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DONG, Jiangli; CHIANG, Kin Seng; JIN, Wei

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Mode multiplexer based on integrated horizontal and vertical polymer waveguide couplers

Jiangli Dong, Kin Seng Chiang,* and Wei Jin

Department of Electronic Engineering, City University of Hong Kong, 83 Tat Chee Ave., Hong Kong, China
**Corresponding author: eeksc@cityu.edu.hk*

We demonstrate a mode (de)multiplexer with two cascaded few-mode polymer waveguide directional couplers fabricated on the same substrate along the horizontal and vertical directions, respectively. The three waveguides that form the two couplers have the same core size. The horizontal and vertical couplers are designed to provide complete power transfer for the LP_{11a} and LP_{11b} modes, respectively, with the LP_{01} mode staying in the central core that incorporates a biconical taper to suppress any remaining LP_{11} modes. A typical fabricated (de)multiplexer, which is 18.5 mm long, shows a coupling ratio higher than ~96% in the wavelength range of 1530 – 1570 nm for both couplers. The device shows negligible crosstalk to the LP_{01}-mode channel, while the crosstalks to the LP_{11}-mode channels are lower than −15.6 and −13.4 dB for the TE and TM polarizations, respectively. The device can be considered polarization-insensitive. The propagation losses for the three modes are about 2.0 dB/cm. This device could find applications in mode-division-multiplexing systems.

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To meet the rapidly growing demand for bandwidth, there is a worldwide interest in pursuing new technologies to further increase the signal-carrying capacity of optical fibers. Mode-division multiplexing (MDM) based on a few-mode fiber, which can expand the transmission capacity of a fiber in proportion to the number of modes used for carrying independent signal channels, has attracted much attention in recent years. A key component in an MDM system is a mode (de)multiplexer for spatially combining or separating different mode channels. Mode (de)multiplexers can be realized with bulk-optic components [1,2], optical fibers [3–6], and planar waveguides [7–16]. Waveguide mode (de)multiplexers, in particular, have the advantages of compactness, fiber compatibility, and integration capability. Various waveguide structures have been proposed for the implementation of mode (de)multiplexers, which include, for example, multimode interferometers [7,8], asymmetric Y-junctions [9–11], and directional couplers [12–15]. Because of the symmetry properties of the modes, it is a challenge to realize a mode (de)multiplexer that can separate orthogonal spatial modes of the same order, e.g., the LP_{11a} and LP_{11b} modes.

Several approaches [6,15–18] have been reported for multiplexing the orthogonal LP_{11} modes. An integrated silicon circuit that follows the bulk-optic layout [16] can provide full multiplexing of six spatial and polarization modes, but the circuit is highly complex and the insertion loss is high. A low-loss photonic lantern formed with carefully arranged fused fiber tapers [6] can provide mode selection, but the mode extinction ratio is yet to be improved. Asymmetric waveguide directional couplers that incorporate a LP_{11}-mode rotator [15] can multiplex the two orthogonal LP_{11} modes, but the use of a LP_{11}-mode rotator adds complication to the design and the fabrication of the device. A particularly simple idea is to use a waveguide structure that consists of three parallel dissimilar cores arranged in a triangular configuration [17], so that the two orthogonal LP_{11} modes can be coupled from the central core to the two side cores, respectively. The principle has been elaborated for a three-core fiber [17] and demonstrated experimentally with a femtosecond-laser-written tapered coupler in a boro-aluminosilicate glass chip [18]. In this paper, we demonstrate a simple waveguide device for the multiplexing of the LP_{01}, LP_{11a}, and LP_{11b} modes.

Our mode (de)multiplexer consists of three identical waveguide cores configured into two cascaded horizontal and vertical directional couplers, as suggested in our previous theoretical work [19]. The horizontal and vertical couplers allow the LP_{11a} and LP_{11b} modes to be coupled out from the central core to the side cores, respectively, with little effect on the LP_{01} mode in the central core. A biconical taper is introduced at the demultiplexing end of the central core to remove any remaining LP_{11} modes. We fabricated the device with polymer materials to take advantage of the spin-coating technology for the fabrication of multilayer structures [20]. Our typical experimental device, which is 18.5 mm long, shows a coupling ratio higher than ~96% in the C-band (1530 – 1570 nm) for both couplers, which is insensitive to the polarization state of light. The crosstalk to the LP_{01} mode in the central core is too small to be measureable, while the crosstalks to the LP_{11} modes are smaller than −15.6 (−13.4) dB for the TE (TM) polarization. The propagation losses for the three modes are ~2.0 dB/cm.

Because the three waveguide cores in our device are identical, the mode patterns are maintained at the outputs, which is different from the situation of using an asymmetrical coupler where the LP_{11} mode is coupled to the LP_{01} mode of the parallel core [15]. Our device can be connected to two-mode fiber leads and used in situations where the mode patterns need to be kept for further processing, such as mode routing. In terms of performance, our mode multiplexer is comparable to many those used in system experiments [12,13,15].

Figure 1 shows the structure of the mode (de)multiplexer, which consists of a horizontal directional coupler followed by a vertical one, formed by three parallel identical cores (Core 1, Core 2, and Core 3), each of which supports only the LP_{01}, LP_{11a}, and LP_{11b} modes. S-bends are applied at one end to separate the three cores.

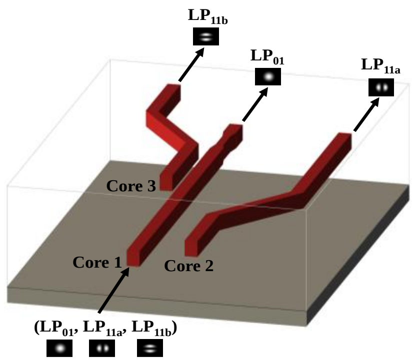
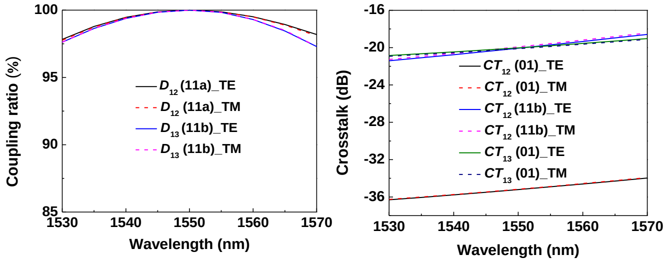


Fig. 1. Proposed mode (de)multiplexer consists of a horizontal coupler followed by a vertical coupler, formed by three identical cores.

To facilitate discussion, a demultiplexer is considered here, where the three modes are launched into Core 1, as shown in Fig. 1. Since the three cores are identical, the effective indices of the corresponding modes in the three cores are equal, which means that the phase-matching condition for evanescent-field coupling for each mode is automatically satisfied. However, whether a mode can be strongly coupled from one core to the other also depends on the magnitude of the coupling coefficient, which is a measure of the spatial overlap between the fields of the two coupled modes in the two cores. For the horizontal coupler, the LP_{11a} mode has a much stronger coupling coefficient than the other two modes, whereas for the vertical coupler, the LP_{11b} mode has the strongest coupling coefficient. In a two-mode core, the LP_{01} mode is well guided with its field mainly confined in the core area, which suggests a weak evanescent field and hence a weak coupling coefficient. Therefore, by using sufficiently separated cores, the coupling between the LP_{01} modes among the three cores can be made negligible and the three spatial modes can be separated, with the LP_{01} mode staying in Core 1, the LP_{11a} mode emerging from Core 2, and the LP_{11b} mode emerging from Core 3.

We analyze the device with the coupled-mode theory [19]. Here we present a specific example to demonstrate the idea and our practical considerations. The idea is to fix the dimensions of the cores and choose the core separations to achieve 100% coupling ratios for the LP_{11} modes at 1550 nm with sufficiently low crosstalks. A large core separation can improve the crosstalk performance, but requires a long device length. To facilitate alignment between Core 1 and Core 3 in the fabrication process, the core separation for the vertical coupler should not be too large. In our design, the refractive indices of the core and the cladding are taken as 1.569 and 1.559, respectively, which are the values of the polymer materials used in our fabrication work. The width and the height of each core are 6.0 and 8.2 μm, respectively. The horizontal coupler has a core separation of 12.5 μm, which corresponds to a coupling length of 5.50 mm for the LP_{11a} mode, while the vertical coupler has a core separation of 9.0 μm, which corresponds to a coupling length of 7.76 mm for the LP_{11b} mode. To strip off the residual LP_{11} modes in Core 1, the width of Core 1 is tapered biconically near the output end to allow only the transmission of the LP_{01} mode, as shown in Fig. 1. The taper has a linear profile with a waist width of 2.2 μm and a length of 3.2 mm. Figure 2(a) shows the calculated coupling ratio of the LP_{11a} mode for the horizontal coupler and that of the LP_{11b} mode for the vertical coupler for the TE and TM polarizations. Over the C-band (1530 – 1570 nm), the coupling ratios of the LP_{11a} and LP_{11b} modes, denoted as $D_{12}(11a)$ and $D_{13}(11b)$, respectively, are higher than 97.8% and 97.3%, respectively, (with 100% at 1550 nm), which are the same for both polarizations.



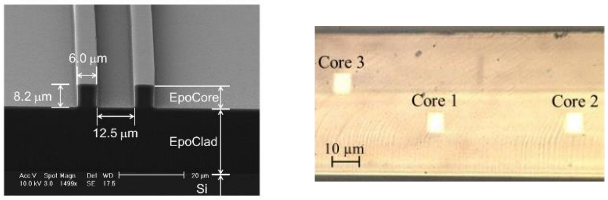
(a) (b)

Fig. 2. (a) Coupling ratios and (b) crosstalks calculated for the horizontal and vertical couplers.

When the device functions as a demultiplexer, there exist crosstalks among the mode channels. For the horizontal coupler, the crosstalks from the LP_{01} and LP_{11b} modes to the LP_{11a} mode are $CT_{12}(01) = P_2(01)/P_2(11a)$ and $CT_{12}(11b) = P_2(11b)/P_2(11a)$, respectively, and for the vertical coupler, the crosstalks from the LP_{01} and LP_{11a} modes to the LP_{11b} mode are $CT_{13}(01) = P_3(01)/P_3(11b)$ and $CT_{13}(11a) = P_3(11a)/P_3(11b)$, respectively, where $P_2(01)$, $P_2(11a)$, and $P_2(11b)$ are the output powers of the LP_{01}, LP_{11a} and LP_{11b} modes from Core 2, respectively, and $P_3(01)$, $P_3(11a)$, and $P_3(11b)$ are the output powers of the LP_{01}, LP_{11a} and LP_{11b} modes from Core 3, respectively. Figure 2(b) shows the calculated crosstalks for the horizontal and vertical couplers. As shown in Fig. 2(b), for the TE (TM) polarization, the crosstalks $CT_{12}(01)$ and $CT_{12}(11b)$ are smaller than –34.0 (–33.9) and –18.6 (–18.4) dB, respectively, while the crosstalk $CT_{13}(01)$ is smaller than –19.0 (–19.1) dB. The crosstalk $CT_{13}(11a)$ is negligibly small, as the residual uncoupled power of the LP_{11a} mode in Core 1 after the horizontal coupler is weak. Because the index difference between the cores and the cladding is small, the device is polarization-insensitive. Our calculation ignores the material dispersion.

For a fabrication tolerance of ±0.3 μm in the dimensions of the cores and the core separations, which is roughly the level of control achievable in our fabrication process, the coupling ratios of the couplers vary by a few percent over the C-band, while the crosstalks vary by a few decibels [19].

We fabricated the mode (de)multiplexer with the conventional micro-fabrication process using the polymer materials, EpoCore and EpoClad (Micro Resist Technology GmbH), as the core and cladding materials, respectively. To achieve high coupling ratios and low crosstalks, the refractive indices and the dimensions of the waveguides must be controlled precisely. The multi-layer structure was formed by the spin-coating process. An EpoClad film was first spin-coated and cured on a silicon substrate to form a 16-μm thick under-cladding. An EpoCore film was then spin-coated and cured on the EpoClad film to form the core layer. The pattern of the horizontal coupler together with the biconical taper was next transferred from a mask to the EpoCore film by photolithography. The height of the cores was controlled precisely by oxygen reactive ion etching (RIE) to the desired



(a) (b)

Fig. 3. (a) Scanning electron microscope image of an unclad horizontal coupler and (b) Microscopic image of the end face of the fabricated device, showing three cores in two levels.

value. Figure 3(a) shows a scanning electron microscope image of the horizontal coupler. Another EpoClad film was then spin-coated and cured on the horizontal coupler to form the middle cladding. The required thickness of the middle cladding, which determines the core separation of the vertical coupler, i.e., 9.0 μm, was obtained by oxygen RIE. By using the same process for the formation of the lower cores, an upper core of EpoCore was formed, where special precaution was taken to achieve precise alignment between the upper and lower cores with the help of a microscope. Finally, a 15-μm thick EpoClad film was applied to form the upper cladding. The total length of device was 18.5 mm. In the fabrication process, we were able to control the refractive indices of the polymer materials precisely by controlling their curing times. The refractive indices of EpoCore for the TE and TM polarizations, measured by a prism coupler (Metricon 2010) at 1536 nm, were 1.5691 and 1.5685, respectively, and those of EpoClad were 1.5593 and 1.5588. The material birefringence was small. Figure 3(b) is a microscopic image of the output end face of the fabricated device as a mode demultiplexer, which shows three cores in two levels. As the three cores are separated by the S-bends, the distances between the three cores at the output end are much larger than those at the input end.

To characterize the fabricated device as a mode demultiplexer, the output beam from a tunable laser (Agilent 8164B) was launched into Core 1. It was possible to launch only the LP_{01} mode into Core 1 with a high efficiency by directly coupling the laser beam into the core. To launch only the LP_{11} mode into Core 1, the laser beam was made to transmit through an all-fiber LP_{01}-LP_{11} mode converter. The mode converter was a long-period fiber grating written in a two-mode fiber with a CO_2 laser, which could convert the LP_{01} mode into the LP_{11a} or LP_{11b} mode with a conversion efficiency higher than 25 dB by controlling the polarization state of the input LP_{01} mode [21]. As shown by the images in Fig. 4, which were taken at the output end of the device with an infrared camera, the three modes are cleanly separated from the three cores. The propagation losses of the LP_{01}, LP_{11a}, and LP_{11b} modes, measured by the cut-back method for other prepared waveguide samples of the same materials and dimensions, were 1.9, 2.0, and 2.1 dB/cm at 1550 nm, respectively. The taper losses of the LP_{01}, LP_{11a}, and LP_{11b} modes were measured to be 0.6, 14.3, and 13.6 dB, respectively. These losses are insensitive to the polarization.

When the device functions as a mode demultiplexer, the output powers from the three cores can be expressed as

$$P_1(m) = P_f(m)C(m)[1 - D_{12}(m)][1 - D_{13}(m)]\alpha_{11}(m)\alpha_T(m)\,, \tag{1}$$

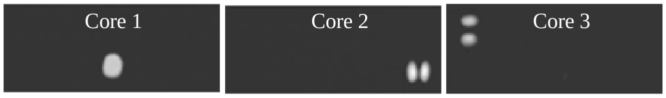


Fig. 4. Output near-field images, showing clean spatial separation of the LP_{01}, LP_{11a}, and LP_{11b} modes from the three cores.

$$P_2(m) = P_f(m)C(m)D_{12}(m)\alpha_{12}(m)\,, \tag{2}$$

$$P_3(m) = P_f(m)C(m)[1 - D_{12}(m)]D_{13}(m)\alpha_{13}(m)\,, \tag{3}$$

where $P_i(m)$ is the output power of mode m measured from Core i (i = 1, 2, 3) with m = "01", "11a", and "11b" for the LP_{01}, LP_{11a}, and LP_{11b} modes, $P_f(m)$ is the output power of mode m from the input fiber lead, $C(m)$ is the coupling coefficient of mode m for coupling light from the fiber to the core, $D_{12}(m)$ and $D_{13}(m)$ are the coupling ratios of the horizontal and vertical couplers for different modes, respectively, $\alpha_{11}(m)$, $\alpha_{12}(m)$, and $\alpha_{13}(m)$ are the transmission coefficients that account for the waveguide losses for mode m propagating from the input end of Core 1 to the output ends of Cores 1, 2, and 3, respectively, and $\alpha_T(m)$ accounts for the taper loss of mode m.

With the above notations, the crosstalks from the LP_{01} and LP_{11b} modes to the LP_{11a} mode in Core 2 are given by

$$CT_{12}(01) = \frac{D_{12}(01)\alpha_{12}(01)}{D_{12}(11a)\alpha_{12}(11a)}\,, \tag{4}$$

$$CT_{12}(11b) = \frac{D_{12}(11b)\alpha_{12}(11b)}{D_{12}(11a)\alpha_{12}(11a)}\,, \tag{5}$$

and the crosstalks from the LP_{01} and LP_{11a} modes to the LP_{11b} mode in Core 3 are given by

$$CT_{13}(01) = \frac{[1-D_{12}(01)]D_{13}(01)\alpha_{13}(01)}{[1-D_{12}(11b)]D_{13}(11b)\alpha_{13}(11b)}\,, \tag{6}$$

$$CT_{13}(11a) = \frac{[1-D_{12}(11a)]D_{13}(11a)\alpha_{13}(11a)}{[1-D_{12}(11b)]D_{13}(11b)\alpha_{13}(11b)}\,. \tag{7}$$

By selectively launching the input mode and measuring the output powers from different cores as well as the output powers from the fiber lead, we can deduce the coupling ratios of the directional couplers from Eqs. (1)–(3) and hence the crosstalks from Eqs. (4)–(7). The results are presented in Figs. 5 and 6 for the fabricated device. As shown in Fig. 5, the coupling ratios of the LP_{11a} and LP_{11b} modes for the TE (TM) polarization, i.e., $D_{12}(11a)$ and $D_{13}(11b)$, for the horizontal and vertical couplers, respectively, are higher than 96.8% (96.4%) and 96.5% (95.9%) in the wavelength range 1530 – 1570 nm, respectively. The difference in the coupling ratio between the TE and TM polarizations is smaller than 1.2%. As shown in

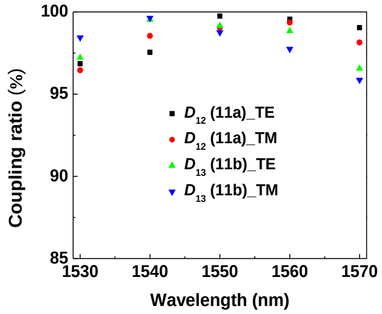
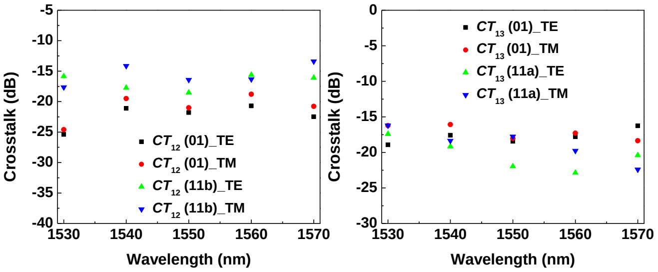


Fig. 5. Coupling ratios for the horizontal and vertical couplers, deduced from the output powers measured for the fabricated device.



(a) (b)

Fig. 6. Crosstalks for the (a) horizontal and (b) vertical couplers, deduced from the output powers measured for the fabricated device.

Fig. 6(a), the crosstalks from the LP_{01} and LP_{11b} modes to the LP_{11a} mode in Core 2 are smaller than –20.7 (–18.8) and –15.6 (–13.4) dB for the TE (TM) polarization, respectively. The lowest crosstalk from the LP_{01} mode to the LP_{11a} mode is –25.4 (–24.6) dB at 1530 (1530) nm, while the lowest crosstalk from the LP_{11b} mode to the LP_{11a} mode is –18.5 (–17.6) dB at 1550 (1530) nm. As shown in Fig. 6(b), the crosstalks from the LP_{01} and LP_{11a} modes to the LP_{11b} mode in Core 3 are smaller than –16.2 (–16.1) and –17.4 (–16.2) dB for the TE (TM) polarization, respectively. The lowest crosstalk from the LP_{01} mode to the LP_{11b} mode is –18.9 (–18.4) dB at 1530 (1570) nm, while the lowest crosstalk from the LP_{11a} mode to the LP_{11b} mode is –22.9 (–22.4) dB at 1560 (1570) nm. Our simulation shows a slow_increase in the crosstalk with the wavelength, which is caused by the increase in the evanescent field of the unwanted mode with the wavelength. This trend does not show up clearly in Fig. 6, possibly because of the uncertainties in the determination of the crosstalk from the power measurements and the presence of material dispersion. Nevertheless, the experimental results agree reasonably well with the simulation, considering the fabrication and measurement errors.

In conclusion, we have demonstrated a simple waveguide mode (de)multiplexer based on two cascaded horizontal and vertical directional couplers composed of three identical waveguide cores. We have fabricated the device with polymer materials, which allow 3D waveguide structures to be formed by the spin-coating process. In the wavelength range 1530 – 1570 nm (C-band), our fabricated device can separate the LP_{01}, LP_{11a} and LP_{11b} modes with crosstalks lower than –15.6 (–13.4) dB for the TE (TM) polarization. The propagation losses of the three modes are ~2.0 dB/cm. This device can be readily used in MDM systems.

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