

Research on Transmission Characteristics of Photonic-crystal Fiber with a Subwavelength Air Core

Zien Zhang^a, Kangwen Zhou^b, Zeyu Jin^a, Chang Liu^a, Zhifa Wang^a, Peng Gong^a, *

^a School of Mechatronical Engineering, Beijing Institute of Technology, China

^b International Institute for Innovation, Beihang University, China

1732955442@qq.com, 1944527916@qq.com, 758743342@qq.com, liuchang0118@bit.edu.cn, 3397073817@qq.com, penggong@bit.edu.cn

Abstract— This paper presents a comprehensive investigation of a subwavelength air-core photonic crystal fiber (PCF) and its application in a high-performance fiber polarizer. Through numerical simulations based on the finite-difference beam propagation method, we demonstrate that the proposed PCF structure enables exceptional light confinement within its subwavelength air core, overcoming the classical diffraction limit. An optimized polarizer design integrating a metal film with the side-polished PCF exhibits outstanding performance with an extinction ratio of 43.393 dB and an insertion loss of 1.553 dB for TE-polarized light. Comparative analysis confirms the superior efficacy of this approach over alternative configurations, establishing its potential for advanced photonic applications.

Keywords— Photonic Crystal Fiber, Subwavelength Optics, Fiber Polarizer, Extinction Ratio, Optical Confinement

I. INTRODUCTION

PHOTONIC crystal fibers (PCFs) have revolutionized fiber optics by enabling unprecedented control over light propagation through their periodic microstructured cladding [1]. Unlike conventional fibers relying solely on total internal reflection, PCFs can guide light via the photonic bandgap effect, yielding unique properties such as endless single-mode operation and Tailorable dispersion [2]. These characteristics make PCFs indispensable in fields ranging from optical communications to advanced sensing and nonlinear optics [3].

A significant advancement in this field is the development of subwavelength air-core PCFs. By incorporating a central air-hole defect with dimensions smaller than the guided wavelength, these fibers leverage the slot-waveguide effect to concentrate and intensify the optical field within the low-index core region [4]. This facilitates enhanced light-matter interaction and enables optical confinement surpassing the classical diffraction limit, opening new avenues for nano-photonics and integrated photonic systems [5].

Capitalizing on these properties, in-fiber polarizers based on PCFs have attracted considerable research interest. However, achieving an optimal balance between high extinction ratio, low insertion loss, and structural robustness remains challenging [6]. Many existing designs exhibit limitations in performance or fabrication complexity. This

work addresses these challenges through a systematic investigation of a novel subwavelength air-core PCF and its implementation in a high-performance polarizer. We elucidate the fiber's exceptional transmission characteristics and demonstrate a polarizer design that effectively integrates the PCF with a metal film, offering a compact and efficient solution for precise polarization control.

II. THEORETICAL FRAMEWORK AND SIMULATION METHODOLOGY

A. Simulation Approach

All numerical analyses in this study were performed using the BeamPROP module within the RSoft Photonics Suite. This simulation environment implements the finite-difference beam propagation method (FD-BPM), which provides computationally efficient and accurate solutions for analyzing light propagation through complex waveguide geometries [7]. The FD-BPM is particularly suited for modeling the evolution of optical fields in the proposed PCF structures, allowing for comprehensive characterization of their guiding properties. The simulation workflow followed in this work is illustrated in Figure 1.

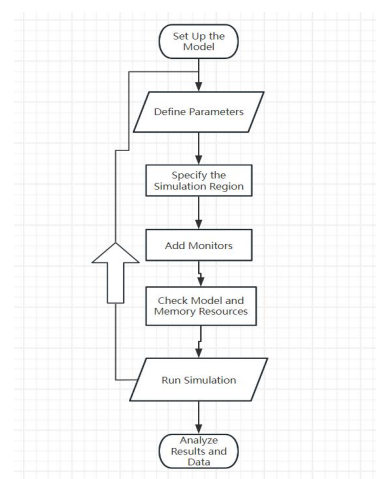


Figure 1. Rsoft Simulation Flowchart

B. Operating Principles

The subwavelength air-core PCF operates primarily based on the slot-waveguide effect. This phenomenon occurs when a low-refractive-index slot region (the air core) is sandwiched between two high-refractive-index regions (silica). The discontinuity of the electric displacement field at these high-contrast interfaces, following Maxwell's boundary conditions, results in a significant enhancement of the electric field within the low-index slot [8]. The fundamental relationship can be expressed through the continuity condition of the normal component of the electric displacement field:

$$D_{\perp, \text{high-index}} = D_{\perp, \text{low-index}} \Rightarrow \epsilon_{\text{high-index}} E_{\perp, \text{high-index}} = \epsilon_{\text{low-index}} E_{\perp, \text{low-index}}$$

The fundamental structure of a slot waveguide is depicted in Figure 2.

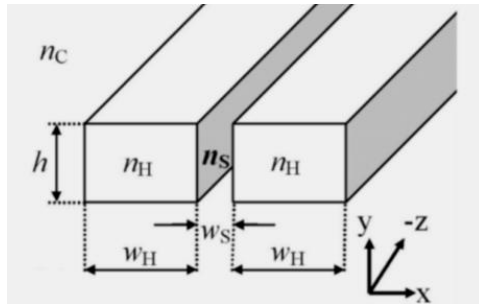


Figure 2. Slot Waveguide Structure Diagram

For the polarizer operation, we utilize principles of surface plasmon polaritons (SPPs). When a metal layer is appropriately integrated with the waveguide structure, TM-polarized light can resonantly couple to SPP modes at the metal-dielectric interface. This coupling leads to preferential attenuation of the TM mode compared to the TE-polarized light, thereby providing the polarization-selective functionality essential for an effective polarizer [9]. The propagation of a surface plasmon wave at a metal-dielectric interface is conceptually shown in Figure 3.

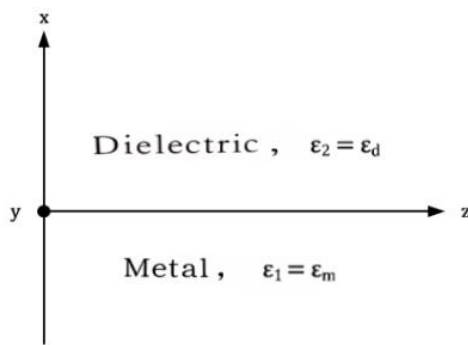


Figure 3. Surface Plasmon Wave Propagation Structure Diagram

III. FIBER DESIGN AND CHARACTERIZATION

A. Structural Configuration

The proposed subwavelength air-core PCF features a triangular lattice of air holes within a pure silica background. The key structural innovation involves a central defect consisting of a single air hole with a diameter of 110 nm, constituting the subwavelength air core. The cladding structure comprises air holes with a diameter of 650 nm arranged with a lattice pitch of 800 nm. This specific configuration was optimized to maximize the slot-waveguide effect while maintaining structural integrity and practical fabricability. The key parameters are summarized in Table 1.

TABLE 1. GEOMETRIC PARAMETERS OF THE SUBWAVELENGTH HOLLOW-CORE PCF

Parameter Name	Value
Incident Wavelength	700、1050、1310、1550(nm)
Refractive Index of Background Material	1.45
Refractive Index of Air Holes	1
Diameter of Core Air Hole	110nm
Diameter of Cladding Air Holes	650nm
Pitch of Cladding Air Holes	800nm

The 3D simulation model constructed in RSoft based on these parameters is shown in Figure 4. The corresponding refractive index profile of the model, confirming its correctness, is displayed in Figure 5.

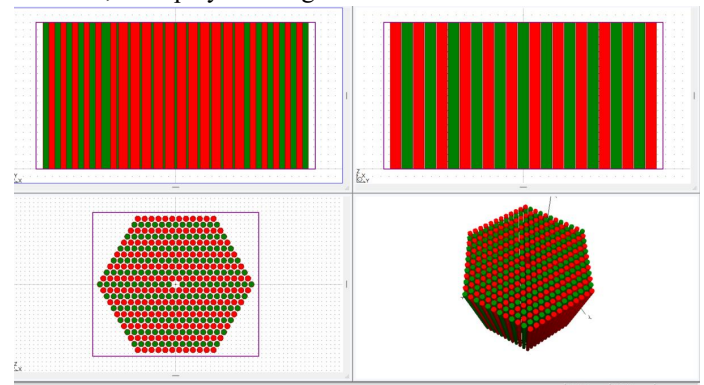
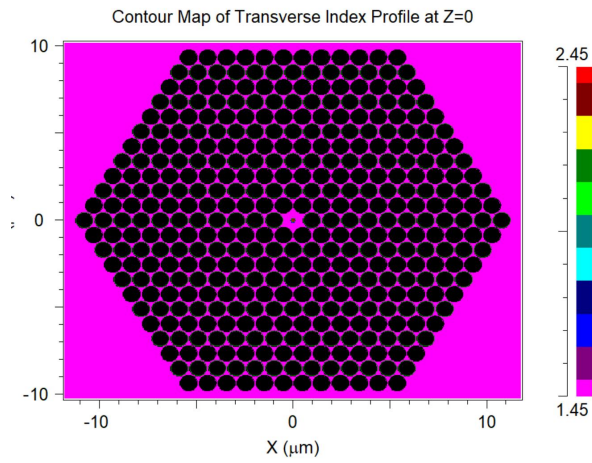
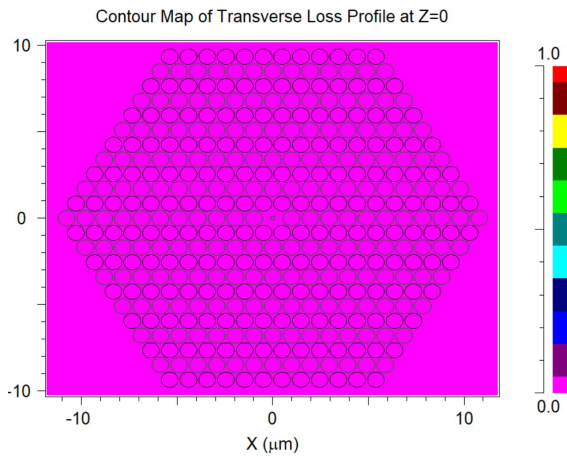


Figure 4. Subwavelength Air-Core Photonic Crystal Fiber Model Diagram



(a) Real Part of Refractive Index



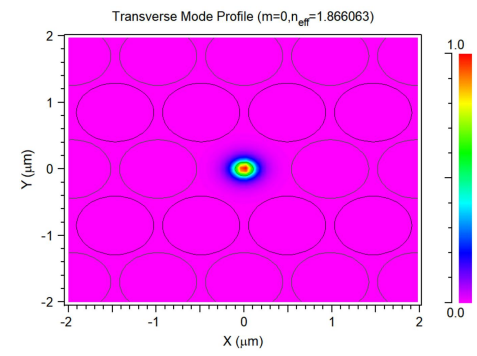
(b) Imaginary Part of Refractive Index

Figure 5. Subwavelength Air-Core Photonic Crystal Fiber Refractive Index Distribution Diagram

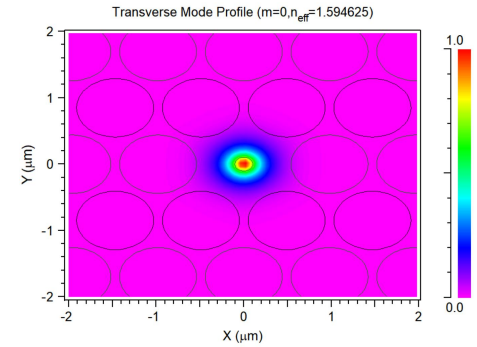
B. Modal Properties Analysis

Numerical simulations reveal that the fiber supports well-confined fundamental modes across the investigated wavelength range from 700 nm to 1550 nm. The electric field distribution demonstrates significant enhancement within the central air core, clearly confirming the operation of the slot-waveguide effect. The effective refractive indices show a consistent decrease with increasing wavelength, ranging from 1.866 at 700 nm to 1.401 at 1550 nm, indicating strong wavelength-dependent guiding characteristics.

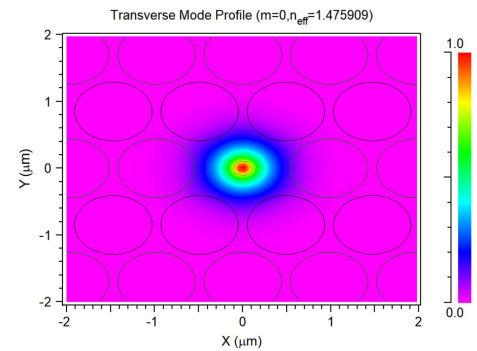
The modal analysis further demonstrates single-mode operation throughout the investigated spectrum, with the fundamental mode effectively confined within the central air core region. This confinement persists even when the operating wavelength exceeds the physical dimensions of the core feature, validating the fiber's ability to overcome the classical diffraction limit. The electric field and energy distributions under unpolarized, TE, and TM excitations are shown in Figure 6.



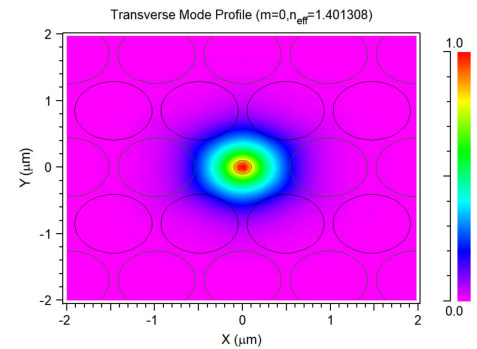
(a) 700nm Wavelength-Dependent Electric Field Distribution



(b) 1050nm Wavelength-Dependent Electric Field Distribution



(c) 1310nm Wavelength-Dependent Electric Field Distribution



(d) 1550nm Wavelength-Dependent Electric Field Distribution

Figure 6. Electric Field and Energy Distribution Diagram of the Subwavelength Air-Core Photonic Crystal Fiber

C. Baseline Analysis with Conventional Single-Mode Fiber

A critical comparative analysis was conducted against a standard single-mode fiber, the model and parameters of which are shown in Figure 7 and Table 2, to establish a performance baseline.

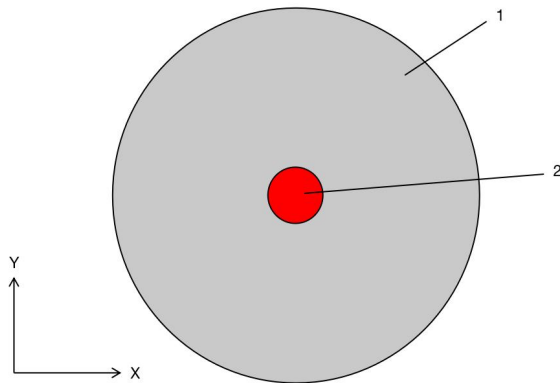


Figure 7. Cross-sectional view of the single-mode fiber

TABLE 2. PARAMETERS OF THE SINGLE-MODE FIBER

Parameter Name	Value
Incident Wavelength	$0.85 \mu\text{m}$
Refractive Index of Cladding	1.444
Refractive Index of Core	1.458
Core Diameter	$5 \mu\text{m}$
Cladding Diameter	$125 \mu\text{m}$

Unlike conventional fibers that suffer from significant signal degradation when the operating wavelength approaches the core dimensions, the subwavelength air-core PCF maintains efficient light guidance and strong field confinement. This remarkable property enables true subwavelength-scale light manipulation, overcoming fundamental limitations of traditional optical fiber technology and opening possibilities for novel photonic applications.

IV. DESIGN AND PERFORMANCE OF THE FIBER POLARIZER

A. Polarizer Structure and Operating Principle

Based on the above PCF, two polarizer designs were investigated:

1. Metal-Film Coated Polarizer: The PCF is side-polished and coated with a 40-nm-thick aluminum film ($n = 2.6 + 8.2i$), as shown in Figure 8 and its 3D model in Figure 9.

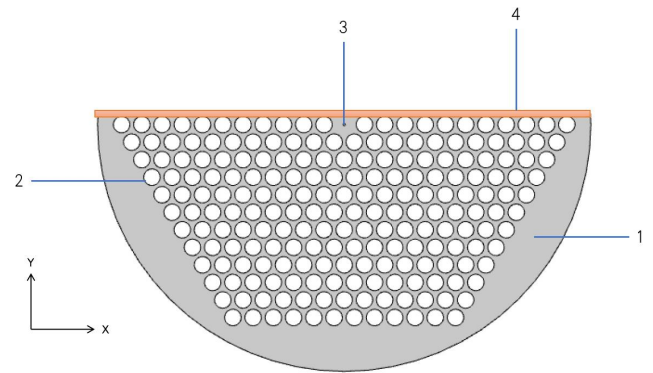


Figure 8. Cross-Sectional Schematic of the Subwavelength HC-PCF Polarizer

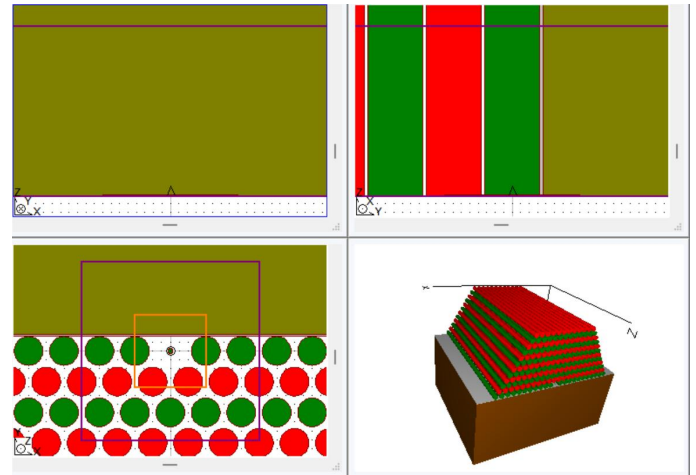


Figure 9. Method 1 — Three-dimensional simulation model for the subwavelength HC-PCF polarizer

2. Metal-Filled Hole Polarizer: The upper air holes adjacent to the core are filled with aluminum, as shown in Figure 10 and Figure 11.

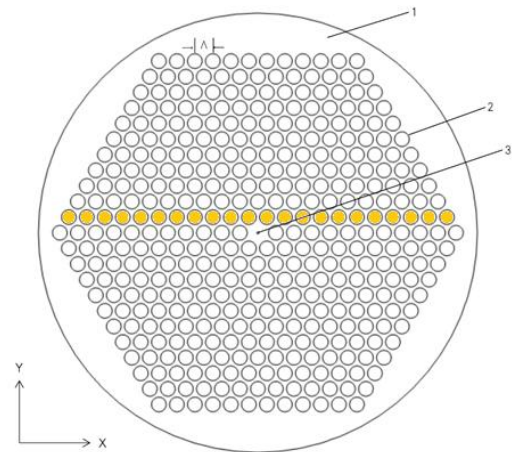


Figure 10. Schematic of the subwavelength HC-PCF polarizer cross-section.

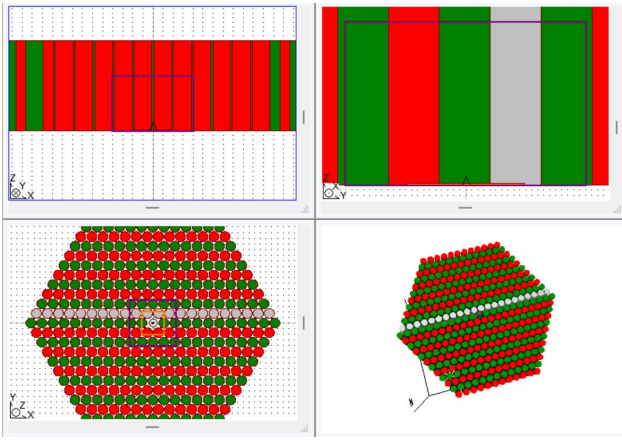
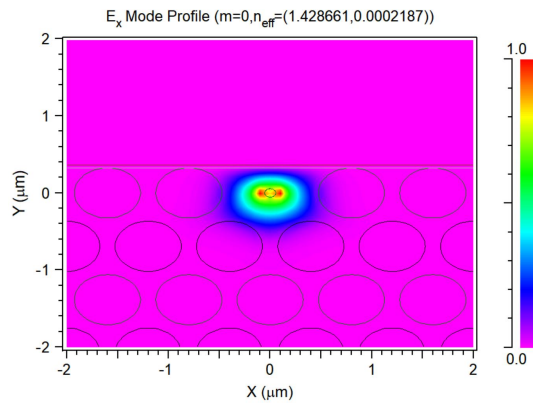


Figure 11. Cross-sectional schematic of the subwavelength hollow-core photonic crystal fiber polarizer.

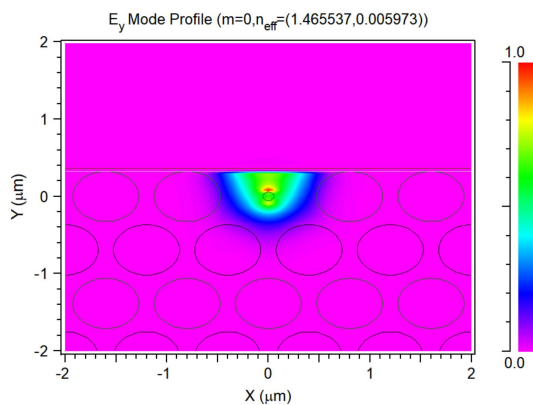
Both designs rely on surface plasmon polariton (SPP) excitation at the metal–dielectric interface to induce polarization-dependent loss.

B. Performance Analysis of the Metal-Film Based Polarizer

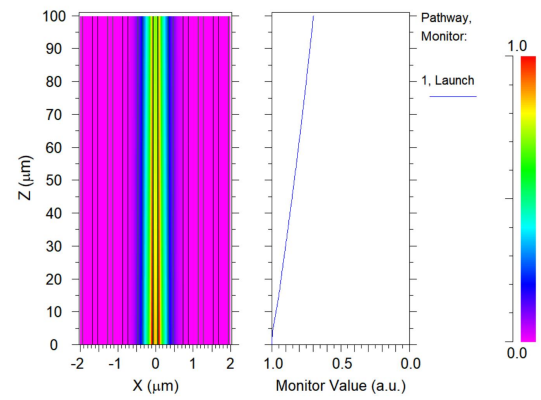
Simulations were conducted under TE and TM excitations at 700 nm. Figure 12 shows the electric field and energy distributions for TE and TM modes. Strong field confinement is observed for TE polarization, while the TM mode couples to lossy SPP modes, leading to high attenuation. The corresponding power transmission curves further confirm this selective behavior.



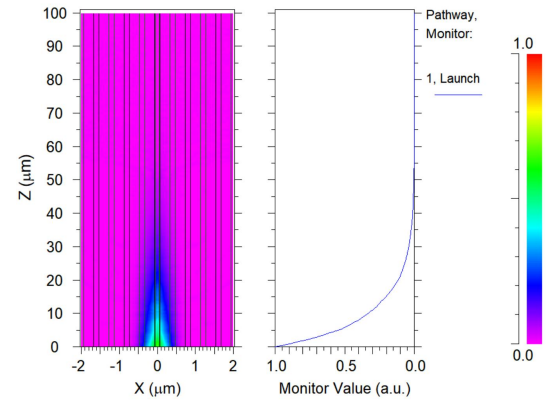
(a) Electric field distribution under TE-wave excitation.



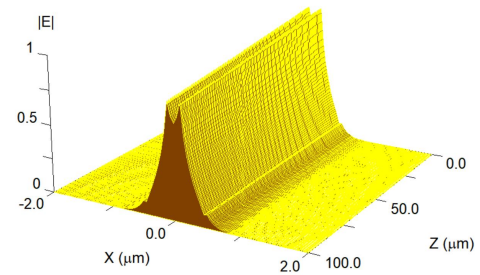
(b) Electric field distribution under TM-wave excitation.



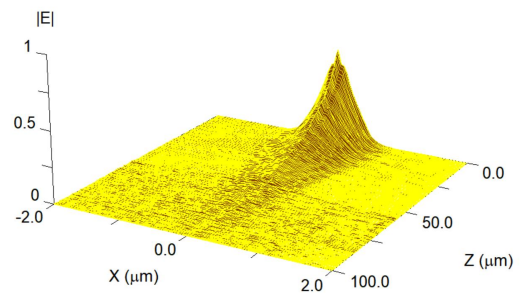
(c) Energy distribution under TE-wave excitation.



(d) Energy distribution under TM-wave excitation.

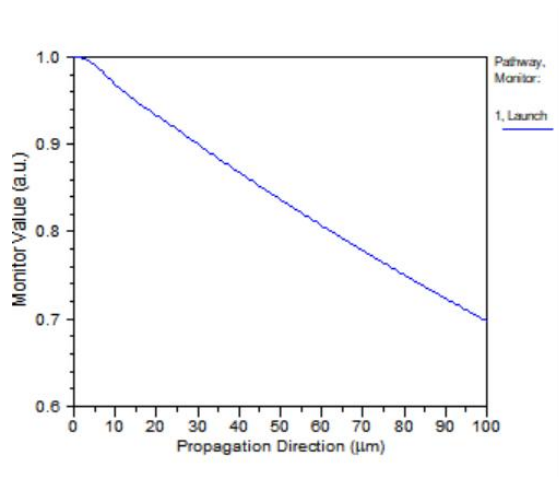


(e) Three-dimensional energy distribution under TE-wave excitation.

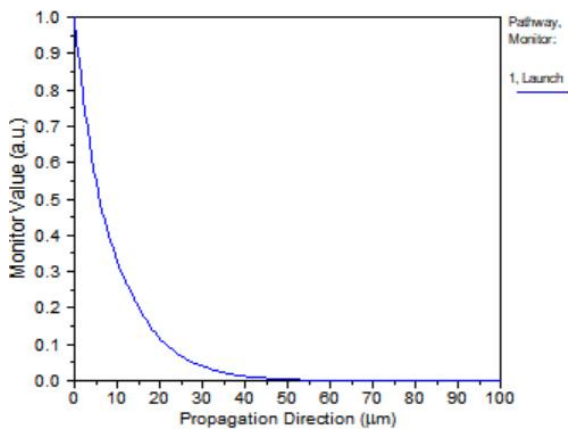


(f) Three-dimensional energy distribution under TM-wave excitation.

Figure 12. Electric field and energy distributions of the polarizer in Method 1



(a) Optical power transmission curve for the TE mode.



(b) Optical power transmission curve for the TM mode.

Figure 13. Optical power transmission curves of the polarizer under different incident light conditions.

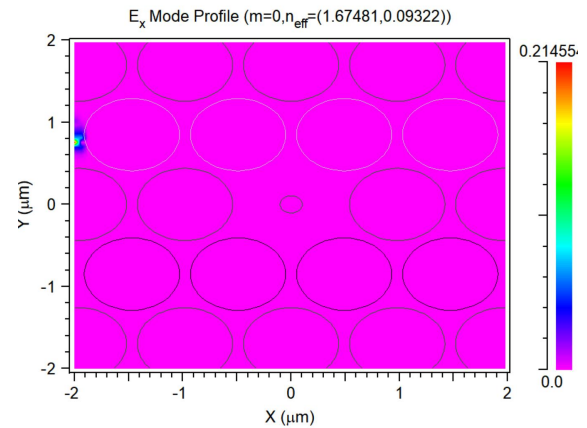
The key performance metrics—insertion loss (IL) and extinction ratio (ER)—were calculated, and the results are summarized in Table 3. The high ER of 43.393 dB and low IL of 1.553 dB for TE light demonstrate excellent polarizing performance, suitable for sensitive photonic systems.

TABLE 3. SUMMARY OF RELEVANT PARAMETERS FOR THE POLARIZER

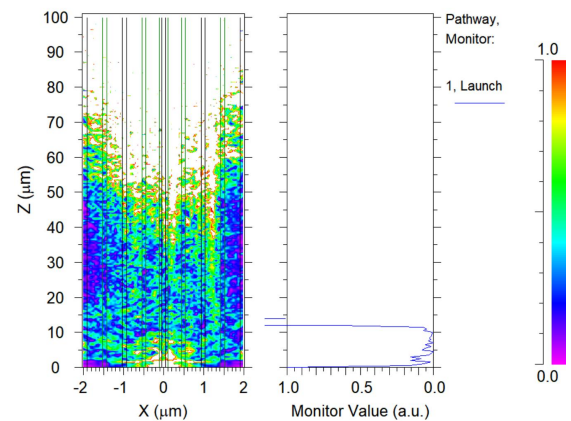
Parameter	Value
P_{in}	1
P_{TE}	0.6989931
P_{TM}	3.2×10^{-5}
$IL_{TE}(dB)$	1.553
$IL_{TM}(dB)$	44.949
$PER(dB)$	43.393

C. Feasibility Comparison of the Two Designs

The metal-filled hole design was found to be ineffective for polarization selection. As shown in Figure 14, the electric field becomes highly scattered, and the guiding mechanism is disrupted, resulting in high loss for both polarizations. This indicates that the side-polished metal-film approach is far more viable for practical polarizer implementation.



(a) Electric field distribution.



(b) Energy distribution.

Figure 14. Electric field distribution of the polarizer based on metal-filled structure.

D. Discussion

The superior performance of the metal-film integrated polarizer stems from the controlled interaction between the guided mode and the SPP layer, which is highly polarization-sensitive. The subwavelength core ensures strong field intensity near the metal interface, enhancing the polarization selectivity. This design balances high ER, low IL, and structural robustness, making it a promising candidate for advanced fiber-optic components.

V. CONCLUSION

This study has successfully established the fundamental transmission properties of a novel subwavelength air-core photonic crystal fiber and demonstrated its effective implementation in a high-performance in-fiber polarizer. The numerical results conclusively confirm the fiber's ability to

achieve optical confinement beyond the diffraction limit through the slot-waveguide effect, enabling nanoscale light manipulation previously unattainable with conventional fiber technology.

The optimized polarizer design achieves an exceptional extinction ratio of 43.393 dB with minimal insertion loss of 1.553 dB, representing a significant advancement in fiber-optic polarization control. The metal-film integration approach proves particularly effective compared to alternative configurations, offering a practical solution for applications requiring precise polarization management.

Future research directions will focus on the experimental realization and characterization of the proposed structures, investigation of alternative plasmonic materials for enhanced performance, and exploration of additional device applications leveraging the unique properties of subwavelength air-core PCFs in advanced photonic systems.

ACKNOWLEDGMENT

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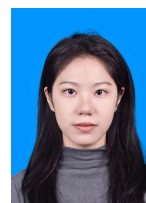
Zien Zhang obtained his Bachelor of Engineering degree from China Agricultural University in 2024. Currently, he is a master's student at the School of Mechatronic Engineering, Beijing Institute of Technology. His research interests include signal processing, target detection, and fuze jamming.



Kangwen Zhou received the B.S. degree in Telecommunications Engineering from China Agricultural University, Beijing, China, in 2024. He is currently pursuing the M.S. degree with Beihang University, Beijing. His research interests include large language models (LLMs) and the FlashAttention algorithm.



Zeyu Jin received the BS degree in Beijing Institute of Technology in 2025. Now he is a master degree candidate in School of Mechatronic Engineering, Beijing Institute of Technology. His research interests include signal processing, signal classification, machine learning and so on.



Chang Liu received the B.S. degree in Mechatronic Engineering from the Beijing Institute of Technology, Beijing, China, in July 2025. She is currently pursuing the M.S. degree with the School of Mechatronic Engineering, Beijing Institute of Technology. Her research interests include deep learning, signal classification, and signal processing.



Zhifa Wang received the BS degree from Beijing Institute of Technology in 2025. He is currently pursuing a Master's degree in the School of Mechatronic Engineering at Beijing Institute of Technology. His research interests include signal processing, signal classification, object recognition, and related applications in intelligent systems.



Peng Gong received the BS degree in Mechatronic Engineering from Beijing Institute of Technology, Beijing, China, in 2004, and the MS and Ph.D. degrees from the Inha University, Korea, in 2006 and 2010, respectively. Now he is a professor in Beijing Institute of Technology. His research interests include link/system level performance evaluation and radio resource management in wireless systems, information security, and the next generation wire-less systems such as UWB, MIMO, Cognitive radio, IoT and so on.