Multi-channel mode converters based on in-line fiber modal interferometer

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Abstract—**A modal interferometer was proposed to realize multi-channel mode conversion in two mode fiber. The near-filed pattern confirmed the LP_{01} mode was converted into LP_{11} mode at the destructive wavelengths. The mode conversion was realized at 20-channels in the C+L wavelength band with conversion efficiency up to 99.5% and insertion loss lower than 0.6 dB.**

Keywords-optical fiber devices; mode converter; two mode fiber; modal interferometer; wavelengthand mode division multiplexing

I. INTRODUCTION

The standard single-mode fiber (SMF) optical network is gradually approaching the theoretical capacity limitation in the last decade [1, 2]. New key technological breakthrough is imminently required to exploit the spatial domain for substantially increasing the per-fiber capacity since all other physical signaling dimensions (i.e. time, frequency, phase/amplitude and polarization) are already used in current single-core single-mode fiber communication system. Mode-division multiplexing in few mode fiber is one of the promising approaches in space-division multiplexing transmission technology that is considered for overcoming current limitation of the transmission capacity in a single mode fiber [3-5]. In the MDM system, the mode converter is required to convert the fundamental mode in standard SMF into higher order modes in FMF. Various schemes for mode multiplexing have been reported. The most well-known and widely used technique is based on spatial light modulators [6] or phase plates [7], but it is complicate and difficult for bulk devices to align the optical path, hence the loss of the mode coupling is large. Low loss and low-crosstalk mode converter based directional coupler have been demonstrated to realize two mode coupling [8], while coupling of the degenerated mode with the same effective indexes is not possible. Recently, photonic lantern was reported to convert multiple beams into the super-mode in FMF [9], while multiple-input and multiple-output processing is required to compensate the signal crosstalk. Another in-fiber mode converter is based on optical fiber gratings [10-12], including both reflection (fiber Bragg gratings, FBGs) and transmission (Long period fiber gratings, LPFGs) gratings. All gratings usually employed expensive laser inscription systems, like UV laser and CO_2 laser. Certainly, mechanical grating is an alternative to fabricate LPFGs [13-15]. But anyway, the grating period has to be carefully designed to make the converter work at the selected single wavelength according to the phase matching condition.

In this paper, we proposed and experimentally demonstrated a multi-channel mode converter in a two mode fiber (TMF). A modal interferometer was designed to convert the LP_{01} into LP_{11} mode in the TMF. The multiple phase matching points in the modal interferometer ensure the proposed mode converter can work at multi-channel wavelengths. We investigated both the transmission spectra and the near-field mode patterns to confirm the mode conversion at multi-channels

II. MECHANISM OF THE MODE CONVETERS

Fig.1 illustrates the mechanism of our proposed multi-channel mode converters. A TMF is employed to support fundamental mode LP_{01} and high order mode LP_{11} in the fiber. A standard SMF is spliced to a TMF for exciting the LP_{01} mode purely. To mechanically induce mode coupling from LP_{01} to LP_{11} mode, a bare metal plate is selected to stressed the TMF from above, and the TMF is deformed as a S-bend section. In the stress section, the LP_{01} mode is partly coupled into LP_{11} mode, and then both LP_{01} and LP_{11} modes propagated in the TMF after the first stress point. Due to the propagation constant mismatch, phase difference is produced between LP_{01} and LP_{11} modes. When two modes arrived at the second stress point, the LP_{11} mode can be coupled back to LP_{01} mode, while the remaining LP_{01} mode can be coupled to LP_{11} mode again. The two stress points constructed a modal interferometer between LP_{01} and LP_{11} modes, and the output intensity in LP_{01} mode is expressed as

$$I = I_{01} + I_{11} + 2\sqrt{I_{01} I_{11}} \cos\phi \qquad (1)$$

with phase difference

$$\phi = 2\pi \Delta n_{eff} L / \lambda \qquad (2)$$

where I_{01} and I_{11} are the intensity after the first stress point, Δn_{eff} is the effective refractive index difference between two modes,

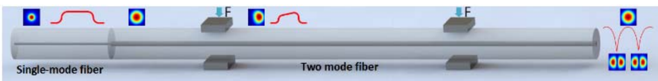

Fig.1 Schematic of the multi-channel mode converter in two mode fiber

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L is separation between two stress points, and λ is the optical wavelength. When the phase difference is an odd multiple of π, constructive interference occurs, and the light is still confined in the LP_{01} mode, showing peaks in spectrum. When the phase difference is an even multiple of π, destructive interference occurs, and the light is converted into LP_{11} mode, showing troughs in spectrum. All LP_{01} and LP_{11} modes at the peaks and troughs should satisfy the follow equations:

$$\lambda_{01}^{k} = \frac{2\Delta n_{eff} L}{2k} \quad \text{for } LP_{01} \text{ mode at peaks;}$$
$$\lambda_{11}^{k} = \frac{2\Delta n_{eff} L}{2k+1} \quad \text{for } LP_{11} \text{ mode at dips.} \qquad (3)$$

where k is an integer. For a given TMF, the channel wavelengths of the proposed mode converter are mainly determined by the interferometer length L, which give a large freedom to design the channel location, channel spacing, and channel numbers in our proposed mode converters.

III. Experimental Setup and Results

A. *Transmission spectra*

Fig.2 (a) illustrates the schematic diagram for measuring the transmission spectra of the mode converters in the TMF (two-mode step-index fiber, OFS). The TMF employed for experiments has a core diameter of 19 µm, a cladding diameter of 125 µm, a cladding index of 1.444 and a core index of 1.449, which can support LP_{01} and LP_{11} modes. A broadband source covered C+L band was injected into the SMF, and the SMF is directly spliced to the TMF. An input LP_{01} mode from the SMF excited the LP_{01} mode in the FMF with low insertion loss and high mode purity. Moreover, the TMF was tightly wrapped around a 12 mm diameter still roll, working as a mode stripper to further suppress the unwanted LP_{11} mode and to ensure a pure LP_{01} launching before the first stress point. After the second stress point, another mode stripper was also used to attenuate the generated LP_{11} mode and make sure only LP_{01} mode is coupled back to the SMF for measuring the transmission spectra.

We constructed several mode converters with different lengths. Fig. 3(a) illustrates typical transmission spectra of the mode converters with L = 5 and 75 cm. The spectra exhibit comb-like fringe patterns. At the peaks, the light is confined in the LP_{01} mode with insertion loss as low as 0.6 dB which includes two S-bend loss at the stress points and two splicing loss between SMF and TMF. At the troughs, the light in LP_{01} mode shows a large loss of 20 dB, which means the light is almost completely transferred from LP_{01} to LP_{11} mode, and the conversion efficiency is as high as 99%. In addition, the transmission spectra have multi-channels in the C+L wavelength band (from 1530 to 1630 nm), and the channel spacing is dependent on the length of the mode converter. The channel spacing will decrease if we increased the length. For instance, when we increased the length from 5 to 75 cm, the channels spacing decreased from 70 to 5 nm, and the channel numbers accordingly increased from 2 to 20.

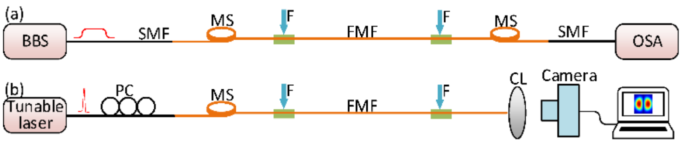

Fig.2 Schematic diagram for measuring (a) the transmission spectra and (b) the mode filed profile in our proposed multi-channel mode converters. BBS: broadband source, SMF: single mode fiber, TMF: two mode fiber, MS: mode stripper, OSA: optical spectrum analysis, PC: polarization controller, CL: collimating lens.

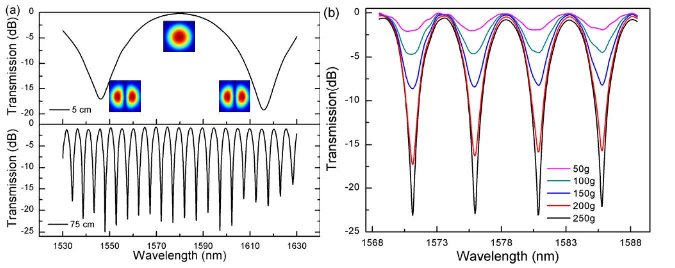

Fig.3 (a) Transmission spectra of the mode converters with L = 5 cm (top panel) and L = 75 cm (bottom panel). (b) Evolution of the transmission spectra when increasing the force at two stress sections.

Furthermore, we also investigated the influence of the applied force on the transmission spectra of the mode converters. When we increased the applied force from 25 to 250 g with a step scale of 25 g, the trough transmission gradually decreased from -1.0 to 23 dB, and the conversion efficiency accordingly increased from 20% to 99.5%. Fig. 3(b) illustrates several typical transmission spectra of the mode converter with L = 75 cm when applied force was increased to 50, 100, 250, 200, and 250 g.

B. *Near-field mode pattern*

In Fig.2 (b), we used a tunable laser and an infrared camera to inspect the output near-field patterns for confirming the mode conversion at the troughs. The tunable laser (TSL510, Santec) has a tuning range from 1500 to 1630 nm. In this experiment, the second mode stripper on the output side was removed for injecting the output mode from TMF into a collimating lens directly. Firstly, we focused on the mode pattern evolution around a certain trough as shown in Fig. 4(a). We selected five typical wavelengths in the transmission spectrum which were labelled as A (1578.28 nm), B (1579.50 nm), C (1580.84 nm), D (1582.00 nm), and E (1583.20 nm). These five

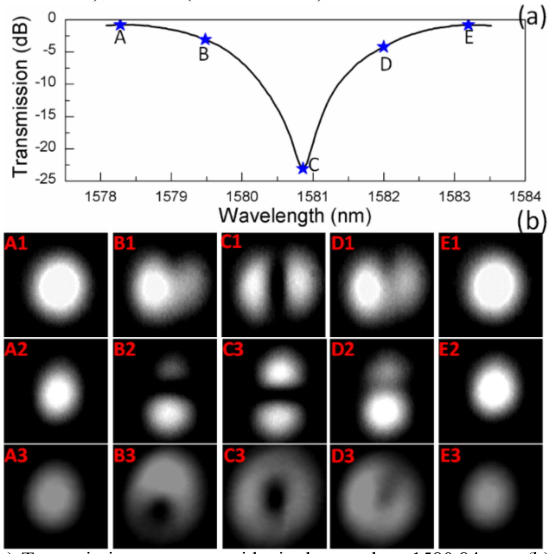

Fig. 4 (a) Transmission spectrum with single trough at 1580.84 nm, (b) Near-field patterns at the points A, B, C, D, and E in (a).

wavelengths include the trough (Point C), two adjacent peaks (Point A and E), and two middle positions (Point B and D), which cover different parts of the spectrum. Fig. 4(b) illustrates the typical near-field output patterns captured for the 75-cm mode converter at these five wavelengths. Initially, the tunable laser was located at the peak, and the output pattern shows clean LP_{01} mode (A1, A2, and A3). As the wavelength gradually moves towards the trough, the output pattern starts to show the contribution from the LP_{11} mode (B1, B2, and B3) and, at the trough, the output pattern shows pure LP_{11} mode (C1, C2, and C3). When the wavelength moves away from the trough, the LP_{11} mode component diminishes and the output pattern shows mixture between LP_{01} and LP_{11} modes. When the wavelength arrived at the next the peak, the output pattern shows LP_{01} mode again. The evolution of the mode pattern proves that LP_{01} mode is completely converted into LP_{11} mode at the trough in the transmission spectra.

At the trough, we were able to obtain three typical LP_{11} mode patterns with different shapes by adjusting the polarization state of the input light. C1 and C2 show the scalar LP_{11} mode patterns with two lobes and orthogonal orientations, calling as LP_{11a} and LP_{11b}. The exact second-order modes supported by the TMF are four vector modes, namely, the TE_{01}, TM_{01}, HE_{21}^{even}, and HE_{21}^{old} modes. Therefore, the transmission troughs in Fig.3 are actually due to the conversion to any of these vector modes or a mix of them, depending on the polarization state of the LP_{01} mode launched into the converter. By carefully adjusting the polarization state of the input LP_{01} mode, we could generate all four vector modes, which showed similar donut-shaped mode patterns. Here, we only gave an example of TM_{01} mode (C3). To identify these vector modes, we placed a rotatable polarizer after the collimating lens and analyzed relationship between the orientations of the polarizer and the orientations of two lobes in the inspected patterns. No matter the scalar mode and vector modes, the spatial interference between the LP_{01} and LP_{11} modes leads to asymmetric field patterns when the wavelengths locate outside the trough (Point B and D), as shown by the patterns B1, B2, B3, D1, D2, and D3 in Fig. 4(b).

Moreover, we measured the near-filed mode patterns at all troughs in the transmission spectrum (bottom panel in Fig. 3(a)) of the mode converter with L = 75 cm. The wavelength of the tunable laser was sequentially located at the 20 troughs in the wavelength range from 1530 to 1630 nm. The state of input polarization controller was adjusted at the channel wavelength of 1580.84 nm, and then it was maintained

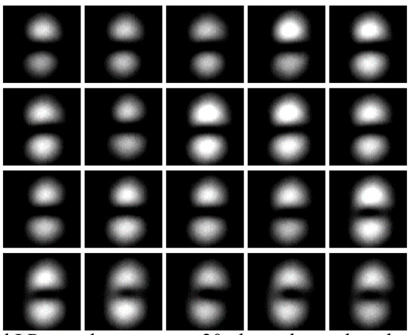

Fig. 5 Near-field LP_{11} mode patterns at 20-channel wavelengths.

throughout all 20 channels. Fig. 5 illustrates the near-field LP_{11} mode patterns at 20 channels. These mode patterns confirm that the proposed mode converter can realize mode conversion from LP_{01} to LP_{11} mode at multi-channels.

IV. CONCLUSION

In conclusion, we have investigated the multi-channel mode converter via a modal interferometer in the two mode fiber. The transmission spectra with multiple constructive and destructive fringes have been demonstrated with different interference length and different applied force at two stressed points. The near-field mode patterns confirmed the mode conversion from LP_{01} to LP_{11} mode at the multi-channel destructive wavelengths.

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