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Research on mode division multiplexer with graded-index distribution, low loss and low crosstalk[*]

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A graded-index mode division multiplexer with low loss and low crosstalk is proposed. The transmission channel adopts a pure silica core with large effective area to achieve low attenuation, which effectively reduces the splicing loss with pure silica core few-mode transmission fiber. Low differential mode group delay is realized by using graded-index distribution. Also the effective index difference of the modes is greater than 0.5×10^{-3} to ensure low crosstalk between modes. The performance of the mode division multiplexer is investigated using the beam propagation method and full-vector finite element method. The result shows that the coupling efficiency of multiplexer is better than −0.479 dB, and the extinction ratio is higher than 31.2 dB in the wavelength of 1 400—1 700 nm. In C band, the average coupling efficiency of all mode channels of multiplexer is better than that of −0.140 dB, which shows flatness. The proposed scheme is an effective way to implement a multiplexer with low crosstalk, low loss, low fusion loss, high coupling efficiency, high extinction ratio and wide operating band.

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With the increasing demand for various communications services, the single-mode fiber transmission system tolerance is challenged. Mode division multiplexing has become the frontier of optical communications, which can make the capacity of the transmission system rapidly increase according to the number of modes and break through the bottleneck of the traditional single-mode optical communication system[1,2]. Realizing high performance of multiplexer is greatly important because it is the core device of mode division multiplexing optical transmission.

At present, there are different kinds of multiplexers. A mode division multiplexer based on a phase plate was proposed[3] to realize the conversion and multiplexing of three spatial modes. A mode multiplexer based on silica liquid crystal spatial light modulator was designed[4] to realize mode multiplexing by matching the single-mode beam to high order mode of few-mode fiber. However, they both require highly accurate spatial coupling calibration, which are difficult to integrate. Furthermore, free space coupling has the disadvantages of large insertion loss and high cost. In 2015, the European Conference on optical communications reported a selective photonic lantern multiplexer that implemented 10 and 15 spatial mode multiplexing[5] and reduced the multiplexing loss and mode dependent loss. However, both taper technology of such a multiplexer and precise control of the coupling region distribution of refractive index are difficult to complete. Also the multiplexer is sensitive to wavelength. Using multiplexer based on laser inscribing of 3D waveguide photon lantern can realize precise control of coupling region distribution of refractive index with high repeatability and stability, while the change scope of refractive index is limited and increasing the mode number of multiplexer remains to be explored[6]. The multiplexer/demultiplexer based on asymmetric planar waveguide realizes the mode multiplexing/demultiplexing and mode conversion[7], but a narrow band and splicing difficulty to fiber exist in such multiplexers. In Ref.[8], a multiplexer was proposed for direct coupling of modes. Manufacturing process of the multiplexer is simple, it can directly fuse with fiber, but the nonlinear and attenuation of the transmission channel in multiplexer is larger, the design did not consider the large differential mode group delay (DMGD) of step-index fiber, which increases the signal recovery difficulty in system.

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The large effective area and pure silica core channel with low attenuation and low nonlinearity[9] can improve the signal-to-noise ratio of the system and achieve large capacity and long distance transmission.

Pure silica fibers with large effective area proposed in Ref.[10] have loss of 0.149 dB at 1 550 nm. The large effective area pure silica fiber channel proposed in Ref.[9] makes low attenuation of 0.146 0 dB at 1 560 nm and the low attenuation of 0.146 7 dB at 1 550 nm, which reduces the splice loss to 0.014 dB. The large effective area pure silica fiber channel proposed in Ref.[11] not only reduces the attenuation caused by Rayleigh scattering to 0.17 dB, but also achieves a splice loss as low as 0.011 dB with a lower splice loss of 0.013 dB across the 1 400—1 700 nm band, effectively reducing the high fusion loss caused by many nodes in trans-oceanic transmission. Large effective area of pure silica fiber not only reduces the attenuation and the fusion loss, but also can effectively reduce the effect to Raman amplification caused by attenuation of Rayleigh scattering in long-distance transmission.

A graded-index multiplexer with low loss and low crosstalk is proposed in this paper. Transmission channel of our proposed multiplexer uses pure silica core with graded-index distribution and large effective area to achieve low attenuation, low DMGD and low nonlinear coefficient, which can effectively reduce the splice loss to few-mode fiber with pure silica core. The effective refractive index difference is greater than 0.5×10^{-3} to ensure low crosstalk between modes. The performance of the mode division multiplexer is investigated using the beam propagation method and full-vector finite element method.

The multiplexer is directly composed of three transmission channels. The performance of the multiplexer can be affected by the characteristics of the transmission channel, channel spacing and channel length. To ensure high performance of the multiplexer, reasonable channel parameters, different channel spacing and different channel lengths must be studied.

In order to reduce signal attenuation and improve stability in transmission channel[9], pure silica core is adopted as the transmission channel, and the refractive index of cladding is reduced by fluorine doping. Therefore, the refractive index of channel core is 1.444 024. The receiver needs to better recover the original signal after long-distance transmission of signal in MIMO system, requiring the transmission channel to have low DMGD. We implement low DMGD using few-mode core with graded-index in this paper. The design of the transmission channel with three spatial modes (LP_{01}, LP_{11} and LP_{11b}) also requires the determination of the cladding refractive index and the core radius.

The normalized frequency is given by

$$V = 2\pi a/\lambda \sqrt{n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2}\ , \tag{1}$$

where n_{co} and n_{cl} are the refractive indices of the channel core and the cladding, respectively, a is the core radius, and λ is the wavelength. The normalized propagation constant is defined as

$$B = (n_{\mathrm{eff,lm}}^2 - n_{\mathrm{cl}}^2)/(n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2)\ , \tag{2}$$

where $n_{\mathrm{eff,lm}}$ refers to the effective refractive index of the mode LP_{lm}. The normalized frequency relation between graded-index fiber and step-index fiber is

$$\overline{V} = V(1+\frac{2}{g})^{1/2}\ , \tag{3}$$

where $\overline{V}$ is the normalized frequency of graded-index fiber, V is the normalized frequency of step-index fiber, and g=2 is exponent number. The refractive index difference between channel core and cladding, the difference between the mode effective refractive index and cladding refractive index as a function of channel radius can be studied by Eqs.(1)—(3) and the relation between normalized propagation constant and normalized frequency of the graded-index fiber[12].

Fig.1(a) and (b) show the refractive index difference between the channel core and cladding and the difference between mode effective refractive index and cladding refractive index varying with the channel core radius at wavelength of 1 550 nm, respectively. The lines in Fig.1 (a) and (b) do not distinguish degeneration modes of LP_{11} because effective refractive indices of degeneration modes of LP_{11} are consistent. However, when two channels are in mode coupling, different phase of degeneration modes leads to different coupling characteristics. Therefore, degeneration modes are discussed separately when the mode is coupled in the next section. It is obtained from Fig.1(a) that the refractive index difference between the channel core and the cladding decreases with the increase of the channel radius. For a given radius, the larger the normalized frequency of step-index fiber V, the greater of refractive index difference between core and cladding, which corresponding to larger propagation constant with better stability of modes. As can be seen from Fig.1(b), the differences between effective refractive index of mode LP_{01} and LP_{11} and cladding refractive index decrease with the increase of channel radius. The result in Ref.[12] shows that the normalized frequency should be V=5.7 if the transmission channel with graded-index is to achieve two mode transmission. The effective refractive index difference in different modes of the transmission channel is greater than 0.5×10^{-3} to avoid mode coupling. Therefore, the channel core radius should be less than 23 μm, and the refractive index difference between channel core and cladding should be greater than 0.001 3, as shown in Fig.1. It is also considered that large core radius can lead to large effective area and low nonlinearity. In order to realize low crosstalk and low nonlinearity, we propose that the channel core radius is 20 μm, the refractive index difference between channel core and cladding is 0.001 5 (obtained by software simulation). And then the effective index difference of the modes is greater than 0.5×10^{-3}. The expression of refractive index of the graded-index fiber is

$$n(r)=\begin{cases} n_1[1-2\Delta(r/a)^2]^{1/2} & (r\le a) \\ n_0 & (r>a) \end{cases}, \tag{4}$$

where n_0=1.442 524, n_1=1.444 024, a=20 μm, $\Delta=(n_1^2-n_0^2)/2n_1^2\approx(n_1-n_0)/n_1$, and r indicates the length of any point to the fiber core center. The refractive index distribution diagram is shown in Fig.2.

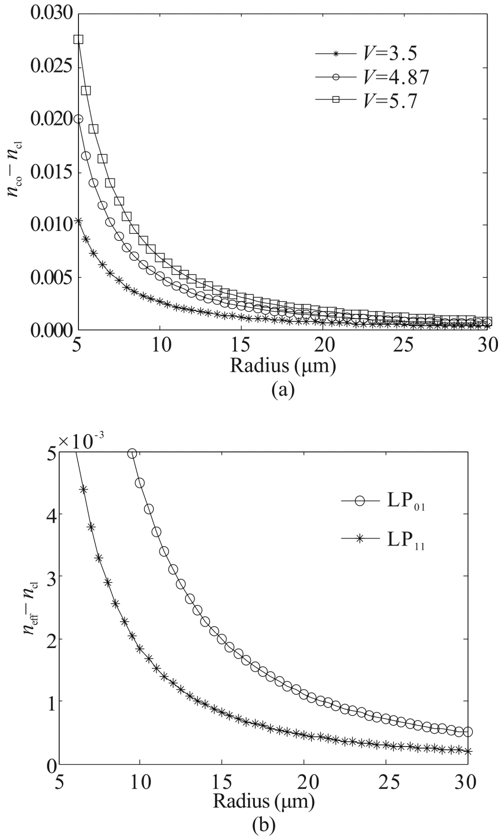


Fig.1 Variation of (a) refractive index difference between channel core and cladding and (b) difference between mode effective refractive index and cladding refractive index with channel core radius

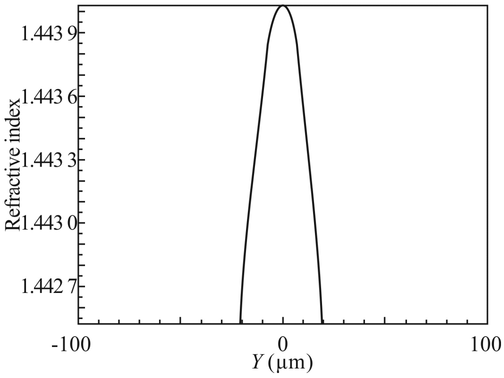
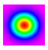


Fig.2 Fiber refractive index distribution diagram at *X*=0

The refractive index distribution and the corresponding mode field distribution of the modes in transmission channel are shown in Tab.1.

Tab.1 Refractive index distribution and mode field distribution of transmission mode

Mode name	LP_{01}	LP_{11a}	LP_{11b}
Mode effective refractive index	1.443 463	1.442 911	1.442 911
Mode field distribution			

Mode coupling occurs in two identical transmission channels in the designed optical fiber. Fig.3 shows the power propagation monitoring of the three spatial modes in two transmission channels at 1 550 nm for transmission channel spacings of (a,c,e) 2 μm and (b,d,f) 6 μm, where the dotted line in Fig.3 denotes the power crosstalk of other modes to the coupling mode. It can be seen from Fig.3 that the propagation periods of different modes are different because the propagation coefficients of three modes consisting of different eigenmodes are different. Transmission channel spacing becomes larger, coupling length of three mode channels becomes larger while the difficulty of channel manufacturing is greatly reduced. The maximum coupling power values of three spatial modes channel are high. The crosstalk of other modes to the mode of being coupled is almost zero, indicating that the crosstalk between different modes is negligible. Fig.3 fully proves that channel coupling length is an extremely important factor in the design of multiplexer.

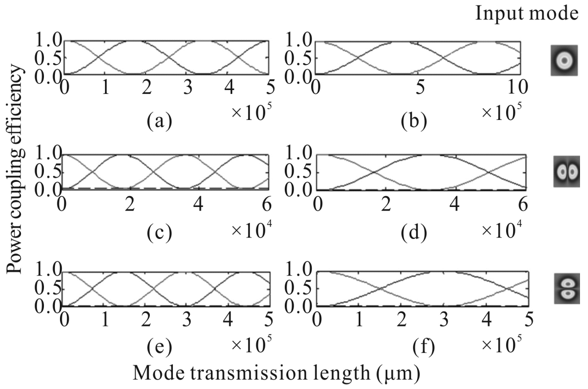


Fig.3 Three spatial modes monitored with the channel spacing of (a,c,e) 2 μm and (b,d,e) 6 μm at 1 550 nm and different input modes

Fig.4(a) and (b) show the variations of coupling length of three spatial modes channels with the interval of the channel in the horizontal and vertical different polarization directions.

Fig.4(a) shows that the coupling lengths of three modes all increase with the increase of interval of the channel in horizontal polarization direction, but the coupling lengths of LP_{01}, LP_{01} and LP_{11a} mode channels are quite different. For a given transmission channel spacing, the coupling length of the LP_{01} mode channel is the longest, while that of the LP_{11a} mode channel is the shortest. The coupling length of the LP_{11b} mode channel is slightly shorter than that of LP_{01} mode channel, which is much longer than that of LP_{11a} mode channel. From Fig.4(b), the coupling length of LP_{01} mode channel in the vertical polarization direction are similar with that in the horizontal polarization direction of the linear polarization mode. The coupling length of LP_{11a} (LP_{11b}) mode channel corresponds to that of LP_{11b} (LP_{11a}) mode channel in the horizontal polarization. This discussion provides the support for selecting the channel spacing, the channel length and the relative position of each mode channel to main transmission channel of multiplexer.

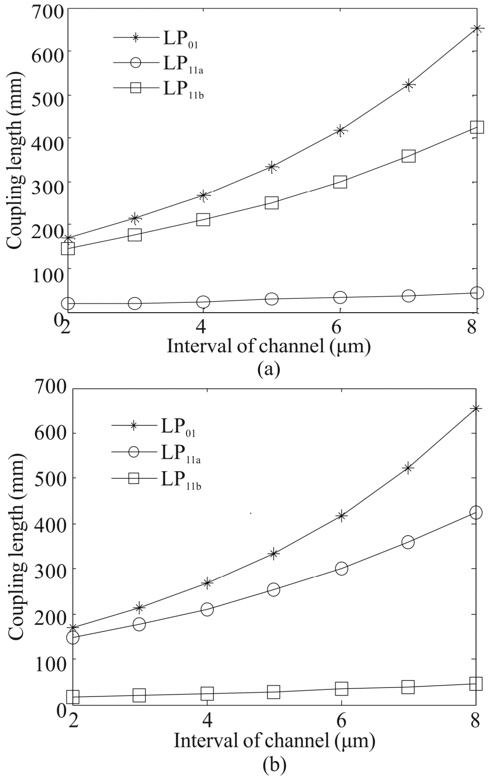


Fig.4 The coupling length of three spatial mode channels varies with interval of the channel in (a) horizontal and (b) vertical polarization directions

Fig.5 (a) and (b) show the variations of coupling efficiency of three independent mode channels with the incident wavelength in the horizontal polarization direction in the wide band and the C-band, respectively. Fig.6 shows those in the vertical polarization direction. It can be seen from Fig.5(a) that channel coupling efficiencies of three modes are better than −0.089 dB and flattened from 1.4 μm to 1.7 μm. The coupling efficiencies of three mode channels are insensitive to the change of wavelength. The maximum coupling efficiencies of the LP_{01}, LP_{11a} and LP_{11b} mode channels are −0.002 dB, −0.007 dB and −0.002 dB, while the minimum values are −0.032 dB, −0.083 dB and −0.089 dB, respectively. The average coupling efficiencies of LP_{01}, LP_{11a} and LP_{11b} mode channels are −0.011 dB, −0.034 dB and −0.032 dB, respectively, which are better than those of −0.37 dB, −1.26 dB and −4.41 dB in C band of Ref.[15]. The high coupling efficiencies of three mode channels show their low loss characteristics when they are independent. For a given incident wavelength, it has similar effect on the coupling efficiency of LP_{01}, LP_{11a} and LP_{11b} mode channels. It can be obtained from Fig.5(b) that the coupling efficiency of three modes channels are better than −0.007 dB and flattened in the C-band. Fig.6 shows that the coupling efficiency of the LP_{01} and LP_{11a} (LP_{11b}) mode channels in the vertical polarization direction is consistent with the coupling efficiency of the LP_{01} and LP_{11b} (LP_{11a}) mode channels in the horizontal polarization direction in Fig.5 from the range of 1 400 nm to 1 700 nm.

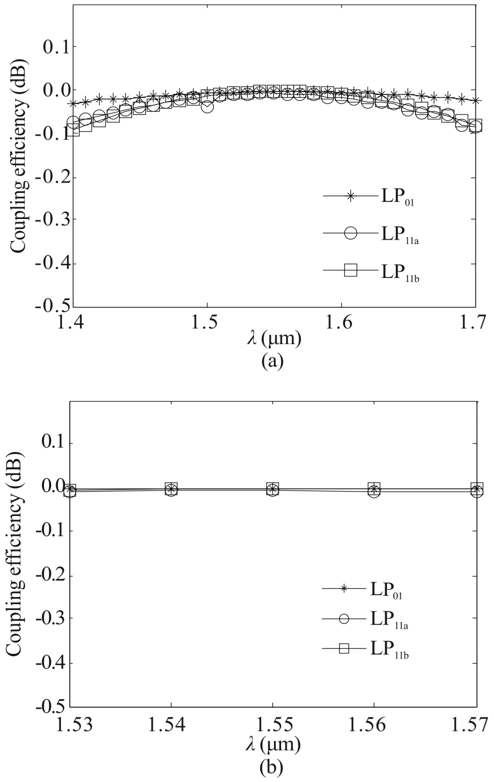
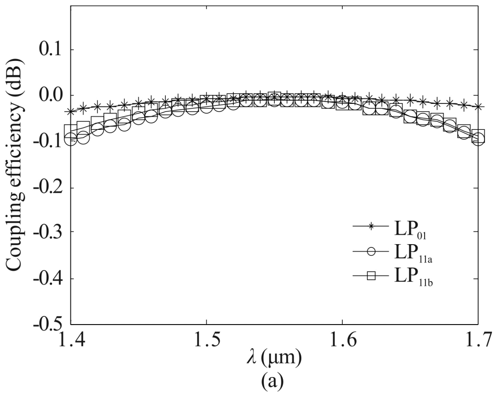
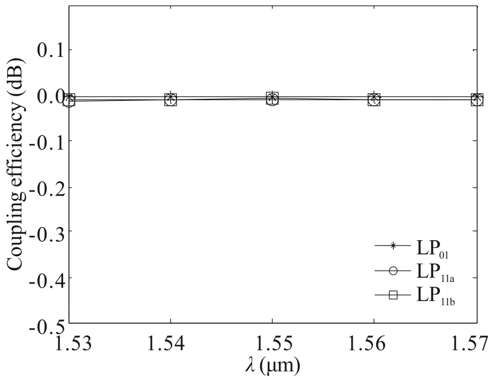


Fig.5 The coupling efficiency of mode channel of multiplexer varies with the incident wavelength in the horizontal direction in (a) wide band and (b) C-band



(a)



(b)

Fig.6 The coupling efficiency of mode channel of multiplexer varies with the incident wavelength in the vertical direction in (a) wide band and (b) C-band

Based on variations of channel length and coupling efficiency with interval of mode channel, the multiplexer structure is determined as shown as Fig.7. Fig.7 shows the overall structure of multiplexer and the cross section of multiplexer in the *x* and *y* directions. The multiplexer consists of three identical transmission channels, one of which is the main transmission channel. The channel parameters use the data obtained above. Considering the changes of mode channel coupling length, channel spacing and coupling efficiency, the mode LP_{01} is directly input the main transmission channel to avoid large coupling loss and large device size caused by the long coupling length of mode channel LP_{01}. The coupling efficiencies of modes LP_{11a} and LP_{11b} have a few differences between horizontal and vertical polarization as shown in Figs.5 and 6, while the coupling length varies greatly as shown in Fig.4. In order to ensure shorter channel length, the mode channels LP_{11a} and LP_{11b} are placed in the *x* and *y* directions of the cross-section of main transmission channel, respectively, with corresponding channel length of 33 mm as shown in Fig.4. Intervals between LP_{11} mode channels and the main channel are all set as 6 μm to solve the problems that production costs is too high and efficiency is too low caused by too small or too large channel spacing, respectively. The above settings can lead to high performance of the multiplexer.

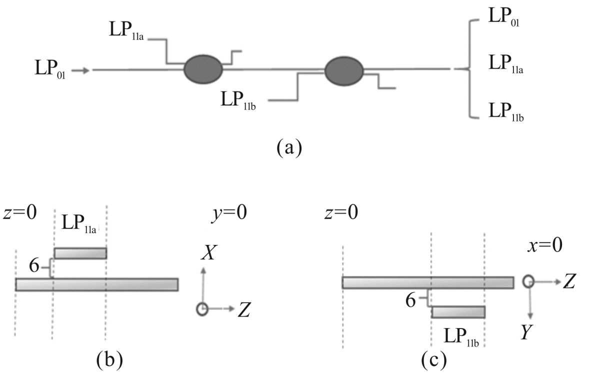
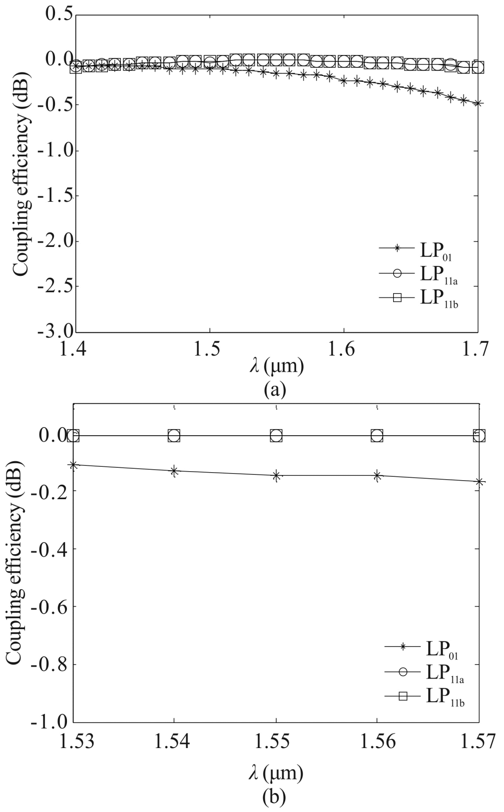


Fig.7 (a) The overall structure of the multiplexer and the cross sections of multiplexer in (b) *x* and (c) *y* directions

Fig.8(a) and (b) show the coupling efficiency of multiplexer versus the incident wavelength in the range from 1 400 nm to 1 700 nm and in the C-band, respectively. It is obtained from Fig.8(a) that the coupling efficiency of LP_{01} mode channel is decreased with the increase of incident wavelength. The coupling efficiencies of LP_{11a} and LP_{11b} mode channels are very high and almost unchanged. It is considered that LP_{11a} and LP_{11b} modes do not affect each other affect transmission because they are orthogonal, their coupling length difference is large, and their channels are very short. However, the power of LP_{01} mode is partly coupled to those LP_{11a} and LP_{11b} mode channels in the transmission process for coupling length of LP_{01} mode channel is longer than those of LP_{11a} and LP_{11b} mode channels, which results in coupling efficiency of LP_{01} mode channel in multiplexer is less than that in independent channel. It can be seen from Fig.8(a) that the maximum values of coupling efficiency of LP_{01}, LP_{11a} and LP_{11b} mode channels are −0.073 dB, −0.007 dB and −0.006 dB, respectively, and the minimum values are −0.479 dB, −0.083 dB and −0.086 dB in the wavelength range from 1 400 nm to 1 700 nm. From Fig.8(b), the values of coupling efficiency of LP_{01}, LP_{11a} and LP_{11b} mode channels are −0.110 dB, −0.007 dB and −0.006 dB, respectively, the minimum values are −0.166 dB, −0.009 dB and −0.009 dB in the C-band. The average coupling efficiencies of LP_{01}, LP_{11a} and LP_{11b} mode channels are −0.140 dB, −0.003 dB and −0.008 dB, respectively, which are much higher than those of −0.40 dB, −1.69 dB and −0.82 dB achieved by the structure used in Ref.[8]. Those differences between maximum and minimum values of all modes coupling efficiency are lower than 0.056 dB, so the variations of coupling efficiencies with wavelength are flattened.

The extinction ratio is another major factor to measure the performance of the multiplexer, which is defined as the maximum value of the mode coupling divided by the maximum value of the mode coupling to other modes at that point. Fig.9 shows the extinction ratio of three modes channels of the multiplexer varying with the wavelength of incident light. As shown in Fig.9, the extinction ratios of LP_{01}, LP_{11a} and LP_{11b} mode channels decrease with the increase of the incident wavelength. Those of LP_{11a} and LP_{11b} mode channels slowly vary with the incident wavelength. That of LP_{01} mode channel greatly fluctuates with the incident wavelength, because the power coupling from LP_{01} mode to LP_{11a} or LP_{11b} mode channel is not uniform and very low. The extinction ratios of three mode channels are all better than 31.2 dB from 1 400 nm to 1 700 nm, which are much higher than that of 20 dB implemented in the C band of Ref.[8]. The extinction ratios of LP_{11a} and LP_{11b} mode channels are consistent, while that of LP_{01} mode channel is significantly higher than those of LP_{11a} and LP_{11b} mode channels. It shows the low crosstalk characteristic of the multiplexer from 1 400 nm to 1 700 nm.



(a)

(b)

Fig.8 The coupling efficiency of multiplexer in (a) the wider band and (b) C-band changing with the wavelength of the incident light

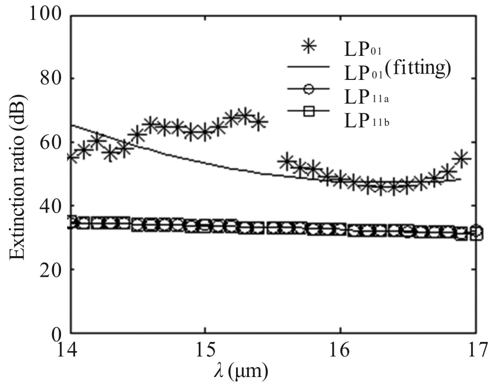


Fig. 9 The extinction ratio of multiplexer

A novel mode-division multiplexer with pure silica core channels is proposed. The pure silica core channels are with large effective area and graded-index distribution. In the wavelength range of 1 400—1 700 nm, the coupling efficiency of multiplexer is better than −0.479 dB, and the extinction ratio is higher than 31.2 dB in the wavelength of 1 400—1 700 nm. Those differences between maximum and minimum values of all modes coupling efficiency are lower than 0.056 dB so the variations of coupling efficiencies with wavelength are flattened. The proposed multiplexer has the advantages of low crosstalk, low loss, low splicing loss, high coupling efficiency, high extinction ratio and wide band. The structure of multiplexer is simple and easy to implement, which can be constructed by optical fiber or optical waveguide. It is of great significance to research on the front-haul optical fiber transmission system with large capacity.

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