

Investigation of the effective refractive index in suspended core photonic crystal fiber based on As_2S_3 with CS_2 -filled air holes

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Abstract. This study investigates how the structural parameters of suspended-core photonic crystal fibers (SC-PCFs) influence their effective refractive index (n_{eff}), focusing on designs based on arsenic sulfide (As_2S_3) with carbon disulfide (CS_2)-filled air holes. As_2S_3 provides a high non-linear refractive index and wide infrared transparency, while CS_2 infiltration enables enhanced optical control due to its high refractive index. Using Lumerical Mode Solutions, numerical simulations were conducted for x-polarized (x-pol.) and y-polarized (y-pol.) modes across the wavelength range from 2 to 5 μm , with structure ratios (w/r_c) varying from 0.35 to 0.85. The results show that the effective refractive index increases with the slot width and reaches 2.2217 at a wavelength of 2150 nm for the CS_2 -filled structure. Compared to air-filled fibers, CS_2 infiltration improves refractive index control and optical confinement. These results provide quantitative design guidance for optimizing modal confinement and birefringence in SC-PCFs targeting non-linear and polarization-sensitive applications in the mid-infrared regime.

Keywords: suspended-core photonic crystal fiber; effective refractive index; polarization dependence; As_2S_3 chalcogenide glass; CS_2 infiltration.

Classification numbers: 42.65.Tg; 42.65.Ky; 42.81.Qb.

1. Introduction

Photonic crystal fibers (PCFs) are a class of optical fibers that guide light based on the microstructured arrangement of air holes in the cladding, enabling strong control over dispersion, confinement, and nonlinearity [1–3]. Since their introduction in the mid-1990s [1], PCFs have supported a wide range of applications in nonlinear optics [4,5], frequency metrology [6,7], biomedical imaging [8], and supercontinuum (SC) generation [9–12]. By tailoring structural parameters such as air-hole diameter, lattice pitch, and core geometry, PCFs can be engineered to exhibit unique properties including endlessly single-mode propagation, high birefringence, tunable dispersion, and low confinement loss [10–12].

Suspended-core photonic crystal fibers (SC-PCFs) form a subclass in which a small central core is held by narrow glass bridges and surrounded by air holes. Since their introduction in 2001 [13,14], SC-PCFs have been fabricated from soft glasses (e.g., lead-silicate, tellurite) [15,16]. The suspended-core geometry increases the overlap between the guided field and the surrounding medium, which is advantageous for sensing applications [17–24]. Furthermore, the reduced core size enhances nonlinear optical interactions, including Raman scattering, harmonic generation, and supercontinuum processes [25–28]. While silica-based PCFs have been extensively studied, their transmission is limited below $\sim 2 \mu\text{m}$ due to material absorption [10,11]. For mid-infrared applications, chalcogenide glasses such as arsenic sulfide (As_2S_3) offer higher refractive index (~ 2.4), wide transparency (up to $\sim 11 \mu\text{m}$), and strong third-order nonlinearity [29–33].

Despite these advantages, controlling the optical properties of SC-PCFs based on As_2S_3 remains challenging. In particular, precise tuning of the effective refractive index is essential, as it influences mode confinement, dispersion, and nonlinear phase matching. Previous studies have primarily focused on dispersion engineering [31,33] or SC bandwidth extension [25–28,34–36], with limited attention given to the direct relationship between geometry and n_{eff} in As_2S_3 -based SC-PCFs.

Moreover, most existing work assumes the air holes are either empty or filled with low-index media such as air or water [17–19]. Infiltrating these holes with high-index liquids provides an effective strategy to tune n_{eff} and enhance light confinement. Carbon disulfide (CS_2) is a nonlinear optical liquid with a high refractive index and favorable transmission in the infrared range. Although its use has been explored in silica-based PCFs [5,10,11], it remains underutilized in chalcogenide-core structures.

A clear gap exists in the literature: few studies have quantitatively examined how variations in slot width, especially the ratio w/r_c , affect the effective refractive index in SC-PCFs based on As_2S_3 with CS_2 -filled air holes. Understanding this dependence is essential for optimizing light confinement and enabling refractive index control in mid-IR fiber designs.

In this study, we address this gap by numerically investigating the effective refractive index in SC-PCFs composed of As_2S_3 , with and without CS_2 infiltration. Using Lumerical Mode Solutions, we simulate the x-pol. and y-pol. modes across the $2\text{--}5 \mu\text{m}$ wavelength range, while varying the ratio w/r_c from 0.35 to 0.85. Here, x-pol. and y-pol. are used to denote the two orthogonal polarization states of the fundamental guided mode, corresponding to the x-polarized and y-polarized modes, respectively. The results reveal how structural parameters and material choices influence n_{eff} , providing a foundation for the design of mid-infrared photonic devices with enhanced tunability and nonlinear performance.

2. Numerical modeling and fiber design

The investigated structure is a suspended-core photonic crystal fiber (SC-PCF) composed of a solid arsenic trisulfide (As_2S_3) core, supported by three narrow bridges (or connecting slots) and surrounded by three evenly spaced air holes forming a triangular cladding pattern, as illustrated in Fig. 1a. This configuration ensures threefold rotational symmetry (120° spacing), which promotes consistent mode confinement and structural stability.

The key geometrical parameters include the core radius r_c , fixed at $0.6 \mu\text{m}$, and the slot width w , defined as the shortest distance between the edges of two adjacent air holes. The ratio w/r_c was systematically changed from 0.35 to 0.85 in increments of 0.05 to assess structural influence on optical confinement.

To ensure consistent symmetry and spacing, the air hole radius R_{hole} was calculated from geometric principles. Exploiting this threefold symmetry ($n = 3$), the air hole radius was computed using the geometric relation: $R_{hole} = \left[\frac{w}{2} - r_c \sin\left(\frac{\pi}{n}\right) \right] / \left[\sin\left(\frac{\pi}{n}\right) - 1 \right]$.

This equation results from analyzing the isosceles triangle formed by the core center and the centers of two adjacent air holes. It ensures consistent spacing between the core and cladding over the entire range of w/r_c . Once R_{hole} is obtained, the lattice constant Λ , defined as the center-to-center distance between neighboring air holes, is computed using: $\Lambda = 2R_{hole} + w$. All corresponding geometric values for each configuration are summarized in Table 1.

Table 1. Structural parameters of the investigated fibers with the w/r_c ratio varied from 0.35 to 0.85.

Structure ratio w/r_c	Slot width w (μm)	Air hole radius R_{hole} (μm)	Lattice constant Λ (μm)
Core radius $r_c = 0.6$ (μm)			
0.35	0.21	3.09	6.39
0.40	0.24	2.98	6.20
0.45	0.27	2.87	6.01
0.50	0.30	2.76	5.82
0.55	0.33	2.65	5.63
0.60	0.36	2.53	5.42
0.65	0.39	2.42	5.23
0.70	0.42	2.31	5.04
0.75	0.45	2.20	4.85
0.80	0.48	2.09	4.66
0.85	0.51	1.98	4.47

The mode field distribution of the fundamental mode is shown in Fig. 1b. The plot demonstrates that the light is strongly confined in the core of the SC-PCF, with high intensity localized in the suspended region and negligible leakage into the surrounding cladding. The structural layout with labeled geometrical parameters, including the core radius, slot width, air hole radius, and lattice constant, is provided in Fig. 1c.

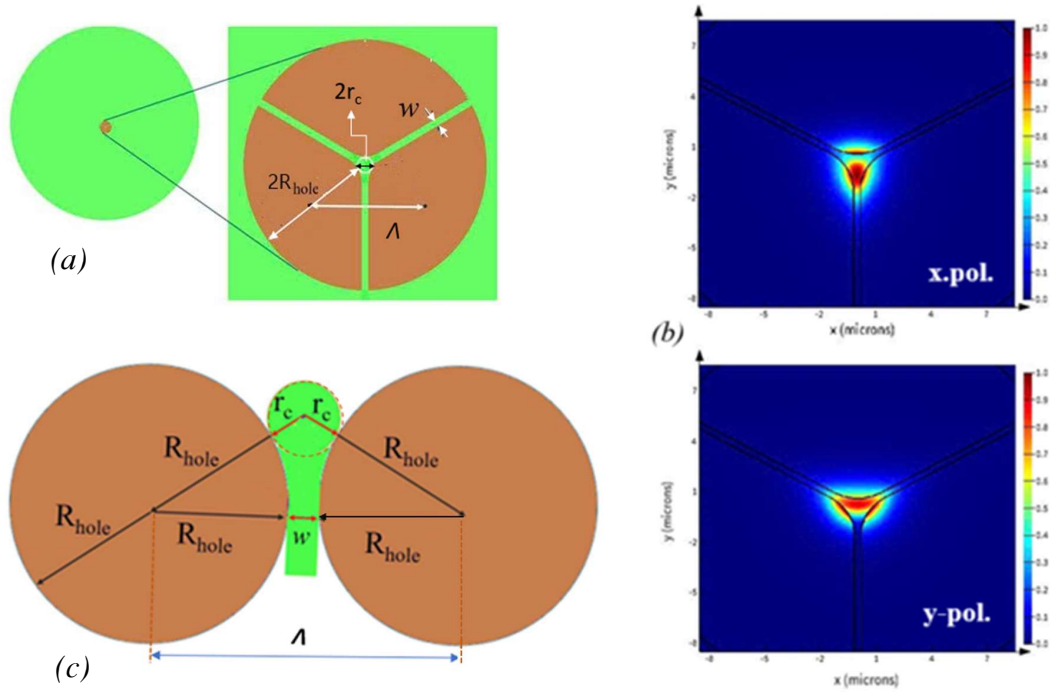


Fig. 1. The geometric cross-section of PCF (a), (c); the light is strongly confined in the core of PCF (b).

Optical simulations were conducted using Lumerical Mode Solutions, which utilizes the finite-element method (FEM) to solve Maxwell's equations in the fiber cross-section. The computational domain was enclosed by perfectly matched layers (PML) of $1\ \mu\text{m}$ thickness with exponential absorption to eliminate artificial reflections.

To validate mesh convergence, simulations were performed using mesh sizes of 100 nm, 200 nm, and 300 nm. The variation in the effective refractive index between the 100 nm and 200 nm meshes was found to be less than 0.05%, indicating that the 200 nm mesh provides accuracy comparable to the finest resolution. In addition, the deviation between the 200 nm and 300 nm meshes was approximately 0.15%, further confirming that the 300 nm mesh is insufficient for accurate mode characterization. Based on these results, a uniform mesh size of 200 nm was selected for all simulations as the optimal balance between numerical accuracy and computational efficiency.

In addition, the refractive indices of arsenic sulfide and carbon disulfide were modeled using the Sellmeier equation, with material-specific coefficients extracted from reliable experimental sources [37,38]. The equation takes the form:

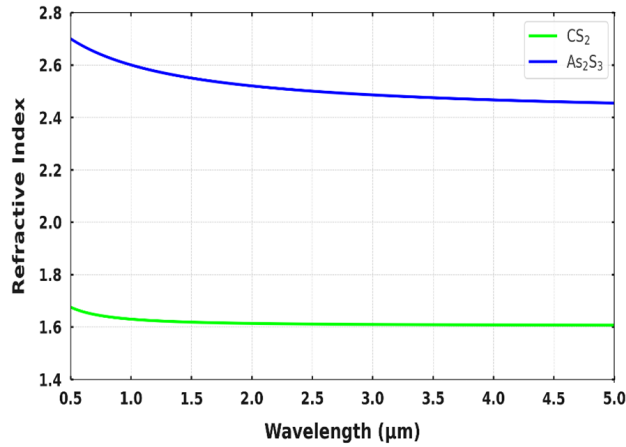
$$n^2(\lambda) = A_0 + \frac{B_1\lambda^2}{\lambda^2 - C_1^2} + \frac{B_2\lambda^2}{\lambda^2 - C_2^2} + \frac{B_3\lambda^2}{\lambda^2 - C_3^2},$$

where λ is the wavelength in micrometers (μm), and A_i , B_i , C_i are material-specific Sellmeier coefficients.

Table 2. The Sellmeier's coefficients of materials used.

The Sellmeier's coefficients	Materials used	
	As ₂ S ₃	CS ₂
A_0	1	1
B_1	1.8983	1.50387
B_2	1.9222	–
B_3	0.8765	–
C_1	0.0225	0.03049
C_2	0.0625	–
C_3	0.1225	–

The refractive index curves derived from this equation are shown in Fig. 2, while the corresponding coefficients for As₂S₃ and CS₂ are summarized in Table 2. This refractive index model ensures accurate simulation of light propagation within the 2–5 μm mid-infrared range, the primary operational window of the proposed SC-PCF structure.

**Fig. 2.** (Color online) The real refractive index of materials used.

3. Results and discussion

The effective refractive index n_{eff} plays a crucial role in determining the modal characteristics and optical confinement of PCFs. It is particularly sensitive to the waveguide geometry, material composition, and wavelength. This section presents simulation results for n_{eff} , focusing on its variation with respect to wavelength, the structure ratio w/r_c , and the cladding filling medium.

The effective refractive index of each guided mode was calculated from

$$n_{eff} = \frac{\beta(\lambda, n_m(\lambda))}{k_0},$$

where β is the propagation constant obtained from FEM simulations, $n_m(\lambda)$ is the wavelength-dependent refractive index of the material, and $k_0 = \frac{2\pi}{\lambda}$ is the free-space wavenumber.

These results help to characterize both the confinement and effective modal propagation of the x-pol. and y-pol. modes. The graphs, illustrating the effective refractive index versus wavelength ranging from 2 μm to 5 μm of the investigated structures, are presented in Fig. 3.

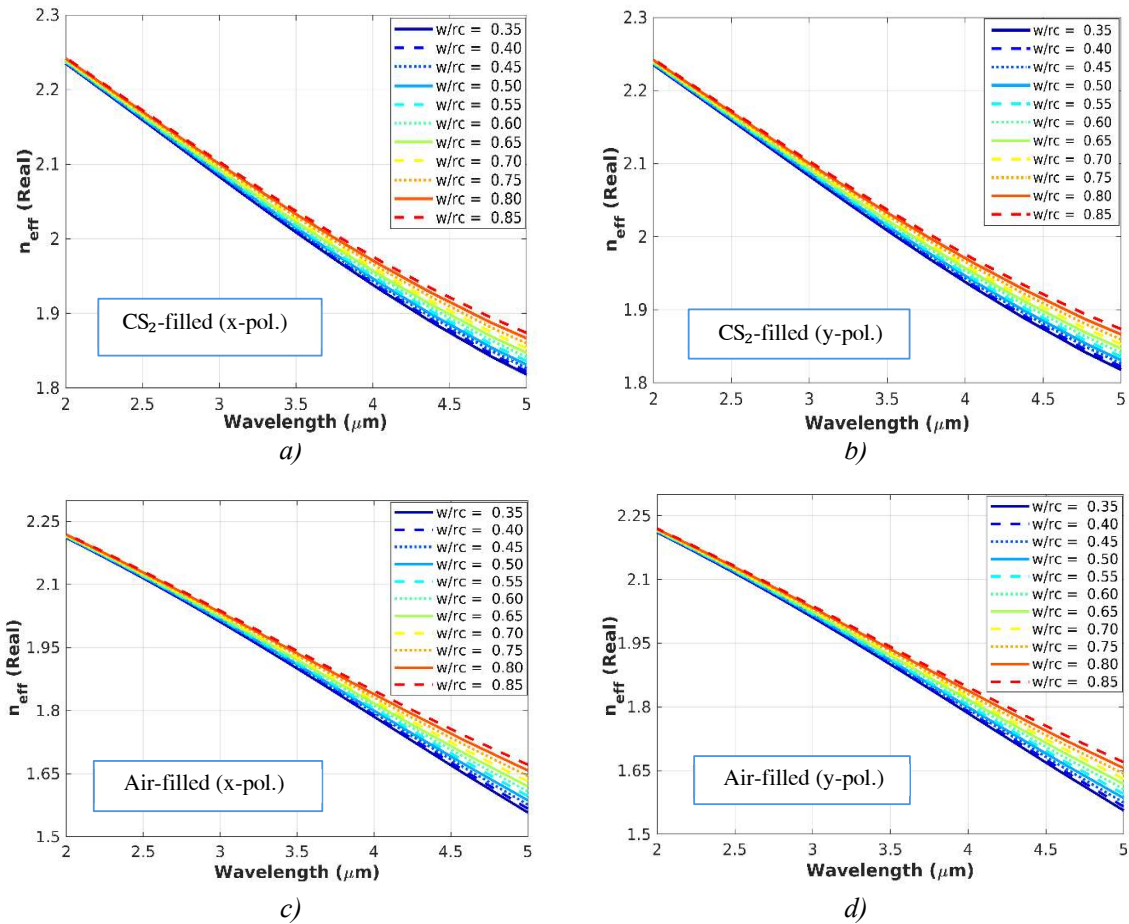


Fig. 3. (Color online) The real part of the effective refractive index as a function of wavelength for structure ratios w/r_c ranging from 0.35 to 0.85, considering two types of air-hole filling: a) x-pol. modes with CS₂-filled holes; b) y-pol. modes with CS₂-filled holes; c) x-pol. modes with air-filled holes; and d) y-pol. modes with air-filled holes.

3.1. Wavelength dependence

In all cases, the simulations show a monotonic decline in n_{eff} as the wavelength increases. This trend reflects weaker optical confinement, as the evanescent field penetrates further into the cladding at longer wavelengths.

For instance, in the x-pol. modes with CS₂-filled air holes and $w/r_c = 0.85$, n_{eff} drops from 2.2417 at 2.0 μm to 1.7702 at 5.0 μm , representing a relative decrease of $\sim 21\%$. Similarly, in the air-filled case with $w/r_c = 0.35$, the effective index decreases from 2.2101 to 1.6351 over the same spectral range. These reductions are attributed to increased modal area and field leakage into the low-index cladding, which becomes more significant at longer wavelengths.

This wavelength dependence is consistent with classical waveguide theory and aligns with previous reports on As₂S₃ and As₂Se₃ PCFs [19,31], supporting the reliability of our design and simulation approach.

3.2. Influence of structure ratio w/r_c

The slot-to-core ratio w/r_c is a key geometrical parameter that directly impacts the effective refractive index n_{eff} of guided modes. In our design, the core radius r_c is held constant at 0.6 μm , while w/r_c is varied from 0.35 to 0.85, corresponding to slot widths w ranging from 0.21 μm to 0.51 μm . This allows for systematic evaluation of modal behavior as the transverse geometry is altered, without changing the material or core scale.

Simulation results show a consistent rise in n_{eff} as w/r_c increases for all of cases. Specifically, at a wavelength of 2.0 μm , the effective refractive index n_{eff} of the x-pol. modes in the CS₂-infiltrated structure increases from 2.2339 when $w/r_c = 0.35$ to 2.2419 when $w/r_c = 0.85$, corresponding to an absolute change of 0.008. While at $\lambda = 5.0$, the same structural variation yields a more pronounced difference: n_{eff} rises from 1.8175 to 1.8733, giving an absolute change of 0.056.

The increase in n_{eff} is attributed to enhanced localization of the optical field in the high-index core region as the slot widens. A larger slot shifts the air holes outward, reducing the spatial overlap between the core and the low-index cladding. This leads to reduced leakage of the guided mode into the surrounding air or CS₂ regions, especially for the x-pol. modes, whose transverse field profile is more susceptible to asymmetry. The mode thus experiences a higher average refractive index along its propagation axis [30].

These values also clearly indicate that the sensitivity of n_{eff} to structural changes becomes stronger as the wavelength increases. Physically, this is because longer wavelengths result in larger mode field diameters and greater evanescent field penetration into the cladding. As the modal field spreads further into the low-index CS₂-filled air holes, it becomes increasingly responsive to the slot width w , which governs the overlap between the mode and the high-index core. Consequently, changes in w/r_c have a more pronounced effect on the effective index at longer wavelengths, due to the enhanced modal interaction with the surrounding geometry.

3.3. Polarization mode dependence

In photonic crystal fibers, the x-pol. and y-pol. modes correspond to two orthogonal polarization states of the fundamental mode. Owing to the asymmetric suspended-core geometry, these x- and y-polarized components are no longer degenerate and therefore exhibit slightly different effective refractive indices. To capture this polarization dependence, we define difference

$\Delta n_{eff} = n_{eff}(x-pol.) - n_{eff}(y-pol.)$, which serves as a convenient metric for quantifying the structure's birefringence-like behavior [21].

Figure 4 shows that Δn_{eff} varies with both wavelength and structural ratio w/r_c . For geometries with $w/r_c = 0.35, 0.45, 0.60$, and 0.75 , Δn_{eff} remains positive over the entire wavelength range, indicating stronger confinement for the x-pol. modes. In contrast, other configurations exhibit sign reversal, where Δn_{eff} becomes negative at shorter wavelengths and turns positive at longer wavelengths. This transition reflects a shift in modal confinement behavior as a function of wavelength and slot geometry.

Table 3 summarizes the effective refractive indices of x-pol. and y-pol. modes at $2.15 \mu\text{m}$, confirming this structural dependence. For example, at $w/r_c = 0.35$, $\Delta n_{eff} = 0.00015$, while at $w/r_c = 0.85$, the value reverses to -0.00004 . These small yet systematic differences arise from the distinct field profiles of the two modes. The x-pol. modes, with symmetric confinement, remain more localized in narrower slots, whereas the y-pol. modes, with a horizontal polarization, can interact more effectively with the core as the slot widens and the field overlaps are redistributed [31].

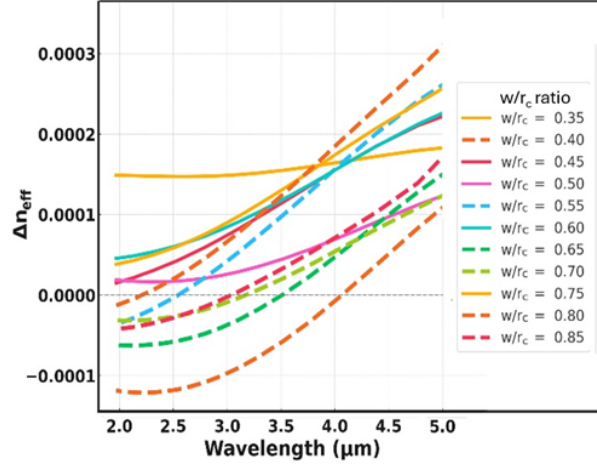


Fig. 4. (Color online) Difference in effective refractive index ($\Delta n_{eff} = n_{eff}(x-pol.) - n_{eff}(y-pol.)$) as a function of wavelength for various structure ratios w/r_c in the CS_2 -filled SC-PCFs.

Table 3. The real part of effective refractive index at 2150 nm wavelength of PCFs with various fiber structure ratio.

Structure ratio w/r_c	Real part of effective refractive index at 2150 nm wavelength			
	CS_2 -filled (x-pol.)	CS_2 -filled (y-pol.)	Air-filled (x-pol.)	Air-filled (y-pol.)
0.35	2.21249	2.21234	2.1798	2.1797
0.40	2.21301	2.21313	2.1806	2.1807
0.45	2.21366	2.21364	2.1813	2.1813
0.50	2.21444	2.21442	2.1823	2.1823
0.55	2.21511	2.21514	2.1830	2.1831
0.60	2.21603	2.21598	2.1843	2.1842
0.65	2.21688	2.21694	2.1852	2.1854
0.70	2.21789	2.21793	2.1864	2.1865
0.75	2.21907	2.21903	2.1879	2.1878
0.80	2.22026	2.22026	2.1892	2.1892
0.85	2.22161	2.22165	2.1909	2.1909

This ability to tune polarization behavior purely through geometrical design, without relying on stress or material anisotropy, offers significant advantages for mid-infrared applications [2,18,35].

3.4. Effect of cladding infiltration

To investigate the impact of material infiltration on optical confinement, we compared two configurations: one with air-filled cladding holes and another in which the holes were infiltrated with carbon disulfide, a high-index nonlinear liquid. In both cases, the fiber core is composed of solid As_2S_3 , ensuring consistency in structure.

Continuing the observation in Fig. 3, it is evident that CS_2 infiltration leads to a consistent increase in n_{eff} across the entire wavelength range for both x-pol. and y-pol. modes. This effect becomes more pronounced for structures with larger slot ratios, where the optical field tends to extend further into the cladding. Replacing air with CS_2 reduces the core-cladding index contrast, effectively pulling the mode back toward the high-index core and enhancing confinement.

Quantitative values at a representative wavelength of $2.15\ \mu\text{m}$ are shown in Table 3. For example, at $w/r_c = 0.85$, the x-pol. modes increase from 2.1909 (air) to 2.22161 (CS_2), while the y-pol. modes shift from 2.1909 to 2.22165. Even at lower ratios, such as $w/r_c = 0.35$, the effect remains evident: n_{eff} increases from 2.1798 to 2.21249 (x-pol.). This demonstrates that infiltration has a consistently enhancing effect, particularly as the structural slot widens.

To better visualize this trend, Fig. 5 compares n_{eff} values for both modes across structural ratios, in both air- and CS_2 -filled configurations. The CS_2 -filled structures exhibit systematically higher n_{eff} , reinforcing the role of cladding composition in enhancing confinement.

Beyond confinement, infiltration with CS_2 offers additional benefits: higher nonlinear coefficients, improved modal overlap, and mid-infrared transparency, factors crucial for applications such as all-optical switching, supercontinuum generation, and polarization-sensitive sensing [19,25,39]. Moreover, this technique allows tuning of optical performance without altering geometry, offering a flexible design parameter for next-generation photonic crystal fiber platforms.

These results confirm that CS_2 infiltration offers a powerful mechanism to enhance modal confinement without altering the fiber's core geometry, especially at higher slot ratios. The ability to increase through refractive index engineering provides a flexible and effective approach to optimizing suspended-core fiber performance. The results of this work contribute to a deeper understanding of suspended-core photonic crystal fibers (SC-PCFs) by quantitatively analyzing how the effective refractive index n_{eff} varies with both the structural ratio w/r_c and cladding infiltration.

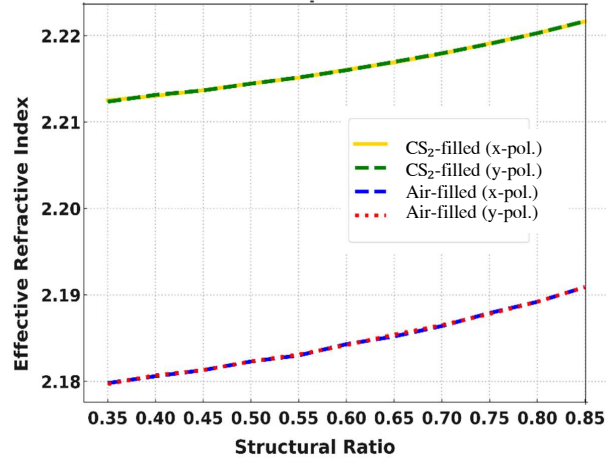


Fig. 5. Effective refractive index of x-pol. and y-pol. modes at $\lambda = 2.15\ \mu\text{m}$ as a function of structural ratio w/r_c , comparing CS_2 -filled and air-filled claddings.

Prior studies on As_2S_3 - and As_2Se_3 -based SC-PCFs have focused mainly on dispersion tailoring and supercontinuum generation [27,28,31,34], but few have examined how these parameters systematically affect modal refractive index and polarization sensitivity.

Compared to previous works using air-filled cladding [19,21,30], where n_{eff} values for TE modes typically remained below 2.21, our CS_2 -infiltrated design achieves values up to 2.2217 at $w/r_c = 0.85$, indicating improved optical confinement. This increase is significant when compared with Gao *et al.* [32] and Si *et al.* [33], where no infiltration or refractive index engineering was employed. Moreover, the ability to switch the sign of the polarization-dependent index difference Δn_{eff} across specific geometries highlights a tunable birefringence-like behavior not observed in earlier reports.

Liquid infiltration using ethanol, nitrobenzene, or water has been demonstrated in silica-based PCFs [5,10,36], but such techniques have not been systematically applied to mid-infrared SC-PCFs with high-index glasses like As_2S_3 . Our approach thus integrates both structural and material tuning in a suspended-core platform, offering enhanced control over optical properties with relevance to nonlinear optics, polarization-maintaining systems, and MIR fiber photonics.

4. Conclusion

This work presents a comprehensive numerical investigation into the effective refractive index characteristics of suspended-core photonic crystal fibers (SC-PCFs) based on As_2S_3 , with a focus on the influence of geometrical parameters and cladding material infiltration. By systematically varying the slot-to-core ratio w/r_c and comparing air-filled versus CS_2 -infiltrated designs, the study reveals clear dependencies of n_{eff} on wavelength, geometry, and polarization mode.

Key findings demonstrate that increasing slot width enhances optical confinement, while CS_2 infiltration significantly boosts n_{eff} , with values reaching 2.2217 at $w/r_c=0.85$. The polarization analysis further reveals that the index difference Δn_{eff} between x-pol. and y-pol. modes is strongly structure- and wavelength-dependent, offering a tunable route for birefringence engineering without external stress or anisotropic materials.

The integration of structural and material tuning in this SC-PCF platform provides a flexible, high-performance foundation for designing mid-infrared photonic devices. These include nonlinear fiber systems, polarization-maintaining components, and refractive index-based sensors, particularly in regimes where silica-based fibers are no longer viable.

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Authors contributions

Phuong Nguyen Thi Hong conducted the investigation and was responsible for writing the original draft of the manuscript. Ngoc Vo Thi Minh provided visualization support, enhancing the graphical representation of data and findings. Lanh Chu Van led the conceptualization of the research project, supervised the overall study, and played a key role in acquiring funding. Trung Le Canh implemented the software tools used in the research, facilitating data analysis and simulations. Trang Do Mai contributed to both visualization and investigative efforts, assisting in the interpretation of results. Tham Tran Hong engaged in investigation activities and contributed

to the review and editing of the manuscript to ensure clarity and accuracy. Thien Nguyen Minh participated in investigative tasks, contributing to data collection and analysis. Nam Nguyen Trong implemented the software tools and participated in investigative efforts, enhancing the research framework. Vinh Doan The Ngo and Huy Do Viet developed the methodology for the study and managed project administration, ensuring the research adhered to planned objectives. Ben Chu Van involved in writing, reviewing, editing and contributing to the refinement of the final manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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