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RESEARCH ARTICLE

Temperature stabilized and broadband fiber waveplate fabricated with a birefringent photonic crystal fiber

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Abstract An all-fiber waveplate made by a piece of birefringent photonic crystal fiber (PCF) is proposed and studied in this paper. The characteristics of the proposed waveplate, including the wavelength dependent phase difference between the orthogonal polarized propagation mode in the waveplate, and temperature stability of the waveplate, were investigated theoretically and experimentally for the first time to our knowledge. Compared with the fiber waveplate made by the stress induced or the conventional geometrical shape formed (such as the elliptical core fiber) birefringent fiber, the waveplate based on the birefringent PCF has distinguishable advantages including high temperature stability and large bandwidth. A prototype quarter-waveplate is fabricated by cutting and splicing a segment of birefringent PCF with conventional single mode fiber. The measurement showed that the fluctuation of the ellipticity of the output light from the waveplate can be kept within ±0.23° for temperatures varying from 25°C to 200°C, and the bandwidth for ellipticity larger than 43° can be as large as 70 nm.

Keywords birefringent photonic crystal fiber, achromatic retardation, fiber quarter-waveplate

1 Introduction

Optical waveplates such as the quarter-waveplate ($\lambda/4$-plate) or the half-waveplate ($\lambda/2$-plate), are important and key components broadly used in many optical devices and systems, as well as in animals which appeared in a recent interesting report about the photoreceptor structure in the eye of a stomatopod crustacean [1]. Because of the increasing demand coming from the fields of optical fiber communications and optical fiber sensor systems, high quality all-fiber waveplates, owing to its size, compatibility, and reliability, etc., in comparison with conventional waveplate consisting of bulk optics, are attractive and essential in many practical applications. However, previously reported fiber waveplates, either based on the bending induced birefringence in a fiber loop [2], or based on the stress induced or geometrical shape formed birefringence in fibers [3], may encounter some difficulties because the fabricated waveplates are sensitive to ambient temperature; consequently, stability of the waveplate may cause problems in its practical application. Another interesting report about fiber waveplates proposed by Huang [4] presented a fabrication method that includes spinning of the birefringent axes of the initial fiber in a specific way. Since the fabrication apparatus are relatively complicated and the fabrication process needs precise control, which is not easy to be implemented in a laboratory or factory.

It is well known that the birefringence can be introduced into a photonic crystal fiber (PCF) by breaking the circular symmetry on the arrangement of the air holes in the cross section of the fiber [5]. Since the birefringence in PCF is formed based on the geometrical effect, this geometrical birefringence is not sensitive to the variation of ambient temperature [6]; thus, it is reasonable to expect that the waveplate made by such PCF is stable when the temperature is changing in the application. In this paper, we investigated theoretically and experimentally the temperature and wavelength dependent characteristics of such waveplate consisted of PCF. The result verified that a temperature stabilized, broadband all-fiber waveplate can be fabricated with a short piece of birefringent PCF.

2 Theoretical simulation of characteristics of quarter-waveplate made by birefringent PCF

The cross section of the PCF used for the numerical simulation is shown in Fig. 1(a). The birefringence of the fiber is introduced simply by setting two large air holes in

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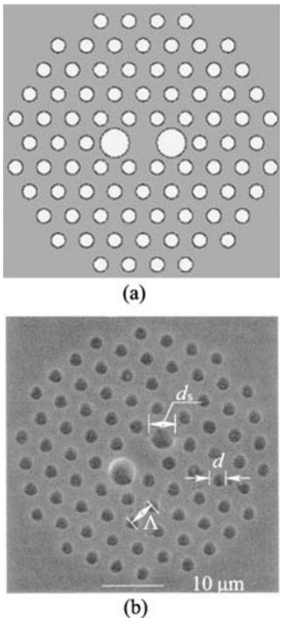
the position symmetrically close to the core of the fiber. In our experiment, the birefringent PCF is obtained from the Blaze Photonics Company (now part of Crystal Fiber A/S, Denmark). The scanning electron microscope (SEM) image of the PCF used in the simulation and experiment is shown in Fig. 1(b). Obviously, the simulation model in Fig. 1(a) is close to the structure of the cross section of practical PCF.



(a)

(b)

Fig. 1 Cross section of birefringent PCF. (a) Numerical calculation model; (b) SEM image of PCF used in experiment (parameters of PCF: $d = 2.2$ μm, $d_s = 4.5$ μm, $\Lambda = 4.4$ μm)

From the SEM image the parameters of the PCF were obtained as follows: diameter of the small air holes d is 2.2 μm; diameter of the large air holes d_s is 4.5 μm; distance between the centers of the holes Λ is 4.4 μm. From these data we use the commercial numerical calculation software APSS produced by the Appolo Photonics Company in Canada, which is based on the full vector finite-difference time-domain (FDTD) method, to calculate the change of the normalized birefringence, B, with the change of optical wavelength. The definition of B is given as

$$B = n_y - n_x = \frac{\beta_y - \beta_x}{k_0}, \tag{1}$$

where n_x, n_y and β_x, β_y are the effective and propagation constant of the x- and y- polarization mode, respectively. $k_0 = 2\pi/\lambda$ is the wave number of optical wave in vacuum.

From the result of B one can obtain the wavelength dependent phase difference, $\Delta\varphi$, between the two orthogonal linearly polarized modes. The phase difference or retardance is defined as

$$\Delta\varphi = \Delta\beta l = (\beta_y - \beta_x) l, \tag{2}$$

where l is the length of the birefringent PCF. Thus, to design a quarter-waveplate, the length and birefringence (which is a function of optical wavelength) should satisfy the following condition:

$$\Delta\varphi = \Delta\beta l = \frac{\pi}{2} + n\pi, \quad n = 0,1,2,\dots. \tag{3}$$

Therefore, if a linearly polarized light is incident with polarization orientation 45° respective to the birefringent axes of the quarter-waveplate, the light exiting from the quarter-waveplate will be circularly polarized.

In practical fabrication process, because of the imperfection either in the length or the incident angle deviated from 45°, the actual phase difference or ratio of the amplitudes of the orthogonal polarization mode of the quarter-waveplate does not meet exactly the condition of circularly polarized light. In addition, since the birefringence of PCF is a function of wavelength, the bandwidth of the waveplate is limited by the acceptable ellipticity or the phase shift difference of the orthogonal linearly polarized modes within the wavelength range. Variation of $\Delta\varphi$ vs. wavelength with different ratio of d_s/d and $\Lambda = 4.4$ μm, as illustrated in Fig. 1, is simulated and depicted in Fig. 2. To maximize the bandwidth, the length of the PCF should be selected at the shortest value, i.e., $\Delta\varphi = \pi/2$ according to Eq. (3) corresponding to the so called zero-order quarter-waveplate.

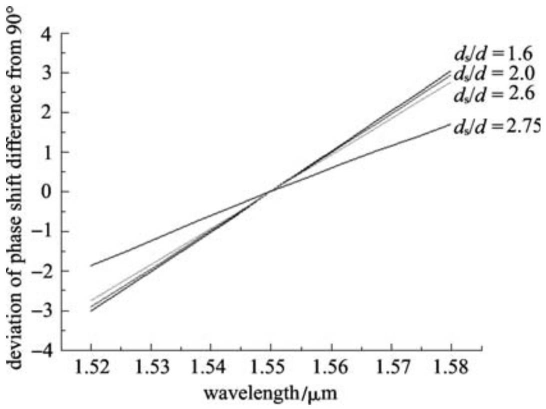


Fig. 2 Calculated phase difference deviation of $\lambda/4$-plate vs. optical wavelength (calculation parameters: $d = 2.0$ μm, $\Lambda = 4.4$ μm)

Although it is convenient to evaluate a waveplate from the phase shift difference, $\Delta\varphi$, provided the incident angle of the linearly polarized light is exactly 45° with respect to the axes of the waveplate, in practice, the required incident condition is hard to be satisfied exactly. Therefore, the measure of phase shift difference is not the only criterion of the circularly polarized light. Therefore, we propose a new parameter called extinction ratio for circularly polarized light (E_c), which can be regarded as an analogy to the definition of the extinction ratio for linearly polarized light, given in the following formula:

$$E_c = 10\log\frac{1+(b/a)^2}{1-(b/a)^2} \quad (\mathrm{dB}), \tag{4}$$

where b and a are the semi-minor and semi-major axis of the ellipse representing the elliptically polarized light exiting from the quarter-waveplate, respectively. Obviously, if the polarization state of the output light is perfectly circularly polarized, i.e., $a = b$, the E_c would become infinite, which is similar as the case in linearly polarized light.

3 Experimental measurement of quarter-waveplate made of birefringent PCF

In the experiment, an automatic polarization measurement instrument PAX5710 produced by Thorlabs Inc., USA, and a tunable semiconductor laser source (Model: Tunics-purity CL) in the wavelength range from 1500 to 1640 nm made by NetTest Company, together with a broadband fiber polarizer with extinction ratio larger than 35 dB at the output, were employed in the measurement to obtain the polarization properties of the waveplate.

To fabricate the fiber waveplate pigtailed with normal single mode fiber, first, a piece of birefringent PCF with parameters the same as that in Fig. 1 is spliced to a section of conventional single mode fiber (SMF) with a fusion machine operated in manual mode. Since splicing PCF with the fusion machine may cause significant change in the size and shape of the air holes, after splicing, the effective length of the birefringent region in PCF could be much shorter than its original length. By monitoring the state of polarization of the light output from PCF as the linearly polarized light is input, we found that the length of the PCF of around 1.32 mm is most appropriate to be cut for further splicing purposes. Finally, another piece of SMF is spliced to the cut PCF. The uniform SMF used in the fabrication and measurement is always kept straight and is short in length (~10 cm); thus, it will not affect the polarization state of the propagation light, which has been verified in experiment separately. Much care should be taken to control the duration and position of the arc to obtain a low loss splicing between the PCF and SMF. With optimized splicing condition the joint loss can be reduced to be less than 3 dB, which is adequate for the demonstration purpose of the fiber waveplate.

With the polarimeter PAX5710 the ellipticity of the output light, η, which is in the unit of degree (°), can be measured and recorded directly, and is related to the ratio b/a as [7]

$$\tan\eta = b/a. \tag{5}$$

Thus, the parameters of E_c of the output light from the waveplate can be obtained from the measured data. We measured the polarization characteristics of the fabricated fiber waveplate in the wavelength range from 1520 to 1640 nm, and obtained the curves of ellipticity η defined in Eq. (5) vs. wavelength plotted in Fig. 3. The oscillations and ripples of the curve $\eta \sim \lambda$ in Fig. 3 are caused by the coherence effect arising from the narrow linewidth laser source used in the measurement. The power fitted curve of $\eta \sim \lambda$ (dashed line) is also given in the same figure. Furthermore, the E_c of the output light can be obtained according to Eq. (4) from the power fitted smooth curve of $\eta \sim \lambda$ (dashed line) in Fig. 3. It can be seen from Fig. 3 that the smoothed ellipticity or extinction ratio (E_c) can be maintained larger than 43.5° or 12.89 dB, respectively, at wavelength range from 1549–1603 nm. Depending on different applications requirements [8], for example, if a bigger tolerance such as $\eta > 43°$ (corresponding to $E_c > 11.56$ dB) is acceptable, the wavelength range or bandwidth of the quarter-waveplate can be extended to 70 nm in Fig. 3.

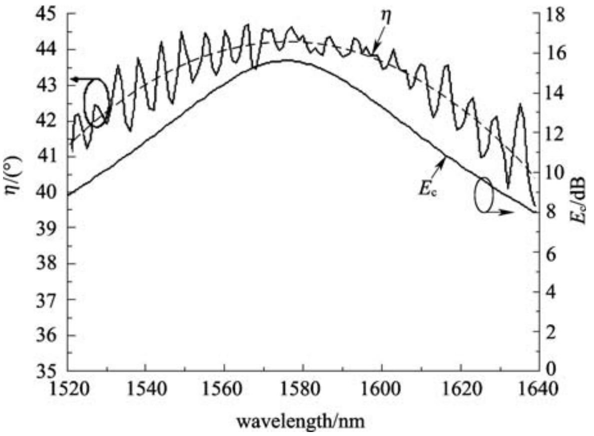


Fig. 3 Experimental measured ellipticity vs. wavelength (curve of E_c is obtained from power-fitted curve of $\eta \sim \lambda$ (dashed line))

Since the geometrical effect induced birefringence in PCF is not sensitive to the ambient temperature change [6], it is reasonable to expect the waveplate made by such PCF should have little temperature dependence compared with similar fiber waveplates made by other birefringent fibers such as those based on the stress effect, e.g., the Panda or Bow-tie fibers. In the experiment, a temperature change from room temperature 25°C to 200°C was applied to the waveplates made by the PCF in Fig. 1. The measured temperature dependences of the ellipticity and E_c of the waveplate at 1560 nm are given in Figs. 4 and 5, respectively. To make the comparison more clearly, a quarter-waveplate made by conventional polarization maintaining fiber (PMF) with beat length of 2.4 mm at 1550 nm has also been fabricated in the laboratory in a similar way as that using PCF, and its temperature dependent behaviors are also given in Figs. 4 and 5. It

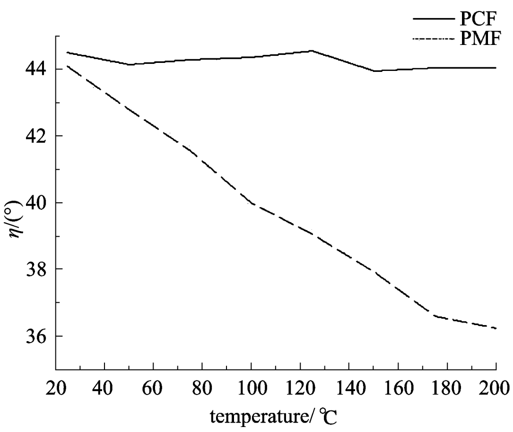


Fig. 4 Measured variation of ellipticity of output light from quarter-waveplate made by PCF and PMF, respectively, with temperature change from 25°C to 200°C

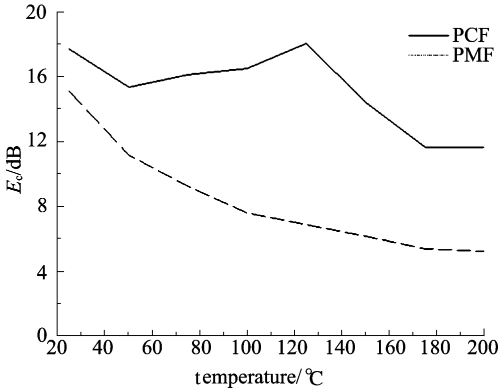


Fig. 5 Measured variation of extinction ratio E_c of quarter-waveplate made by PCF and PMF, respectively, with temperature change from 25°C to 200°C

can be seen from the measurement data that when the temperature is changed from 25°C to 200°C, the fluctuation of the ellipticity of the output light from the quarter-waveplate made by PCF is within 43.96°–44.52°, or the extinction ratio E_c within 14.42–18.08 dB, respectively, while the corresponding changes for the quarter-waveplate made by PMF are from 44.23° to 35.71°, and from 15.12 to 5.21 dB at 1560 nm wavelength, respectively. Obviously, the waveplate made by PCF has much better temperature stability in comparison with other types of fiber waveplates esp. those made by PMF with stress applying parts inside the fiber.

4 Conclusion

With theoretical analysis and experimental measurement it has been demonstrated that the all-fiber quarter-waveplate can be fabricated by splicing a segment of birefringent PCF to normal single mode fiber. The temperature stability of the quarter-waveplate made by PCF is significantly better than the quarter-waveplate made by conventional PMF, and the bandwidth of the quarter-waveplate is quite broad according to the practical measurement. Such type of all-fiber waveplates, owing to their distinguished properties, should have many potential application prospects in various optical engineering areas.

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