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Design and fabrication of Panda-type erbium-doped polarization-maintaining fibres*

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To obtain the stable operation of erbium-doped fibre laser, the simple and ideal technology is adopted by use of the erbium doped polarization maintaining fibre (EDPMF). The design criteria of the Panda-type EDPMF are presented, which take into account the cutoff wavelength, mode field diameter, modal birefringence and background loss. Four groups of optimum structural parameter combinations are determined in terms of the design criteria. Two kinds of the Panda-type EDPMFs are selected to be fabricated. The fabrication process and the parameter control of the Panda-type EDPMFs are presented in detail. Their refractive index profiles, birefringence and absorption spectra are experimentally investigated. The absorption coefficient of the EDPMF, whose core is co-doped with Bi, Ga, Al and Ge, is about 57.9 dB/m at 1.53 μm. Co-doping Bi, Ga and Al can greatly increase the erbium concentration in the silica-based fibre. The high birefringence is obtained for the Panda-type EDPMF. The group birefringence of the EDPMF, whose outer cladding diameter is 125 μm, is about 4.8×10^{-4}.

Keywords: erbium-doped fibre, polarization-maintaining fibre, birefringence, absorption coefficient
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1. Introduction

Erbium-doped fibre lasers have attracted much attention in the optical fibre communication systems and sensing fields, due to their narrow linewidths and inherent compatibility with optical fibre systems. And operation under stable linear polarization has become a requirement for many practical fibre laser applications. However, stable operation of fibre lasers is quite difficult to realize because the competitions among longitudinal modes and among polarization modes easily occur.[1]

In the past, different approaches have been investigated to obtaining the polarization-maintaining operation without using the polarization-maintaining fibre.[1,2] But these methods have their limitations. If an erbium-doped polarization-maintaining fibre (EDPMF) is available, the polarization mode can easily be stabilized by the combination of an EDPMF and a polarizer. Edvold and Palsdottir [3] reported an EDPMF with an elliptical stress-inducing cladding and an elliptical core. But the elliptical-cladding-type preform has substantial limitations in terms of manufacturability and scalability. The technology used to make the Panda-type EDPMF offers many merits. It has the advantage of effectively decoupling the fabrication of the erbium-doped preform from the stress members.[4] Thus it can provide independent and highly effective control of the polarization properties and the absorption coefficient. So the Panda-type technology is suitable for fabricating the EDPMF.

In this paper, the structural parameters of the Panda-type EDPMFs are optimized in terms of the design criteria, which take into consideration EDPMFs' cutoff wavelengths, mode field diameters, background loss and modal birefringence. According to the results of optimization, two kinds of EDPMFs with different structural parameters have been selected to be fabricated. Their refractive index profiles, birefringence and absorption spectra are experimentally investigated.

2. Optimal design of structural parameters

The cross section of the Panda-type EDPMF is schematically shown in Fig.1. The erbium ions are

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confined in a central region and the core diameter is d. Two stress-applying parts (SAPs) in the cladding region are on the opposite sides of the core and their diameters are t. The nearest distance between the core centre and the SAP's circumference is $D_{\rm sc}$ and the dopant concentration of B_2O_3 in the SAPs is m. The outer diameter of the cladding is D. The refractive indices of the core, silica cladding and SAPs are $n_{\rm core}$, $n_{\rm clad}$ and $n_{\rm SAP}$, respectively. In the following discussion, the parameters q, b and Δ are defined as $q = 2D_{\rm sc}/d$, $b = 2t/D$ and $\Delta = n_{\rm core} - n_{\rm clad}$, respectively.

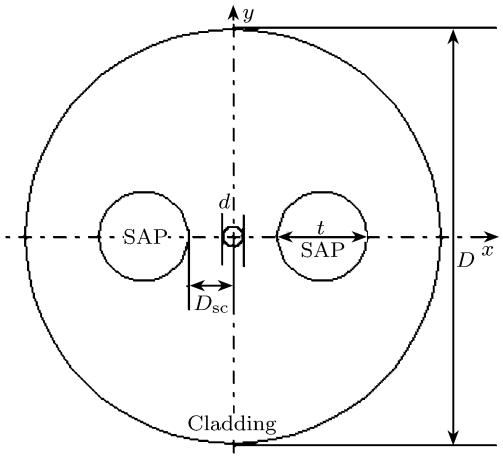


Fig.1. Schematic representation of the Panda-type EDPMF.

The structural parameters should be optimized according to the design considerations. The large-mode-area double-clad fibres are required if the pump sources are high-power multimode diode lasers. And a single clad fibre is satisfied when the power of the pump is less than 1 watt. Here, we only discuss the latter one and the design criteria are summarized as follows.

1) EDPMF is in the single-mode operation at the wavelengths of pump and signal. Thus the cutoff wavelength of the second-order mode is usually $0.92\,\mu$m $\pm$ $0.05\,\mu$m if the 980 nm pump is used. And the cutoff wavelength can be $1.40\,\mu$m $\pm$ $0.05\,\mu$m if the pump wavelength is about 1480 nm.

2) The mode field diameter at the operating wavelength should be controlled in a certain range. Generally, its value at the wavelength of $1.55\,\mu$m is $7\,\mu$m $\pm$ $1\,\mu$m .

3) As the B_2O_3 in the SAPs can induce large absorption in the infrared region, the SAPs are not very close to the core. Generally, the distance $D_{\rm sc}$ should be larger than the mode field diameter at the operating wavelength. Thus the B_2O_3 absorption loss can be decreased to less than 1 dB/km.[5]

4) EDPMF should have good polarization-maintaining characteristics. Modal birefringence should increase to more than 3×10^{-4}.

5) EDPMF should have a high erbium concentration to keep the necessary fibre length used for the lasers and short pulse amplification.[3]

As the SAPs are not very close to the core, the SAPs will make little impact on the cutoff wavelength of the second-order mode and the mode field diameter of the fundamental mode. Hence, an EDPMF can be considered as a two-layer step-index fibre when calculating its cutoff wavelength and mode field diameter. Thus the cutoff wavelength $\lambda_{\rm c}$ can be numerically calculated by using the formula

$$\lambda_{\rm c} = \frac{\pi d\sqrt{(n_{\rm clad} + \Delta)^2 - n_{\rm clad}^2}}{2.4048}. \qquad (1)$$

And the second moment of the normalized longitudinal power flow intensity can be adopted as the definition of mode field diameter. Thus the mode field diameter ω can be given by

$$\omega = 2\sqrt{2}\left(\frac{\iint_\infty P_z(x^2+y^2)\mathrm{d}x\mathrm{d}y}{\iint_\infty P_z \mathrm{d}x\mathrm{d}y}\right)^{1/2}, \qquad (2)$$

where P_z is the longitudinal power flow intensity, $P_z = \frac{1}{2}\mathrm{Re}(\boldsymbol{E} \times \boldsymbol{H}^*)_z$. And the electric and magnetic field intensities $\boldsymbol{E}$ and $\boldsymbol{H}$ can be obtained by using the finite element method. We calculate the cutoff wavelengths of the EDPMFs with the different parameter combinations of d and Δ. And the contour maps of cutoff wavelengths in the Δ–d plane are plotted by the dash lines in Fig.2. Their mode–field diameters at the wavelength of $1.55\,\mu$m are also numerically calculated by using the formula (2), and their contour lines are depicted by the solid lines in Fig.2. It can be seen that the mode field diameters range from 6 to $8\,\mu$m while the core diameters vary from 2.8 to $3.8\,\mu$m, when fixing the cutoff wavelength at $0.92\,\mu$m. And the values of the mode field diameters remain in the same range from 6 to $8\,\mu$m when the core diameters vary from 5.0 to $6.7\,\mu$m, while the cutoff wavelengths increase to $1.40\,\mu$m.

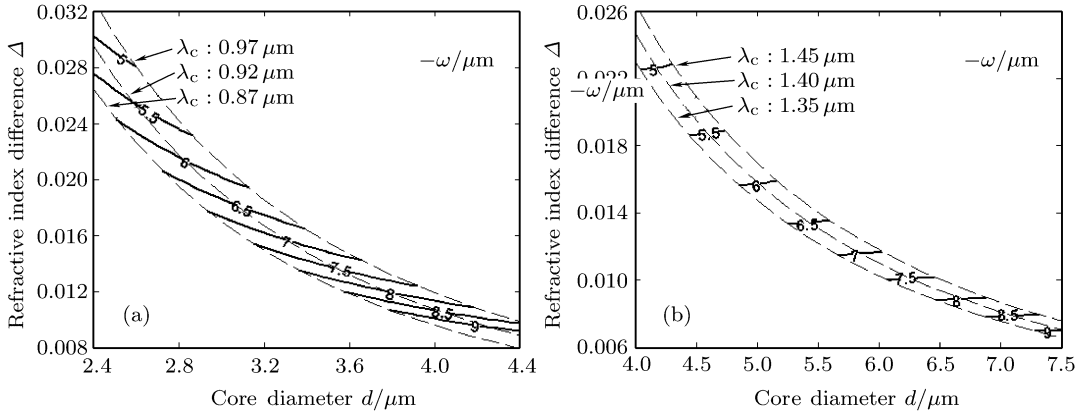


Fig.2. Contour lines of cutoff wavelengths and mode field diameters in the $\Delta - d$ plane

It is clear that the mode field diameters at 1.55 μm are about 2 times as large as the core diameters with the cutoff wavelength setting to be 0.92 μm. And the mode field diameters are about 1.2 times the size of the core diameters if the cutoff wavelengths are 1.40 μm. According to the third item of the design criteria, the structural parameter q should be not less than 4 if $\lambda_c \simeq 0.92\,\mu$m, and q should be more than 2.4 if $\lambda_c \simeq 1.40\,\mu$m.

The optimal values of the parameters d, Δ and q are approximately determined by the first three items of the criteria. As the parameters m and b have a great influence on the modal birefringence, they can be determined by the fourth item of the criteria.

As the thermal expansion coefficient of the SAPs is higher than that of the cladding, it induces the difference in stress between the x- and y-directions during drawing process. And the stress difference can induce modal birefringence by the photo-elastic effect. The thermal expansion coefficient of the SAPs can be estimated by the formula[6]

$$\alpha_{\rm SAP} = (1-m)\alpha_{\rm SiO_2} + m\alpha_{\rm B_2O_3}, \tag{3}$$

where $\alpha_{\rm SiO_2}$ and $\alpha_{\rm B_2O_3}$ are the thermal expansion coefficients of silica and B_2O_3, respectively. The thermal expansion coefficient is in direct proportion to the value of m. By increasing $\alpha_{\rm SAP}$, the modal birefringence increases. But it is quite difficult to fabricate the boron-doped preform with a high dopant concentration. The good-quality boron-doped preforms with about 18 mol% of B_2O_3 have been fabricated. Hence the thermal expansion coefficient of the SAPs is about $2.24 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$ as $\alpha_{\rm SiO_2} = 5.4 \times 10^{-7}\,^\circ\mathrm{C}^{-1}$ and $\alpha_{\rm B_2O_3} = 1.0 \times 10^{-5}\,^\circ\mathrm{C}^{-1}$.

As the dimension of the z-direction is very large in comparison with those of the x- and y-directions, the stress problem in the fibre can be considered to be a plane strain problem. The stress components can be numerically calculated by the finite element method.[3,6] The parameters used in the following simulations are Young's modulus $E = 7.8 \times 10^{10}\,\mathrm{N/m^2}$, Poisson's ratio $v = 0.186$, thermal expansion coefficients $\alpha_{\rm core} = 1 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$ $\alpha_{\rm SAP} = 2.24 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$ $\alpha_{\rm clad} = 5.4 \times 10^{-7}\,^\circ\mathrm{C}^{-1}$ and the difference between the softening temperature and room temperature $\Delta T = 1300\,^\circ$C. According to the photo-elastic theory, the relation between the principle index and the principle stress can be expressed as[6,7]

$$\begin{aligned} N_x &= N_0 + c_1\sigma_x + c_2(\sigma_y + \sigma_z), \\ N_y &= N_0 + c_1\sigma_y + c_2(\sigma_x + \sigma_z), \end{aligned} \tag{4}$$

where σ_x, σ_y and σ_z are the stress components along the x-, y- and z- directions; N_x and N_y are the principle index; c_1 and c_2 are stress-photoelastic coefficients. As the modal birefringence of the Panda-type EDPMF is mainly the stress-induced one, the birefringence B can be approximately expressed as[7]

$$B \simeq C(\sigma_x(0,0) - o_y(0,0)). \tag{5}$$

Here, C is the relative stress-photoelastic coefficient and $C = c_1 - c_2 = 3.43 \times 10^{-12}\,\mathrm{m^2/N}$; $\sigma_x(0,0)$ and $\sigma_y(0,0)$ are the values of the stress components σ_x and σ_y at the centre of the fibre, respectively, which can be calculated by the finite element method software.

It is well known that the modal birefringence increases when the structural parameter q decreases.[5] So the values of q can be as small as possible on condition that the third item of the criteria is satisfied. Hence the parameter q can be chosen as 4 if $\lambda_c \simeq 0.92\,\mu$m, and the value of q can be 3 if $\lambda_c \simeq 1.40\,\mu$m. The outer diameters of fibre cladding

are usually 125 μm and 80 μm for the telecommunication and gyroscope applications, respectively.

First, we discuss the optimal values of b when $D = 125\,\mu$m. We numerically calculate the modal birefringence as a function of the relative size of the SAPs when $q = 4$ and $D = 125\,\mu$m, and the results are shown in Fig.3(a). It is clear that the values of corresponding structural parameter b should be more than 0.20, 0.23 and 0.27 if the core diameters are given 2.8, 3.3 and 3.8 μm, respectively. Thus the modal birefringence can be more than 4×10^{-4}. Figure 3(b) shows the modal birefringence versus the relative size of the SAPs when $q = 3$ and $D = 125\,\mu$m. It can be seen that the values of parameter b should be more than 0.27, 0.32 and 0.37 if the core diameters are given 5.0, 5.9 and 6.7 μm, respectively. Then B is increased to more than 4×10^{-4}.

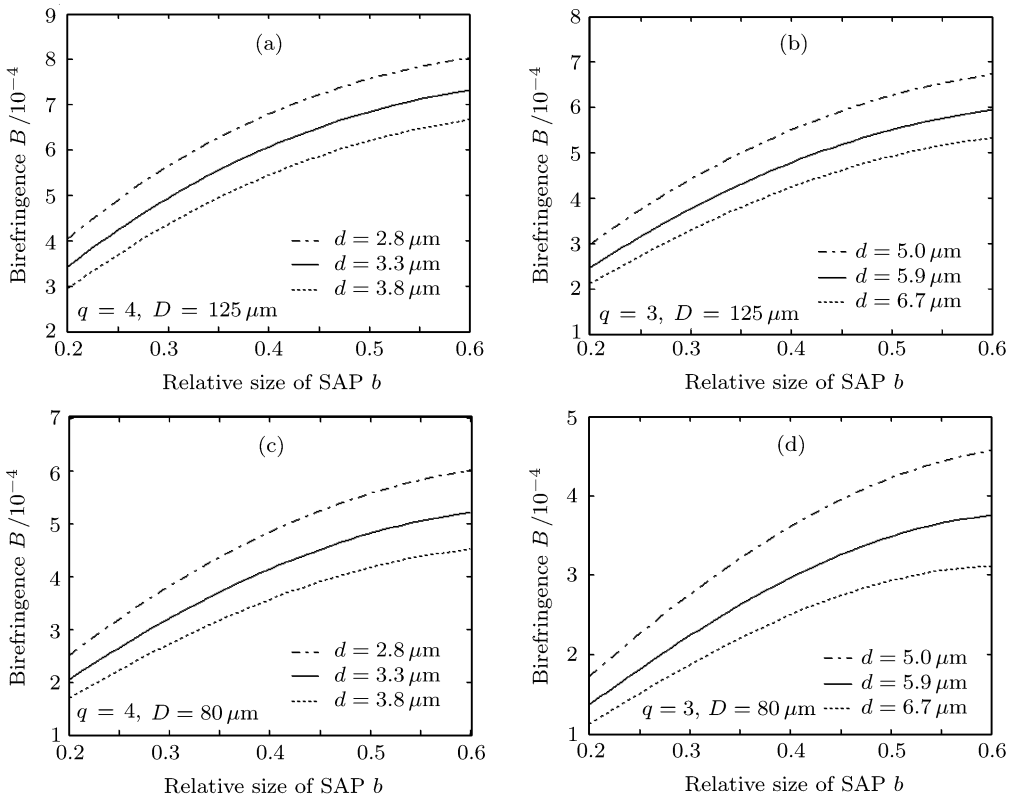


Fig.3. Modal birefringence versus the relative size of SAPs.

Next, the optimal values of b are investigated when $D = 80\,\mu$m. The modal birefringence of the EDPMFs with $D = 80\,\mu$m and $q = 4$ is shown in Fig.3(c). It is clear that the values of parameter b should be more than 0.24, 0.28 and 0.33 if the core diameters are given 2.8, 3.3 and 3.8 μm, respectively. Then B is more than 3×10^{-4}. From Fig.3(d) in which the parameters are $q = 3$ and $D = 80\,\mu$m, it can be seen that the values of parameter b should be more than 0.33, 0.40 and 0.53 if the core diameters are given 5.0, 5.9 and 6.7 μm, respectively. Then B is more than 3×10^{-4}.

Thus four groups of optimal parameter combinations are obtained. The cutoff wavelength should be about 0.92 μm if the 980 nm pump is used. Thus $d \simeq 3.3\,\mu$m and $\Delta \simeq 1.6 \times 10^{-2}$. And q can be chosen as about 4. If $D = 125\,\mu$m, b should be more than 0.23, then $B > 4 \times 10^{-4}$; If $D = 80\,\mu$m, $b > 0.28$, then $B > 3 \times 10^{-4}$.

The cutoff wavelength can be about 1.40 μm if the pump wavelength is about 1480 nm. Thus $d \simeq 5.9\,\mu$m and $\Delta \simeq 1.1 \times 10^{-2}$. And q can be 3. If $D = 125\,\mu$m, $b > 0.32$, then $B > 4 \times 10^{-4}$; If $D = 80\,\mu$m, $b > 0.40$, then $B > 3 \times 10^{-4}$.

3. Fabrication and characteristics

According to the results of optimization, we selected two kinds of EDPMFs to be fabricated and they are referred to as E#1 and E#2. The design targets of E#1 are that $D = 125\,\mu$m and $\lambda_c = 1.40\,\mu$m. And the requirements of E#2 are that $D = 80\,\mu$m and

$\lambda_c = 0.92\,\mu$m.

Fabrication process of the Panda-type EDPMF is as follows. First, the erbium-doped preform is fabricated by the combination of the MCVD process and the solution doping technique. Here, the core layer containing SiO_2 and GeO_2 should remain porous to allow for solution doping. The soot is immersed for about one hour in the solution in which high-purity erbium chloride and other chlorides have been dissolved. It is pointed that the solution of E#1 contains $ErCl_3$ and $AlCl_3$, and the solution of E#2 contains $ErCl_3$, $BiCl_3$, $GaCl_3$ and $AlCl_3$. And the erbium ion concentrations in the solutions of E#1 and E#2 are the same. Further process includes dehydration, sintering and collapsing.

Next, the erbium-doped preform is ground on both sides and two symmetrical grooves are formed. Then two boron-doped preforms are inserted into the grooves. Last, the silica tubes are collapsed over the composite unit. Thus a Panda-type EDPM preform is completed. EDPMF is drawn from the preform by using the conventional fibre drawing technique.

The difference in refractive index between the core and cladding can be adjusted and increased to the design target by controlling the ratio of silicon tetrachloride flow to germanium tetrachloride flow in the deposition process. We use a Photon Kinetics P104 Preform Analyser to study the refractive index profiles and the core dimension of the erbium-doped preforms. And the refractive index differences of E#1 and E#2 are increased to about 1.1×10^{-2} and 1.5×10^{-2}, respectively, through making trial of fabrication several times.

The core diameter of the fibre can reach the design target through the process of overcladding. Finally, the ratios of the core and cladding diameter in the preforms E#1 and E#2 are about 1:21.6 and 1:23.3, respectively. And the ratios of the core diameter to the SAP diameter in E#1 and E#2 are both 1:4. The parameters q of E#1 and E#2 are approximately 3 and 4, respectively.

The refractive index profiles (RIPs) of EDPMF E#1 and E#2 are measured by using the refracted near-field technique of EXFO NR-9200 Optical fibre analyser. Figure 4 shows the RIP of E#1. And the 3D RIP view of E#2 is shown in Fig.5. The cutoff wavelengths are measured by using the Photon Kinetics 2210 Optical fibre analysis system. The cutoff wavelengths of E#1 and E#2 are $1.392\,\mu$m and $0.938\,\mu$m, respectively.

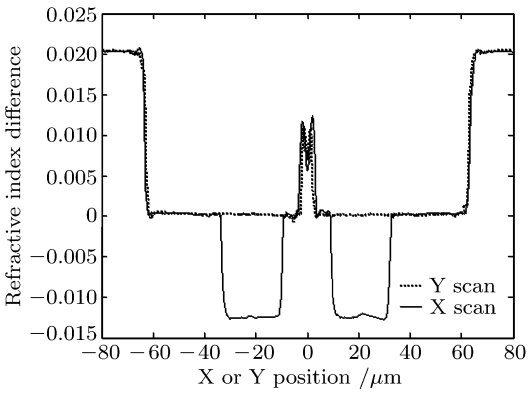


Fig.4. Refractive index profile of E#1.

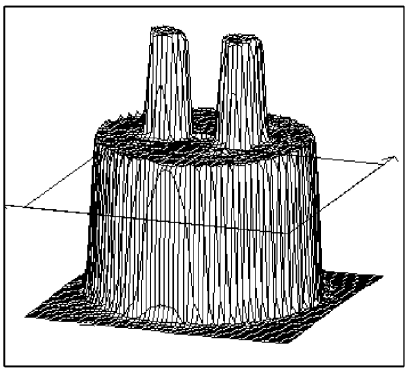


Fig.5. 3D RIP view of E#2.

The absorption spectra are investigated by the cut-back method (PK 2210 Optical fibre analysis system). Figure 6 shows the absorption coefficient of E#1 and it can be seen that the absorption coefficient of E#1 is 12.5 dB/m at $1.53\,\mu$m and 4.7 dB/m at $1.48\,\mu$m. The erbium concentration can be estimated from the peak absorption coefficient at $1.53\,\mu$m. The relation between the absorption coefficient $\alpha_a(\lambda)$ and erbium concentration n_t satisfies the formula[8]

$$\alpha_a(\lambda) = \sigma_a(\lambda)\Gamma(\lambda)n_t. \tag{6}$$

Here, Γ and σ_a are the overlap factor and absorption cross section, respectively. The absorption cross section of erbium in the GeO_2–SiO_2–Al_2O_3 at $1.53\,\mu$m is about $4.9 \times 10^{-25}\,m^2$.[9] The overlap factor can be numerically calculated by

$$\Gamma = \frac{\iint_{core} P_z \mathrm{d}x\mathrm{d}y}{\iint_{\infty} P_z \mathrm{d}x\mathrm{d}y}. \tag{7}$$

Here, P_z is the longitudinal power flow intensity. The overlap factor of E#1 is calculated according to the structural parameters of E#1 and its value at $1.53\,\mu$m is about 0.783. Thus, the erbium concentration of E#1 is estimated to be about $7.5 \times 10^{24}\,\mathrm{ion/m^3}$.

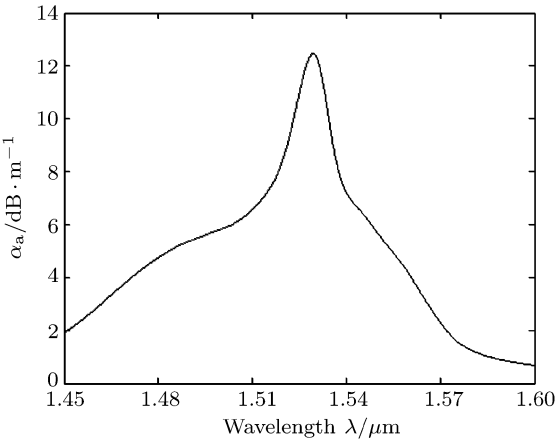


Fig.6. Absorption coefficient of E#1.

The absorption spectrum of E#2 is shown in Fig.7. It is clear that the absorption coefficient of E#2 is 57.9 dB/m at 1.53 μm and 29.1 dB/m at 0.98 μm. The absorption coefficient of E#2 is much higher than that of E#1. The overlap factor of E#2 at 1.53 is calculated to be about 0.525 by using the formula (7). In addition, co-doping elements in the silica-based fibre have little effect on the absorption cross section of erbium at 1.53 μm.[9] Thus the erbium concentration of E#2 is estimated to be 5.2×10^{25} ion/m^3. It can be deduced that co-doping Bi, Ga and Al can greatly increase the erbium concentration in the silica based fibre.

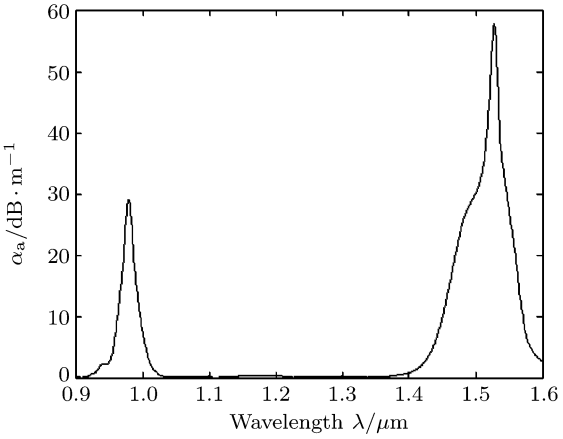


Fig.7. Absorption coefficient of E#2.

The birefringence of EDPMF is studied by using the HP 8509B Polarization Analyser. The differential group delay (DGD) of the fibre E#1 with the length of 1.1m is measured and the result is depicted in Fig.8. The relation between the differential group delay $\Delta\tau$ and the walk-off parameter Δn_g satisfies the formula[10]

$$\Delta n_g = \frac{c\Delta\tau}{L}, \tag{8}$$

where c is the velocity of light in vacuum and L is the fibre length. The walk-off parameter is defined as the difference in group refractive index between the x-polarization mode and y-polarization mode.[11] From Fig.8, it can be seen that the mean value of DGD is about 1.77 ps. Thus the walk-off parameter of E#1 is estimated to be about 4.8×10^{-4}. The walk-off parameter is also called the group birefringence, and the relation between the modal birefringence and the walk-off parameter satisfies the expression[10]

$$\Delta n_g = B - \lambda \frac{\mathrm{d}B}{\mathrm{d}\lambda}. \tag{9}$$

As the birefringence of the Panda-type EDPMF is the stress-induced one, the difference between B and Δn_g is very little. So the modal birefringence of the fibre E#1 is about 4.8×10^{-4}.

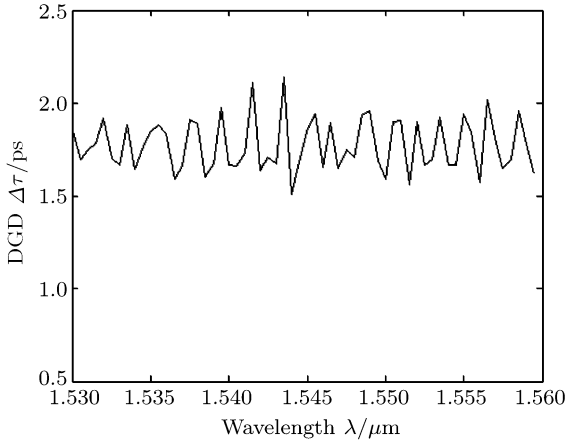


Fig.8. DGD of E#1 with $L = 1.1$ m.

In addition, the DGD of the fibre E#2 with the length of 1.0 m is measured and the result is shown in Fig.9. The mean DGD of E#2 with $L = 1$ m is about 1.23 ps. Thus the group birefringence of E#2 is about 3.7×10^{-4}. Their birefringence achieves the design target.

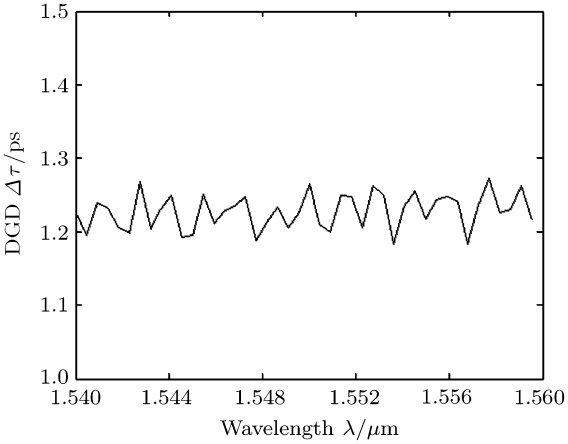


Fig.9. DGD of E#2 with $L = 1.0$ m.

4. Conclusion

The Panda-type technology is suitable for fabricating the EDPMF as it has the advantage of effectively decoupling the fabrication of the erbium-doped preform from the stress members. The design criteria of the Panda-type EDPMF are presented, which take into account the cutoff wavelengths, mode field diameters, background loss and modal birefringence. Four groups of optimum structural parameter combinations are determined in terms of the design criteria. These structural parameters include core diameter, the refractive index difference between the core and cladding, the relative distance between the core and the SAPs, the relative size of the SAPs and the cladding diameter. Two kinds of EDPMFs with different structural parameters have been selected to be fabricated. The fabrication process and the parameter control of EDPMF are given in detail. Their refractive index profiles, absorption spectra and birefringence are experimentally investigated. The absorption coefficient of the EDPMF, whose core is co-doped with Bi, Ga, Al and Ge, is about 57.9 dB/m at 1.53 μm. Its erbium concentration is estimated to be about 5.2×10^{25} ion/m^3. Co-doping Bi, Ga and Al can greatly increase the erbium concentration in the silica based fibre. The high birefringence is obtained for the Panda-type EDPMF. The group birefringence of the EDPMF, whose outer cladding diameter is 125 μm, is about 4.8×10^{-4}.

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