Optimization of Photonic Crystal Fiber Based Optical Sensors for Intelligent Optical Communication Sensing

Sandeep Vyas[1], Anand Nayyar[2]

[1]Post Doctoral Researcher, Lincoln University College, Petaling Jaya, Selangor Darul Ehsan-47301, Malaysia as the primary affiliation, [2]Duy Tan University, Da Nang, Viet Nam

Email ID: [1]sandypvyas@gmail.com, [2]anandnayyar@duytan.edu.vn

1. Introduction

1.1 Background of the Study

The process of supercontinuum generation has turned out to be one of the most significant nonlinear optical processes in recent times because of its ability to generate coherent sources of ultra-wideband light. Supercontinuum sources combine wide bandwidth with compact all-fiber design and are well suited for use in applications like precision metrology, biomedical imaging, broadband spectroscopy, optical coherence tomography, and photonic device characterization. The development of high-performance supercontinuum sources is thus a major research topic in optical communications and nonlinear optics [1-3].

Photonic crystal fibers (PCFs), or microstructured optical fibers (MOFs), are indispensable in supercontinuum formation due to their dispersion engineering capabilities, large nonlinearity coefficients, and tunable designs. In contrast to regular optical fibers, photonic crystal fibers have periodic arrangements of air holes throughout the fiber core, which allows for the engineering of parameters like dispersion, confinement losses, birefringence, and effective mode area. Due to these exceptional properties, PCFs are excellent candidates for nonlinear broadening [4-6].

1.2 Need for the Study

The increasing needs for broadband mid-infrared sources have been resulting in considerable requirements for highly efficient and compact supercontinuum generators. Although broadband radiation sources including synchrotrons can provide excellent radiation intensity and spectral coverage, these types of sources are rather expensive, bulky, and difficult to access, which limits their wide use. This way, nonlinear frequency conversion and supercontinuum generation inside optical fibers can be considered one of the most promising methods of development of broadband mid-IR sources. It is currently shown that chalcogenide PCFs can produce ultra-broadband supercontinuum spectra covering several octaves. However, supercontinuum generation is still quite challenging.

1.3 Research Problem

1) Traditional silica-based optical fibers are not compatible with the mid-infrared (mid-IR) regime because of their limited infrared transmission above 2.5 µm.
2) The chalcogenide or semiconductor-based photonic crystal fibers (PCFs) despite being highly nonlinear and mid-IR transparent, face issues including:
   • Manufacturing difficulties
   • Thermal instability
   • High propagation losses
3) Conventional silica-based optical fibers are unsuitable for mid-infrared (mid-IR) applications due to their limited infrared transparency beyond 2.5 µm.

4) Chalcogenide and semiconductor-based photonic crystal fibers (PCFs), although highly nonlinear and mid-IR transparent, suffer from:
   - Fabrication complexity
   - Thermal instability
   - High propagation losses
   - Sensitivity to geometrical imperfections
5) Simultaneously achieving the following optical characteristics remains a major challenge:
   - Low dispersion
   - High nonlinearity
   - Low confinement loss
   - High coherence
   - Broad spectral bandwidth

Therefore, the major research problem is the development of optimized photonic crystal fiber structures capable of generating broadband, coherent, stable, and power-scalable mid-IR supercontinuum spectra.

2. Literature Review

2.1 Review of Existing Studies

The following section presents a review of recent research works related to supercontinuum generation (SCG) in photonic crystal fibers (PCFs), chalcogenide waveguides, and mid-infrared nonlinear photonic structures. The reviewed studies highlight the importance of material selection, dispersion engineering, nonlinear optimization, and structural design for efficient broadband SC generation.

1) ***Anindya Saha et al. (2025)*** proposed a cascaded SiC–$AsSe_2$ waveguide structure for broadband mid-IR supercontinuum generation. Using a 50 fs pulse at 1550 nm with only 1 kW peak power, the design generated a spectrum spanning 1.41–12.43 µm. The study demonstrated that cascaded waveguides can achieve much broader spectral coverage compared to single-stage chalcogenide waveguides [1].
2) ***Lalkrishna et al. (2024)*** the optical characteristics of photonic crystal fibers of varying core sizes were examined through finite element analysis. Parameters studied included the fiber's birefringence, nonlinearity, effective area, confinement loss, and dispersion for wavelengths between 0.8 µm and 1.4 µm. The PCF fiber with the smallest core size showed the greatest nonlinearity and birefringence coefficients owing to high confinement of the light modes [2].
3) ***Genjian Yu et al. (2026)*** presented an all-solid chalcogenide microstructured fiber with cubic symmetry for coherent mid-IR supercontinuum generation. The optimized structure achieved octave-spanning spectra from 3210 nm to 7593 nm with improved nonlinearity and flat all-normal dispersion characteristics [3].
4) ***Deepak Garg et al. (2024)*** proposed a highly nonlinear ethanol-filled $Ga_8Sb_{32}S_{60}$ chalcogenide PCF for ultra-broadband supercontinuum generation in the mid-IR region. The designed fiber generated spectra from 1.5 µm to 14 µm using a 5 µm pump source with only 8 mm fiber length [4].
5) ***Deepak Garg et al. (2026)*** introduced a trench-assisted rib waveguide for enhanced broadband mid-IR supercontinuum generation. The trench-engineered structure reduced the effective mode area and significantly improved the nonlinear coefficient. Numerical results showed coherent spectral broadening from 1.7 µm to 6.2 µm under femtosecond pulse excitation [5].
6) ***Tianjiao Wang et al. (2026)*** experimentally demonstrated a high-power all-polarization-maintaining white-light supercontinuum source with 30.8 W average output power. The

generated spectrum covered 430–2400 nm using a three-stage PM-MOPA system and a 1.2 m PM-PCF [6].

2.2 Key Findings from Previous Research

Previous theoretical and numerical studies have demonstrated highly promising results for broadband mid-IR supercontinuum generation.

1. Chalcogenide-based photonic crystal fibers (PCFs) are considered highly promising platforms for mid-infrared (mid-IR) supercontinuum generation due to:
    a. High nonlinear refractive index
    b. Wide infrared transparency window
2. Researchers have successfully demonstrated broadband supercontinuum spectra extending:
    a. From near-infrared wavelengths
    b. Up to 15 µm in the mid-IR region
3. Efficient supercontinuum generation has been achieved using:
    a. Optimized PCF geometries
    b. Ultrafast laser pump sources
4. Dispersion engineering plays a crucial role in determining:
    a. Spectral flatness
    b. Coherence
    c. Bandwidth of the generated supercontinuum

3. Research Gap

3.1 Identified Knowledge Gaps

Even though great strides have been achieved in supercontinuum generation through photonic crystal fibers, there are still some important knowledge gaps that have remained.

1. Most research efforts have been devoted either towards achieving high bandwidth generation or increasing nonlinearity, but relatively little work has been done towards optimizing other parameters such as coherence, power scalability, thermal stability, and fabrication tolerance at the same time.
2. The other notable shortcoming has been in the use of smart optimization techniques such as Artificial Intelligence and Machine Learning in PCF design and dispersion engineering. The conventional 'trial-and-error' method turns out to be inefficient in doing so.

3.2 Limitations in Existing Studies

There are certain deficiencies in existing research. Chalcogenide fibers, although having high nonlinearity, have poor thermal characteristics and have very narrow manufacturing windows. Many PCF structures are very sensitive to changes in geometry, and therefore they display great dispersion and nonlinearity variations.

In addition, there are some broadband SC generation methods that demand the use of ultrashort pulses with very high peak power. There is another deficiency in the coherence of some systems caused by unstable nonlinear dynamics in the case of anomalous dispersion.

4. Research Objectives

1. To study and design optimum photonic crystal fibers (PCFs) that can generate broadband mid-infrared (mid-IR) supercontinua efficiently with coherence, high nonlinearity, low confinement loss, and flatness in their spectrum.
2. To examine the technique of dispersion and material optimization for generating supercontinua in the mid-IR regime.
3. To study the potential integration of intelligent optimization approaches, including Artificial Intelligence (AI) and Machine Learning (ML), for efficient PCF design and performance enhancement.

5. Hypotheses

5.1 Formulation of Hypotheses

Hypothesis 1

- Suitable photonic crystal fiber geometries can lead to enhanced broadband mid-IR supercontinuum generation.

Hypothesis 2

- A technique for designing photonic crystal fibers using AI/machine learning could be less computationally complex than trial and error simulation methods.

5.2 Testable Variables

Independent Variables	Dependent Variables	Controlled Variables
Air-hole diameter (d)	Supercontinuum	Simulation conditions
Pitch (Λ)	Spectral flatness	Boundary conditions
Fiber geometry	Coherence	Numerical methods
Pump wavelength	Nonlinear coefficient	
Pump pulse width	Confinement loss	
Peak power	Dispersion profile	
Fiber length	Thermal stability	

6. Scope and Significance

6.1 Scope of the Study

- The study focuses on supercontinuum generation in photonic crystal fibers operating in the mid-infrared spectral region.
- The research primarily investigates:
  - Chalcogenide-based PCFs
  - Semiconductor-based PCFs

  due to their high nonlinearity and wide transparency windows.
- The research also explores the application of:
  - Artificial Intelligence
  - Machine Learning

  for intelligent PCF optimization.
- The scope includes potential applications of mid-IR SC sources in:
  - Spectroscopy
  - Biomedical diagnostics
  - Environmental monitoring
  - Optical sensing

- Optical communication systems.

6.2 Importance of the Research

The mid-IR supercontinuum sources have become highly significant because of the numerous applications in molecular spectroscopy, bio-imaging, chemical sensors, environment monitoring, optical coherence tomography, and optical communication networks.

7. Summary

Photonic crystal fibers (PCFs) have become very promising candidates for the generation of broadband mid-IR supercontinuum thanks to their nonlinearity and dispersion management possibilities. Chalcogenide and semiconductor-based PCFs exhibit broad infrared transparency window and spectral broadening capacity. Yet, problems of complex manufacturing, thermal instability, losses and coherence control still exist. Advances in the field of dispersion engineering as well as artificial intelligence-based optimization have opened up novel prospects for creating PCF designs. Thus, additional investigation is needed for designing efficient and thermally stable mid-IR supercontinuum sources.

Reference:

[1] Saha, A., Sengupta, A., Rafi, R., Al Kayed, N., Karim, M.R., Akhtar, J., Reja, M.I.: Low-power telecom-pumped broadband mid-infrared supercontinuum generation in a SiC–AsSe2 cascaded waveguide. *Journal of Optics* 27(11), Article 115502 (2025). https://doi.org/10.1088/2040-8986/ae1c4d

[2] Sharma, L., Kumar, A.: Design and analysis of hexagonal astroid-like shaped core photonic crystal fiber for highly non-linear applications. *Journal of Optics* 54(3) (2024). https://doi.org/10.1007/s12596-024-01837-

[3] Yu, G., Huang, C.: Highly nonlinear microstructured chalcogenide optical fiber with high tolerance for coherent mid-infrared supercontinuum generation. *Optics Communications* 610, Article 133129 (2026).

[4] Garg, D., Khamaru, A., Kumar, A.: Supercontinuum generation in Ga-Sb-S chalcogenide-based PCF using optofluidic approach. *Microwave and Optical Technology Letters* (2024). https://doi.org/10.1002/mop.34316

[5] Garg, D., Kumar, A.: Trench-assisted silicon–germanium photonic rib waveguide for enhanced supercontinuum generation in mid-infrared regime. *Modern Physics Letters B* 40(10), Article 2650064 (2026). https://doi.org/10.1142/S

[6] Wang, T., Wang, T., Zhang, B., Liu, S., Hou, Y., Du, S., Li, B., Deng, G.: All-PM fiber supercontinuum source with 30.8W output average power and spectral span from 430 nm to beyond 2400 nm. *Optics Express* 34(6), 10788–10797 (2026). https://doi.org/10.1364/OE.583494