High Performance Fused-Type Mode-Selective Coupler Using Elliptical Core Two-Mode Fiber at 1550 nm

Kwang Yong Song, In Kag Hwang, Seok Hyun Yun, and Byoung Yoon Kim, *Fellow, IEEE*

***Abstract*—In this letter, we demonstrate a high performance fused-type mode selective coupler that couples the LP_{11} mode in one fiber and the LP_{01} mode in another using highly elliptical core two-mode fibers. The phase-matching condition was achieved by etching and prepulling portions of two-mode fibers. The coupling efficiency and the mode extinction ratio of 56% to 80% and 22–32 dB, respectively, were achieved with high temperature stability over 1515- to 1595-nm wavelength range.**

***Index Terms*—Directional couplers, mode coupling, optical fiber couplers, optical fiber devices, optical fiber filters.**

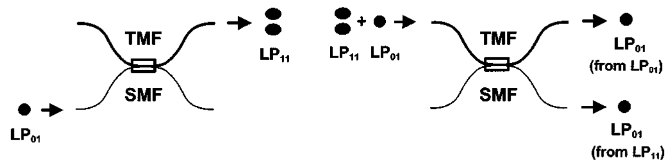

Fig. 1. The function of mode selective coupler. (a) The mode conversion from the LP_{01} mode in SMF arm to the LP_{11} mode in TMF arm. (b) The LP_{01} mode and the LP_{11} mode in TMF arm are divided into the LP_{01} modes of two arms. TMF: Two-mode fiber. SMF: Single-mode fiber.

I. Introduction

Fiber-optic devices utilizing LP_{11} mode in two-mode fiber (TMF) provide unique functions useful for optical communication systems and sensors. Several examples have been reported such as dispersion compensators [1], optical add-drop multiplexers [2], optical switches [3], acoustooptic modulators and filters [4]. Elliptical core TMFs were used to achieve the stability of intensity distribution [5]. One of the key functions needed in such devices is broad-band mode conversion and/or mode selection between the LP_{01} and the LP_{11} mode. Mode selective couplers (MSCs) in the form of a polished coupler [6] have been demonstrated with high coupling efficiency and high mode extinction ratio. However, polished-type couplers have poor environmental stability and cannot be used in practical systems. Therefore, the development of a fused-type MSC with environmental stability and reliability is essential for the practical application of various TMF devices. Some previous efforts to develop the fused-type MSCs [7], [8] at the visible wavelength range have suffered from too large insertion loss with poor mode extinction ratio to be considered practical. Recently, we have demonstrated a high performance fused-type MSC with circular core TMF at 1064 nm [9].

In this letter, we newly present a high performance fused-type mode-selective coupler (FMSC) operating around 1550 nm using elliptical core (e-core) TMF, which can be practically applied to optical communication systems. We describe a simple numerical modeling used to achieve phase-matching condition in the coupler waist, the fabrication process, and the experimental results.

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K. Y. Song and B. Y. Kim are with the Department of Physics, Korea Advanced Institute of Science and Technology, 305-701 Taejon, Korea (e-mail: songky@kaist.ac.kr).

I. K. Hwang and S. H. Yun are with Novera Optics, Inc., San Jose, CA 95131 USA.

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II. Device Principle

MSC is formed with a TMF arm and a single-mode fiber (SMF) arm, and its function is to couple the antisymmetric LP_{11} mode of the TMF arm and the symmetric LP_{01} mode of the SMF arm. Fig. 1 shows the function of MSC. As shown in Fig. 1(a), when LP_{01} mode is launched to the SMF arm, it is converted into the LP_{11} mode of the TMF arm (mode conversion). Fig. 1(b) shows the opposite situation. When both the LP_{01} and the LP_{11} mode propagate in the TMF arm, they are separated into the LP_{01} modes of two different fibers (mode selection). For these functions, phase-matching condition between the LP_{01} mode of SMF arm and the LP_{11} mode of TMF arm should be satisfied in the coupling region. In addition, large phase mismatch with the other modes is necessary to reduce insertion loss and enhance mode extinction ratio by suppressing unwanted mode coupling.

In a circular core TMF, the intensity distribution (or lobe orientation) of LP_{11} mode is not maintained as it propagates along the fiber, which can limit the practicality of TMF devices. When a highly elliptical core TMF is used, the lobe orientation of LP_{11} mode is maintained over a long length with respect to the major (even LP_{11} mode) or minor (odd LP_{11} mode) axis of the core ellipse [5], [10]. In this work, we newly designed the parameters of an e-core TMF operating around 1550 nm to guide only the even LP_{11} mode with the odd LP_{11} mode cutoff to avoid the unwanted interference between them. The fiber had a step index profile and the parameters were the index difference Δ of 0.9%, the core radius of 4.2 μm $\times$ 2.8 μm, and the cladding diameter of 90 μm. The same TMF was used for the SMF arm after prepulling the fiber to a smaller diameter.

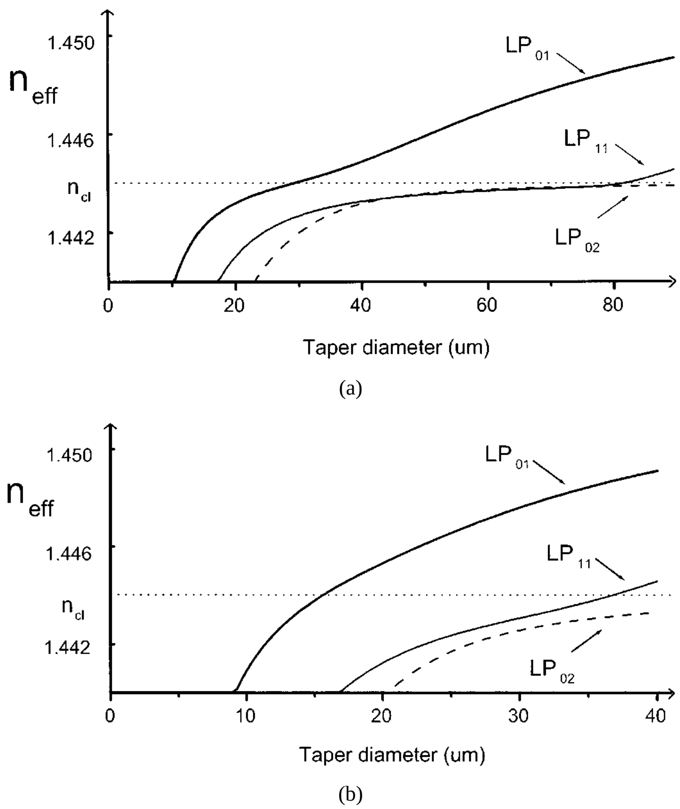


Fig. 2. The effective refractive indices of propagating modes as a function of taper diameter at 1550 nm (a) in original TMF, (b) with cladding etched to 40 μm. $n_{\rm cl}$: refractive index of cladding.

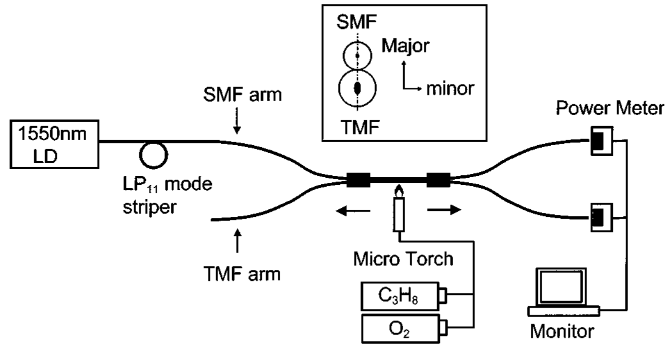


Fig. 3. Experimental setup for the fabrication of fused-type mode selective coupler. SMF: Single-mode fiber. TMF: Two-mode fiber. LD: Laser diode.

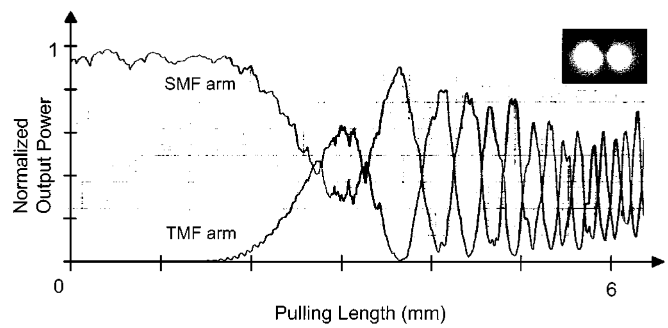


Fig. 4. Normalized output power in both arms as a function of pulling length.

III. Numerical Modeling

In order to estimate the required experimental parameters for the fabrication of FMSC, we calculated the change of effective refractive indexes ($n_{\rm eff}$'s) of propagating modes as a function of the taper diameter of the TMF. In this calculation, we approximated the e-core fiber to an equivalent step-index circular core fiber for simplicity [10]. In order to determine the parameters of an equivalent circular-core fiber, the original fiber was tapered into three different diameters and the $n_{\rm eff}$'s of guided modes were experimentally measured. The obtained parameters of an equivalent circular core fiber were the index difference Δ of 0.86%, the core radius of 3.24 μm, $V = 2.49$ at $\lambda = 1550$ nm. In this circular core approximation, we expect the errors in the calculated $n_{\rm eff}$'s of propagating modes to become smaller with higher degree of taper because the effect of core ellipticity is reduced with the expansion of the mode field into the cladding.

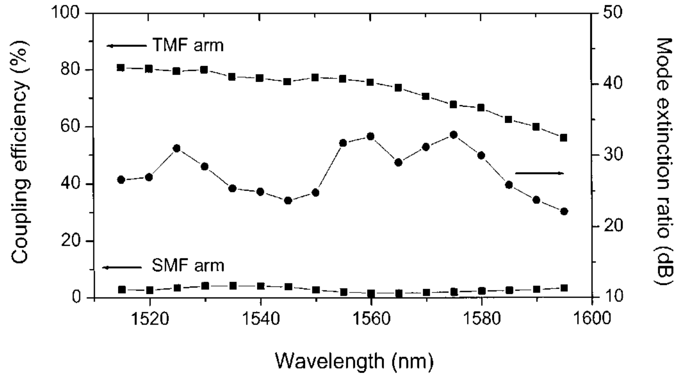
Fig. 2 shows the $n_{\rm eff}$'s as a function of the taper diameters in (a) the original fiber and (b) when its cladding is etched to 40 μm before tapering at the wavelength of 1550 nm. In Fig. 2(a), it is remarkable that the $n_{\rm eff}$ of the LP_{11} mode becomes very close to and even crosses that of the LP_{02} mode in the taper waist which is not a guided mode in the core of the TMF. The well-phase-matched large coupling to LP_{02} mode induces large insertion loss and inconsistent coupling behavior in the fabrication of FMSC. However, when the cladding is initially etched to a proper diameter (40 μm in this case) before tapering, the $n_{\rm eff}$'s of LP_{11} mode and LP_{02} mode can be clearly separated as shown in Fig. 2(b). The realization of this feature is critical for the reduction of insertion loss. For a simple numerical estimation to find the phase-matching condition in the coupler waist, we assume the two fibers are weakly fused and the waveguide properties of each one are preserved in the fabrication process.

IV. Experiments

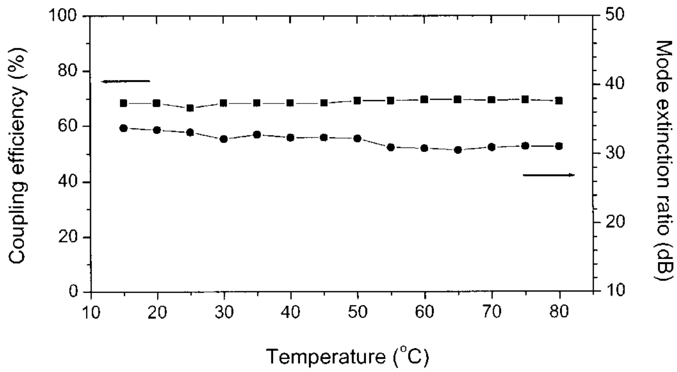
Fig. 3 shows the experimental setup for FMSC fabrication along with an in-situ performance test equipment. The light source was 1550-nm DFB laser diode. The fibers were heated using traveling flame with propane and oxygen. We monitored the cross section of sample fibers and the gas flow was carefully controlled to ensure the weak fusion of two fibers based on the sample test.

An SMF arm was prepared by pulling a section of the TMF to the diameter of 25 μm and a section of TMF arm was etched using HF solution to the diameter of 40 μm according to the simulation result. The major axis of e-core TMF arm was aligned parallel to the plane determined by the two fibers to achieve the maximum coupling strength as shown in the inset of Fig. 3. We used a LP_{11} mode stripper (tight bend) to launch only the LP_{01} mode in the input port of SMF arm. The SMF arm and the TMF arm were pulled together in the flame to form a fused coupler. The optical power from the output ports of both arms was monitored during the process. The pulling was stopped when the coupled power reached the maximum. The mode extinction ratio—the ratio of the coupled LP_{11} mode power to the coupled LP_{01} mode power in the output port of the TMF arm—was measured after the fabrication by using mode stripper.

Fig. 4 shows the normalized output power in both arms as a function of the elongation. The initial insertion loss about 10% in the SMF arm is thought cladding mode coupling which came



(a)



(b)

Fig. 5. (a) Wavelength and (b) temperature dependence of fused-type mode selective coupler. Temperature dependence was measured at 1550 nm and different couplers were used in the two measurements.

from some deformation of the narrow SMF arm by the initial fusion of the two fibers because the LP_{01} mode field expanded to the cladding-air boundary at initial diameter. We observed the over-coupling behavior similar to that of typical fused coupler. The gradual decrease of the local maxima could be attributed to the phase mismatch and the unwanted coupling to another cladding mode. In addition, due to a slight misalignment of fiber axis, the coupling to odd LP_{11} mode with orthogonal lobe orientation could contribute to the insertion loss. Since 100% mode coupling is desirable in most applications [1]–[3], the remaining uncoupled power in the SMF arm is also regarded as the insertion loss. The inset in Fig. 4 is the far-field pattern from the output port of the TMF arm, where the mode extinction ratio is about 25 dB.

We measured the spectral characteristics of fabricated coupler using tunable LD and power meter in the same launching condition shown in Fig. 3, and the result is shown in the Fig. 5(a). The coupling efficiency of more than 56% is maintained from 1515 to 1595 nm with the maximum of 80% at 1520 nm.The maximum coupling wavelength depends on the position of pulling stop in the fabrication. We expect further improvement in the coupling efficiency will be possible by reducing unwanted cladding mode coupling coming from the initial deformation of fibers in the fusion with more careful control of fiber alignment and heating temperature.The mode extinction ratio is from 22 to 32 dB over the wavelength range, which shows its characteristics as a highly selective modal filter. The remaining power in the SMF arm is less than 4%. The polarization dependence of the coupling efficiency in the TMF arm is less than 5% in the wavelength range, which mainly originated from the polarization dependence of LP_{11} mode in e-core TMF. When LP_{01} mode is launched to the input port of the TMF arm, insertion loss was about 4% through the coupler.

We measured the temperature dependence of FMSC and it is shown in Fig. 5(b). The variation of coupling efficiency and the extinction ratio are less than 3% and 3 dB, respectively, over the temperature range of 65°, which shows its high environmental stability.

We expect the same fabrication scheme can be applied to higher order mode coupling device such as LP_{01}-LP_{02} mode selective coupler.

V. Summary

In conclusion, we have demonstrated a novel high performance fused-type mode selective coupler operating around 1550 nm using elliptical core TMF. The phase-matching condition in the coupler waist was satisfied by etching and prepulling portions of TMFs. This component will be useful in two-mode fiber applications for optical communication systems.

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