Modular interference characteristic of two-mode fiber

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The modular interference characteristics of circular-core and elliptical-core two-mode fibers are investigated in theory. The intensity distribution and figure of two-lobe mode patterns are evaluated and simulated quantitatively for different phase difference change between LP_{01} and LP_{11}^{even} mode. The interference mode patters of elliptical-core and circular-core two-mode fibers are compared, the result shows that the two-lobe interference patters of the two-mode fibers generate energy exchange and oscillation, and the difference is that the interference mode patterns of circular-core two-mode fiber are almost elliptical, while the interference mode pattern of elliptical-core two-mode fiber is approximately circular on condition that proper selection of the ellipticity. Their two-dimensional (2D) profile determines the choice of the core shape of the information pick-up fiber.

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Two-mode fibers are used widely in fiber devices such as laser sensors[1], grating coupling[2], modal filter[3], frequency shifters[4], fiber switches[5], and voltage sensors[6]. The method of generating two modes is to operate a single-mode fiber at a wavelength shorter than the nominal wavelength[7]. The interference of modes in the fiber results in an intensity pattern with two lobes whose structure depends on the amplitude, phase, and the choice of the first two modes. Based on these mode patterns, a number of physical quantities can be measured: hydro-static pressure[8], strain[9], vibration[10], acoustic waves[11], etc.. Therefore, it is important for the practical use to understand profoundly the two-mode interference characteristic.

For a weakly guiding circular-core two-mode fiber, merely considering one polarized direction (for example, x-polarized modes), modular field amplitude of the linearly polarized LP_{01} and LP_{11}^{even} modes can be expressed in a cylindrical coordinate system as[12]

$$\psi_{01} = A_{01} f_{01}(r) \exp(-j\beta_{01} z + j\theta_{01}), \quad (1)$$

$$\psi_{11}^{even} = A_{11}^{even} f_{11}^{even}(r) \cos\phi \exp(-j\beta_{11}^{even} z + j\theta_{11}^{even}), \quad (2)$$

where ψ_{01} and ψ_{11}^{even} describe the scalar field function of LP_{01} and LP_{11}^{even} modes respectively, A_{01} and A_{11}^{even} are the amplitude coefficients of the modes, θ_{01} and θ_{11}^{even} are the phases of the two modes, β_{01} and β_{11}^{even} are the longitudinal propagation constants of the modes, which are attained by solving character equation[13]

$$\frac{U_{x1} J_{x+1}(U_{x1})}{J_x(U_{x1})} = \frac{W_{x1} K_{x+1}(W_{x1})}{K_x(W_{x1})}, \quad \text{for } x = 0, 1. \quad (3)$$

In the core, $f_{x1}(r)$ is the scalar field amplitude given as

$$f_{x1}(r) = J_x(U_{x1} r/a)/J_x(U_{x1}), \quad \text{for } x = 0, 1, \quad (4)$$

$$U_{x1} = a\sqrt{k_0^2 n_1^2 - \beta_{x1}^2}, \quad \text{for } k_0 = \frac{2\pi}{\lambda}, \quad (5)$$

where a is the radius of the fiber core, k_0 the free space wave number, n_1 the refraction index of the fiber core, and λ the free space wavelength. At the output of the fiber, the output light intensity is the synthesization of LP_{01} and LP_{11}^{even} modes. Neglecting the impact of radial strain, temperature change, and modular coupling, when the fiber is stretched by a mount ΔL in axial strain under function, the intensity pattern due to the interference of LP_{01} and LP_{11}^{even} modes is given by

$$I(r,\phi) = |\psi_{01} + \psi_{11}^{even}|^2$$
$$= A_{01}^2 f_{01}^2(r) + A_{11}^2 [f_{11}^{even}(r)]^2 \cos^2(\phi)$$
$$+ 2A_{01}A_{11} f_{01}(r) f_{11}^{even}(r) \cos(\phi) \cdot \cos(\Delta\beta\Delta L - \Delta\theta), \quad (6)$$

where $\Delta\beta = \beta_{01} - \beta_{11}^{even}$ is the difference of the two-mode propagation constants, which depends on the structure of fiber and operation wave. $\Delta\theta = \theta_{01} - \theta_{11}^{even}$ is the quasi-static modal phase difference which may vary, e.g., due to the temperature changes. $n_1 = 1.458$, $\Delta = (n_1 - n_2)/n_1 = 0.005$, $A_{11} = 1$, $A_{01}/A_{11} = 0.5$, and $\lambda = 850$ nm are set to numerically evaluate Eq. (6). Figure 1 shows the distribution of the output intensity and Fig. 2 shows the profile of the interference patterns for a fiber operated at $\Delta\theta = 0$ and normalized frequency $V = 3.67$, when $\Delta\beta\Delta L$ equals 0°, 45°, 90°, 120°, 135°, 180°.

When ΔL varies, the two lobes of the output intensity generate energy exchange and oscillation, but the whole energy is invariable, as shown in Fig. 1. Therefore, in order to measure the external distribution, the variation of intensity in one lobe needs to be monitored, and then ΔL can be obtained. Figure 2 shows that the interference patterns of circular-core fiber are almost elliptical, the energy exchange is the same as Fig. 1. Especially, the energies of the two lobes are equal when $\Delta\beta\Delta L = 90°$.

Assume that the transmitted beam of light in the fiber is Gaussian model, 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 studying the questions conveniently. These two quantities are used as the only free parameters. No attempt is made to connect them to the fiber parameter, although this can be done straightforwardly.

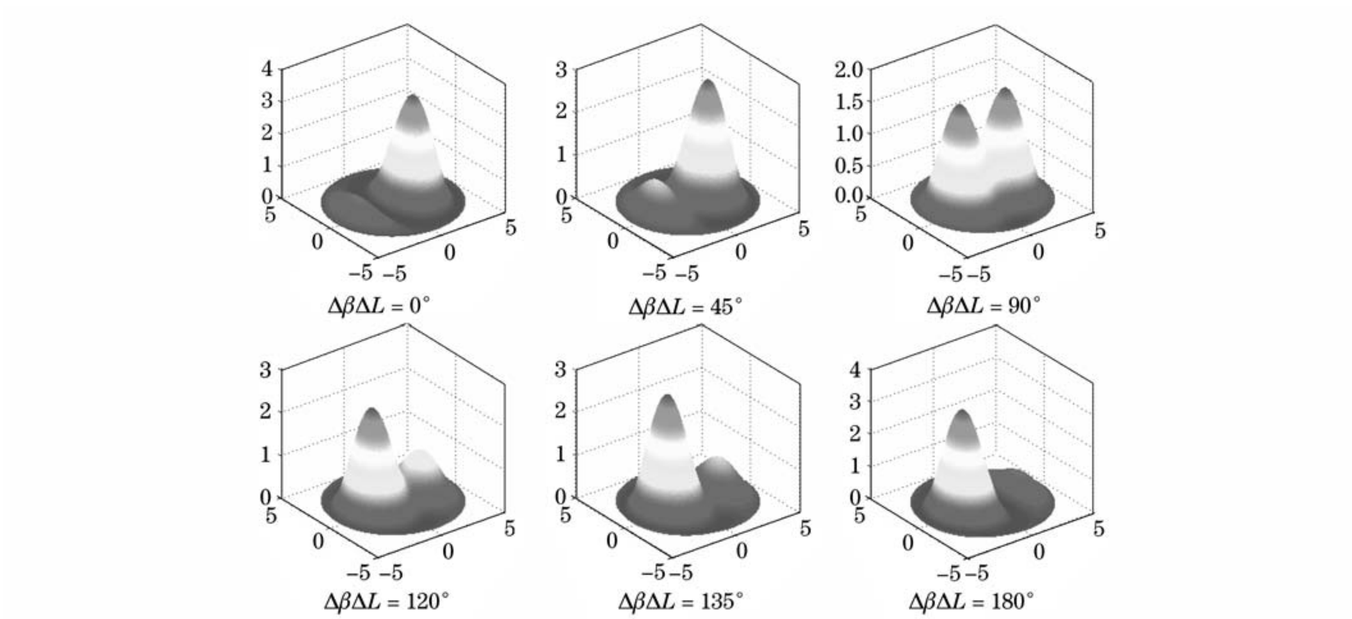

Fig. 1. Circular-core fiber output intensity distributions at $\Delta\theta = 0$ and different angles $\Delta\beta\Delta L$.

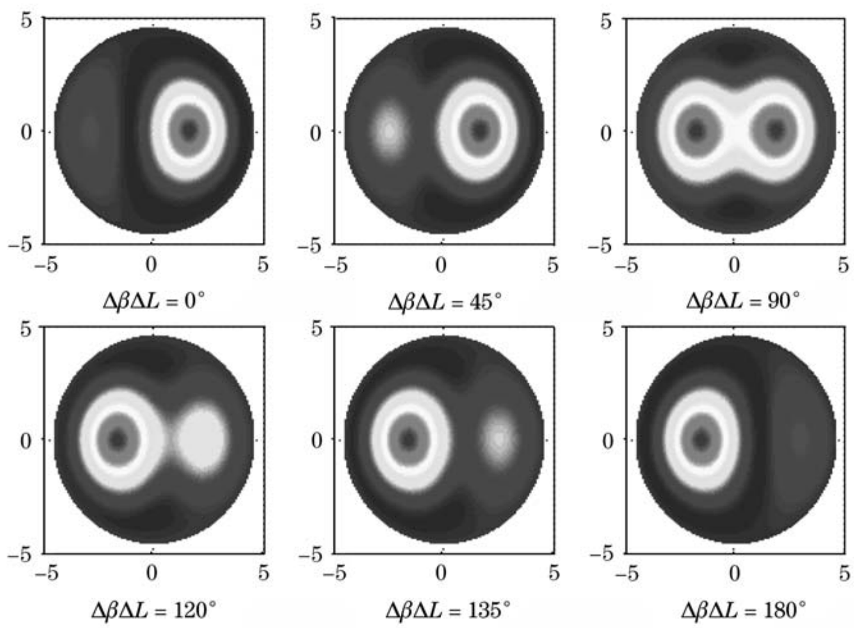

Fig. 2. Circular-core fiber output interference patterns at $\Delta\theta = 0$ and different angles $\Delta\beta\Delta L$.

The E-field of the first- and second-order modes in the elliptical-core two-mode fiber can be written as[14]

$$E_{01}(x,y) = \left[\frac{Z_0}{n_1}\cdot\frac{2}{\pi W_x W_y}\right]^{1/2} \times \exp\left[-\frac{1}{2}\left(\frac{x^2}{W_x^2}+\frac{y^2}{W_y^2}\right)\right], \quad (7)$$

$$E_{11}(x,y) = \left[\frac{Z_0}{n_1}\cdot\frac{4}{\pi W_x W_y}\right]^{1/2} \times \frac{x}{W_x}\exp\left[-\frac{1}{2}\left(\frac{x^2}{W_x^2}+\frac{y^2}{W_y^2}\right)\right], \quad (8)$$

where Z_0 is the plane wave impedance of vacuum.

Suppose that the energies of the excited two modes are equal and have the same polarization at the output of the fiber, the output interference intensity is described by

$$I = |E(x,y)|^2 = |E_{01}(x,y) + E_{11}(x,y)\exp(i\Delta\varphi)|^2, \quad (9)$$

where $\Delta\varphi = \Delta\beta\Delta L$ is the modular phase difference change.

To numerically evaluate Eq. (9), set $W_x/W_y = 1.4$. Figure 3 shows the distribution of the output intensity and Fig. 4 shows the profile of the interference patterns for a fiber operated at $V = 3.67$ and $\Delta\theta = 0$ when $\Delta\beta\Delta L$ equals 0°, 45°, 90°, 120°, 135°, 180°.

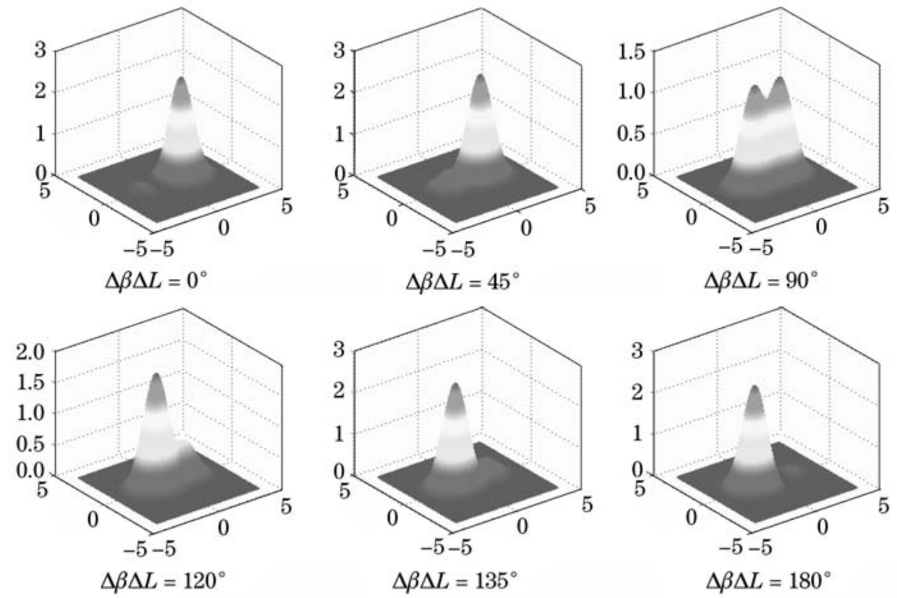

Fig. 3. Elliptical-core fiber output intensity distributions at $\Delta\theta = 0$ and different angles $\Delta\beta\Delta L$.

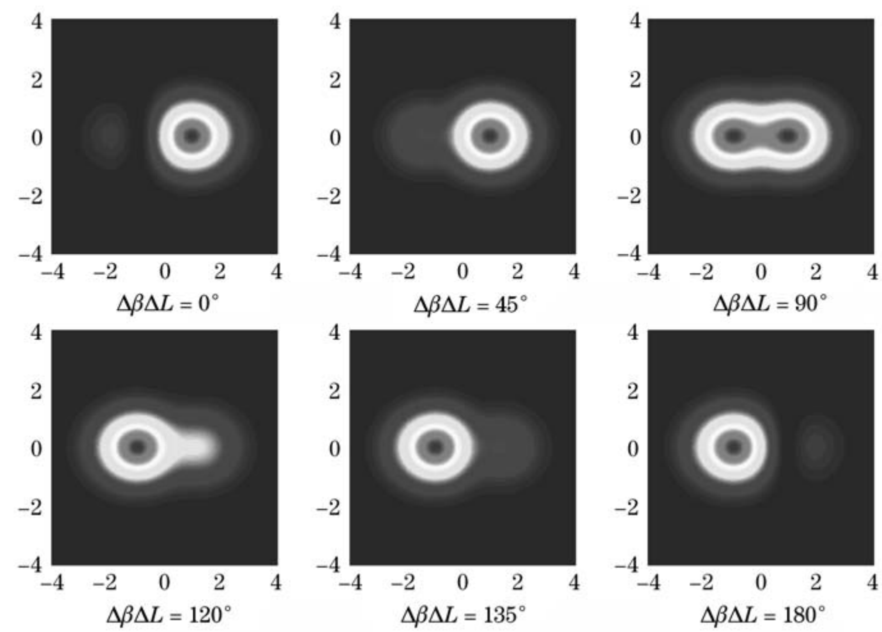

Fig. 4. Elliptical-core fiber output interference patterns at $\Delta\theta = 0$ and different angles $\Delta\beta\Delta L$.

Figures 3 and 4 indicate that the output intensity distributions and interference patterns of elliptical-core two-mode fiber have the same change law as circular-core two-mode fiber. But they are not completely uniform. e.g., the interference patterns are approximately circular.

In order to understand the interference mode patters characteristic of two-mode fibers profoundly, let us compare the two-dimensional (2D) profile of the intensity pattern of circular-core and elliptical-core two-mode fibers. Figure 5 shows the 2D profile of the output intensity pattern. In Fig. 5(a), since the mode field of circular-core fiber is absolutely symmetric[15], we set $W_x/W_y = 1.0$, while the mode field of elliptical-core fiber is asymmetric[16], which is corresponding to $W_x/W_y = 1.4$, as is shown in Fig. 5(b).

Comparing two fibers' 2D profile, it is easy to see that the main lobe of circular-core two-mode fiber is almost elliptical, while the interference patterns of elliptical-core two-mode fiber on condition that proper selection of the ellipticity are approximately circular. Therefore, the pick-up fibers should be consistent with two-mode fibers' 2D interference profile when picking-up interference information. In other words, circular-core two-mode fiber should match elliptical-core single-mode pick-up fiber, while elliptical-core two-mode fiber should match circular-core single-mode pick-up fiber when using photoelectric diodes with single mode fiber to pick up

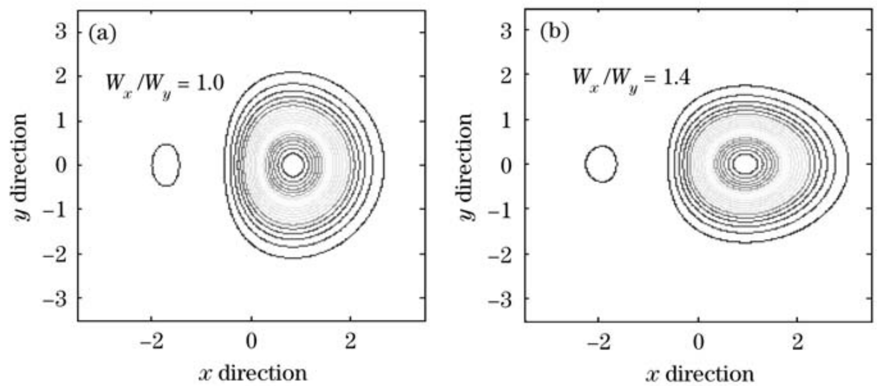

Fig. 5. Two-dimensional profiles of the intensity patterns of Fig. 2 (a) and Fig. 4 (b) for $\Delta\varphi = 0$ at the output of two-mode fiber, the contour interval is constant and equal to 1/20.

interference information. Whether the two-mode fiber matches the pick-up fiber is important to improve coupling efficiency and enhance measurement precision of the system.

In conclusion, the intensity distribution and mode patterns which result from modular phase difference change in circular-core two-mode fiber generate periodic oscillation between LP_{01} and LP_{11}^{even} modes. Especially, the energies of the two lobes are equal when the phase difference is $\Delta\beta\Delta L = 90°$. The output intensity distributions and interference patterns of elliptical-core two-mode fiber have almost the same change rule as circular-core two-mode fiber, but the difference is that the interference mode patterns of circular-core two-mode fiber are almost elliptical, while the interference mode patterns of elliptical-core two-mode fiber on condition that proper selection of the ellipticity are approximately circular. Furthermore, the core shape of the pick-up fiber depends on the 2D interference profile of the two-mode fibers when using diodes with single-mode fiber to pick up interference information. With selecting the matched fiber properly, we can expect that coupling efficiency can be improved and the measurement precision of the system may be enhanced.

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