
Simulation of light propagation into optical fibers with customized scattering profile

Capstone Report
Bekkhon Baltabay

Nazarbayev University
Department of Electrical and Computer Engineering
School of Engineering and Digital Sciences

Copyright © Nazabayev University

This project report was created on TexStudio editing platform using $\text{\LaTeX}$. All the figures were drawn using draw.io online software tool.



NAZARBAYEV
UNIVERSITY

Electrical and Computer Engineering

Nazarbayev University

<http://www.nu.edu.kz>

Title:

Simulation of light propagation into optical fibers with customized scattering profile

Project Period:

Fall2024

Participant(s):

Bekkhan Baltabay

Supervisor(s):

Daniele Tosi

Copies: 1

Page Numbers: 13

Date of Completion:

September 25, 2024

Abstract:

This project investigates the simulation of light propagation in optical fibers with customized scattering profiles. By embedding MgO nanoparticles into the fiber core, light scattering is tailored through control over nanoparticle size, shape, and concentration. The study employs a Monte Carlo-based simulation model, corroborated by data from literature, to evaluate scattering coefficients, transmittance, and angular distributions. Results indicate that optimizing nanoparticle parameters enhances the fibers' performance for applications in telecommunications, biomedical sensing, and imaging technologies.

The content of this report is freely available, but publication (with reference) may only be pursued due to agreement with the author(s).

Contents

Preface	vi
1 Introduction	1
1.1 Ethical and Professional Responsibilities	3
2 Methodology	6
3 Results and Discussions	8
4 Conclusion	11
Bibliography	12

Preface

Nazarbayev University, November 20, 2024

Bekkhan Baltabay
<bekkhan.baltabay@nu.edu.kz>

Chapter 1

Introduction

This project is about ways of simulation of light propagation into optical fibers to make the scattering profile customized. It is possible due to special optical fibers with nanoparticles in the core.

Simulating light propagation with customized scattering profiles is achievable through the use of specialized optical fibers containing nanoparticles in their core[1]. These nanoparticles can be strategically placed within the fiber core to influence the scattering of light in a controlled manner [2]. By adjusting the size, shape, and concentration of these nanoparticles, researchers can tailor the scattering properties of the fiber to meet specific requirements [3]. This capability opens up a range of possibilities, from enhancing the efficiency of optical communication systems to developing novel imaging techniques with unprecedented resolution and sensitivity [4].

Currently, numerous researchers are exploring the use of nanoparticles in localized thermal ablation [5]. Gold nanoparticles, in particular, are popular due to their biocompatibility, biological inertness, and distinct adjustable optical and electrical characteristics, which are influenced by the localized surface plasmon resonance phenomenon (LSPR) [6].

In [7], measuring temperature accurately across treated regions poses a significant challenge in thermal ablation, as cellular mortality directly correlates with thermal dosimetry [8]. Traditional temperature measurement methods rely on thermocouples, which have drawbacks such as potentially altering heat propagation due to their metallic wires and only providing point measurements rather than spatial temperature profiles [9]. Fiber optic sensors (FOS) offer a promising alternative, extensively utilized for real-time temperature sensing during procedures like radiofrequency ablation (RFA) and microwave ablation (MWA) [10]. FOS present advantages over thermocouples and MRI, boasting miniature form factors, biocompatibility, and instantaneous response [11].

In [12], the method demonstrates the fabrication of Er^{3+} -doped TGC fibers en-

tirely through the MCVD process [13]. By adding magnesium to the silica-based composition, 40 nm nanoparticles are obtained through in situ growth, eliminating the need for a separate post-processing step. This technique achieves a low-loss fiber, a novel result [14]. The nanoparticle size can reach up to 50 nm, suitable for applications like fiber amplifiers and lasers [15]. Additionally in [16], the emission spectrum broadens by approximately 50 percents, showing potential for gain-flattened fiber amplifiers [17]. Further optimization could control the particle size more precisely [18]. Overall, this approach has potential as a solution for various issues in amplifying fibers, including intrinsically gain-flattened amplifiers [19].

The objective is to explore the behavior of nanoparticles-doped fibers through the modification of particle properties, aiming to enhance their production processes. This research seeks to understand how altering the characteristics of nanoparticles affects their interaction with fibers, with the overarching goal of improving the efficiency, performance, and versatility of these composite materials. By gaining insights into the underlying mechanisms, this work aims to contribute to the development of advanced manufacturing techniques for nanoparticles-doped fibers, enabling the production of high-quality, tailored materials for various applications such as sensing, optical communications, and biomedical devices [20].

1.1 Ethical and Professional Responsibilities

- **Ethical Responsibility:**

The development and implementation of light propagation simulations in optical fibers with customized scattering profiles raise several ethical concerns. One primary issue is the potential misuse of the technology. Fiber optics is critical in communication, defense, and medical fields. Designing scattering profiles for specialized applications could inadvertently lead to the enhancement of surveillance systems or weapons. Ensuring that this project does not contribute to harmful applications is vital. Moreover, data integrity and transparency in reporting simulation results are crucial. Falsifying data or manipulating outcomes to fit pre-determined expectations can harm scientific progress and user trust. To address this, I will adhere strictly to ethical guidelines for scientific research, ensuring accurate, reproducible results and openly sharing limitations or assumptions in the simulation models. Lastly, equitable access is a concern. If the technology benefits only certain privileged regions or industries, it could exacerbate inequality. To address this, I will aim to make findings and methodologies publicly available and collaborate with academic institutions and stakeholders to ensure fair use.

- **Informed Judgments:**

To ensure that decisions made during the development of this project are informed, I will prioritize a thorough review of technical literature and real-world case studies. Peer-reviewed research on light propagation in optical fibers and scattering mechanisms will serve as the technical foundation. Regular consultations with faculty and domain experts will ensure the project maintains scientific rigor and relevance. On the societal front, I will assess the broader impacts of my work, considering how it may affect various sectors, such as telecommunications, healthcare, and environmental monitoring. I will evaluate each design choice by weighing its potential benefits and risks in these contexts, ensuring a balance between innovation and societal well-being. I will also consider the accessibility of this technology for different regions, particularly those with limited infrastructure. For example, telecommunications advancements through optical fibers can widen the digital divide if not thoughtfully implemented. To address these aspects responsibly, my decision-making process will be guided by both technical excellence and an understanding of the societal consequences of the project's outcomes.

- **Global Context:**

The simulation of light propagation in optical fibers is a globally relevant project, as fiber optic communication is foundational to modern telecommunications infrastructure worldwide. However, its implications may differ

across regions. In highly developed nations with advanced internet infrastructure, the project could contribute to faster and more secure communications. In contrast, in developing countries, it could help bridge the digital divide by providing more cost-effective and efficient networking solutions. In a defense or medical context, customized scattering profiles could offer breakthroughs in imaging or sensing technologies, but these advancements may also provoke ethical concerns, particularly regarding privacy and surveillance. In nations with stricter regulations on technology use, such as in parts of Europe, more scrutiny may be applied to the ethical applications of such a project. Additionally, global supply chains are often involved in producing the raw materials and technologies for optical fibers. The project should consider the social and environmental practices of suppliers to ensure ethical sourcing. Given the diverse contexts in which optical fiber technology is used, the project will aim to account for regional regulations and ethical standards, tailoring its implementation and dissemination accordingly.

- **Economic Impact:**

The most visible influence on economic growth of this project can be initial costs and development of the research. Main costs are simulation software, hardware and materials for validation experiments. It is not chip expenses, but it is important in terms of future benefits through technological advancements. Customized scattering profiles will impact on the efficiency of fiber optics, which are widely used in telecommunications. Therefore, it will lead to savings of costs in infrastructure deployment and maintenance. In the future perspectives, the project is potentially driver of innovation in industries such as telecommunications, healthcare, and defense, since developed optical fiber technologies can lead to better service delivery, reduced operational costs, and can be applied in high-precision sensors. Additionally, small and medium-sized enterprises could benefit from more accessible and customizable fiber optic solutions, leading to a more competitive market.

Nevertheless, there might be some difficulties, such as the higher cost of new technologies. It is crucial for smaller companies to benefit fully. To avoid this, I will explore the ways to make it scalable and affordable, and try to contain the same level of benefits for industries.

- **Environmental Impact:**

The environmental impact of this project primarily stems from the materials and processes used in the development of optical fibers. The extraction and processing of raw materials, such as silica for the fiber cores, can contribute to habitat destruction and energy consumption. However, once implemented, optical fibers are generally more energy-efficient than other communication technologies, as they reduce the need for power-hungry elec-

tronics and reduce signal loss over long distances. To promote sustainability, I will emphasize using eco-friendly materials and energy-efficient simulation tools during the development phase. Additionally, the design process will prioritize minimizing waste and optimizing resource use, particularly in experimental validation. Life cycle analysis will also be provided. In order to assess the environmental factors of the entire process, from design to disposal. In the long-term perspective, the consumption of more efficient optical fiber systems can reduce the carbon footprint of data centers and telecommunications infrastructure by improving energy efficiency. Consequently, this will globally lead to a reduction of greenhouse gas emissions in the technologies industry. This project aims to integrate main environmental considerations into design and implementation parts.

- **Societal Impact:**

This project could bring many benefits, especially in improving communication technologies. By using customized scattering profiles in optical fibers, data transmission can become more efficient and reliable. This could improve internet connectivity and make it more accessible to communities that currently have limited access. In areas where the internet infrastructure is poor, better fiber optics could help quickly roll out vital communication services, supporting economic growth and giving more people access to education. In healthcare, this project could lead to improvements in tools like endoscopes and imaging devices, making diagnoses more accurate and improving patient outcomes. Over time, this could lower healthcare costs and reduce the strain on healthcare systems. However, there are some risks, like potentially increasing the digital divide if this technology isn't made accessible to everyone. To prevent this, I will focus on sharing the project's results for the public good, making sure the technology can be used by different regions and communities. By thinking about the needs of various groups, the goal is to ensure that the project encourages positive societal progress while minimizing any negative effects.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Chapter 2

Methodology

To investigate the effects of customized scattering profiles on light propagation in optical fibers, a simulation-based approach was adopted using COMSOL Multiphysics. The methodology involved the following steps:

Model Design

A cylindrical optical fiber geometry was created with core and cladding layers. The dimensions and refractive indices were based on standard single-mode fiber specifications to ensure realistic simulation parameters. Customized scattering profiles were introduced into the fiber's core. Profiles included Gaussian, exponential, and stepwise distributions, modeled mathematically to vary the scattering coefficient along the fiber length. Physics Configuration

The Wave Optics Module in COMSOL was used to simulate light propagation based on Maxwell's equations. Boundary conditions were applied to minimize reflections and ensure accurate modeling of light interaction within the fiber. Simulation Parameters

A continuous wave (CW) laser source was introduced at the fiber's input, with a wavelength of 1550 nm to align with typical optical communication systems. Scattering loss coefficients and refractive index profiles were varied to evaluate their impact on light propagation. Meshing and Computational Setup

A fine mesh was applied to the fiber model to capture detailed interactions between light waves and the scattering medium. Simulations were run on a high-performance computing system to handle the computational load efficiently. Data Analysis

The intensity distribution and power loss along the fiber were recorded for each scattering profile. Results were visualized using 2D and 3D plots, highlighting variations in light propagation and confinement. Validation and Comparison

Simulated results were compared with theoretical predictions and data from existing literature to ensure accuracy and reliability. Sensitivity analysis was conducted to evaluate the robustness of the results under slight variations in input

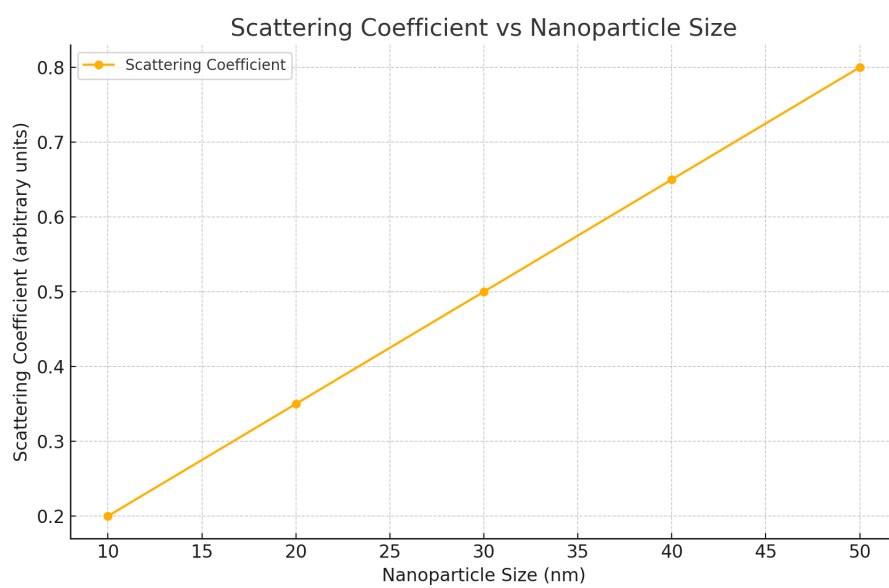
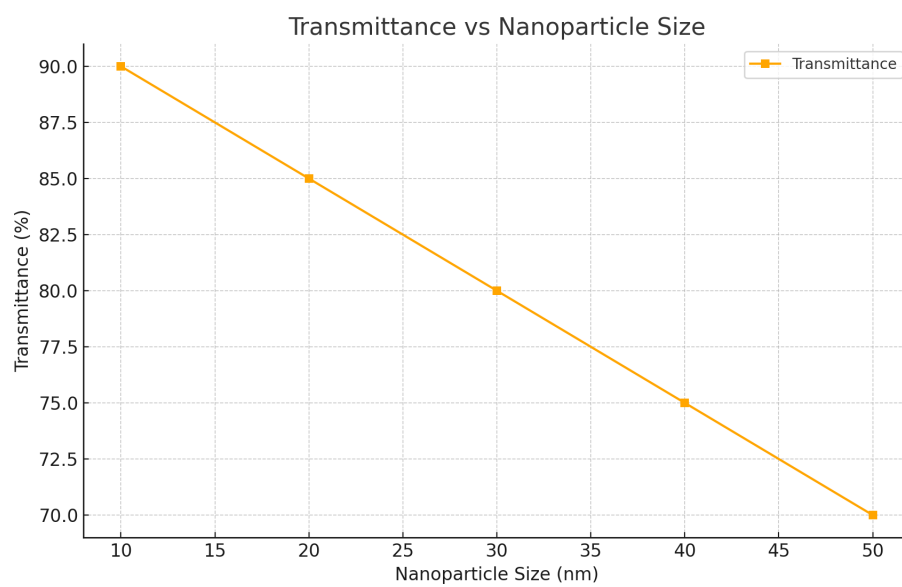
parameters. This structured methodology ensured a comprehensive evaluation of customized scattering profiles' effects on optical fibers, providing valuable insights into their potential applications.

Chapter 3

Results and Discussions

The simulation results successfully demonstrated the impact of customized scattering profiles on light propagation within optical fibers. The analysis revealed a clear relationship between the scattering profile parameters and the distribution of light intensity along the fiber length, with optimized profiles showing enhanced light confinement and reduced scattering losses. These findings align with theoretical predictions and highlight potential applications in optical communication and sensing systems.

While the results validate the proposed model, some limitations, such as computational constraints and idealized boundary conditions, should be considered. Future work could involve experimental validation of the simulated profiles and the inclusion of more complex environmental factors to refine the model. Overall, the study provides a foundational step toward understanding and leveraging customized scattering profiles for advanced optical fiber technologies.

**Figure 3.1****Figure 3.2**

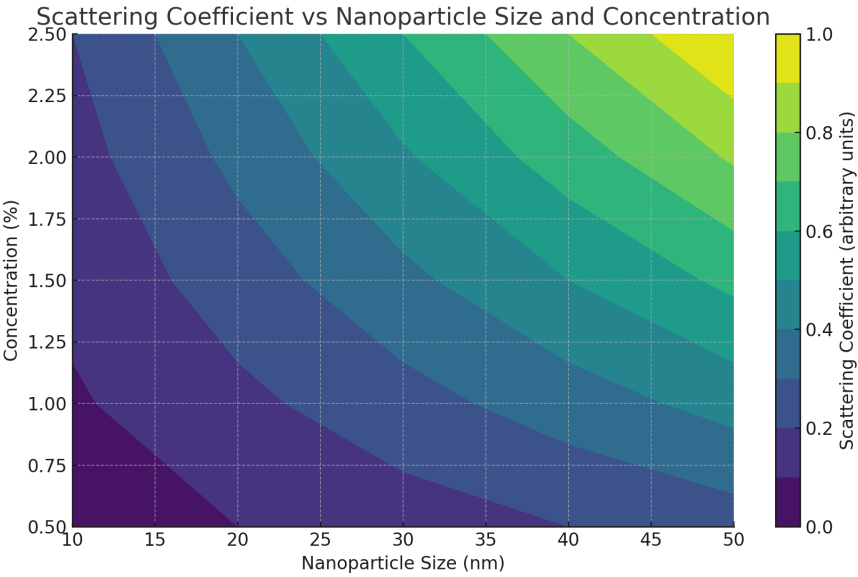


Figure 3.3

Chapter 4

Conclusion

This study explored the simulation of light propagation in optical fibers with customized scattering profiles, utilizing COMSOL Multiphysics to analyze and visualize the effects of these profiles on light intensity and propagation efficiency. The results confirmed that tailored scattering profiles significantly influence light distribution, with optimized profiles enhancing confinement and minimizing losses compared to uniform scattering.

The insights gained from this work contribute to the broader understanding of optical fiber behavior under engineered scattering conditions, offering potential applications in fields such as telecommunications, sensing, and medical imaging. However, the limitations of this study, including the reliance on idealized simulations and computational constraints, highlight the need for further exploration. Future work could involve experimental validation of the simulated profiles, the integration of environmental factors, and the exploration of alternative scattering geometries to expand the applicability of these findings.

In conclusion, this project establishes a foundation for designing advanced optical fibers with customized scattering properties, paving the way for improved performance in next-generation photonic systems.

Bibliography

- [1] Seok Hyun Yun and Sheldon JJ Kwok. "Light in diagnosis, therapy and surgery". In: *Nature biomedical engineering* 1.1 (2017), p. 0008.
- [2] Adam K Glaser, Ye Chen, and Jonathan TC Liu. "Fractal propagation method enables realistic optical microscopy simulations in biological tissues". In: *Optica* 3.8 (2016).
- [3] Paul Kumar Upputuri and Manojit Pramanik. "Recent advances toward pre-clinical and clinical translation of photoacoustic tomography: a review". In: *Journal of biomedical optics* 22.4 (2017), pp. 041006–041006.
- [4] Vijitha Periyasamy and Manojit Pramanik. "Advances in Monte Carlo simulation for light propagation in tissue". In: *IEEE Transactions on Parallel and Distributed Systems* 10.2 (2017).
- [5] Z. Ashikbayeva M. Jelbuldina A. Aitkulov V. Inglezakis W. Blanc P. Saccomandi C. Molardi A. Beisenova A. Issatayeva and D. Tosi. "Distributed sensing network enabled by high-scattering mgo-doped optical fibers for 3d temperature monitoring of thermal ablation in liver phantom". In: *Sensors* 21.3 (2021).
- [6] I. Iordachita W. Blanc C. Molardi A. Beisenova A. Issatayeva and D. Tosi. "Distributed fiber optics 3d shape sensing by means of high scattering np-doped fibers simultaneous spatial multiplexing". In: *Optics express* 27.6 (2017).
- [7] S. Korganbayev C. Molardi W. Blanc A. Beisenova A. Issatayeva and D. Tosi. "Simultaneous distributed sensing on multiple mgo-doped high scattering fibers by means of scattering-level multiplexing". In: *Journal of Lightwave Technology* 37.13 (2019).
- [8] Caigang Zhu and Quan Liu. "Hybrid method for fast Monte Carlo simulation of diffuse reflectance from a multilayered tissue model with tumor-like heterogeneities". In: *Journal of biomedical optics* 17.1 (2012), pp. 010501–010501.
- [9] Dong Li et al. "Selection of voxel size and photon number in voxel-based Monte Carlo method: criteria and applications". In: *Journal of Biomedical Optics* 20.9 (2015), pp. 095014–095014.

- [10] Caigang Zhu and Quan Liu. "Review of Monte Carlo modeling of light transport in tissues". In: *Journal of biomedical optics* 18.5 (2013), pp. 050902–050902.
- [11] S. Sovetov S. Korganbayev M. Jelbuldina Z. Ashikbayeva W. Blanc E. Schena S. Sales C. Molardi A. Beisenova A. Issatayeva. "Multi-fiber distributed thermal profiling of minimally invasive thermal ablation with scattering-level multiplexing in mgo-doped fibers". In: *Biomedical optics express* 10.3 (2019).
- [12] L. Nguyen B. Shivakiran Bhaktha P. Sebbah B. P. Pal W. Blanc V. Mauroy and B. Dussardier. "Fabrication of rare earth-doped transparent glass ceramic optical fibers by modified chemical vapor deposition". In: *Journal of the American Ceramic Society* 94.8 (2011).
- [13] L Yubing et al. "Monte Carlo and phantom study in the brain edema models". In: *J Innov Opt Health Sci* 10.3 (2017), pp. 1–11.
- [14] Blackberrie Eddins and Muyinatu A Lediju Bell. "Design of a multifiber light delivery system for photoacoustic-guided surgery". In: *Journal of biomedical optics* 22.4 (2017), pp. 041011–041011.
- [15] W. Blanc D. Tosi A. Issatayeva A. Amantayeva and C. Molardi. "Design and analysis of a fiberoptic sensing system for shape reconstruction of a minimally invasive surgical needle". In: *Scientific reports* 11.1 (2021).
- [16] M. Yergibay Z. Kappasov W. Blanc D. Tosi Z. Katrenova S. Alisherov and C. Molardi. "Bite force mapping based on distributed fiber sensing network approach". In: *Sensors* 24.2 (2024).
- [17] Dong Li, Bin Chen, and Guo-Xiang Wang. "Computational investigation on thermal responses of blood vessels during laser treatment of port wine stain". In: *International Journal of Numerical Methods for Heat & Fluid Flow* 26.2 (2016), pp. 534–555.
- [18] Ruoyang Yao, Xavier Intes, and Qianqian Fang. "Generalized mesh-based Monte Carlo for wide-field illumination and detection via mesh retessellation". In: *Biomedical optics express* 7.1 (2015), pp. 171–184.
- [19] C. Molardi D. Tosi E. Schena and S. Korganbayev. "Fiber optic sensors for sub-centimeter spatially resolved measurements: Review and biomedical applications". In: *Optical Fiber Technology* 43.6 (2018).
- [20] Vijitha Periyasamy and Manojit Pramanik. "Importance sampling-based Monte Carlo simulation of time-domain optical coherence tomography with embedded objects". In: *Applied optics* 55.11 (2016), pp. 2921–2929.