup effectively minimizes interference and maximizes photon detection, streamlining the overall system configuration.

7.4 Capabilities of FM-OCT

Figure 7.2 presents a series of images from the resolution target, organized by the four different illuminations and detections used with the FM-OCT system. The illumination and detection of the LP_{01} mode adhere to the standard OCT configuration, resulting in the gold-standard

image. The observed performance indicates that the lantern's reciprocity remains consistent, as observed in confocal microscopy.

In contrast, the illuminations and detections using LP_{11} ports emphasize edge detection, as reported in two other journal articles. This configuration provides directional information about the samples, enabling accurate identification of their borders. On the other hand, structures illuminated and detected with the LP_{21} mode begin to introduce aberrations characterized by shadowing or the superposition of two images. Notably, a specific scenario involving LP_{21} - LP_{11a} shows clearer numbers of the resolution target than the gold standard, suggesting an improvement in resolution despite the duplication of numbers. This approach appears promising for achieving super-resolution in OCT imaging.

Additionally, illumination and detection using the same port, such as LP_{11a} - LP_{11a} , LP_{11b} - LP_{11b} , and LP_{21} - LP_{21} , demonstrate performance similar to the gold standard, albeit with a decrease in resolution. This highlights that the observable structures exhibit a comparable response to that observed in confocal microscopy.

FM-OCT has different imaging capabilities that are influenced by the density of scatterers present within the samples. Several structures were analyzed to identify the main features that can be extracted from the current system. This chapter explores the three primary scenarios encountered in FM-OCT imaging: samples containing single scatterers, samples with dense scatterer distributions, and samples that exhibit a combination of both, as found in biological tissues. FM-OCT addresses each of these scenarios and compares them with the LP_{01} channel. The LP_{01} channel produces an image identical to standard OCT images, allowing for avoiding the need to add a new configuration to the system.

7.4.1 Single Scatterers Response

The interaction of light with matter exhibits significant variability based on the properties of the scatterers, including size, polarization response, index of refraction, and shape. Scattering simulations reported in indicate that quasi-isotropic Rayleigh scattering excites the first two LP modes equally. This phenomenon is easier to observe using microbeads for analysis, particularly when examining samples with a low-density distribution of scatterers.

Figure 7.3 presents a series of images of microbeads, organized according to the four different illumination and detection configurations employed in the FM-OCT system. Each image displays distinct point spread functions (PSFs) that depend on the specific illumination and detection methods used. Notable observations include: 1. The density of scatterers per mode; higher-order modes lead to a decrease in intensity per particle. 2. The directional integrity of

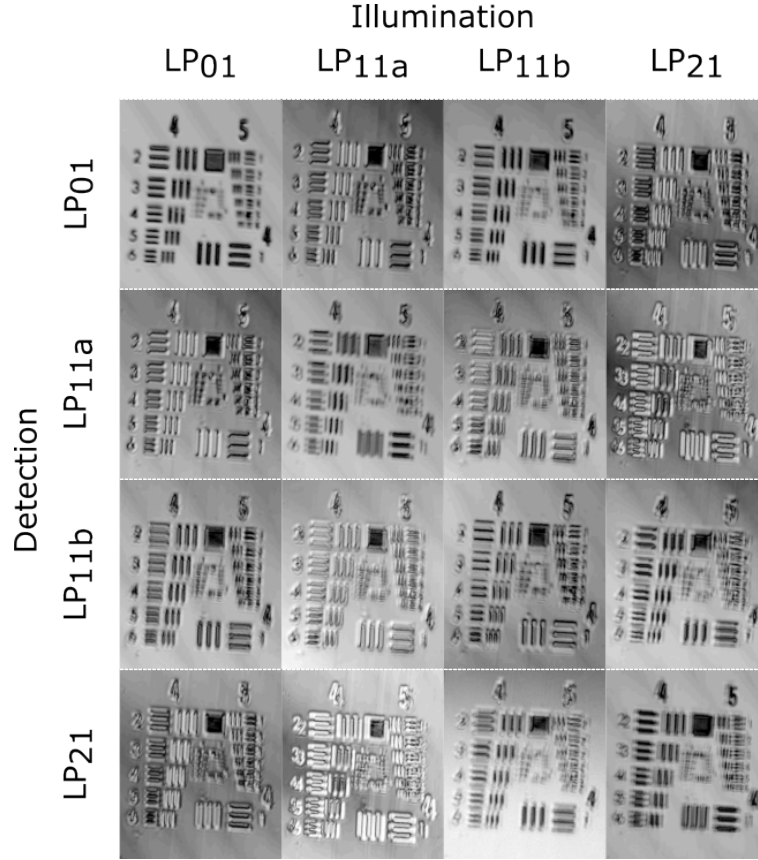


Figure 7.2 Resolution target: Arrangement of the four illuminations and detections obtained in the FM-OCT. The illuminated port is shown at the top, and the detection port is on the left.

the LP modes is maintained. 3. The pseudo LP_{21} PSF arises from the cross-illumination and detection of LP_{11b} - LP_{11b} . 4. The divergence of lobes at higher-order modes, such as in LP_{11a} - LP_{01} compared to P_{11a} - LP_{11a} and P_{11a} - LP_{21} , indicates a gradual separation of the principal two lobes. Due to the side-by-side arrangement of the images, synthesizing the information can be challenging, particularly when analyzing structures in single scatterers. For instance, in the P_{21} configuration, the reduced intensity and resolution further complicate structural analysis.

To facilitate more effective analysis, the introduction of fake colors for each mode serves to highlight and differentiate the various structures. Figure 7.4 illustrates the same microbead structures as Figure 7.3, but enhanced with fake colors in a maximum projection of 10 slides. The top row displays images of the beads illuminated with LP_{01} and detected with LP_{01} (red), LP_{11a} (green), LP_{11b} (yellow), and LP_{21} (blue). The bottom row provides a composite maximum intensity projection of beads illuminated with LP_{01} and detected across

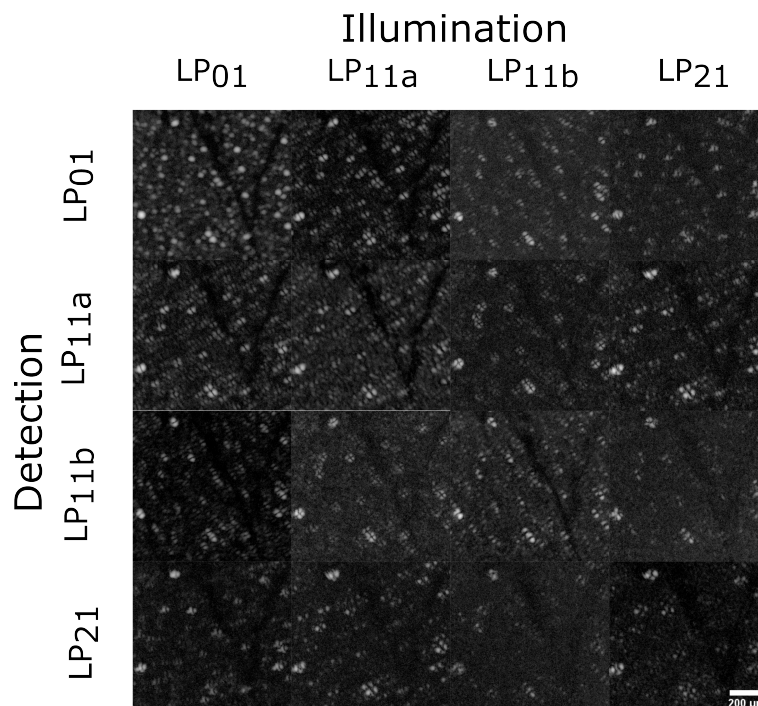


Figure 7.3 Microbeads: Arrangement of the four illuminations and detections obtained in the FM-OCT. The illuminated port is shown at the top, and the detection port is on the left.

various configurations: LP_{01} - LP_{21} , LP_{11a} - LP_{11b} , LP_{01} - LP_{11a} - LP_{11b} , and LP_{01} - LP_{11a} - LP_{11b} - LP_{21} , while maintaining the established color scheme.

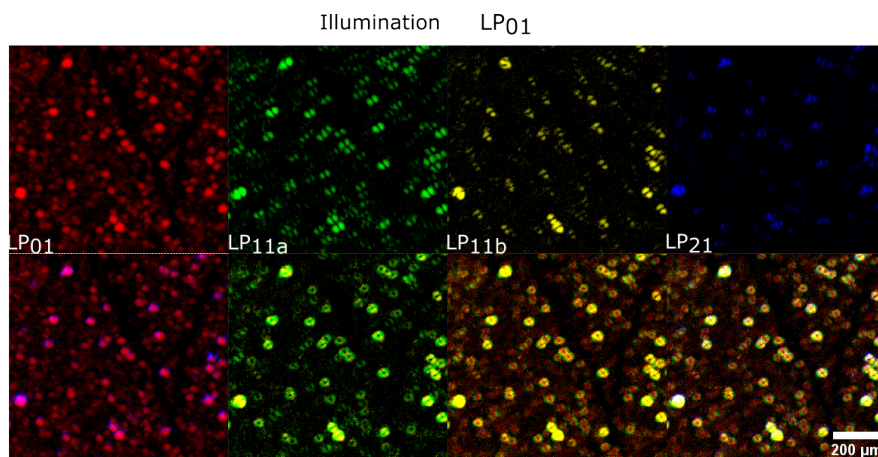


Figure 7.4 Top: En face maximum intensity projections of beads, it consistent of 10 images from the same region, the illumination was performed by LP_{01} and the detection by LP_{01} (red), LP_{11a} (green), LP_{11a} (yellow) and LP_{21} (blue). Bottom: Composition of the fourth different channels, form left to right the compiosition is done though LP_{01} - LP_{21} , LP_{11a} - LP_{11b} , LP_{01} - LP_{11a} - LP_{11b} , and LP_{01} - LP_{11a} - LP_{11b} - LP_{21}

Analysis of the top row reveals distinct profiles produced by different scatter sizes. The most prominent color, red, reflects the standard backscattering response, whereas blue, originating from LP_{21} detection, indicates larger scatterers, illustrating clear differences among the images. The areas depicted in the top row show significant disparity between the first three modes and LP_{21} , as well as varying scattering responses between LP_{01} and the two LP_{11} modes. Furthermore, the first composite image illustrates that larger scatterers predominantly contribute to higher-order modes, which may have implications for cellular differentiation. The subsequent composite image reveals a donut-shaped PSF, suggesting potential applications in super-resolution techniques such as STED microscopy. This is supported by the third composite image, which indicates that all red points align concentrically with the donut structures.

While subtraction methods for enhanced clarity are feasible in scatter structures, they could compromise intensity in continuous samples. An alternative approach might involve interference patterns between LP_{11} modes and LP_{01} ; however, the inherent phase de-phase of LP_{11} lobes by π limit this possibility. Nevertheless, creating these devices in the visible range and integrating them into fluorescence microscopy could lead to STED applications. The final composite image showcases all detection channels simultaneously.

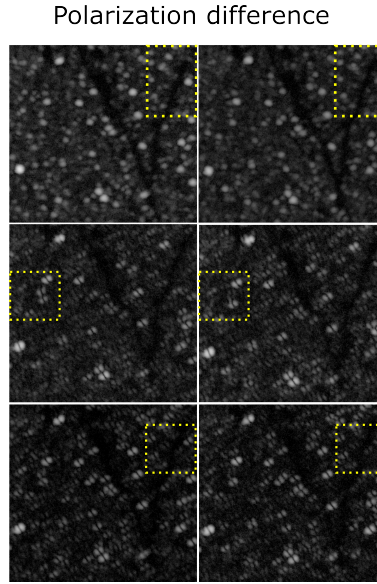


Figure 7.5 Difference in polarization between beads. The six images were obtained by illuminating LP_{01} with three main detections: the top row shows LP_{01} , the middle row shows LP_{11a} , and the bottom row shows LP_{11b} . Each column represents a different polarization.

The final point to consider in single-scatter samples is polarization response. Each port can detect polarization differently, allowing for the simultaneous measurement of different

polarizations on the sample. Figure 7.5 shows two columns of the same microbead as in Figure 7.4, but with different polarization conditions. The three rows show the microbead illuminated using LP_{01} . In the first row, detection is performed with LP_{01} , while the second row uses LP_{11a} for detection, and the third row employs LP_{11b} .

Each dashed square in every row of Figure 7.5 compares the same illumination and detection. Comparing the columns shows that some particles are visible in certain regions, while others are not, as in the LP_{01} and LP_{11a} detections. Another case is by comparing the rows, the dashed square of the LP_{01} detection reveals that some particles exhibit greater intensity than those detected with LP_{11a} due to their unique polarization and phase function response.

Analyzing single scatterers under various illumination and detection configurations offers valuable insights into sample characteristics. This analysis helps distinguish between scatterer sizes, evaluate polarization responses, and understand phase functions. It can even enable super-resolution for particle tracking.

However, light-matter interactions with high-density samples exhibit different behaviors in certain aspects, such as the phase function response and scatterer size dimensions. Despite these differences, edge detection remains consistent with polarization detection across other ports, providing new insights and bringing other advantages that will be discussed in the following section.

7.4.2 High-Density Samples

High-density samples, such as larger biological structures including fruits or tissues, exhibit distinct responses to structured illumination. As mentioned in the introduction section, specific particles respond differently to each mode and are referenced in the PyMising package, which provides more details on the interaction between a particle and light; however, these simulations cannot be fully applied effectively to complex media. For instance, Figure 7.6 shows the maximum projection of a stack of images for three different samples: a tomato, a mandarin, and beads, all illuminated under conditions that result in oversampling. Each structure responds uniquely while displaying some similarities.

For example, in Figure 7.6 a), we observe a tomato slice illuminated with the LP_{01} mode and detected using LP_{01} , LP_{11a} , and LP_{11b} . The LP_{01} features are represented in red, LP_{11a} in green, and LP_{11b} in blue. Most of the structure appears white, a result of the combination of the three colors. Notably, the majority of the white areas are concentrated around the sample, while the red highlights the inner structure. Additionally, the branches visible in the samples are more pronounced in the white-green area, emphasizing the LP_{11a} - edge detection

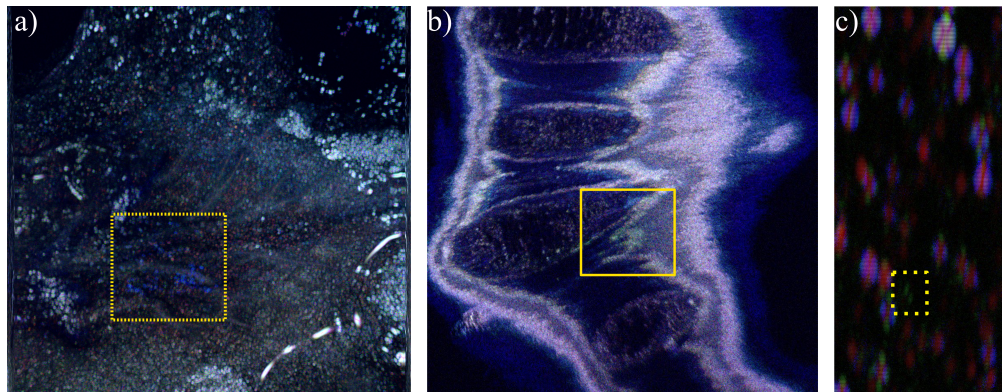


Figure 7.6 Maximum projection images when illuminated with LP_{01} and detected with different modalities. a) A tomato slice detected using LP_{01} (red), LP_{11a} (green), and LP_{11b} (blue). b) A mandarin sample with detection LP_{01} (red), LP_{11a} (green), and LP_{21} (blue). c) Beads detected using LP_{01} (red), LP_{11b} (blue), and LP_{21} (yellow).

of these branches within the tomato and revealing the surrounding structure of the tomato's inner branches. A specific region appears in blue, stemming from LP_{11b} , surrounded by a dashed square. This area also contains LP_{11a} detection showing some green color. However, minimal compared to the detection of LP_{11b} , meaning that the primary detection is observed preferentially in one specific direction of the lobes. Two possible interpretations arise: either this structure exhibits higher contrast due to the particles' inclination, or certain planes went undetected by the other two modes, thereby enhancing the intensity of the blue contribution.

A similar pattern is observed in Figure 7.6 b), where a mandarin sample was illuminated using LP_{01} and detected with LP_{01} , LP_{11a} , and LP_{21} . Again, LP_{01} features are shown in red, LP_{11a} in green, and LP_{21} in blue. Here, the dominant color is white, indicating significant detection similarity among the three modes. In the mandarin sample, the green segment is highlighted within the internal structure, particularly around the solid square, where the structure's boundary is distinctly captured, demonstrating edge detection. However, a challenge arises: in LP_{21} detection, higher-order modes tend to suffer from reduced resolution, as shown in the introduction section. In this case, a blue halo surrounding the structure suggests an aberration that adds noise to the images, despite the maintained overall structure, possibly due to dispersion.

One of the main advantages in edge detection is that by identifying the boundaries of a sample, we can achieve significant advancements in various fields, such as targeted irradiation of those samples or the extraction of specific structures. For example, another scientific group demonstrated that higher-order modes could be used to detect cancerous regions. With precise edge detection, we can effectively delineate the frontiers of these areas and potentially

achieve higher contrast in those sections. It is important to note that edge detection is evident in most large sample structures.

Lastly, Figure 7.6 c) illustrates another example involving beads, allowing for a comparative analysis of responses to high-density samples. The beads were illuminated with LP_{01} and detected using LP_{01} , LP_{11a} , and LP_{21} . Here, LP_{01} features are red, LP_{11a} blue, and LP_{21} yellow. In this image, some beads do not excite the modes equally; in some instances, only LP_{21} is detected (as shown in the low-dashed-square), while in others, only red is detected. Cases where all three modes are excited are rare, such as in the upper section of the image. This disparity highlights the distinct behavior of each mode, suggesting that polarization and the modes' responses may play a crucial role in the observed differences.

A closer examination of the characteristics of high-density samples reveals that sharing information among different modes is advantageous for photon acquisition. Figure 7.7 presents two slides depicting different b lines of a Kiwi. The left image shows the raw data collected from a b line under illumination and detection with the LP_{01} mode, while the right image illustrates the same illumination combined with data from four distinct detection modes: LP_{01} , LP_{11a} , LP_{11b} , and LP_{21} .

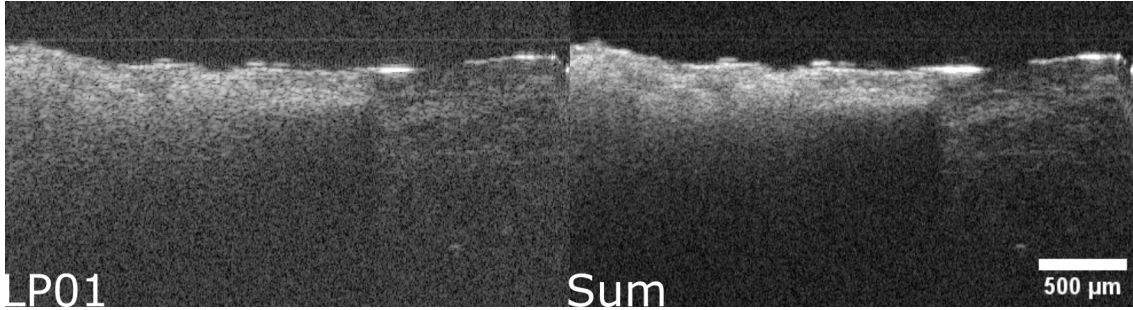


Figure 7.7 Comparison of photon acquisition in Kiwi Samples. The left image displays raw data of a b line using the LP_{01} mode of illumination and detection. The right image showcases the same sample illuminated with LP_{01} mode but summing four modes detection : LP_{11a} , LP_{11b} , and LP_{21} .

When a sample is solely illuminated and detected using the LP_{01} mode, a significant amount of information is lost because this approach primarily captures ballistic scattering. The sample also generates diffuse scattering in all directions, leading to a majority of photons going undetected. This is where the multiplexer comes into play, enabling the acquisition of photons from different directions or modalities and transforming them into single-mode performance. By leveraging this technique, we can capture more photons and obtain a richer dataset.

Figure 7.7 serves as an excellent illustration of this concept. The image that aggregates all modes demonstrates improved contrast, a higher SNR, and a notable reduction in speckle, resulting in more defined structures. This enhanced photon acquisition capability is particularly crucial for applications where the available photon count is limited.

Speckle Contrast Per Mode

As previously discussed, Figure 7.7 demonstrates improved contrast when the four channels are summed. A key factor in this enhancement is the reduction of speckle contrast, a phenomenon that typically appears as noise in systems using coherent illumination and detection. Speckle contrast is a type of intrinsic noise that manifests as patterns in acquired images and can distort true sample features. Such noise not only degrades overall image quality but can also hinder accurate diagnosis or quantitative analysis, especially in fields such as medical imaging or material inspection. Therefore, reducing speckle contrast is essential for enhancing image interpretability and improving the reliability of diagnostic outcomes.

In Reference 1, our research group investigated the various speckle contrasts that can be detected in a two-mode PL to reduce this type of noise. This phenomenon can be explained by considering the differences in optical paths between the two modes. The optical path is similar when a shared illumination is used, but detection occurs at spatially distinct points; photons traverse different optical paths across sections, resulting in markedly different speckle patterns.

Reference 1 provides a more detailed exploration of this, which uses the PLs fabricated for this thesis. Importantly, speckle contrast can often be identified by the granular patterns observed in certain samples. Figure 7.8 presents an en face OCT image showing the letter 'R' from a plastic cap on the left side of the image. Adjacent to this, there is a zoomed-in view of the upper part of the 'R', obtained using LP_{01} illumination and detection. To the right of this zoomed-in image, a second image shows the same section with a different illumination scheme (LP_{11a}) but the same detection. As noted in Reference 1, the granular patterns in Figure 7.8 are visually distinct, indicating different speckle contrasts. This has also been demonstrated in Reference 1 by using the same illumination and varying only the detection.

Building upon the goal of reducing speckle contrast, the next approach involved implementing multiple illumination and detection configurations in the current system. Figure 7.9 illustrates a 4-by-4 matrix arrangement, where each cell corresponds to a different combination of illumination and detection modes (LP_{01} , LP_{11a} , LP_{11b} , and LP_{21}). For each combination, an en face image is constructed as a maximum intensity projection of 30 images of a plastic cap's surface, without applying oversampling during scanning.

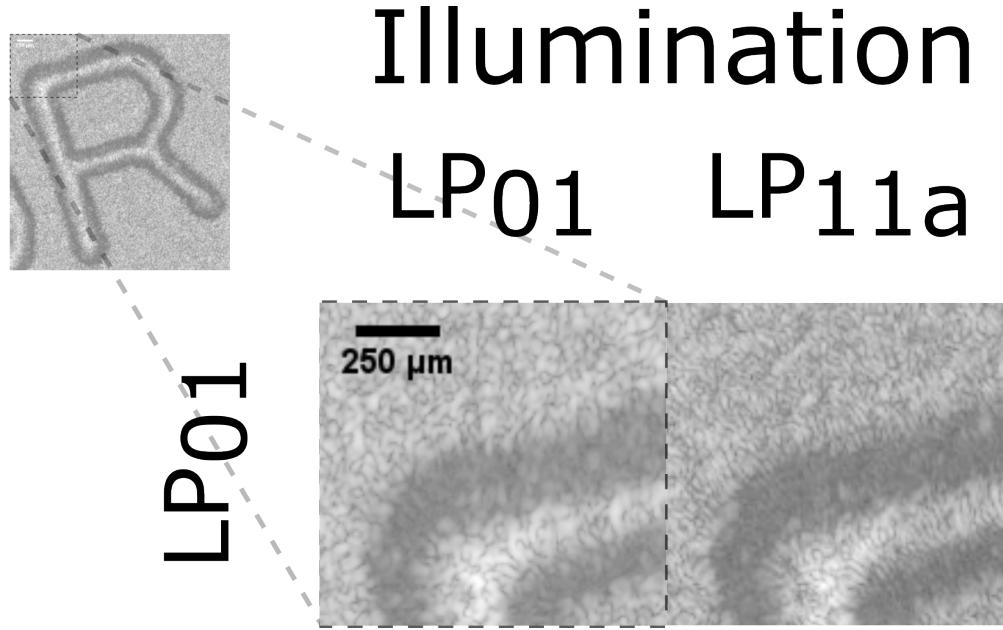


Figure 7.8 En face OCT image with a zoomed-in section showing illumination and detection using LP₀₁. Next to it is a zoomed en face OCT image of the same section, illuminated with LP_{11a} and detected with LP₀₁.

This matrix configuration reveals significant variation in speckle contrast across the different mode pairings. These variations arise from the unique optical paths introduced by each illumination-detection combination. Importantly, the fundamental structure of the sample remains consistent with minimal distortion. Interestingly, certain pairs—such as LP₀₁-LP_{11a} and LP_{11a}-LP₀₁—display reciprocal speckle contrast, which aligns with the principle of optical reciprocity: interchanging the roles of illumination and detection yields nearly identical results. As a result, the 4-by-4 matrix in Figure 7.9 effectively produces 10 distinct speckle contrast values. Reference 1 validates the advantage of this strategy, showing that combining multiple speckle contrasts from the same sample can effectively reduce overall speckle noise in the reconstructed image, though it may introduce a modest trade-off in resolution.

In summary, FM-OCT enables edge detection, improved photon acquisition, enhanced contrast, and speckle reduction in large-scale samples. While modal contrast and polarization effects are less pronounced than in single-scatterer samples, they can still provide valuable analytical insights in select cases.

7.4.3 Biological Sample

To simultaneously demonstrate both key advantages of the system, a zebrafish larva was selected as the biological sample. Due to its ongoing development, this specimen exhibits

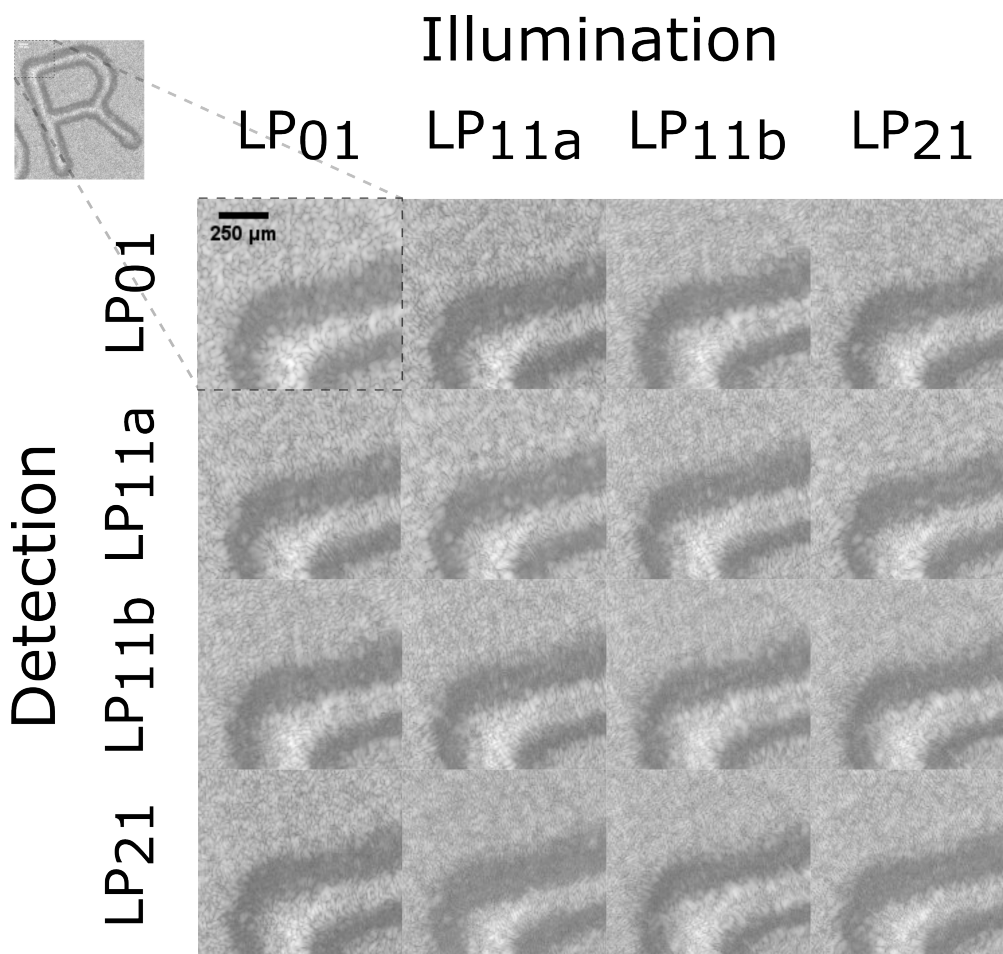


Figure 7.9 En face OCT image on the top left with its zoomed-in section showing illumination and detection using LP₀₁. This zoom is in an 4-by-4 matrix of en face images, each corresponding to a unique combination of illumination and detection modes (LP₀₁, LP_{11a}, LP_{11b}, and LP₂₁). The matrix demonstrates how varying these configurations affects speckle patterns, with maximum projection images used to visualize differences in speckle contrast for each mode pairing.

significant cellular movement and a mix of small-scale features within a relatively large structure. In such in vivo samples, both low- and high-density scattering behaviors are present. Figure 7.10 displays parallel data acquisition at 58.8 B-scans per second from a 7-day-old zebrafish embryo (in vivo). The figure consists of three cross-sections of the same embryo, all illuminated using the LP₀₁ mode. The top image shows detection with LP_{11a} (green), the middle image shows detection with LP₀₁ (red), and the bottom image overlays both channels, with yellow indicating regions where green and red signals coincide.

Figure 7.10 clearly illustrates the dual advantages provided by the system for both high- and low-density regions. In areas of high density, such as the eye and yolk, the yellow regions

in the composite image indicate overlapping contrast, reflecting enhanced photon acquisition and improved image quality. Meanwhile, the modal contrast seen in single-scatterer scenarios is also evident: the tail appears predominantly red, and the head more green, suggesting that distinct anatomical regions preferentially scatter into different modes, likely corresponding to variations in sub-resolution particle distribution. Each detection channel provides unique information, and fusing data from both channels yields the most comprehensive representation of the sample.

This example highlights the system’s potential to increase contrast in specific regions and even differentiate particle or cell sizes using higher-order modes.

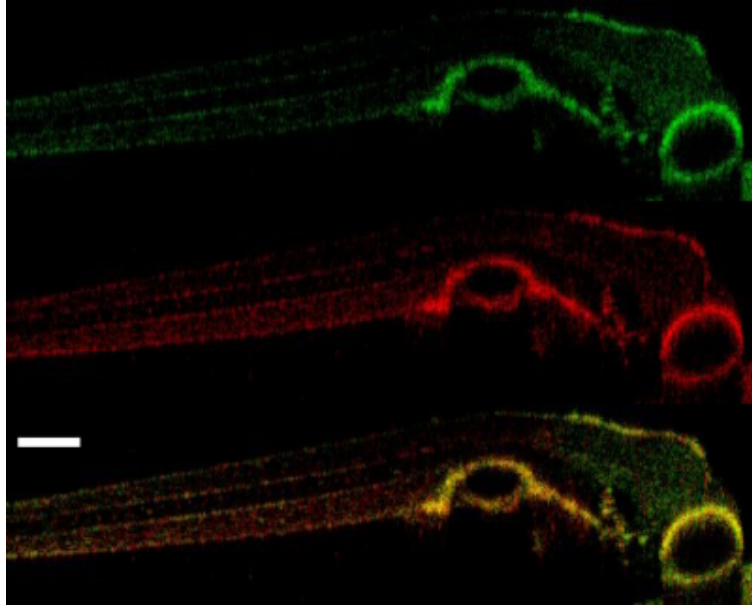


Figure 7.10 Side section of a zebrafish embryo of 7-days. The red channel represents the detection using the LP_{01} port, the green for LP_{11} , and the yellow the composition of both. Scalebar $200\mu m$.

7.5 Limitations

While MSPL in OCT systems provide substantial advantages—including enhanced photon acquisition, improved contrast, and advanced imaging versatility—there are notable limitations and areas for further research and development.

First, the fabrication and integration of PLs with precise, concentric structures remain challenging, particularly when considering scalable production for commercial systems. Many current designs are still in the research stage, and developing cost-effective, robust lanterns suitable for widespread clinical or industrial use requires significant engineering advances.

Second, the effective use of FM-OCT often relies on a thorough understanding and characterization of the samples being imaged. Interpreting the unique responses from different spatial modes may necessitate specialized knowledge or additional sample pre-characterization, which could limit immediate adoption in some settings.

Moreover, while the system demonstrates clear benefits for complex and heterogeneous samples, realizing its full potential may require collaboration with domain experts—such as biologists—to assess the impact and optimize performance for specific applications. Further, expanding the utility of FM-OCT in complex system simulations or high-power scenarios will require dedicated studies to address power handling and multi-sample analysis.

Another consideration is the trade-off between system complexity and cost. Although the current FM-OCT design effectively avoids inter-modal interference and maximizes photon detection, the use of multiple ports, detectors, and polarization controllers increases overall system expenses. Determining the optimal number of supported spatial modes for efficient imaging remains an open area of research, with potential to reduce costs without sacrificing performance.

Finally, while the results presented in this chapter are promising, further analysis and optimization are required to translate FM-OCT systems into clinical experiments and routine practice. Ongoing work should focus on improving lantern fabrication, reducing system costs, and validating performance across a broader range of biological and industrial samples.

7.6 Conclusion

This chapter has presented the development, implementation, and characterization of a FM-OCT system featuring a MSPL. Through a comprehensive series of experiments and analyses, the unique advantages of this approach have been demonstrated across a spectrum of sample types, ranging from single scatterers and high-density materials to complex biological tissues.

By leveraging multiple spatial modes—enabled by the PL—the FM-OCT system achieves significant improvements over conventional OCT. Notably, it provides enhanced photon acquisition, improved contrast, and the ability to differentiate scatterers based on their size and spatial distribution. The results from single-scatterer samples illustrate how higher-order modes can reveal subtle structural and polarization-dependent features, while studies with dense and mixed samples demonstrate the system’s capacity for advanced edge detection, speckle reduction, and comprehensive image formation through modal data fusion.

The application to biological specimens, such as the zebrafish larva, underscores the power of FM-OCT to resolve and distinguish features within dynamic, heterogeneous tissues. This

capability is crucial for biomedical imaging, where both structural detail and functional information are paramount.

Overall, the integration of MSPLs into OCT systems opens new avenues for advanced imaging modalities. The findings in this chapter highlight the potential for FM-OCT to address longstanding challenges in optical imaging, such as speckle noise and limited contrast, and to expand the diagnostic and research applications of OCT. Future work may further optimize lantern design, explore additional detection strategies, and translate these technological advances into clinical and industrial practice.

CHAPTER 8 DISCUSSION

This thesis systematically analyzed photonic lantern architectures to find optimal setups for biomedical imaging. The study used theoretical modeling, fabrication, and experiments. This work showed that these devices are practical and transformative for confocal microscopy and OCT. The research demonstrated that PLs can be integrated into imaging systems, adding versatility to the field.

The in-depth exploration of PLs in this thesis helped identify essential characteristics and requirements for specific applications. Initial studies showed that power transfer efficiency, modal coupling, wavelength dependence, polarization response, and phase control are all pivotal for device performance. Devices with strong coupling excel in scalability, enabling more ports and higher power throughput. This feature is highly valued in fields such as astrophysics and telecommunications. Semi-mode-selective configurations are promising for specialized applications, including optical tweezers, single-port orbital angular momentum generation, and grouped-mode PLs for cylindrical-symmetry fiber communications. In contrast, mode-selective biomedical imaging PLs allow precise control over illumination and detection pathways, improving image versatility and system functionality. These findings show that each PL type has unique advantages and limitations. The comparative analysis in this thesis provides a framework for selecting and optimizing devices for specific imaging needs.

After identifying MSPLs as the most promising for biomedical imaging, attention turned to their engineering challenges, particularly packaging and mechanical robustness. Although this technology has existed since 2005, real-world deployment remains limited due to the fragile nature of these structures. This thesis introduced innovations—especially the use of double-clad fiber designs—which resulted in lanterns that are both more compact and resilient while enabling scalability by adjusting cladding dimensions. These advances streamlined packaging, reduced optical losses from back reflections, and increased the feasibility of integration into commercial and clinical systems. A reliable characterization methodology further ensures consistent manufacturing to high standards, supporting industry adoption and a smooth transition from prototypes to impactful biomedical tools.

The advantages of MSPLs led to their integration in this thesis, enabling rapid prototyping and design improvements. Further refinement of packaging and durability may require industrial collaboration and longer development cycles. The immediate objective was to demonstrate their impact on advanced imaging modalities. By demonstrating functional

benefits and practical applications in biomedical imaging, this work lays the foundation for future commercial development. These findings are expected to inspire research in packaging, reliability, and scalability, promoting adoption from laboratories to clinical and technological use.

It may have seemed in the first chapters that by fabricating a component with the lowest possible values of the adiabatic criterion, one could create any component. However, as the logarithmic slope decreases, the component reaches a point where it becomes fragile and lacks sufficient robustness, compromising all mechanical properties necessary for mounting and long-term stability. Conversely, making the structure larger to maintain robustness would render the components impractical for implementation. Thus, the main limitations are imposed by practical and experimental conditions, even though the theoretical limits could potentially be achieved. On the other hand, far-field images were considered because, in optical imaging, they represent the primary profile interacting with the sample. Near-field images respond differently compared to far-field images, exhibiting distinct modal modifications during propagation.

The changes in the optical profile of photonic lanterns depend strongly on the coupling between each port. As demonstrated in Chapter Four, components composed of similar fibers exhibit stronger interactions within the optical profile. To achieve a polarization-independent response in these structures, the symmetry must be broken—meaning that different types of fibers should be used during fabrication. This approach minimizes potential interactions between modes arising from polarization effects.

It is important to highlight that the characterization processes described in Chapters Three and Four can be quite time-consuming. While it is technically feasible to implement monitoring stations and characterization systems for each component, the time required to analyze and monitor these structures increases significantly. Ultimately, time management becomes a practical consideration rather than a fundamental limitation of the components themselves.

Experimental demonstrations in chapters four and five show the broad impact of PLs on biomedical imaging. The implementation of multiplane scanning and rapid three-dimensional imaging in confocal microscopy highlights their potential to dramatically improve throughput, efficiency, and diagnostic accuracy. These advances are not limited to traditional confocal setups. Extending lantern technology into the visible spectrum allows breakthroughs in fluorescence microscopy, enabling real-time volumetric imaging of biological processes and potentially transforming cell biology and pathology workflows. PLs also enable the generation and manipulation of structured light, opening new frontiers in super-resolution imaging, such as STED microscopy. They enhance techniques like angular and dark-field detection. In

OCT, using multiple spatial modes expands the information content of acquired images. This enables enhanced photon acquisition, detailed analysis, polarization-sensitive imaging, and effective speckle noise reduction. The emerging possibility of flow measurement integration further supports their value in next-generation biomedical imaging.

Translating these technological advances into clinical practice holds great promise. In confocal microscopy, PLs can significantly speed up three-dimensional structural analysis. This streamlines diagnostics and may improve patient outcomes. In OCT, as shown in the final chapter introduction, using higher-order modes may help detect and characterize cancerous regions. This could lead to earlier and more accurate diagnoses. The societal impact of such improvements may be profound, paving the way for better healthcare and advancing medical diagnostics.

8.1 Limitations

Despite the significant progress reported in this thesis, some limitations remain before PLs reach their full practical potential. First, the detailed characterization required for each lantern type, especially those with strong modal coupling, can be time-consuming and resource-intensive. Double-clad components offer scalability and robustness but often behave differently from standard components, such as showing different coupling efficiencies. This makes the full characterization of each device before use even more important.

Another key constraint found in the third study is the difficulty of maintaining precise fiber concentricity during packaging and connectorization. Achieving high alignment accuracy often requires specialized, and more costly, capillary tubes and alignment tools. This can be a barrier to large-scale manufacturing. The current reliance on custom-fabricated fibers for each device design also affects scalability and increases production costs. These issues make widespread commercial and clinical adoption harder. Developing standardized fabrication protocols and cost-effective alignment solutions will be needed to overcome these barriers.

From an imaging system perspective, additional limitations exist. Integrating PLs into imaging platforms can be hindered by packaging constraints and increased back reflections, especially with custom illumination setups. Using higher-order modes brings benefits for multiplexing and information content but may lower spatial resolution. This trade-off needs careful management. Implementing multi-channel detection architectures, as shown in the systems developed here, requires more detectors or readout channels. This adds complexity and cost. Future work should focus on reducing these trade-offs to make PL-based systems more accessible and efficient.

To fully benefit from PLs in imaging, advances in point-spread-function engineering and image-processing algorithms are necessary. These efforts will help optimize image reconstruction, enhance contrast, and extract more information from the complex multimodal signals provided by these devices.

CHAPTER 9 CONCLUSION

This thesis has advanced the field of fiber-based biomedical imaging by designing, fabricating, and characterizing novel PLs, with a particular focus on mode-selective architectures using double-clad fibers. Through a systematic combination of theoretical modeling, numerical simulations, and experimental validation, the work has demonstrated how tailored fiber geometries and innovative fabrication processes can overcome longstanding challenges in spatial mode multiplexing. This has enabled robust, broadband, and low-loss PLs optimized for integration into advanced imaging modalities, including confocal microscopy and few-mode OCT.

The integration of these custom lanterns into imaging systems has yielded several key outcomes: (1) improved photon acquisition and enhanced contrast through selective modal collection, (2) multiplane and multimodal imaging capabilities that accelerate volumetric data acquisition, and (3) the ability to exploit higher-order spatial modes for advanced functionalities such as speckle reduction, edge detection, and polarization analysis. Experimental results confirm that these devices maintain high modal isolation and low excess loss over broad spectral ranges, and can be reliably produced using scalable fabrication techniques.

Beyond the immediate technical advancements, this work demonstrates the versatility and scalability of PLs for diverse biomedical applications. The systematic methodology developed here—spanning from theoretical design to experimental implementation—provides a blueprint for future research and industrial translation. The robust performance of the fabricated devices highlights their potential for integration into compact, high-throughput imaging systems and their adaptability to new imaging modalities, such as fluorescence microscopy and advanced OCT.

Collectively, the research presented here provides a comprehensive framework—from design to practical implementation—for the deployment of PLs in biomedical optics. The findings not only deepen the understanding of light–matter interactions in complex fiber structures but also establish a foundation for the development of next-generation fiber-based imaging systems. These advances open new avenues for high-resolution, high-throughput, and application-specific imaging in biomedical research and clinical diagnostics.

9.1 Achievement of Research Objectives

The primary objective of this thesis was to design, fabricate, and characterize compact and efficient PLs, and to explore their integration into confocal microscopy and OCT imaging systems to enhance imaging performance by enabling multimodal operation beyond the fundamental mode. This goal was achieved through the successful accomplishment of the following specific objectives: (1) Design of 3×1 PLs: This objective was addressed in the early stages of the research, combining theoretical and experimental analyses to understand the fundamentals of PLs and establish an international benchmark for their characterization. The work also introduced new parameters, such as polarization, for consideration in practical implementations. (2) Development of a fusion-tapering fabrication process for biomedical imaging: Using fluorine-doped capillary tubes and double-clad fibers, a robust process was established for fabricating broadband, MSPLs with high modal isolation. This set a new benchmark for device characterization and demonstrated their suitability for integration into free-space optical systems. (3) Implementation of 3×1 PLs in imaging systems: The PLs were successfully integrated into confocal microscopy and OCT setups, as reported in the final chapters and publications of this thesis.

Regarding the research question—how novel fiber optic components, particularly PLs, can enhance resolution, imaging acquisition speed, and contrast in optical imaging applications—the results indicate that while resolution was not significantly improved in these particular implementations, imaging acquisition speed increased, and contrast was enhanced in ways beneficial for advanced image analysis, such as edge detection and identification of regions of interest. These findings suggest valuable new capabilities, even as further research is needed to fully realize the potential for resolution enhancement in other contexts.

As for the hypothesis—that specialized fiber coupler geometries can significantly enhance the selective collection of optical signals in few-mode configurations and improve imaging resolution and contrast—this work demonstrated the feasibility of such approaches and their practical integration into imaging systems. While not all aspects of the hypothesis were fully realized, the research establishes a solid foundation for further exploration. Given that the implementation of these devices in biomedical imaging is still emerging, and our group is among the pioneers in this area, the outcomes represent important progress while also highlighting the need for continued investigation to fully understand and maximize their impact in biomedical optics.

9.2 Future Research

Looking ahead, several promising research directions emerge from this thesis. One key avenue is the fabrication and implementation of visible-wavelength PLs. These devices could revolutionize biomedical imaging by enabling high-resolution, real-time volumetric imaging across diverse biological samples. Although this transition presents challenges in fabrication complexity and material selection, the scientific and clinical rewards could be substantial. In parallel, advancing PSF engineering and image processing research will maximize the potential of MSPLs. These efforts will push the boundaries of optical imaging and drive the development of innovative fiber-based devices for life sciences, clinical diagnostics, and more. Achieving these goals requires interdisciplinary collaboration, sufficient infrastructure investment, and sustained academic and industry engagement.

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APPENDIX A SCIENTIFIC CONTRIBUTIONS

Publications

A Poiffaut, O Bélanger, JS Boisvert, MP de Sivry-Houle, **RI Becerra-Deana**, C. Boudoux, S. Loranger. "Distributed Directional Force Sensing in Few-Mode Polarization-Maintaining Fibers via Low-Coherence Interferometry" *Journal of Lightwave Technology*. (October 2025) DOI: 10.1109/JLT.2025.3620218

R Maltais-Tariant, **RI Becerra-Deana** S Brais-Brunet, M Dehaes, C. Boudoux. "Accurate flow speed measurement through correlation ratios using a mode-selective photonic lantern in optical coherence tomography" *Biomedical Optics Express*. (July 2025) DOI: 10.1364/BOE.564589

RI Becerra Deana, R Maltais-Tariant, G Ramadier, MP de Sivry-Houle, S Virally, C. Boudoux, N. Godbout. "Three-mode photonic lanterns: comprehensive analysis from theory to experiments" *Optics Continuum*. (June 2025) DOI: 10.1364/OPTCON.564008

RI Becerra Deana, MP de Sivry-Houle, S Virally, C. Boudoux, N. Godbout. "Mode-selective photonic lanterns with double-clad fibers" *Journal of Lightwave Technology*. (March 2025) DOI: 10.1109/JLT.2025.3555793

MP de Sivry-Houle, **RI Becerra Deana**, S Virally, N Godbout, C Boudoux. "SuPy-Mode: an open-source library for design and optimization of fiber optic components" *Journal of Lightwave Technology*. (February 2024) DOI: 10.1109/JLT.2025.3555793

R Maltais-Tariant, **RI Becerra-Deana** S Brais-Brunet, M Dehaes, C. Boudoux. "Speckle contrast reduction through the use of a modally-specific photonic lantern for optical coherence tomography" *Biomedical Optics Express*. (November 2023) DOI: 10.1364/BOE.504861

A Séguin, **RI Becerra-Deana**, S Virally, C Boudoux, N. Godbout. "Fabrication and characterization of indium fluoride multimode fused fiber couplers for the mid-infrared" *Optics Express*. (September 2023) DOI: **10.1364/OE.501849**

É. Ducharme, S. Virally, **R. I. Becerra-Deana**, C. Boudoux, N. Godbout.
 "Viscosity of fluoride glass fibers for fused component fabrication." *Applied Optics*.
 (June 2022) DOI: **10.1364/AO.455528**

RI Becerra-Deana, J. Lamarre, R. Maltais-Tariant, A. Zolnai, N. Godbout, S. Virally, C. Boudoux "Optical Profile Response to Polarization and Wavelengths Across Photonic Lantern Architectures" *Optics Continuum*. (January 2025) Under review

S. Albos, **RI Becerra-Deana**, R. Maltais-Tariant, N. Tebchrany, G. Ramadier, C. Boudoux "Few-Mode Confocal Microscopy with a Mode-Selective Photonic Lantern" *Optica Open*. (March 2025) Soon to be transferred to Optics continuum.

RI Becerra-Deana, S. Desrochers, R. Maltais-Tariant, S. Brais-Brunet, G. Ramadier, L. E. Weiss, S. Virally, and C. Boudoux "Simultaneous plane illumination and detection in confocal microscopy using a mode-selective photonic lantern," *Optics Letters*. (April 2025) Under review

G. Ramadier, **RI Becerra-Deana**, S. Virally, N. Godbout, L. E. Weiss, and C. Boudoux "Mode- Selective Photonic Lanterns in the visible range" *Optics Letters*. In preparation

G. Ramadier, **RI Becerra-Deana**, L. E. Weiss, and C. Boudoux "STED microscopy using a Mode- Selective Photonic Lanterns," In preparation

Reviewer in scientific journals

Optical Materials Express | 1 Paper (2025)

Optics Express | 1 Paper (2025) (special thanks received "Dear Dr. Becerra-Deana,
 Thank you for your recent review of the above manuscript. I particularly appreciate the level of detail in your comments. I realize that the referee process is a difficult and often thankless task, and I greatly appreciate the substantial amount of time and effort that you obviously dedicated to your response...")

Optics Express | 1 Paper (2026)

Publications in the acknowledgments

I have contributed to several papers in various aspects, and in some of them, I have been mentioned in the acknowledgements sections, such as in the following examples.

Gisell Lorena Osorio | Strategies for generating separable photon triplets in waveguides and ring resonators | DOI 10.1088/2058-9565/ae0759 | Quantum Science and Technology

Marc-Antoine Bianki |Suspended whispering gallery mode resonators made of different polymers and fabricated using drop-on-demand inkjet printing for gas sensing applications | <https://doi.org/10.1016/j.snb.2024.136460> | Sensors and Actuators B: Chemical

Marc-Antoine Bianki |Temperature sensitivity control of an inkjet-printed optical resonator on pillar | <https://doi.org/10.1021/acsami.3c14406> | ACS Applied Materials & Interfaces

Shilong Liu |Engineering Spectro-Temporal Light States with Physics-Embedded Deep Learning | DOI: 10.34133/ultrafastscience.0107 | Ultrafast Science

Shilong Liu |Experimental Emulator of Pulse Dynamics in Fractional Nonlinear Schrödinger Equation | <https://doi.org/10.1002/lpor.202401714> | Laser Photonics Rev2025

Xavier Attendu |Calibration procedure for enhanced mirror artifact removal in full-range optical coherence tomography using passive quadrature demultiplexing | DOI: 10.1117/1.JBO.27.11.116006 | Journal of biomedical optics

Thesis in the acknowledgments

I have mentored and supported several students during their internships, master's theses, and even PhD programs. Some of their special acknowledgements are included here, providing motivation to continue being the researcher I am.

Alexis Séguin |Fabrication et caractérisation de coupleurs optiques en verre fluoré pour l'infrarouge moyen "*Une mention spéciale pour Rodrigo, ce fut un bonheur de discuter avec toi, autant sur le plan technique que personnel. Cette maîtrise n'aurait vraiment pas été la même sans toi.*"

Colin Dietrich |Development of a Low-Noise Ultrafast Fiber Laser and Optimization of Nonlinear Crystals for Bright, High-Purity Entangled Photon Sources. "*Special thanks*

to Rodrigo Becerra for teaching me so much, for his contagious positivity, and his humanity."

Sarah Albos | Few-Mode Confocal Microscopy "*Un agradecimiento especial a Rodrigo. Tu presencia, apoyo, y consejos ha sido inestimable, gracias para todo.*"

Joseph Lamarre | Time Domain Quantum Light Source Based On Bright Spontaneous Parametric Down Conversion "*...and Rodrigo Becerra, whose optimism and fiber whispering skills lifted most setbacks.*"

International Oral Presentations

Analysis of the Polarization and Wavelength dependence of Photonic lanterns | 86th JSAP Autumn meeting 2025 | Nagoya, Japan. | Sept 2025

Bio-Optics: Design and Application | Specialized Fiber Couplers and Bundles for Biomedical Sensing and Imaging | San Diego, CA, United States. | Apr 2025

Bio-Optics: Design and Application | Improving Detection Capabilities of Few-Mode Optical Coherence Tomography Using a 4-Mode Selective Photonic Lantern | San Diego, CA, United States. | Apr 2025

Photonics West | Short mode-selective photonic lanterns using double-clad fibers | San Francisco, CA, United States. | Feb 2023

International Poster Presentations

Photonics West | San Francisco, CA, United States. | February 2025

Photonics West | San Francisco, CA, United States. | February 2024

SUSSP79 Photonic Sensing & Spectroscopy | St Andrews, Scotland. | July 2023

Optics and the Brain | Vancouver, BC, Canada. | April 2023

Gordon Research Seminar and Conference (GRS&GRC) | Lewiston, Maine, United States. | July 2022

Work Experience

Co-founder Peregrine Photon | October 2025 - present

Optics Physicist | September 2020 - present

R&D Optical fibers and production

Castor Optics

Montreal, Quebec, Canada

Patents

Capteur de déformation entièrement fibré par démultiplexage sélectif des modes spatiaux - In process

Illumination device for microscopy - pending

Participation in Commitees

Commitee member of COPL Equity, Diversity and Inclusion | Former treasurer of Optica polytechnique Montreal Chapter 2024-2025

APPENDIX B SUPPLEMENTAL MATERIAL CHAPTER 3

Funding

Caroline Boudoux and Stéphane Virally acknowledge funding from the Mid-Infrared Quantum Technology for Sensing (MIRAQLS) project, supported by the European Union's Horizon Europe research and innovation program under grant agreement 101070700. Natural Sciences and Engineering Research Council (NSERC) of Canada grants #RGPIN-2018-06151 (CB).

Acknowledgment

The authors thank Mikaël Leduc for his invaluable work on the fabrication and characterization setup.

Disclosures

RIBD: Castor Optics, inc. (E), CB: Castor Optics, inc. (I), NG: Castor Optics, inc. (I,P).

Data availability

The data underlying the results presented in this paper is not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document

See Supplement 1 for supporting content.

Supplement 1

Adiabatic criteria and logarithmic slope

In the context of fiber devices, adiabaticity refers to the absence of coupling of one specific mode with any other mode. This happens as long as the logarithmic slope $\frac{1}{I} \frac{\partial I}{\partial z}$ remains below the adiabatic criteria $\overline{\alpha}_{ij}$ between the specific mode i and all other modes j , at every point

along the taper

$$\frac{1}{\mathbf{I}(z)} \frac{\partial \mathbf{I}(z)}{\partial z} < \min_j \bar{\alpha}_{ij}(z) \quad \forall z. \quad (\text{B.1})$$

If an adiabatic criterion becomes lower than the logarithmic slope for a significant amount of time, amplitude interference between modes will occur, and power will potentially be transferred from one mode to another. Tools such as SuPyMode compute adiabatic criteria for custom structures at various ITRs. They can, in turn, be compared to the logarithmic slope expected from the fabrication sequence [115].

The computation of the logarithmic slope is described in reference [117], where a longitudinal section of length

$$L = L_0 + \alpha \delta z \quad (\text{B.2})$$

is heated up. Here, L_0 is the initial length of the heated section, α is a unitless coefficient (see below), and δz is the total elongation of the component (i.e., the difference between the current length of the component and its initial length). The coefficient α ranges from -1 to $+1$: a positive value indicates an increase in the length of the heated segment as the fabrication progresses. A negative value means a decrease of that same length throughout the recipe. The value of α determines the longitudinal shape of the component, following

$$\mathbf{I}(z) = \left[1 + \frac{2\alpha z}{L_0(1 - \alpha)} \right]^{-\frac{1}{2\alpha}}, \quad (\text{B.3})$$

such that the choice of fabrication parameters L_0 and α is sufficient to determine the logarithmic slope along the component and, thus, the expected adiabaticity of the component. In general, smaller values of L_0 and α yield shorter components, which is beneficial for robustness at the cost of increasing the logarithmic slope and, thus, the potential of coupling between modes.

For a PL with a final few-mode structure of $\sim 10 \mu\text{m}$ of diameter, L_0 is limited to the range between the size of the heating element (typically around 1 mm) and the length at which the component becomes too fragile for practical purposes (typically 10 mm).

Furthermore, heuristics dictate that the manufacturability of fused components is limited to adiabatic criteria greater than 10^{-4} .

Fig. B.1 presents the design of a three-mode MSPL using single-mode fibers. The simulation was performed using SuPyMode [115, 116]. Fig. B.1 (a) shows the cross-section of the fiber bundle making up the 3-mode MSPL after an initial fusion with a degree of fusion of 0.8—the degree of fusion varying between 0 (no fusion) and 1 (fully-fused structure). The

core diameters of the single-mode fibers are 8, 10, and 12 μm for fibers labeled A', B', and C', respectively, with refractive indices equivalent to those of the typical SMF-28 (ITU-T 6.657.A1, Corning, NY, USA) for the core and cladding in all cases. Fig. B.1 (b, top row) shows the field amplitudes of the transverse modes at the single-mode inputs. Fig. B.1 (b, bottom row) shows the corresponding outputs for an ITR=0.05, i.e., at the end of the tapering process. Note that the scale changes between the top and bottom row of Fig. B.1 (b). At the top, the full-scale is the structure before tapering, while the scale at the bottom is that of the minimum cross-section (waist) after tapering. The first three columns show the three desired modes obtained from selective LP₀₁ illumination. The last three columns show that other higher-order modes (e.g., LP₂₁ and LP₀₂) can be obtained by illuminating with non-fundamental modes (LP₁₁). In reality, this cannot happen as those modes are unguided in the structure. Instead, coupling to those modes creates loss channels and contributes to excess loss. For the structure simulated in Fig. B.1, the only guided modes of interest are the fundamental mode LP₀₁ and the first two higher order modes, LP_{11a} and LP_{11b}.

Fig. B.1 (c) displays adiabatic criteria computed by CMT (in solid lines) and the logarithmic slopes (dashed lines) as a function of ITRs, computed for different values of *alpha*. In this example, three different taper fabrication recipes are depicted, represented by a null, a positive, and a negative α , respectively, each with an initial value of $L_0 = 10$ mm.

For practical purposes, only the three most relevant curves are plotted into Fig. B.1(c) to highlight the possible responses of the device. In contrast, Fig. B.2 presents the typical “jungle” of adiabatic criteria produces by the model. Ideally, all modes that interact with the guided modes should be included in the plot. However, adiabatic criteria between higher-order modes tend to be larger, and a cutoff of about 20 pairs is usually implemented in the code to avoid computing too many irrelevant criteria.

Three main crossing types are shown in Fig. B.1(c). They all occur with the blue dashed line, which represents the design with the steepest slopes. The blue dot corresponds to a crossing between two guided modes, leading to power transferred between the modes. This is intended in some components, such as conventional PLs or standard couplers. The red dot illustrates a crossing between a guided and an unguided modes. These are always to be avoided, as they result in excess loss. The green dot indicates coupling between two unguided modes, which does not affect the structure at all as these modes do not propagate. In components such as MSPLs, all types of crossings are avoided, leading to full modal isolation.

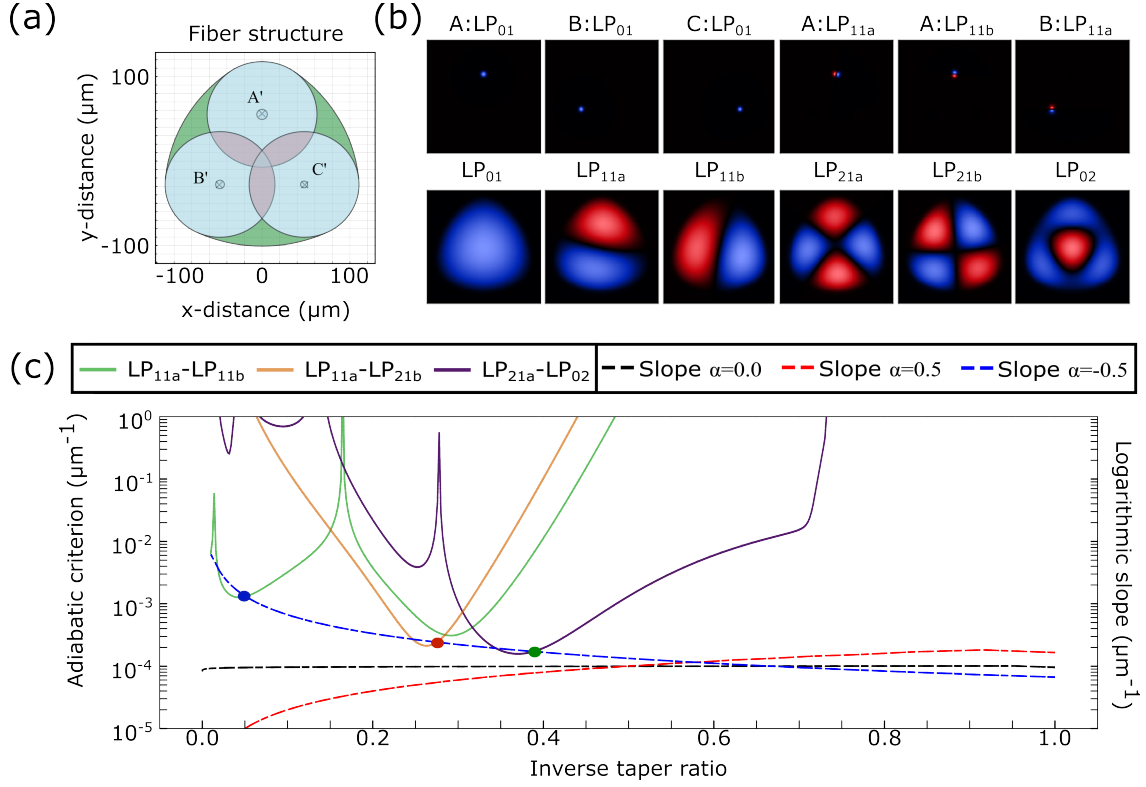


Figure B.1 Simulating the design of a 3-mode MSPL with single-mode fibers. (a) Cross-section of the MSPL after fusion using a fusion coefficient of 0.8. (b) Field amplitudes of the transverse modes at the input (first row) and after tapering (ITR=0.05—second row). (c) Adiabatic criteria for each mode pair (solid lines) and logarithmic slopes (dashed lines) for three fabrication sequences using an initial heating length of 10 mm and three different α values. The red and blue dots show instances of crossing between α and mode mode-coupling curves.

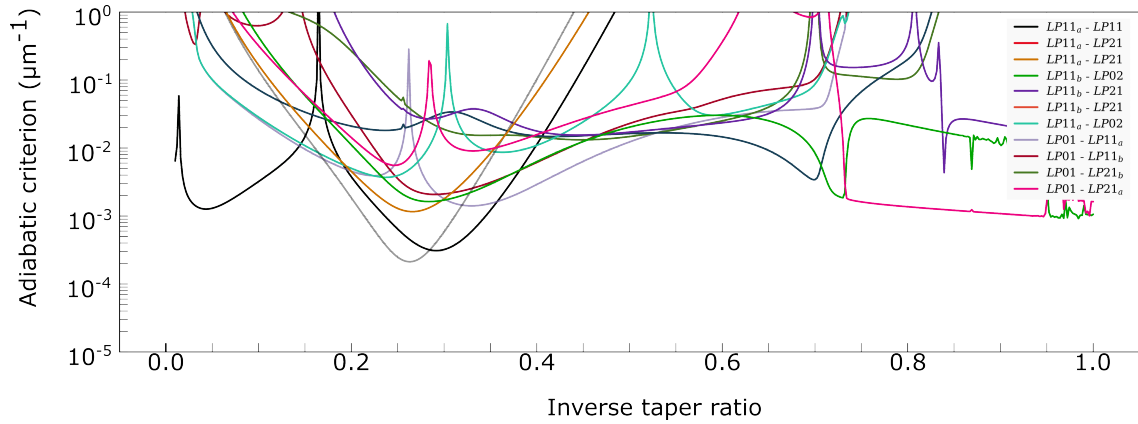


Figure B.2 Adiabatic criteria for each mode pair of a 3-mode MSPL with single-mode fibers.

Further analyses

To fabricate any component, it is crucial to run simulations at various wavelengths and with different fusion degrees. This is important in particular when the exact degree of fusion cannot be determined in advance, and when the component is intended to be broadband.

Figure B.3 shows four distinct columns. The first column represents the degree of fusion for a 3-by-1 structure of each row with the fiber configuration ABC, as described in the paper. The second, third, and fourth columns illustrate the adiabatic criteria for the first four pairs of modes at three wavelengths: 1550 nm, 1300 nm, and 1100 nm. This example illustrates an MSPL, which is the most stable structure. It is intended as a didactical shortcut by simplifying the analysis while still identifying changes in behavior that can arise during the fabrication process. We observe, for instance, that the adiabatic criteria tend to increase with the degree of fusion. Interestingly, at reduced degrees of fusion, coupling starts to occur at smaller ITRs. Finally, as wavelength increases, the areas of potential coupling tend to compactify. It is thus expected that for the same recipe, relatively less coupling will occur at higher wavelengths.

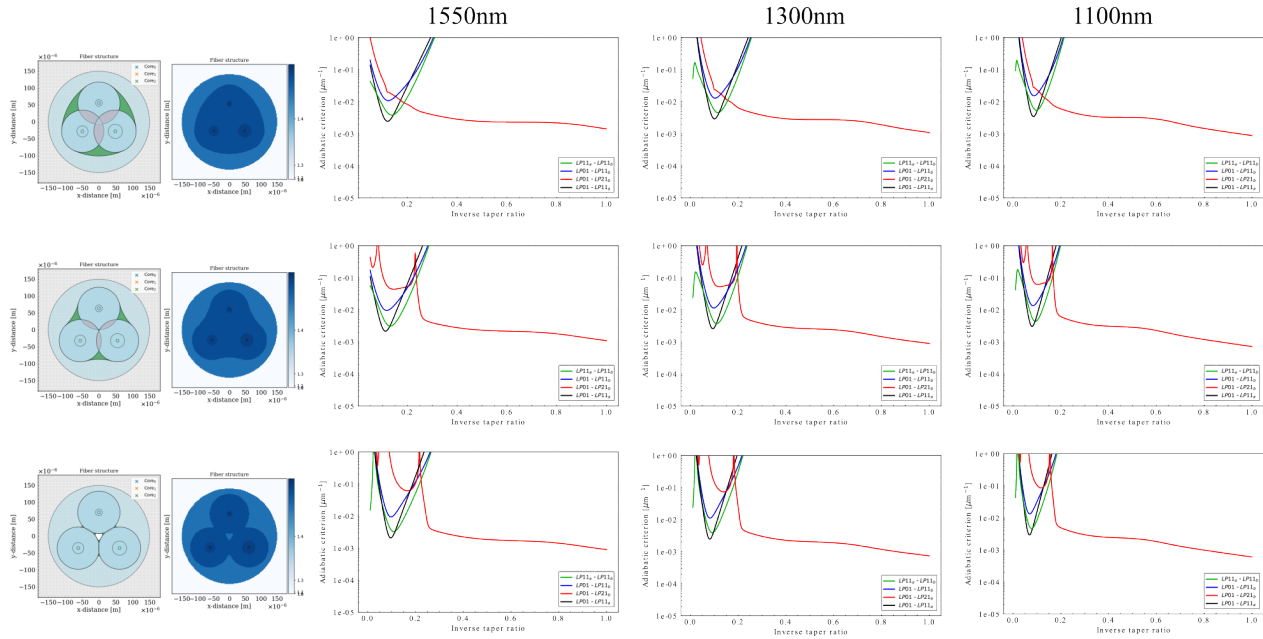


Figure B.3 Analysis of the adiabatic criteria at different degrees of fusion and wavelengths. The first column details the degree of fusion corresponding to each row, using the ABC fiber configuration described in the paper. The second, third, and fourth columns display the adiabatic criteria for the first four pairs of modes across three wavelengths: 1550 nm, 1300 nm, 1100 nm.

Figure B.4 shows the adiabatic criteria for the first four pairs of modes at three different wavelengths (merging the plots of the three degrees of fusion).

In contrast, Figure B.5 shows the adiabatic criterion at three distinct degrees of fusion while combining the plots for the three wavelengths.

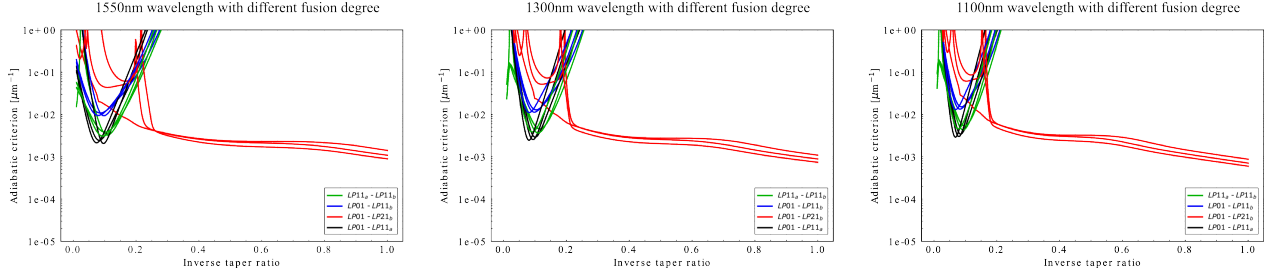


Figure B.4 Adiabatic criteria of an MSPL at 1550 nm, 1300 nm, and 1100 nm for the initial four pairs of modes used in combining all the fusion degrees.

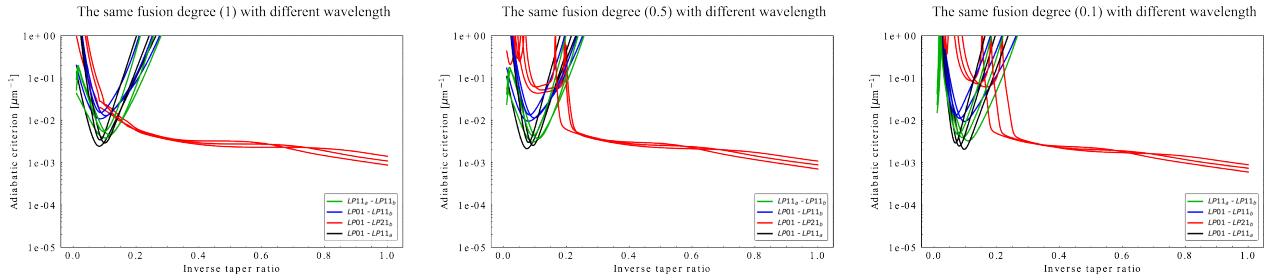


Figure B.5 Adiabatic criteria for the initial four pairs of modes of an MSPL at three different fusion degrees, combining the three operational wavelengths: 1550 nm, 1300 nm, and 1100 nm

Figure B.6 shows the adiabatic criteria for all degrees of fusion and all wavelengths. This enables to consolidate our view of all potential variations of behavior during fabrication. A good fabrication sequence for an MSPL would steer the logarithmic slope away from all the adiabatic criteria curves in this plot.

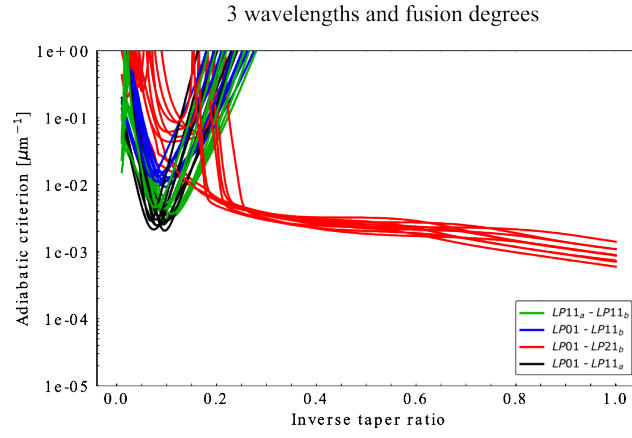


Figure B.6 Adiabatic criteria for each mode pair of a 3-mode MSPL at three fusion degrees and wavelengths.

APPENDIX C SUPPLEMENTAL MATERIAL CHAPTER 4

Funding

Caroline Boudoux and Stéphane Virally acknowledge funding from the Mid-Infrared Quantum Technology for Sensing (MIRAQLS) project, supported by the European Union's Horizon Europe research and innovation programme under grant agreement 101070700. Natural Sciences and Engineering Research Council (NSERC) of Canada grants #RGPIN-2018-06151 (CB).

Acknowledgment

The authors thank Mikaël Leduc for his invaluable work on the fabrication and characterization setup.

Disclosures

RIBD: Castor Optics Inc. (E). CB: Castor Optics Inc. (I). NG: Castor Optics Inc. (I). The other authors declare no conflicts of interest.

Data availability

Data underlying the results presented in this paper is not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document

Polarization measurements

This section includes measurements for four PLs, five polarizations, and three light sources, detailing the optical profiles of composition, as well as horizontal and vertical polarization with their respective measurements from the polarization analyzer. The polarization analyzer provides several key measurements: the polarization extinction ratio (PER), which compares the power of two linear polarization states on a logarithmic scale. Another measurement is linear PER, representing the proportion of linearly polarized light to the total light detected,

also expressed logarithmically. Additionally, φ denotes the azimuthal angle indicating the alignment of the primary polarization axis. Lastly, the degree of polarization (DOP) indicates the fraction of light that is polarized.

The measurements of the PL are systematically organized by wavelength, providing a comprehensive overview of the optical profiles along with a detailed table of measurements for each port. Each figure is configured into three columns per port:

- Column 1: Displays the 2D projection of the polarization, illustrating the orientation and distribution of the polarization states.
- Column 2: Presents the optical profile, showcasing the intensity distribution across the beam for the respective port.
- Column 3: Offers a dual representation of the optical profile, displaying the configurations in both horizontal and vertical orientations.

It is important to note that in certain instances, there may be a lack of polarization projection. This is attributed to abrupt measurement as discussed in the main paper. Each row corresponds to one of the five defined polarizations, ensuring clarity in the representation of polarization states across all ports.

Adjacent to the figures, a comprehensive table provides the polarization measurements, following the same sequence as the corresponding optical profiles for each port. This arrangement allows for easy cross-reference between the visual data and the numerical measurements, facilitating a thorough understanding of the PL's performance across different wavelengths and polarization states.

AAA configuration

Figure C.1, C.2, and C.3 illustrate the optical response of a standard PL with configuration AAA at wavelengths of 1300 nm, 1550 nm, and a broad spectrum centered at 1300 nm, respectively. Additionally, Table C.1, C.2, and C.3 present the optical measurements for the same lantern at the same wavelengths: 1300 nm, 1550 nm, and broadband centered at 1300 nm.

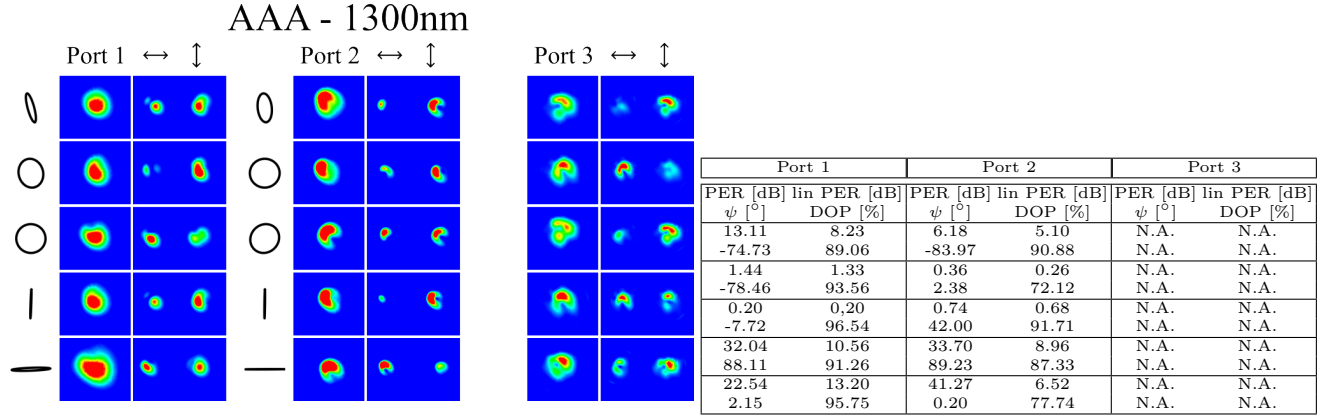


Figure C.1 Optical profile response at five different polarizations of a standard PL at 1300 nm.

Table C.1 Measurements of a PL for each port across five polarizations at 1300 nm.

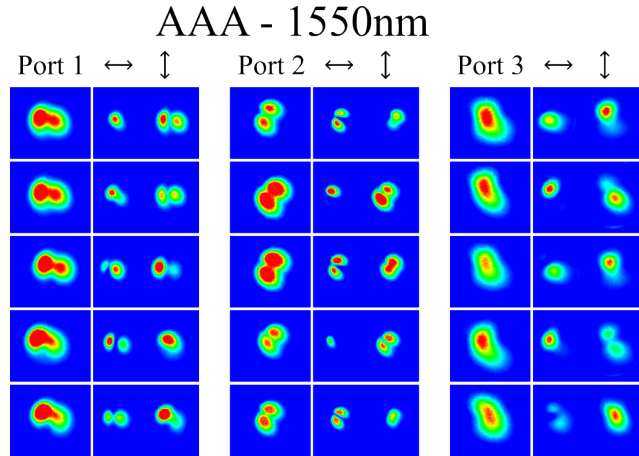


Figure C.2 Optical profile response at five different polarizations of a standard PL at 1550 nm.

Port 1		Port 2		Port 3	
PER [dB]	lin PER [dB]	PER [dB]	lin PER [dB]	PER [dB]	lin PER [dB]
ψ [°]	DOP [%]	ψ [°]	DOP [%]	ψ [°]	DOP [%]
N.A.	N.A.	N.A.	N.A.	25.25	14.79
N.A.	N.A.	N.A.	N.A.	-3.85	96.97
N.A.	N.A.	N.A.	N.A.	30.38	10.80
N.A.	N.A.	N.A.	N.A.	88.93	91.57
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Table C.2 Measurements of a PL for each port across five polarizations at 1550 nm.

AAB configuration

Figure C.4, C.5, and C.6 show the optical response of a semi-MSPL configured as AAB at wavelengths of 1300 nm, 1550 nm, and a broad spectrum centered around 1300 nm, respectively. Furthermore, Table C.4, C.5, and C.6 display the measurements for the same lantern at the identical wavelengths: 1300 nm, 1550 nm, and broadband centered at 1300 nm.

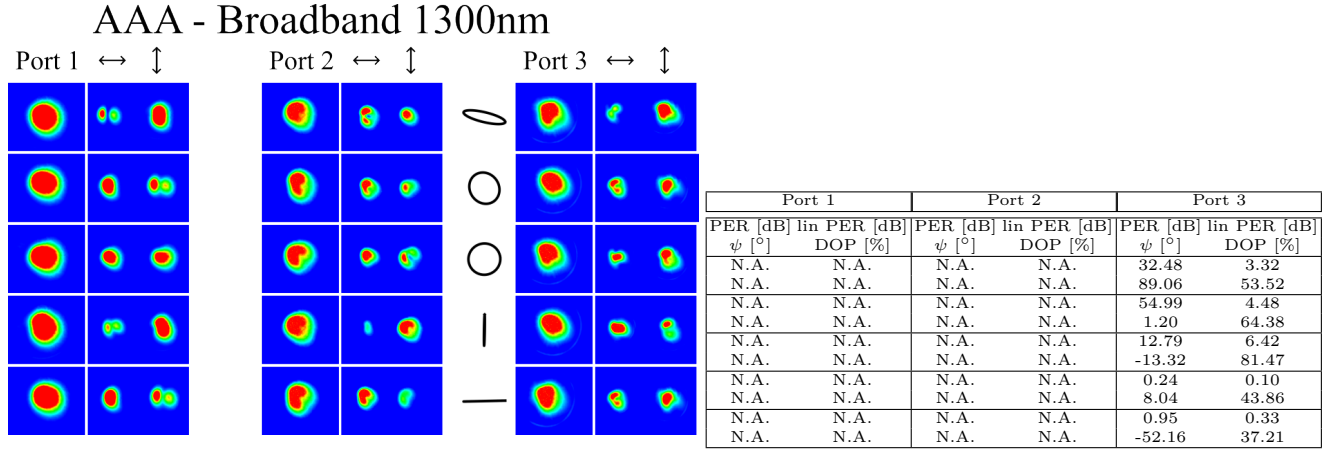


Figure C.3 Optical profile response at five different polarizations of a standard PL using a broadband source centered at 1300 nm.

Table C.3 Measurements of a PL for each port across five polarizations using a broadband source centered at 1300 nm.

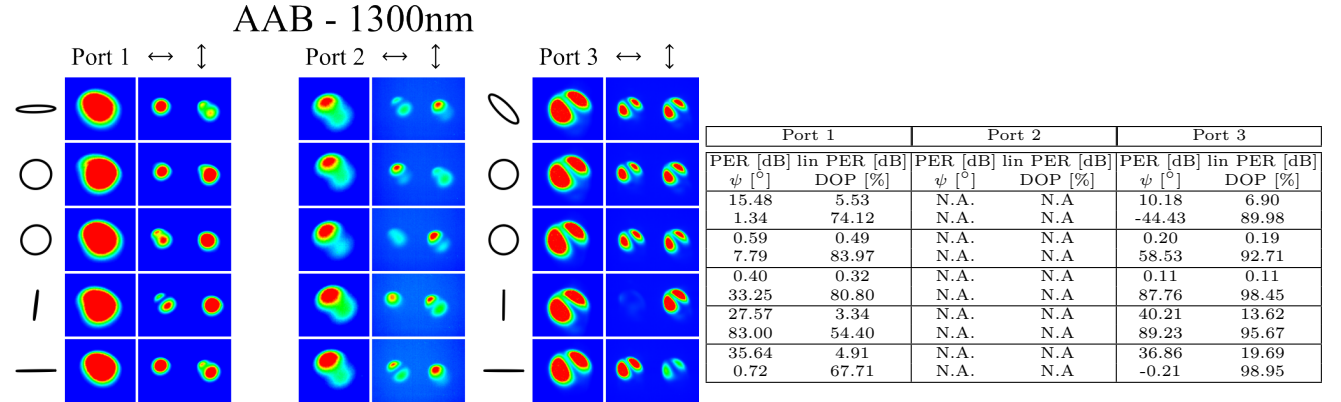


Figure C.4 Optical profile response at five different polarizations of a semi-MSPL at 1300 nm.

Table C.4 Measurements of a semi-MSPL for each port across five polarizations at 1300 nm.

ABB configuration

Figure C.7, C.8, and C.9 illustrate the optical response of a group-MSPL set up in the ABB configuration at wavelengths of 1300 nm, 1550 nm, and a broad spectrum centered around 1300 nm, respectively. Additionally, Table C.7, C.8, and C.9 present the measurements for the same lantern at the corresponding wavelengths: 1300 nm, 1550 nm, and the broadband spectrum centered at 1300 nm.

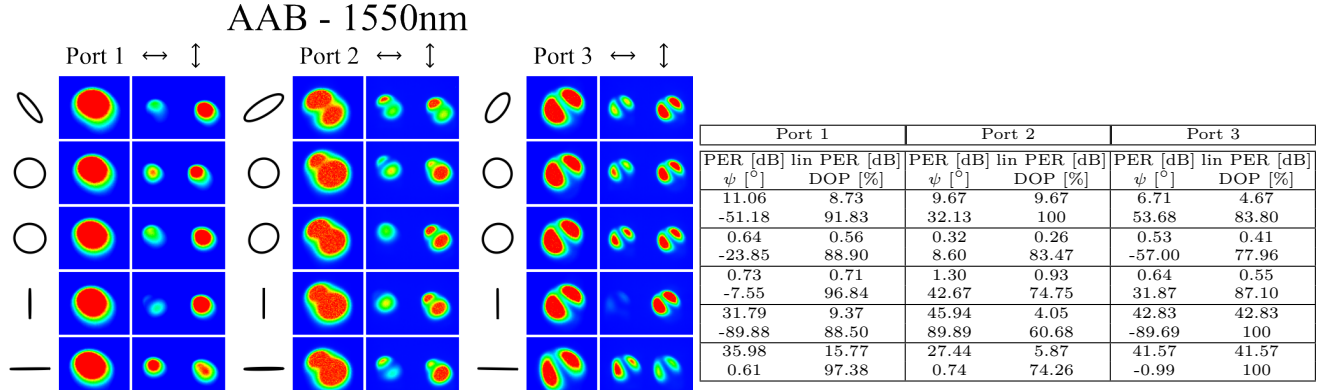


Figure C.5 Optical profile response at five different polarizations of a semi-MSPL at 1550 nm.

Table C.5 Measurements of a semi-MSPL for each port across five polarizations at 1550 nm.

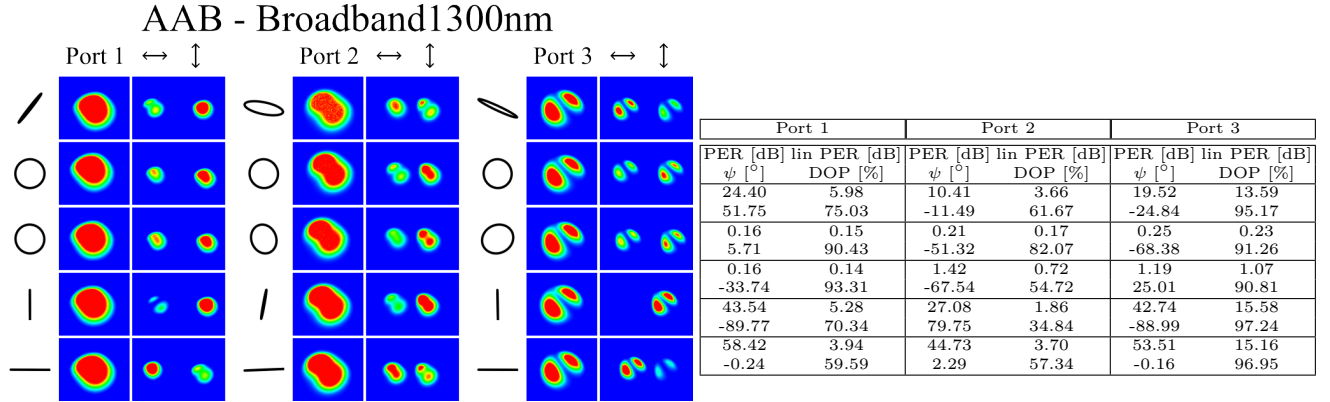


Figure C.6 Optical profile response at five different polarizations of a semi-MSPL using a broadband source centered at 1300 nm.

Table C.6 Measurements of a semi-MSPL for each port across five polarizations using a broadband source centered at 1300 nm.

ABC configuration

Figures C.10, C.11, and C.12 display the optical response of a MSPL with configuration ABC at wavelengths of 1300 nm, 1550 nm, and across a broad spectrum centered at 1300 nm, respectively. Moreover, Tables C.10, C.11, and C.12 provide the optical measurements for the same lantern at those wavelengths: 1300 nm, 1550 nm, and broadband centered at 1300 nm.

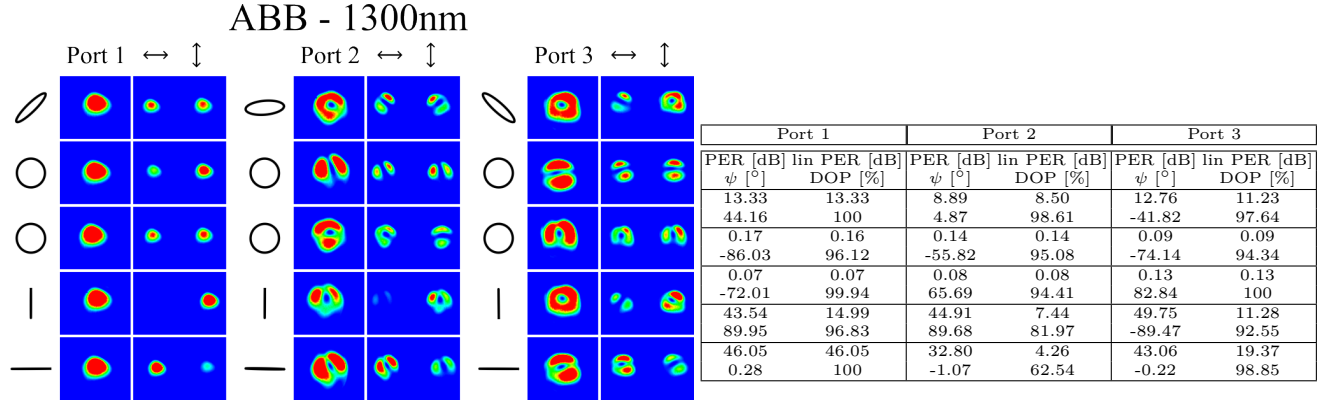


Figure C.7 Optical profile response at five different polarizations of a group-MSPL at 1300 nm.

Table C.7 Measurements of a group-MSPL for each port across five polarizations at 1300 nm.

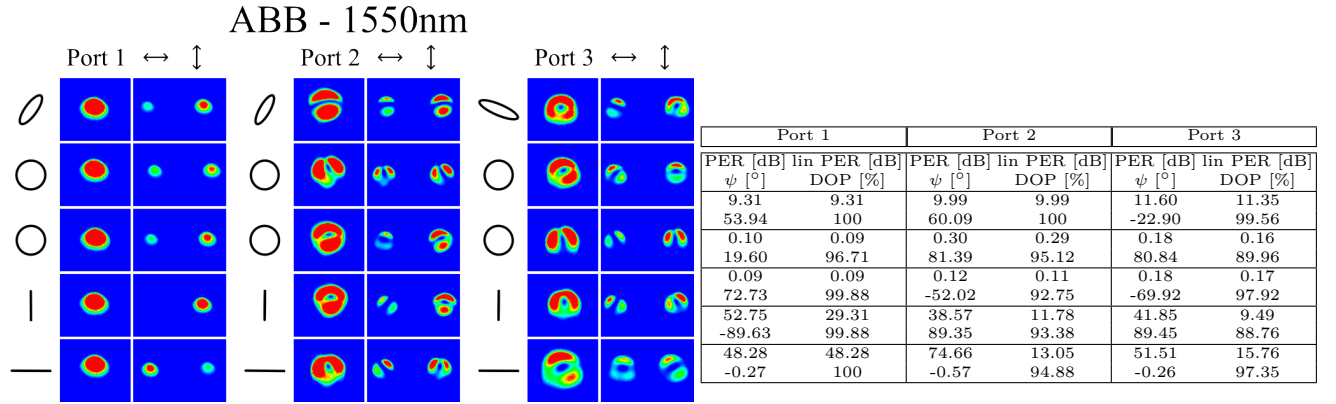


Figure C.8 Optical profile response at five different polarizations of a group-MSPL at 1550 nm.

Table C.8 Measurements of a group-MSPL for each port across five polarizations at 1550 nm.

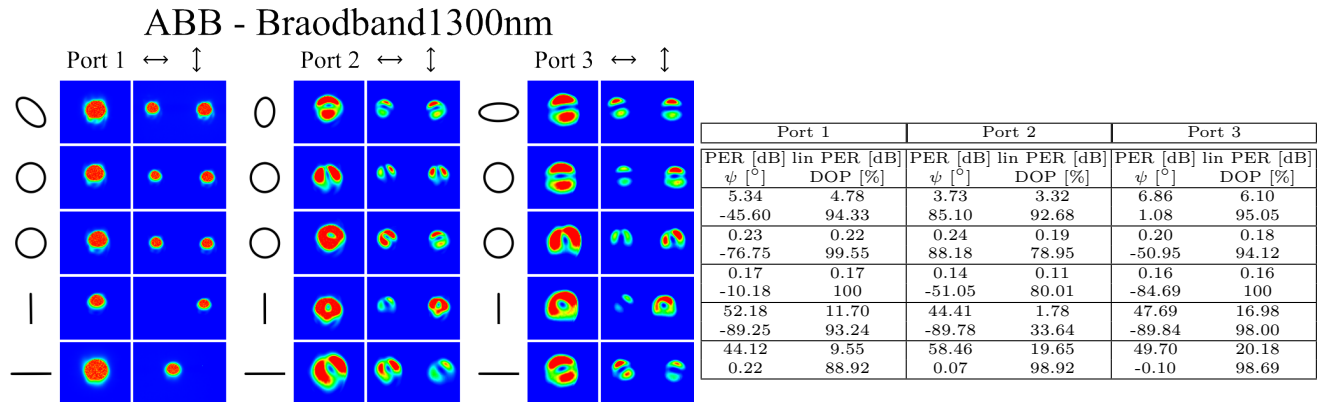


Figure C.9 Optical profile response at five different polarizations of a group-MSPL using a broadband source centered at 1300 nm.

Table C.9 Measurements of a group-MSPL for each port across five polarizations using a broadband source centered at 1300 nm.

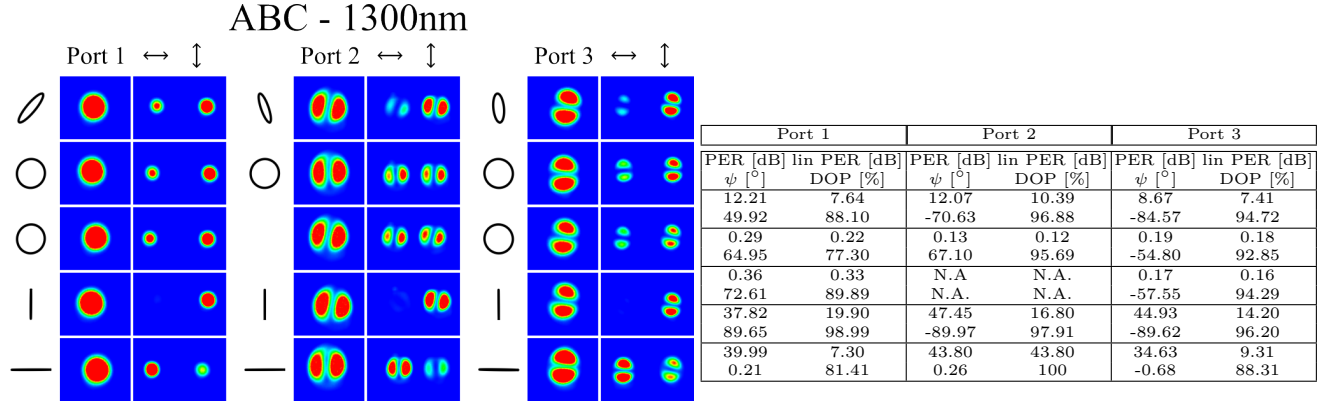


Figure C.10 Optical profile response at five different polarizations of a MSPL at 1300 nm.

Table C.10 Measurements of a MSPL for each port across five polarizations at 1300 nm.

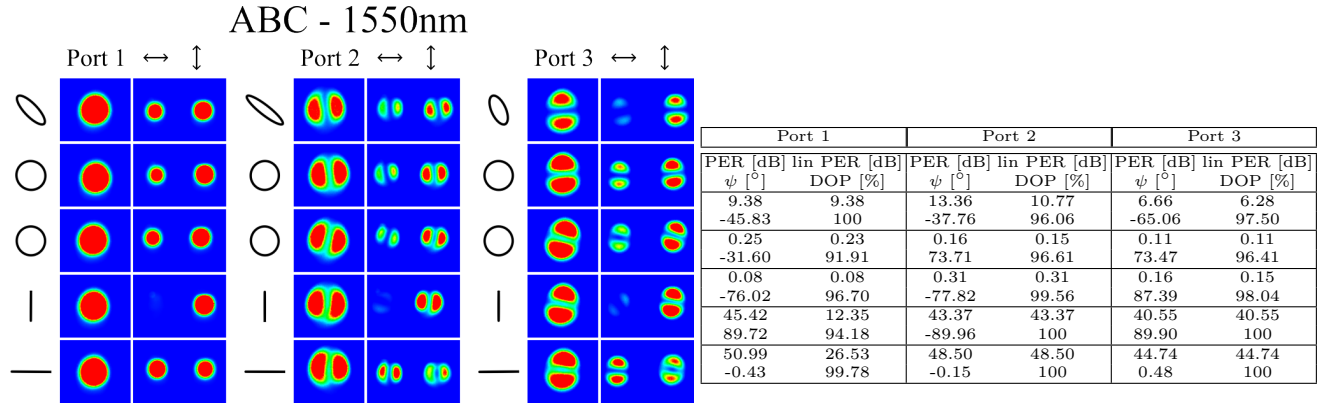


Figure C.11 Optical profile response at five different polarizations of a MSPL at 1550 nm.

Table C.11 Measurements of a MSPL for each port across five polarizations at 1550 nm.

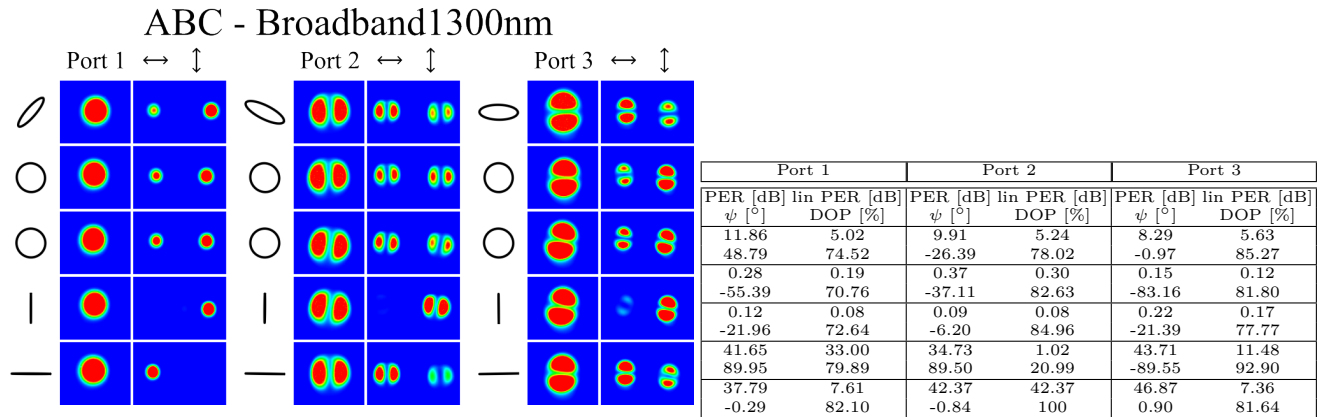


Figure C.12 Optical profile response at five different polarizations of a MSPL using a broadband source centered at 1300 nm.

Table C.12 Measurements of a MSPL for each port across five polarizations using a broadband source centered at 1300 nm.

APPENDIX D SUPPLEMENTAL MATERIAL CHAPTER 5

Disclosures

RIBD: Castor Optics, inc. employee, CB: Castor Optics, inc. co-presidents, co-founders, and co-owners, NG: Castor Optics, inc. co-presidents, co-founders, co-owners, and patent. Data can be obtained upon request to the corresponding author.

Acknowledgements

We thank Mikaël Leduc for his technical support. We thank the reviewers who substantially contributed to the clarity of this paper.

Supplemental materials

Figure D.1 shows three different adiabatic criteria with the best logarithmic slope scenarios, and the resulting final length configurations, for MSPLs at 1550 nm, using 125 μm step-index optical fibers with a final layer made of silica. Crossing of an adiabatic criterion with the logarithmic slope indicates coupling between modes during fabrication [115]. The characteristics of the fibers are as follows: (a left) fibers with core diameters of 9, 11, and 13 μm , each having a numerical aperture (NA) of 0.14; (b left) fibers with the same core diameters, but with a first cladding thickness of 30 μm and NAs of 0.14 and 0.19, respectively; and (c left) our MSPL configuration utilizing the fiber mentioned above. A comparison of Figure D.1(a) and (b) reveals that the adiabatic criterion becomes more constrained at lower taper ratios simply by adding an additional cladding to each fiber. As indicated by SuPymode, the heating length significantly influences the longitudinal profile of the tapers while considering the adiabatic criteria [115]. By examining the red plots in both cases, we observe that at around a taper ratio of 0.15 from 0.4, the adiabatic criterion values reach approximately 10^{-3} ((b) left) instead of 10^{-4} ((a) left), resulting in a smoother slope in the fabrication process, reducing the dimensions of the device by 17 %. In Figure D.1(c), the adiabatic criteria are significantly changed and reach a much higher value of 10^{-3} . This allows the maximum practical logarithmic slope of $10^{-3} \mu\text{m}^{-1}$ to be used for the entire fabrication sequence without crossing any adiabatic criterion. Figure D.1 (a right), (b right), and (c right) show the shape and dimensions of the taper considering the logarithmic slope. This best-case scenario would allow the final component length to be reduced by a factor of 3,

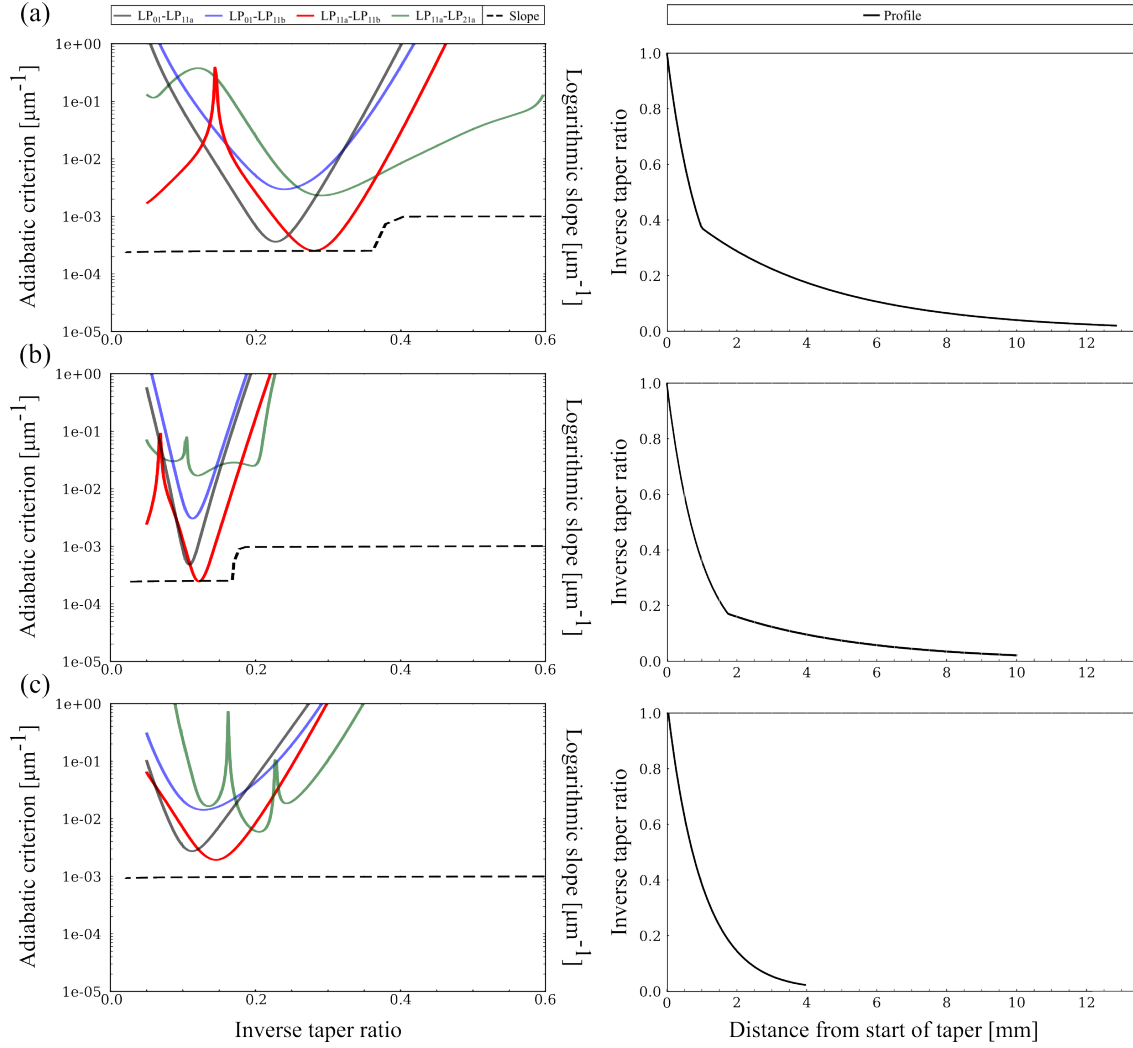


Figure D.1 Three different adiabatic criteria for MSPLs are shown: (top) standard step-index optical fibers with differences in the core size, (center) DCFs with similar cladding and differences in the core size, and (bottom) using DCFs with single-mode compatibility and varying first cladding dimension per fiber.

from 12 to 4 mm.