Design of large-mode-area rare earth doped fiber for high power coiled fiber amplifier

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Received December 1, 2008

The numerical study on the performance of large-mode-area (LMA) fibers coiled onto a spool in high power amplifier is carried out as the bend-induced distortion of fiber modes severely affects the output characteristics of amplifier systems. The variations for high-order mode bend distortion with different orientations relative to the plane of the fiber bend are observed and shown. Concerning the practical applications, a bend-resistant LMA fiber with the mode area larger than 1000 μm^2 and excellent high-order mode suppression is designed completely by optimizing the refractive index (RI) and dopant profile. The results indicate that a hybrid profile of RI and dopant is the best choice for LMA fiber with coiling.

OCIS codes: 060.2280, 140.3510, 060.2320.

doi: 10.3788/COL20090708.0671.

In recent years, high power fiber lasers and amplifiers have attracted increasing attention because of their high gain, excellent beam quality, outstanding efficiency, high reliability, good compactness, etc.[1,2] Rare earth doped fibers are critical to improve the performances of the amplifier and laser systems, such as power gain of signal, beam quality, nonlinear effects, etc. Large-mode-area (LMA) fiber is designed to reduce the energy density so as to restrain the nonlinear effects in the high power fiber laser and amplifier systems[3]. One simple way to get LMA fiber is to enlarge the core, which will support high-order modes (HOMs) and lead to the degeneration of the beam quality, but to lower the core numerical aperture (NA) of the large-core fiber may be sensitive to bending and coiling even if single-mode operation and good beam quality output are available[4,5]. In view of this, multi-mode core fibers with restricted dopant profiles are introduced to suppress the HOMs so that both good beam quality and low bend sensitivity are attained. In actual conditions, however, the fiber is usually coiled onto a spool at a certain package size, and the bend distortion is unavoidable. So an excellent LMA fiber used in an amplifier needs to keep good performance in coiling condition.

Recently, many researches have been carried out on bend distortion and the mode distortion which is induced by coiling to explore a fiber that can suppress the bend distortion. One of the most significant studies in this field was conducted by Fini who stimulated the bend-induced mode distortion by using equivalent index model[5], contributed to the design of LMA amplifier fibers resistant to bend-induced distortion, and made many constructive proposals in this regard[6,7]. However, the destruction of HOMs' degeneracy with their different orientations relative to the plane of fiber bend, which actually determines the gain-coefficient of HOMs and has an impact on the HOM-suppression LMA fiber design[6,7], has not been considered.

In this letter, we present a detailed study on the bend distortion of mode field, especially the double degeneracy of HOMs. A numerical investigation into the design of LMA fibers for high power coiled-fiber amplifiers, which have excellent performance in both large effective mode area and HOM suppression, is reported.

The bend distortion is modeled by using the well-known equivalent index model[8]. As illustrated in Fig. 1, when the curvature is R_{bend}, the equivalent index alters in accordance with the bending which is expressed by

$$n_{\text{eq}}(x,y)^2 = n(x,y)^2 + \frac{2x}{R_{\text{bend}}}n(x,y). \tag{1}$$

where $n(x,y)$ is the index at point (x,y) in the fiber cross section.

Equation (1) indicates that the index change Δn varies with x. Based on this model, mode distortions with different bend curvatures can be numerically simulated by triangular-mesh finite-difference (TMFD) method. Figuer 2 shows the fundamental modes of fibers in different coiling conditions (bend curvatures $R_1 > R_2$). It is seen that the circular symmetry of mode is broken, and the effective made field area A_{eff} in the bending condition is different from the straight one. The standard effective mode field area definition is defined as

$$A_{\text{eff}} = \frac{(\int \mathrm{d}A\,|E_i|^2)^2}{\int \mathrm{d}A\,|E_i|^4}, \tag{2}$$

where E_i is the electric field intensity of the ith mode.

When the bend radius is reduced, mode distortion

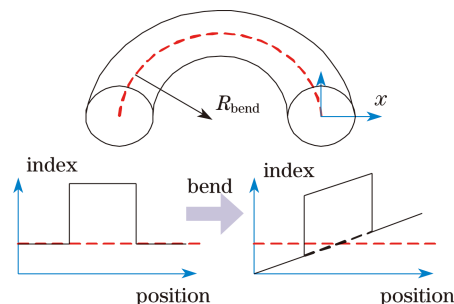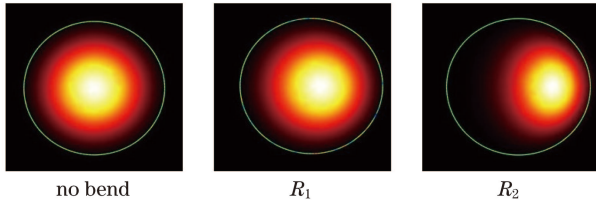Fig. 1. Conformal mapping model of bending.

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Fig. 2. Bend-induced distortion as seen in intensity distributions of LP_{01} mode.

becomes more serious and the mode field departs from the center of the core with the area reduced. Here we define an offset variable $\Delta x = \langle x \rangle$ to indicate the displacement:

$$\langle x \rangle = \frac{\int x \mathrm{d}A \, |E_i|^2}{P_{\mathrm{total}}}, \tag{3}$$

where P_{total} is the total power in the fiber cross section.

Besides, the distribution of power among various modes has an impact on the performance of the amplifier. The power fractions of modes might be controlled by different gain coefficients as well as losses, mode areas, etc. The evolution of the power $P_i(z)$ of the guided transverse mode LP_{mn} is described by[9]

$$\frac{\mathrm{d}P_i(z)}{\mathrm{d}z} = \left[\gamma_i(z) - \alpha_i(z) \right] P_i(z)$$
$$- \sum_j d_{ij} \left[P_i(z) - P_j(z) \right], \tag{4}$$

where γ_i is the gain, α_i is the loss coefficient of LP_{mn} mode, and d_{ij} is the power coupling coefficient between the ith mode and jth mode. The gain of the signal light in the fiber amplifier not only depends on the density and distribution of doped ions, but also is determined by the interaction between light and pumped rare earth ions, in other words, the number of laser rays through the doped region. The gain coefficient γ_i is given by

$$\gamma_i(z) = \int_0^{2\pi} \int_0^{r_{\mathrm{gain}}} \Gamma_{si}(r, \varphi)[-\sigma_a(\lambda_s)N_1(r, \varphi, z)$$
$$+ \sigma_e(\lambda_s)N_2(r, \varphi, z)]r\mathrm{d}r\mathrm{d}\varphi, \tag{5}$$
$$N_1(r, \varphi, z) + N_2(r, \varphi, z) = N(r, \varphi, z), \tag{6}$$

where $\Gamma_{si}(r, \varphi)$ is the overlap of the mode field $\psi_i(r, \varphi)$, r and φ are the radial and angle coordinates, $N_{1,2}(r, \varphi, z)$ are the specific distributions of the population densities of up- and sub-level doped ions, r_{gain} is the radius of the dopant area, σ_a and σ_e are respectively the absorption

and emission cross sections, λ_s is the signal wavelength. The overlap integral can be written as

$$\Gamma_{si}(r, \varphi) = \frac{\psi_i(r, \varphi)}{\int_0^{2\pi} \int_0^\infty r\psi_i(r, \varphi)\mathrm{d}r\mathrm{d}\varphi} . \tag{7}$$

The difference in gain coefficient between LP_{01} mode and other HOMs determines the power fractions of modes. In the case of the power fraction of LP_{11} mode specially, the beam quality of output light is significantly affected. Thus, we define a coefficient for HOM suppression as $\gamma_{\mathrm{HOM-sup}} = \gamma_{01} - \gamma_{11}$ with saturated pumping (γ_{01} and γ_{11} are the gain coefficients for LP_{01} and LP_{11} modes). Larger value of $\gamma_{\mathrm{HOM-sup}}$ might optimize the performance of output beam.

What is worth noting is that bend-induced mode distortion leads to a complex but interesting calculation of $\gamma_{\mathrm{HOM-sup}}$. In a bent fiber, HOMs are doubly degenerated with respect to orientation of transverse field distributions. As noted in Fig. 3, there is a great divergence between LP_{11o} and LP_{11e} modes due to coiling, and the average of the gain coefficient of LP_{11} mode is modified as $\gamma_{11} = (\gamma_{11o} + \gamma_{11e})/2$ (γ_{11o} and γ_{11e} are the gain coefficients for LP_{11o} and LP_{11e} modes).

Based on the analysis of mode field and HOM suppression in LMA fiber, fibers applied to high power amplifier should be designed to minimize nonlinear effects and improve near-diffraction-limited beam quality. However, it is difficult to achieve because large-core fibers which may help avoid nonlinear effect will degrade the beam quality. Therefore, the design of rare earth-doped fiber is largely governed by tradeoffs. Thus, four design goals are proposed as follows.

The first one is the large A_{eff} for LP_{01} mode. Based on recent experiments and researches, the efficient mode area of the fundamental mode should be increased by over 1000 $\mu\mathrm{m}^2$, which can deal with 1-mJ and 2-MW peak power pulses in the core[3].

The second one is the less mode distortion for smaller package size. A tradeoff still exists between mode area and bend sensitivity. A fixed coiling radius is selected with less bend sensitivity as $R_{\mathrm{bend}} = 15$ cm.

The third one is the manufacturable core-cladding refractive index (RI) contrast. We restrict the core-cladding RI contrast of $\Delta n > 0.001$.

The fourth one is the best suppression of HOMs. The value of $\gamma_{\mathrm{HOM-sup}}$ should be higher, while the offset variable Δx should be lower.

The design of RI profiles is proved to be the most useful against bend distortion[10]. Firstly we define a new RI profile named hybrid profile, which can be expressed by

$$n(r) = \begin{cases} n_1 - \left(\dfrac{r}{R_0} \right)^{p_0} (n_1 - n_3), & r < R_0 \\[2ex] n_3 - \left(\dfrac{r - R_0}{R_{\mathrm{core}} - R_0} \right)^{p_1} (n_3 - n_2), & R_{\mathrm{core}} < r < R_0 \\[2ex] n_1, & r > R_{\mathrm{core}} \end{cases}, \tag{8}$$

where R_0 and $R_{\rm core}$ are the radii of the central layer and the core of the fiber, respectively; n_1, n_2, n_3 are refractive indices at different positions (see Fig. 4); $\Delta n = n_1 - n_2$; and the values of p_0 and p_1 might equal ∞, 1, or 2. The profile of hybrid fiber and two typical hybrid fiber designs are illustrated in Fig. 4 with $p_0 = \infty$, $p_1 = 1$ for hybrid-1 and $p_0 = \infty$, $p_1 = 2$ for hybrid-2 fiber.

The effective mode area of LP_{01} and offset variable Δx of different RI fibers with $R_{\rm bend} = 15$ cm are shown in Fig. 5. The coefficients of calculations are selected as $\Delta n > 0.001$, $n_1 = 1.450$, and $R_0 = R_{\rm core}/2$. In contrast to other fibers such as step, triangular, and square fibers, the hybrid fiber can find a better tradeoff between mode area and bend distortion. So the fiber with RI profile of hybrid-2 ($R_{\rm core} = 35~\mu$m) is the best choice. The value

of R_0 has been optimized to 15 μm for $n_2 = 1.4480$.

Moreover, the value of $\gamma_{\rm HOM-sup}$ of the designed LMA fiber is calculated, and the intensity distributions in the core of LP_{01} mode and LP_{11} mode are shown in Fig. 6.

Our design goal for dopant profile is to achieve high gain coefficient of LP_{01} mode and the efficient suppression of HOMs. Thus, five profiles are investigated: step, triangle, parabola, trapezoid, and hybrid, as shown in Fig. 7.

We calculate the values of γ_{01} and $\gamma_{\rm HOM-sup}$, which are shown in Fig. 8, with different radii of doped area $R_{\rm gain}$. The design parameter $R_{0-{\rm gain}}$ for hybrid fibers is
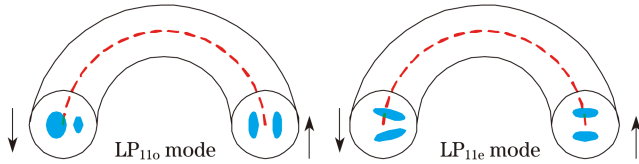

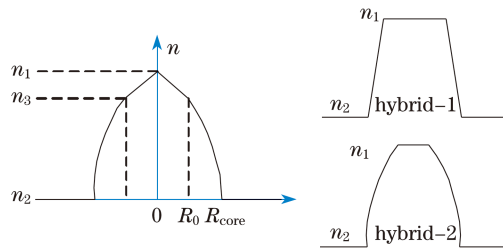Fig. 3. Mode field distortions of LP_{11} mode with respect to the orientation relative to the plane of fiber bend.

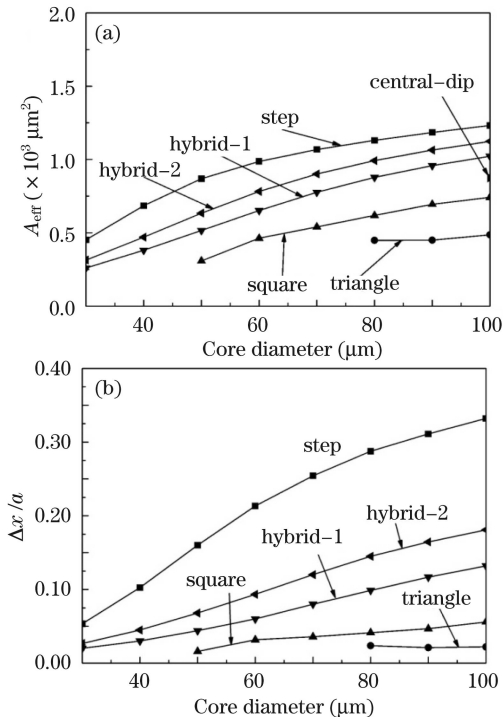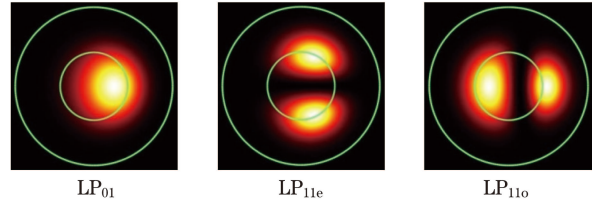Fig. 4. Index profiles of hybrid fibers.

Fig. 6. Intensity distributions of LP_{01} and LP_{11} modes with bending.
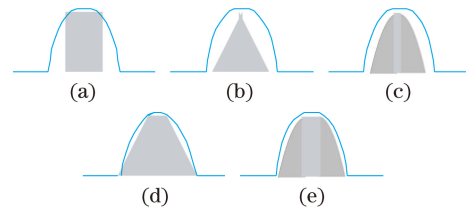

Fig. 7. Main dopant profiles selected. (a) Step, (b) triangle, (c) parabola, (d) trapezoid, (e) hybrid.
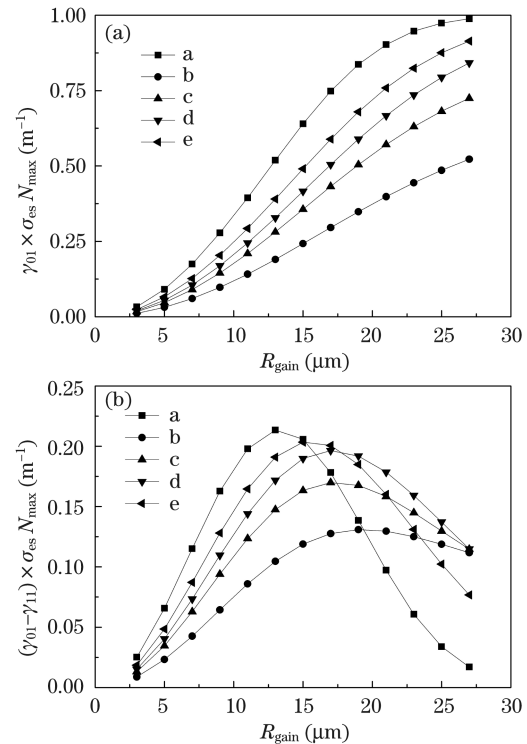

Fig. 5. Dependences of (a) $A_{\rm eff}$ and (b) Δx on core diameter for various RI profiles. $R_{\rm bend} = 15$ cm. a is the core radius.

Fig. 8. Dependences of (a) γ_{01} and (b) $\gamma_{\rm HOM-sup}$ on core diameter for various RI profiles shown in Fig. 7. $N_{\rm max}$ is the maximal concentration of dopant ions.
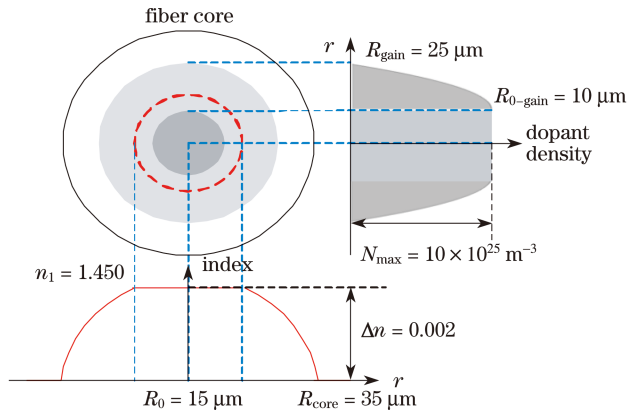
Fig. 9. Configuration of the finally designed fiber.

set as $R_{0-\text{gain}} = \frac{2}{5} R_{\text{gain}}$. The result indicates that step-doped and hybrid-doped designs can offer high gain of LP_{01} mode and good suppression of HOMs. Thus, on the basis of both γ_{01} and $\gamma_{\text{HOM-sup}}$, hybrid-doped fiber with $R_{\text{gain}} = 20$ μm is selected. The coefficients γ_{01} and $\gamma_{01} - \gamma_{11}$ are determined by the dopant profiles. In Fig. 8, σ_{es} is the emission cross section of Yb in germanosilicate glass and N_{max} is the maximal density of YB ions.

The complete design parameters are obtained based on the analyses and numerical simulations above. The optimized configuration of the fiber is illustrated in Fig. 9 with the following parameters: $A_{\text{eff}} > 1000$ μm^2, $\gamma_{01} = 14$ dBm^{-1} and $\gamma_{\text{HOM-sup}} = 8$ dBm^{-1} with

$R_{\text{bend}} = 15$ cm.

In conclusion, we focus on the effect of bend distortion on the performance of LMA coiled fiber for high power amplifiers and propose a set of design goals in contribution to applicable fibers in actual use. In addition, hybrid RI and dopant profiles are used to analysis the double-clad Yb-doped LMA fiber which can offer a large efficient mode area over 1000 μm^2 and less bend distortion propitious to high power amplifier.

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