Ultra-Wideband Mode Selective Couplers for Weakly-Coupled WDM-MDM Transmission

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Abstract: Ultra-wideband mode selective couplers satisfying strict phase-matching conditions across S+C+L bands for mode multiplexing/demultiplexing of a 4-LP-mode FMF are designed and fabricated with side-polishing processing, based on which weakly-coupled FMF transmission is experimentally demonstrated. ©2024 The Author(s)

1. Introduction

The mode division multiplexing (MDM) technique utilizing different linearly-polarized (LP) modes in few-mode fibers (FMFs) has been widely recognized as a promising solution for capacity enhancement of single fiber [1]. Although different kinds of mode multiplexers/demultiplexers (MMUX/MDEMUX) including free-space optics, photonic lanterns (PL) and multi-plane light conversion devices (MPLC) have been extensively investigated [2,3]. The all-fiber approaches consisting of cascaded mode selective couplers (MSCs) are appealing for multiple merits such as low insertion loss, high conversion purity, flexible combination and easy fabrication [4]. Especially, it could play strong support in weakly-coupled FMF transmission requiring ultra-low modal crosstalk because the modal crosstalk induced by mode field mismatching at the junctions between optical components and fibers could be avoided if the MSCs are fabricated utilizing the transmission fiber [5]. Although broadband MSC-type MMUX/MDEMUX operating at the whole C-band has been successfully demonstrated for MDM and wavelength division multiplexing (WDM) transmission [6], it's highly expected that the operation bandwidth could be further enhanced.

In this paper, we propose an ultra-wideband MSC-type MMUX/MDEMUX by designing each custom SMF for each higher-order LP mode respectively to satisfy strict phase-matching conditions across multiple wavelength bands. Three kinds of custom SMFs for phase matching with the high-order LP_{11}, LP_{21}, and LP_{02} modes of a 4-LP-mode FMF are designed and fabricated. The MSCs are fabricated by side-polishing processing. Measurement results show that all of the MSCs achieve high coupling efficiencies exceeding 84% across the wavelength range of 1490~1610 nm. Furthermore, weakly-coupled MDM transmission at S+C+L bands based on these MSCs is successfully demonstrated.

2. Design and characteristics of the proposed ultra-wideband MSCs

Although typical MSCs could be easily fabricated by fused tapering method [7], the large insertion loss for the cascading structure will greatly limit its application in MDM transmission systems. Low-loss MSCs could be fabricated by side-polishing processing with the schematic structure shown in Fig. 1(a), in which both the SMF and the FMF are side-polished with proper depth and then mated together [4]. At optimized core-to-core distance and length of coupling area, light in the fundamental mode in SMF could be converted into the specific LP mode in the FMF with high selectivity and conversion efficiency. If the standard SMF is chosen for the fabrication, pre-tapering may be required for one of the two fibers to achieve the same n_{eff} at a specific central wavelength. However, the n_{eff} deviation across a wide band may lower the conversion efficiency. Designing different custom SMFs for strict phase matching across multiple wavelength bands with different LP modes in FMFs could solve this problem.

The proposed MSC scheme is verified by a design example for three high-order LP modes of a 4-LP-mode multiple-ring-core (MRC) FMF with the structure shown in Fig. 1(b) [8]. Three kinds of custom step-index SMFs are designed by sweeping parameters including the core diameter and the core/cladding index difference. For each set of parameters, the n_{eff} of the SMF over S+C+L bands is calculated to find the optimized designs for different high-order LP modes. The designed and fabricated index profiles of the three kinds of custom SMFs are shown in Fig. 1(c). Fig. 1(d) depicts the calculated n_{eff} of three kinds of fabricated custom SMFs and three high-order modes in the fabricated MRC-FMF ranging from 1460 nm to 1630 nm. It can be seen that the n_{eff} deviation is very slight. The maximum n_{eff}

deviation is 4.1× 10^{-4} for the LP_{02} mode, while it is only 7× 10^{-5} for the LP_{11} mode. No pre-tapering should be adopted for the fabrication of MSCs using side-polishing processing.

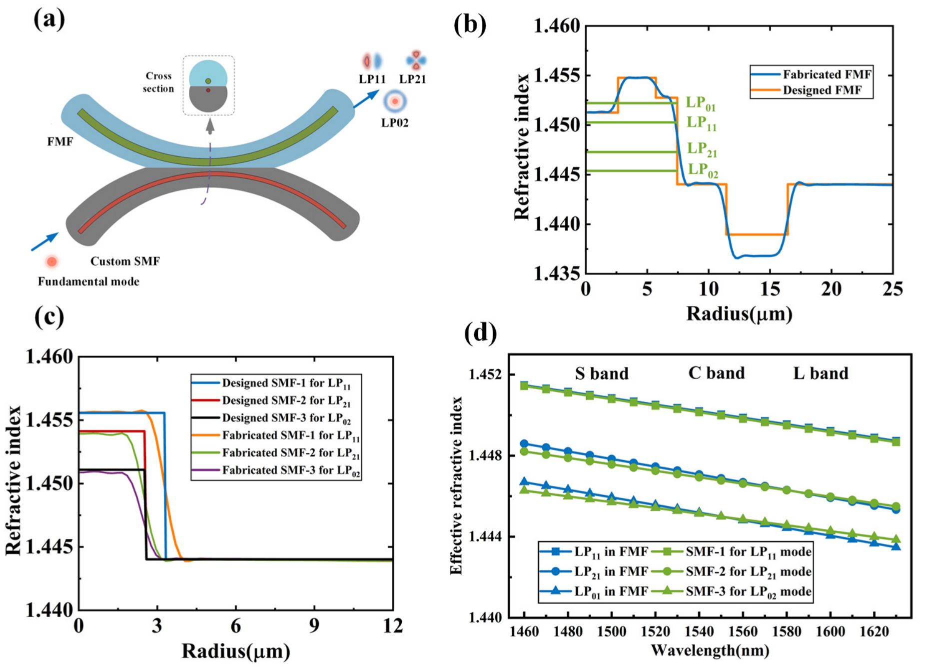

Fig. 1 (a) Schematic structure of a MSC with side-polishing processing. (b) Index profiles of designed and fabricated MRC-FMF. (c) Index profiles of designed and fabricated custom SMFs. (d) Calculated n_{eff} of fabricated custom SMFs and high-order LP modes of fabricated MRC-FMF.

The picture of the fabricated MSCs is shown in Fig. 2(a). We adopt the experimental setup in Fig. 2(b) to measure their characteristics. The coupling efficiencies of fabricated MSCs are measured by injecting light into the fundamental mode of the custom SMF with different wavelengths and monitoring the power at both output ports of the MSC. The coupling efficiencies of three kinds of MSCs are measured across the S+C+L bands, as shown in Fig. 2(c). The influence of insertion loss at the junction between standard SMF and custom SMF is not included for the calculation of coupling efficiencies. We can find that all the coupling efficiencies are larger than 84% across 1490~1610 nm. Fig. 2(d) shows the output mode patterns captured by a charge coupled device (CCD) camera of each MSC.

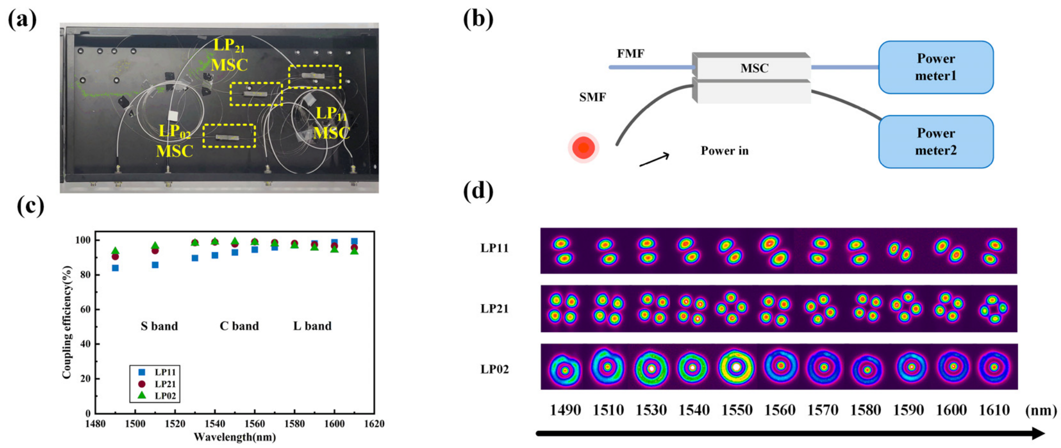

Fig. 2 (a) The picture of the fabricated MSCs. (b) The experimental setup for coupling efficiency measurement. (c) The measured coupling efficiency of each mode across 1490~1610 nm. (d) Measured mode fields across 1490~1610 nm.

3. Experimental setup and results for weakly-coupled FMF transmission

The characteristics of a pair of 4-LP-mode MUX/DEMUX consisting of the fabricated MSCs is measured, the cascading structure of which is shown at the bottom of Fig. 3(a). The cascading order for these MSCs are adjusted to balance their performance. For the excitation of the LP_{01} mode, the center alignment method is adopted by directly fuse standard SMF with the transmission MRC-FMF. The typical crosstalk matrix in back-to-back (B2B) cases at 1550 nm and 1590 nm. The results are shown in Table 1 and Table 2.

Table 1. Modal crosstalk for B2B case at 1550 nm (Unit: dB)

	LP_{01} out	LP_{11} out	LP_{21} out	LP_{02} out
LP_{01} in	—	-15.6	-25.8	-26.1
LP_{11} in	-14.7	—	-17.5	-18.6
LP_{21} in	-25.9	-22.7	—	-20.9
LP_{02} in	-25.2	-22.4	-20.1	—

Table 2. Modal crosstalk for B2B case at 1590 nm (Unit: dB)

	LP_{01} out	LP_{11} out	LP_{21} out	LP_{02} out
LP_{01} in	—	-16.3	-26.4	-27.9
LP_{11} in	-15.5	—	-16.8	-19.2
LP_{21} in	-26.1	-23.3	—	-20.6
LP_{02} in	-24.1	-23.5	-18.7	—

The experimental setup for the weakly-coupled FMF transmission to verify the performance of the ultra-wideband MSC-type MMUX/MDEMUX is shown in Fig. 3(a). At the transmitter, external cavity laser (ECL) sources with different wavelengths are utilized to generate a continuous-wave light. Then, 24.5-GBaud Nyquist-shaped dual-polarization quadrature phase shift keying (DP-QPSK) signal is generated by a dual-polaxrization in-phase and quadrature modulator (DP-IQ-MOD), which is driven by electrical baseband signals from an arbitrary waveform generator (AWG). After transmission over the MSC-type MMUX/MDEMUX and 1 km weakly-coupled FMF, the polarization-diversity coherent receiver is applied. Light from another ECL with the same wavelength is used as the local oscillation (LO). The received electrical signals are sampled by a real-time digital storage oscilloscope (DSO, Keysight UXR0594AP) for offline digital signal processing (DSP).

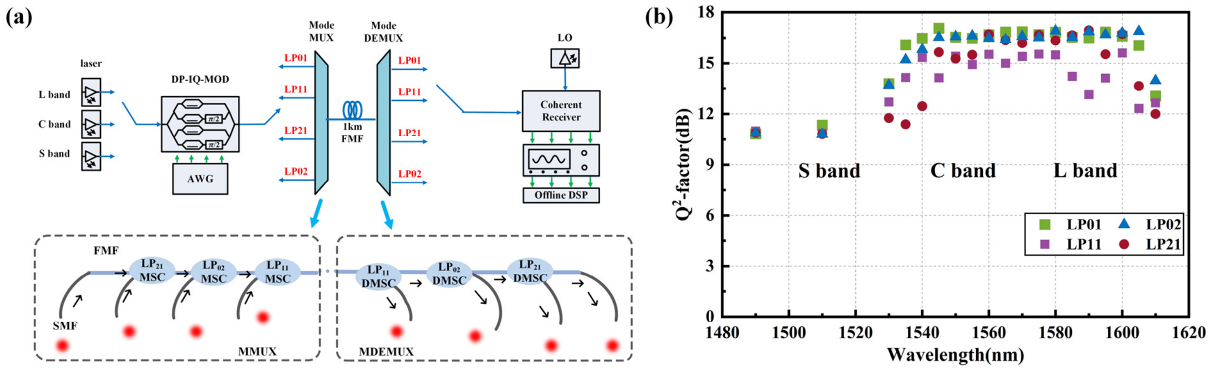

Fig. 3 (a) Experimental setup of transmission. (b) The Q^2-factor performance after FMF transmission.

Figure 3(b) shows the measured Q^2-factor performance after FMF transmission for all the 4 LP modes across 1490~1610 nm. It can be observed that signals in all the LP modes could still achieve Q^2-factor performance higher than 10.8 dB after 1 km transmission. It should be noted that the performance degradation in S band is mainly due to the limited supported wavelength range of the transceiver in this experiment.

4. Conclusions

Ultra-wideband MSC is designed by applying different custom SMF for phase matching with different high-order LP modes. Three kinds MSCs satisfying strict phase-matching conditions across S+C+L bands for mode multiplexing/demultiplexing of a 4-LP-mode FMF are designed and fabricated. The measurement results show that the coupling efficiencies of all the MSCs exceed 84% across the wavelength range of 1490~1610 nm. Weakly-coupled FMF transmission based on the proposed MSCs is experimentally demonstrated. *This work is supported by NSFC (U20A20160), the Major Key Project of Peng Cheng Laboratory (PCL2023AS2-4) and China Postdoc. Foundation (2022M721740).*

5. References

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