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Design of three layered step index fiber for femtosecond pulse delivery at 1550 nm wavelength

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ABSTRACT

This paper presents the design and numerical analysis of a step index three-layered fiber optimized for single-mode operation at a wavelength of 1550 nm. The fiber exhibits an extraordinary mode area, measuring 2020 µm², enabling the delivery of ultra-short pulses without distortion. We have used the Transfer Matrix Method for analysis and the Split-Step Fourier Method to solve the nonlinear Schrödinger equation. The study also incorporates considerations for Raman scattering response and self-steepening phenomena in the analysis, enhancing the comprehensive understanding of the proposed step index three-layered fiber for single-mode operation. Demonstrating the propagation of 100-fs pulses with a peak power of 57.7 kW over a 3.4 m length, the fiber maintains a dispersion length-to-nonlinear length ratio of 1 to ensure pulse fidelity. This research offers insights into designing high-performance optical fibers for efficient and distortion-free pulse transmission in ultra-fast laser applications.

INTRODUCTION

Ultra-short pulse (USP) lasers have become indispensable tools in various fields including micro-machining [1], laser ablation of solids [2], femtochemistry [3], multiphoton fluorescence microscopy[4], terahertz generation and detection[5],and frequency combs[6]. The ability to generate ultra-short pulses with durations typically on the order of femtoseconds or picoseconds opens up a wide array of applications due to their unique properties such as high peak powers and precise temporal control.

Advancements in high-power fiber amplifiers and specialty optical fibers have revolutionized the landscape of USP laser systems, providing enhanced performance and versatility. These developments have paved the way for compact, reliable, and cost-effective USP laser sources, capable of meeting the evolving demands of industrial and scientific applications. To deliver these pulses at desired location Traditional free space optics, while effective, suffer from design complexities, lack of compactness, and maintenance challenges, limiting their utility in practical settings. This drawback underscores the need for alternative solutions, such as optical fibers capable of delivering high peak power USPs, which can address these limitations and enable the creation of more versatile and portable systems.

The preference for single-mode fibers over their multimode counterparts arises from their intrinsic ability to prevent mode conflict and intermodal dispersion, ensuring a higher level of performance in the transmission of optical signals. In optical systems where preserving the integrity of pulse characteristics is predominant, single-mode fibers offer an extensive range of pulse preservation. By confining light to a single well-defined mode, these fibers ensure minimal dispersion, enabling the faithful transmission of ultra-short laser pulses over long distances without significant degradation. However, while single-mode fibers mitigate the likelihood of mode coupling, their design also introduces nonlinearities due to the tight confinement of pulses within the narrow core region. The interaction of femtosecond pulses with the small core of standard optical fibers leads to exceedingly high optical power densities, reaching the gigawatt per square centimeter range. Such intense power levels can induce optical damage and introduce nonlinear effects, such as self-phase modulation (SPM), which distorts the pulse waveform.

To mitigate the adverse effects of SPM, one viable strategy is to employ large-core fibers to reduce the optical power density[7]. However, conventional large-core fibers introduce challenges of their own. Intermodal dispersion within these fibers can severely distort ultra-short pulses, compromising their integrity. Additionally, the presence of multiple modes in multi-mode fibers leads to poor beam quality, further exacerbating the issue.

Preserving the fidelity of the pulse during propagation through the fiber necessitates the mitigation of dispersion and nonlinear effects. Dispersion can be managed through techniques like applying suitable frequency chirp to the input pulses. Meanwhile, addressing nonlinear effects requires a delicate balance between increasing the mode area by enlarging the core size and reducing the numerical aperture (NA) to maintain single-mode operation[7].

However, this balancing act presents its own set of challenges. Decreasing the NA to reduce nonlinearity results in heightened bending loss due to weakened mode confinement. Conversely, increasing the core radius can lead to multi-mode cross-coupling, which undermines the single-mode operation crucial for high-resolution microscopy applications.

Thus, the pursuit for single-mode fibers with a large mode area becomes imperative. Such fibers strike a delicate balance, offering a wider core diameter to mitigate nonlinear effects while maintaining the advantages of single-mode operation. By providing a larger cross-sectional area for the optical field, these fibers effectively reduce the optical intensity, minimizing nonlinearities and preserving the integrity of ultra-short laser pulses[8].

The development of single-mode fibers with a large mode area holds significant promise for a multitude of applications. From enabling the efficient delivery of high-power laser beams for material processing to enhancing the performance of optical communication networks, these fibers play a pivotal role in advancing various fields of science and technology. In the pursuit of single-mode fibers with a large mode area, researchers employ innovative design strategies and advanced fabrication techniques. These endeavors aim to optimize the core structure while minimizing mode coupling and maintaining single-mode operation. Researchers have explored various specialty fibers, including photonic crystal fibers (PCF's)[7,9], photonic band gap fibers (PBG's)[10], Omni Guide fibers[11], multi-mode high dispersion fibers[12], rigid glass rod fibers[13], and higher-order mode fibers[14], to address challenges in optical devices. Glass rod fibers have garnered attention due to their large mode area and low susceptibility to mode coupling, yet their compact packaging remains problematic for long-length devices.

PCF's offer higher modal purity by designing a large differential leakage loss between modes, but still face challenges with modal coupling. Hollow core photonic bandgap fibers show promise by significantly reducing optical nonlinearities compared to silica-core fibers. However, guiding laser beams through the hollow core precludes the construction of distributed amplifiers using rare earth dopants. Each specialty fiber type presents unique advantages and limitations, reflecting ongoing efforts to optimize optical device performance. To obtain the above condition of large mode area with single mode operation we have designed a three layered step index fiber for the delivery of pulses of wavelength 1550 nm. Step-index optical fibers offer advantages over other fibers due to their simplicity and cost-effectiveness. The core has a uniform refractive index, facilitating easier manufacturing and alignment. This design simplifies signal transmission, making step-index fibers suitable for short-distance communication and sensing applications. Their straightforward structure also results in easier signal coupling and splicing processes. The fiber exhibits an extraordinary mode area, measuring 2020 μm², enabling the delivery of ultra-short pulses without distortion. Fiber has shown the distortion-less delivery of 100-fs pulses with a peak power of 57.7 kW over a 3.4 m length.

METHOD OF ANALYSIS

Transfer Matrix Method has been used to analyse the fiber. To pulse propagation we have used split –step Fourier method. In split-step Fourier method we have solved second order Non-linear Schrodinger equation

Transfer Matrix Method

The transfer matrix method is a fundamental tool in analyzing the propagation of light within optical fibers. In this context, optical fibers are composed of multiple layers with different refractive indices, typically a core surrounded by cladding. The method involves dividing the fiber into infinitesimally thin slices, each characterized by a transfer matrix that relates the electric field amplitudes and phases at the boundaries of the slice.By cascading these transfer matrices along the length of the fiber, one can determine how the electric field evolves as light travels through the fiber. This allows for the calculation of important properties such as the transmission coefficient, modal distribution, and polarization effects.The transfer matrix method is particularly valuable in analyzing the behavior of light in optical fibers with complex structures, such as those with multiple cores or varying refractive index profiles. It provides a systematic approach to understanding how different factors, such as core size, numerical aperture, and wavelength, affect light propagation within the fiber.Through its ability to model the intricate interactions of light with the fiber's structure, the transfer matrix method enables the design and optimization of optical fiber-based devices and systems, including telecommunications networks, sensors, and laser systems. Its versatility and accuracy make it an indispensable tool in the field of optical fiber optics.

Split-step Fourier method for pulse propagation in fiber:

Non-linear Schrodinger equation (NLSE) has been used to study the propagation of pulses through the fiber given by

$$\frac{\partial A(t,z)}{\partial z} + \frac{\alpha}{2}A + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \frac{\beta}{6}\frac{\partial^3 A}{\partial T^3} = i\Gamma\{(|A|^2 A) + \frac{\iota}{w_0}\frac{\partial(|A|^2 A)}{\partial T} - T_R A\frac{\partial |A|^2}{\partial T}\} \qquad (6)$$

Where, Γ is Fiber's non-linearity, α is fiber loss, β_3 denotes the fiber's third-order dispersion, and β_2 denotes the fiber's second-order dispersion. The central frequency is denoted by ω_0, the Raman constant by T_R and the pulse envelope amplitude at spatial position z in time t is represented by A(t, z). The value of β_2 and β_3 can be calculated by using the following relation [15].

$$\beta_2 = -D\frac{\lambda^2}{2\pi C} \qquad \beta_3 = \frac{\partial D}{\partial \lambda} \qquad (7)$$

Nonlinearity parameter is defined as

$$\Gamma(\omega_0) = \frac{n(\omega_0)\omega_0}{cA_{eff}} \qquad (8)$$

Where, n is the Non-linear refractive index of the fiber material.

The Split-step Fourier method yielded the solution to the Non-linear Schrodinger equation (6). The pulses are distorted along the fiber's length by dispersion and nonlinearity. The fiber's length is first divided into segments. The pulses propagate from segment to segment. Dispersion and nonlinearity act independently in the fiber. We consider the pulses propagate for the small length h. Dispersion is at play and nonlinearity is zero in the first step. The next step has zero dispersion and nonlinearity acts. Accuracy can be achieved when pulses propagate from z to z+h. At the end of the fiber, both effects dispersion and nonlinearity compensate each other. The dispersion length L_D and nonlinear length L_{NL} indicated in the following equations reflect the effects of these parameters [15].

$$L_D = -\frac{2\pi c\tau^2}{\lambda_0^2 D} L_{NL} = \frac{\lambda_0 A_{eff}}{2\pi np} \qquad (9)$$

where n is the nonlinear refractive index of the fiber material, P is the peak power, τ represents the pulse duration, λ_0 represents the center wavelength, and c is the speed of light in a vacuum. D represents the dispersion and is given by

$$D = -\frac{\lambda_0}{C}\frac{d^2 n_{eff}}{d\lambda_0^2} \qquad (10)$$

P represents peak power and is given by

$$p = \frac{\lambda_0^3 D A_{eff}}{4\pi^2 cn\tau^2} \qquad (11)$$

The fiber's effective area of mode (A_{eff}), is a measure of the power density inside the fiber. The effective area has a strong influence on nonlinear effects in the fiber [10].

1. Fiber design

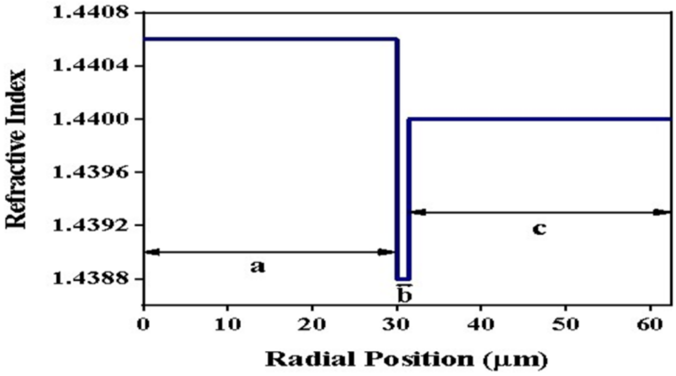
When laser pulses propagate through optical fibers, they encounter various challenges stemming from material dispersion and nonlinear effects induced by their confinement within the fiber's small core. Even pulses with moderate peak powers can undergo distortion during propagation, primarily due to these nonlinearities and dispersion effects. Achieving distortion-free propagation of ultra-short pulses (USP's) in a fiber necessitates striking a delicate balance between pulse broadening caused by dispersion and pulse distortion caused by self-phase modulation (SPM)[7,8]. These phenomena are typically characterized by two parameters: the dispersion length (L_D) and the nonlinear length (L_{NL}).To mitigate the challenges associated with nonlinearities and dispersion in ultra-short pulse (USP) propagation through optical fibers, a three-layered step-index fiber structure has been designed. This innovative structure comprises a core with refractive index n_1, a depressed cladding with refractive index n_2, and an outer cladding with refractive index n_s.

The core, which plays a central role in guiding the light, is engineered with germanium (Ge) doping to achieve the desired refractive index n_1. This doping strategy enhances the core's refractive index, thereby facilitating efficient light confinement within the fiber. Surrounding the core is the depressed cladding, designed with fluorine (F) doping to achieve a lower refractive index n_2 compared to the core. This depressed cladding serves to reduce the effective mode area of the guided light, thereby mitigating nonlinear effects such as self-phase modulation. Finally, the outer cladding of the fiber is realized using pure silica, ensuring a refractive index $n_{s.}$

a=30 µm, b=1.5 µm, c=31 µm, n_1=1.4406, n_2=1.4388, n_3=1.4400

Where a represents core radius of the fiber, b width of depressed cladding and c is the width of the outermost layer. The parameters are carefully chosen at which the fiber shows single mode operation. The value of v-parameter which is less than 2.4 proves the single mode operation for the fiber. The v-parameter has been calculated from the eq as

$$V = k_0 a\sqrt{n_1^2 - n_2^2}$$

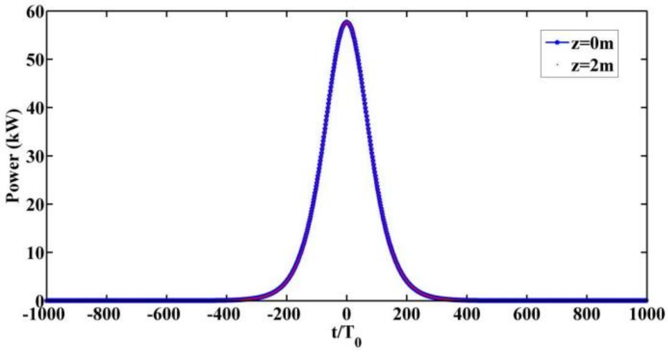


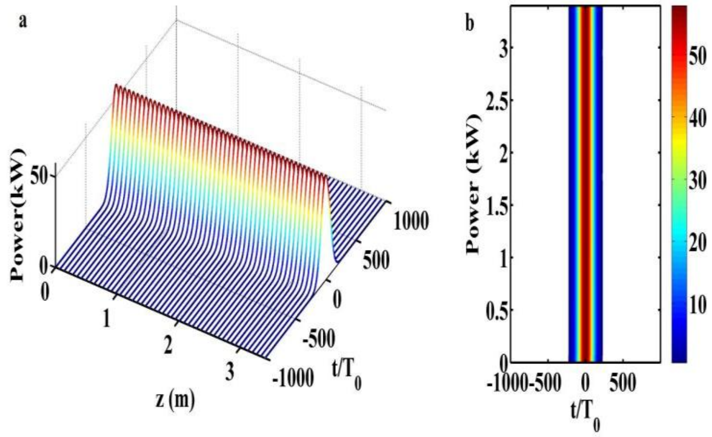
RESULT AND DISCUSSION

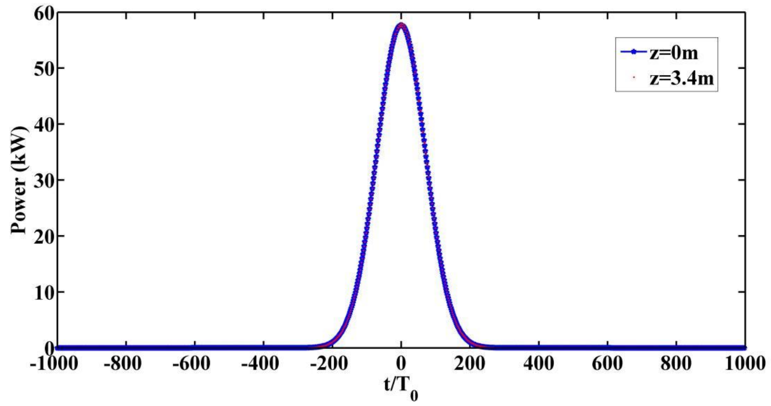
Pulse propagation within optical fibers is governed by the interplay of dispersion and non-linearity, encapsulated by the ratio L_D/L_{NL}, with L_D representing dispersion length and L_{NL} denoting non-linear length, as derived from equation [15]. This ratio serves as a crucial gauge for the behavior of pulse evolution along the fiber. When L_D/L_{NL} is less than 1, dispersion takes precedence over non-linearity, leading to pulse broadening in the absence of any chirp. Alternatively, when L_D/L_{NL} exceeds 1, non-linearity dominates, resulting in a distortion of the pulse shape. In the former case, without any initial chirp, pulses undergo broadening, while in the latter, compression or stretching is observed based on the chirp applied initially. At L_D/L_{NL} is approximately 1, dispersion and non-linearity harmonize, giving rise to fundamental soliton propagation. This delicate balance ensures that pulses neither excessively broaden nor distort, providing a stable platform for the transmission of information. The L_D/L_{NL} ratio, therefore, serves as a critical parameter in understanding and optimizing pulse dynamics within optical fibers[15].

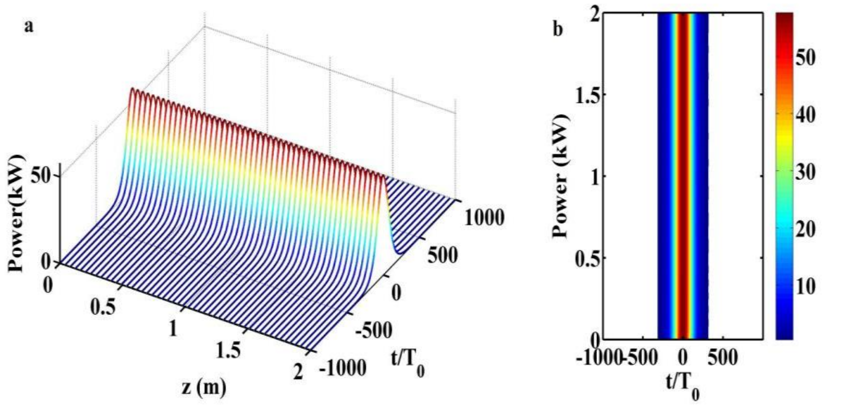
In our investigation of pulse propagation within a fiber, we employed a rigorous approach by solving the non-linear Schrödinger equation (eqn 6) using the split-step Fourier method. In the reported fiber, the value of dispersion at wavelength 1550nm is 21.8 ps/(nm/km). Fiber shows propagation of pulses 100 fs of Peak power 57.7 kW. We have taken the value of $n=2.4\times10^{20}$ m^2/w. Both Raman scattering and Self-steepening were considered in our simulations. Self-steepening, (s), is defined as $s = 1 / \omega_0\tau$ where, ω_0 is the central frequency of the pulse and τ is its width. The definition of the Raman scattering method is $\tau_{R=}$ T_R/τ where T_R represents the Raman time constant [1]. The value of T_R=3 fs at a wavelength of 1550 nm has been utilized.

Maintaining a delicate equilibrium between non-linearity and dispersion, we set L_D/L_{NL} equal to 1, effectively compensating for the interplay between these two critical factors. Our calculations involved meticulous consideration of third-order and second-order dispersion, revealing a calculated third-order dispersion in the power of 10^{-5}. This fine-tuned value plays a pivotal role in counteracting the nonlinear effects within the fiber, ensuring a balanced and stable propagation of pulses. The robustness of our model lies in its ability to account for these intricate details, providing valuable insights into the dynamic behavior of pulses within optical fibers. We examined how sech and Gaussian pulses propagate through the fiber. The fiber delivers 100 fs Gaussian pulses without distortion up to 2.3 m and sech pulses with a peak power of 85.4 kW up to 1.4 m. Figure 2 displays the input-output profile of Gaussian pulses along the 2.3 m fiber length, while Figure 3(a) illustrates the pulse evolution, and Figure 3(b) shows the corresponding contour profile. In addition to Gaussian pulses, sech pulses were investigated, with their input-output profile presented in Figure 4. The evolution of sech pulses and their contour profile after traversing 1.4 m is depicted in Figures 5(a) and 5(b). Remarkably, distortion-less delivery was achieved for both Gaussian and sech pulses, further underscoring the fiber's robust performance.









CONCLUSION

We've designed a step-index fiber tailored for the precise delivery of femtosecond laser pulses. This fiber exhibits exceptional performance, seamlessly transmitting 100 fs pulses with a peak power of 57.7 kW at a wavelength of 1550 nm. Ensuring single-mode operation with a large mode area, our fiber guarantees distortion-free delivery over lengths of 3.4 m and 2 m for Gaussian and sech pulses, respectively, as demonstrated through rigorous numerical simulations. With its proven capability for high-power pulse transmission and minimal distortion, this fiber emerges as a superior choice for a wide array of optical communication and sensing applications, promising unparalleled reliability and efficiency in demanding scenarios.

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Author Contributions

Manju: Writing the initial and final draft of the manuscript reviewing and editing. Fiber design, data collection and analysis.

Swati: Helps in data collection.

Babita: Supervision.

Data Availability

Data that supports the research will be made available upon reasonable request. We believe in the importance of open and transparent research practices and are committed to providing access to our data to promote collaboration and further scientific inquiry.

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