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Application of COMSOL Multiphysics for Fiber Beam Profiling

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Abstract

Fiber optic beam profiling is essential across scientific and engineering realms, demanding precise characterization of light beams for optimized system performance, accurate alignment, and efficient resource utilization. This study employs COMSOL Multiphysics to comprehensively analyze single-mode and multimode fiber beam profiles, encompassing diverse parameters such as wavelengths and modal distributions. The investigation of beam profiles is based on 850nm, 1310nm and 1550nm wavelengths; with three different modes (1, 5, and 20). COMSOL Multiphysics enhances beam profiling by providing precise numerical techniques, multiphysics modeling, and flexible parameter analysis. Its user-friendly interface facilitates efficient research, while validation and innovative possibilities underscore its value in photonics advancements. The research addresses the need for advanced profiling techniques, offering a robust methodology that captures intricate modal interactions and boundary conditions. Key findings include distinctive beam waist evolution, mode distribution patterns, and beam shaping behaviors, impacting data transmission, medical procedures, and manufacturing. By integrating computational power, this study advances our understanding of photonics, providing practical insights for future fiber optic technologies and their broader implications.

I. INTRODUCTION

Fiber optic beam profiling is a critical technique that plays a crucial role in numerous scientific and engineering applications [1]. The beam profiling representation has attracted much attention due to some applications requiring an alternative beam distribution instead of the inherent Gaussian distribution provided by typical optics. By accurately characterising the properties of light beams propagated through fiber optics, beam profiling enables the optimisation of system performance, precise alignment, and efficient utilisation of resources. The importance of beam intensity distribution analysis cannot be overstated.

Beam profiles are important in fiber optics since they include fiber optic coupling, optical trapping laser processing, and lithography, and can be altered in several ways, including spiral rays in multi-mode fibers (MMF), interference in MMF, misaligned fiber coupling, fiber optics with end-facet shaping, wedge prisms, and more [2].

Studies by [3][4] have demonstrated the use of fiber optic beam profiling in optimising laser beam delivery systems for precise medical surgeries. By analysing the intensity distribution, including power distribution, peak intensity, and beam quality, researchers can gain valuable insights into beam behaviour and make informed decisions regarding system design and performance improvement.

There are a few key aspects in beam profiling. Accurate determination of the beam waist parameters focuses on the minimum spot size. This directly influences various applications such as laser materials processing and fiber optic communications. [5] demonstrated the use of fiber optic beam profiling in accurately measuring the ultrafast laser beam waist. By obtaining precise measurements of the beam waist size and location, researchers can optimise system efficiency and achieve desired focusing capabilities, thereby enhancing the performance of laser machining and other manufacturing processes.

Mode analysis is another important area of knowledge in beam profiling. It provides insights into the modal structure of a fiber optic beam, including the number, shape, and spatial distribution of guided modes. Understanding these characteristics is crucial for optimising beam quality and propagation. While beam shaping, which involves modifying the spatial profile to achieve desired intensity distributions, is an area where beam profiling plays a vital role. Profiling the input and output beams allows for precise evaluation of shaping techniques, such as diffractive optics, holography, and spatial light modulators.

Geometrical tolerances and low loss spectral attenuations are critical fiber properties. Appropriate beam profile measurements are important to describe the beam quality of the fibers utilised in beam delivery. Standard M2 instruments are used to measure how close a beam is to a perfect Gaussian output. [2][6] demonstrates experimental studies of beam profiling. While [7][8] demonstrated beam shape study based on computational modelling. Previous studies used silicon-based CCDs, CMOS detector-array cameras and goniometric radiometers, which are not cost effective and time consuming.

The aforementioned studies collectively underscore the pivotal role of fiber optic beam profiling in diverse applications. Precise characterization of beam intensity distribution, spatial mapping, beam waist, mode analysis, and beam shaping empowers researchers and engineers to optimize system performance, achieve meticulous focusing, decipher beam behavior, and tailor beams to distinct application prerequisites. The recent references cited herein testify to the practical significance and ongoing progress in the field of fiber optic beam profiling, charting a course for further advancements. Hence, the primary motivation behind this study is to showcase how critical optical insights can be gleaned from captured output beam images, thereby yielding insightful conclusions. In this investigation, we delve into the intensity profile of output beams for both single-mode fiber (SMF) and MMF, establishing connections to novel insights.

This study aims to illustrate how precise optical information can be extracted from captured output beam images, leading to insightful conclusions. Our investigation delves into the intensity profile of output beams for both single-mode fiber (SMF) and multimode fiber (MMF), offering new perspectives on their characteristics and behaviors. By employing COMSOL Multiphysics, we enhance the accuracy and depth of our analysis, allowing us to contribute valuable insights to the field of fiber optic beam profiling.

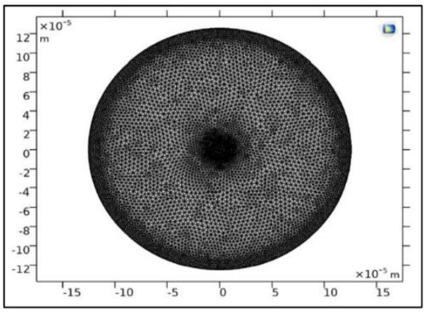
II. METHODOLOGY

The utilization of COMSOL Multiphysics introduces a novel avenue for simulating fiber structures through the finite element method, resulting in enhanced accuracy of beam profile outputs. The study was conducted across three wavelengths: 850nm, 1310nm, and 1550nm, encompassing three distinct modes: 1, 5, and 20. Employing COMSOL Multiphysics software package V.5.2, we undertook the design and analysis of the fiber. The 2D Model Wizard facilitated the construction of an optical fiber structure, utilizing parameters as outlined in Table 1 to engender multi-technical specifications including frequency domain and mode analysis for a two-dimensional (2D) optical fiber. The finite element mesh model for SMF and MMF is depicted in Figure 1.

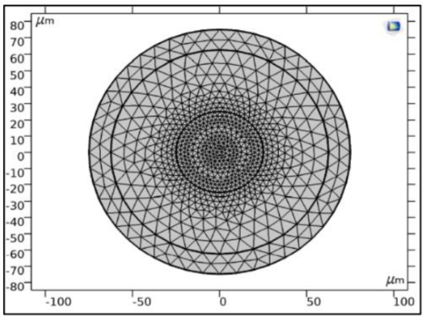
Table 1
SMF and MMF simulation parameters

Items	SMF	MMF
Core Diameter	50 µm	8 µm
Cladding Diameter	125 µm	125 µm
Air	-	1
Silica Core (Doped) Refractive Index	1.478	1.45
Silica (Pure) Refractive Index	1.45	1.45 – 0.0001
Air Boundary for Impedance	-	1

The analysis of mode profiles and their associated characteristics, encompassing power confinement and spatial distribution of refractive index, holds substantial significance in the realm of fiber optic beam profiling. These attributes are pivotal as they offer insights into how light propagates within optical fibers, shedding light on critical aspects that profoundly impact system performance and application suitability.



(a) SMF mesh model



(b) MMF mesh model

Figure 1 Finite element mesh model (a) Single-mode fiber, (b) Multi-mode fiber.

Power confinement within different modes directly influences the efficiency of signal transmission and manipulation within optical fibers. Understanding how power is distributed among different modes aids in optimizing the efficiency of signal transmission, particularly in scenarios where specific modes are favored or suppressed to achieve desired outcomes. Efficient power confinement ensures that the majority of the transmitted light is effectively utilized, contributing to enhanced signal integrity, reduced losses, and improved overall system efficiency.

The spatial distribution of refractive index, on the other hand, characterizes how light is guided and confined within the fiber structure. It directly influences the behavior of light modes, their interaction, and their transmission characteristics. An accurate understanding of this distribution helps engineers and researchers tailor the fiber's properties to achieve specific beam shaping requirements, optimize beam quality, and minimize unwanted effects such as mode coupling or signal degradation. Additionally, the spatial distribution of refractive index is a crucial factor in designing and optimizing specialty fibers for applications like medical treatments, sensing, and telecommunications.

The characteristics of mode profiles and their associated attributes are intimately linked to the overarching field of fiber optic beam profiling. A thorough comprehension of mode behavior aids in the precise design of optical systems, enabling engineers to manipulate beam properties, achieve targeted beam shapes, and optimize coupling efficiency. For instance, in medical applications, the ability to control power distribution and confinement ensures the accurate delivery of laser energy to a specific treatment site, minimizing damage to surrounding tissues. In telecommunications, understanding mode profiles contributes to efficient data transmission and signal quality, impacting bandwidth and data rates.

In essence, the mode profiles and their characteristics provide a detailed insight into the fundamental behavior of light within optical fibers. This understanding underpins the optimization of system performance, accurate beam shaping, and effective utilization of fiber optic resources. By unraveling the intricate details of mode profiles, researchers and engineers can make informed decisions, resulting in innovative solutions and enhanced capabilities across a wide array of applications within the realm of fiber optic beam profiling.

III. RESULTS AND DISCUSSION

The COMSOL-generated mode profiles of SMF and MMF are illustrated in Table 2 and Table 3 respectively. The real-time fiber output is represented in RGB format, where red has the highest intensity, green has less power, and blue has the lowest intensity. A decrease in light intensity is observed towards the outer circles of the images. The output intensity distribution appears to be virtually a Gaussian beam based on the colour map of concentric circular images.

For the SMF output illustrated for mode 1, the blue shade region shows the fiber has more power confined in the core. As the mode is increased to 5, the profile output shows that the diameter of the core slightly bigger and has less propagation of the concentrated refractive index compared to mode 1. When the number mode is 20, the profile index output illustrates that the blue shade region is no longer visible as it proved there is no confined power. This basically explains why SMF only allows one guided mode.

Table 3 illustrates the COMSOL-generated mode profiles for MMF. For 1 number of mode, the effective mode index is set to 1.45. The blue shade with red centre point indicates the multiple paths are sloppy. For 5 number of modes, the profile index shows that the red region surrounding the core indicates higher propagation of refractive index. While for 20 modes, the red region remains the same. Therefore, this proves that lower-order modes tend to confine light spatially in the core of the fiber and higher-order modes tend to confine light spatially near the core and cladding interface.

The intensity profiles of SMF at 850nm, 1310nm and 1550nm with 20 modes are not smooth and a clear spot is not obtained. Similar pattern is observed for 850nm MMF with 5 and 20 modes. This is due to interference effects. The maximum bandwidth for identifying individual modes in terms of mode analysis capability can be calculated as equation (1)

$$\Delta\lambda \ll \frac{\lambda}{2\pi\Delta n L} \tag{1}$$

where: λ = wavelength
Δn = core-cladding relative refractive index
L = fiber length

The results based on 850nm, 1310nm and 1550nm wavelengths show no significant differences between diverse modes for both SMF and MMF.

Table 2
SMF beam profiles

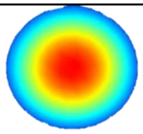
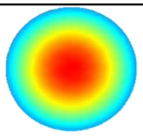
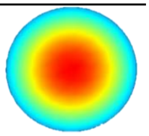
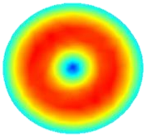
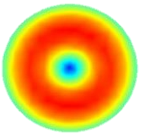
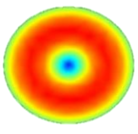
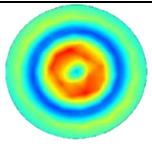
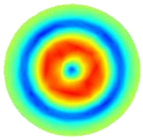
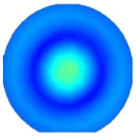
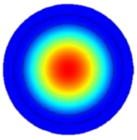
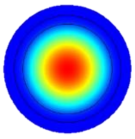
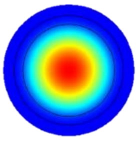
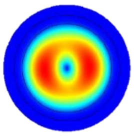
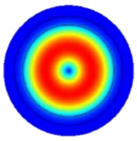
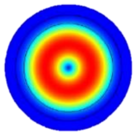
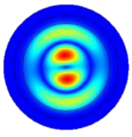
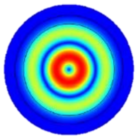
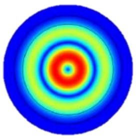
Number of Modes	Wavelength		
	850nm	1310nm	1550nm
1			
5			
20			

Table 3
MMF beam profiles

Number of Modes	Wavelength		
	850nm	1310nm	1550nm
1			
5			
20			

Part two of this study focuses on operating wavelengths of 1310nm for SMF and 850nm for MMF based on commonly used industrial standard wavelengths.

The default graphic depicts the normal electric field distribution for the computed mode with the highest effective index (the one with the lowest effective mode index), as shown in Table 4 and Table 5 for SMF and MMF, respectively. A slight difference for electric fields in higher modes, which also affects the contour of the electric field in both 5 and 20 modes. There are three components that can be observed, which refers to the surface of the electric field, the contour, and the surface arrow in both modes of optical fibers.

As the number of modes increases, the value of the surface on electric fields decreases because the light dispersion occurs. It is noticed that the effective mode index also decreases in all SMFs from 1.4771, 1.4757 and 1.4704, respectively. Since single mode fiber supports four modes, regardless of the polarization state. Fiber typically has single-mode properties only over a narrow wavelength range with a width of a few hundred nanometers. Next, in single mode, the contour of the electric field can be seen clearly according to the number of modes used. Table 3 also illustrates that the value of the contour mode slightly decreases depending on the number of modes applied. However, the different number of modes does not affect any changes at the arrow surface of the electric fields, which displays only single arrow.

Table 4
SMF electric field profiles

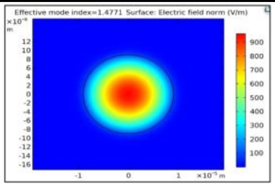
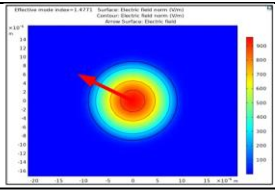
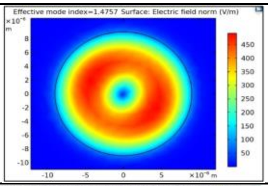
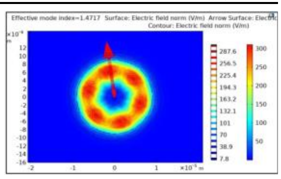
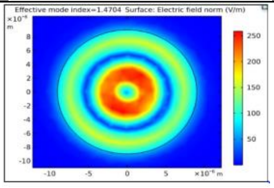
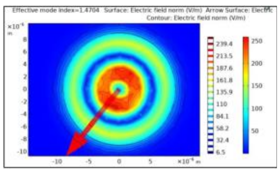
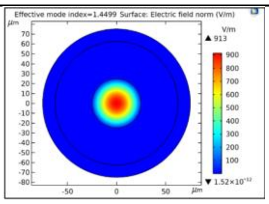
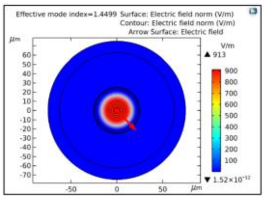
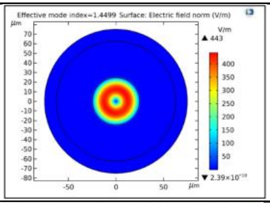
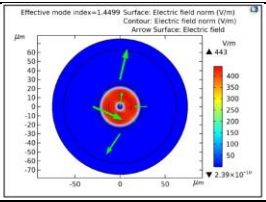
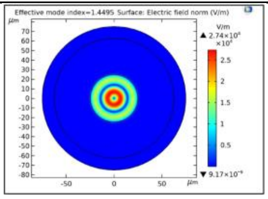
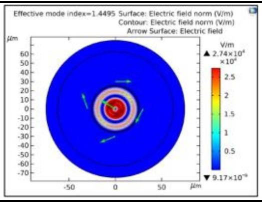
		1310nm wavelength	
		Surface electric field	*Contour arrow surface*
Number of Modes	1		
	5		
	20		

Table 5
MMF electric field profiles

		850nm wavelength	
		Surface electric field	*Contour arrow surface*
Number of Modes	1		
	5		
	20		

In Table 4, the higher number of modes applied in multimode varies the value of the electric field on the surface. The electric field varies from the center towards the outer of the core. The effective mode index is 1.449. The contour pattern for three different modes in MMF differs from each other. It can be observed that the higher the modes used, the higher the value of contour obtained for the electric field, which shows the colour become redder (dense) at the core.

This study proves that the observed results are comparable to experimental research. Based on the power distribution, the application of different fiber at different wavelengths and the transmission bandwidth can be easily determined for industrial applications, laser surgeries and treatments, or telecommunication systems.

The importance of mode profiles and their associated characteristics in fiber optic beam profiling lies in their ability to provide a comprehensive understanding of how light propagates within optical fibers. Power confinement and spatial distribution of refractive index directly influence the behavior of light modes, impacting various aspects of system performance and application suitability. Power confinement elucidates how efficiently light energy is transmitted, guiding the optimization of signal integrity and minimizing losses. This attribute is particularly crucial in scenarios where specific modes need to be harnessed for tailored outcomes. On the other hand, the spatial distribution of refractive index governs the propagation behavior of light, affecting mode interaction and transmission properties. Understanding this distribution empowers engineers to customize fiber properties for precise beam shaping, optimizing beam quality, and mitigating undesirable effects such as mode coupling. Both attributes are instrumental in designing efficient fiber optic systems, fine-tuning beam characteristics, and ensuring effective resource utilization.

The observation of interference effects in the intensity profiles of both SMF and MMF at specific wavelengths and modes offers valuable insights into the behavior of light within the fibers. Interference effects result from the superposition of multiple light waves, leading to intensity fluctuations and patterns that deviate from the expected smooth profiles. These effects are particularly pronounced in scenarios involving multiple modes or wavelengths, where the interaction of light waves can lead to constructive or destructive interference patterns. In practical applications, interference effects can impact beam quality, signal transmission, and the accuracy of beam shaping. They may lead to variations in beam intensity, spatial distribution, and mode coupling, potentially affecting the performance of fiber optic systems. Acknowledging interference effects is critical for accurate system design, ensuring that potential anomalies are considered and mitigated to achieve desired outcomes. By understanding interference patterns, engineers can devise strategies to minimize their impact, optimize system performance, and enhance the reliability of fiber optic technologies in diverse applications, ranging from telecommunications to laser surgeries and treatments.

The implications of these interference effects extend significantly within technical applications and system performance:

1) *Precision of Beam Quality and Fidelity*

Interference-induced fluctuations in beam intensity can undermine the precision of beam shaping and power control. This is especially pertinent in applications like intricate laser procedures or precision material processing, where exact beam characteristics are imperative for achieving desired outcomes. As interference effects introduce irregularities, meticulous assessment and management become essential to align the emitted beam with its intended specifications.

2) *Influence on Signal Transmission and System Functionality*

In domains such as telecommunication and data transmission, interference effects can introduce variability in signal quality. The fluctuations in intensity profiles can precipitate signal distortions, attenuations, and even data loss. This can potentially curtail data transmission distances and rates, compromising the efficacy and robustness of the communication system. Consequently, understanding and mitigating the influence of interference effects on signal fidelity are crucial for optimizing fiber optic communication systems.

3) *Sensitivity to Fabrication and Installation* Factors

Fiber optic systems' sensitivity to manufacturing and installation perturbations is exacerbated by interference effects. Minor deviations in fiber geometry, alignment precision, or environmental conditions can perturb interference patterns, and thereby influence beam quality or signal propagation. The ramifications of this sensitivity underscore the necessity for stringent manufacturing processes and meticulous installation methodologies to avert undesirable fluctuations stemming from interference.

The presence of interference effects within fiber optic beam profiles at designated wavelengths and modes can exert profound implications across technical applications and system efficacy. The deviations they introduce can compromise beam precision, signal reliability, and the overall viability of the system. Engineers and researchers, operating within diverse domains encompassing medical procedures to advanced telecommunications, must cognize these effects and devise strategies to abate their impact. By composing meticulous system design, optimization, and parameter control, practitioners can safeguard against the encumbrances posed by interference effects and ensure the functional prowess of fiber optic technologies within practical contexts. Thus, the preliminary beam profile obtained represent a good starting point for the characterisation of SMF and MMF at various wavelengths and modes. The research would be expanded on the use of coherent and noncoherent optical sources.

IV. CONCLUSION

In this paper, we have demonstrated a comprehensive study of the SMF and MMF beam profiles using the COMSOL Multiphysics finite element method technique. This simple and effective method is very useful for finding the characteristics of the beam profile of different fiber types at different wavelengths and the number of modes. This technique offers extra advantages in comprehending the characteristics of beam propagation for evaluating transmission capabilities, as well as suitable beam size for medical treatment and suitable beam power for industrial applications.

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