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Author(s)	Saitoh, Fumiya; Saitoh, Kunimasa; Koshiba, Masanori
Citation	Optics Express, 18(5), 4709-4716 https://doi.org/10.1364/OE.18.004709
Issue Date	2010-03-01
Doc URL	http://hdl.handle.net/2115/46825
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Type	article
File Information	OE18-5_4709-4716.pdf

A design method of a fiber-based mode multi/demultiplexer for mode-division multiplexing

Fumiya Saitoh*, Kunimasa Saitoh, and Masanori Koshiba

Graduate School of Information Science and Technology, Hokkaido University, Sapporo, 060-0814, Japan
**humiya@icp.ist.hokudai.ac.jp*

Abstract: In the mode-division multiplexing (MDM) optical transmission system, a mode multi/demultiplexer is an important key device for excitation, multiplication, and separation of light signals which have distinct modes. In this report, we propose a fiber-type mode multi/demultiplexer based on selective phase matching between different cores/modes. Design method and device characteristics of 1×4 mode multi/demultiplexer are investigated through finite element analysis. In order to expand operating wavelength range, we reveal the structural parameters that satisfy phase matching conditions over wide wavelength range. Our numerical results demonstrate that the mode multi/demultiplexer with broadband, polarization-insensitive operation can be realized by applying the proposed fiber structure.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication.

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1. Introduction

Recently, the multi-core fiber (MCF) technology that expands transmission capacity per fiber has newly attracted attention toward future optical networks, and new types of MCFs for space/mode-division multiplexing have been reported [1, 2]. By using these multiplexing schemes or together with the wavelength division multiplexing (WDM), the transmission capacity of single fiber is expected to expand further [3]. In the WDM, a wavelength multi/demultiplexer is a key device for inserting and splitting of different wavelengths lights. Similarly in the MDM, a mode multi/demultiplexer is needed for exciting and separating different modes lights. Arrayed waveguide grating, multimode interference waveguide, and Y-splitter, etc. have been used in making up such device [2, 4–7]. However a stable

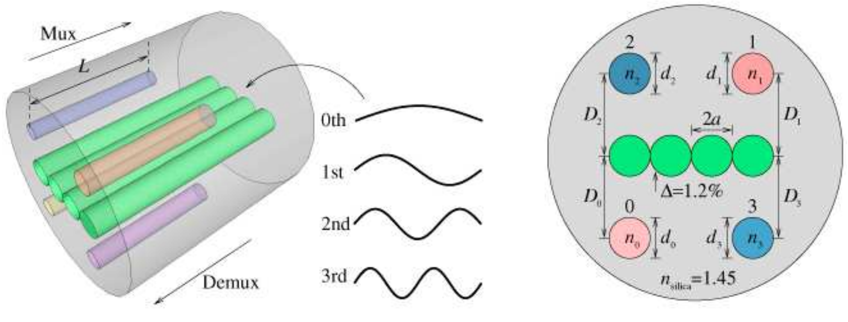
#122406 - $15.00 USD Received 7 Jan 2010; accepted 1 Feb 2010; published 22 Feb 2010

connection with the transmission fiber is not easy because these elements are composed of planar lightwave circuit (PLC).

In this report, we propose a fiber-based 1×4 mode multi/demultiplexer that connects to the fiber easily compared with PLC devices. The fiber-based 1×4 mode multi/demultiplexer consists of four identical coupled cores surrounded by four non-identical cores. It is shown that selective phase matching between different cores/modes can be realized by properly choosing the core diameter and the relative refractive index difference. We reveal the structural parameters that satisfy phase matching conditions over wide wavelength range, and the 1×4 mode multi/demultiplexer with broadband, polarization-insensitive operation is demonstrated numerically.

2. Device design

Figure 1(a) shows schematic configuration of the 1×4 mode multi/demultiplexer. The cross section under consideration is illustrated in Fig. 1(b), where the relative refractive index difference of central coupled core group is $\Delta = 1.2\%$, the core diameter is $2a = 5$ µm, and the back ground material is silica with refractive index of 1.45 [2]. At the fiber center, four identical cores are closely arranged so that the cores are strongly coupled to each other to form four coupled modes, each of which corresponds to a transmission channel [2]. Four non-identical cores 0~3 which multi/demultiplex four coupled modes are arranged in surroundings of coupled core group, where the core diameters $d_{0\sim3}$, the refractive indices $n_{0\sim3}$, and the core intervals $D_{0\sim3}$ are different from each other. The core number 0~3 represents the mode number of each coupled mode.



(a) (b)

Fig. 1. (a) Schematic configuration of the 1×4 mode multi/demultiplexer. (b) Cross section of the 1×4 mode multi/demultiplexer.

The operation of this mode multi/demultiplexer is based on selective phase matching between four coupled modes and four fundamental modes in core 0~3 that occurs when the effective indices of each coupled mode and each fundamental mode in core 0~3 are matched. The index matching is achieved by adjusting structural parameters of core 0~3, and the 1×4 mode multi/demultiplexer can be realized by designing the core intervals $D_{0\sim3}$ to make the coupling length of four modes to be same.

Firstly, we performed numerical simulations using finite-element method (FEM) [8] to clarify the structural parameters that fulfill phase matching conditions. Figure 2 shows the effective index of the fundamental mode in core 0~3 at a wavelength of 1.55 µm, with $d_{0\sim3}$ = 2 µm, 3 µm, 5 µm, as a function of $n_{0\sim3}$. The dashed lines inside the graph indicate the effective indices of the four coupled modes in coupled core group at a wavelength of 1.55 µm. We can see the crossing points in the effective index curves. These crossing points correspond to the structural parameters that meet phase matching conditions. Therefore the fundamental mode in core 0~3 can be coupled with desired coupled mode by tuning structural parameters. Figure 3 shows structural parameter conditions for achieving selective phase matching. From Fig. 3, we can estimate the structural parameters to achieve mode multi/demultiplexing function according to the value of the refractive index or the core diameter. For example, if the core diameter is to be enlarged, its refractive index has to be set small.

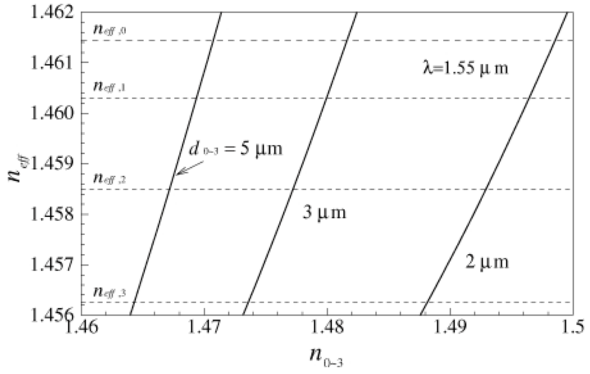


Fig. 2. Effective index of the fundamental mode in core 0~3 at a wavelength of 1.55 μm, with $d_{0\sim3}$ = 2 μm, 3 μm, 5 μm, as a function of $n_{0\sim3}$.

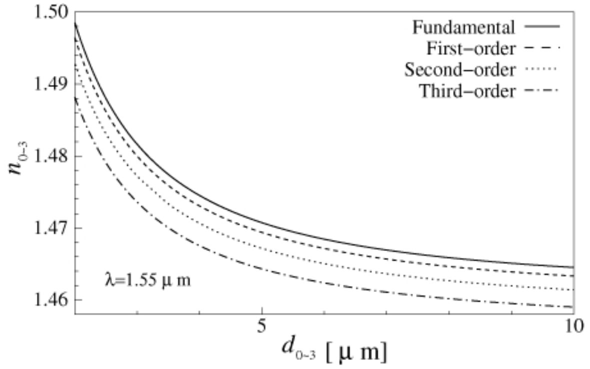


Fig. 3. Structural parameter conditions for achieving selective phase matching.

Next, the parameters of core 0~3 used for the mode multi/demultiplexer are decided. In general, the mode coupling using the phase matching between dissimilar cores arises at particular wavelength, so operation wavelength range of the mode multi/demultiplexer based on this mechanism becomes a narrowband. Moreover, there is polarization dependence of the effective index in the coupled modes. If phase matching condition is fulfilled only for the one polarization mode, the signal output of the other polarization mode decreases. In considering the use of the MDM, it is preferable that operating wavelength range is wide and the polarization dependence is small. Consequently, we decided to use the value of the core diameter and the refractive index as shown in Table 1 to attain such a characteristic, where i denotes the core number (mode number). These parameters are obtained by examining the effective index dependence on the wavelength for different structural parameters. Figure 4 shows the wavelength dependence of the effective index of four coupled modes in coupled core group and the fundamental mode in core 0~3. The structural parameters of core 0~3 are set as in Table 1. Although the lower order mode has larger polarization dependence compared with the higher order mode, the dispersion relations in each coupled mode (x and y polarization modes) and each fundamental mode of core 0~3 are almost the same, namely phase matching condition is satisfied over wide wavelength range. Therefore it is predicted that the fiber with structural parameters shown in Table 1 operates as a polarization-insensitive mode multi/demultiplexer over wide wavelength range.

Table 1. Structural parameters of core 0~3 for broadband, polarization-insensitive operation.

	i=0	i=1	i=2	i=3
d_i [μm]	7.75	6.13	4.29	2.54
n_i	1.466094	1.466916	1.469416	1.47849
D_i [μm]	9.08	9.14	8.63	7.78

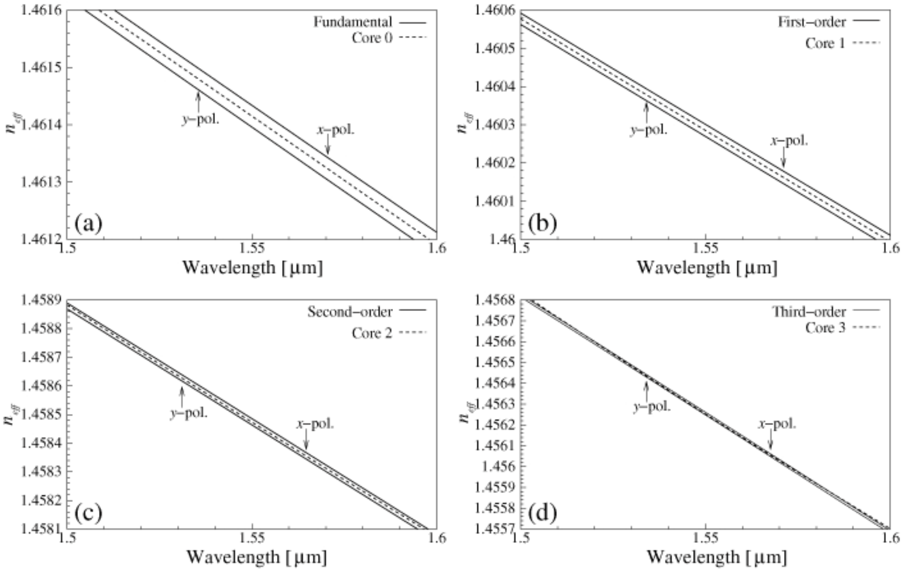


Fig. 4. Wavelength dependence of the effective index of (a) the fundamental coupled mode and the outer core-0 mode, (b) the first-order coupled mode and the outer core-1 mode, (c) the second-order coupled mode and the outer core-2 mode, (d) the third-order coupled mode and the outer core-3 mode. The structural parameters of core 0~3 are set as in Table 1.

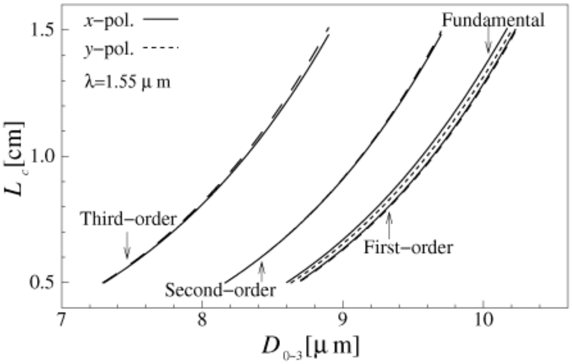


Fig. 5. Coupling length L_c of the each coupled mode as a function of $D_{0\sim3}$.

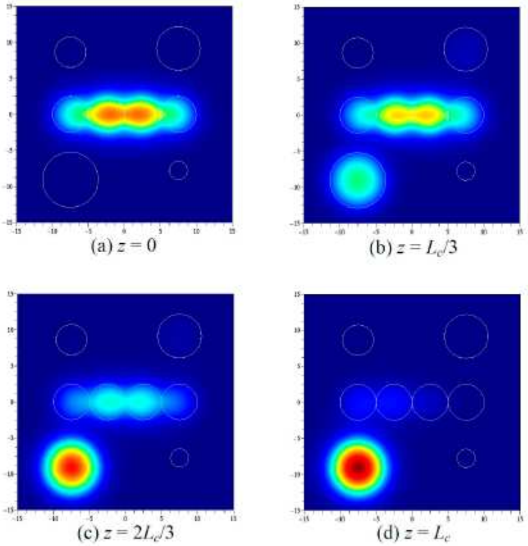
In order to multi/demultiplex four coupled modes simultaneously, it is necessary to match the coupling length of each mode. Figure 5 shows the coupling length L_c of the each coupled mode as a function of $D_{0\sim3}$, with the structural parameters in Table 1. There is little polarization dependence of coupling length, and it is possible to make coupling length of four modes approximately same if the core intervals are appropriately adjusted. The selection of the core interval determines coupling length and operating wavelength range. If we decrease the core interval, the coupling length decreases and operating wavelength range will be broadened due to the increase of the coupling efficiency. Here, we choose the core intervals

Received 7 Jan 2010; accepted 1 Feb 2010; published 22 Feb 2010

as shown in Table 1 to obtain a relatively wide operating wavelength range (~100 nm). At these parameters, the length of the device becomes about 0.7 cm.

3. Device characteristics

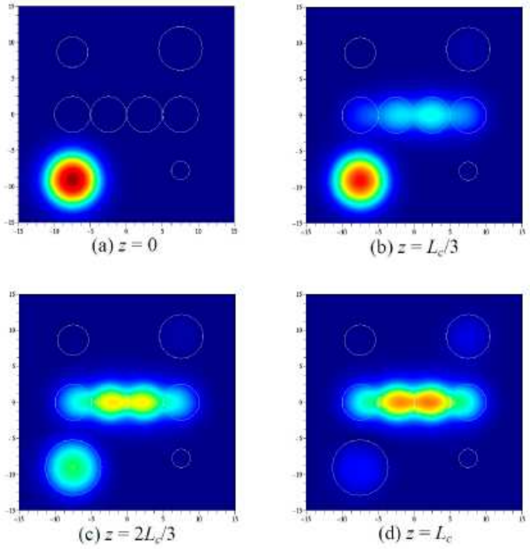
A full-vector finite-element beam propagation method (BPM) [9] has been applied to the 1 × 4 mode multi/demultiplexer designed as Table 1 to confirm the design adequacy. Figure 6 shows the electric field distributions at propagation lengths of $z = (0, L_c/3, 2L_c/3, L_c)$ at a wavelength of 1.55 μm. As shown in the figure, the fundamental coupled mode is launched to the central coupled core group. The input lightwave transfers from the coupled core group to core 0 at the propagation distance $z = L_c$, and there is little lightwave transferring to other cores. Figure 7 shows the electric field distributions when the initial condition in Fig. 6 is reversed. We can see that the input lightwave launched into core 0 excites the fundamental coupled mode in the coupled core group at the propagation distance $z = L_c$. These results are validating the multiplexing and demultiplexing operations. Figure 8 shows the wavelength dependence of the normalized power at the fiber output end ($L = 0.7$ cm) in core 0~3. The input coupled modes are launched to coupled core group, respectively. It is found that both of the polarization modes have similar demultiplexing properties for all coupled modes. We also see that the wavelength range with the normalized output power higher than 90% has exceeded 100 nm. The cross talk between each core is smaller than −26.53 dB at a wavelength of 1.55 μm, as shown in Table 2. The reason why such a characteristic is attained is that the structural parameters are designed to meet phase matching conditions over wide wavelength range as shown in Fig. 4. If we increase the core diameters $d_{0\sim3}$ more than those in Table 1 referring to Fig. 3, the slope of the dispersion relation shown in Fig. 4 becomes gradual. On the other hand, if we decrease the core diameter $d_{0\sim3}$, the slope of the dispersion relation becomes steep. In these cases, operating wavelength range narrows because the phase matching condition is fulfilled only at the neighborhood of a wavelength that the effective index intersects. This means that it is also possible to design the mode multi/demultiplexer with narrowband operation by tuning structural parameters.


(a) $z = 0$ (b) $z = L_c/3$

(c) $z = 2L_c/3$ (d) $z = L_c$

Fig. 6. Electric field distributions at propagation lengths of $z = (0, L_c/3, 2L_c/3, L_c)$ at a wavelength of 1.55 μm (Demultiplexing of the fundamental coupled mode).

#122406 - $15.00 USD Received 7 Jan 2010; accepted 1 Feb 2010; published 22 Feb 2010


(a) $z = 0$ (b) $z = L_c/3$

(c) $z = 2L_c/3$ (d) $z = L_c$

Fig. 7. Electric field distributions at propagation lengths of z = (0, $L_c/3$, $2L_c/3$, L_c) at a wavelength of 1.55 μm (Multiplexing of the fundamental coupled mode).

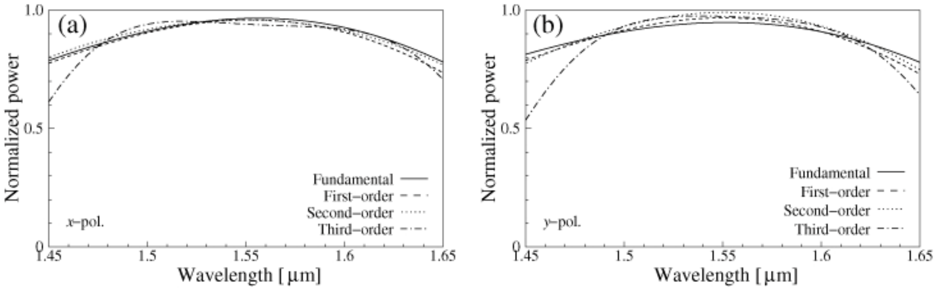


Fig. 8. Wavelength dependence of the normalized output power for (a) the x-polarized and (b) the y-polarized modes at the fiber output end (L=0.7 cm) in core 0~3.

Table 2. Cross talk (in dB) between each core at a wavelength of 1.55 μm

	Core 0		Core 1		Core 2		Core 3	
	x-pol.	*y*-pol.	*x*-pol.	*y*-pol.	*x*-pol.	*y*-pol.	*x*-pol.	*y*-pol.
Fundamental			–48.71	–34.03	–42.21	–44.72	–42.37	–39.52
First-order	–30.83	–35.12			–40.42	–39.14	–44.38	–42.08
Second-order	–36.53	–37.95	–36.31	–41.27			–39.25	–43.63
Third-order	–26.53	–26.57	–40.24	–40.34	–41.88	–45.91		

Finally, we investigated the effects of variation of the surrounding core diameters on the cross talk. Figure 9 shows the cross talk of the mode multi/demultiplexer with the structural parameters shown in Table 1 as a function of $\Delta d_{0\sim3}$. Here the operating wavelength is 1.55 μm and $\Delta d_{0\sim3}$ is the variation from the value of Table 1. As the value of $\Delta d_{0\sim3}$ increases, because of phase mismatching, the coupling efficiency decreases and cross talk is deteriorated. The lower order mode with large core diameter is more tolerant to $\Delta d_{0\sim3}$, because in the large diameter core variation of the effective index with $\Delta d_{0\sim3}$ becomes gradual, and so the phase mismatching is suppressed. The tolerance of $\Delta d_{0\sim3}$ that maintains the cross talk smaller than –20 dB is about ± 0.5% for all coupled modes. We also investigated the tolerance for the

#122406 - $15.00 USD Received 7 Jan 2010; accepted 1 Feb 2010; published 22 Feb 2010

refractive indices of the surrounding cores. It was found that the cross talk of smaller than −20 dB for most coupled modes was kept if the variation of the refractive indices was up to ± 0.0001. From these results, the tolerance to structural parameters is not so large. Accurate fabrication is required for good device characteristics. One way for improving the structural tolerance is to minimize the cross talk by reducing leakage of the lightwave to undesired core. If we chose higher relative refractive index difference as coupled core group, the light confinement is enhanced and transferring to undesired core will be reduced. The investigation of such a configuration is a future work.

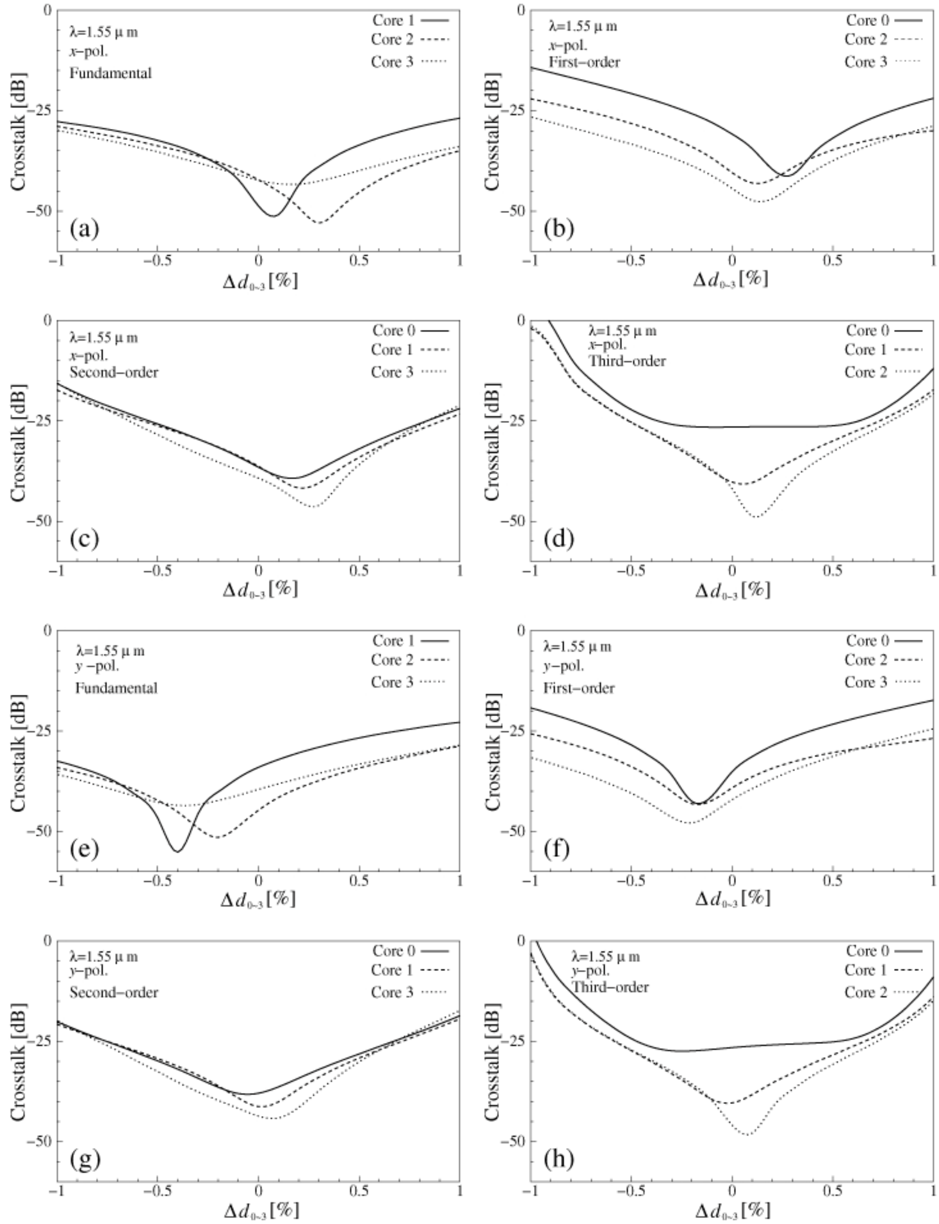


Fig. 9. Effects of variation of the surrounding core diameters on the cross talk for (a)~(d) the x-polarized and (e)~(h) the y-polarized modes.

Received 7 Jan 2010; accepted 1 Feb 2010; published 22 Feb 2010

4. Conclusion

We have proposed a fiber-type mode multi/demultiplexer based on selective phase matching between different cores/modes, and have reported its design method and device characteristics. Numerical simulations have presented that the mode multi/demultiplexer with broadband, polarization-insensitive operation can be realized when the effective indices of four coupled modes are matched with the surrounding cores over wide wavelength range. The effects of variation of structural parameters on the cross talk were also discussed. The proposed mode multi/demultiplexer is expected to make contributions in the MDM optical transmission system.