Design and Analysis of High Birefringence Photonic Crystal Fiber with Sandwich Structure

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Abstract. A novel photonic crystal fiber (PCF) with sandwich structure in cross section is proposed. Then the influences of the size of air holes in cladding on the propagation properties are investigated. By adjusting the size of air holes in cladding, the proposed PCF offers an ultrahigh birefringence of 3.85×10^{-2} and a large negative dispersion of \(-1000 \text{ ps}\cdot\text{km}^{-1}\cdot\text{nm}^{-1}\) for the optimal structure of the fiber at the wavelength of 1550nm. The nonlinear coefficient of the optimal structure can reach a large value about 50 W^{-1}\cdot\text{km}^{-1} at the wavelength of 1550nm. The proposed PCF may have some potential applications in the fields of long-distance optical communication and polarization maintaining fiber.

1. Introduction
Optical fiber has been widely used in the fields of optical communication [1, 2] and optical fiber sensing [3, 4], such as distributed sensing [5-7]. In order to overcome the limitations of traditional single-mode optical fiber, the concept of photonic crystal fiber (PCF) was proposed by Russel. PCF is a kind of microstructure fiber which consisting of a central defect region in a regular lattice of air holes [8]. Compared with conventional fibers, PCFs have many unique characteristics, such as excellent nonlinear effect, birefringence effect and large negative dispersion. The high birefringence PCF could decrease the signal coupling degree of the two polarization modes, which is conducive to increase the signal transmission distance. On the other hand, dispersion causes the broadening of the light pulse, which severely limits the transmission capacity and bandwidth of the fibers [9]. Therefore, we can reduce the effect of dispersion by dispersion compensation.

The most significant distinction between the structures of PCFs discussed by others and the general form discussed here is that the PCF shows sandwich structure in this work. We explore the propagation properties the proposed fiber systematically by use of the full vector finite element method [10]. The results reveal that the fiber with optimal structure offers an ultrahigh birefringence of 3.85×10^{-2} and a large negative dispersion -1000 ps\cdot km^{-1}\cdot nm^{-1}, the nonlinear coefficient can reach a large value about 50 W^{-1}\cdot km^{-1} at the wavelength of 1550 nm. The PCF proposed in this work may be helpful for applications in the fields of the polarization-maintaining fiber and the long-distance transmission of optical signal.
2. Fiber design and theory
The general form of our fiber is shown in Figure 1. As shown in Figure 1, the thickness of the perfectly matched layer (PML) is denoted as $h$; the minor axes and the major axes of elliptical air holes are denoted by $a$ and $b$ respectively, the horizontal distance between the elliptical air holes is $A_1$; the circular air holes with a diameter of $d$ arranged of pitch $A_2$. The radius of the cladding is $r_1$. $d_1$ is the vertical distance from the core to the first row of circular air holes and $d_2$ is the vertical distance between two lines of elliptical holes.

![Figure 1. Cross section of the proposed PCF with sandwich structure.](image)

After the systematically numerical analysis, the special fiber structure parameters are finally determined as shown in Table 1.

| Fiber material | $A_1$ (μm) | $A_2$ (μm) | $h$ (μm) | $b$ (μm) | $r_1$ (μm) | $d$ (μm) | $d_1$ (μm) | $d_2$ (μm) |
|----------------|------------|------------|----------|----------|------------|----------|------------|------------|
| SiO$_2$        | 0.5        | 0.9        | 0.2      | 0.8      | 5          | 0.6      | 1.56       | 0.77       |

The effective indexes of $x$- and $y$-polarization are represented as $n_{\text{eff}}^x$ and $n_{\text{eff}}^y$. So the modal birefringence ($B$) is defined as:

$$B = |n_{\text{eff}}^x - n_{\text{eff}}^y|$$  \hspace{1cm} (1)

The dispersion ($D$) can be calculated by the following formula:

$$D(\lambda) = -\frac{\lambda}{c} \frac{\partial^2 \text{Re}(n_{\text{eff}})}{\partial \lambda^2}$$  \hspace{1cm} (2)

The nonlinear coefficient ($\gamma$) is defined as:

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}$$  \hspace{1cm} (3)

where $n_2$ is the nonlinear refractive index of SiO$_2$; $\lambda$ is the wavelength of incident light; $A_{\text{eff}}$ is the effective mode field area of the fiber.
3. Results and discussion

3.1. Birefringence
Figure 2 shows the birefringence as a function of wavelength for different \( a \).

![Figure 2. Change of birefringence of the proposed PCF with \( a \).](image)

By adjusting the minor axes of air holes \( a \), we obtain the birefringence curves as a function of wavelength. Figure 2 exhibits that an ultrahigh birefringence of \( 3.85 \times 10^{-2} \) is obtained at the value of \( a=0.3 \mu m \) when wavelength is 1550nm. As \( a \) changes from 3μm to 3.6μm, the asymmetry of the core will be improved, so the birefringence level also increases distinctly. High birefringence reduces the energy coupling of two polarization axes effectively and it helps to increase the distance of the communication system.

3.2. Dispersion
Figure 3 shows the dispersion as a function of wavelength for different \( a \).

![Figure 3. Change of dispersion of x-polarization and y-polarization of the proposed PCF with \( a \).](image)

As shown in Figure 3, the level of negative dispersion decreases significantly as \( a \) becomes larger and a particularly large negative dispersion of \(-1400 \text{ ps} \cdot \text{km}^{-1} \cdot \text{nm}^{-1} \) is obtained at the value of 3.6μm with wavelength of 1550nm. The possible reason of the decrease in the negative dispersion level is that the increase of \( a \) causes the air holes occupancy in cladding to rise.

Finally, based on the above simulation results and taking into account the ultrahigh birefringence, large negative dispersion and feasibility of the structure, the fiber can offer an ultrahigh birefringence of \( 3.85 \times 10^{-2} \) and a large negative dispersion of \(-1000 \text{ ps} \cdot \text{km}^{-1} \cdot \text{nm}^{-1} \) at the wavelength of 1550nm with optimal parameter \( a=0.3 \mu m \).
3.3. Nonlinearity

After designing the optimal structure, a propagation property worth discussing is the nonlinear coefficient. Figure 4 shows the nonlinear coefficient of x-polarization and y-polarization of the proposed PCF as a function of wavelength.

![Figure 4. Change of nonlinear coefficient of x-polarization and y-polarization of the proposed PCF with wavelength.](image)

From Figure 4, it is obvious that the nonlinear coefficient can reach a large value about 50 W\(^{-1}\)·km\(^{-1}\) at the wavelength of 1550nm. The increase of the nonlinear coefficient contributes to the realization of nonlinear effects such as supercontinuum and optical soliton, but it also causes the loss of optical power, inter-channel crosstalk and so on.

3.4. Comparison with existing research

Table 2 shows the comparison of birefringence (B), dispersion (D) and nonlinear coefficient (γ) between the proposed PCF and the PCFs designed by previous researchers.

| Refs. | [11] | [12] | [13] | [14] | [15] | Proposed |
|-------|------|------|------|------|------|----------|
| γ (W\(^{-1}\)·km\(^{-1}\)) | —— | —— | 450.2 | 43.6 | 31.85 | 50 |
| B | 10\(^{-4}\) | 0.87×10\(^{-2}\) | 2.29×10\(^{-2}\) | 3.02×10\(^{-2}\) | 1.81×10\(^{-2}\) | 3.85×10\(^{-2}\) |
| D (ps·km\(^{-1}\)·nm\(^{-1}\)) | 0 | —— | -491.16 | -200 | -588 | -1000 |

The comparison results reveal that the properties of the proposed PCF have been enhanced significantly. Therefore, the proposed fiber in this paper is more applicable to optical communication system.

4. Conclusion

In this paper, a novel PCF with air holes in cladding arranged in sandwich structure is designed. The conclusions of this paper are as follows:

1. The fiber with optimal structure can offer an ultra-high birefringence of 3.85×10\(^{-2}\), a large negative dispersion of -1000 ps·km\(^{-1}\)·nm\(^{-1}\) and a large nonlinear coefficient of 50 W\(^{-1}\)·km\(^{-1}\) at the wavelength of 1550nm.

2. Compared with existing research results, the birefringence of the proposed PCF has an increase of 1.31×10\(^{-2}\). Moreover, the PCF has the characteristic of large negative dispersion which makes the fiber the best choice for dispersion compensation.

In summary, the PCF designed in this paper has potential applications in the fields of long-distance transmission communication system and dispersion compensation.
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