Investigation of Tapered Fiber for Ultrafast Application

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Abstract

Supercontinuum generation (SCG) is a nonlinear optical phenomenon that enables the transformation of narrowband ultrafast laser pulses into a broad, continuous spectrum. This study presents a detailed investigation into the performance of tapered and untapered optical fibers specifically standard single-mode fiber (SMF-28) and photonic crystal fiber (PCF) for SCG under ultrashort pulse excitation. Using a 1060 nm femtosecond laser source with 30 fs pulse duration, we conducted numerical simulations based on the Generalized Nonlinear Schrödinger Equation (GNLSE) in MATLAB. Key nonlinear effects including self-phase modulation, four-wave mixing, Raman scattering, and soliton dynamics were analyzed in both fiber types. The simulation results demonstrated significant spectral broadening, with the output spectrum extending from 500 nm to 1300 nm, confirming efficient supercontinuum generation. This work provides critical insights into the design and optimization of fiber geometries for ultrafast optical applications and lays the groundwork for compact, broadband light sources used in spectroscopy, biomedical and high-speed optical communication

Keywords: Supercontinuum Generation (SCG), Single-Mode Fiber (SMF-28), Photonic Crystal Fiber (PCF), Nonlinear Optics, Self-Phase Modulation (SPM), Raman Scattering.

Introduction

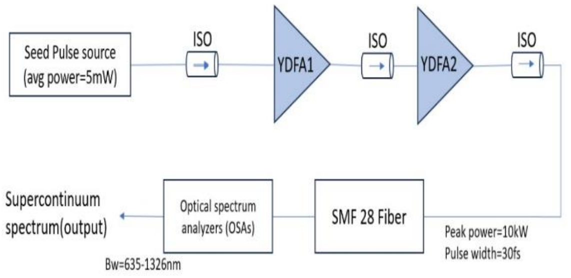
In recent years, the demand for broadband light sources has surged across numerous scientific and industrial domains, including biomedical imaging, optical coherence tomography (OCT), spectroscopy and high-speed telecommunications. Among the various technologies enabling broadband generation, *supercontinuum generation (SCG)* in optical fibers has emerged as a highly efficient and compact solution. SCG is a nonlinear optical process in which a narrowband ultrafast laser pulse undergoes extreme spectral broadening when propagated through a nonlinear medium, resulting in the formation of a continuous and wide optical spectrum.

Optical fibers, due to their excellent light confinement, long interaction lengths, and controllable dispersion characteristics, serve as ideal platforms for SCG. Specifically, *single-mode fibers (SMF)* and *photonic crystal fibers (PCF)* have proven to be effective media for generating high-brightness supercontinuum light. However, to further enhance the nonlinear effects and tailor the dispersion profiles, researchers have increasingly explored the use of *tapered fiber.*

This research presents a comprehensive investigation into the role of tapered optical fibers in enhancing supercontinuum generation. Using a femtosecond pulsed laser at 1060 nm, we simulated pulse propagation through both untapered SMF-28 and tapered PCF fibers by solving the Generalized Nonlinear Schrödinger Equation (GNLSE) in MATLAB. The study focuses on the influence of key parameters—such as fiber geometry, dispersion, and pulse characteristics—on spectral broadening and energy distribution across the supercontinuum.

By comparing tapered and untapered fiber configurations, this work aims to establish a deeper understanding of how structural modifications in fiber design can optimize nonlinear performance. The insights gained not only contribute to the fundamental knowledge of ultrafast fiber optics but also pave the way for the development of compact, tunable, and high-efficiency supercontinuum sources suitable for real-world ultrafast photonic applications.

Block Diagram



Methodology

This study investigates supercontinuum generation (SCG) using ultrashort laser pulses in optical fibers, emphasizing the role of fiber tapering on spectral broadening. The experimental setup is represented by a block diagram consisting of seven key components: a seed laser, optical isolators, dual-stage Ytterbium-Doped Fiber Amplifiers (YDFA1 and YDFA2), a single-mode fiber (SMF), and an Optical Spectrum Analyzer (OSA). Each component plays a critical role in ensuring efficient SCG and system stability.

1. Seed Laser

The experiment begins with a femtosecond pulsed seed laser emitting at 1060 nm with a typical average power of 5 mW. This wavelength is carefully selected due to its position near the zero-dispersion wavelength of the SMF-28 fiber, which enhances nonlinear interactions. The pulse duration is approximately 30 fs, enabling the generation of high peak powers essential for nonlinear effects in the fiber.

2. Optical Isolators (ISO)

Isolators are placed between the seed laser and the amplification stages to prevent back-reflected light from destabilizing or damaging upstream components. These devices allow unidirectional light flow and are crucial for maintaining system safety and signal integrity during amplification.

3. Ytterbium-Doped Fiber Amplifier Stage 1 (YDFA1)

The first amplification stage boosts the low-power seed signal to an intermediate level while preserving pulse integrity. The gain medium, Ytterbium-doped fiber, is chosen for its compatibility with the 1060 nm wavelength and its high gain efficiency. Proper pump diode alignment and current regulation ensure noise-free amplification.

4. Ytterbium-Doped Fiber Amplifier Stage 2

The second amplification stage further increases the pulse energy to reach the nonlinear threshold required for supercontinuum generation. Care is taken to manage amplified spontaneous emission (ASE) and avoid pulse distortion, ensuring the output remains suitable for effective nonlinear propagation in the fiber.

5. Fiber (SMF-28 or PCF)

After amplification, the high-power pulse is launched into a 15 cm section of fiber—either a standard SMF-28 or a specially tapered photonic crystal fiber (PCF). In this region, intense light-matter interaction initiates a series of nonlinear effects.

6. Optical Spectrum Analyzer

The output from the fiber is directed into an Optical Spectrum Analyzer, which measures and visualizes the resulting supercontinuum spectrum. The analyzer provides a high-resolution spectral profile, typically ranging from 635 nm to 1326 nm, allowing for bandwidth, flatness, and peak intensity evaluation.

7. Supercontinuum Output

The final output is a broad, continuous optical spectrum that encompasses visible and near-infrared wavelengths. This broadband light source is suitable for numerous applications including biomedical imaging, optical coherence tomography, spectroscopy, and telecommunications.

Results and Discussion

This section presents and analyzes the outcomes of supercontinuum generation (SCG) in both untapered single-mode fiber (SMF-28) and photonic crystal fiber (PCF) configurations using a femtosecond laser source at 1060 nm and at 832 nm. The numerical simulations were carried out using MATLAB, with the Generalized Nonlinear Schrödinger Equation (GNLSE) solved via the Split-Step Fourier Method. The focus is on comparing spectral broadening behavior, temporal evolution, and the influence of fiber tapering.

4.1 Supercontinuum Generation in SMF-28 Fiber

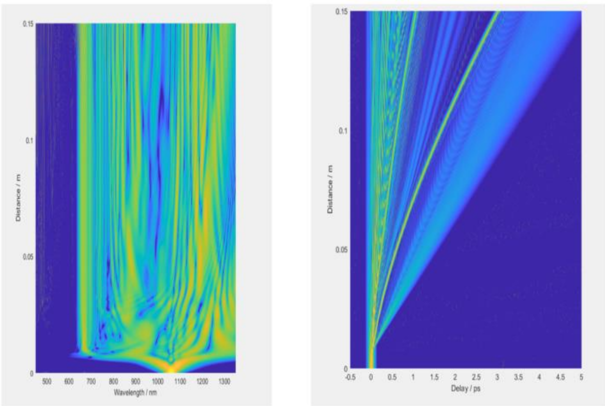


Fig 1: Supercontinuum using SMF 28 fiber

illustrates the spectral and temporal evolution of ultrashort pulses in a 15 cm SMF-28 fiber at 1060 nm. The input pulse undergoes significant spectral broadening (500–1300 nm) due to SPM, SRS, and FWM. Temporal plots reveal pulse splitting and soliton dynamics, confirming strong nonlinear interactions and efficient supercontinuum generation.

4.2 Supercontinuum Generation in Photonic Crystal Fiber (PCF)

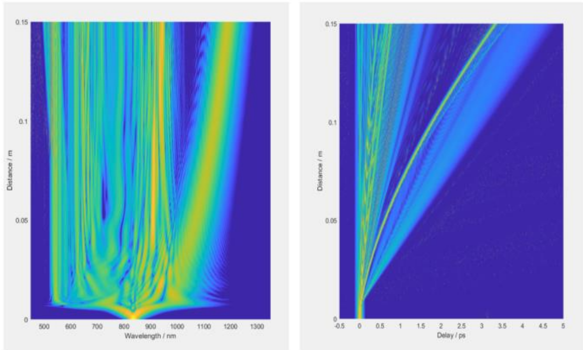
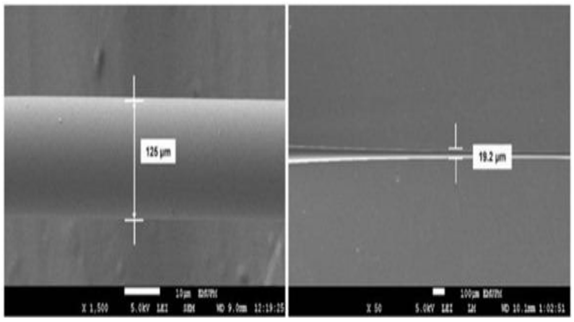


Fig 2 : Supercontinuum using PCF fiber

Output for simulation results for PCF at 832 nm. The output spectrum shows broader and flatter expansion than SMF-28, enhanced by tapering and tight mode confinement. Temporal evolution indicates soliton fission and dispersive wave formation, demonstrating PCF’s superior nonlinear performance.

4.3 Fiber Tapering Impact



Tapered and Untapered Fiber Comparison This figure compares the physical structure of a tapered and untapered optical fiber. The tapered fiber shows a reduced core diameter, which enhances the effective nonlinear coefficient by concentrating the optical field. This structural modification increases the interaction between light and the medium, allowing more efficient nonlinear effects at lower power levels.

As a result, tapered fibers demonstrate improved bandwidth and spectral uniformity, making them more suitable for broadband and compact supercontinuum source development.

Future Scope

1. **Use of Alternative Nonlinear Media**
   Exploring advanced fiber types such as hollow-core photonic crystal fibers, highly nonlinear chalcogenide fibers, or silicon-based waveguides could enable even broader spectral generation and integration into compact systems.
2. **Integration into Compact Photonic Systems**
   The miniaturization and packaging of supercontinuum sources into plug-and-play photonic modules can facilitate their deployment in fields like biomedical imaging, remote sensing, and optical coherence tomography (OCT).
3. **Machine Learning–Driven Optimization**
   Incorporating AI and machine learning algorithms to dynamically adjust input pulse parameters and fiber geometries can result in self-optimizing SCG systems that adapt to environmental and operational changes in real time.
4. **High-Power and High-Repetition Rate Operation**
   Extending SCG to high-average-power and high-repetition-rate laser regimes will be important for industrial scalability, requiring further investigation into thermal management, nonlinear thresholds, and fiber damage mechanisms.
5. **Tunable and Application-Specific Supercontinuum Sources**
   Designing application-targeted SC sources with user-defined bandwidths (e.g., visible for microscopy, near-infrared for telecommunications) could open commercial opportunities across multiple industries.

Conclusion

This research comprehensively explored the generation of supercontinuum (SC) spectra through numerical simulation and analysis of tapered and untapered optical fibers. By employing ultrashort femtosecond pulses at 1060 nm in SMF-28 and at 832 nm in PCF fibers, and simulating the propagation using the Generalized Nonlinear Schrödinger Equation (GNLSE) in MATLAB, we successfully demonstrated significant spectral broadening driven by nonlinear phenomena such as self-phase modulation (SPM), four-wave mixing (FWM), Raman scattering, and soliton dynamics.

The results affirm that even with relatively short fiber lengths (15 cm), a broadband supercontinuum can be achieved.

This work not only establishes a strong theoretical and simulation foundation for supercontinuum generation but also opens avenues for designing compact, efficient, and application-specific broadband light sources suitable for fields such as spectroscopy, biomedical imaging, and high-speed optical communication.

References

[1] J. M. Dudley, G. Genty, and S. Coen, “Supercontinuum generation in photonic crystal fiber,” *Rev. Mod. Phys.*, vol. 78, no. 4, pp. 1135–1184, 2006. doi: 10.1103/RevModPhys.78.1135

[2] R. R. Alfano, *The Supercontinuum Laser Source: Fundamentals with Updated References*, 3rd ed. New York, NY, USA: Springer, 2016.

[3] F. W. Wise, A. Chong, and W. H. Renninger, “High-energy femtosecond fiber lasers based on pulse propagation at normal dispersion,” *Laser Photonics Rev.*, vol. 2, no. 1–2, pp. 58–73, Jan. 2008. doi: 10.1002/lpor.200710022

[4] A. V. Husakou and J. Herrmann, “Supercontinuum generation of higher-order solitons by fission in photonic crystal fibers,” *Phys. Rev. Lett.*, vol. 87, no. 20, p. 203901, 2001. doi: 10.1103/PhysRevLett.87.203901

[5] G. P. Agrawal, *Nonlinear Fiber Optics*, 6th ed. Academic Press, 2019.

[6] M. E. Fermann and I. Hartl, “Ultrafast fiber laser technology,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 1, pp. 191–206, Jan.–Feb. 2009. doi: 10.1109/JSTQE.2008.2007498

[7] M. Hofer, M. E. Fermann, F. Haberl, M. H. Ober, and H. Hochreiter, “Mode locking with cross-phase and self-phase modulation,” *Opt. Lett.*, vol. 17, no. 7, pp. 502–504, Apr. 1992. doi: 10.1364/OL.17.000502

[8] J. M. Chavez Boggio et al., “Spectral broadening in tapered photonic crystal fibers,” *J. Opt. Soc. Am. B*, vol. 24, no. 7, pp. 1449–1455, Jul. 2007. doi: 10.1364/JOSAB.24.001449