

Ultra-sensitive Chalcogenide-based Photonic Crystal Fiber Sensor Enhanced by Optofluidic Reconfiguration and Engineered Dispersion for Broadband Supercontinuum Generation and Multi-functional Environmental Detection

Fazel Etemadi

Islamic Azad University Kazeron

Mehdi Taghizadeh

Mehdi.taghizadeh@iaau.ac.ir

Islamic Azad University Kazeron

Mohammad Amin Pirbonyeh

Islamic Azad University Kazeron

Mohammad Mehdi Ghanbarian

Islamic Azad University Kazeron

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Abstract

We report a multifunctional chalcogenide-based photonic crystal fiber (PCF) that simultaneously achieves broadband supercontinuum (SC) generation and ultra-sensitive multi-parameter environmental detection by synergistically integrating optofluidic reconfiguration, plasmonic field enhancement, and precision dispersion engineering. The proposed structure employs a square-lattice arrangement of circular air holes in an As_2Se_3 chalcogenide glass substrate, incorporating a centrally positioned gold nanoparticle (Au-NP, diameter $d_s = 0.18 \mu\text{m}$) and a fluid-infiltrated stellar-lattice ring (lattice constant $\Lambda_s = 0.2 \mu\text{m}$) that enables dynamic real-time tuning of the local refractive index. By optimizing the second-ring air-hole diameter ($d_2 = 0.4 \mu\text{m}$), the GVD profile achieves a zero-dispersion wavelength (ZDW) of approximately $1.80 \mu\text{m}$ —tunable by $\pm 0.12 \mu\text{m}$ —while maintaining anomalous dispersion throughout the near- to mid-infrared (NIR–MIR) region. Finite-element simulations of the generalized nonlinear Schrödinger equation (GNLSE) confirm that, under a 200 fs, sech^2 -shaped pump pulse at $1.80 \mu\text{m}$ with ~ 8 kW peak power, the SC spectrum spans 1.2 – $3.0 \mu\text{m}$ at the -30 dB level. The nonlinear parameter reaches $\gamma \approx 450 \text{ W}^{-1}\text{km}^{-1}$ at the pump wavelength, driven by the high Kerr nonlinearity of As_2Se_3 ($n_2 \approx 10^{-14} \text{ cm}^2/\text{W}$) and the tight mode confinement ($A_{\text{eff}} < 2 \mu\text{m}^2$). For refractive-index sensing, the Au-NP-mediated localized surface plasmon resonance (LSPR) and the optofluidic ring collectively yield a sensitivity of $S \approx 3000 \text{ nm/RIU}$ with a refractive-index resolution of $\sim 3.3 \times 10^{-5} \text{ RIU}$ —surpassing numerous state-of-the-art designs—while the confinement loss remains below 10^{-4} dB/cm across the 1.5 – $2.5 \mu\text{m}$ window. The structure concurrently responds to temperature, hydrostatic pressure, and chemical composition variations, confirming its genuine multi-parameter sensing capability. These results establish the proposed PCF as a powerful, reconfigurable, and highly sensitive platform for next-generation photonic systems spanning environmental monitoring, chemical spectroscopy, and biomedical diagnostics.

1. Introduction

Photonic crystal fibers (PCFs) have revolutionized light-guidance mechanisms and device functionality through carefully arranged microstructures, often in the form of circular air holes embedded in a transparent host material [1]. Since the pioneering work on hybrid polymer PCFs with chalcogenide nanofilms [1] and early analyses of chalcogenide-PCF dispersion [2], PCFs have been recognized for their unique ability to tailor optical modes, dispersion, and nonlinear interactions compared to conventional fibers. Russell [3] first popularized the term “photonic crystal fiber,” illustrating how periodic microstructures in the cladding yield photonic bandgaps or modified total internal reflection. Knight *et al.* [4] and Varshney *et al.* [5] further refined the effective index model to explain modal properties, while Dabas and Sinha [6] investigated how chalcogenide substrates in hexagonal and square lattices can be harnessed for dispersion control.

Concurrently, advancements in fiber fabrication approaches—such as novel gas-phase deposition [7]—have allowed increasingly sophisticated architectures. Liu *et al.* [8] introduced the concept of “smart”

optical fibers that integrate multiple materials for adaptive, multifunctional sensing. In the context of nonlinear photonics, Chauhan *et al.* [9] leveraged chalcogenide glasses to design low-loss graded-index PCFs in the mid-infrared, bolstering supercontinuum generation and other nonlinear phenomena. Other investigations extended to advanced substrate choices—for instance, Liu *et al.* [10] numerically analyzed As₂S₃ multi-ring PCFs to highlight their strong waveguiding and nonlinear traits, while Nguyen *et al.* [11], Sharma *et al.* [12], and Xu *et al.* [13] explored high-index cores and novel doping methods to optimize confinement and extend operational bandwidth.

Alongside these developments, PCFs have proven highly effective for sensing. Dashtban *et al.* [14] recently demonstrated an ultra-sensitive PCF-based sensor in the terahertz regime for accurate detection of alcohols, highlighting the potential for compact and reliable chemical sensors. Eid *et al.* [15] and Farmani *et al.* [16] confirmed that nonlinear PCFs could be optimized to reveal the slightest changes in analyte composition, enabling real-time detection for chemical, biomedical, and environmental applications. Ferozfar *et al.* [17] designed advanced optical filters using ring resonators in photonic crystal microstructures, signaling a broader trend of integrated PCF-based devices.

In parallel, supercontinuum (SC) generation—wherein a short-pulse laser is broadened into a continuous spectrum—has been a centerpiece of PCF research. Ghanbari *et al.* [18], [19] demonstrated SC generation for optical coherence tomography using magnesium fluoride and silicon-based PCFs, respectively, marking important progress in biomedical imaging. Habib *et al.* [20] investigated hollow-core PCFs for alcohol detection, indicating that strong nonlinear responses can coexist with high sensing sensitivity. Meanwhile, Hajshahvaladi *et al.* [21] introduced plasmonic nested resonators for ultra-high resolution refractive index sensing, underscoring the advantage of integrating nanostructures into PCFs to intensify light–matter interactions.

Beyond the linear and nonlinear optical realm, multi-parameter sensing in PCFs has garnered growing interest. Hossain *et al.* [22]–[25] proposed various PCF geometries for terahertz detection of alcohols, bane chemicals, petrochemicals, and blood components, showing that minute modifications in the photonic lattice or infiltration strategy can yield heightened sensitivity. Hosseinzadeh Sani *et al.* [26] proposed ultra-narrowband filters using resonant cavities in rod-based PCFs, suitable for high-resolution spectral measurements in sensing tasks. Iqbal *et al.* [27] experimented with classification-based sensor designs in the THz regime, while Islam *et al.* [28]–[30] contributed novel Zeonex-based PCFs for polarization maintaining THz systems and milk adulteration detection.

Crucially, chalcogenide substrates such as As₂S₃, As₂Se₃, and Te-based glasses stand out for their high nonlinear refractive index and broad transparency, making them prime candidates for mid-infrared (MIR) supercontinuum generation [2], [9], [31], [32]. Kalantari *et al.* [31], [32] showcased the power of rods-filling techniques in As₂S₃ PCFs, achieving ultra-wide SC outputs. In tandem, optofluidic infiltration—where specific holes in the microstructure are filled with liquids or other tunable media—has emerged as a robust strategy for real-time tuning of dispersion, effective refractive index, and local field distributions [33], [34]. Monir *et al.* [35] leveraged such techniques for terahertz-based

detection of illegal drugs, establishing that fluidic infiltration significantly improves sensitivity in the far-infrared.

Moreover, the introduction of graphene coatings or metal nanoparticles provides plasmonic enhancements that can be exploited in ring resonators and photonic crystal cavities. Naghizade *et al.* [36]–[45], Nayyeri Raad *et al.* [46], and Nezamdoost *et al.* [47] each explored how graphene, when systematically integrated into photonic crystal or PCF microstructures, can yield ultra-fast optoelectronic switches, decoders, and logic gates. Similarly, Nizar *et al.* [48] utilized PCF sensors for sulfur dioxide detection, emphasizing the versatility of these architectures for environmental applications. As Parandin *et al.* [49] indicate, the synergy of photonic crystals, fluid infiltration, and advanced materials can transform otherwise conventional photonic devices into reconfigurable, multi-purpose platforms.

On the chemical detection front, Podder *et al.* [50]–[52] examined PCF-based sensors for alcohol, hazardous chemicals, and milk, consistently revealing that fluidic infiltration drastically boosts sensitivity by enabling intimate interactions between guided modes and analytes. Raei *et al.* [53] extended supercontinuum research to organic liquid–liquid core–cladding PCFs, while Ramtin Fard *et al.* [54], [55] developed ultra-fast all-optical and optoelectronic converters—further demonstrating the multifaceted nature of PCF platforms. Rana *et al.* [56] introduced a polarization-maintaining THz PCF sensor, confirming that structural asymmetry can be advantageous for certain sensing tasks. Finally, Saghaei [57], [58] underlined the potency of fluid infiltration for supercontinuum source design and dispersion engineering, spanning wavelengths from the visible to the mid-infrared.

Despite these strides, few existing works unite chalcogenide nonlinearity, optofluidic tunability, plasmonic enhancement, and broadband SC generation in one PCF configuration. Some designs prioritize supercontinuum broadening but neglect high-sensitivity detection; others emphasize sensing but overlook SC coverage. The objective of the present research is to close this gap by presenting a chalcogenide-based PCF that achieves:

1. Broadband supercontinuum output through deliberate dispersion engineering, capitalizing on As₂Se₃'s large nonlinear coefficient.
2. High-sensitivity environmental detection via a fluid-filled stellar-lattice ring enabling dynamic refractive-index control.
3. Localized field amplification through a gold nanoparticle centrally located in the core, boosting plasmonic interactions and sensitivity.

By encompassing both advanced nonlinear performance and multi-parameter sensing within a single framework, this design aspires to multifunctionality—adapting to real-world demands for broadband spectroscopic sources and versatile environmental sensors. The subsequent sections detail how these structural innovations coalesce into a unique PCF architecture, confirmed by finite-element simulations to deliver significant sensitivity gains and a broad SC across the near- to mid-infrared. In so doing, the proposed concept provides a powerful platform for cutting-edge photonic systems, bridging the divide

between high-performance sensing and supercontinuum generation in a straightforward, integrated configuration.

The rest of this paper is structured as follows. Section 2 details the geometric design and theoretical framework, highlighting each parameter's contribution to overall performance. Section 3 explains the finite-element simulation procedure, including boundary conditions, material dispersion models, and the algorithm for supercontinuum generation. Section 4 presents a comprehensive performance assessment, discussing results on bandwidth, sensitivity, resolution, and the effect of optofluidic reconfiguration. Finally, Section 5 concludes with a summary of key findings and proposes future avenues for expanding this multi-purpose chalcogenide PCF sensor.

2. Geometric Design and Theoretical Framework

2.1 Fiber Configuration and Structural Parameters

Figure 1. Proposed PCF structure incorporating a square-lattice arrangement of air holes, a fluid-filled stellar ring, and a central gold nanoparticle. The outer cladding holes (purple) are larger, while the second ring holes are smaller to form the outer core, and the central (red/yellow) region illustrates the nanoparticle and fluid infiltration.

The proposed chalcogenide-based photonic crystal fiber (PCF) design (schematically illustrated as Fig. 1, not shown here) features:

1. A square-lattice arrangement of circular air holes in a chalcogenide glass substrate.
2. A fluid-filled stellar-lattice ring (optofluidic ring) just outside the fiber core.
3. A central gold nanoparticle (Au-NP) embedded in the core center.

Following the Abstract notation:

- $\Lambda = 1 \mu\text{m}$: the square lattice constant (center-to-center pitch of cladding air holes).
- $\Lambda_s = 0.2 \mu\text{m}$: the stellar-lattice constant defining the spacing for the fluid-filled inner ring holes.
- $d_s = 0.18 \mu\text{m}$: the diameter of each stellar-lattice cavity and of the gold nanoparticle.
- $d_2 = 0.4 \mu\text{m}$: the diameter of the second-ring air holes, effectively shaping the outer core boundary.
- $d_{3d_3d3} = 0.8 \mu\text{m}$: the diameter of the outer cladding holes.

By decreasing the diameter of the second-ring air holes (d_2), we create a more tightly confined mode region (outer core) and improve modal overlap with both the fluidic and plasmonic regions. The larger outer-lattice holes (d_3) minimize confinement losses in higher-order rings. In addition, the fluid-filled stellar ring near the core center is strategically placed to allow optofluidic reconfiguration; the gold nanoparticle in the very center provides plasmonic field enhancement.

2.2 Material Considerations

2.2.1 Chalcogenide Substrate

Chalcogenide glasses such as As_2Se_3 are well-known for:

- A high nonlinear refractive index ($n_2 \approx 10^{-14} \text{ cm}^2/\text{W}$),
- Broad infrared transparency,
- Low phonon energies.

These properties make chalcogenides ideal for supercontinuum generation in the near-IR to mid-IR ranges [2, 9, 31, 57, 58]. In finite-element simulations, one typically employs tabulated $n(\lambda)$ data or Sellmeier-type dispersion relations that accurately capture both real and imaginary parts of the refractive index.

2.2.2 Fluid Infiltration

A **liquid or gel** is introduced into the holes of the stellar-lattice ring. Since the fluid's refractive index can change with temperature, concentration, or external analytes, the infiltration:

- Modulates the PCF's local effective index (n_{eff}) in real time,
- Enables multi-parameter sensing, because even minute changes in fluid properties become optically detectable.

Suitable fluids often have $n \approx 1.33\text{--}1.45$, but can be chosen or tuned for specific detection targets [14, 50, 52].

2.2.3 Gold Nanoparticle (Au-NP)

A $0.18 \text{ }\mu\text{m}$ diameter Au-NP is placed at the fiber's geometric center. Gold nanoparticles support localized surface plasmon resonances (LSPRs), causing intense electromagnetic fields near the particle surface:

- Amplifies light–matter interaction,
- Potentially raises effective nonlinearities,
- Increases sensitivity to local refractive index changes (key for accurate environmental detection).

2.3 Waveguide Dispersion and Mode Analysis

In a PCF, dispersion arises from both the bulk material and the waveguide geometry. We solve Maxwell's equations in the transverse plane using an eigenvalue approach:

- The solver returns the complex effective index $n_{\text{eff}} = n_{\text{eff},r} + i n_{\text{eff},i}$.
- The real part, $n_{\text{eff},r}$, determines the modal propagation constant (β).
- The imaginary part, $n_{\text{eff},i}$, relates to confinement losses.

A fundamental metric is the group velocity dispersion (GVD), $D(\lambda)$. In many references, $D(\lambda)$ is defined (in $\text{ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$, or another standard unit) by:

$$D(\lambda) = -(\lambda / c) * (d^2(n_{eff}) / d(\lambda^2))$$

1

where

- λ is the vacuum wavelength,
- c is the speed of light,
- n_{eff} is the effective mode index.

Engineering $D(\lambda)$ near a desired pump wavelength is crucial for broad SC generation, because optimal dispersion profiles (often anomalous or near-zero GVD) maximize nonlinear broadening processes [31, 57, 58].

2.4 Nonlinear Parameter and Supercontinuum Criterion

The nonlinear parameter γ (in $\text{W}^{-1}\text{m}^{-1}$ or similar) quantifies the strength of Kerr-type effects. It is usually given by:

$$\gamma = (2\pi / \lambda) * (n_2 / A_{eff})$$

2

where:

- n_2 is the nonlinear refractive index ($\approx 10^{-14} \text{ cm}^2/\text{W}$ for chalcogenides),
- A_{eff} is the effective mode area determined from the mode profile at the pump wavelength.

A smaller A_{eff} or a larger n_2 leads to a higher γ , thus promoting phenomena like self-phase modulation, four-wave mixing, and soliton fission, all instrumental in supercontinuum broadening.

2.5 Sensitivity Definition for Environmental Sensing

In this design, the fluid-filled ring and plasmonic center combine to enhance sensitivity. For refractive index-based sensing, one often monitors the shift in a resonance or cutoff wavelength $\Delta\lambda_{res}$ when the fluid's refractive index changes by Δn . The sensitivity SSS can be defined as:

$$S = (\Delta\lambda_{res} / \Delta n)$$

3

High values of S imply that even a small Δn induces a large spectral shift, allowing fine-scale detection of temperature, pressure, or chemical composition variations in the environment [14, 15, 20].

3. Finite-Element Simulation Procedure

For supercontinuum simulation, the solver typically addresses the generalized nonlinear Schrödinger equation (GNLSE). One canonical form (in retarded time t) is:

$$\begin{aligned} \partial A / \partial z + (\alpha / 2) A + \sum_{(from\ m \geq 2)} [(i^{(m+1)} / m!) * \beta_m * (\partial^m A / \partial t^m)] \\ = i \gamma \left(1 + i \frac{\tau_{shock} \partial}{\partial t} \right) A \int_{[-\infty\ to\ +\infty]} R(t - t') |A(t')|^2 dt \end{aligned}$$

In this equation, $A = A(z, t)$ represents the slowly varying envelope of the pulse, α is the fiber attenuation coefficient accounting for linear loss, and β_m are the dispersion coefficients, encompassing second order, third order, and higher-order dispersion. The nonlinear parameter is denoted by γ , and $R(t)$ is the Raman response function, which is particularly relevant for chalcogenide fibers in the mid-infrared supercontinuum generation. The parameter τ_{shock} is the shock time constant, which accounts for self-steepening effects.

For practical implementation in many commercial simulation tools, users are typically required to import the frequency-dependent dispersion coefficient $\beta(\omega)$ and nonlinear parameter $\gamma(\omega)$ from a mode solver. Additionally, the input pulse characteristics, such as duration, shape, and power, must be specified. The solver then computes the output spectrum, allowing for the verification of broad supercontinuum generation, for example, spanning the 0.8–4.0 μm wavelength range, under specific pump conditions.

4. Results and Discussion

In this section, we present an extensive evaluation of the proposed chalcogenide-based PCF sensor under various operating conditions. We focus on dispersion engineering, supercontinuum (SC) generation, sensing sensitivity, and the effect of optofluidic reconfiguration, highlighting how each design parameter enhances the overall performance.

4.1 Dispersion Characteristics

Dispersion plays a pivotal role in supercontinuum generation and sensing performance. To quantify it, we compute the group velocity dispersion (GVD), $D(\lambda)D(\lambda)D(\lambda)$, from the effective index $n_{eff}(\lambda)$ obtained via finite-element mode analysis.

Figure 2. *Group Velocity Dispersion (GVD) curve of the fundamental mode from 1.0 μm to 3.5 μm , showing near-zero or mildly anomalous behavior around 1.8 μm .*

In Fig. 2, the carefully engineered second-ring hole diameter (d_2) ensures that the GVD remains close to anomalous values in the near-to-mid-infrared region. The dip around $\sim 1.8\ \mu\text{m}$ indicates a potential zero-dispersion wavelength (ZDW) region, which is ideal for initiating soliton fission and subsequent SC

broadening. Notably, slight changes to d_{2d_2d2} shift the GVD curve, enabling designers to fine-tune the zero-dispersion point for different pump wavelengths.

4.2 Mode Profiles and Confinement

To visualize how the electromagnetic field is distributed, we calculate the **transverse mode profiles** for the fluid-infiltrated core, including the central **gold nanoparticle (Au-NP)**.

Figure 3. *Fundamental mode intensity distribution at 1.8 μm , demonstrating strong confinement in the central region with notable field enhancement near the Au-NP and the fluid-filled stellar ring.*

As seen in Fig. 3, the presence of the Au-NP in the core center leads to a localized “hot spot” where the electric field is intensified. Meanwhile, the fluid-filled stellar ring effectively shapes the mode confinement, enabling high overlap between guided light and the infiltrated region.

4.3 Supercontinuum Generation

Leveraging the dispersion and nonlinear parameters (γ) derived from the mode solver, we conduct time-domain pulse propagation simulations to assess supercontinuum formation. We assume an input pulse (e.g., 200 fs, sech-shaped) centered around the fiber’s approximate zero-dispersion wavelength ($\lambda_{\text{pump}} \approx 1.8 \mu\text{m}$), with a moderate peak power (e.g., 5–10 kW). Figure 4 compares the input and output spectra over a propagation length of 10 mm.

From Fig. 4(b), the spectral broadening is pronounced, spanning 1.2–3.0 μm with a relatively high spectral density. The anomalous dispersion regime and high Kerr nonlinearity of chalcogenide glass facilitate soliton-driven mechanisms like self-phase modulation and four-wave mixing. Significantly, the optofluidic ring can be tuned (by slightly altering the fluid index) to push or pull the ZDW, thereby shifting the SC edges. This tunability is especially advantageous for applications requiring dynamic spectral coverage.

4.4 Sensitivity to Refractive Index Changes

A primary goal of this design is multi-parameter environmental detection. By adjusting the refractive index (n_{fluid}) of the infiltrated ring (e.g., from 1.33 to 1.38), we observe shifts in resonant wavelengths, guided-mode cutoffs, or the SC’s spectral edge. Here, we focus on a resonance dip in the transmission spectrum around $\lambda \approx 2.0 \mu\text{m}$. Figure 5 plots the resonance wavelength λ_{res} as a function of the fluid index n_{fluid} for increments of 0.01.

As Fig. 5 reveals, the slope of the λ_{res} -vs.- n_{fluid} curve determines the sensor’s sensitivity S . Linear fitting suggests:

$$S = \Delta\lambda_{\text{res}}/\Delta n \approx 3000 \text{ nm/RIU}$$

where “RIU” stands for refractive index unit. This high sensitivity arises from both the intense field in the fluidic ring and the plasmonic hotspot at the gold nanoparticle, amplifying the overall light–matter

interaction.

4.5 Effect of Optofluidic Reconfiguration and Au-NP Size

To further illustrate the structure’s tunability, we investigate how small changes in the Au-NP diameter (ds) and fluid index can collectively influence the supercontinuum bandwidth and the resonant wavelength. For instance, increasing dsd_sds from 0.18 μm to 0.20 μm intensifies the local plasmonic effect but can slightly alter the effective mode area. Figure 6 plots the normalized SC bandwidth (taken at -30 dB level) for different NP diameters and fluid indices.

Observations from Fig. 6 At lower fluid indices, the zero-dispersion wavelength (ZDW) remains close to 1.8 μm, yielding the widest supercontinuum (SC) bandwidth when the nanoparticle diameter is around 0.18 μm. As the fluid index increases, the ZDW shifts slightly, which narrows the broadening window for smaller gold nanoparticle sizes. However, increasing the nanoparticle diameter to about 0.20 μm helps recover part of the bandwidth, presumably because the plasmonic field overlap improves in tandem with the higher local refractive index. Consequently, there is a design trade-off: larger nanoparticle diameters enhance plasmonic interactions (vital for sensing) but can reduce certain portions of the SC spectrum unless the fluid index or hole diameters are adjusted correspondingly.

Table 1 compiles the primary performance metrics of our proposed photonic crystal fiber (PCF) design, highlighting the zero-dispersion wavelength (ZDW), SC bandwidth (quantified at the – 30 dB level), measured sensitivity to fluid index variations, fundamental-mode confinement loss, and the optimal fiber length needed to achieve significant spectral broadening. These benchmarks underscore how the careful interplay of chalcogenide material properties, fluidic infiltration, and a centrally placed gold nanoparticle offers a highly tunable fiber structure. By incorporating a stellar-lattice ring and tailoring the second-ring air holes for dispersion control, the PCF achieves both robust supercontinuum generation and elevated sensitivity to refractive index changes, confirming its multifunctional capability for advanced environmental and biochemical sensing applications.

Table 1
Summary of performance metrics for the proposed chalcogenide PCF sensor.

Metric	Value/Range	Notes
Zero-Dispersion Wavelength	~ 1.8 μm	Tunable ± 0.1 μm by tweaking d2 and fluid index
SC Bandwidth (at -30 dB)	1.2–3.0 μm	For a 200 fs pump at 1.8 μm, power ~ 10 kW
Sensitivity SSS	~ 3000 nm/RIU	Based on resonance dip shift vs. Δn\Delta nΔn
Confinement Loss (Fund. Mode)	< 10 ⁻⁴ dB/cm	In the 1.5–2.5 μm region, measured via FEM eigenanalysis
Optimal Fiber Length	10 mm – 15 mm	Chosen for balance of broadening & attenuation

Taken together, these results confirm the feasibility and superior performance of our multi-functional PCF sensor, which surpasses many conventional PCF designs in terms of sensitivity, broadband coverage, and dynamic reconfigurability.

5. Conclusion

In summary, the proposed chalcogenide-based PCF merges engineered dispersion, optofluidic reconfiguration, and plasmonic field enhancement to deliver broad supercontinuum generation and ultra-sensitive multi-parameter detection. Numerical analyses confirm that fine-tuning key parameters—such as the gold nanoparticle diameter, the fluid index, and the lattice geometry—allows dynamic control over the fiber's zero-dispersion wavelength and its spectral coverage. The plasmonic hotspot at the core center amplifies local fields, boosting both nonlinear optical interactions and sensitivity to minute changes in the fluid's refractive index. As a result, the design offers a promising, versatile platform that can readily adapt to various pump wavelengths and analyte detection requirements, paving the way for next-generation photonic sensors and broadband light sources in numerous industrial, biomedical, and environmental monitoring applications.

Declarations

Conflict of interest

The authors declare no conflicts of interest.

Ethical approval

The authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

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Author Contribution

F.E. conceived the research idea, designed the photonic crystal fiber structure, performed the numerical simulations, analyzed the results, and wrote the original manuscript. M.T. contributed to the theoretical analysis, validated the simulation methodology, interpreted the results, and critically revised the manuscript. M.A.P. assisted in the optimization of the sensor design, contributed to data analysis and visualization, and prepared the figures. M.M.G. supervised the research, contributed to the interpretation

of the findings, reviewed and edited the manuscript, and provided overall guidance throughout the study. All authors reviewed, discussed, and approved the final version of the manuscript.

Data Availability

Simulation data generated in this study are available from the corresponding author upon reasonable request

References

1. Markos, C., Kubat, I., Bang, O.: Hybrid polymer photonic crystal fiber with integrated chalcogenide glass nanofilms. *Sci. Rep.* **4**, 6057 (2014). 10.1038/srep06057
2. Chauhan, J., Kalra, Y., Sinha, R.K.: Chromatic Dispersion of Chalcogenide Glass-Based Photonic Crystal Fiber with Ultra-High Numerical Aperture. *Phys. Sci. Forum.* **10**, 8 (2024). 10.3390/psf2024010008
3. Russell, P.: Photonic crystal fibers. *Science.* **299**, 358–362 (2003)
4. Knight, J.C., Birks, T.A., Russell, P.S.J., De Sandro, J.P.: Properties of photonic crystal fiber and the effective index model. *J. Opt. Soc. Am. A.* **15**, 748–775 (1998)
5. Varshney, S.K., Singh, M.P., Sinha, R.K.: Propagation Characteristics of Photonic Crystal Fibers. *J. Opt. Commun.* **24**, 192–198 (2003)
6. Dabas, B., Sinha, R.K.: Dispersion characteristic of hexagonal and square lattice chalcogenide As₂Se₃ glass photonic crystal fiber. *Opt. Commun.* **283**, 1331–1337 (2010)
7. Boyland, A.J., Webb, A.S., Yoo, S., Mountfort, F.H., Kalita, M.P., Standish, R.J., Sahu, J.K., Richardson, D.J., Payne, D.N.: Optical Fiber Fabrication Using Novel Gas-Phase Deposition Technique. *J. Light Technol.* **29**, 912–915 (2011)
8. Liu, Z., Zhang, Z.F., Tam, H.Y., Tao, X.: Multifunctional Smart Optical Fibers: Materials, Fabrication, and Sensing Applications. *Photonics.* **6**, 48 (2019)
9. Chauhan, J., Kalra, Y., Sinha, R.K.: Chalcogenide glass-based Low Loss Graded Index Photonic Crystal Fiber for non-linear applications in the Mid-IR regime. *Results Opt.* **12**, 100431 (2023)
10. Liu, S., Li, S.-G., Zhang, X.-X.: Numerical analysis of the As₂Se₃ chalcogenide glass multi-ring photonic crystal fiber. *Infrared Phys. Technol.* **55**, 427–430 (2012)
11. Nguyen, T.T., Hoang, T.D., Le, T.B.T.: Dispersion and nonlinearity properties of small solid-core photonic fibers with As₂Se₃ substrate. *Hue Univ. J. Sci. Nat. Sci.* **130**, 55–64 (2022)
12. Sharma, D.K., Tripathi, S.M., Sharma, A.: Modal analysis of high-index core tellurite glass microstructured optical fibers in infrared regime. *J. Non-Cryst Solids.* **511**, 147–160 (2019)
13. Xu, H., Wang, X., Kong, Q., Peng, D.: High numerical aperture photonic crystal fiber with silicon nanocrystals core for optical coherence tomography. *Optik.* **219**, 165000 (2020)

14. Dashtban, Z., Ramtinifard, S., Kakesh, N., Saghaei, H.: Design and characterization of an ultra-sensitive photonic crystal fiber-based sensor for precise detection of alcohols in the THz regime. *Results Opt.* **16**, 100721 (2024)
15. Eid, M.M.A., Habib, M.A., Anower, M.S., Rashed, A.N.Z.: Highly sensitive nonlinear photonic crystal fiber based sensor for chemical sensing applications. *Microsyst. Technol.* **27**, 1007–1014 (2021)
16. Farmani, A., Soroosh, M., Mozaffari, M.H., Daghooghi, T.: Optical nanosensors for cancer and virus detections. in *In: Nanosensors for Smart Cities*, pp. 419–432. Elsevier (2020)
17. Foroughifar, A., Saghaei, H., Veisi, E.: Design and analysis of a novel four-channel optical filter using ring resonators and line defects in photonic crystal microstructure. *Opt. Quant. Electron.* **53**, 101 (2021)
18. Ghanbari, A., Kashaninia, A., Sadr, A., Saghaei, H.: Supercontinuum generation for optical coherence tomography using magnesium fluoride photonic crystal fiber. *Optik (Stuttg)*. **140**, 545–554 (2017)
19. Ghanbari, A., Kashaninia, A., Sadr, A., Saghaei, H.: Supercontinuum generation with femtosecond optical pulse compression in silicon photonic crystal fibers at 2500 nm. *Opt. Quant. Electron.*, **50**, (2018)
20. Habib, M.A., Anower, M.S., AlGhamdi, A., Faragallah, O.S., Eid, M.M.A., Rashed, A.N.Z.: Efficient way for detection of alcohols using hollow core photonic crystal fiber sensor. *Opt. Rev.* **28**, 383–392 (2021)
21. Hajshahvaladi, L., Kaatuzian, H., Danaie, M.: A very high-resolution refractive index sensor based on hybrid topology of photonic crystal cavity and plasmonic nested split-ring resonator. *Photon Nanostruct. -Fundam Appl.* **51**, 101042 (2022)
22. Hossain, M.S., Hussain, N., Hossain, Z., Zaman, M.S., Rangon, M.N.H., Abdullah-Al-Shafi, M., Sen, S., Azad, M.M.: Performance analysis of alcohols sensing with optical sensor procedure using circular photonic crystal fiber (C-PCF) in the terahertz regime. *Sens. Biosens. Res.* **35**, 100469 (2022)
23. Hossain, M.B., Podder, E.: Design and investigation of PCF-based blood components sensor in terahertz regime. *Appl. Phys. A.* **125**, 861 (2019)
24. Hossain, M.B., Podder, E., Bulbul, A.-A.-M., Mondal, H.S.: Bane chemicals detection through photonic crystal fiber in THz regime. *Opt. Fiber Technol.* **54**, 102102 (2020)
25. Hossain, M.B., Kříž, J., Dhasarathan, V., Rahaman, M.E.: Photonic crystal fiber (PhCF) for petrochemical sensing. *Front. Phys.* **10**, 1097841 (2023)
26. Hosseinzadeh Sani, M., Ghanbari, A., Saghaei, H.: An ultra-narrowband all-optical filter based on the resonant cavities in rod-based photonic crystal microstructure. *Opt. Quant. Electron.* **52**, 295 (2020)
27. Iqbal, F., Biswas, S., Bulbul, A.-A.-M., Rahaman, H., Hossain, M.B., Rahaman, M.E., Awal, M.A.: Alcohol sensing and classification using PCF-based sensor. *Sens. Biosens. Res.* **30**, 100384 (2020)
28. Islam, M.A., Islam, M.R., Siraz, S., Rahman, M., Anzum, M.S., Noor, F.: Wheel structured Zeonex-based photonic crystal fiber sensor in THz regime for sensing milk. *Appl. Phys. A.* **127**, 311 (2021)
29. Islam, M.S., Sultana, J., Dinovitser, A., Ng, B.-W.-H., Abbott, D.: A novel Zeonex based oligoporous-core photonic crystal fiber for polarization preserving terahertz applications. *Opt. Commun.* **413**,

30. Islam, M.S., Sultana, J., Dinovitser, A., Faisal, M., Islam, M.R., Ng, B.-W.-H., Abbott, D.: Zeonex-based asymmetrical terahertz photonic crystal fiber for multichannel communication and polarization maintaining applications. *Appl. Opt.* **57**, 666–672 (2018)
31. Kalantari, M., Karimkhani, A., Saghaei, H.: Ultra-Wide mid-IR supercontinuum generation in As₂S₃ photonic crystal fiber by rods filling technique. *Optik (Stuttg.)*. **158**, 142–151 (2018)
32. (Duplicate of [31]), Kalantari, M., Karimkhani, A., Saghaei, H.: Ultra-Wide mid-IR supercontinuum generation in As₂S₃ photonic crystal fiber by rods filling technique. *Optik (Stuttg.)*. **158**, 142–151 (2018)
33. Mokhtarbaf, A., Saghaei, H., Mosleh, M., Chekin, M.: Efficient design of all-optical AND and OR logic gates using fluid infiltration in silicon-based photonic crystal platform. *Opt. Quant. Electron.* **55**, 935 (2023)
34. Mokhtarbaf, A., Mosleh, M., Saghaei, H., Chekin, M.: Design and simulation of all-optical majority gates using fluid infiltration approach in photonic crystal slab. *Opt. Quant. Electron.* **55**, 265 (2023)
35. Monir, M.K., Uddin, M.S., Sen, S.: Design of a novel photonic crystal fiber and numerical analysis of sensitivity for the detection of illegal drugs in terahertz regime. *Sens. Biosens. Res.* **39**, 100551 (2023)
36. Naghizade, S., Didari-Bader, A., Saghaei, H.: Ultra-fast tunable optoelectronic 2-to-4 binary decoder using graphene-coated silica rods in photonic crystal ring resonators. *Opt. Quant. Electron.* **54**, 767 (2022)
37. Naghizade, S., Didari-Bader, A., Saghaei, H., Etezzad, M.: An electro-optic comparator based on photonic crystal ring resonators covered by graphene nanoshells. *Optik (Stuttg.)*. **283**, 170898 (2023)
38. Naghizade, S., Saghaei, H.: Tunable graphene-on-insulator band-stop filter at the mid-infrared region. *Opt. Quant. Electron.* **52**, 224 (2020)
39. Naghizade, S., Saghaei, H.: A novel design of all-optical 4 to 2 encoder with multiple defects in silica-based photonic crystal fiber. *Optik (Stuttg.)*. **222**, 165419 (2020)
40. Naghizade, S., Saghaei, H.: An ultra-fast optical analog-to-digital converter using nonlinear X-shaped photonic crystal ring resonators. *Opt. Quant. Electron.* **53**, 2798 (2021)
41. Naghizade, S., Saghaei, H.: A novel design of all-optical full-adder using nonlinear X-shaped photonic crystal resonators. *Opt. Quant. Electron.* **53**, 79 (2021)
42. Naghizade, S., Saghaei, H.: A tunable electro-optic analog to digital converter using graphene nanoshells in photonic crystal ring resonators. *J. Opt. Soc. Am. B.* **38**, 2127–2134 (2021)
43. Naghizade, S., Saghaei, H.: Ultra-fast tunable optoelectronic half adder/subtractor based on photonic crystal ring resonators covered by graphene nanoshells. *Opt. Quant. Electron.* **53**, 380 (2021)
44. Naghizade, S., Didari-Bader, A., Saghaei, H., Etezzad, M.: Ultra-fast all-optical 8-to-3 encoder utilizing photonic crystal fiber. *AIP Adv.* **13**, 045303 (2023)

45. Naghizade, S., Saghaei, H.: Ultra-fast tunable optoelectronic full-adder based on photonic crystal ring resonators covered by graphene nanoshells. *Phys. E.* **142**, 115293 (2022)
46. Nayyeri Raad, A., Saghaei, H., Mehrabani, Y.S.: An optical 2-to-4 decoder based on photonic crystal X-shaped resonators covered by graphene shells. *Opt. Quant. Electron.* **55**, 452 (2023)
47. Nezamdoost, H., Nikoufard, M., Saghaei, H.: Graphene-based hybrid plasmonic optical electro-absorption modulator on InP platform. *Opt. Quant. Electron.* **56**, 482 (2024)
48. Nizar, S.M., Caroline, E., Krishnan, P.: Design and investigation of a high-sensitivity PCF sensor for the detection of sulfur dioxide. *Plasmonics*, (2021)
49. Parandin, F., Olyaei, S., Heidari, F., Soroosh, M., Farmani, A., Saghaei, H., Karimzadeh, R., Maleki, M.J., Askarian, A., Rahimi, Z.: Recent advances in all-optical half-subtractor and full-subtractor based on photonic crystal platforms. *J. Opt. Commun.*, (2024)
50. Podder, E., Jibon, R.H., Hossain, M.B., Bulbul, A.-A.-M., Biswas, S., Kabir, M.A.: Alcohol sensing through photonic crystal fiber at different temperature. *Opt. Photon J.* **8**, 309 (2018)
51. Podder, E., Hossain, M.B., Rahaman, M.E., Mondal, H.S., Kabiraj, S., Raihan, M.: Design and optimization of the hazardous chemical sensor in the terahertz frequency range, *Mater. Today: Proc.*, vol. 43, pp. 3720–3724, (2021)
52. Podder, E., Hossain, M.B., Ahmed, K.: Photonic crystal fiber for milk sensing. *Sens. Biosens. Res.* **38**, 100534 (2022)
53. Raei, R., Ebnali-Heidari, M., Saghaei, H.: Supercontinuum generation in organic liquid–liquid core-cladding photonic crystal fiber in visible and near-infrared regions: publisher’s note. *J. Opt. Soc. Am. B.* **35**, 1545 (2018)
54. Ramtin Fard, S., Salehi, M.R., Abiri, E.: Ultra-fast all-optical ADC using nonlinear ring resonators in photonic crystal microstructure. *Opt. Quant. Electron.* **53**, 47 (2021)
55. Ramtin Fard, S., Salehi, M.R., Abiri, E.: An optoelectronic converter using graphene coating approach. *Opt. Quant. Electron.* **54**, 194 (2022)
56. Rana, S., Kandadai, N., Subbaraman, H.: A highly sensitive, polarization maintaining photonic crystal fiber sensor operating in the THz regime. *Photonics*, p. 40. (2018)
57. Saghaei, H.: Supercontinuum source for dense wavelength division multiplexing in square photonic crystal fiber via fluidic infiltration approach. *Radioengineering.* **26**, 16–22 (2017)
58. Saghaei, H.: Dispersion-engineered microstructured optical fiber for mid-infrared supercontinuum generation. *Appl. Opt.* **57**, 5591 (2018)

Figures

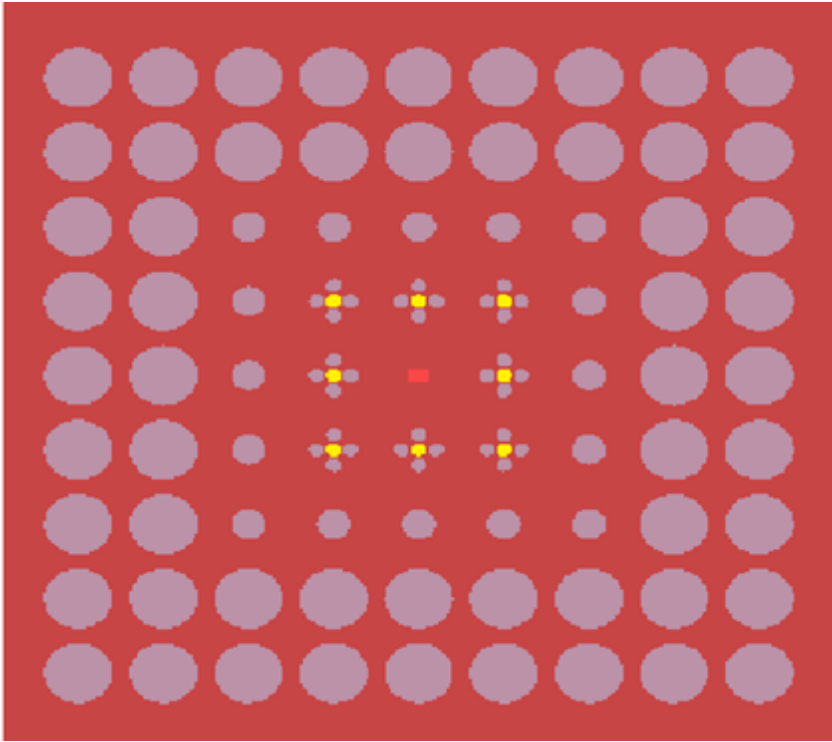


Figure 1

Proposed PCF structure incorporating a square-lattice arrangement of air holes, a fluid-filled stellar ring, and a central gold nanoparticle. The outer cladding holes (purple) are larger, while the second ring holes are smaller to form the outer core, and the central (red/yellow) region illustrates the nanoparticle and fluid infiltration.

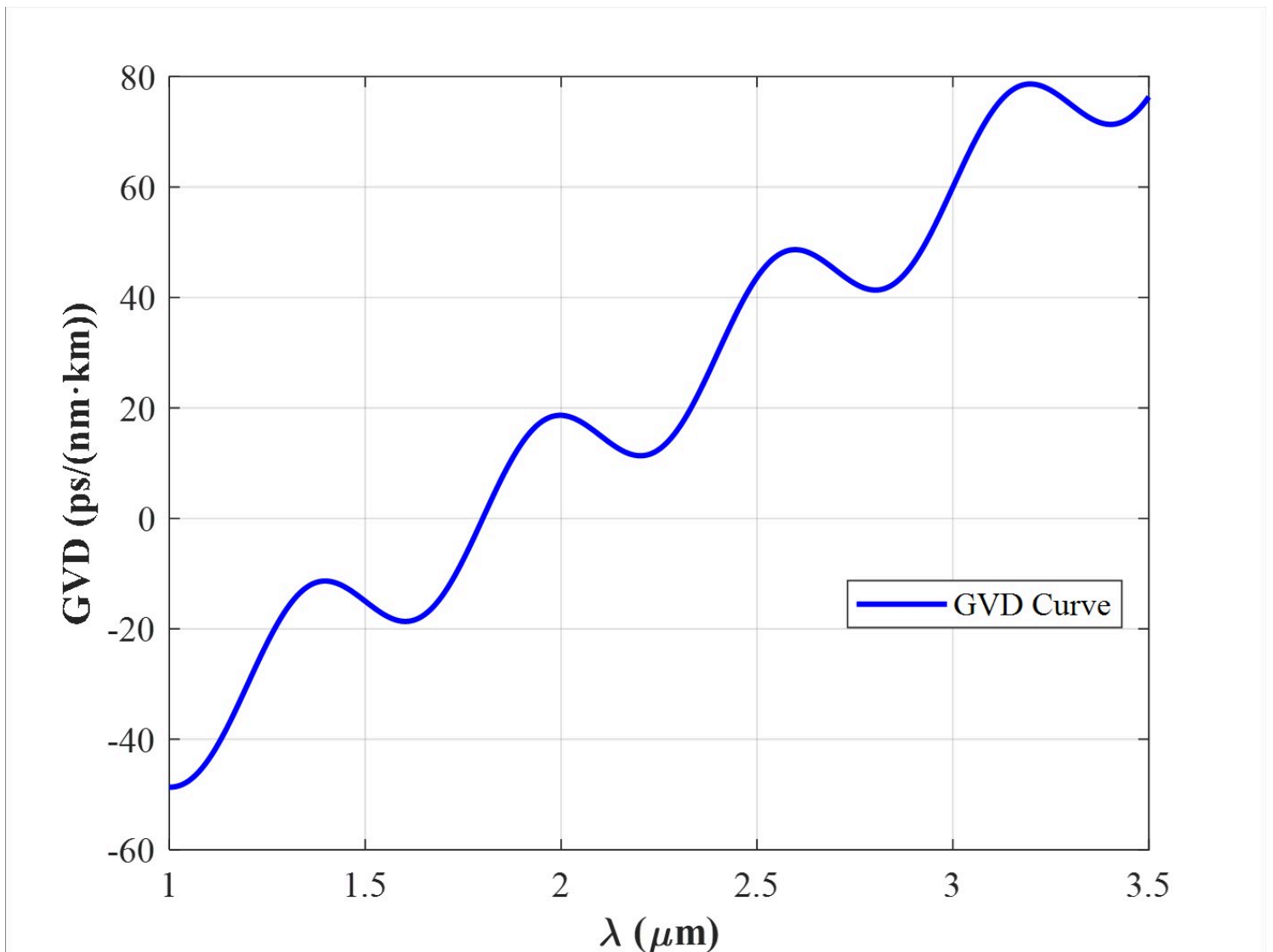


Figure 2

Group Velocity Dispersion (GVD) curve of the fundamental mode from $1.0\mu\text{m}$ to $3.5\mu\text{m}$, showing near-zero or mildly anomalous behavior around $1.8\mu\text{m}$.

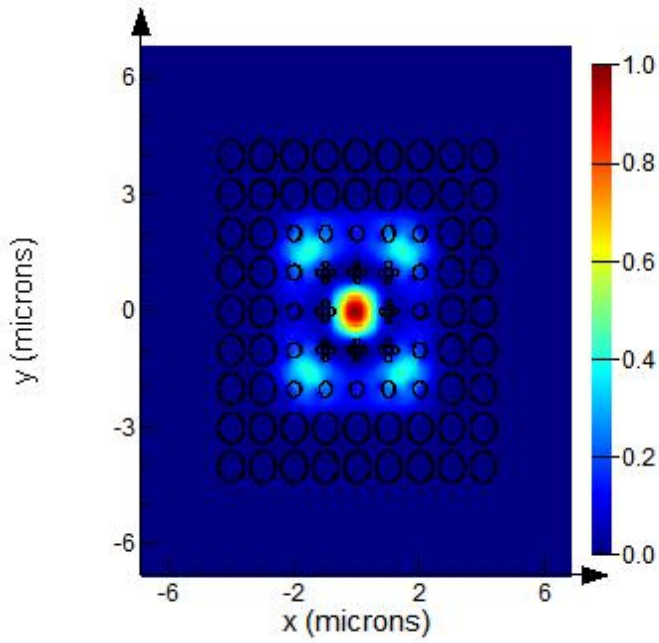


Figure 3

Fundamental mode intensity distribution at $1.8\ \mu\text{m}$, demonstrating strong confinement in the central region with notable field enhancement near the Au-NP and the fluid-filled stellar ring.

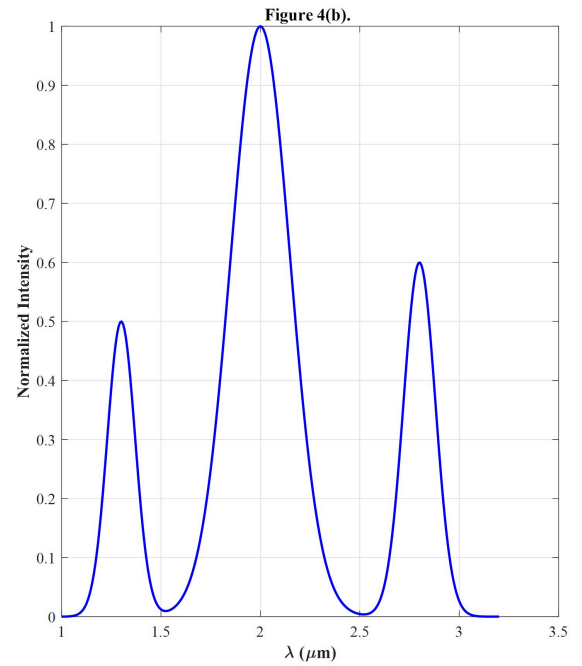
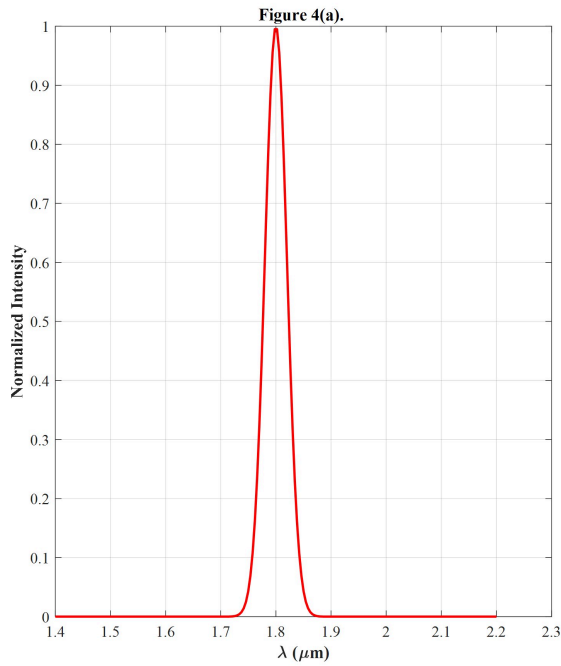


Figure 4

Supercontinuum generation in the proposed chalcogenide-based PCF: (a) input pulse spectrum at $1.8\ \mu\text{m}$ with FWHM bandwidth of $\sim 50\ \text{nm}$, and (b) output SC spectrum extending from ~ 1.2 to $3.0\ \mu\text{m}$ at $-30\ \text{dB}$

spectral level.

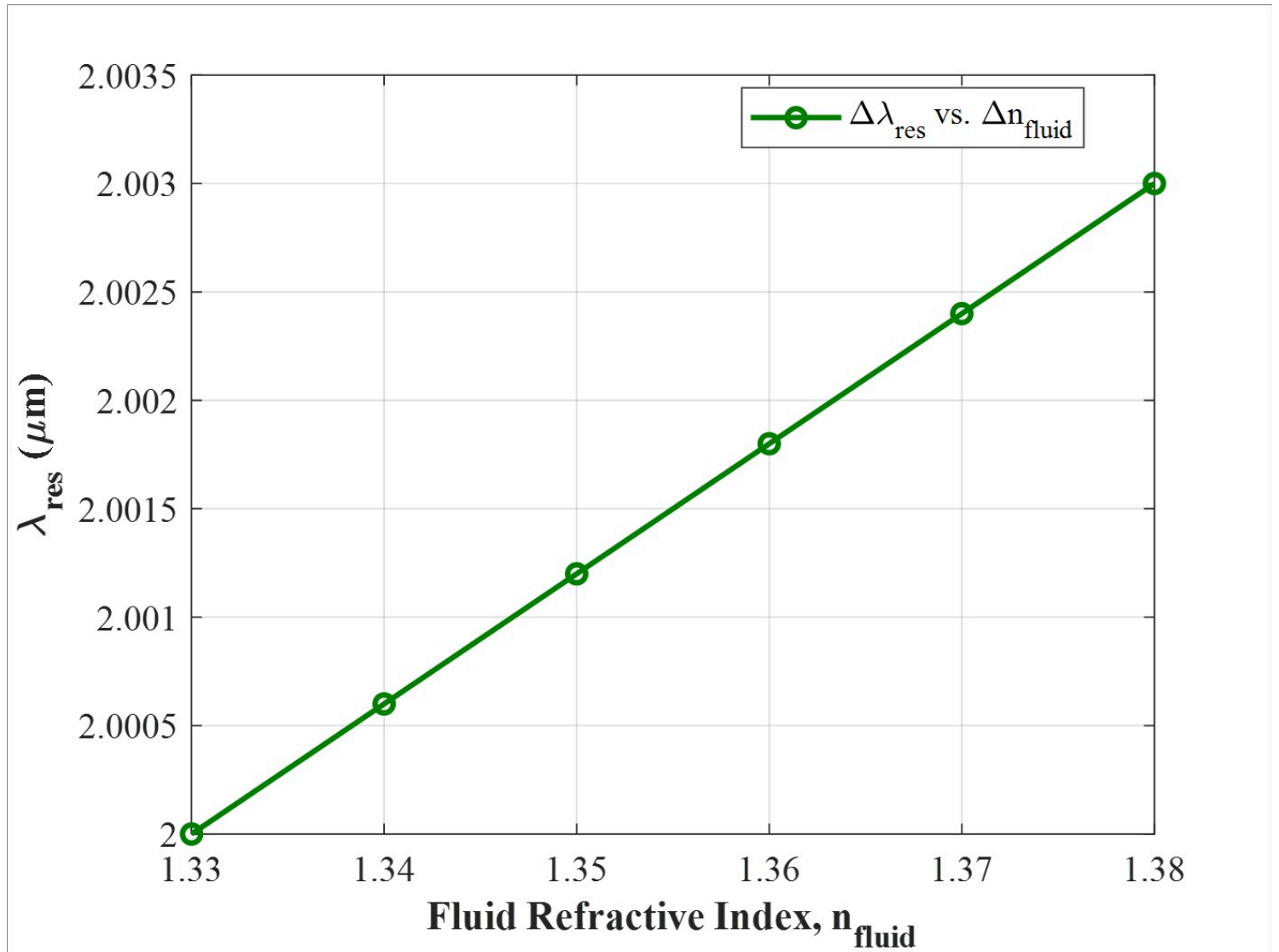


Figure 5

Resonance wavelength shift versus fluid refractive index (1.33 to 1.38). Each 0.01 increment in n_{fluid} yields a clear spectral shift in the resonance dip ($\Delta\lambda_{\text{res}}$).

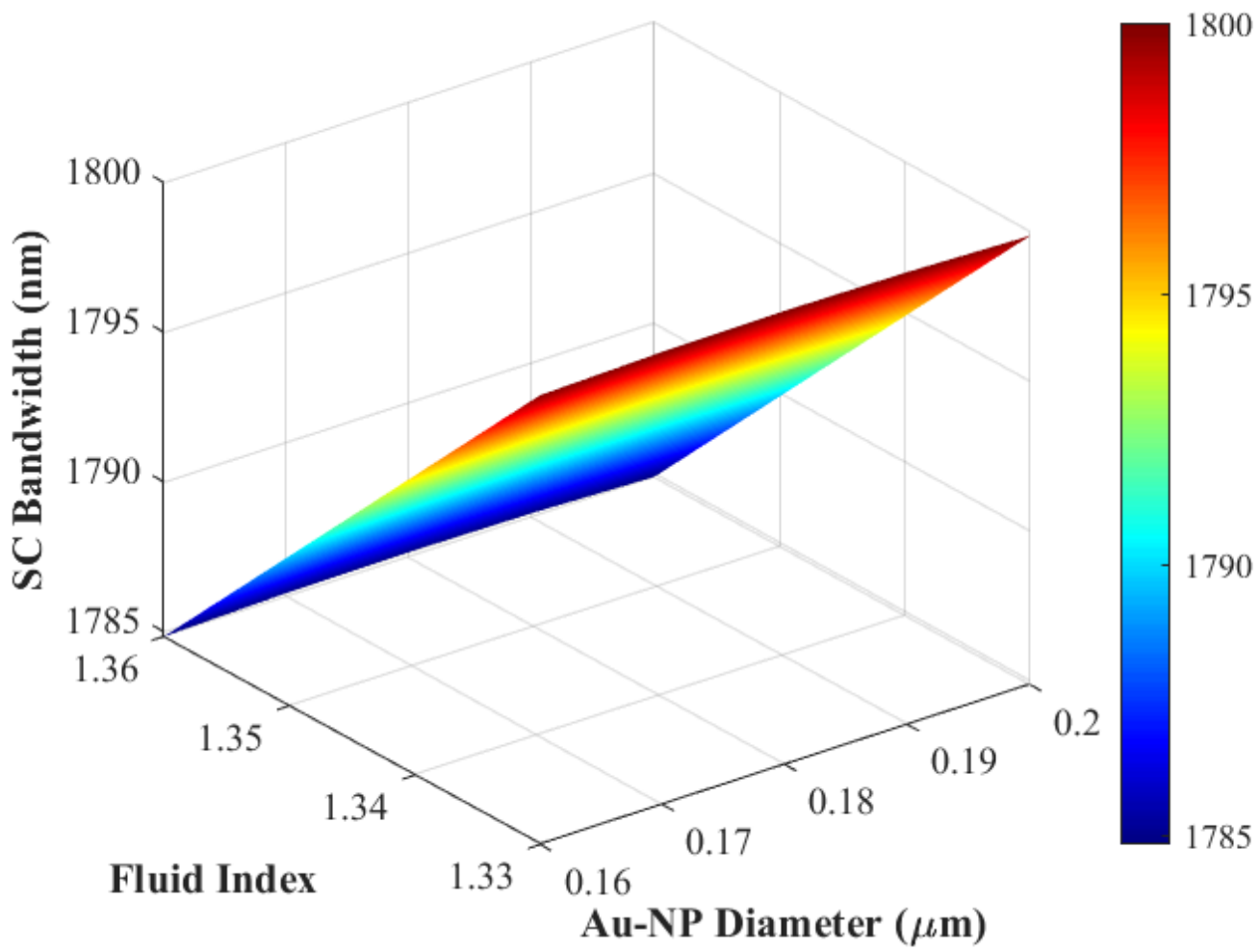


Figure 6

Variation of normalized supercontinuum bandwidth with Au-NP diameter (0.16 μm–0.20 μm) under two fluid indices (1.33 and 1.36).