Central distance of interferential mode patterns of elliptical core two-mode fiber

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By means of the weakly guiding approximation, the mode spot sizes W_x and W_y of the fundamental mode along the semimajor (x-direction) and semiminor (y-direction) axes of the fiber core in elliptical core two-mode fiber are discussed. The variation of their ratio value W_x/W_y with the operation wavelength λ and the length ratio a/b between the semimajor axis and the semiminor axis of the fiber core is analyzed. Based on this analysis, the distribution figures of two-lobe interferential mode patterns are evaluated and simulated quantitatively for different phase difference changes between LP_{01} and LP_{11}^{even} modes. The two-lobe interferential mode patterns have the same profile and distribute symmetrically when the phase difference equals $\pi/2$. Their central distance S becomes larger when W_x/W_y augments gradually. Furthermore, the equation about the central distance S of the two-lobe interferential mode patterns is given when the operation wavelength varies between 0.65 and 1.31 μm, which is important to applications shuch as sensors and coupling devices between different fibers.

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Two-mode fibers have been widely used in the applications such as sensors for measurement of pressure[1], strain[2], vibration[3], acoustic waves[4], acousto-optic filter[5], acousto-optic switches[6], mode coupling[7−9]. Two-lobe far-field intensity distributions are obtained at the output end by exciting appropriate modes in the fiber[10]. The standard method of analysis involves a measurement of the exchange of optical power between the two lobes in order to determine the nature of the external perturbation. With two-mode propagation, an external disturbance causes a differential phase shift between the modes which in turn results in the variation of the intensity of mode patterns. Periodic variations in the intensity patterns, such as oscillation of power between the lobes, are examples of changes which can be used for voltage sensor[11].

The related detection techniques for two-mode interferential signals have been discussed. One of the elementary techniques involves the placement of a spatial demodulation in the form of a pin-pole, which samples only part of the far-field patterns[12]. Another optical signal processing technique that uses a charge-coupled device (CCD) array for the analysis of the pattern at the output of a highly multimode fiber sensor has also been demonstrated[13]. Most of such methods require the output fiber to display the far-field pattern on the monitoring system and achieve satisfying results. Recently, A new detection method for fiber voltage sensor in Fig. 1 is put forward as shown in Ref. [14], where two single-mode fibers are tapered, placed very close to each other and are spliced onto the output end of the two-mode fiber. Using a fusing splice, the two tapered fibers with photoelectric diodes are fused together at the output of two-mode fiber for signal detection. This way is superior to the former because interferential signals are not disturbed by external noises during the transmission. But how to value central distance between the mode spots and choose appropriate fibers to effectively pickup the two-lobe interferential signals are not discussed before, which are always important in practice.

In order to resolve above problems, firstly, a mode spot size of the fundamental mode is numerically valued by computer and relevant equations are given in the paper. Secondly, based on the fundamental mode spot size, the
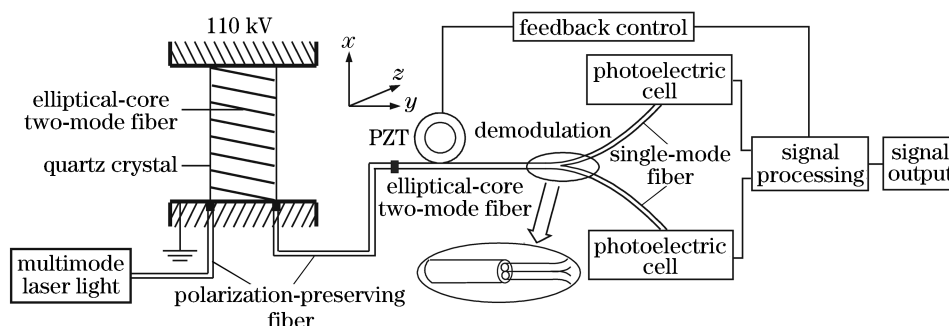

Fig. 1. Fiber voltage sensor and demodulation of the interference pattern of the elliptical-core two-mode fiber. PZT: piezoelectric ceramic.

interferential patterns of the elliptical-core two-mode fiber are discussed. Finally, the central distance of two-lobe interferential mode patterns is analyzed for improving output coupling.

For a weakly guiding elliptical-core two-mode fiber, we assume that the transmitted light in the fiber is a Gaussian beam. In this situation, the fundamental mode of elliptical-core two-mode fiber is characterized by $1/e^2$ power radii W_x and W_y in the x and y directions respectively for convenience. The two quantities are related to the fiber parameters. According to Ref. [15], by means of computing simulation for the practical ranges $1.0 < \Omega < 3.0$ and $1.5 < V < 2.4$, the spectral dependence of the spot size of elliptical-core step-index fibers can be described by the following relations:

$$\frac{W_x}{W_y} = \Omega \cdot \frac{A_1(\Omega) + B_1(\Omega)/V + C_1(\Omega)/V^2}{A_2(\Omega) + B_2(\Omega)/V + C_2(\Omega)/V^2}, \quad (1)$$

where the normalized frequency V is given by

$$V = k_0 b \sqrt{n_1^2 - n_2^2} = \frac{2\pi}{\lambda} n_1 b \sqrt{2\Delta},$$

$$\Omega = \frac{a}{b}, \quad \Delta = \frac{n_1^2 - n_2^2}{2n_1^2}, \quad (2)$$

and

$$A_1(\Omega) = 0.249051 + 1.168967/\Omega$$
$$-1.653089/\Omega^2 + 1.242264/\Omega^3,$$

$$B_1(\Omega) = 0.553682 - 1.674148/\Omega$$
$$+4.774802/\Omega^2 - 4.643775/\Omega^3,$$

$$C_1(\Omega) = -0.431343 + 2.746133/\Omega$$
$$-4.878364/\Omega^2 + 5.309500/\Omega^3,$$

$$A_2(\Omega) = 0.634367 + 0.261726/\Omega$$
$$-0.420852/\Omega^2 + 0.532219/\Omega^3,$$

$$B_2(\Omega) = 0.983584 - 1.499912/\Omega$$
$$+1.853356/\Omega^2 - 2.329100/\Omega^3,$$

$$C_2(\Omega) = 0.317501 + 1.569950/\Omega$$
$$-1.617991/\Omega^2 + 2.479242/\Omega^3, \quad (3)$$

a and b represent the lengths of the semimajor (x-direction) and the semiminor (y-direction) axes of the fiber core respectively, n_1 and n_2 are the refractive indices of the core and the cladding respectively, and λ is the incident wavelength.

In order to analyze the spot size of the fundamental mode LP_{01}, we set $a = 4$ μm, $b = 2$ μm, $n_1 = 1.458$, and $\Delta = 0.005$ in this paper. Figure 2 shows the variation of W_x, W_y, V, and W_x/W_y with the variation of λ (0.65 μm $< \lambda < 1.31$ μm). Figure 2 indicates that the values of W_x and W_y become larger gradually when the
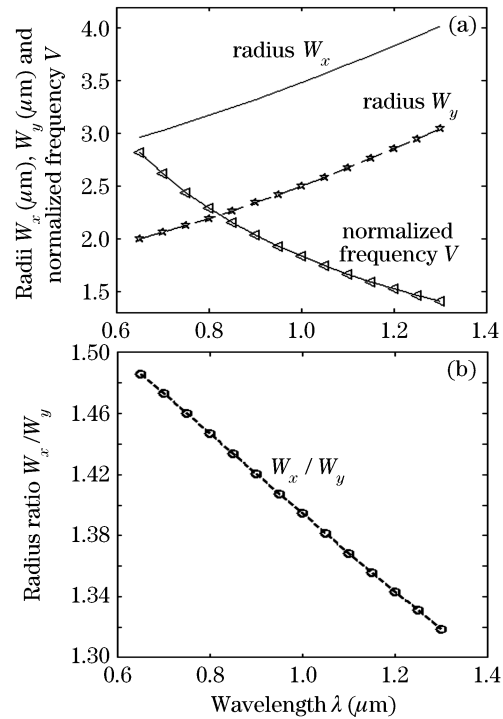

Fig. 2. Variation characteristics of W_x, W_y, V, and W_x/W_y with λ.

wavelength λ varies from 0.65 to 1.31 μm. Inversely, their ratio value becomes smaller gradually, which approximately changes linearly and is limited between 1.3 and 1.5. In view of the range of Ω and V, the incident light wavelength λ should be limited between 0.75 and 1.2 μm, which results that W_x/W_y should be close to 1.4. For convenience, we choose $W_x/W_y = 1.4$ in the following section, which decides the mode pattern radius of the two-mode elliptical core. The changeable tendency of normalized frequency can also be seen in Fig. 2.

Making use of the above defined power radii W_x and W_y of the fundamental mode, the E-fields of the fist-order mode LP_{01} and second-order mode LP_{11} in the elliptical-core two-mode fiber can be written as[16]

$$E_{01}(x, y)$$

$$= \left[\frac{Z_0}{n_1} \frac{2}{\pi W_x W_y}\right]^{1/2} \exp\left[-\frac{1}{2}\left(\frac{x^2}{W_x^2} + \frac{y^2}{W_y^2}\right)\right], \quad (4)$$

$$E_{11}(x, y)$$

$$= \left[\frac{Z_0}{n_1} \frac{4}{\pi W_x W_y}\right]^{1/2} \frac{x}{W_x} \exp\left[-\frac{1}{2}\left(\frac{x^2}{W_x^2} + \frac{y^2}{W_y^2}\right)\right], \quad (5)$$

where Z_0 is the plane wave impedance of vacuum.

Supposed that the energies of the two excited modes are equal and they have the same polarization at the output of the fiber, the output interference intensity can be described by

$$I = |E(x, y)|^2 = |E_{01}(x, y) + E_{11}(x, y) \exp(i\Delta\varphi)|^2, \quad (6)$$

where $\Delta\beta = \beta_{01} - \beta_{11}$ is the difference in propagation constant of the two modes, which depends on the structure of fiber and operation wave. ΔL is the transmitting
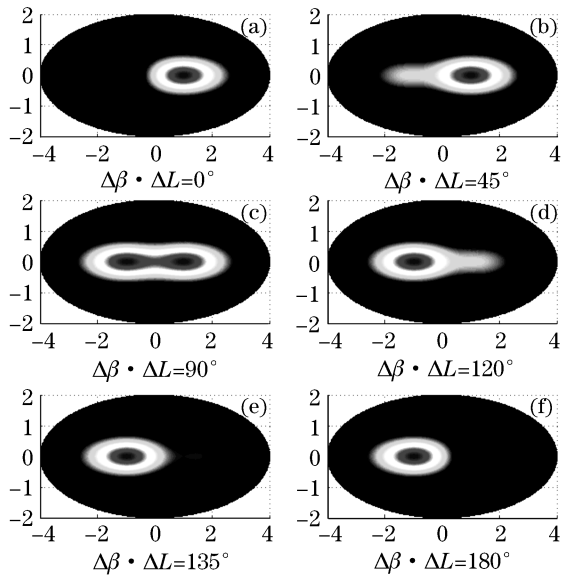
Fig. 3. Elliptical-core fiber output interference patterns when $\Delta\theta = 0$ and $\Delta\beta \cdot \Delta L$ set as different angles.

length in the fiber which can be changed by external perturbation, and $\Delta\varphi = \Delta\beta \cdot \Delta L$ is the modular phase difference.

To numerically evaluate Eq. (6), we set $W_x/W_y = 1.4$. Figure 3 shows the profiles of the interference patterns for a fiber operated at $V = 3.67$, when $\Delta\theta = 0$ and $\Delta\beta \cdot \Delta L$ equals 0°, 45°, 90°, 120°, 135°, 180°, respectively. Figure 3 indicates that the two-lobe interference patterns of elliptical-core two-mode fiber generate periodic oscillation when ΔL varies periodically. In fact, the output intensity distributions of the two-lobe interference patterns also generate periodic change, but the whole energy is invariable because of the conversation of energy. Therefore, to measure the external perturbation, the variation of intensity in one lobe or two lobes should be monitored, and then ΔL can be obtained. Especially, the two lobes have the same energy and profile, and distribute symmetrically when $\Delta\beta \cdot \Delta L = 90°$.

In the practical applications, such as fiber voltage sensor, the central distance between the two-lobe mode patterns should be further analyzed so that the applicable optical system can be designed and interferential signals can be efficiently detected at the output end-face of fiber. Here, we get the changeable tendency of their central distance with radius ratio W_x/W_y of the fundamental mode which depends on the operation wavelength λ. Figure 4 shows the variable rule of the central distance of the two-lobe interferential mode patterns when $\Delta\varphi = \pi/2$ and W_x/W_y equals 1.36, 1.40, 1.44, 1.48, respectively.

Figure 4 indicates that the central distance S of the two-lobe interferential mode patterns when W_x/W_y becomes larger gradually along the fiber main axis. Commonly, to obtain enough signal light, the core diameter D of the pick-up fiber is a little smaller than the core radius of the circular-core two-mode fiber or the major semi-axis of the elliptical-core two-mode fiber, so the core diameter of the pick-up fiber should be chosen to be $D \approx S$. Some exact numerical values are given in Table 1. As a result, the core-profile and radius of the pick-up fiber
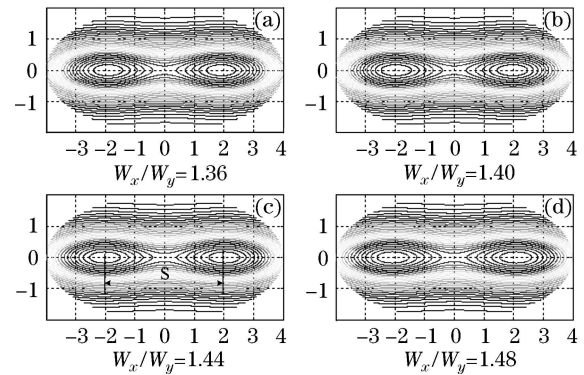

Fig. 4. Central distance variation of the two-lobe interferential mode patterns with W_x/W_y.

Table 1. Variation of S with W_x/W_y for $a = 4$ μm, $b = 2$ μm, $\Delta\varphi = \pi/2$

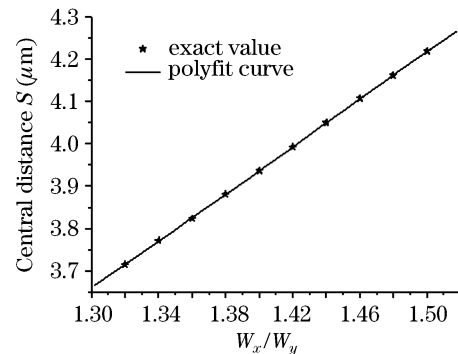| W_x/W_y	$D \approx S$ (μm)	W_x/W_y	$D \approx S$ (μm)
1.32	3.714285714	1.42	3.992307692
1.34	3.771482571	1.44	4.050000000
1.36	3.823076923	1.46	4.107692308
1.38	3.880769231	1.48	4.161538462
1.40	3.936538462	1.50	4.219230769

Fig. 5. Polyfit curve of central distance of the two-lobe interferential mode patterns with W_x/W_y.

are determined by the central distance S of the two-lobe interferential mode patterns, when the signal pick-up fiber is used to detect the interferential signal. Furthermore, the profiles of their interferential mode patterns are almost ellipse when W_x/W_y is between 1.32 and 1.50 at semimajor axis direction.

From Table 1, we get the polyfit curve by means of computer fitting, which is shown in Fig. 5. We also obtain the following approximate equation between S and W_x/W_y:

$$S = -110.96724 + 325.38131 \times (W_x/W_y)$$

$$-350.93255 \times (W_x/W_y)^2 + 169.36189 \times (W_x/W_y)^3$$

$$-30.59441 \times (W_x/W_y)^4 . \tag{7}$$

The standard difference is 0.00146 compared with the exact value. Therefore, using Eq. (7), we can determine

the fiber-core radius of the signal pick-up fiber. The interferential mode patterns can be restricted in the fiber core by choosing appropriate incident light wave for reducing the fusing loss and detecting much more signals, although central distances of the two-lobe interferential mode patterns vary according to Fig. 5.

In conclusion, we discussed the mode-pattern characteristics of the fundamental mode LP_{01} and modular interference of the elliptical-core two-mode fiber. We showed the calculating equation of the fundamental mode, and brought forward the estimating equation for the central distance S of the two-lobe interferential mode patterns. The result shows that W_x and W_y become larger gradually when λ varies from 0.65 to 1.31 μm, while the central distance S of the two-lobe interferential mode patterns becomes smaller when the radius ratio value W_x/W_y decreases. Based on the central distance S, the core diameter of the pick-up fiber should be chosen to make $D \approx S$, which is advantageous to elevate coupling efficiency in some practical applications.

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