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Ultrahigh birefringence of elliptic core fibers with irregular air holes

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We have investigated experimentally and theoretically the birefringence of the elliptic core fiber with irregular air holes. The wavelength dependence of the beat length and the birefringence was measured by the wavelength scanning method. The fiber exhibits ultrahigh birefringence of 1.12×10^{-2} at 1550 nm. We also calculated the modal birefringence of the fundamental modes in the fiber by using the plane wave expansion method. The calculated birefringence is in excellent agreement with the measured one.
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Optical fibers with birefringence are of significant research interest because they are expected to find many applications in optical communication systems, devices, and fiber sensors. The birefringent fibers such as bow-tie fibers, panda fibers, and elliptic core side tunnel fibers have utilized either geometrical or stress-induced birefringence.[1–5] The birefringence of those fibers is about 10^{-4}, which is an order of magnitude higher than that of a conventional single mode fiber.

Recently, photonic crystal fibers (PCFs) consisted of periodic arrays of air holes in cladding have been intensively studied due to their novel optical properties such as endlessly single-mode operation, anomalous group velocity dispersion in the visible region, and high nonlinearity.[6,7] In the PCFs, lights are guided by the total internal reflection along the core, similar to conventional optical fibers, because the core refractive index is higher than the effective cladding index, which is an average of air holes and background silica. The large index contrast between the core and the cladding is useful in achieving high birefringence. Various high birefringent PCFs have been theoretically proposed by breaking the circular symmetry or implementing asymmetric defect structures such as dissimilar air hole diameters along the two orthogonal axis,[8–11] asymmetric core design,[12] elliptical core design,[13] and elliptic air holes in the cladding with squeezed lattice.[14] The birefringence of proposed PCFs is an order of $10^{-3}-10^{-2}$. The birefringence of fabricated PCFs is up to 7.5×10^{-3}, which is one order of magnitude higher than that of the commercial high birefringent fibers.

It has been demonstrated that the fibers with the irregularly arranged air holes or irregularly shaped air holes in cladding can also guide light through the core surrounded by the air holes[15–17] because the irregularly arranged air holes reduce the effective cladding index. The irregularity of arrangement and shapes of air holes can make the core design more flexible. Thus, an elliptic core with large ellipticity to give high birefringence can be realized by the irregularly arranged air holes with different shapes.

In this article, we present the experimental and theoretical results of the birefringence of the elliptic core fiber with the irregular air holes in cladding. The fiber exhibits very high birefringence of an order of 10^{-2} in the range of from 1300 to 1600 nm. The calculated birefringence is in excellent agreement in the measured one.

Figure 1 shows the scanning electron microscopic image of the elliptic core fiber with irregular air holes in cladding which was fabricated by crystal/fiber. The dimensions of the

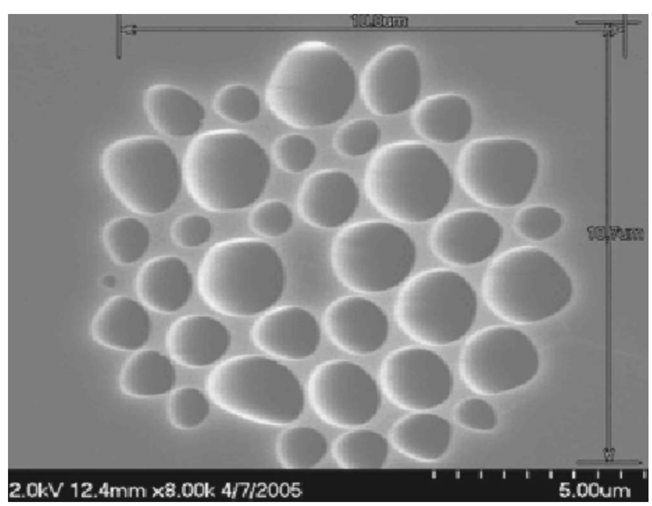

FIG. 1. Scanning electron micrograph of the elliptic core fiber with irregular air holes in cladding.

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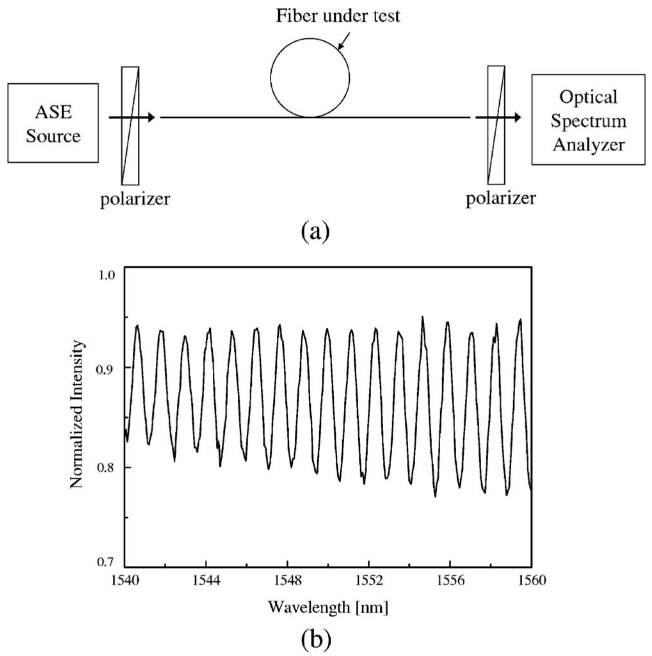

FIG. 2. (a) Schematic of beat length measurement by using the wavelength scanning method. (b) The optical spectrum collected by an optical spectrum analyzer.

elliptic core are 1.2 and 2.4 μm for the short and long axes, respectively, and the ellipticity of the core is 2.

For measuring the beat length and the birefringence of the elliptic core fiber, the wavelength scanning method is utilized.[18,19] This method has been successfully used to measure the birefringence of PCF as a function of wavelength.[20] The experimental setup is shown in Fig. 2(a). A broadband amplified spontaneous emission source with a spectrum span from 1530 to 1600 nm is used. Since the light from the amplified spontaneous emission source is randomly polarized, the first polarizer is used to polarize the light launched into the sample fiber. After the light passes through the fiber, the second polarizer is used to analyze it. Because the sample fiber is highly birefringent, the state of polarization incident on the second polarizer is highly wavelength dependent, resulting in a modulation in the spectrum is observed in the optical spectrum analyzer (OSA). Figure 2(b) shows the optical spectrum collected by the OSA. The original OSA trace is processed to remove the spectral background. This is achieved by taking the difference between the OSA traces with and without the fiber.

The separation between two adjacent maxima ($\Delta\lambda$) is related to the group beat length (L_B) and the birefringence (B) by the following simple equations:

$$L_B = \Delta\lambda L/\lambda_0, \tag{1}$$

$$B = \lambda/L_B, \tag{2}$$

where λ_0 is the center wavelength between the two peaks and L is the length of the sample fiber. Figure 3(a) shows the wavelength dependence of the beat length from Eq. (1) and Fig. 3(b) shows the wavelength dependence of the birefringence from Eq. (2). At wavelength 1550 nm, the beat length is 0.138 mm, corresponding to the birefringence $B=1.12 \times 10^{-2}$. To the best of our knowledge, the measured birefringence is higher than those reported previously.

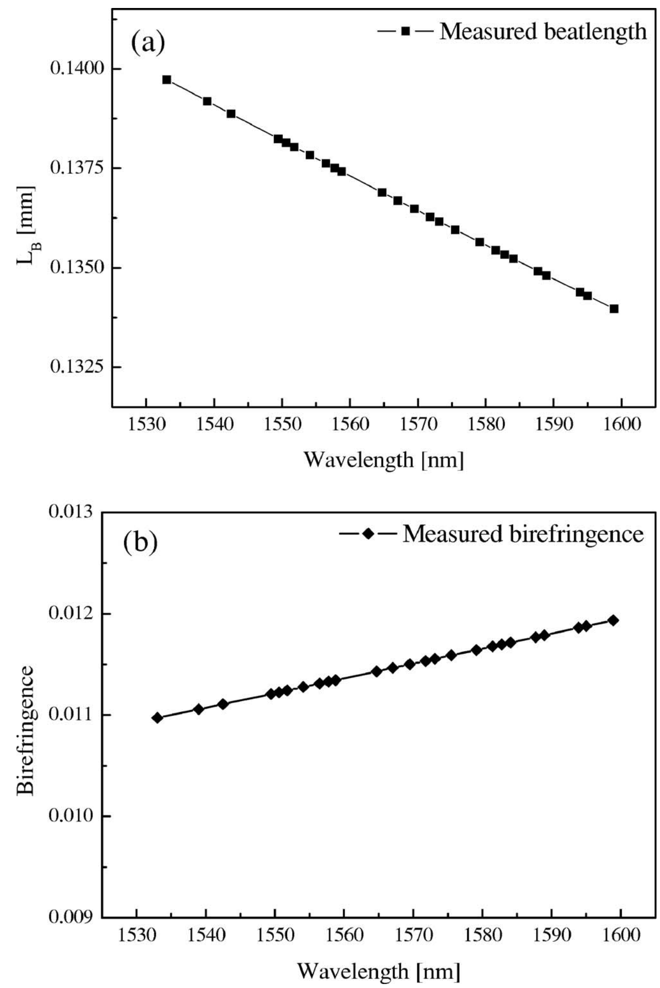

FIG. 3. The measured beat length (a) and the birefringence of the elliptic core fiber as a function of wavelength (b).

The modal birefringence B of the fiber is defined by

$$B = |n_x - n_y|, \tag{3}$$

where n_x and n_y are effective indices of the two orthogonally polarized fundamental modes. By using the plane wave expansion method, we obtained n_x and n_y shown in Fig. 4(a) and the modal birefringence calculated from Eq. (3) is plotted in Fig. 4(b). At wavelength 1550 nm, the calculated birefringence is 1.11×10^{-2}. This value is in excellent agreement with the measurement one. The structure of the elliptic core fiber considered in the modeling is shown in Fig. 5(a), which is drawn by using a computer aided design program in order to take account of the scanning electron microscopy

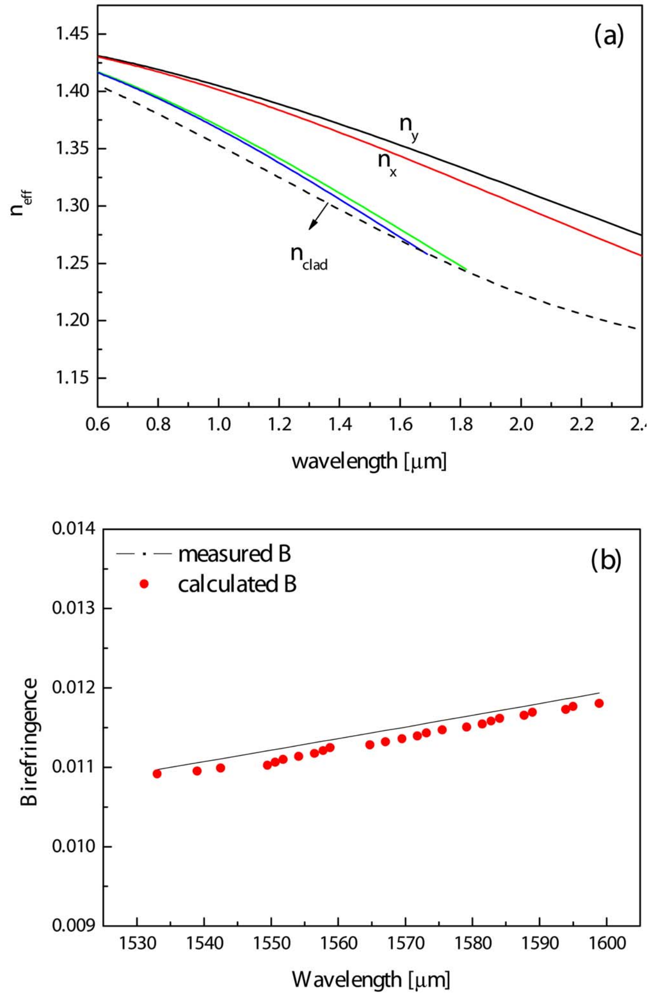

FIG. 4. (a) Effective indices of two orthogonally polarized fundamental modes. (b) The calculated (circles) and the measured (line) birefringence of the elliptic fiber as a function of wavelength.

image of the elliptic core fiber shown in Fig. 1. It is found that an important factor yielding the high birefringence is the high ellipticity of the core and the variation of shapes and sizes of air holes in the first layer forming the elliptic core affects the value of birefringence.

The near field beam pattern of the fiber measured by a charge coupled device camera and its calculated result are shown in Figs. 5(a) and 5(b), respectively. In Fig. 5(a), the mode shape of the fiber is an ellipse with the dimensions of 1.47 and 1.66 μm in x and y axis, respectively. The result is in good agreement with the calculated one in Fig. 5(b).

In conclusions, we have investigated experimentally and theoretically the birefringence property of the elliptic core fiber with irregular air holes in cladding. The beat length and the birefringence of the fiber were measured by the wavelength scanning method. The elliptic core fiber exhibits high birefringence of 1.12×10^{-2} at the wavelength of 1550 nm. The birefringence calculated by the plane wave expansion method is in excellent agreement with the measured one. The high birefringent elliptic core fiber can be useful in implementing polarization and maintaining fibers and polarization sensors.

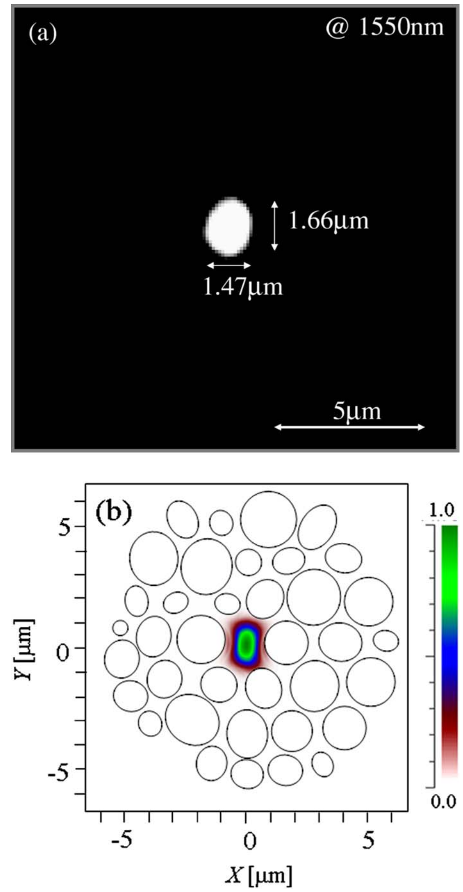

FIG. 5. The measured (a) and calculated (b) near field beam patterns of the fiber at 1550 nm. The circles in (b) denote air holes.

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