Mode multiplexer for multimode transmission in multimode fibers

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Abstract: We have numerically demonstrated an efficient mode multiplexer which can tailor the input field patterns by using a phase controller and a mode coupler formed by four single-mode fibers (SMFs). By connecting the mode multiplexer to a multimode fiber (MMF), two orthogonal higher-order modes of the MMF can be simultaneously excited to form two communication channels. The simulated results show that very low modal interference between the two excited modes can be achieved by using the proposed mode multiplexer. We have also discussed the effect of the distance and size of the SMFs in the mode coupler on the performance of the proposed mode multiplexer.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (060.2280) Fiber design and fabrication; (060.2330) Fiber optics communications.

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1. Introduction

Due to the rapidly increased Internet traffic, demand for large transmission capacity has grown dramatically and leaded to research toward polarization-division multiplexing (PDM) [1,2] and higher-order modulation. However, the Shannon limit places a restriction on the transmission capacity over single-mode fibers (SMFs) [3]. One possible way to conquer this problem is applying space-division multiplexing (SDM), such as employing multicore fibers (MCFs) [4–11] or using multiple-input multiple-output (MIMO) technique [12–15]. The MCFs usually contains several hexagonally distributed cores with a larger cladding diameter to avoid coupling of power to the outer polymer coating. Each core functions as an individual transmission channel and thus the transmission capacity can be enlarged several times [6–8]. However, to employing MCFs in the transmission systems requires precise coupling technique to couple power into and out of each channel of MCFs [7,11]. In addition, the crosstalk resulted from the closely distributed cores also limits the performance of MCFs [9].

Another way of performing SDM technique is adopting MIMO signal processing over multimode fibers (MMFs) [12–15]. By using mode-multiplexing technique, such as the mode-selective couplers [14] or filters [15], different signals independently excite different higher-order modes of MMFs and form independent transmission channels in MMFs. If precise excitation can be carried out, the transmission capacity over MMFs can be several times than that over SMFs [14]. However, excitation in conventional MMFs is usually accompanied with too many unexpected higher-order modes [16–18], which may degrade the transmission performance over MMFs. To overcome this problem, few-mode fibers (FMFs) with specially-designed index profile are proposed to avoid the excitation of unexpected modes [19–22].

In this paper we numerically propose a simple mode multiplexing technique by using a phase controller and a mode coupler formed by four SMFs. Two input signals can be transmitted as two different higher-order modes on a conventional graded-index MMFs without the requirement of specially-designed FMFs. Each mode in the MMF forms a transmission channel and the crosstalk between each channel can be very low due to the orthogonal properties of the guided modes. By varying the core size and core distance of the SMFs in the mode coupler, the properties and performance of the proposed mode multiplexer are discussed.

2. Geometry of the mode coupler

The commercial graded-index MMF we considered contains a 62.5-μm core. By using a beam-propagation-method-based mode solver from Rsoft, we can find out the first ten guided modes on the MMF. The mode numbers and mode patterns of the first ten guided modes are shown in Fig. 1 with mode 1 is the fundamental mode. The value of *m* in Fig. 1 is assigned in the order of the value of the corresponding modal index. That is mode 1 which is the LP_{01}

mode possesses the largest modal effective index in the first guided modes shown in Fig. 1. Except for the fundamental LP_{01} mode, some other guided modes form several degenerate sets. For example, mode 2 (m = 2) and mode 3 (m = 3) form a degenerate set of LP_{11} mode, and mode number 4 (m = 4) and mode number 5 (m = 5) are degenerate modes of LP_{21} mode. In our design of mode multiplexer, we choose mode 2 and mode 3 as the transmission channels due to their simple field distributions for excitation. By careful tailoring the input field patterns as those of mode 2 and mode 3, we can successfully build up independent communication channels in the MMF via mode 2 and mode 3. In addition, if we can control the polarization of the input signals, we can achieve a dual-mode dual-polarization transmission and the transmission capacity can be increased to four times.

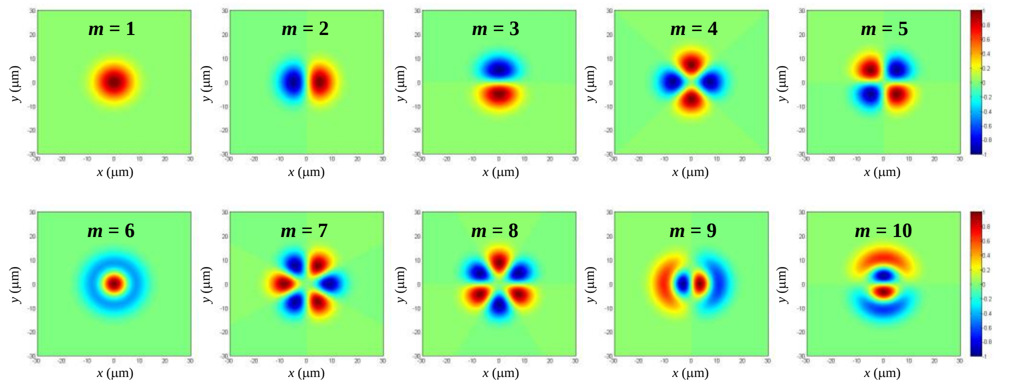

Fig. 1. The first ten guided modes of the MMF and m is the corresponding mode number.

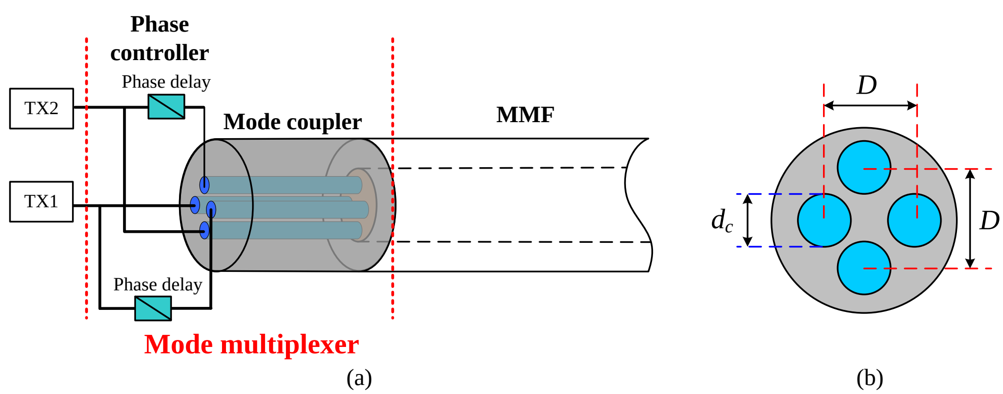

Fig. 2. (a) Schematic of the proposed mode multiplexer with the transmitted signals and MMF. (b) Cross-sectional view of the mode coupler with D and d_c are the distance and diameter of the cores of the SMFs, respectively.

Figure 2(a) depicts the configuration of the mode multiplexer which contains a phase controller and a mode coupler. To tailor field patterns similar to mode 2 and mode 3, we employ a mode coupler consisting of four SMFs. The mode coupler can be fabricated by fusing four SMFs or using the tapering method to have a smaller core size [6,8]. The four SMFs can be connected to phase controllers or power splitters to help tailoring the field patterns as shown in Fig. 2(a). Figure 2(b) demonstrates the cross-sectional view of the mode coupler. The distance and size of the core of the SMFs are D and d_c, respectively. The mode coupler can be fabricated by fusing four SMFs or using the tapering method to have a smaller core size [6,8]. To excite mode 2 on the MMF, input signal from TX1 are equally separated into two optical paths. A 180° phase delay is introduced to one of the paths to have similar mode profile as mode 2. After the phase controller, the tailored field pattern propagates along the mode coupler and is transmitted into the MMF. Similarly, input signal from TX2 is tailored similar to mode 3 and transmitted into the MMF to form another communication channel. In previous studies, the location of excitation has an important effect on the number of excited modes [17,18]. To reduce modal interference of other modes with mode 2 and mode 3, the geometry of the mode coupler should be carefully designed to avoid the excitation of other unexpected higher-order modes. We then use the BPM method to find out the power ratio of the guided modes on the MMF to verify the performance of the mode coupler for various values of D and d_c.

3. Results and discussions

In our simulation, we only discuss the effects of the mode coupler. Thus, the simulation is started with Gaussian-shaped input signals with 180° phase difference at the beginning of the mode coupler. We set the length of the mode coupler to be 1 cm for numerical demonstration. After propagating along the mode coupler, signals are coupled into the MMF. We then measure the power ratio of the first ten guided modes on the MMF to verify the resulted excitation in the MMF. We first consider transmission of signals only from TX1. The SMF core size is fixed at 8.3 μm for the mode coupler formed by the fusing method. As the mode-2-like input signal is transmitted into the MMF, the power ratios of the first ten guided modes are plotted in Fig. 3 for variant values of D. As D is 10 μm, the calculated insertion loss is 0.11dB, and one can see that more than 95% power in the MMF is coupled into mode 2. Due to the similar field distribution for mode 9, there is about 1.2% power coupled to mode 9 as shown in Fig. 3(a). The other lost power can be attributed to the coupling to other higher-order modes and mode-field mismatch at the beginning and end of the mode coupler. If we increase the value of D to be 13 μm and 16 μm, the 180°-phase-difference signals becomes more separated, which makes the input filed more unlike the field pattern of mode 2. Thus, other modes are excited and the power coupled to mode 2 is reduced as demonstrated in Figs. 3(b) and 3(c).

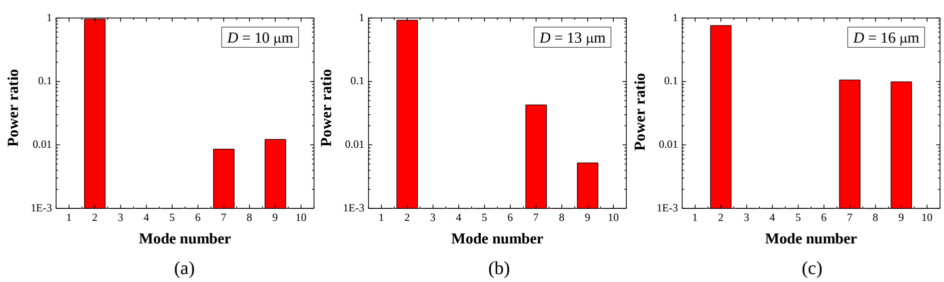

Fig. 3. Power ratios for the first ten modes of the MMF for only TX1 transmission. The core size of the SMFs is 8.3 μm and the core distances are (a) D = 10 μm, (b) D = 13 μm, and (c) D = 16 μm.

We then consider the effect of core size d_c on the performance of the mode coupler. Figure 4(a) shows the power ratio of mode 2 in the MMF versus core distance D for d_c is 8.3 μm, 7.0 μm, and 6.0 μm with only TX1 transmission. The smaller values of d_c can be accomplished by tapering SMFs to the desired size. For the three values of d_c, one can see that the largest power ratio of mode 2 appears as D is around 10~11 μm. As D is larger than 12 μm, the power coupled to mode 2 dramatically decreased for the mismatching of field pattern between the input field and mode 2 field. Thus, as mentioned previously, more unexpected higher-order modes are excited. We have also plotted the calculated power ratio of mode 3 in the MMF with only TX2 transmission in Fig. 4(b). Due to the symmetry of the mode coupler, the same results as in Fig. 4(a) can be obtained.

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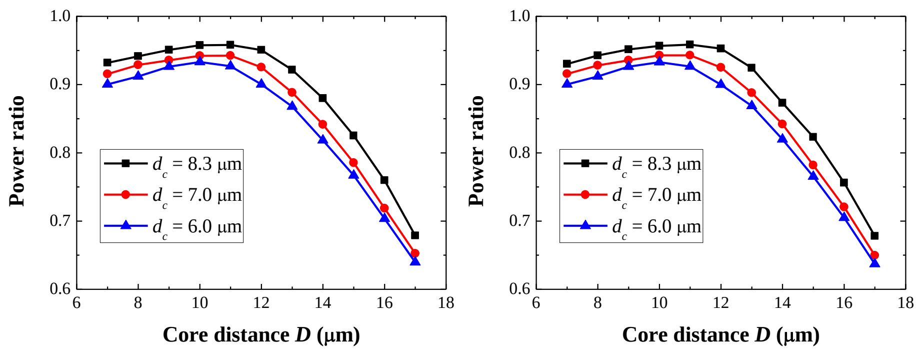
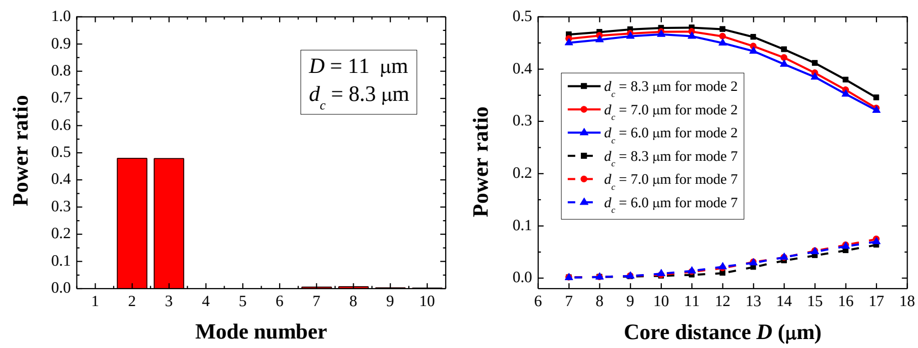
As both TX1 and TX2 signals are transmitted with the same amplitude, the calculated power ratios to the first ten modes are shown in Fig. 5(a) for D = 11 µm and d_c = 8.3 µm. We can see that the input power is almost equally coupled to mode 2 and mode 3 while very small amount of power (< 0.7%) is coupled to mode 9 and mode 10, respectively. If we vary the value of D, the calculated power ratios for mode 2 are presented in Fig, 5(b) for d_c is 8.3 µm, 7.0 µm, and 6.0 µm. Similar to the previous results, for all value of d_c, the power ratio of mode 2 is reduced as D is increased due to the increasing mode mismatch. In addition, as D is larger than 12 µm, a significant amount of power is coupled to mode 7 as demonstrated in Fig. 5(b).



(a) (b)

Fig. 4. Power ratio versus the core distance D with variant values of d_c for (a) mode 2 in MMF with only TX1 transmission and (b) mode 3 in MMF with only TX2 transmission.



(a) (b)

Fig. 5. (a) Power ratio for the first 10 modes in the MMF as D = 11 µm and d_c = 8.3 µm. (b) Power ratio for the mode 2 and mode 7 in the MMF versus the core distance D for both TX1 and TX2 transmission.

Although larger values of D will excite more unexpected higher-order modes, the power coupled to higher-order modes can be collected at the end of the MMF with a very low loss if we use the same mode coupler. Figure 6(a) depicts the configuration of the MMF connected with two mode couplers at both ends. If we only transmit TX1 signals, the output field distribution at the end of the second mode coupler is demonstrated in Fig. 6(b) as the length of the MMF is 1m, D is 11 µm, and d_c is 8.3 µm. By coupling the power of each peak into SMFs and using the phase controller to compensate the phase difference, we can receive very good signals at RX1. Figure 6(c) shows the calculated received power at the end of the second mode coupler for variant MMF lengths. Due to the lossless property of the MMF, the amount of the power loss only depends on the mismatches between the mode coupler with the input signals and the MMF. It can be seen that more than 96% power can be received at the end of

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the second coupler. In addition, to avoid possible modal dispersion in the MMF, one can use FMFs to replace the MMF for reduction of excitation of other higher-order modes. We also obtain the same calculated results for signals form TX2.

From the simulation results, it shows that the proposed mode multiplexer can help to realize the excitation of two specified modes in the MMF to form independent communication channels. The proposed mode coupler is an all-fiber device which can realize all-fiber communication systems with compact sizes. The fiber-based mode coupler is a passive device and has no electrical interference. These advantages also make our proposed mode coupler suitable to be applied in other systems, such as WDM-PON. As for the splicing to a MMF, we can use a laser source, power meters, and a polarization maintaining (PM) splicer to achieve rotational fiber core alignment and lateral alignment [6] to realize low loss splicing for our mode coupler. In addition, by making use of the polarization controllers, 4x4 MIMO processing can also be achieved with our proposed mode multiplexer.

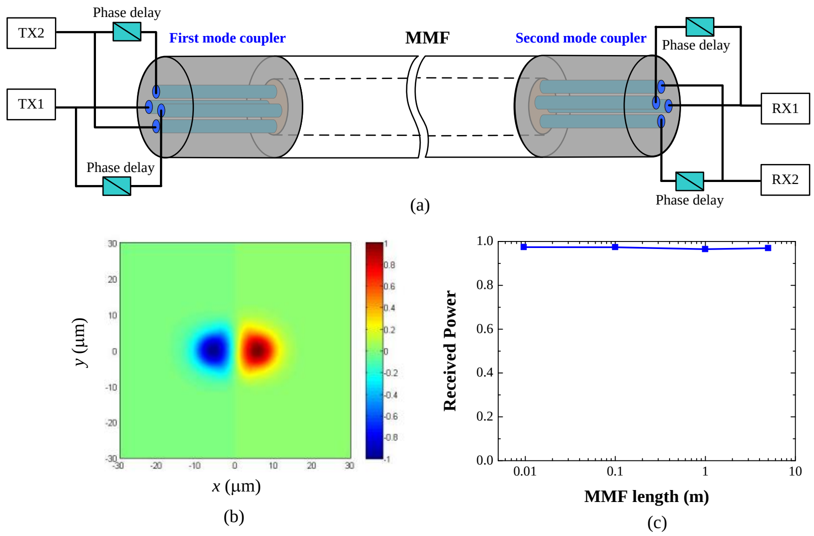

Fig. 6. (a) Configuration of the MMF connected with two mode couplers at both ends. (b) The output field distribution at the end of the second mode coupler for only TX1 transmission. (c) The calculated received power at the end of the second mode coupler for MMFs with variant lengths.

5. Conclusion

We have proposed a simple mode multiplexer consisting of a phase controller and a mode coupler which is formed by four SMFs. By using the phase controller to provide signals with 180° phase difference, field patterns similar to the LP_{11} mode on the MMF can be obtained at the end of the mode coupler. The numerical results show that we can form two independent communication channels via the two orthogonal LP_{11} modes with very low modal interference. We have also calculated the received power as the MMF is connected with two mode multiplexer. More the 96% power can be received at the end of the second mode coupler. Our proposed mode multiplexer has been numerically proved to successfully excite two independent transmission channels in the MMFs, which is quite useful for enlarging the communication capacity.

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