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A Comparative Exploration of Femtosecond Optical Pulse Propagation In Hollow Core Photonic Crystal Fiber And Conventional Optical Fiber

P. Talukdar[1], **D. Phukan**[2], **S. Hazarika**[3]

[1,2*]Department of Physics, Royal Global University, Guwahati, 781035, Assam, India

[3]Department of Physics, Assam University, Diphu Campus, 782462, Assam, India

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Abstract
The current study aims to explore the reduction of optical fiber dispersion by creating a photonic crystal optical fiber with a hollow core. To analyze this, both a hollow core photonic crystal fiber and a standard solid core optical fiber are employed, with a Gaussian pulse as the input source centered at a wavelength of 0.55 m. The findings reveal the efficiency of a hollow core fiber in minimizing dispersion effects. The investigation involves a comprehensive analysis of the optical output spectra and transmission characteristics of both the photonic crystal fiber and the conventional optical fiber. When compared to the conventional fiber, the novel hollow core photonic crystal fiber demonstrates a remarkable enhancement, achieving approximately 20% higher maximum transmission.

Keywords: Dispersion, Hollow core optical fibers, Gaussian pulse, Conventional solid core optical fiber, Transmission

1 Introduction

In the realm of optical communication systems, the potential superiority of hollow core photonic crystal fibers (HCPCFs) becomes evident when compared to the conventional solid core optical fibers currently in use. A HCPCF configuration encloses a two-dimensional lattice of air holes, featuring an exceptionally high air filling factor spanning the entire length of the fiber. The constraints imposed by Rayleigh scattering and the nonlinear Shannon limit sets limit to the performance of conventional solid core optical fibers [1]. Hollow core photonic crystal fibers emerge as an optimal choice for tasks demanding rapid data transmission and the conveyance of potent pulses. This preference stems from their markedly low nonlinearity, a robust damage threshold, minimal latency, and insensitivity to temperature fluctuations [2]. The principal advantage of this fiber design lies in its ability to maintain single mode waveguiding across a broad spectral range [3]. In contrast, a typical single mode conventional optical fiber transitions into a multimode state as the frequency of optical radiation increases, which in turn leads to increase in optical losses as the radiation frequency decreases [4]. However, the situation takes a different turn when considering hollow core photonic crystal fibers. The two-dimensional structured cladding reduces the overall fiber nonlinearity by an order exceeding 1000 times. This is achieved through the establishment of a photonic bandgap that facilitates the guidance of light within a low-refractive zone within the hollow core fibers [5]. This investigation employs simulations of femtosecond pulses to scrutinize their spectral broadening and dispersion characteristics within both conventional and hollow core photonic crystal fibers. Photonic Crystal Fiber (PCF) stands as a revolutionary innovation that offers a number of distinct advantages over conventional optical fibers. Its unique structural design, featuring a pattern of air holes that surrounds the light-guiding core, opens up numerous opportunities in the field of photonics. One of the key advantages of PCF lies in its ability to confine light within an air core, enabling low-loss transmission even in situations where traditional fibers would suffer from high levels of dispersion. This results in improved signal quality and higher data transmission rates, making PCF particularly appealing for high-speed communication systems. Additionally, the air holes in PCF can be strategically manipulated to achieve a range of desired properties, such as tailor-made dispersion characteristics, enhanced nonlinear effects, and even the capability to guide light in hollow cores, offering unique possibilities for applications in gas and chemical sensing. Furthermore, the design flexibility of PCF allows for the integration of functionalities that would require complex setups in conventional fibers. Overall, PCF's ability to offer reduced dispersion, enhanced nonlinear effects, and versatile design options positions it at the forefront of modern photonics, promising breakthroughs in communication, sensing, and beyond. The practical implications of photonic crystal fibers are extensive and transformative. In the domain of lasers, these fibers contribute to both enhanced performance and increased versatility. They play a pivotal role in sensors, enabling the development of highly sensitive and specific devices capable of detecting a multitude of parameters. Moreover, photonic crystal fibers are essential in the creation of efficient optical switches, driving advancements in communication technologies. Additionally, their role in optical fiber communication systems is central, elevating signal quality and transmission efficiency.

Recent literature has witnessed notable progress in photonic crystal fiber (PCF) simulations, driving innovations across a spectrum of applications. Comprehensive studies have explored light propagation behaviors using advanced computational techniques. Nonlinear effects and dispersion management in PCFs have been extensively investigated, contributing to a deeper understanding of their potential for enhancing optical communication systems, high-power lasers, and ultrafast pulse generation [6][7][8]. Moreover, the exploration of novel PCF designs, such as dual-core and multicore fibers, has showcased their versatility in beam shaping, sensing, and quantum photonics [9]10]. These advancements reflect the evolving landscape of PCF simulations, with references including works by Abdelkader et al. on PCF sensing [6], Roy et al. on broadband supercontinum generation [7], and comprehensive study on nonlinear fiber optics [8]. Additionally, research by Li et al. has investigated mode division multiplexing in dual-core PCFs for optical communication [9], and Cheng et al. have explored all-optical quantum gates using PCFs [10]. These studies collectively underline the critical role of simulations in advancing PCF research and shaping the trajectory of photonic technologies.

The present study illuminates the extraordinary potential of hollow core photonic crystal fibers, indicating their unique spectral broadening capabilities to revolutionize various applications. This advancement in the ability to tailor fiber properties positions photonic crystal fibers as a driving force in shaping the future of optical technologies.

2. Optical Simulations

We have modeled pulse propagation inside the fiber using the non linear envelope equation, from which the propagation equation can be written as [11]

$$\frac{\partial \mu}{\partial \in} = \sum_{n=2}^{4} - (i)^{n-1} \frac{L_{ds}}{n! L_{ds}^{(n)}} \frac{\partial^n \mu}{\partial \tau^n} + i \left(1 + \frac{i}{\omega_o \tau_p} \frac{\partial}{\partial \tau}\right) p^{nl} \qquad (1)$$

Where $\tau = \frac{t - \frac{z}{v_g}}{\tau_p}$ is the retarded frame time normalized to the input pulse width $\tau_{p.}$ τ is the normalized time, ω_0 is the central frequency, v_g is the group velocity, n is the order number, p^{nl} is the non linear polarization and L_{ds} is the dispersion length.

The Finite Difference Time Domain (FDTD) method emerges as a widely adopted simulation technique for solving electromagnetic equations. It is particularly adept at simulating dispersive and nonlinear electromagnetic phenomena [12]. The fabricated fiber is a silicon photonic crystal fiber featuring a hexagonal lattice with five concentric air hole rings forming the cladding. Notably, the central air hole, serving as the core of the fiber, is absent. The pitch, denoted as "ʌ," represents the presumed distance between adjacent holes and is set at 2 µm.

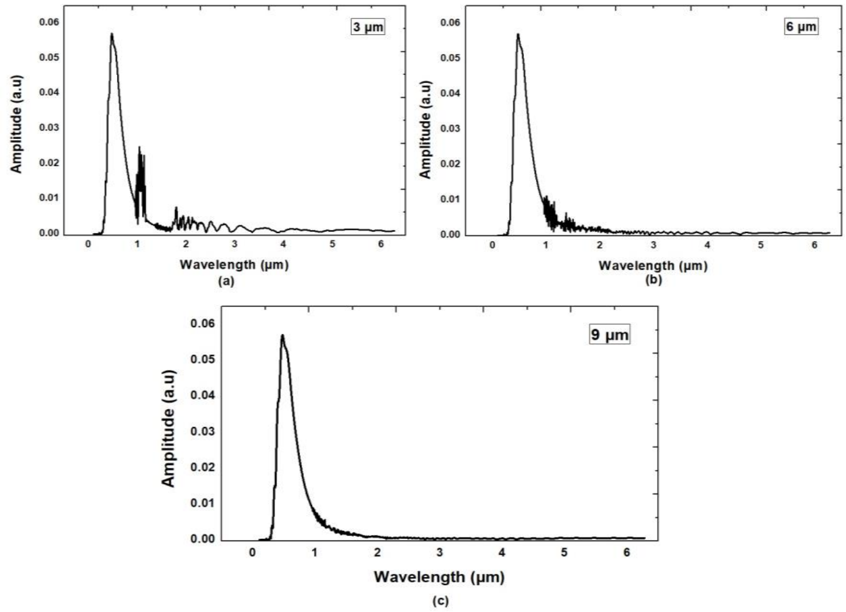


Figure 1: The broadened spectrum of a 2.6 femtosecond laser pulse at the output of a 1 metre long conventional optical fiber for (a) 3 µm (b) 6 µm (c) 9 µm core radius

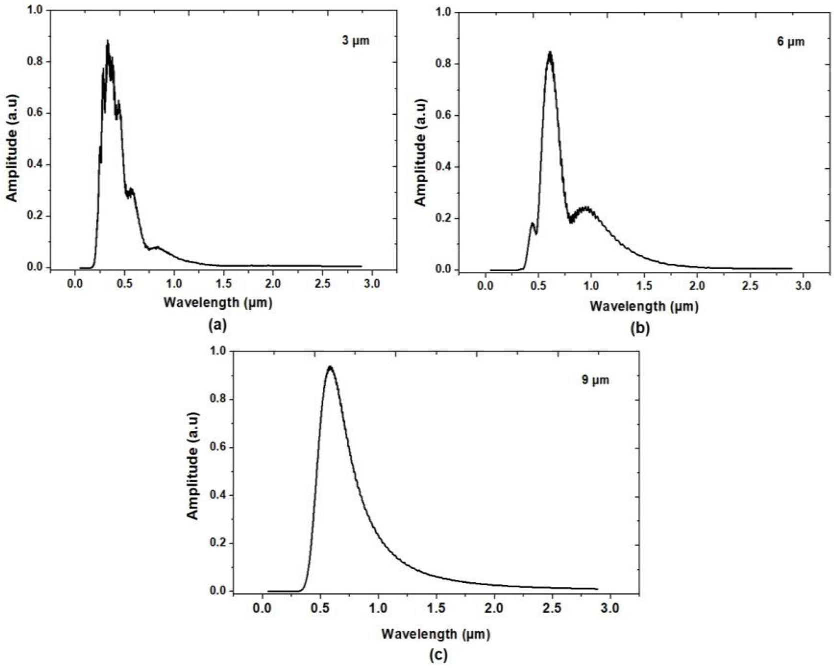
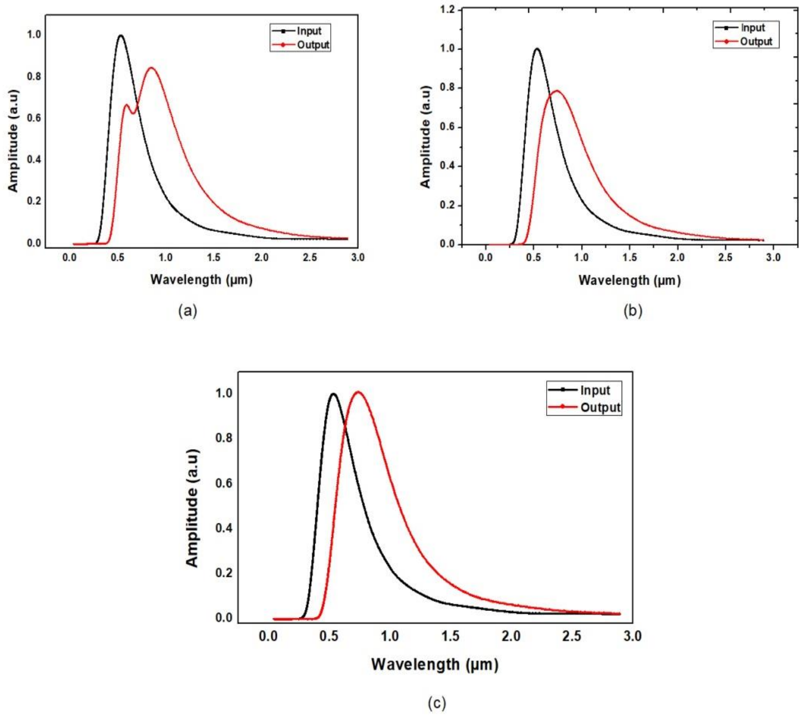


Figure 2: Output spectrum for (a) 3 µm (b) 6 µm (c) 9 µm core radius of the designed hollow core photonic crystal fiber

When light travels through a conventional optical fiber that is 1 meter long, a significant amount of its energy is scattered and dispersed, leading to the presence of only a small fraction of this energy being present in the resulting output spectrum. Additionally, the femtosecond pulse observed at the fiber's output undergoes considerable broadening. The oscillating pattern observed at the trailing edge of the pulse, which effectively mitigates optical compression, arises due to a phenomenon called third-order dispersion (as illustrated in figure 1).

For a core radius of 9 µm, as the size of the core increases, the fundamental mode of light propagation becomes more tightly confined within the core itself. Consequently, this results in the emergence of a more efficient output spectrum being detected at the far end of the fiber (as depicted in figure 2). When the air hole rings are increased, the fundamental mode gets more confined inside the core and hence the loss decreases and as a result, the output spectrum obtained has a pulse width almost equal to the input pulse (figure 3). Raman scattering shifts the optical pulse towards longer wavelengths. To minimize the Raman frequency shifts, the core of the fiber is filled with a noble gas like Xenon at 4.5 atm pressure that can also be used in compression of femtosecond pulses as shown in figure 4. The effective fiber nonlinearity is primarily due to the Xenon gas that results into the absence of a Raman contribution to the nonlinear refractive index as noble gases don’t have Raman component. Figure 4 shows that after injecting Xenon into the fiber, the output pulse width reduces to almost half of the input pulse. The study also examines various core radii, presenting transmission graphs that show the relationship between transmission and wavelength. In both types of fibers studied, it was observed that transmission increases with an increase in the size of the core. The highlighted innovation in this study is the designed hollow core photonic crystal fiber, which exhibits a significantly higher maximum transmission rate of about 20% compared to the conventional solid core optical fiber. This suggests that the novel hollow core fiber design is more capable of maintaining the quality of transmitted light signals, which is particularly beneficial in optical communication systems.



(a) (b) (c)

Figure 3: Input and Output spectrum of the femtosecond pulse passing through the designed hollow core photonic crystal fiber with (a) 3 rings (b) 4 rings and (c) 5 rings

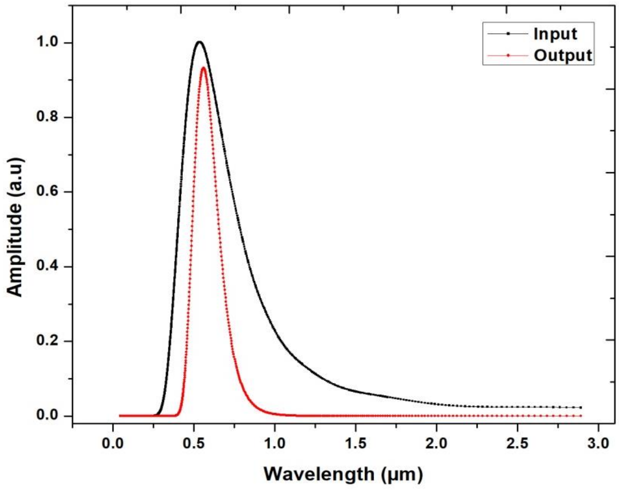
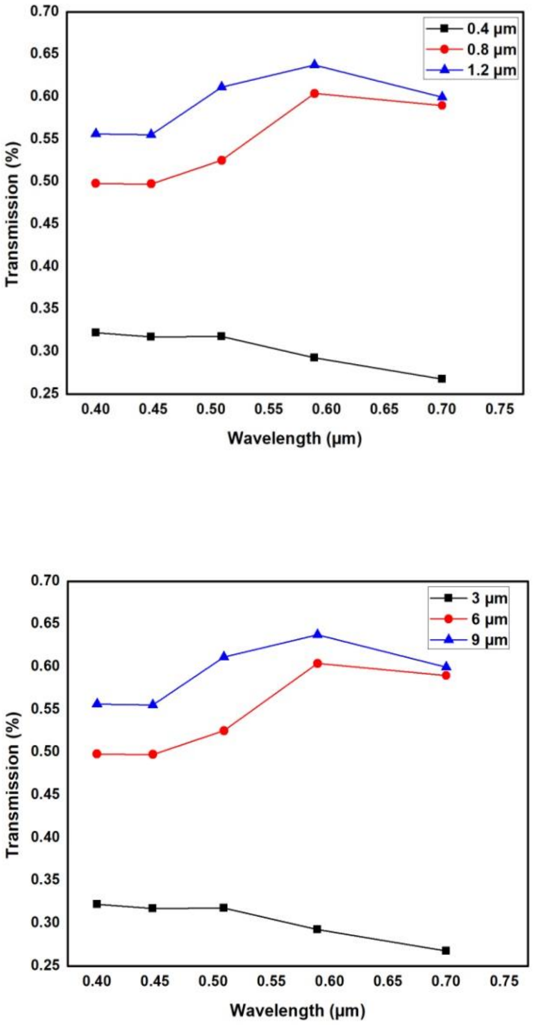


Figure 4: Input and output spectrum of the femtosecond pulse passing through a 100 meter long hollow core photonic crystal fiber the core filled with Xenon gas



(a)

(b)

Figure 5: Transmission (%) vs. wavelength plot for (a) conventional optical fiber and (b) designed hollow core photonic crystal fiber

3. Conclusion

The investigation reveals an important advantage: the spectral broadening of femtosecond pulses within hollow core photonic crystal fibers far outperforms what can be achieved with conventional optical fibers. This substantial enhancement can be attributed to the distinct properties inherent in these advanced fibers. Their exceptional adaptability sets them apart, allowing dispersion properties to be tailored precisely. This adaptability is realized through the flexibility within the design of photonic crystal fibers, which permits adjustments to their structural parameters. The significance of this flexibility is the ability to finely tune the dispersion characteristics of photonic crystal fibers to match specific requirements. The research showcases a significant advancement, underscoring the considerable superiority of hollow core photonic crystal fibers in terms of spectral broadening, in comparison to conventional fibers. The capability to engineer fibers with finely tuned dispersion properties opens up innovative approch across many fields of optics and photonics.

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