Fused Fiber Mode Couplers for Few-Mode Transmission

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***Abstract*— Space-division multiplexing (SDM) based on few-mode fibers has been studied as a promising technique to increase fiber capacity. In this letter, we show optimal design and simulation of a low-loss fused fiber mode coupler, one of the most critical enabling components for SDM transmission systems. We first analyze the performance of a 3×1 fused fiber mode coupler with asymmetric waveguide structure by fusing a single-mode fiber and a two-mode fiber (TMF) together. A minimum loss of <−1.9 dB and extinction ratio above 19 dB is predicated for both LP$_{11}$ modes, over a wide wavelength range of 1505–1600 nm. We then analyze the performance of another fused fiber mode coupler with symmetric waveguide structure by fusing two TMFs together. A minimum loss of below 0.4/0.7 dB is predicated for both LP$_{11}$ and LP$_{01}$ modes.**

***Index Terms*— Few-mode fiber, optical communications, optical fiber couplers, space-division-multiplexing.**

I. Introduction

FEW-MODE fiber (FMF) has been proposed as a promising candidate for overcoming the capacity limit of standard single mode fiber (SSMF). The feasibility of using mode-division multiplexing (MDM) and MIMO digital signal processing on FMF transmission has been experimentally demonstrated by several groups [1]–[4]. Since amplification for FMF transmission has also been very recently demonstrated such as in [5] and [6], FMF has emerged as a very promising candidate for the next-generation fiber with capacity much beyond that of SMF. The advance in few-mode transmission requires brand new research ranging from device to system level. In FMF fiber based MDM transmission systems, mode selective components play a critical role. A few examples of these components are given in our previous work [7]. In this letter, we focus on the optimal design of fused fiber mode couplers with theoretical analysis of the performance.

II. Mode Coupler

The main function of spatial mode coupler (SMC) in a two-mode fiber (TMF) [1], [2] based MDM system is to couple the optical signals from LP$_{01}$ mode of three SMF inputs into the LP$_{01}$, LP$_{11a}$ and LP$_{11b}$ modes at the TMF output. A spatial mode splitter (SMS) performs the analogous function in the reverse direction, i.e., from TMF input to three SMF outputs. Several groups have demonstrated the use of free-space SMC/SMS [2]–[6] to combine or split spatial modes. However, free-space SMC/SMS is usually bulky and has high loss. A novel tapered mode coupler was proposed to reduce the coupling loss [8]. Besides, fused fiber mode couplers have attracted more interest due to apparent advantages of compactness and low loss [9]–[11], and therefore they may be a promising solution for the MDM transmission systems.

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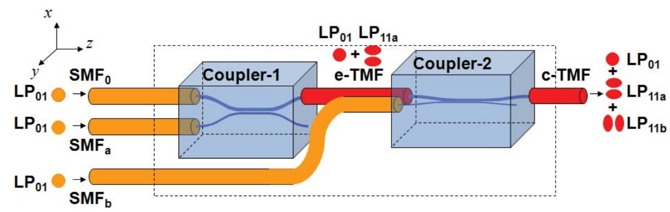

Fig. 1. 3 × 1 asymmetric mode coupler consisting of cascaded LP$_{11}$ mode couplers. c-TMF: circular-core TMF. e-TMF: elliptical-core TMF.

A. Asymmetric Mode Coupler

An asymmetric waveguide structure is usually realized through fusing two dissimilar fibers together, e.g., a SMF and a TMF. A similar type of mode coupler was proposed in [10] about ten years ago. However, the coupler was based on highly elliptical core fiber, where the odd LP$_{11}$ mode (along minor axis) was intentionally cut off to avoid interference to the even LP$_{11}$ mode (along major axis), and therefore combining two spatial LP$_{11}$ modes was not achieved. Recently we proposed a SMC design supporting both LP$_{11}$ modes [11].

Fig. 1 shows our design of the SMC/SMS consisting of cascaded LP$_{11}$ mode couplers: coupler-1 and -2, respectively. Both couplers have asymmetric waveguide structure by fusing one SMF and one TMF together. It is well known that a SMC can be made by satisfying the phase-match condition according to the coupled-mode theory (CMT) [12]. Denoting the amplitudes of the guided modes in the two waveguides as A_1 and A_2, the coupling equations of a uniform TMF fiber coupler can be represented as

$$\frac{\partial A_{1(l,a)}}{\partial z} = -i(\beta_{1(l,a)} + K_{11})A_{1(l,a)} - iK_{12}A_{2(m,a)}$$
$$\frac{\partial A_{2(l,a)}}{\partial z} = -i(\beta_{2(l,a)} + K_{22})A_{2(l,a)} - iK_{21}A_{1(m,a)} \quad (1)$$

where $A_{(l,a)}$ and $\beta_{(l,a)}$ are the amplitude and propagation constant of the input spatial mode $l(= 1\ or\ 2)$ in polarization a $(=x\ or\ y)$. K_{11} and K_{22}, K_{12} and K_{21} are the self-coupling and mutual coupling coefficients, respectively. Furthermore, if the coupled-mode system is lossless, self-consistency requires that K must satisfy the relations $K_{12} = K_{21}^* = \kappa$, and K_{11}, K_{22} must be real. The coupled mode equation Eq. (1) can be solved analytically for a coupling length of d in a Jones matrix form via the following equation [12]

$$\begin{pmatrix} A_1(d) \\ A_2(d) \end{pmatrix} = e^{-i\beta_{(0)}d} \times \begin{bmatrix} \cos(Sd) - i\frac{\delta}{S}\sin(Sd) & -i\frac{\kappa}{S}\sin(Sd) \\ -i\frac{\kappa}{S}\sin(Sd) & \cos(Sd) + i\frac{\delta}{S}\sin(Sd) \end{bmatrix} \begin{pmatrix} A_1(0) \\ A_2(0) \end{pmatrix} \tag{2}$$

where $\beta_{(0)} = (\beta_{(1)}+K_{11}+\beta_{(2)}+K_{22})/2$ is the common propagation constant, $\delta = (\beta_{(1)}+K_{11}-\beta_{(2)}-K_{22})/2$ is the detuning factor, and $S = \sqrt{\delta^2+\kappa^2}$ is the coupling strength. We can easily see that when the phase mismatch factor δ between the two modes in the two waveguides is zero, we can obtain nominal 100% coupling ratio to the target mode. In a circular-core TMF (c-TMF), the two eigen spatial orientations of LP_{11} mode (LP_{11a} and LP_{11b}) have similar modal indices, and therefore the two modes are coupled to each other as they propagate along the fiber and the signal spatial orientations are not maintained. However, in an elliptical-core TMF (e-TMF), the two LP_{11} modes split and their spatial orientations can be maintained for a long distance with one mode along the major axis (LP_{11a}) and the other minor axis (LP_{11b}) [10]. We therefore design an e-TMF such that the modal indices of the two spatial modes are well separated but are not cut off. The e-TMF has a core radius of 6.5 × 4.5 μm, and the cladding diameter is standard 125 μm. It has a step index profile with a fractional index difference $\Delta = 0.47\%$ at 1550 nm. We use the alternating direction implicit (ADI) method and find six eigenmodes (three spatial modes times two polarizations). Here we denote the major axis of core as x and the minor axis as y. With the knowledge of modal indices of the two spatial orientations, we can readily design the two SMFs to match the phase velocities of LP_{11a} and LP_{11b}. We simulate the case for which the core diameters of two samples of Corning's SMF-28e fiber (r = 4.1 μm and $\Delta = 0.36\%$) are reduced to 89.2% (SMF_a) and 62.9% (SMF_b) of their original size. This can be achieved by pre-pulling the Corning's SMF-28e fiber in practice [10]. The effective refractive index mismatch between LP_{01} of SMF_a ($LP_{01(a)}$) and LP_{11a} of e-TMF, or LP_{01} of SMF_b ($LP_{01(b)}$) and LP_{11b} of e-TMF, is estimated to be less than 10^{-5}. In addition, because LP_{11} mode is spatially asymmetric, the coupling is also sensitive to the position where we place the single-mode fiber. Ideally for LP_{11a} mode we align SMF_a along the x-axis, and for LP_{11b} mode we align SMF_b along the y-axis, where we obtain best coupling performance and discrimination against the other mode.

We first analyze the performance of coupler-1 with a simple parallel line setup, as shown in Fig. 2. The space between two fiber cores is first maintained at a constant 15 μm, which is feasible with most standard fused biconic tapering (FBT) stations [10], [11]. The parameters used for simulation are as follows: designed waveguide is made of pure silica with a wafer length of 30 mm and a width of 125 μm. At the output port of SMC the e-TMF is connected to a circular core two-mode fiber (r = 6.2 μm), which will be used for transmission.

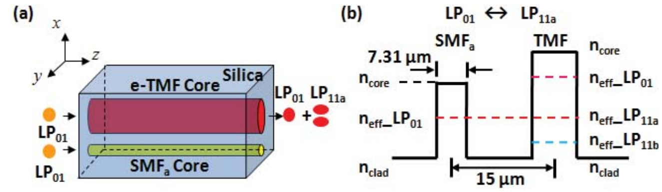

Fig. 2. (a) Waveguide structure of coupler-1. (b) Refractive index profile of the coupler. SMF is preprocessed to phase-match LP_{11a} mode in e-TMF.

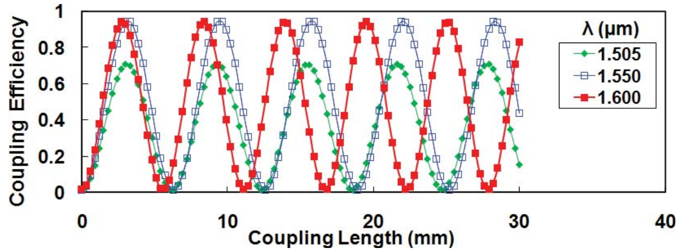

Fig. 3. Power coupled into LP_{11ax} mode (target mode) versus coupling length for coupler-1.

We assume an initial LP_{01x} mode launched into the SMF, and the coupling efficiency dependence on the coupling length is shown in Fig. 3 at wavelengths of 1.505, 1.550 and 1.600 μm. It can be seen that almost 100% power has been coupled into only one (LP_{11ax}) mode that has the same propagation constant and polarization as the launched LP_{01x} mode. Furthermore, only the spatial LP_{11} mode at the orientation where SMF core and e-TMF core are aligned is excited in the coupler because this spatial LP_{11} mode has non-zero overlap integral to the LP_{01} mode. Because the cores are aligned along x in coupler-1, it suggests that only LP_{11a} mode will be coupled. In addition to the coupling power, we are also interested in the modal crosstalk of the coupler which is characterized by mode extinction ratio (ER) [2]. The wavelength dependence of ER is shown in Fig. 4. We find out that the achievable ER at the first maximum (L = 3 mm) is above 20 dB. Then we estimate the performance of coupler-2. The waveguide structure of coupler-2 is shown in Fig. 5. The results for coupling efficiency and ER are given in Figs. 6 and 7, respectively. We find out that the achievable ER at the first maximum is above 19 dB for coupler-2. This result confirms that although the coupling performance depend strongly on the working wavelength and coupling length, by appropriate design the ER can be maintained at very high values. Therefore we conclude that our designed SMC could have potential applications in TMF fiber based optical transmission systems [1]–[6].

Fig. 8 shows the coupling efficiency wavelength dependence at two possible coupling lengths: 3 mm (first maxima) and 9 mm (second maxima), for both couplers. It is observed that the maximum coupling efficiency varies with wavelength, and it is preferable to use the first coupling maximum to minimize the coupling efficiency variance for different wavelengths when making a coupler. The coupling efficiencies are scanned over the wavelength range from 1.505 to 1.600 μm and estimated to be about 70∼97.5% for LP_{11a} mode in coupler-1 and 65∼96.5% for LP_{11b} mode in coupler-2 at L = 3 mm,

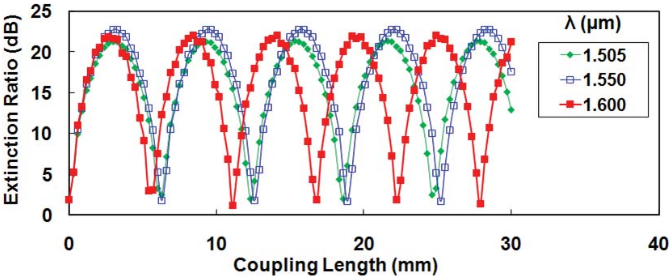

Fig. 4. Extinction ratio of LP_{11ax} mode versus coupling length for coupler-1.

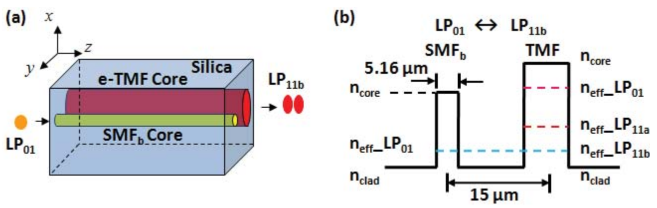

Fig. 5. (a) Waveguide structure of coupler-2. (b) Refractive index profile of the coupler. SMF is preprocessed to phase-match LP_{11b} mode in e-TMF.

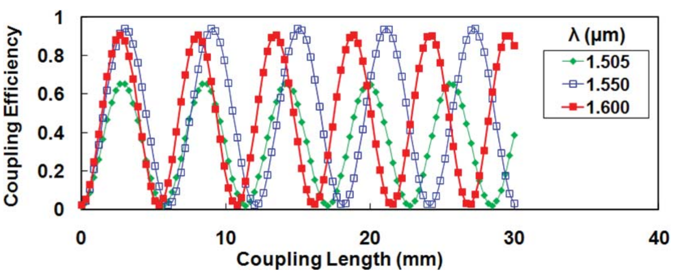

Fig. 6. Power coupled into LP_{11bx} mode versus coupling length for coupler-2.

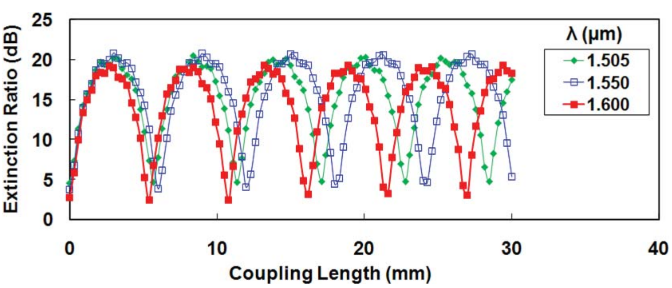

Fig. 7. Extinction ratio of LP_{11bx} mode versus coupling length for coupler-2.

which translate into losses of 0.11$\sim$1.55 dB for LP_{11a} mode and 0.16$\sim$1.87 dB for LP_{11b} mode. The wavelength dependence of ER is shown in Fig. 9. It can be seen that the ER can be maintained above 19 dB within wavelength range at a coupling length of 3 mm. We also perform the simulation for TM excitation and find both coupling efficiency and extinction ratio has similar performance to that of TE excitation as shown in Fig. 3 $\sim$ Fig. 9. This indicates a good polarization insensitivity of our proposed SMC design.

B. Symmetric Mode Coupler

In an asymmetric mode coupler, mode coupling is achieved through phase-matching by manipulating the core size of SMF

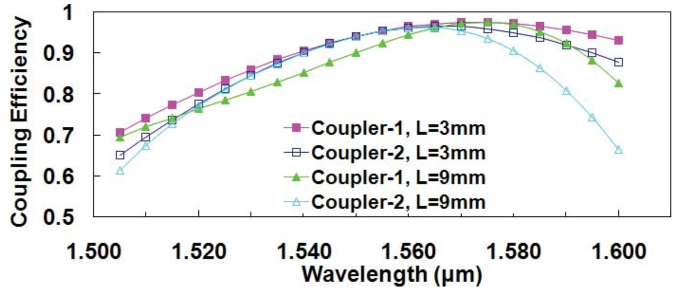

Fig. 8. Coupling efficiency versus wavelength for both coupler-1 and -2, at coupling lengths of 3 and 9 mm.

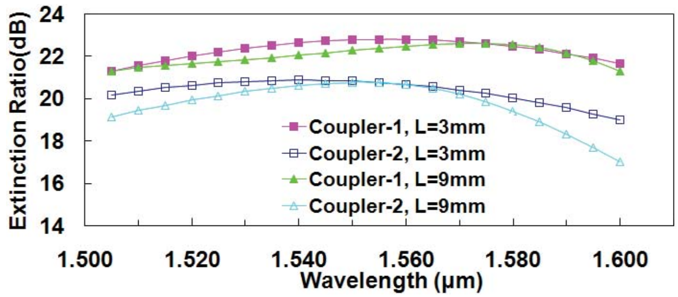

Fig. 9. Extinction ratio versus wavelength for both coupler-1 and -2, at coupling lengths of 3 and 9 mm.

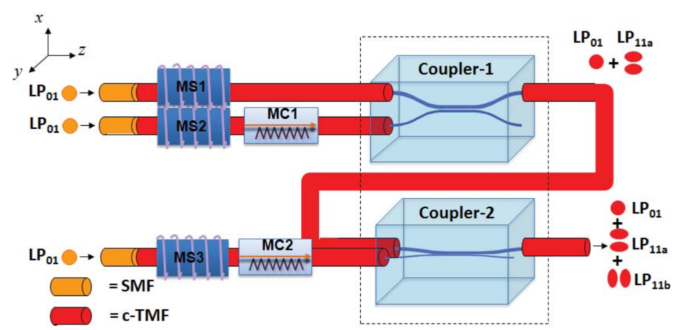

Fig. 10. 3 × 1 symmetric mode coupler consisting of cascaded LP_{11} mode couplers. c-TMF: circular-core TMF. MS: mode stripper. MC: mode converter.

thus effective index of fundamental mode. However because of different wavelength dependence of effective index in TMF and SMF, the phase velocity between the two modes in two fiber cores could still be mismatched over a large optical bandwidth, which explains the decrease in both coupling efficiency and ER on both sides from the center frequency in Figs. 8 and 9. In a low-loss SMF coupler, identical single mode fibers are often used and fused together so the phase-match condition is always satisfied over the entire coupler region even after tapering. We therefore apply this idea to the mode coupler where two identical TMF fibers are used to form a symmetric waveguide structure. A similar idea was proposed and experimentally demonstrated in [11], however, the combination of two degenerate LP_{11} modes was also not considered. Therefore, the mode coupler in [11] is not suitable for long distance transmission where the spatial orientation of LP_{11} mode is not maintained [2]. In this letter, we design a symmetric mode coupler that can also combine three spatial modes. The design of such a symmetric mode coupler is shown in Fig. 10.

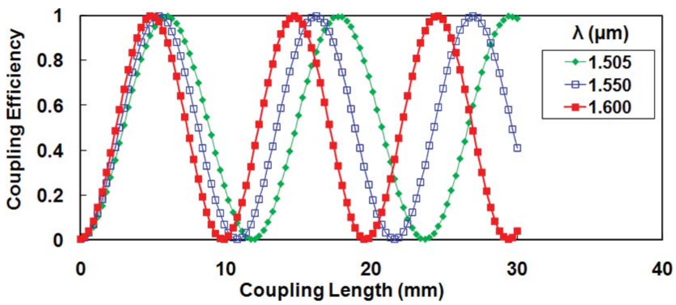

Fig. 11. Power coupled from LP_{01} to LP_{01} mode as a function of coupling length for both coupler-1 and -2.

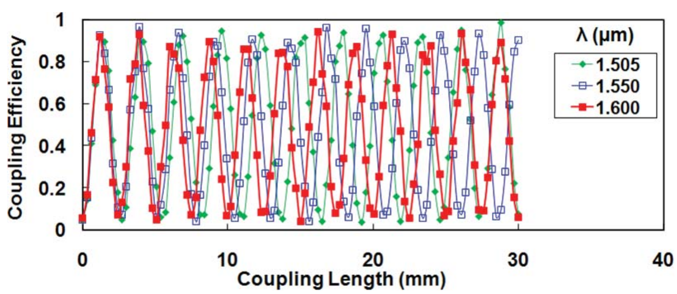

Fig. 12. Power coupled from LP_{11a} to LP_{11a} (or LP_{11b} to LP_{11b}) mode as a function of coupling length for coupler-1 (or -2).

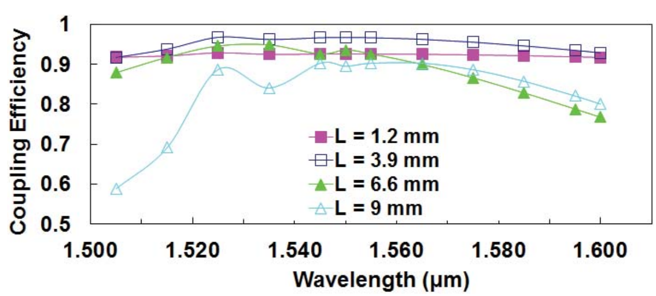

Fig. 13. Coupling efficiency of LP_{11a}-LP_{11a} (or LP_{11b}-LP_{11b}) versus wavelength for both coupler-1 and -2.

Similarly to the asymmetric case, in coupler-1 we align the two identical c-TMFs in x-axis, and in coupler-2 we align the two c-TMFs in y-axis. Coupler-1 and coupler-2 have the same parameters except the axis of core alignment. Because the overlap integral for LP_{11a}-LP_{11a} in coupler-1 is equal to the overlap integral of LP_{11b}-LP_{11b} in coupler-2 (only one pair is coupled each time depending on the axis of core alignment), the performances of the two couplers are also expected to be identical.

We simulate the center splicing technique for the connection of SMF to c-TMF. We also assume ideal mode strippers (MS) and mode converters (MC) for the generation of high-ER LP_{01} or LP_{11} modes into the c-TMFs. The simulation parameters are the same as in Section A except that c-TMFs ($r = 6$ μm and $\Delta = 0.47\%$) are used. According to the phase match condition, LP_{01} modes in the two c-TMF cores will couple to each other, whose coupling efficiency is illustrated in Fig. 11. Simultaneously, LP_{11a} (or LP_{11b}) modes in the two c-TMF cores will also couple to each other, whose coupling efficiency is illustrated in Fig. 12. We can see that due to the different gap and overlap integral, the coupling between LP_{01} modes is weaker and the coupling length to reach maxima is longer than the coupling between LP_{11} modes. Therefore we may find a position where the LP_{01}-LP_{01} coupling reaches minimum while the LP_{11}-LP_{11} coupling reaches maximum. However, to minimize wavelength dependence we need also use the first maximum of LP_{11}-LP_{11} coupling, therefore we choose $L = 1.26$ mm as the optimal coupling length. The coupling efficiencies as a function of wavelength at $L =$ 1.2, 3.9, 6.6 and 9 mm (maxima at $\lambda = 1.55$ μm) are plotted in Fig. 13. We find out that the theoretical loss is less than 0.15~0.38 dB for LP_{11} mode and 0.46~0.67 dB for LP_{01} mode, respectively, over a wide wavelength range of 1505~1600 nm. The ER between LP_{01} and LP_{11} mode are not plotted since it will only introduce additional loss rather than interference as MCs are used as mode selector. Because of the phase mismatch between LP_{01} and LP_{11} modes, there is no appreciable coupling between them over a short length. The modal crosstalk between LP_{11a} and LP_{11b} mode is also minimized through precise core alignment.

III. Conclusion

In summary, we show two optimal designs of fused fiber mode couplers for use in FMF transmission. Space-division multiplexing based on FMF may have a promising potential with the enhancement and optimization of these critical mode selective and coupling components.

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