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Research on the influence of alignment error on coupling efficiency and beam quality for Gaussian beam to multimode fiber

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ABSTRACT

The effect of alignment error on the coupling efficiency and beam quality of a Gaussian beam coupled into a large-core multimode fiber is studied in this paper. The equations for evaluating the effect of alignment error on the coupling efficiency are derived separately, and verified with the method of simulation. The calculation and simulation results obtained are highly consistent. In the same way, the effects of alignment error on the beam power distribution are discussed. The results show that the lateral error will change the path of partial light to a large extent, and have a greater influence on the power distribution of the Gaussian beam than the longitudinal error and angular error do.

Introduction

Laser has unique advantages in brightness, directivity, monochrome and coherence, and thus be widely used in various fields. Applying high-power laser to materials processing, laser surgery, and optoelectronic countermeasures can bring revolutionary changes. The use of optical fiber to transmit high power laser has significant advantages such as flexible transmission, high transmission efficiency, small size, light weight, good environmental adaptability and so on. In particular, the continuous advancement of related technologies for the large-core multimode optical fiber has greatly increased the energy transfer capacity of optical fiber.

Coupling of laser and optical fiber is a core part of optical fiber transmission of high-power laser, specifically related to the aspects of coupling efficiency, coupling capacity and beam quality. While maintaining the highest coupling efficiency possible, reducing the negative impact on beam quality is an important goal pursued by coupler design. The factors that affect the performance of the coupler include alignment error, transmittance of the end face of the fiber and so on [1]. This paper concentrates on the impact of alignment error on the coupling process in the transmission of high power lasers with large-core multimode fiber, especially the effect on coupling efficiency and power distribution of the Gaussian beam.

Classification of alignment error

Alignment error occurs when the laser beam deviates from its theoretical position relative to the actual position of the optical fiber, including longitudinal error l, lateral error d and angular error γ [2,3], as shown in Fig. 1 below.

In order to perform theoretical calculation and simulation, the following assumptions are made:

1) The effects of Fresnel reflection, absorption loss, scattering loss, bend loss and other factors are ignored. In this way, the calculation and simulation can be simplified, and we can better concentrate on the influence of alignment error on coupling efficiency [4–6].
2) The light entering the fiber cladding is completely absorbed and does not contribute to the coupling efficiency. Although the fiber cladding has the capability of transmitting light, the process will increase the risk of optical fiber damage. At the same time, beam quality will deteriorate after the beam is transmitted through the fiber cladding [7,8]. Therefore, it is necessary to filter the light in the fiber cladding, especially in the case of high power laser transmission.

Effect of alignment error on coupling efficiency

At present, many formulas for the alignment error are based on the assumption of uniform light intensity distribution, and coupling

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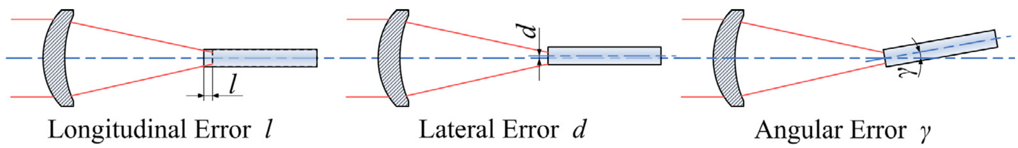

Fig. 1. Classification of alignment error.

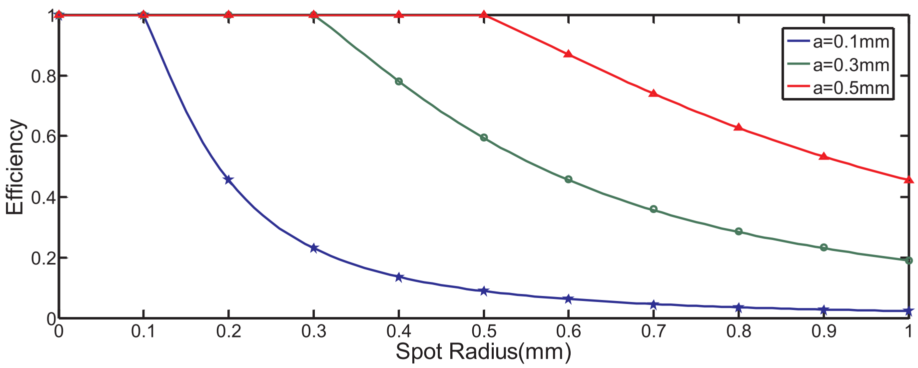

Fig. 2. Calculation results (solid line) and simulation results (the marks: ☆, ○, **Δ**) of the effect of beam spot on coupling efficiency with different fiber core radius: $a = 0.1$ mm (blue), $a = 0.3$ mm (green), $a = 0.5$ mm (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

efficiency is proportional to the overlapping area [9]. Although the calculation method is simplified, there is a large deviation between the assumption and the actual situation, especially for the fiber coupling problem of a Gaussian beam discussed in this paper. To ensure accuracy in the equations for evaluating the effects of alignment error, a strict derivation will be made based on the basic concept of the Gaussian distribution.

The amplitude of the electric field vector of a Gaussian beam at any distance z in the beam propagation direction is:

$$E = \frac{A_0}{\omega(z)}\exp\left[-\frac{r^2}{\omega^2(z)}\right] \tag{1}$$

where A_0 is the center light amplitude at the origin ($z = 0$), $\omega(z)$ is the spot radius.

The relationship between light intensity I and E is $I \propto E^2$ [10]. Thus the light intensity I can be expressed as:

$$I(r) = kE^2 = k\left\{\frac{A_0}{\omega(z)}\exp\left[-\frac{r^2}{\omega^2(z)}\right]\right\}^2 = k\frac{{A_0}^2}{\omega^2(z)}\exp\left[-\frac{2r^2}{\omega^2(z)}\right] \tag{2}$$

where k is a scale coefficient.

The Gaussian beam power with semi-aperture ρ is:

$$P(\rho) = \iint_s I(r)ds = \frac{k\pi A_0^2}{2}\left[1 - \exp\left(\frac{-2\rho^2}{\omega^2(z)}\right)\right] \tag{3}$$

where s is the overlapping area of the Gaussian beam and the fiber core in the incident end face of the fiber.

The total power is:

$$P(\infty) = k\frac{{A_0}^2}{\omega^2(z)}\int_0^\infty \exp\left[-\frac{2r^2}{\omega^2(z)}\right]\cdot 2\pi r\cdot dr = \frac{k\pi A_0^2}{2} \tag{4}$$

The efficiency of the Gaussian beam passing through a semi-aperture of ρ is:

$$\eta(\rho) = \frac{P(\rho)}{P(\infty)} = 1 - \exp\left(-\frac{2\rho^2}{\omega^2(z)}\right) \tag{5}$$

In addition, a Gaussian laser beam can be converted into an angular Gaussian distribution with a high-power lens, and the angular Gaussian distribution is more convenient for the analysis of angular error [11]. The normalized angular power distribution of a Gaussian beam with a width θ_W has the form [12]:

$$p(\theta_x, \theta_y) = \exp\left(-\frac{\theta_x^2 + \theta_y^2}{\theta_W^2}\right) \tag{6}$$

Longitudinal error

The longitudinal error l will lead to the change of the spot radius of the laser beam at the coupling end of the fiber, and the energy distribution of laser beam will also be changed. When the longitudinal error reaches a certain value, the laser spot diameter will be larger than the fiber core diameter, resulting in coupling loss.

Coupling a Gaussian beam into an optical fiber with fiber core radius a can be completely equivalent to passing the Gaussian beam through a circular aperture with radius of a. Therefore, the influence of longitudinal error on coupling efficiency can be calculated by:

$$\eta_l = 1 - \exp\left(\frac{-2a^2}{\omega^2(z)}\right) \tag{7}$$

To verify the accuracy of Eq. (7), a simulation using ZEMAX was performed. The combination of sequential mode and non-sequential mode is adopted in the simulation. This method can well simulate the process of laser and fiber coupling, and has the following advantages: 1) It can completely satisfy the assumptions mentioned at the beginning; 2) The value of the alignment error can be controlled accurately, which can facilitate the simulation.

The fiber core radius were set to $a = 0.1$ mm, $a = 0.3$ mm and $a = 0.5$ mm respectively, and the Eq. (7) was used to obtain the relationship between longitudinal error and coupling efficiency, as shown in Fig. 2 below. It can be seen that the coupling loss occurs when the beam spot radius $\omega(z)$ is larger than the fiber core radius a, and the coupling efficiency shows a nonlinear decreasing trend with the increase of spot radius. Then simulation is performed using the same parameters, the results are also shown in Fig. 2. By comparison, it can be found that the calculation results are highly consistent with the simulation data.

In addition, with the waist radius of the Gaussian beam ω_0, Eq. (8) can be used to calculate the spot radius $\omega(z)$ of a Gaussian beam at any position z.

$$\omega^2(z) = \omega_0^2 + \frac{\lambda^2 z^2}{\pi^2\omega_0^2} \tag{8}$$

and

$$z = z_0 + l \tag{9}$$

where z_0 is the corresponding z-value of the Gaussian beam at the theoretical coupling position.

Then the new expression of η_l can be obtained:

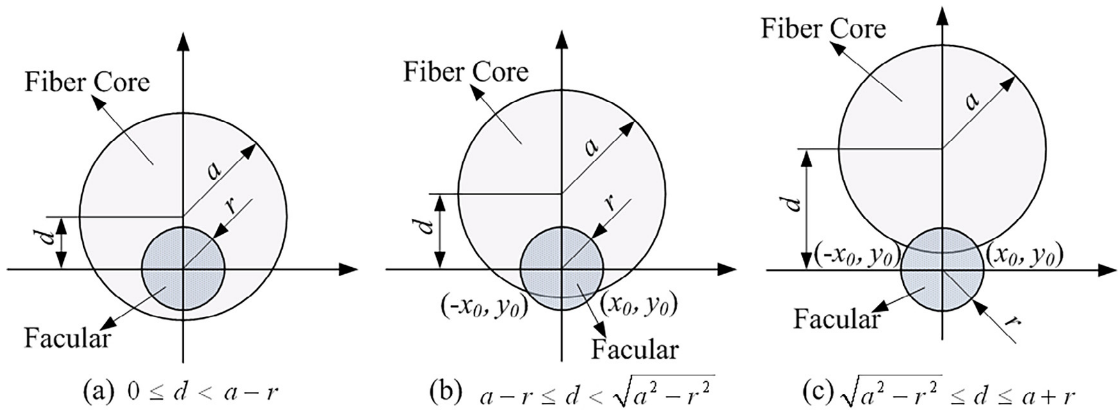

Fig. 3. Schematic diagram of the effect of lateral error on coupling efficiency.

$$\eta_l = 1 - \exp\left[\frac{-2(z_0+l)^2}{\omega_0^2 + \frac{\lambda^2 z^2}{\pi^2\omega_0^2}}\right] \tag{10}$$

Lateral error

The overlapping area of the beam spot and the optical fiber core will be changed when lateral error d reaches a certain value, resulting in a decrease in coupling efficiency, as shown in Fig. 3 below.

From Eq. (3) above, we know that in the absence of alignment error, the power of a Gaussian beam with spot radius r coupled into the fiber with core radius a ($a > r$) is:

$$P_0 = \iint_s I(x,y)ds = \frac{k\pi A_0^2}{2}[1-\exp(-2)] \tag{11}$$

When there is lateral error d, the power $P(d)$ has the following forms:

$$P(d) = \begin{cases} P_0 & (0 \leqslant d < a-r) \\ P_1(d) & (a-r \leqslant d < \sqrt{a^2-r^2}) \\ P_2(d) & (\sqrt{a^2-r^2} \leqslant d \leqslant a+r) \end{cases} \tag{12}$$

where

$$\begin{aligned} P_1(d) = \iint_{s(d)} I(x,y)dxdy &= k\frac{A_0{}^2}{r^2}\int_{-x_0}^{x_0}\int_{d-\sqrt{a^2-x^2}}^{y_0}\exp\left[-\frac{2(x^2+y^2)}{r^2}\right]dxdy \\ &+ k\frac{A_0{}^2}{r^2}\int_{y_0}^{0}\int_{-\sqrt{r^2-x^2}}^{\sqrt{r^2-x^2}}\exp\left[-\frac{2(x^2+y^2)}{r^2}\right]dxdy \\ &+ k\frac{A_0{}^2}{r^2}\int_{-r}^{r}\int_{0}^{\sqrt{r^2-x^2}}\exp\left[-\frac{2(x^2+y^2)}{r^2}\right]dxdy \end{aligned} \tag{13}$$

$$P_2(d) = \iint_{s(d)} I(x,y)dxdy = k\frac{A_0{}^2}{R^2}\int_{-x_0}^{x_0}\int_{d-\sqrt{a^2-x^2}}^{\sqrt{r^2-x^2}}\exp\left[-\frac{2(x^2+y^2)}{r^2}\right]dxdy \tag{14}$$

with

$$x_0 = \frac{\sqrt{2a^2d^2+2r^2d^2+2a^2r^2-a^4-d^4-r^4}}{2d} \tag{15}$$

$$y_0 = \frac{r^2+d^2-a^2}{2d} \tag{16}$$

Using Eqs. (11)–(14) derived above, the following equation for the effect of lateral error on coupling efficiency can be obtained:

$$\eta_d = P(d)/P_0 \tag{17}$$

Although the double integral equation derived above cannot be solved analytically, the results can be easily obtained by numerical calculations with the method of integral area subdivision.

Similarly, the simulation method is used to verify the equation obtained. The fiber core radius is set to a = 0.5 mm, and the spot radius r to 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm respectively. The relationship between the lateral error and the coupling efficiency obtained by using Eq. (17) is shown in Fig. 4. From the figure, it can be found that the coupling error decreases nonlinearly with the increase of the lateral error, and when the lateral error is equal to the fiber core radius a, the coupling efficiency decreases fastest. The simulation results obtained are shown in Fig. 4. By comparison, it can also be found that the calculated results are in good agreement with the simulation data.

Angular error

The effect of the angular error γ on the coupling efficiency is mainly due to the fact that the angular error may cause the incidence of partial beam to be larger than the numerical aperture of the optical fiber,

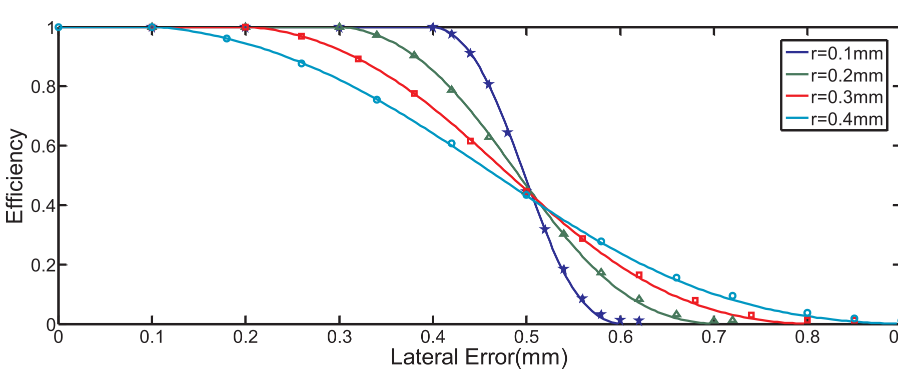

Fig. 4. Calculation results (solid line) and simulation results (the marks: ☆, **Δ**, □, ○) of the effect of lateral error on coupling efficiency with different spot radius: r = 0.1 mm (blue), r = 0.2 mm (green), r = 0.3 mm (red), r = 0.4 mm (cyan). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

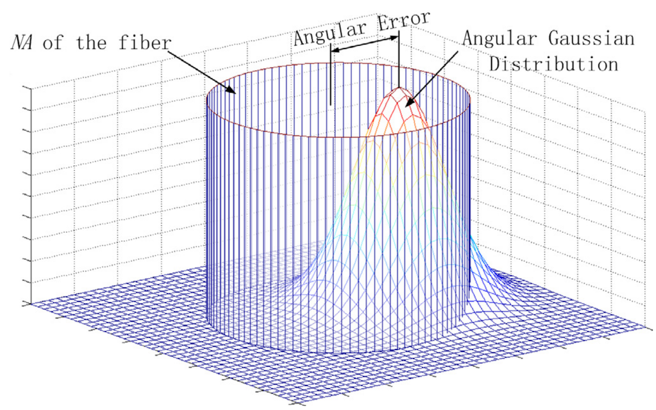

Fig. 5. Schematic diagram of the effect of angular error on coupling efficiency.

causing leakage into the fiber cladding [13], as shown in Fig. 5.

Using Eq. (6), the form of the normalized angular Gaussian distribution with an angular error γ is obtained [14]:

$$p(\gamma) = \exp\left[-\frac{(\theta_x - \gamma)^2 + \theta_y^2}{\theta_W^2}\right] \tag{18}$$

And an approximate form of the total power of the Gaussian beam coupled into the fiber core can be found by integrating $p(\gamma)$:

$$P(\gamma) = \iint_s p(\gamma)ds = \int_{-\theta_M}^{\theta_M}\int_{-\theta_M}^{\theta_M} \exp\left[-\frac{(\theta_x - \gamma')^2 + \theta_y^2}{\theta_{IN'}^2}\right]d\theta_x d\theta_y \tag{19}$$

where θ_M is the critical angle of the fiber (inside the fiber core), $\theta_{IN'}$ and γ' are the corresponding values in the fiber core of incidence θ_{IN} and angular error γ after coupling. In addition, the following equations can be easily obtained using Snell's law:

$$\theta_M = \arcsin(\sqrt{n_1^2 - n_2^2}/n_1) \tag{20}$$

$$n_0 \sin\theta_{IN} = n_1 \sin\theta_{IN'} \tag{21}$$

$$n_0 \sin\gamma = n_1 \sin\gamma' \tag{22}$$

where n_0 is the refractive index of medium, n_1 is the refractive index of fiber core, and n_2 is the refractive index of fiber cladding.

Substitution of Eqs. (20)–(22) into (19) yields the equation for evaluating the effect of angular error on coupling efficiency:

$$\eta_\gamma = \frac{P(\gamma)}{P(0)} \tag{23}$$

To verify the equations derived above, another simulation is conducted with parameters: $n_0 = 1$, $n_1 = 2.07$ and $n_2 = 2.065$. Three incidences ($\theta_{IN} = 2.34°$, $\theta_{IN} = 4.74°$ and $\theta_{IN} = 7.1°$) are selected for the calculation and simulation, and the results obtained are shown in Fig. 6.

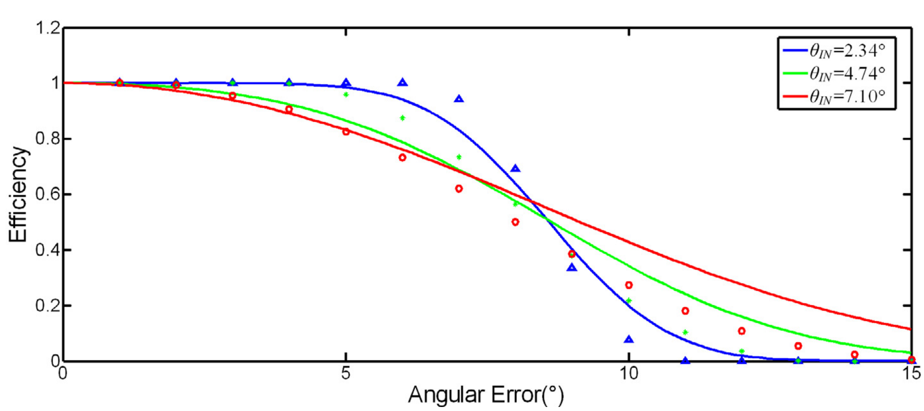

Fig. 6. Calculation results (solid line) and simulation results (the marks: **Δ**, *, ○) of the effect of angular error on coupling efficiency with different incidences: $\theta_{IN} = 2.34°$ (blue), $\theta_{IN} = 4.74°$ (green), $\theta_{IN} = 7.10°$ (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

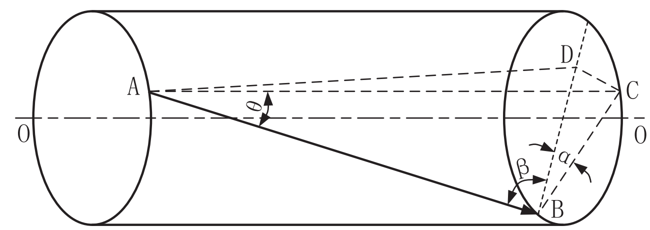

Fig. 7. The trajectory of skewed light.

It can be found that the calculation results are in agreement with the simulation results to a large extent. There are two main reasons for the difference of the two results: one reason is to use the laser source with Gaussian distribution instead of angular Gaussian distribution in the simulation, and the other one is that the form of the total power P(γ) is approximate.

Effect of alignment error on beam quality

It is quite difficult to obtain the specific power distribution of a laser beam transmitted through a large-core multimode fiber to analyze the effect of alignment error on beam quality, because the mode distribution of the beam will change gradually in the fiber [15]. However, it is feasible to analyze the effect qualitatively from the point of view of geometrical optics.

The path of any light in the fiber can be determined by two parameters: the axial angle θ and the azimuth angle α. The axial angle θ is the angle between the light ray and the fiber axis, the azimuth angle α is the angle between the projection of the light onto the cross section of the fiber and the line connecting the reflection point to the center of the cross section, as shown in Fig. 7. The light transmitted in the optical fiber can be divided into meridian light and skewed light. The meridian light always transmits in the meridian plane, in other words, the azimuth angle of meridian light always equals to 0°. The trajectory of skewed light is a spiral line, which is equidistant from the fiber axis.

Longitudinal error

Since the longitudinal error l does not change the relative position of the optical axis of the beam and the axis of the fiber core, it does not change the meridian light into skewed light, but the spot diameter at the incident end face of the fiber will be changed. When the longitudinal error makes the radius of the spot larger, the distribution of skewed light coupled into the fiber will change, the one near the axis of fiber will move outwards, resulting in decrease of diameter of the power densely distribution area in the center of the fiber core. Fig. 8 below shows the simulation results of the effect of the spot radius on the power distribution of the beam. The fiber length is 0.5 m and the fiber core radius is 0.5 mm.

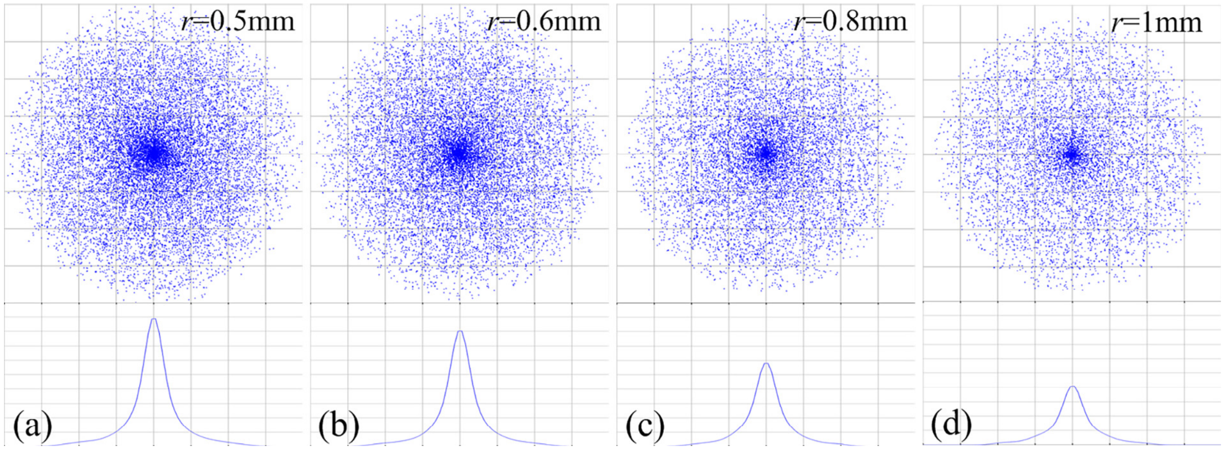

Fig. 8. Power distribution of the beam with different spot radius: (a) r = 0.5 mm, (b) r = 0.6 m, (c) r = 0.8 mm, and (d) r = 1 mm.

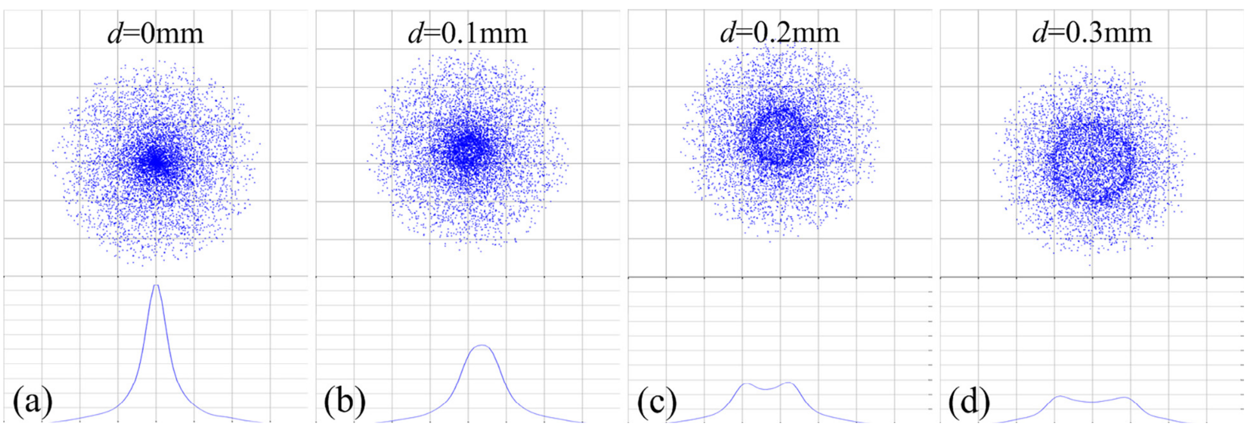

Fig. 9. Power distribution of the beam with different lateral errors: (a) d = 0 mm, (b) d = 0.1 mm, (c) d = 0.2 mm, and (d) d = 0.3 mm.

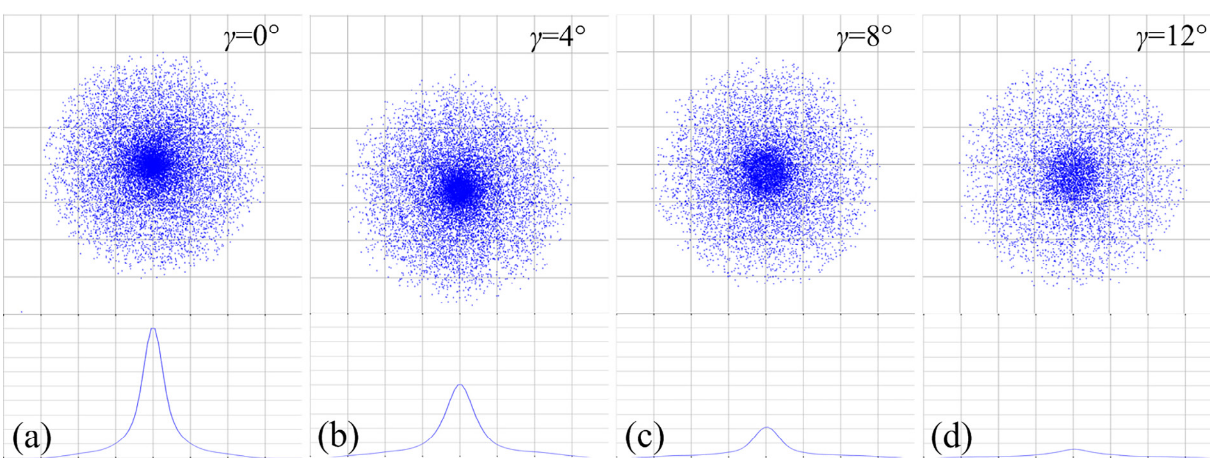

Fig. 10. Power distribution of the beam with different angular errors: (a) γ = 0°, (b) γ = 4°, (c) γ = 8°, and (d) γ = 12°.

Lateral error

The ratio of meridian light and skewed light of a Gaussian beam will be changed significantly by the lateral error d. When there is lateral error, the azimuth angle of the meridian light originally concentrated on the axis of the fiber will no longer be equal to zero. In other words, most of the meridian light will be changed into skewed light. In addition, the azimuth angle increases with the lateral error, resulting in the outward expansion of power concentrated in the center. Fig. 9 below shows the simulation result of the influence of the lateral error d on the power distribution of the beam. The fiber length is 2 m and the fiber core radius is 0.5 mm.

Angular error

The angular error γ also changes the relative position between the beam axis and the fiber axis, so the distribution ratio between meridian and skewed light will be changed. However, when the angle error changes, the axial angle θ of the skewed light is mainly changed, but the impact on the azimuth angle α is much smaller. Therefore, the diameter of the power densely distribution area in the center does not increase significantly with the increase of the angle error. Fig. 10 below shows the simulation result of the influence of the angular error γ on the power distribution. The fiber length is 1 m and the fiber core radius is 0.5 mm.

Through the above analysis, we know that: When the optical axis of the beam is precisely aligned with the axis of the fiber, the meridian light dominates the fiber, the power distribution is approximately Gaussian. When the number of skewed light in the beam increases, the spot will gradually become a ring, and the radius of the ring will increase as the azimuth angle increases. Therefore, the incident conditions in the fiber coupling process affect the ratio and distribution of the meridian and skewed light in the beam, which in turn determines the near-field distribution of the beam.

Conclusion

Ignoring the effects of Fresnel reflection, absorption loss, scattering loss, bend loss and other factors, the formulas for evaluating the effect of three kinds of alignment errors on the coupling efficiency are derived respectively in this paper. If the laser has a strict Gaussian distribution, then the formulas derived is very accurate.

With the help of the software ZEMAX, the two forms of light (meridian light and skewed light) transmitted through the fiber core are analyzed, and the effects of longitudinal, lateral and angular errors on the energy distribution of the laser beam are obtained. The conclusions we have obtained can not only guide the design of a large-core multimode fiber coupler, but also serve as a basis for the performance evaluation and fault diagnosis of the coupler.

Declarations of interest

None.

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