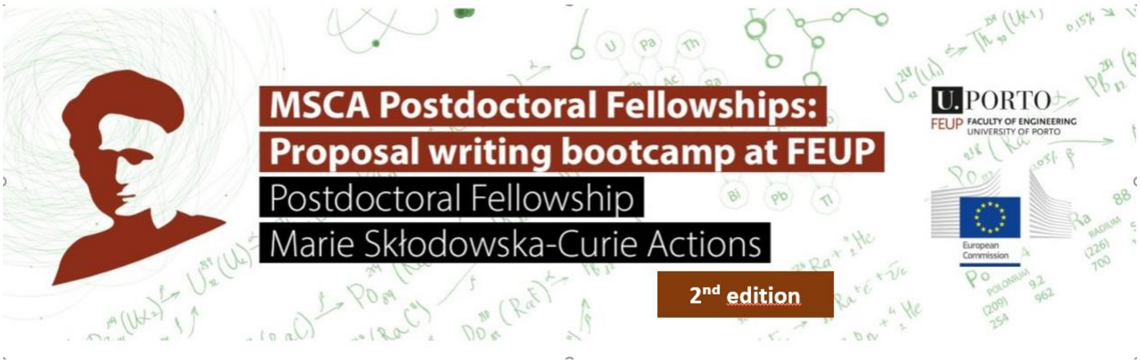

SUPERVISOR INFORMATION	
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Department	Electrical and Computer Engineering
Field(s) of research	QKD satellite optical communications
PROJECT PROPOSAL	
Title (optional)	**Optimizing Free-Space to Fiber Coupling for Secure Quantum Key Distribution (QKD) Systems using Hollow-Core Photonic Crystal Fibers (HCPCFs) in Satellite Communications**
Brief project description	This one year PhD project aims to optimize the coupling of free-space light into Hollow-Core Photonic Crystal Fibers (HCPCFs) to enable efficient and reliable Quantum Key Distribution (QKD) systems for secure global communications. The research addresses challenges such as wavefront distortions, alignment precision, and minimizing coupling losses, which are critical for QKD implementation between satellites and ground stations.

Introduction

The advent of quantum computing presents a substantial threat to conventional encryption methods that secure today's communications. Quantum Key Distribution (QKD) has emerged as a promising solution to establish unbreakable encryption, leveraging quantum principles to ensure security. For global QKD implementation, optical communication between satellites and ground stations is essential, enabling secure long-distance key distribution. However, achieving efficient coupling of light between free space and optical fibers remains a critical challenge due to environmental disturbances, wavefront distortions, and alignment precision.

Hollow-Core Photonic Crystal Fibers (HCPCFs) represent a novel solution for QKD systems due to their exceptional optical properties, including low transmission losses, reduced nonlinear effects, and thermal stability. This proposal aims to optimize the free-space-to-fiber coupling process into HCPCFs, ensuring high efficiency and robust performance even under operational challenges, such as distorted wavefronts. The outcome will enable reliable QKD systems for secure global communications.

Objectives

The primary goal of this PhD project is to design, optimize, and validate a robust free-space-to-HCPCF coupling system that enhances the efficiency and reliability of QKD systems. The specific objectives are:

- Define system requirements and specifications for coupling efficiency in free-space optical communications.
- Develop a theoretical model to analyze wavefront aberrations and their impact on coupling efficiency.
- Perform numerical simulations to validate the theoretical model and optimize lens-fiber alignment.
- Design and assemble an experimental setup for HCPCF coupling with precision alignment tools.
- Characterize and optimize the system's performance under realistic environmental conditions, including wavefront distortions.

Tasks

Task 1: Literature review and State-of-the-Art Analysis

The project will begin with a comprehensive literature review and state-of-the-art analysis. This task involves studying existing research on free-space optical communications, quantum key distribution (QKD), and the role of Hollow-Core Photonic Crystal Fibers (HCPCFs) in optical systems. The objective is to identify the current limitations, challenges, and gaps in coupling efficiency for free-space-to-fiber systems. The review will focus on theoretical models, experimental approaches, and technological advancements related to wavefront aberrations, numerical aperture (NA) matching, and precision alignment techniques. The insights gained will establish the scientific foundation for the proposed research and highlight the novelty of the project.

Task 2: System Design and Component Selection

Following the literature review, the project will move to system design and component selection, focusing on defining the coupling efficiency requirements, numerical aperture (NA), and alignment precision. Suitable HCPCF fibers, lenses, and alignment tools will be carefully evaluated and selected to ensure compatibility with free-space optical communication systems. This step establishes the fundamental specifications for the coupling system.

Task 3: Theoretical Modeling and Simulation

Next, the project will develop a theoretical model to analyze wavefront aberrations using, which will help assess their impact on coupling efficiency. Numerical simulations will complement this effort, utilizing optical beam propagation analysis and FDTD to model light confinement within the HCPCF. These simulations will validate the theoretical model, ensuring alignment precision and optimized coupling performance.

Task 4: Experimental Setup and Alignment

Following the theoretical groundwork, the experimental setup will be assembled. This phase involves integrating lenses, HCPCF fibers, and micro-positioners to enable precision alignment of the light beam into the fiber core. Testing will focus on minimizing reflections and scattering losses while achieving accurate alignment and optimal mode compatibility between the light source and fiber core.

Task 5: System Characterization and Optimization

The next phase involves system characterization and optimization. Key performance metrics such as coupling efficiency, transmission losses, and alignment stability will be measured under controlled conditions. Simulated operational challenges, including wavefront distortions, will be introduced to evaluate the system's robustness. The setup will undergo iterative adjustments to refine its performance and ensure it meets real-world requirements for QKD systems.

Task 5: Documentation and dissemination

Finally, the project will emphasize documentation and dissemination. This task involves compiling comprehensive technical documentation detailing the system design, theoretical modeling, experimental results, and optimization strategies. The outcomes will be disseminated through scientific publications, conference presentations, and technical reports, ensuring the project contributes meaningfully to the scientific and engineering community working on QKD and optical communication systems.

Research Outcomes

The project will deliver the following outcomes:

- Optimized Coupling System: A fully developed system ensuring efficient free-space-to-HCPCF coupling for QKD applications.
- Theoretical Model: A validated model to analyze and predict coupling efficiency under wavefront aberrations.
- Numerical Simulations: Simulation results, guiding component selection and system refinement.
- Performance Characterization: Empirical data on coupling efficiency, transmission losses, and environmental robustness.

- Scientific Contributions: Published research papers advancing knowledge in free-space optical communications and HCPCF technologies.

Conclusion

This PhD project addresses a critical challenge in secure quantum communication by optimizing free-space light coupling into HCPCFs for QKD systems. The outcomes will significantly advance optical communication technology, providing a robust and efficient system capable of withstanding real-world operational challenges, ultimately contributing to secure global communications in the quantum era.