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Enhancing optical fiber performance through liquid infiltration in photonic crystal fiber

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Liquid infiltration into photonic crystal fibers (PCFs) opens new horizons in optical fiber design. This innovation allows precise control of the refractive index, dispersion, and nonlinear effects within the PCF core, expanding its adaptability for various applications. Through numerical simulations, we explore the impact of different liquids on chromatic dispersion in PCFs, emphasizing the role of filling ratios. Our findings unveil shifts in zero dispersion wavelengths, with chloroform causing significant changes. Lower filling ratios reduce dispersion sensitivity, while higher ratios enable dispersion compensation. This study advances our understanding of liquid-filled PCFs, vital for cutting-edge photonics research and practical applications.

Keyword: photonic crystal fiber, liquid infiltration, refractive index, chromatic dispersion, optofluidics

1 Introduction

Photonic crystal fiber (PCF), also known as micro-structured optical fiber, represents a fascinating innovation in the field of optical communication and photonics. It is a specialized type of optical fiber that boasts a unique and intricate internal structure, offering a range of exceptional optical properties and enabling a wide array of applications. PCF's inception can be traced back to the late 20th century, and its development has since spurred numerous breakthroughs in the field of photonics [1, 2].

The concept of photonic crystal fiber emerged in the late 1990s as a response to the limitations of conventional optical fibers [3]. These early optical fibers, though highly efficient at transmitting light [4], possessed limitations in terms of bandwidth [5], dispersion [6], and mode confinement [6]. Researchers sought to overcome these challenges by developing a novel class of optical fibers with a fundamentally different internal structure [7-10].

The two fundamental geometrical parameters in photonic crystal fiber (PCF) design are the hole diameter (d) and hole spacing (Λ). These parameters are crucial in determining the optical properties and guiding mechanisms of PCFs (Fig. 1).

Photonic crystal fibers (PCFs) enable effective management of dispersion by meticulously designing their internal structure. Numerous facets of dispersion characteristics have already undergone thorough investigation and analysis, including the zero-dispersion wavelength shift [11], ultra-flattened dispersion characteristic [12], optimization of chromatic dispersion [6], tailored dispersion profiles [13], dispersion compensation [14].

The ability to introduce liquids into photonic crystal fibers represents an intriguing capability that offers an extra layer of versatility in the design process [15, 16]. By allowing the infiltration of liquids into the hollow or air-filled channels within PCFs [17, 18], designers gain an additional degree of freedom for customizing the fiber's properties and functionality. This innovative feature opens up a range of opportunities, as it enables precise control over factors such as refractive index [19], dispersion [20], and nonlinear effects within the fiber's core [21]. Consequently, researchers and engineers can tailor PCFs to suit specific applications, making them highly adaptable for purposes such as sensing [22, 23], optical modulation [24], and the development of novel optical devices [10, 25-27]. This liquid infiltration technique expands the horizons of what PCFs can achieve [28], making them a valuable platform for cutting-edge photonics research and practical applications [29].

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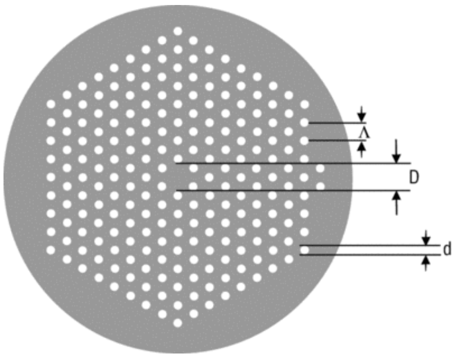


Fig. 1. Photonic crystal fiber

Liquids often exhibit higher nonlinear refractive indices compared to solids, leading to interesting optical phenomena. For example, the nonlinear refractive index of water. The ability to alter the refractive index within liquid-filled photonic crystal fibers through changes in an external electric field offers a valuable means to manipulate and control the characteristics of these fibers. This refractive index modulation can be harnessed to dynamically adjust the properties of the PCF, making it a versatile platform for various applications.

Such tunable PCFs can be used in ultrafast couplers [34], dispersion-related devices [35], or waveguide sensors [36].

PCFs that have been infused with liquids find utility in microfluidic devices, significantly expanding the capabilities for the manipulation and interaction with microscopic entities [37]. Optofluidics, a swiftly advancing field that merges microfluidic devices with optical components, holds great promise [38]. Within this realm, PCFs prove to be an ideal selection, offering a multitude of applications, including couplers, gas sensors, and waveguides [36, 39]. It is worth noting that there have been only a limited number of research papers exploring the optical proprieties in liquid-infiltrated PCFs for optofluidic applications [40, 41]. However, many of these studies did not account for the attenuation or material dispersion characteristics of real liquids. This is the primary reason why we are conducting this study: to assess the influence of different liquids on chromatic dispersion and understand how they affect this crucial optical parameter.

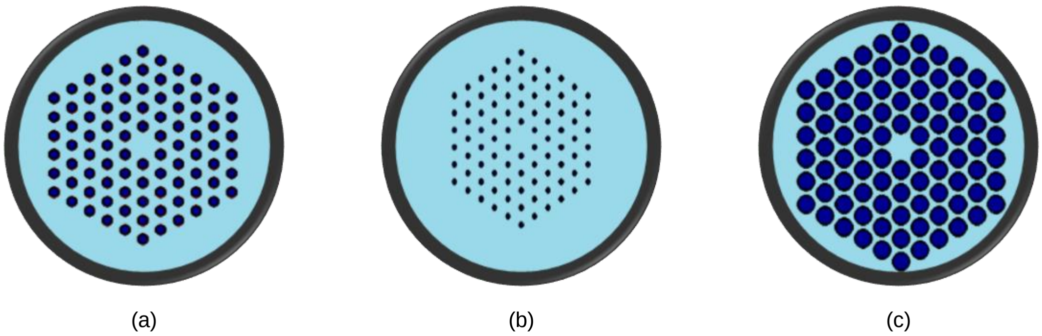
2 Design consideration

Figure 2 provides a visual representation of our designed photonic crystal fiber (PCF) structures. Within our design framework, we have developed three distinct types of PCFs, each characterized by a hexagonal arrangement of air holes. This specific hexagonal lattice configuration comprises five rows of precisely positioned air holes, with a deliberate omission of the central hole, resulting in the creation of a solid core structure. The spacing between two consecutive air holes is denoted as Λ and measures 6.5 μm.

What sets these three PCF types apart are their respective filling ratios, which are critical in determining the PCF's optical properties. These filling ratios are as follows: 0.46, 0.26, and 0.76. Essentially, these values represent the proportion of the PCF's core area that is occupied by air holes, thus influencing the PCF's ability to guide light.

Furthermore, it is essential to note that all three PCF types share a common coating diameter of 245 μm. This coating serves to protect the core and cladding of the fiber. Additionally, the outer cladding diameter, which defines the overall dimensions of the PCF, is consistently maintained at 125 μm across all three PCF types.

These meticulously designed PCF structures lay the foundation for our exploration of their optical properties and applications, and the variations in filling ratio offer a range of possibilities for tailoring their performance to specific needs.



(a) (b) (c)

Fig. 2. Cross-sectional view of hexagonal PCF
(a) $d/\Lambda = 0.46$, (b) $d/\Lambda = 0.26$, (c) $d/\Lambda = 0.76$

3 Numerical simulations

Subsequently, our research team embarked on an extensive and rigorous numerical investigation to delve deeper into the characteristics of the developed photonic crystal fiber using the Beam Propagation Method (BPM), a powerful computational approach widely employed in the study of optical waveguide structures. In this endeavor, we adopted a fundamental assumption that proved pivotal to our analysis: the air holes meticulously designed within the intricate structure of the PCF could be filled with a carefully curated selection of distinct liquids, each chosen for its unique and precisely characterized optical properties.

The choice of liquids for our investigation was far from arbitrary; rather, it was a result of meticulous consideration and a comprehensive understanding of their optical characteristics, particularly with regard to their refractive indices. The refractive index, a fundamental parameter in optics, plays a crucial role in determining how light propagates within optical fibers. Our selection of liquids included water (H_2O), heavy water (D_2O), chloroform ($CHCl_3$), and ethanol (EtOH). Each of these liquids was chosen for its well-documented and precise optical properties.

The significance of this selection lies in the fact that these liquids offered a wide spectrum of refractive indices, ranging from the well-known values of water and ethanol to the distinct characteristics of heavy water and chloroform. This diversity allowed us to conduct a comprehensive exploration of how variations in refractive indices, achieved by filling the PCF's air holes with these carefully chosen liquids, influenced the optical behavior of the fiber.

By employing the BPM, we were able to simulate and analyze the propagation of light within the PCF under different conditions, effectively creating a versatile platform for studying the effects of refractive index variations. Our investigation sought to unravel the intricate interplay between the refractive indices of these liquids and the PCF's unique structure, shedding light on how changes in the optical properties of the filling materials could be harnessed for various applications, ranging from optical sensing to telecommunications and beyond.

In essence, our research represented a meticulous and systematic exploration of the optical potential of the developed PCF, driven by a thorough understanding of the optical properties of the chosen liquids and the versatile capabilities of computational tools like the BPM. The results of this investigation provided valuable insights into the manipulation of light within photonic crystal fibers, opening up exciting possibilities for the advancement of optical technologies.

Our numerical investigation using these liquids serves as a pivotal cornerstone of our research, providing a comprehensive understanding of the intricate interplay between liquid infiltration and optical performance within PCFs. This analysis not only sheds light on the potential applications of liquid-infiltrated PCF structures but also contributes valuable insights into the design and optimization of such fibers for a wide array of optical and photonic applications.

Figure 3 illustrates the refractive index of the liquids as a function of wavelength within the optical transmission range of three key optical windows (0.6 to 1.7 micrometers). This plot provides valuable insights into how the refractive index of these liquids varies across the specified wavelength range, which is particularly relevant for optical applications operating within these optical windows. Understanding how the refractive index behaves at different wavelengths is essential for optimizing the performance of optical components, sensors, and devices designed to operate in this spectral range.

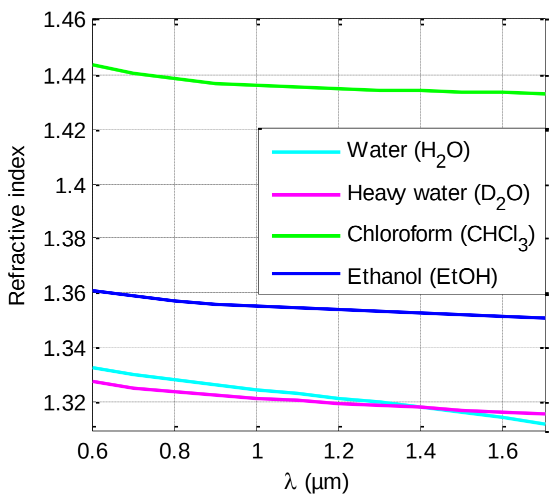


Fig. 3. Refractive index as a function of wavelength for different liquids

The intensity distribution of the fundamental mode at the specific wavelength of 1.55 μm, as depicted in Fig. 4, is a critical aspect of our study. This wavelength holds paramount importance in optical communication systems due to its unique optical characteristics. At 1.55 μm, the attenuation of optical signals is significantly minimized. This wavelength range corresponds to the minimum point of signal loss, making it the wavelength of choice for long-distance optical communication. This low attenuation property is a result of the intrinsic properties of optical fibers, where they exhibit minimal absorption and scattering. Consequently, it has become the standard wavelength for numerous telecommunication applications globally.

To comprehensively evaluate how different liquids affect the optical properties of photonic crystal fibers, we carried out a meticulous comparative analysis. In this analysis, we used the first type of optical fiber with a filling ratio of 0.46 as a reference point. This specific filling ratio is crucial as it represents a balance between air (no infiltration) and the various liquids we studied, including water, heavy water, chloroform, and ethanol. The choice of this reference point allows us to understand how different liquids impact the fiber's optical behavior, facilitating insights into potential applications.

Within the realm of PCFs, the guiding mechanism relies on total internal reflection. This mechanism ensures effective light confinement and propagation within the core of the fiber. It is essential to note that the fundamental guided mode, characterized by its single-mode behavior, is consistently observed throughout the entire analyzed wavelength range. This single-mode behavior indicates that PCFs maintain their optical integrity even in the presence of various infiltrating liquids or changing environmental conditions.

This observed phenomenon highlights the innate capacity of PCFs to support the fundamental guided mode, showcasing their versatility and robustness. This characteristic makes PCFs highly adaptable and suitable for a wide range of applications, including telecommunications, sensing, and beyond.

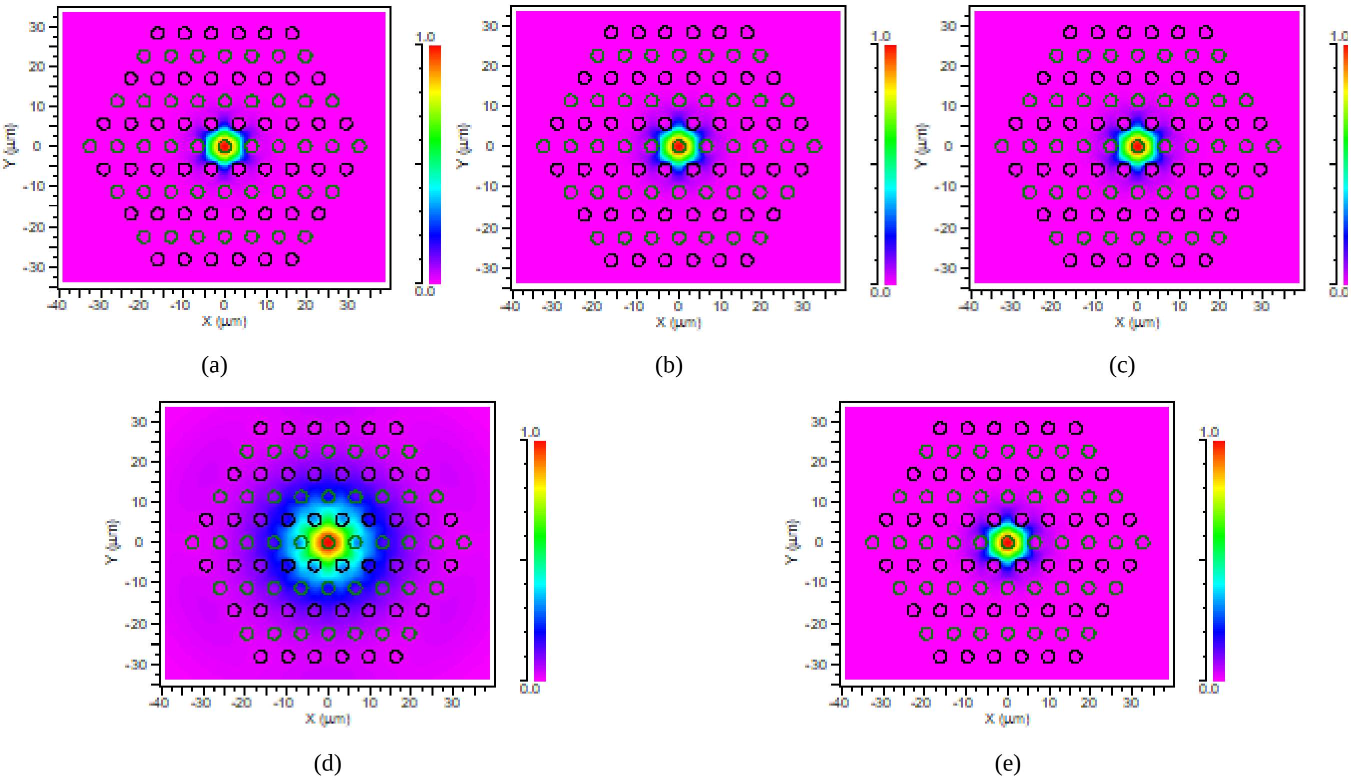


Fig. 4. Intensity distribution in the PCF
(a) air hole, (b) water, (c) heavy water, (d) chloroform, (e) ethanol

4 Influence of liquids on dispersion properties

We conducted a comprehensive analysis of dispersion as a function of wavelength within the range of 0.6-1.8 μm for the simulated fiber filled with various liquids. The results of this analysis are graphically presented in Fig. 5. Notably, the red lines in the plot represent the dispersion characteristics of the fiber without any liquid infiltration.

A key finding of our investigation is the noticeable shift in the zero dispersion wavelength (ZDW) towards longer wavelengths when different liquids are introduced into the fiber's core. Specifically, the use of water or heavy water (D_2O) causes a ZDW shift of approximately 20 nm, whereas the introduction of chloroform ($CHCl_3$) results in a substantial shift of about 370 nm.

For reference, the ZDW for the photonic crystal fiber (PCF) with air holes alone is determined to be at 1.2 μm. However, when the air holes are filled with liquids, the ZDW is consistently pushed towards longer wavelengths. Furthermore, it is noteworthy that the dispersion characteristic exhibits a decreasing slope as a consequence of this shift in the ZDW.

Of particular significance is the observation that the most substantial ZDW shift occurs when chloroform is employed as the infiltrating liquid, pushing the ZDW to approximately 1.57 µm. In contrast, the least significant shift is observed when water is used as the infiltrating liquid, with the ZDW extending to approximately 1.21 µm.

These findings underscore the profound influence of liquid infiltration on the dispersion characteristics of the PCF and have important implications for tailoring the optical properties of the fiber to suit specific applications, such as dispersion compensation or the generation of supercontinuum spectra.

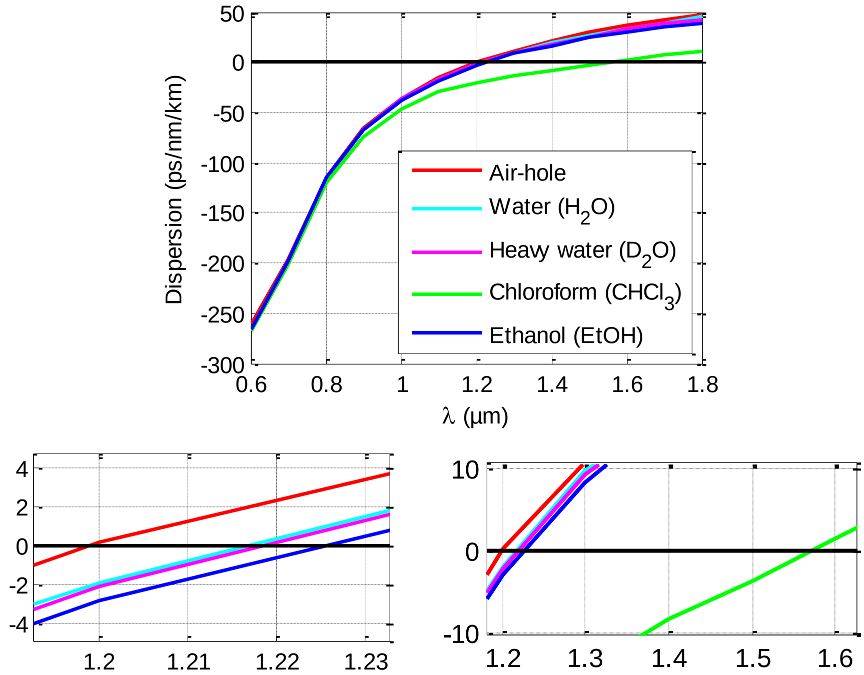


Fig. 5. Dispersion of the fiber filled with liquids (fiber 1)

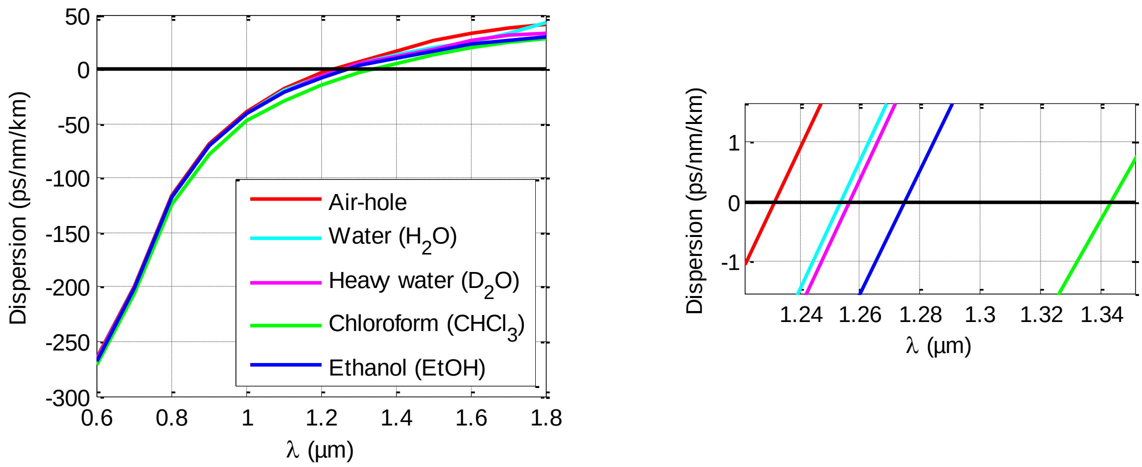


Fig. 6. Dispersion of the fiber filled with liquids (fiber 2)

Following this study, we are embarking on a transition to a different type of optical fiber to explore how geometric parameters are influenced by the infiltration of liquids into the air holes. Our investigation commences with Fiber Number 2 (Fig. 2b), as depicted in Fig. 6. Notably, when chloroform is introduced as the infiltrating liquid, we observe a significant shift in dispersion, amounting to 120 nm. These findings prompt us to draw noteworthy conclusions regarding the role of the filling ratio, which emerges as a pivotal factor in this context.

It is important to emphasize that we are transitioning from a filling ratio of 0.46 to 0.26, a shift that leads to a noticeable reduction in the dispersion shift. This indicates that a lower filling ratio results in decreased sensitivity to changes in dispersion, especially when compared to higher filling ratios. The transition from 0.46 to 0.26 signifies a shift towards a reduced amount of liquid infiltrating the air holes, which, in turn, has implications for the dispersion behavior, highlighting the inverse relationship between filling ratio and dispersion shift.

Shifting our focus to higher filling ratios, exemplified by Fiber Number 3 (Fig. 2c) with a ratio of 0.76, our findings, as illustrated in Fig. 7, reveal a fascinating phenomenon – dispersion compensation. Even with chloroform as an infiltrating liquid, the dispersion values consistently remain negative. This intriguing behavior can be attributed to the substantial quantity of liquid within the holes, which allows for effective dispersion compensation. Furthermore, it results in the elimination of positive dispersion values, giving rise to a scenario where negative dispersion is maintained across various wavelengths.

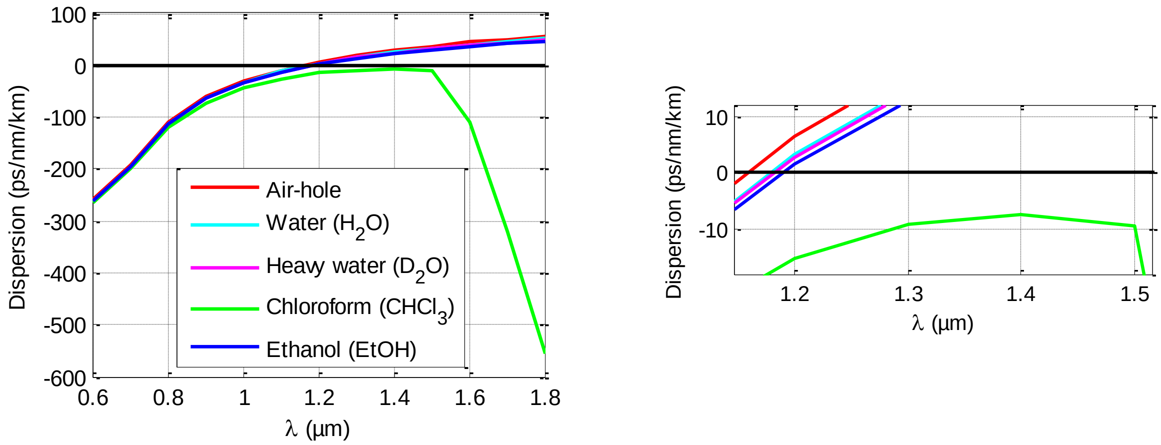


Fig. 7. Dispersion of the fiber filled with liquids (fiber 3)

These outcomes shed light on the intricate interplay between filling ratios, liquid infiltration, and dispersion characteristics within the optical fiber. They provide valuable insights into the nuanced manipulation of dispersion properties for specific applications. This research underscores the critical role of the filling ratio as a key parameter in shaping the optical response of the fiber to liquid infiltration.

5 Conclusion

The advent of liquid infiltration in photonic crystal fibers marks a significant milestone in optical fiber design, offering unparalleled versatility and control over optical properties. This study has delved into the multifaceted implications of liquid-filled PCFs, shedding light on their potential and highlighting key considerations.

Firstly, our research underlines the pivotal role of filling ratios in shaping the dispersion characteristics of liquid-infiltrated PCFs. Lower ratios exhibit reduced sensitivity to dispersion changes, while higher ratios facilitate dispersion compensation. This insight provides valuable guidance for tailoring PCF designs to meet specific optical requirements.

Furthermore, the ability to infiltrate PCFs with diverse liquids, each with unique refractive indices, introduces a wealth of opportunities. The liquids' nonlinear properties and tunability through external electric fields extend the applicability of PCFs in fields like ultrafast couplers, dispersion-related devices, and waveguide sensors.

The integration of liquid-filled PCFs into the emerging field of optofluidics enhances microfluidic device capabilities, paving the way for innovative applications in sensing and manipulation of micro-entities. PCFs serve as ideal platforms for couplers, gas sensors, and waveguides within this promising domain.

In conclusion, this study underscores the transformative potential of liquid-infiltrated PCFs, offering precise control over optical properties and expanding the horizons of photonics research and practical applications. As the field continues to evolve, liquid infiltration in PCFs promises to revolutionize the way we harness light for various technologies and industries.

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