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Design and analysis of a kind of large flattened mode optical fibre*

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In this paper, a refractive index profile design enabling us to obtain a flat modal field around the fibre centre is investigated. The theoretical approach for designing such multilayer large flattened mode (LFM) optical fibres is presented. A comparison is made between the properties of a three-layer LFM structure and a standard step-index profile with the same core size. The obtained results indicate that the effective area of the LFM fibre is about twice as large as that of the standard step-index fibre, but the LFM fibre has less effective ability to filter out the higher order modes than the standard step-index fibre with the same bending radius.

Keywords: LFM optical fibre, nonlinear effects, effective area, bending loss
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1. Introduction

The pursuit of highest power together with highest brightness can be efficiently fulfilled by rare-earth-doped fibre lasers. As opposed to conventional diode-pumped solid-state laser systems the significantly longer interaction length and the tight confinement of the laser radiation enforce disturbing nonlinear effects, such as self-phase modulation, stimulated Raman scattering, and stimulated Brillouin scattering, which constitute the main restriction of rare-earth-doped fibre based laser systems.[1] It is the dominant challenge if high peak powers from pulsed fibre based laser system are generated, and even for the generation of continuous-wave radiation. However, using innovative fibre designs such as large-mode-area fibres, we can achieve a significant reduction in power density in the fibre core with the retention of the outstanding thermo-optical properties. Large flattened mode (LFM) fibre has large mode area. It was proposed firstly by Ghatak.[2] Its outstanding capability to reduce nonlinear effects in optical fibre lasers has been demonstrated at the Lawrence Livermore National Laboratory.[3]

Most applications require diffraction-limited beam quality. The requirement of single-transverse mode confinement translates this into a maximum core diameter of $\approx 15\mu$m in a conventional, step-index fibre in the one micron wavelength region. A larger core would normally lead to the propagation of higher-order transverse modes. However, several techniques have been demonstrated to ensure single-mode operation in slightly multimode fibres, such as the application of bending losses,[4] which are significantly higher for higher-order transverse modes compared with the LP_{01} mode. Therefore, a properly coiled fibre can prefer single-mode operation in a fibre that would otherwise be slightly multimode. Other techniques include suitably manipulating the fibre index and dopant profiles,[5−7] using special cavity configurations,[8,9] tapering the fibre ends,[10] adjusting the seed launch conditions.[11]

In this paper, we give a multilayer design for the refractive index profile enabling us to get flat modal field around the fibre core, in addition to the increase in the effective area. A generalized formula for designing the multilayer LFM fibres is given. For the simplest three layer LFM fibres, the modal field, effective area, and bending loss are discussed and comparisons are made with the standard step-index fibres.

2. Theoretical analysis

In order to obtain the flat modal field over the entire central region, the effective index ($n_{\rm eff}$) of the

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mode should be equal to the refractive index of the central dip. The refractive index profile is depicted in Fig.1. The modal field (ψ) of the fundamental mode of the fibre can be obtained by solving the following wave equation:[12]

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}\psi}{\mathrm{d}r} + k_0^2(n^2(r) - n_1^2)\psi = 0, \tag{1}$$

where $k_0 = 2\pi/\lambda$, λ is the wavelength. To obtain generalized field solutions, which can accommodate an arbitrary number of claddings, we consider a fibre consisting of N homogeneous dielectric regions, a central region, and $N-1$ claddings. The ith region has a refractive index n_i. In all the regions, n_N is the minimum refractive index and $n_i > n_1 > n_N$ (i=2,3, $\cdots$,N-1), the index difference between two layers is small. $r = a_i$(i=1,2, $\cdots$,N-1) defines the boundary between the ith and $i+1$th regions.

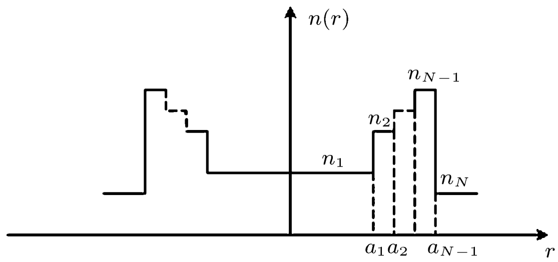

Fig.1. Schematic diagram of the refractive index profile of the LFM fibre.

The radial dependence of the fields is described in terms of the Bessel and the modified Bessel functions, it is essentially what is needed for the evaluation of transmission properties.[13−16] The scalar modal field of the fundamental mode is summarized as

$$\psi(r) = \begin{cases} A_1; 0 \le r \le a_1, \\ A_i J_0(x_i r) + \bar{A}_i Y_0(x_i r); a_{i-1} \le r \le a_i, i = 2, 3, \cdots, N-1, \\ \bar{A}_N K_0(x_N r); r > a_{N-1}, \end{cases} \tag{2}$$

where

$$x_i = \left(\left|k_0^2 n_i^2 - k_0^2 n_1^2\right|\right)^{1/2},$$

and J_0 and Y_0 are Bessel functions of the first and second kind respectively, I_0 and K_0 are modified Bessel functions of the first and second kind respectively. A_i and $\bar{A}_i$ are the constant amplitude coefficients.

Solving Eq.(2) in different regions and applying the continuity conditions, one obtains the following equation, which should be satisfied by the fibre parameters:

$$\begin{vmatrix} 1 & -J_0(x_2a_1) & -Y_0(x_2a_1) & 0 & 0 & 0 & \cdots & 0 \\ 0 & -J_0(x_2a_2) & -Y_0(x_2a_2) & J_0(x_3a_2) & Y_0(x_3a_2) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & K_0(x_N a_{N-1}) \\ 0 & -x_2J_0'(x_2a_1) & -x_2Y_0'(x_2a_1) & 0 & 0 & 0 & \cdots & 0 \\ 0 & -x_2J_0'(x_2a_2) & -x_2Y_0'(x_2a_2) & x_3J_0'(x_3a_2) & x_3Y_0'(x_3a_2) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & x_NK_0'(x_Na_{N-1}) \end{vmatrix} = 0.$$

The model can deal with multilayer LFM fibres, but the most simplest and typical is the three layer device. So we can get the corresponding transcendental equation:

$$\frac{x_3K_0'(x_3a_2)}{x_2K_0(x_3a_2)} = \frac{J_0'(x_2a_2)Y_0'(x_2a_1) - J_0'(x_2a_1)Y_0'(x_2a_2)}{J_0(x_2a_2)Y_0'(x_2a_1) - J_0'(x_2a_1)Y_0(x_2a_2)}, \tag{3}$$

where $x_2 = k_0(n_2^2 - n_1^2)^{1/2}$, $x_3 = k_0(n_1^2 - n_3^2)^{1/2}$. Given the values of n_1, n_2, n_3 and a_2, the optimum value of a_1 can be obtained.

Once the scalar field for the LP_{01} mode is calculated, the effective area A_{eff} is calculated from

$$A_{\mathrm{eff}} = 2\pi \left[\int_0^\infty \psi^2(r) r \mathrm{d}r \right]^2 \Big/ \int_0^\infty \psi^4(r) r \mathrm{d}r, \qquad (4)$$

where $\psi(r)$ is given by Eq.(2). The expression for effective area is based on the so-called Petermann definition.[17]

In calculating the bending loss, we used the method outlined in Ref.[18] (Chap. 23). The fibre core and inner claddings are substituted by an equivalent current radiating as an antenna in an infinite medium of index equal to n_N. To a first approximation and using the Maxwell's equation $\nabla \times \boldsymbol{H} = \boldsymbol{J} + \mathrm{j}w\varepsilon\boldsymbol{E}$, we get the current density of the equivalent radiating antenna

$$\boldsymbol{J} = -2\pi\mathrm{j}\sqrt{\varepsilon_0/\mu_0}\left[n_N^2 - n^2(r)\right]\boldsymbol{E}(r)/\lambda, \qquad (5)$$

where $\boldsymbol{E}(r)$ is the exact electric field of the fibre. As an approximation, it is sufficient to assume that this field is the same as the field of the straight fibre, provided that the bending radius is large enough compared with the fibre dimensions. The bending loss is essentially the power radiated from the current distribution in Eq.(5).

3. Results and discussions

The LFM fibres with different claddings can be designed according to the desired properties. In this article, we mainly discuss the simplest and most typical three-layer LFM fibre consisting of a central dip, core and outer cladding. The refractive index can be chosen by using different materials. In our calculations, $n_1 = 1.458$, $n_2 = 1.459$, $n_3 = 1.457$, where n_1, n_2, n_3 are the refractive indices of the central dip, the core and the outer cladding respectively.[3]

With the transcendental equation (3), the variation of the radius of the central dip a_1 versus that of the core a_2 at $\lambda = 1.06\mu$m is shown in Fig.2. The black squares are the computed values and the line is for fitting. With the increasing core size, the optimum value of the central dip increases approximately linearly. Fitted linearly, we can get the fitting relation $a_1 = -3.71853 + 1.05676a_2$. The inset of Fig.2 shows the dependence of the radius of the central dip on the wavelength for $a_2 = 15\mu$m. It can be seen that the optimum value of the central dip decreases approximately linearly with the increasing wavelength. We can also get the fitted linear relation $a_1 = 15.39389 - 3.02718\lambda$. If fitted by polynomial approximation, better fitting results can be achieved.

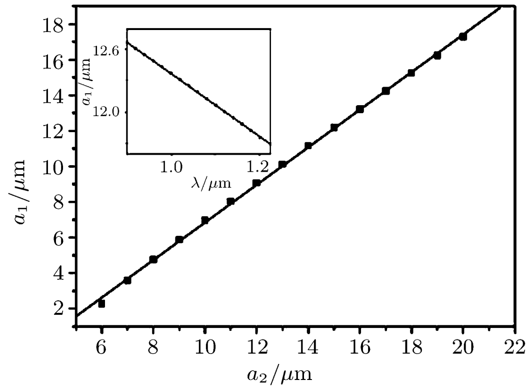

Fig.2. The radius of the central dip versus that of the core at $\lambda = 1.06\mu$m, the inset shows the variation of the radius of the central dip versus wavelength when $a_2 = 15\mu$m.

Figure 3 gives the normalized modal field $(\psi(r)/\psi(0))$ profiles of the fundamental mode calculated for LFM fibres with the core sizes 30μm, 40μm and 50μm at $\lambda = 1.06\mu$m respectively. The optimum central dip sizes are 24.3772μm, 34.5724μm and 44.6836μm. In the central dip, the modal fields are flat, while in the core and outer claddings the fields drop dramatically. It can be explained as follows. For the LFM fibre, light trace in the core is quite different from that in a standard step-index fibre.

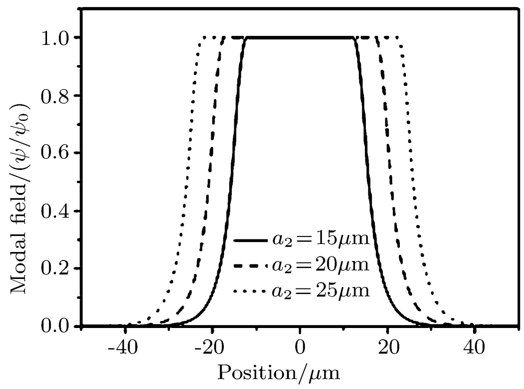

Fig.3. The normalized mode field $(\psi(r)/\psi(0))$ profiles of the fundamental mode calculated at $\lambda = 1.06\mu$m for LFM fibres with core sizes 30μm, 40μm and 50μm respectively.

At the interface of central dip and the core, reflection and refraction occur because the index of central dip is lower than that of the core. Part of the light energy leaks away from the central dip for the total internal reflection is not satisfied. Energy redistribution takes place as light propagates along the fibre.

Finally, a stable homogeneous intensity distribution of the fundamental mode is formed.

The variations of the effective area versus wavelength for LFM and standard step-index fibres with the same core sizes 30μm, 40μm and 50μm over the wavelength range of $\lambda = 0.96\mu$m to $\lambda = 1.12\mu$m are shown in Fig.4. The core and outer cladding refractive indices of the standard step-index fibre are $n^{\rm s}_{\rm core} = 1.458$ and $n^{\rm s}_{\rm clad} = 1.457$ respectively. The LFM refractive index profile differs from the standard step-index fibre profile by the inclusion of a ring raised by 0.001μm in refractive index above the inner core. It can be found that LFM fibre with core size 30μm has nearly the same effective area as the standard step-index fibre with core size 40μm. By comparison, the effective area of the LFM fibre is about twice as large as that of the standard one. It is obvious that manipulating the refractive index in this way is an efficient method to deal with the conflicts between the high power and onset of nonlinear effect.

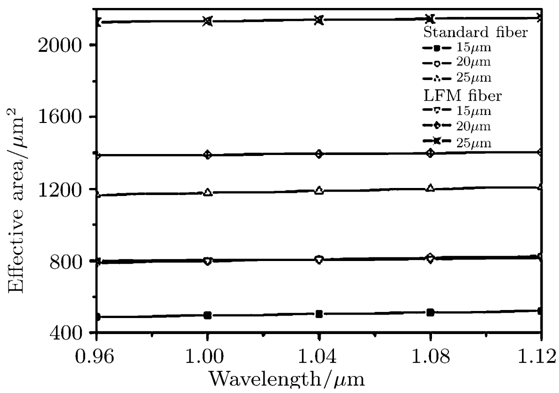

Fig.4. The effective areas versus wavelength for LFM and standard step-index fibres with the same core sizes 30μm, 40μm and 50μm respectively.

The bending losses are presented in Fig.5, which illustrates variations of bending loss versus bending radius for LFM and standard step-index fibres with the same core sizes 30μm, 40μm and 50μm at $\lambda = 1.06\mu$m.

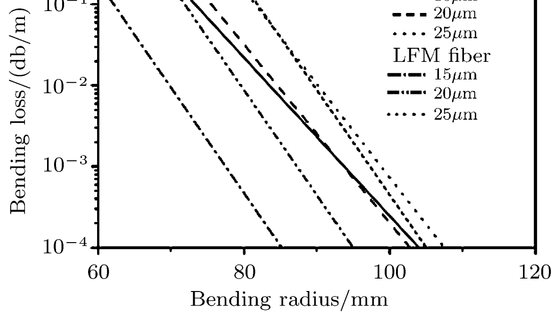

Fig.5. Bending loss characteristics calculated at $\lambda = 1.06\mu$m for LFM and standard step-index fibres with the same core sizes 30μm, 40μm and 50μm respectively

It can be found that the fibre with large core size usually suffers larger bending loss. Comparing the LFM fibre and the standard step-index fibre with the same core size, we know that the LFM fibre has smaller bending loss than the standard one and the bending loss difference between two kinds of fibre becomes smaller with increasing core size.

In order to clarify whether bending loss filtering for the LFM fibre is more efficient than the standard step-index fibre, we discuss the bending loss difference between $\rm LP_{11}$ mode and $\rm LP_{01}$ mode with different bending radius. Fig.6 shows the calculated differences for LFM and standard step-index fibres with the same core sizes at $\lambda = 1.06\mu$m. It can be seen that the standard step-index fibre has larger bending loss difference than the LFM fibre for a fixed bending radius. That is to say, with the same bending radius, bend-loss-induced filtering of the standard step-index fibre is more effective than that of the LFM one.

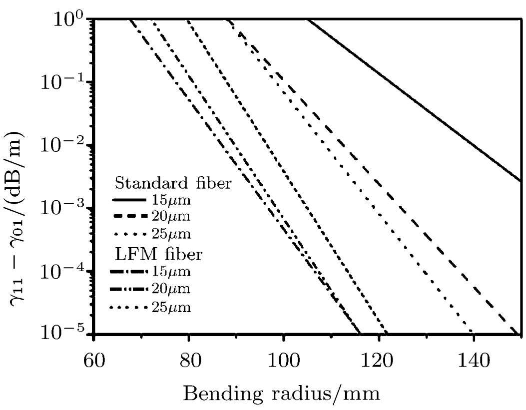

Fig.6. Bending loss differences between LP11 and LP01 modes versus bending radius calculated at $\lambda = 1.06\mu$m for LFM and standard step-index fibres with the same core sizes 30μm, 40μm and 50μm respectively

4. Conclusions

In this paper, we have given a new refractive index profile design which can help us to obtain flat modal field around the fibre centre. We mainly discuss the simplest and most typical three-layer LFM fibres. The optimum central dip size is analysed and the size behaves linear behaviours with the core size and wavelength approximately. The comparison between LFM fibre and standard step-index fibre testifies that the LFM fibre has larger effective area. Comparing the bending loss of the LFM fibre with the standard step-index one with the same bending radius, however, we find that bend-loss-induced filtering is more effective for the standard step-index fibre.

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