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Design and fabrication of triangular inner cladding double-clad ytterbium doped fibre for high power lasers*

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To improve the performance of double clad high power fibre lasers, inner cladding design plays a significant role. A triangular inner cladding and silica structure second cladding with large air holes to acquire high inner cladding numerical aperture are designed. Single mode and high power output of the fibre lasers need the double clad Yb doped fibre with large core. A fibre with annular refractive index distribution core and low numerical aperture to acquire a large mode area fibre core is designed and fabricated. Furthermore co-doping with aluminium (Al) has been used to improve the solubility of ytterbium (Yb) into silicate network, and the core absorption coefficients of two Yb doped fibres are compared with different Al concentration experimentally.

Keywords: ytterbium, triangular inner cladding, high power fibre laser
PACC: 7855, 4281, 4280S

1. Introduction

Rare earth doped glass and fibre amplifiers and lasers have made great strides in optical power amplification and laser fields.[1−3] Cladding-pumped fibre technology has revolutionized fibre lasers over the last decade, dramatically increasing the output power. Design of the double clad fibre is the key step, including design of the inner cladding shape with high numerical aperture (NA) and large mode area (LMA) fibre core with low NA. For a circular double clad fibre, most modes have almost zero intensity at the core. Only meridional rays can pass through the doped core and contribute to pump absorption, so the circular double clad fibre has low pump absorption efficiency. In order to increase the pump absorption, optimization of inner cladding is very important, which often destroys the circular symmetry. Traditionally the double clad fibre often has D-shaped[4] or rectangular inner cladding[5] to increase pump absorption. At the same time, the high inner cladding NA is required for improving the pump absorption. Photonic crystal fibre is undergoing rapid development,[6] and some rare earth doped photonic crystal fibres are demonstrated.[7,8] The inner cladding with small holes[9] can acquire LMA, but it cannot realize the real cladding pump. The design of triangular inner cladding surrounded with three large air holes as outer cladding is first reported. The triangular inner cladding has dramatically decreased the ratio of cladding to core areas while it destroys the circular shape. And large holes have increased the inner cladding NA the most. This is a real cladding pump design for high power lasers. Because of the higher power density involved and the risk of optical damage, a large core is needed for high power operation. Single mode operation of fibre laser requires that the core must have low NA and LMA. In this paper, we have demonstrated a method to realize such a low NA and LMA triangular inner cladding Yb doped fibre (YDF). According to this design, we have successfully fabricated such YDFs. In addition, we have explored the function of the codopant Al for improving the solubility of Yb to the silicate glass network.

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2. Design of the fibre core

Yb doped double clad fibre has an Yb doped core for guiding the signal, surrounded by a pure silica inner cladding. A single mode realization is much more challenging. A CW YDF laser usually has a damage threshold of $\sim 1\mathrm{W}/\mu\mathrm{m}^2$.[10] So LMA fibre is indispensable for high power fibre lasers, which can increase the output power and reduce the detrimental effects of various nonlinear interactions such as stimulated Raman and Brillouin scattering. According to the condition of single mode operation, it is necessary to decrease the core effective index for LMA. Scaling of the fibre mode field area (MFA) in single mode fibres is ultimately limited by the accuracy with which one can reliably control the index difference between the core and cladding and which defines the maximum core dimension that supports pure single mode guidance. Here we present a novel refractive index profile. This core refractive index distribution can effectively decrease the index difference and can dramatically increase the core diameter. The refractive index profile model of our fibre is shown in Fig.1. The finite element method (FEMLAB software) is used to calculate effective refractive index and mode distribution. And then the propagation constant β and the mode field diameter are evaluated.

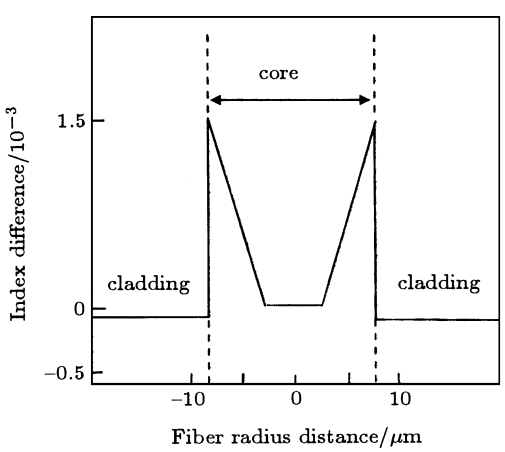


Fig.1. Theoretical model of the refractive index profile for LMA core.

The laser wavelength is set to 1.06μm. The material of the inner cladding is silicon dioxide, the refractive index of which is calculated as 1.449678 at laser wavelength through Sellmeier formula. The core can be divided into two parts: the inner circle of low refractive index and the outer ring with triangular refractive index profile. The refractive index of the inner ring is about 0.02% higher than that of the inner cladding. The index difference between the maximum index of the outer ring of the core and the index of the inner circle is only 0.15%. The maximum refractive index of the core is 1.451878. Guidance in the fibre is purely single mode for a core radius (the radius of the inner circle and the width of the outer ring) $< 7.4\mu$m. The fundamental mode relative optical intensity distribution is shown in Fig.2. Where $n_{\mathrm{eff_whev}}$=1.450012 is the effective index of fundamental mode, which is the only guidance mode. The right bar shows the relative intensity, where the maximum relative intensity is 1.977×10^{-11} at the centre of the core and the minimum relative intensity is 1.547×10^{-22} at clad.

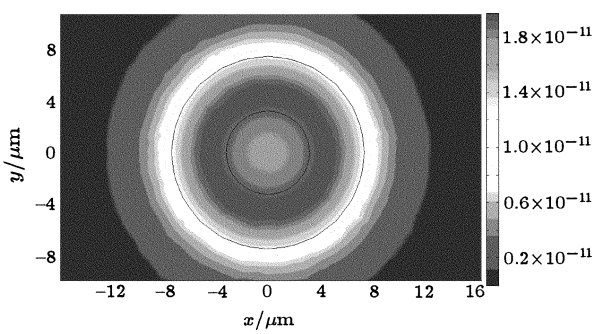


Fig.2. The calculated fundamental mode distribution of the fibre for LMA design.

The mode area is defined as:

$$A_{\mathrm{eff}} = \frac{\left(\int\int_{-\infty}^{\infty} |F(x,y)|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\int\int_{-\infty}^{\infty} |F(x,y)|^4 \mathrm{d}x\mathrm{d}y}, \qquad (1)$$

where $F(x,y)$ is mode distribution function of fundamental mode. Using sub-domain integration of $F(x,y)$ in FEMLAB software, we find that the mode area of the structure is $332.6\mu\mathrm{m}^2$ and the mode field diameter is 20.6μm at wavelength of 1.06μm.

As the design proposed, we have fabricated a low NA single mode fibre. Its refractive index profile is shown in Fig.3. The refractive index profile is quasi-triangular and the core diameter is slightly larger than that of the model in Fig.1. The mode field diameter (MFD) is measured by variable aperture method (PK2210 Spectrum Analyzer). The MFD of this fibre is 22.5μm at wavelength of 1550nm.

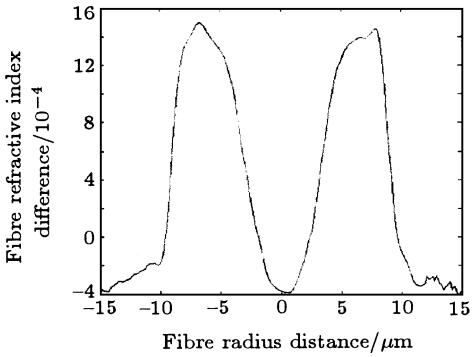


Fig.3. Measured refractive index profile of the LMA fibre.

3. Design and fabrication of the inner cladding

Inner cladding shape design is a key problem of the fabrication of double clad fibres. Any symmetry of the inner cladding favours periodic trajectories which can exhibit poor overlap with the doped core. If the circular symmetry is destroyed, the ideal pump absorption efficiency is determined by the ratio of inner cladding to the core.[11] The effective absorption rate $\alpha_{\text{eff}} = \alpha_{\text{core}} s/(s+S)$, where α_{core} is the absorption coefficient of the core, s and S are the core area and inner cladding area respectively. The triangular inner cladding can decrease the inner cladding area effectively. Here we first proposed a triangular structure inner cladding with large air holes as outer cladding. This triangular inner cladding design introduces better pump couple from the inner cladding to the doped core because this structure has strong asymmetric deformation which can effectively eliminate helical rays. High inner cladding NA maintains a tight pump confinement and makes the threshold relatively low. This allows efficient pumping with inexpensive and high power broad area pump source. With three large air holes around the triangular inner cladding, the NA of inner cladding approximates 1.

Using modified chemical vapour deposition (MCVD) combined with solution doping technique, we dope Yb into the core of the preform. By grinding process, the inner cladding of the fibre perform realizes triangular shape. The most difficult step in fabrication of the triangular inner cladding fibre is the drawing process. To keep the shape of triangular inner cladding and three large holes, we have designed rigid control system for our special fibre drawing tower. At last we have successfully fabricated the triangular inner cladding with three large holes. The photo of the cross section of triangular inner cladding YDF is shown in Fig.4. It can be clearly seen that the shape of air holes and the triangular shape are kept well.

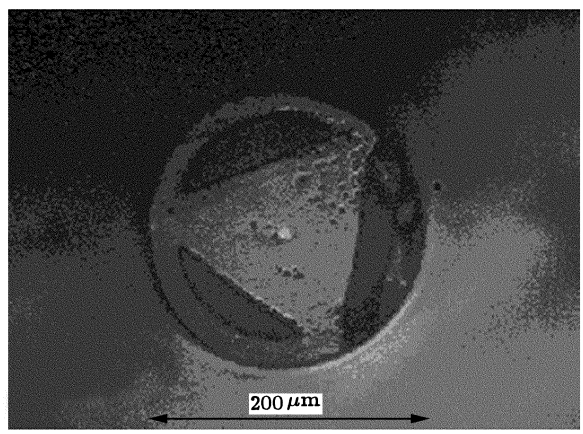


Fig.4. The photo of the cross section of triangular inner cladding YDF.

4. Experiment of heavily YDF

Double clad fibre often has high ratio of inner cladding to core area, so the absorption coefficient of the inner cladding is relatively low, which means that double clad high power fibre laser need long fibre. High power pump input and long length fibre will bring severe well-known fibre nonlinearities. To shorten the double clad fibre length of the cladding pump fibre laser, increasing the core absorption is necessary. We have explored the absorption coefficients of Yb doped silica host fibres with different codopant aluminium. We find that the aluminium concentration is a very important factor for ytterbium concentration in silica host fibre. Two YDFS using MCVD method combined with solution doping technique are fabricated. Before these two YDFs, we have found that it is hard for Yb ions to be incorporated into silicate network with no aluminium. The core of the YDF preform with high Yb concentration and with no aluminium is crystalline. After drawing, the light cannot propagate in this YDF. Based on this acknowledgement, the first YDF with aluminium is fabricated and called as YDF-1. The absorption coefficient of YDF-1 is shown in Fig.5.

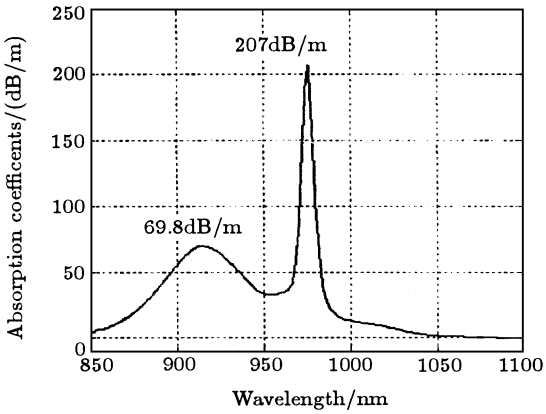


Fig.5. Absorption coefficient of YDF-1.

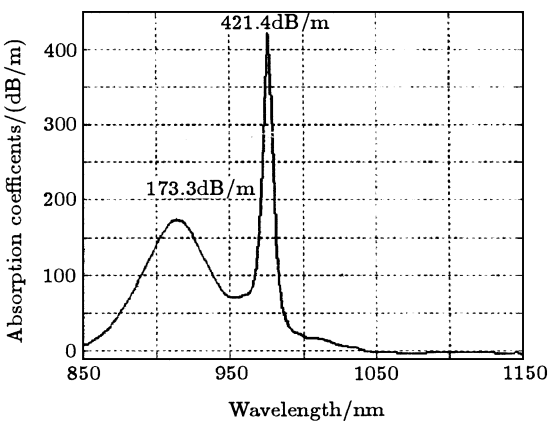


Fig.6. Absorption coefficient of YDF-2.

In solution, the aluminium concentration is 10 times of Yb concentration. The absorption coefficients are 69.8dB/m at 915nm and 207dB/m at 975nm respectively. According to the relationship between the absorption coefficients and the ions concentration, we can get the Yb^{3+} ions concentration

$$\alpha(\lambda) = \sigma_a(\lambda)\Gamma(\lambda)n_t, \qquad (2)$$

where $\alpha(\lambda)$ is the absorption coefficient, $\sigma_a(\lambda)$ is the absorption cross section of Yb at wavelength λ,[12] $\Gamma(\lambda)$ is the overlap integral factor between the dopant and optical mode, n_t is the Yb^{3+} ions concentration. The overlap integral factor calculated from the fibre data is 0.9. According to the formula (2), the Yb^{3+} ions concentration is $2.23\times10^{19}\mathrm{cm}^{-3}$.

But we hope that the YDF have higher absorption coefficient. So YDF-2 is fabricated by changing the aluminium and Yb concentration. The Yb concentration in solution for YDF-2 is 1.8 times that for YDF-1. And the aluminium in solution for YDF-2 is 1.6 times that for YDF-1. The absorption coefficient of YDF-2 is shown in Fig.6. The absorption coefficients are 173.3dB/m at 915nm and 421.4dB/m at 975nm respectively. According to formula (2), we get the Yb concentration of YDF-2 as $5.54\times10^{19}\mathrm{cm}^{-3}$. The Yb concentration in YDF-2 is about 2.5 times that of YDF-1, but the Yb concentration in solution for YDF-2 is 1.8 times of that for YDF-1. From our study, we find that Al can help increasing the Yb ions concentration, more Al can lead to higher Yb concentration, which is an important codopant for high concentration YDF.

5. Conclusion

A fibre with annular index profile low NA core has been fabricated, the mode area of which is over $300\mu\mathrm{m}^2$. To improve the pump efficiency, we have successfully fabricated a triangular inner cladding fibre surrounded by three large holes. To increase the core absorption coefficients, we have explored the YDF with different aluminium concentration. At last a YDF with high absorption coefficient is fabricated. The absorption coefficients of this YDF are 173.3dB/m at 915nm and 421.3dB/m at wavelength of 975nm. Combined these characteristics, we presented a triangular inner cladding double-clad YDF for high power laser.

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