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Characteristics of Uniform Fiber Bragg Gratings in High Birefringence Photonic Crystal Fiber

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Abstract: Fiber Bragg Grating (FBG) is a crucial optical waveguide device widely used in sensing, filtering, and optical communication. In recent years, High Birefringence Photonic Crystal Fiber (HB-PCF) has emerged as an important optical transmission medium in complex optical environments due to its outstanding polarization-maintaining capability and structural design flexibility. This paper investigates the spectral characteristics of uniform FBGs embedded in HB-PCF through theoretical modeling and coupled-mode analysis, systematically examining the dual reflection peaks phenomenon, polarization-dependent spectral response, mode-selective reflection behavior, bandwidth and reflectivity properties, as well as dispersion characteristics. The results demonstrate that the HB-PCF-FBG structure exhibits significant advantages for polarization-sensitive applications, high-precision sensing, and dispersion control, highlighting its excellent potential for engineering applications.

Keywords: photonic crystal fiber (PCF), high birefringence, fiber bragg grating (FBG), spectral characteristics

Introduction

With the increasing demand for highly stable and high-performance optical devices, Photonic Crystal Fiber (PCF) has become a key research focus in fiber optics due to its unique structural advantages. Among them, High Birefringence Photonic Crystal Fiber (HB-PCF), known for its exceptional polarization-separation capability and mode stability, holds broad application prospects in sensor construction, photonic filters, and polarization control systems. Fiber Bragg Grating (FBG), as a structure based on periodic refractive index modulation for selective reflection, can not only retain the wavelength-selective characteristics of Bragg gratings when combined with HB-PCF but also introduce polarization-dependent coupling mechanisms, leading to unique spectral behaviors. This paper aims to explore the various spectral characteristics exhibited when uniform FBGs are embedded in HB-PCF, providing foundational research for the theoretical design and performance optimization of novel polarization-sensitive photonic devices.

1. Structure and Optical Properties of High Birefringence Photonic Crystal Fiber

1.1 Formation mechanism of birefringence

High Birefringence Photonic Crystal Fiber (HB-PCF) typically employs an asymmetric air-hole structure design, such as introducing one or more pairs of large holes along a specific axis around the core or controlling the size and arrangement density of air holes in the transverse direction to break the original rotational symmetry. This structural inhomogeneity causes the core region to exhibit different effective refractive indices along two orthogonal polarization directions, thereby inducing modal birefringence. The birefringence magnitude can often reach the order of 10^{-3}, far exceeding that of traditional polarization-maintaining fibers (e.g., elliptical cladding fibers or Panda-type fibers), significantly enhancing polarization stability and directional retention (Liao et al., 2024).

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1.2 Influence of birefringence on light propagation

Due to inherent birefringence, different polarization modes (e.g., the LP_{01}^{x} mode with a transverse electric field along the x-direction and the LP_{01}^{y} mode along the y-direction) exhibit different propagation constants and phase velocities under the same propagation conditions. This difference in propagation characteristics causes the two polarization components to gradually separate in the fiber, resulting in spatial and spectral polarization decoupling effects. Birefringence also leads to group velocity differences, giving rise to Polarization Mode Dispersion (PMD), which must be controlled and compensated in optical communication systems. However, in sensing or polarization modulation applications, this characteristic becomes a critical parameter. In structures combining Fiber Bragg Gratings (FBGs) with HB-PCF, the inherent birefringence manifests as a splitting of the reflection spectrum—where two polarization states satisfy different Bragg matching conditions, forming two distinct reflection peaks in the spectrum. This phenomenon is of great significance for enhancing the device's polarization resolution and multi-parameter detection capabilities.

2. Formation and Coupling Mechanism of Uniform Fiber Bragg Gratings in High-Birefringence PCF

2.1 Fundamental principles of Fiber Bragg Gratings

A Fiber Bragg Grating is a structure formed by periodically modulating the refractive index along the axial direction of the fiber core. This periodic modulation creates an optical resonant cavity that enables strong reflection of specific wavelengths while transmitting others, playing a critical role in wavelength-selective filtering, sensing, and signal modulation. The reflection wavelength of an FBG is closely related to the modal effective refractive index in the fiber and the modulation period, representing a typical manifestation of the photonic bandgap effect.From a physical mechanism perspective, the working principle of an FBG is based on the coupling between forward-propagating and backward-propagating light waves in the fiber. When the phase-matching condition is satisfied, the scattering centers provided by the periodic refractive index modulation of the grating reflect a portion of the optical energy back, forming a reflected wave. This process not only enables selective reflection of light but also endows the FBG with high wavelength resolution and reflection efficiency.Additionally, parameters such as the refractive index modulation amplitude, grating length, and fiber material characteristics collectively determine the shape, bandwidth, and sidelobe structure of the FBG's reflection spectrum. In practical applications, FBGs can be precisely inscribed into fibers using ultraviolet laser irradiation techniques, achieving controllable periodic refractive index variations. Their stability and repeatability provide an important foundation for fiber-optic sensors, laser feedback, and dispersion compensation. Traditional FBG research has primarily focused on standard single-mode fibers. However, in specialty fibers such as polarization-maintaining fibers, multimode fibers, and photonic crystal fibers, the coupling mechanism of FBGs exhibits more complex and diverse spectral response characteristics due to differences in the fibers' intrinsic properties (Fu et al., 2025).

2.2 Special characteristics of inscribing FBGs in High-Birefringence Photonic Crystal Fiber

HB-PCF significantly enhances the birefringence effect through asymmetric structural design, resulting in substantial differences in the effective refractive indices along two orthogonal polarization directions. The birefringence magnitude is much higher than that of traditional polarization-maintaining fibers, typically reaching 10^{-3} or even higher, leading to distinct transmission characteristics between the two polarization states. When a uniform FBG is inscribed in HB-PCF, the modes of the two orthogonal polarization states independently satisfy their respective reflection conditions, manifesting as a distinct dual-peak reflection spectrum in the reflection spectrum. The dual-peak structure is a direct manifestation of the birefringence effect and reflects the dual-channel coupling characteristic between the FBG and the polarization modes in the HB-PCF. Each reflection peak corresponds to a strong coupling reflection wavelength for a specific polarization direction, exhibiting clear polarization dependence. This characteristic holds significant implications in several aspects. First, the dual-peak reflection structure provides a physical basis for designing polarization-selective filters and polarization beam splitters, enabling efficient polarization discrimination while maintaining structural simplicity. Second, the spacing and shape of the reflection peaks of FBGs in HB-PCF can be controlled by designing the fiber's geometric parameters and grating period, enabling composite modulation and filtering of multiple wavelengths and polarization states (Chen et al., 2025). Furthermore, the air-hole structure of HB-PCF offers greater flexibility and control precision during the inscription process. By optimizing the hole size, arrangement pattern, and spacing, the refractive index distribution around the core can be precisely adjusted to improve the modulation quality of the FBG and enhance selective coupling for specific polarization modes. Compared to traditional fibers, FBGs in HB-PCF exhibit higher modulation depth and lower insertion loss, contributing to improved overall optical device performance. In terms of environmental stability, the high birefringence enhances the fiber's resistance to external disturbances. Since coupling between polarization modes is suppressed, the FBG reflection spectrum demonstrates higher stability and repeatability under varying conditions such as temperature and mechanical stress. This establishes a solid foundation for high-precision sensing and optical communication system applications in complex environments.

3. Spectral Characteristics Analysis of Uniform FBG in High-Birefringence PCF

3.1 Dual-Peak reflection structure

The introduction of uniform Fiber Bragg Gratings (FBG) into high-birefringence photonic crystal fiber (PCF) results in a distinctive dual-peak reflection spectrum. This phenomenon fundamentally stems from the modulation of light transmission characteristics by the unique microstructure of high-birefringence PCF. The periodically arranged air-hole structure in the PCF cladding breaks the axial symmetry of conventional fibers, creating significant differences in optical properties along two orthogonal polarization directions (x and y axes). Consequently, the fundamental modes in these two polarization directions exhibit different effective refractive indices (Xiao et al., 2020). When light propagates through the high-birefringence PCF-FBG structure, the Bragg reflection principle dictates that the reflection wavelengths for different polarization states are determined by their respective effective refractive indices. The polarization mode with higher effective refractive index corresponds to a longer Bragg wavelength, while the mode with lower effective refractive index corresponds to a shorter Bragg wavelength. This results in two reflection peaks at distinct central wavelengths in the reflection spectrum, corresponding to the fundamental mode reflections in the x and y polarization directions, respectively. The emergence of this dual-peak structure not only visually demonstrates the birefringence characteristics of high-birefringence PCF but also provides researchers with an effective method for precisely characterizing the degree of fiber birefringence through spectral analysis. By meticulously measuring and analyzing the positions and spacing of the reflection peaks, researchers can obtain the birefringence variations of high-birefringence PCF under different conditions, providing crucial parameter references for fiber device design and optimization.

3.2 Polarization-Dependent spectral response

The spectral response of FBG in high-birefringence PCF exhibits strong polarization dependence. This characteristic originates from the optically anisotropic structure within high-birefringence PCF, which causes the two orthogonal polarization modes to propagate independently without coupling. In the FBG region, each polarization mode follows its own independent coupling equation, efficiently reflecting only the light signals that match its polarization direction, thus forming separate reflection channels (Xu, 2023). From the perspective of light-matter interaction, the coupling efficiency between polarization modes and FBG largely depends on their polarization matching degree. When the polarization state of input light aligns with a reflection channel's polarization direction, the light signal can strongly couple with the grating structure of that channel, resulting in high reflectivity. Conversely, when the input light's polarization state mismatches the channel, the coupling efficiency becomes extremely low, leading to significantly reduced reflectivity. This polarization-dependent spectral response characteristic makes the high-birefringence PCF-FBG structure highly promising for optical communication and signal processing applications. For instance, it can be used to construct high-performance polarization filters for selective reflection and transmission of specific polarization states. It can also be applied in polarization multiplexing systems, where different polarization states are modulated onto separate reflection channels, effectively enhancing transmission capacity and spectral efficiency in optical communication systems.

3.3 Mode-Selective reflection

Beyond its excellent polarization mode discrimination capability, uniform FBG in high-birefringence PCF can also achieve selective reflection of different modes. In PCF structures supporting multimode transmission, significant differences exist in the optical field distributions and effective refractive indices of different modes. Even with identical grating periods, the different effective refractive indices of various modes result in distinct Bragg wavelengths, manifesting as multiple separated reflection peaks in the spectrum and enabling effective mode discrimination. The essence of mode-selective reflection lies in the differences in coupling characteristics between various modes and the FBG. Each mode's optical field distribution determines the degree and manner of its interaction with the grating structure. Modes with higher overlap between their optical fields and the grating structure exhibit higher coupling efficiency with the FBG and consequently higher reflectivity. This characteristic provides important technical means for mode processing in multimode fiber communication systems. In multimode transmission scenarios, proper design of FBG parameters enables selective enhancement or suppression of specific modes, effectively mitigating mode crosstalk issues in multimode fibers and improving signal transmission stability and reliability. Simultaneously, the mode-selective reflection feature offers new approaches for mode-based sensing technologies. Researchers can utilize changes in the reflection spectra of different modes to detect minute variations in environmental parameters, enabling highly sensitive sensing applications (Di et al., 2023).

3.4 Bandwidth and reflectivity characteristics

The reflection peaks of x-polarized and y-polarized modes in high-birefringence PCF typically exhibit symmetric or nearly symmetric distribution patterns in the reflection spectrum. However, closer observation reveals a certain degree of asymmetry in their reflectivity and bandwidth characteristics. This asymmetry primarily stems from differences in the modal field distributions of the two polarization modes within the PCF. Due to the asymmetric structure of high-birefringence PCF, the x- and y-polarized modes demonstrate distinct differences in their modal field distribution shapes, sizes, and interaction degrees with the cladding air holes across the fiber cross-section. These differences directly affect the light-FBG coupling efficiency. The polarization mode with greater overlap between its modal field and the grating structure, and consequently stronger interaction, achieves higher coupling efficiency in the FBG, manifesting as higher reflectivity and relatively narrower bandwidth. Conversely, the polarization mode with weaker interaction exhibits lower reflectivity and relatively broader bandwidth. Additionally, factors such as inherent fiber material losses and the precision of grating fabrication processes also influence reflectivity and bandwidth. In practical device design and manufacturing, a thorough understanding and precise control of these factors are crucial for optimizing the performance of high-birefringence PCF-FBG devices. This requires comprehensive consideration of multiple aspects, including fiber structural parameters and grating fabrication techniques, to achieve precise optimization of reflectivity and bandwidth through meticulous design and regulation, meeting specific performance requirements for different application scenarios (Zhao et al., 2021).

3.5 Dispersion characteristics

The high-birefringence PCF-FBG structure exhibits significant polarization-dependent dispersion characteristics. The wavelength splitting of reflection peaks directly reflects differences in group refractive indices between the x and y polarization directions, leading to different group delays for optical signals propagating along different polarization axes. During light propagation, the group refractive index determines the group velocity of optical signals. A larger group refractive index results in slower group velocity, meaning optical signals require more time to travel the same distance (i.e., greater group delay). In high-speed optical communication systems, this polarization-dependent dispersion significantly impacts signal transmission quality. Because optical signals of different polarization states experience different group delays during propagation, optical pulses may broaden and distort in the time domain. In severe cases, this can cause inter-symbol interference, reducing system transmission rates and reliability. However, researchers have ingeniously exploited this characteristic for important applications. In polarization mode dispersion compensation, specially designed high-birefringence PCF-FBG structures with specific dispersion properties can effectively compensate for polarization mode dispersion in transmission links, restoring signal quality. In slow-light control applications, the unique dispersion characteristics enable precise manipulation of optical signal group velocity, allowing signals to propagate through fibers at speeds significantly slower than the speed of light in vacuum. This provides critical technical support for advanced applications like optical buffering and signal processing. Through in-depth research and flexible control of the dispersion characteristics in high-birefringence PCF-FBG structures, further advancements in optical communication and signal processing technologies can be anticipated (Fan, 2023).

Conclusion

In summary, this paper systematically analyzes the spectral characteristics of uniform fiber Bragg gratings in high-birefringence photonic crystal fibers. By examining structural fundamentals, birefringence mechanisms, grating coupling properties, and spectral response behaviors, we observe that this composite structure demonstrates distinct dual-peak reflection features and polarization-dependent responses in the spectral domain, along with excellent mode selectivity and dispersion control capabilities. Particularly under birefringence effects, the reflection wavelengths of two orthogonal polarization states show significant separation, substantially enhancing the device's polarization resolution. Future research could combine high-precision experimental platforms to thoroughly validate the response sensitivity and stability of HB-PCF-FBG structures under multi-parameter environments (e.g., temperature and stress), while exploring their practical application potential in multi-mode coupling control, integrated optics, and tunable filtering.

Conflict of Interest

The authors declare that they have no conflicts of interest to this work.

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