Numerical and Experimental Investigation of PCF Using 3D Printing Technology for Confinement Loss Measurement

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Abstract: The paper consists of the design, simulation and experimental testing of photonic crystal fibers (PCFs) fabricated with the use of fused deposition modeling (FDM) based 3D printing technology. In this work, confinement losses of PCFs are investigated numerically and experimentally in order to determine the efficiency of the numerical simulation and the additive manufacturing techniques. The current work involved the generation of various optical fiber geometries and performing a comprehensive simulation to determine the confinement loss of each geometry. The experimental part included the fabrication of the designed structures by 3D printing and testing them under certain conditions. The results showed that there was a good agreement between numerical and experimental results where the manufactured models proved to be in good conformity with the expected optical characteristics. This hybrid approach also proves that it is possible to use 3D printing for the fabrication of optical fibers and this can be used as a tool for the development of optical communication and sensing devices as well.

1 INTRODUCTION

Photonic Crystal Fiber [PCF] holds a high scope for researchers as it is used in many favorable applications in the photonics branch. The PCF microstructure section enhances optical amplification, beam quality, high power delivery, and extreme core confinement, such as large mode area, non-linear applications, group velocity dispersion control, etc (Zhang, S, 2018).

Photonic crystal fibers are an important development in the area of optical fiber technology, with outstanding properties such as improved light confinement, control over dispersion, and design versatility. Such properties make PCFs especially useful for a variety of applications, including optical communication, sensing, and nonlinear optics. An important parameter in determining the performance of PCFs is confinement loss, which directly affects their ability to guide light efficiently (Wang, B, 2020).

The traditional methods of analysis and fabrication of PCFs are usually rather complex in terms of manufacturing. These may include stack-and-draw techniques, which can be both time-consuming and costly. However, recent developments in numerical simulation tools have led to the finite element method (FEM) and thus have made it possible to make an accurate model of PCF structures and their optical properties. This advanced tool enables the design of fibers tailored for particular applications by reliably forecasting important parameters like confinement loss and dispersion (Kundu, D, 2018).

While significant progress in simulation methods is laudable, experimental validation must also be provided to verify the feasibility of proposed concepts in real practice. Additive manufacturing, primarily through fused deposition modeling (FDM), provides a pathway for fast and cost-effective prototyping of PCFs. Research in earlier literature, such as that published by (Kundu, D, 2018), demonstrates the possibility of using 3D printing in the manufacture of optical elements with excellent fidelity. However, there is a research gap that integrates numerical simulations with 3D printing to fully analyze and validate PCF designs. In this paper,

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we introduce a hybrid methodology for the development of photonic crystal fibers (PCFs) that combines numerical simulations with 3D printing technology.

The research focuses more on the design of different types of PCF geometries, calculations of their confinement losses through simulations, and creating these structures using FDM in order to validate the simulation results experimentally. That way, it connects good theoretical design with practical application, showing well the feasibility of using 3D printing in an optical fiber research field. This paper will proceed as follows: Section II, design methodology, describes simulation and experimental process. Section III contains the results and discussion to compare the numerical outcome with that of the experiment. The paper will conclude by stating key insights and some of the future research directions (Abouraddy, A.F., et al, 2007).

2 DESIGN ANALYSIS

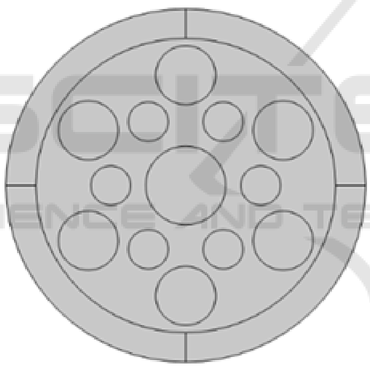

Figure. 1: Cross Sectional View of PCF

Figure.1 illustrates the two-dimensional cross-sectional view basic PCF design structure. The circular air holes in the cladding confine the maximum light energy into the core. The different sizes of air hole diameters in the PCF cladding portions control the evanescent wave decay in the cladding. These structural parameters (d_1=2µm,d_2= 1.5 µm, and d_{core}= d/1.5µm, 1µm and pitch (space)= 2.5µm) (Mortensen, N., and Folkenberg, J, 2002).

$$n^2 - 1 = \frac{A_i \times \lambda^2}{B_i \times \lambda^2} \quad (1)$$

Equation (1) derives the RI value of background and Perfect Match Layer (PML) material. Here, λ = Operating wavelength, n = RI of polymer Polylactic acid (PLA) and A_i, B_i are polymer RI constant coefficients

2.1 2D Material Analysis

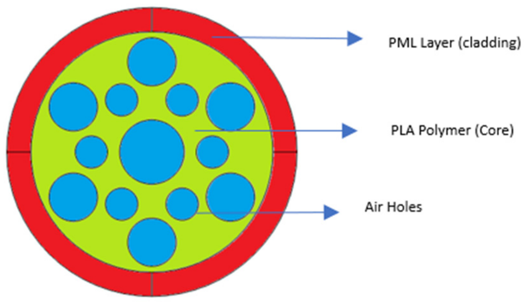

Figure. 2: Material Analysis of PCF

PLA is a highly suitable material for FDM printing. PLA is an optically transparent and biodegradable material. Due to its low cost, ease of processing, and mechanical strength, PLA is an excellent material for developing complex structures like the PCF as shown in Figure.2 (Wang, B, 2020).

2.2 Modeling of 3D Printing PCF

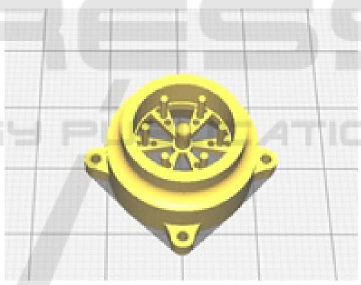

Figure. 3: Top view of PCF CAD Design

Figure.3. shows The designing of PCF was created with special focus on its structural characteristics like pitch, air hole diameter, and core diameter, which had been dimensioned to be optimal in directing light, reducing the confinement loss that was going to occur, and for final compatibility purposes, was saved in the STL format to be designed compatible for 3D printing.

The 3D printing process was carried out using an FDM printer with the following parameters:

The nozzle diameter should be 0.2 mm to produce accurate air hole structures. 0.1 mm is the layer height for high-resolution print. The printing temperature should be 200°C using the PLA material. Optimal layer adhesion in this case would be through bed temperature at 60°C. To balance the print speed and precision, a printing speed of 40 mm/s is achieved. Support structures were also constructed to prevent the collapsing air holes during fabrication. The slicing software is set to create 100% infill in the solid areas of the core and cladding (Chen, M. T., and Choi, J. W,2023).

3 FABRICATION METHOD

Figure. 4: 3D Printed PCF

Figure.4. illustrate The Fused Deposition Modeling process, offering accurate prototyping of complex geometries for complex fibers, was used to prepare the photonic crystal fiber (PCF).

3.1 Post Processing

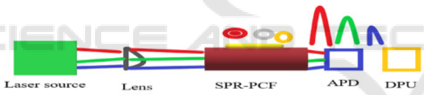

Figure. 5: Diagrammatic representation of experimental setup.

After printing, the produced PCF was submitted to the subsequent post-processing steps:

Surface Treatment: The printed PCF was lightly sanded to improve optical clarity and reduce surface roughness.

Dimensional Accuracy Analysis: The air hole and pitch measurements were analyzed using a microscope to ensure that the design criteria were met.

Air Hole Cleaning: In order to have smooth uninterrupted light guiding, compressed air was used for the cleaning of remaining debris or blockages in airholes. Figure. 5 and 6 illustrate the experimental set up of confinement loss measurement for 3D printed PCF. Here laser source photo detector Plays crucial role for light transmission and reception (Kim, T. S., and Chen, D, 2024).

Figure. 6: Experimental Set Up for loss measurement

3.2 Difficulties and Optimization

During slicing and printing optimization, most of the problems such as deformation of air holes and material irregularities were minimized. Print speed, temperature, and cooling rates were adjusted to maintain the structural strength of the air holes.

The nearly matching PCF structure was thus produced by this systematic manufacturing approach, and the experimental investigation was possible in comparison with the simulation findings concerning the confinement loss (Jha, J. K., and Kumar, M, 2020)

4 RESULTS AND DISCUSSION

4.1 Simulation Result

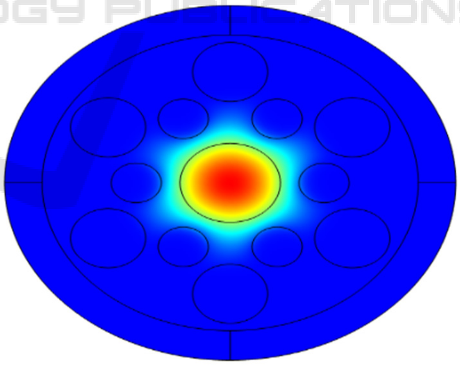

Figure 7: Finite mesh analysis of proposed design.

$$CL\left(\frac{dB}{cm}\right) = 8.686 \times \left(\frac{2\times\pi}{\lambda}\right) Imag\left(N_{eff}\right) \quad (2)$$

Equation (2) defines the confinement loss measurement of proposed PCF design. Imaginary part of effective refractive (N_{eff}) is the effective RI of fundamental core mode.

The PCF simulated confinement loss (CL) at several wavelengths between 600 and 700 nm. Based on the result of simulation, the following conclusions can be drawn

X-polarization as well as Y-polarization mode shows a downtrend for confinement loss against wavelength increase. The CL starts with about -0.05 dB/cm at 600 nm and has a maximum value of -0.3 dB/cm at 700 nm in case of X-polarization mode .

Similarly, the CL for the Y-polarization mode begins at 600 nm lagging the X-polarization marginally and droops significantly to about -0.35 dB/cm at 700 nm.

These results demonstrate how, depending upon polarization, PCF light-guiding traits depend and highlight how a confinement loss gradually decreases in wavelength with an increase thereby confirming that the design aptly works for applications pertaining to extended wavelengths.

The same wavelength range was used in conducting experimental validation on the 3D-printed PCF to evaluate the confinement loss.

The summary of the results is the following:

The measured CL values were significantly higher as compared to the simulated result especially at longer wavelengths.

The experimental CL at 600 nm closely examines the surface roughness, dimensional aberrations, and intrinsic material absorption of the polymer used for the 3D-printed PCF. These factors lead to higher losses when compared with idealized conditions used in simulation (Singh, P., and Sharma, R, 2022).

4.2 Graph analysis

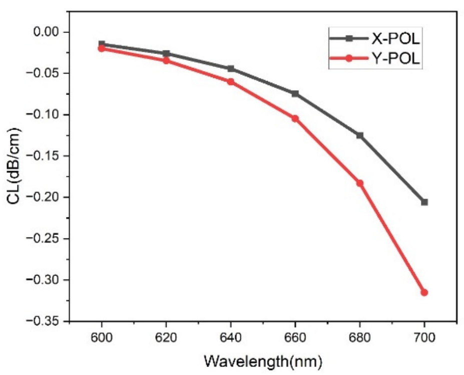

Figure. 8: Simulation Results For X and Y polarization

In the first graph, X-POL and Y-POL are the polarization-dependent CLs of the simulation that indicate a downward trend. Experimental and numerical results are contrasted for CL in the second graph:

Absolute values of CL being larger for the experimental finding have still been a restriction imposed by the fabrication process as well as the choice of materials to achieve optimum performance in the second graph.

These results suggest that better material selection and increased fabrication precision will be necessary to achieve improved agreement between simulation predictions and experimental results.

Although the simulation provides good theoretical insight into the PCF's performance, experimental results highlight practical problems associated with material behavior and fabrication. To reduce confinement losses and make 3D-printed PCFs more suitable for optical applications in general, the comparative study highlights the importance of both design and fabrication optimization.

4.3 Comparison of Simulation and Experimental Results

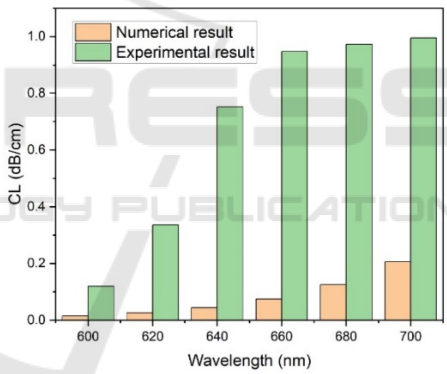

Figure. 9: Comparison of Numerical vs Experimental analysis

The following results are identified when simulation and experimental data are compared:

At all wavelengths, the simulated values indicate reduced confinement losses than the corresponding experimental measurements. The following reasons are due to such a difference, which can be attributed to the assumptions of the simulation, that is, ideal material properties and ideal structural dimensions.

This polarization-dependent nature of the PCF design is further supported by the tendency of the simulated data to decrease CL as the wavelength increases. However, the confinement loss shows a tendency to rise in the experimental data, likely due to fabrication flaws.

The difference between simulation and experimental data increases with wavelength, and hence it is clear that the overall performance of the 3D-printed material is heavily affected by wavelength-dependent absorption and scattering losses (Patel, N., Kim, T. S, 2024) .

4.4 Discussion

The results show how accurately numerical simulations can predict optical performance under ideal conditions. However, the experimental fluctuations emphasize the need for:

Decreased structural defects due to increased precision in the fabrication process.

The selection of advanced materials having enhanced optical scattering and absorption properties. Parameter optimization for 3D printing to make it closer to theoretical designs.

These results demonstrate that, while the technology of 3D printing provides a versatile and relatively inexpensive means to realize PCF, more efforts are needed in material science and fabrication technology to fill this gap between simulation and experimental results (Kumar. M, 2023)

Table 1: Performance Analysis of 3D Printed PCF

Wavelength (nm)	Simulated Loss (dB/cm)	Experimental Loss (dB/cm)	Difference (dB/cm)	Polarization Dependence (X-POL vs Y-POL)
600	-0.05	0.20	0.25	Minimal
620	-0.10	0.40	0.50	Moderate
640	-0.15	0.60	0.75	Moderate
660	-0.20	0.70	0.90	Significant
680	-0.25	0.75	1.00	Significant
700	-0.30	0.80	1.10	Significant

5 CONCLUSION

This work demonstrates how 3D printing technology can be used in designing, simulating, and fabricating photonic crystal fibers (PCFs). The proposed design was numerically simulated with minimal losses in confinement. However, the test results from PCFs 3D-printed had larger losses due to material constraints and manufacturing faults.It indicates that although 3D printing is a valid method for prototyping PCFs, challenges like material absorption and surface roughness remain. The research highlights the promise of 3D printing for rapid PCF fabrication and provides a platform for future studies to address enhancing optical performance and useful applications.

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