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Beam quality factor of mixed modes emerging from a multimode step-index fiber

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Abstract

The beam quality factors (or M^2 parameter) of coherent and incoherent superposition of the several lower-order LP modes emerging from a step-index fiber have been calculated by using the second-order moment method. The results indicate that, for an individual LP mode, the M^2 parameter takes its maximum value when the normalized frequency V of the step-index fiber approaches the cut-off frequency, and it gradually becomes constant as V increases. In the case of incoherent superposition, the larger the fraction intensity carried by the higher-order mode, the larger the beam quality factor M^2. Under certain circumstances, the value of the M^2 parameter of the mixed mode that comprises several LP-modes contents may become even smaller and closer to the ideal Gaussian beam than that of the fundamental mode in a step-index fiber. However, in the case of the coherent superposition, the value of the M^2 parameter of the mixed mode may be greater than that of the higher-order constituent mode. The results reported here could be helpful for the application of the high-power fiber laser systems.

Keywords: Electric field distribution; Beam quality factor; Linear polarization mode (LP); Step-index fiber

1. Introduction

The development rate of the fiber lasers is so quick in recent years that their output power is in the range of kilowatt [1]. For such high output power, the nonlinear effects in the fiber such as stimulated Brillouin scattering and stimulated Raman scattering become the major factors, limiting further power upscaling [2,3]. In order to reduce the limitations that these effects impose on the output power, one can increase the active fiber core area while maintaining a high beam quality of the laser output. However, following the increase of the fiber core area, it will happen that the fiber supports several spatial modes, and the high-order modes may eventually degrade the beam quality of the output radiation [4]. So, it is necessary to study the field distributions of the high-order modes of the multimode step-index fibers and the propagation characteristics of the beams generated from the lasers based on these types of fibers.

2. Theoretical calculations

The step-index fiber, under the consideration in this work, is made of a core, a cladding and a coated layer; the refractive index of the cladding is slightly smaller than that of the core as shown in Fig. 1 [5]. The radius of

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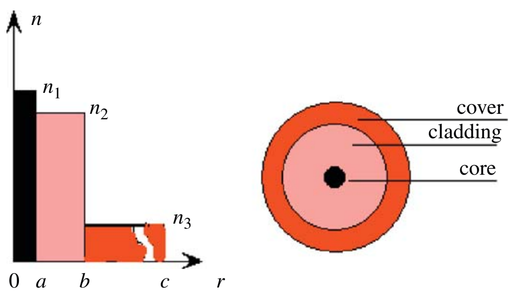

Fig. 1. Refractive index distribution of the step-index fiber.

the fiber core is a, and that of the cladding and the coating layer are b and c, respectively, and the corresponding refractive indexes are μ_1, μ_2 and μ_3, respectively. The beam energy will mostly be limited in the fiber core if the mediums of the core and cladding make up a wave guide structure when $\mu_1 > \mu_2$.

According to the scalar method [5], the electromagnetic fields of the LP_{mn} modes for the weakly guided step-index fiber satisfy the standard Bessel equation:

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + (k^2n^2 - \beta_{mn}^2 - m^2/r^2)R = 0 \qquad (1)$$

where the function R describes the variation of the electromagnetic field along the radial coordinate r, k is the wave number in free space, β_{mn} is the propagation constant that depends on the order mn. The refractive index μ in Eq. (1) is μ_1 for the fiber core area and μ_2 for the cladding area.

Using the standard procedure and assuming a y-polarization wave, the field distribution can be obtained, which reads

$$E_y = \frac{1}{J_m(U_{mn})} J_m(U_{mn}r/a)\cos(m\theta)\exp(-j\beta_{mn}z) \qquad (2)$$

$$H_x = \frac{\omega\mu_0}{\beta_{mn}} \frac{1}{J_m(U_{mn})} J_m(U_{mn}r/a)\cos(m\theta)\exp(-j\beta_{mn}z) \qquad (3)$$

for the fiber core area, and

$$E_y = \frac{1}{K_m(W_{mn})} K_m(W_{mn}r/a)\cos(m\theta)\exp(-j\beta_{mn}z) \qquad (4)$$

$$H_x = \frac{\omega\mu_0}{\beta_{mn}} \frac{1}{K_m(W_{mn})} K_m(W_{mn}r/a)\cos(m\theta)\exp(-j\beta_{mn}z) \qquad (5)$$

for the cladding area. In the above equation, J_m and K_m are the mth-order Bessel function of the first kind and the modified Bessel function of the second kind, respectively, n identified the nth root of the Bessel function. $U_{mn} = (k_1^2 - \beta_{mn}^2)^{1/2}a$ is the normalized transverse propagation constant in the fiber core area, while $k_1 = \mu_1 k$ for the wave number in the fiber core area and $W_{mn} = (\beta_{mn}^2 - k_{mn}^2)^{1/2}a$ is the normalized transverse propagation constant in the fiber cladding area, while $k_2 = \mu_2 k$ for the wave number in the fiber cladding area.

Many methods can be used to measure the beam quality factor of the beam in free space, such as the aggregation two-point method, waist two-point method, focusing two-point method, three-point method, multi-point fitting method, etc. In this work, we adopt the last one to measure the beam quality factor exiting the fiber laser, in accordance with the ISO9000 standard. This method involves evaluating the half-width w of the beam in different positions along the propagation axes at first, and then determining the beam profile by using hyperbolic curve fitting, and finally calculating the M^2 factor. As is well known, the hyperbolic curve fitting equation of the beam is given by [6]

$$w^2(z) = A + Bz + Cz^2 \qquad (6)$$

By using the knowledge of mathematical statistics to obtain the coefficient of the hyperbolic curve, we have the following formulas for the beam waist ω_0, position z_0 of the beam waist and divergence angle ϕ of the beam:

$$w_0 = \sqrt{A - B^2/4C},\ z_0 = -B/2C,\ \phi = \sqrt{C} \qquad (7)$$

The M^2 factor can be specified by using the relation $M^2 = \pi w_0 \phi/\lambda$.

At this stage, the issue of calculating the beam quality factor determines the quantity $w^2(z)$. According to Siegman [7], the z-dependent beam width can be evaluated by

$$w^2(z) = \frac{2\int\int_0^{2\pi} |E(r_2,\theta,z)|^2 r_2^3\, dr_2\, d\theta}{\int\int_0^{2\pi} |E(r_2,\theta,z)|^2 r_2\, dr_2\, d\theta} \qquad (8)$$

while the quantity $E(r_2,\theta,z)$ can be deduced from the following equation:

$$E(r_2,\theta,z) = -\frac{ik}{z} e^{ikz} e^{i(kr_2^2/2z)} \int_0^{+\infty} E(r_1,\theta,0) J_0\left(\frac{kr_1r_2}{z}\right) e^{i(kr_1^2/2z)} r_1\, dr_1 \qquad (9)$$

3. Calculations and discussions

3.1. Beam quality factor versus V

The parameters used in the calculations include $\mu_1 = 1.454$, $\mu_2 = 1.453$, $\lambda = 1\,\mu m$, V is selected from 0 to 14 and a is gained from the relation $a = V/(2\pi/\lambda\sqrt{n_1^2 - n_2^2})$. The M^2 factor versus V in several lowest-order LP_{mn} modes is shown in Fig. 2. From this diagram, it can be observed that the M^2 factor of an individual LP mode becomes very large when V approaches its cut-off frequency of the respective LP mode, and becomes constant as V increases beyond a certain value.