All-fiber Fused-type Mode Selective Coupler with High Performance And Free of Pre-tapering

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ABSTRACT

In this paper we propose and demonstrate a novel all-fiber fused-type mode selective coupler (MSC) that capable of converting LP01 mode to LP11 mode with high efficiency and purity. Unlike other coupler fabrication techniques for which single mode fiber (or few mode fiber) must be pre-tapered, the advantage of our proposed coupler is that pre-tapering is not required. Two different fibers of the MSC have the same diameter. We achieve LP11 mode with a high modal purity of > 90% and a coupling efficiency of >20%, with a low insertion loss of about 0.3 dB at the wavelength of 1064 nm.

Keywords: mode selective coupler; few mode fiber; phase match; weak fusion

1. INTRODUCTION

Over twenty years ago, mode selective couplers (MSCs) are widely used in optical switches [1], filters [2], sensors [3], dispersion compensators [4], etc. Especially in optical fiber communications [5], since the MSCs can provide unique functions useful for mode multiplexer and demultiplexer in the space division multiplexing (SDM) system.

Various kinds of achieve mode conversion couplers are demonstrated, such as the polished couplers [6], fused etched multi-mode couplers [7], stress induced modal couplers [8]. However, fabrication techniques of these MSCs have high loss and low coupling efficiency [9]. Furthermore, their environmental stability is poor [6]. In order to improve the MSC performance, K. Y. Song et al. demonstrate an environmentally stable fused-type MSC with low loss and high efficiency. They use a tapered two mode fiber (TMF) as the single mode fiber (SMF) which was then fused together with another pre-etched TMF as to remove degeneracy between the high order modes [10]. In 2014, Ismaeel et al. proposed a mode selective coupler made from the combination of a few mode fiber (FMF) and a SMF, which has an improved performance and simplicity. They pre-taper a SMF to a specific diameter and use the weak fusing method to convert the LP01 mode (in SMF) into LP11, LP21 and LP02 modes (in the FMF) respectively [11]. However, the SMF (or FMF) must be pre-tapered to achieve phase matching between the LP01 mode in the SMF and high order modes in the FMF. Pre-tapering complicates the fabricating process and limit the coupling efficiency due to the different diameters of the two fibers of coupler.

In this letter, we theoretically and experimentally present a novel all-fiber MSC capable of exciting LP11 mode in TMF at 1064 nm with high coupling efficiency and low insertion loss. The MSC is made from weak fusion of a special SMF at 1064 nm and a conventional single mode telecom fiber as the TMF. Pre-tapering process is eliminated in the fabrication process of the MSC which improves its performance and simplicity.

2. THEORETICAL ANALYSIS

The basic structure of the MSC is depicted in Fig. 1. It consists of a TMF and a SMF. The conventional single mode telecom fiber (SMF-28, core/cladding diameter = 8.2/125μm, NA = 0.14) is used as the TMF at wavelength of 1064 nm. A special fiber is used as the SMF, requiring that the refractive index of its core and cladding at the wavelength of 1064 nm is smaller than that of the TMF (SMF-28). The principle of the coupler is to phase match the fundamental mode in the SMF with a high-order mode in the TMF, and achieve mode conversion to high-order modes [11].

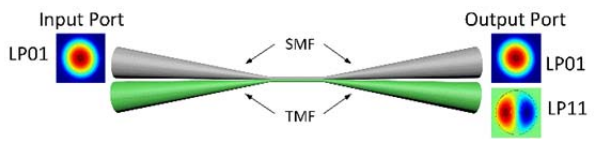

Fig. 1. Schematic of the MSC. The LP01 mode is launched into the SMF input port, the LP11 mode is expected to be excited at the TMF output port, while the uncoupled LP01 mode will propagate along the SMF.

According to the coupling mode equation [12]:

$$P_1(z) = \left|A_1(z)\right|^2 = 1 - F^2 \sin^2\left(\frac{C}{F}z\right) \quad (1)$$

$$P_2(z) = F^2 \sin^2\left(\frac{C}{F} z\right) \quad (2)$$

$$F = \left[1 + \frac{(\beta_1 - \beta_2)^2}{4C^2}\right]^{-1/2} \quad (3)$$

Where z is the distance along the coupling region of the coupler, A_1 is the modal field amplitudes of the fundamental mode (LP01) in the SMF. β_1 and β_2 are the propagation constants of the fundamental mode in the SMF and a certain high order mode in the FMF, respectively. C is the coupling efficiency. Suppose β_2 is the propagation constant of the LP11 mode in the TMF. When β_1 is equal to β_2, the phase mismatch $\Delta\beta=\beta_1-\beta_2$ is equal to 0, indicating that the fundamental mode (LP01) in the SMF and the high order mode (LP11) in the TMF meet the phase matching conditions. Under phase matching conditions, Eqs.1 and 2 can be simplified as: $P_1(z) = \cos^2(Cz)$ and $P_2(z) = \sin^2(Cz)$ indicating a complete periodic power exchange between the two modes in the lossless case and achieve the conversion between LP01 mode and LP11 mode.

Since the propagation constant of the mode varies with the diameter of the fiber, in order to meet the phase matching conditions, it is necessary to find the optimum fiber diameter. We use the finite element method (FEM) simulation mode effective refractive index with the fiber diameter changes, as shown in Fig. 2. The curve SMF-LP01 and the curve TMF-LP11 have a point of intersection at a radius of about 11.2μm. The reason for the point of intersection is explained as follows. Firstly, the refractive index of the cladding and core of the SMF is smaller than that of the cladding and the core of the TMF fiber at wavelength of 1064 nm. Secondly, according to the optical waveguide theory, the effective refractive index of the higher order mode decreases faster than the effective refractive index of the fundamental mode as the diameter of the fiber decreases [13].

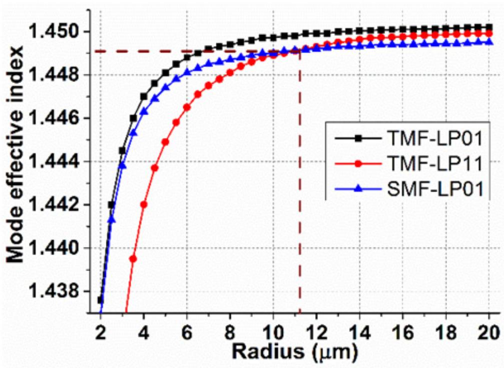

Fig. 2. The mode effective index of the LP01 mode (in the SMF) and the LP11 mode (in the TMF) versus different fiber radius at the wavelength of 1064 nm.

We use beam propagation method (BPM) to calculate the modes propagating in the MSC and confirm the phase matching condition. As shown in Fig. 3, the diameter of the SMF and the diameter of TMF have a same diameter of 11.2 μm in the coupling region. The simulation results show that the mode power of the LP01 mode (in the SMF) and the LP11 (in the TMF) are periodically exchanged in the coupled region. Fig. 3(a) and (b) show the power exchange in the coupling region when LP01 mode in the SMF converts to LP11 in the TMF. Fig. 3(c-f) show the mode field distributions along the coupling region when LP01 mode converts to the LP11 mode in one period.

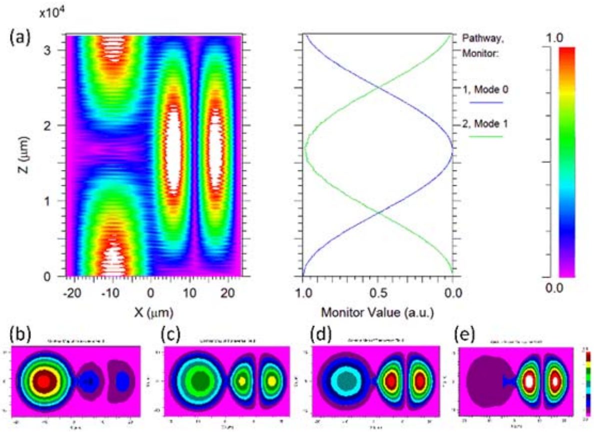

Fig. 3. Simulation results: (a) mode intensity distribution in the fiber; (b) The power exchange in the coupling region when LP01 mode in the SMF converts to LP11 mode in the FMF; (c-f) Evolutions of the mode field distribution in the coupling region when LP01 mode converts to LP11 mode in one period.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

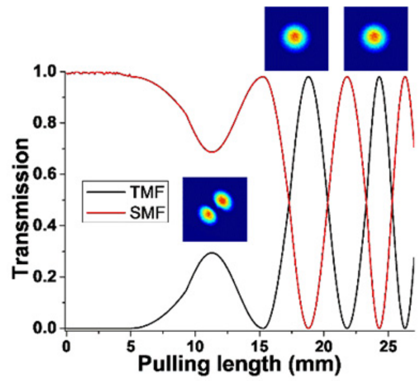

Fig. 4. Power transfer between the two ports of the coupler against pulling length: a periodic power transfer between the output ports is observed.

In order to maintain the geometry of the two fibers and ensures accurate modal conversion efficiency and mode purity, we use weak fusion rather than strong fusion to fabricate the MSC. The SMF was aligned directly (without pre-tapered) with the TMF and they are fused together using the modified flame brushing technique. During the pulling process, a laser source with the wavelength of 1064 nm is launched into the SMF input port. Meanwhile, optical power of the two output ports is monitored. Fig. 4 shows the power curves for the SMF output port and the TMF output port against pulling length. From Fig. 4 we can see a sinusoidal power transfer between the two output ports. We detected the mode field distribution at the output of the TMF with different pulling lengths by a CCD detector

(CinCam IR). The LP11 mode could be selectively excited at extensions of 6 to 13 mm in the TMF, however, when the pull length exceeds 13 mm, the LP01 mode is selectively excited in the TMF.

At the pulling length of 11 mm, we use the CCD to detect the modal distribution at the MSC's SMF output port and the TMF output port. As shown in Fig. 5, the measured coupling efficiency of the LP11 mode is >20%. The purity of the LP11 mode is measured to be > 90% by tight bend approach, while insertion losses of the MSC is <0.3dB.

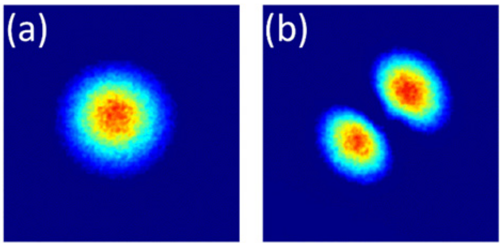

Fig. 5. The measured mode field distribution at the output ports of the coupler: (a) SMF output port; (b) TMF output port.

In order to confirm whether the experimental results and simulation results are consistent, at the pulling length of 11 mm, the MSC coupling region and cross-section were measured by a high-precision optical microscope, as shown in Fig. 6(a) and 6(b), it is confirmed that the SMF and the TMF have the same diameter of about 22.4 μm and the coupler cross-section is weakly fused. The experimental results are in good agreement with the simulation results.

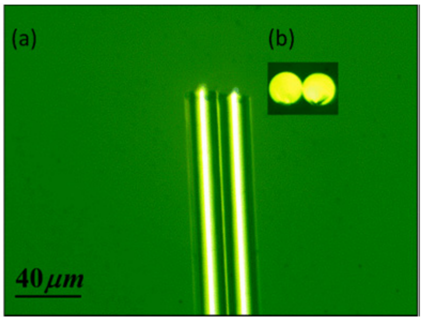

Fig. 6. Optical microscope image of the MSC: (a) Coupling region of the MSC; (b) Weakly fused coupler cross section.

4. SUMMARY

We present a very simple all-fiber fused-type mode selective coupler having a high coupling efficiency and low insertion loss for converting the LP01 mode into the LP11 mode at the wavelength of 1064 nm. Weak fusion without pre-fusing technique is used for fabrication of the MSC consists of a TMF and a SMF, based on the principle of phase-matching. This MSC could have potential applications in the fields of optical fiber communications and sensing systems.

5. ACKNOWLEDGMENTS

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