Highly birefringent photonic crystal fibers with flattened dispersion and low confinement loss*

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A highly birefringent index-guiding photonic crystal fiber (PCF) with flattened dispersion and low confinement loss is proposed by introducing two small air holes with the same diameter in the core area. The fundamental mode field, birefringence, confinement loss, effective mode area and dispersion characteristic of the fibers are studied by the full-vector finite element method (FEM). Simulation results show that a high birefringence with the order of 10^{-3} and a low confinement loss of 0.001 dB/km are obtained at 1550 nm. Furthermore, flattened chromatic dispersion from 1450 nm to 1590 nm is obtained.

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The photonic crystal fiber (PCF) is a new kind of optical fiber with photonic crystal structure. There are many unique optical characteristics in the PCF, such as endless single mode, low loss, flexible dispersions, adjustable non-linear and high birefringence[1-5]. The PCF has attracted a lot of interest during past years, and quickly develops in aspect of optical fiber communication, optical fiber sensing and optical passive devices[6-8].

Highly birefringent fiber is used in many sensing applications and some other applications in which light is required to maintain a linear polarization station. In the conventional highly birefringent fiber, the core is mixed with GeO_2, the confinement loss can increase in the nuclear radiation environment, the nuclear explosion tolerance is low, and the temperature stability performance is bad. However, highly birefringent PCF is made up with pure silica materials. Different structures can be designed to improve the properties of the fiber. It has some incomparable advantages compared with the conventional highly birefringent fiber. The structures of the highly birefringent PCF can be designed flexibly, by introducing air holes with different sizes to the cladding, or changing the core or the cladding air holes shape[9-11]. We can get the highly birefringent PCF with outstanding performance. The dispersion properties of PCF are significantly different from those of conventional fibers for the novel cladding structure. It consists of an array of micrometer-sized air holes allowing for flexible tailoring of the dispersion curves. To achieve the near-zero flattened dispersion in PCF, several designs have been proposed[12,13]. By introducing the elliptical air holes in the core area, a highly birefringent PCF with flattened dispersion and low effective mode area was presented by Hu[12], but the confinement loss is increased, and it makes process difficult for introducing the elliptical air holes. Highly nonlinear bending-insensitive birefringent PCF was presented by Huseyin[14]. Although the confinement loss is low, the dispersion is not flat. By introducing the elliptical air holes in the cladding, a highly birefringent PCF with flattened dispersion and low effective mode area was presented by Liang[15], but the confinement loss is increased, and it makes the light signal transmission difficult for introducing the elliptical air holes.

In this paper, we employ the index-guiding PCF structure with uniform air-silica lattice, and a highly birefringent index-guiding photonic crystal fiber with flattened dispersion and low confinement loss is proposed by introducing two small air holes with the same diameter in the core area. The fundamental mode field, birefringence, confinement loss, effective mode area and dispersion characteristic of the fiber are studied by the full-vector finite element method (FEM). A high birefringence with the order of 10^{-3} and the low con-

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finement loss of 0.001 dB/km are obtained at wavelength 1550 nm by adjusting the diameters of the two small air holes. Furthermore, flattened chromatic dispersion from 1450 nm to 1590 nm is obtained.

FEM is an algorithm that can solve mathematics and physics problems based on variational principle. PCF with any irregular section shape and refractive index under any combination material can be solved well by FEM which has higher calculation accuracy in analyzing mode field. In this work, we have employed full-vector finite element method to investigate key modal properties of the proposed index-guided PCF.

Fig.1 shows the cross-section of the PCF. Two small air holes with the same diameter d are introduced into the core area for more high birefringence. The pitch of the two small air holes is H. At the same time, in order to reduce the confinement loss, four rings of air holes are considered, the diameter of the air holes is D, the air hole pitch is Λ=2.11 μm and D/Λ = 0.73. In this paper, the refractive index of the silica background is n = 1.45.

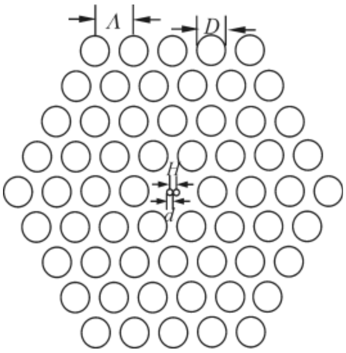


Fig.1 Cross-section of the proposed PCF structure

Fig.2 shows the birefringence of the fiber as a function of wavelength at different pitches of the two small air holes as H=0.36 μm and H=0.41 μm when the small air hole diameter is d=0.36 μm. It can be found that the birefringence increases with the increase of wavelength, and at the same wavelength, the smaller the air hole pitch H, the bigger the birefringence. At wavelength of λ=1550 nm, while the pitches of the two small air holes are 0.36 μm and 0.41 μm, the birefringences are 2.5 × 10^{-3} and 2.1 × 10^{-3}, respectively.

Fig.3 shows the birefringence of the fiber as a function of wavelength at different pitches of the two small air holes as H=0.426 μm and H=0.476 μm when the small air hole diameter is d=0.426 μm. It can be found that the birefringence increases with the increase of wavelength. At wavelength of λ=1550 nm, while the pitches of the two small air holes are 0.426 μm and 0.476 μm, the birefringences are 3.0 × 10^{-3} and 2.7 × 10^{-3}, respectively.

Figs.4 and 5 show the total dispersion of the HE^x_{11} mode and the HE^y_{11} mode of the fiber as a function of wavelength

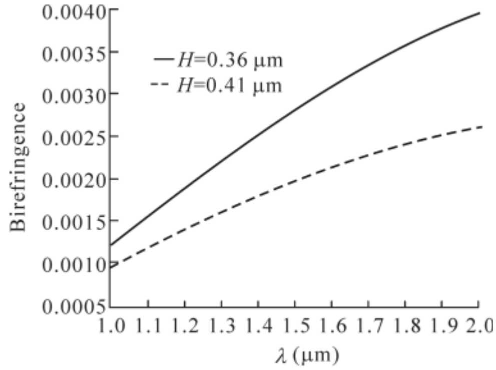


Fig.2 Birefringence of the fiber as a function of wavelength when *d*=0.36 μm

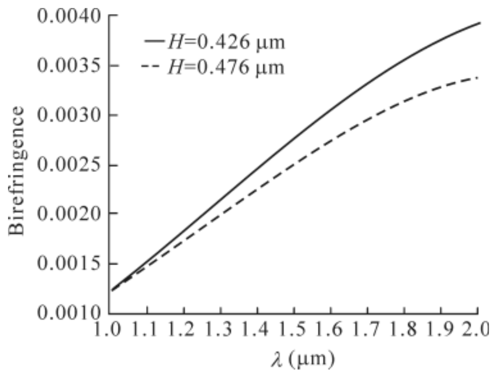


Fig.3 Birefringence of the fiber as a function of wavelength when *d*=0.426 μm

with the small air hole diameter of d=0.36 μm and d=0.426 μm. It can be observed that from 1150 nm to 1850 nm, the total dispersion is less than 2 ps/(nm • km). When d=0.36 μm and H=0.41 μm, the flattened dispersion from 1450 nm to 1590 nm is obtained, and the total dispersion is about -0.08 ps/(nm • km). That is in the single-mode optical fiber communication band place, which contains the short wavelength bands (1460 nm−1530 nm), the regular wavelength bands (1530 nm−1565 nm) and the long wavelength bands (1565 nm−1625 nm).

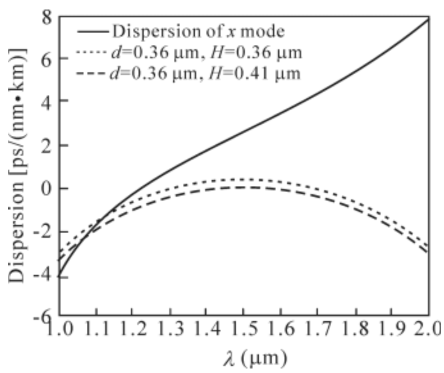


Fig.4 Total dispersion of the HE^x_{11} mode and the HE^y_{11} mode of the fiber as a function of wavelength when *d*=0.36 μm

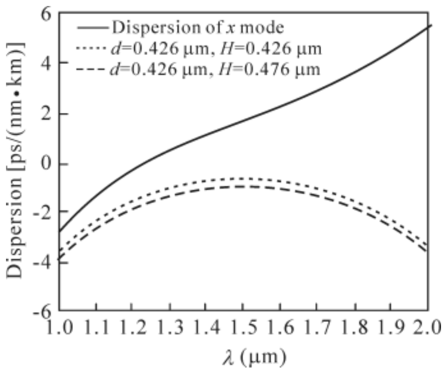


Fig.5 Total dispersion of the HE^{x}_{11} mode and the HE^{y}_{11} mode of the fiber as a function of wavelength when *d* = 0.426 μm

A highly birefringent index-guiding PCF with flattened dispersion and low confinement loss is obtained by introducing two small air holes in the core area. The effective mode areas and the confinement losses of the *y*-polarized fundamental mode as a function of wavelength at *d*=0.36 μm, *H*=0.36 μm and *d*=0.426 μm，*H*=0.426 μm are shown in Figs.6 and 7, respectively. At wavelength of λ=1550 nm, the birefringences are 2.5×10^{-3} and 3.0×10^{-3}, respectively, which are higher than those of the reported design[12]. It should be noted that the effective mode area is small, e.g. at λ=1550 nm, the effective mode area of the *y*-polarized fundamental mode is as small as 6 μm^2 and 6.5 μm^2, respectively. We also observe the remarkable low confinement loss of the proposed structure, e.g. at λ=1550 nm, the confinement loss is 0.006 dB/km and 0.001dB/km, respectively, which are lower than the reported 0.01 dB/km[12] and 0.019 dB/km[20]. The confinement loss is increased for introducing the elliptic air hole. Compared with introducing the elliptic air hole, the process of introducing circular air hole is easier.

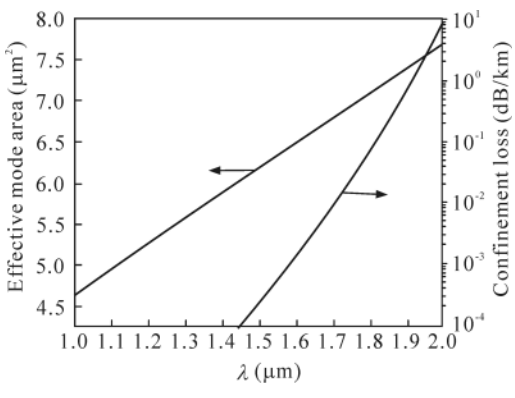


Fig.6 Effective mode area and confinement loss of the *y*-polarized fundamental mode as a function of wavelength at *d*=0.36 μm and *H*=0.36 μm

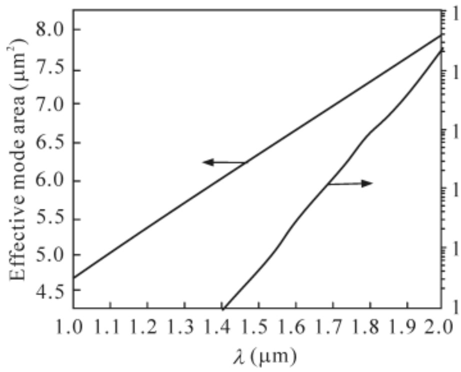
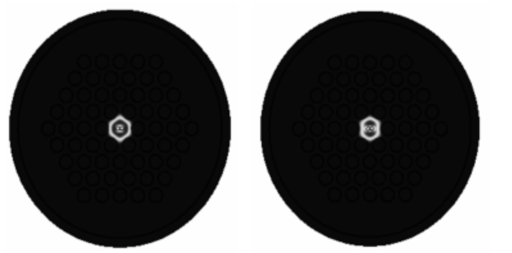


Fig.7 Effective mode area and confinement loss of the *y*-polarized fundamental mode as a function of wavelength at *d*=0.426 μm and *H*=0.426 μm

Fig.8 shows the normalized electric field distribution of the *y*-polarized fundamental mode at wavelength λ=1550 nm. It is easy to find that the fundamental mode field energy is completely constrained in the core area.



(a) *d*=0.36 μm, *H*=0.36 μm (b) *d*=0.426 μm, *H*=0.426 μm

Fig.8 Normalized electric field distributions of the *y*-polarized fundamental mode at wavelength λ=1550 nm

In this paper, a highly birefringent index-guiding PCF with flattened dispersion and low confinement loss is proposed by introducing two small air holes with the same diameter in the core area. The fundamental mode field, birefringence, confinement loss, effective mode area and dispersion characteristic of the fiber are studied by the full-vector FEM. The birefringence reaches the order of 10^{-3} at the wavelength of 1550 nm by adjusting the parameters of the air holes, which is higher by about two orders of magnitude than the regular polarization maintaining fiber. At the same time, a low effective mode area of 6 μm^2 and low confinement loss of 0.001 dB/km are obtained. Furthermore, the flattened dispersion from 1450 nm to 1590 nm is obtained, and the total dispersion is about -0.08 ps/(nm • km), which is useful for the light signal transmission. Such a design provides a new approach to get a highly birefringent PCF with flattened dispersion and low confinement loss, and the fiber has a broad prospect of applications in the polarization control, nonlinear optics, dispersion control, etc.

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