60+60 km Weakly-coupled MDM-WDM Transmission Enabled by 4-LP-mode FM-EDFA

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Abstract: A 4-LP-mode FM-EDFA utilizing multiple-ring-core FM-EDF is designed and fabricated to support weakly-coupled MDM transmission, based on which 60+60 km simultaneous $LP_{01}/LP_{11}/LP_{21}/LP_{02}$ MDM-WDM transmission is experimentally demonstrated only adopting 2×2 or 4×4 MIMO-DSP. © 2024 The Author(s)

1. Introduction

In recent years, mode division multiplexing (MDM) technique utilizing different linearly-polarized (LP) modes in few-mode fibers (FMFs) has been extensively investigated as a promising approach for capacity enhancement of single fiber [1], for which the few-mode Erbium-doped fiber amplifier (FM-EDFA) is the key component for all-optical loss compensation both in mode and wavelength dimensions without the need of signal multiplexing/demultiplexing or O/E conversion [2, 3]. Recently, long-haul weakly-coupled MDM transmission by suppressing all kinds of modal crosstalk as much as possible to avoid inter-modal MIMO-DSP has been experimentally demonstrated [4], for which multiple single-mode Erbium-doped fiber amplifiers (SM-EDFAs) accompanied with mode multiplexer/demultiplexer (MMUX/MDEMUX) have to be adopted in each span for loss compensation, which will induce extra loss and modal crosstalk. It's expected that the transmission performance would be significantly improved by adopting FM-EDFAs. However, the introduction of FM-EDFAs should not break the weakly-coupled transmission condition, which has been a great challenge for previous investigations. In this paper, a few-mode Erbium-doped fiber (FM-EDF) adopting similar multiple-ring-core (MRC) structure with a 4-LP-mode MRC-FMF is designed and fabricated utilizing modified chemical vapor deposition (MCVD) processing. Then, the FM-EDFA supporting weakly-coupled MDM transmission is realized and the characteristics is measured. Thanks to the low modal crosstalk of the FM-EDFA, 60+60 km simultaneous $LP_{01}/LP_{11}LP_{21}/LP_{02}$ MDM transmission is successfully demonstrated with 28-GBaud quadrature-phase-shift-keyed (DQPSK) signals only adopting 2×2 or 4×4 MIMO-DSP.

2. Design and characterization of FM-EDFA

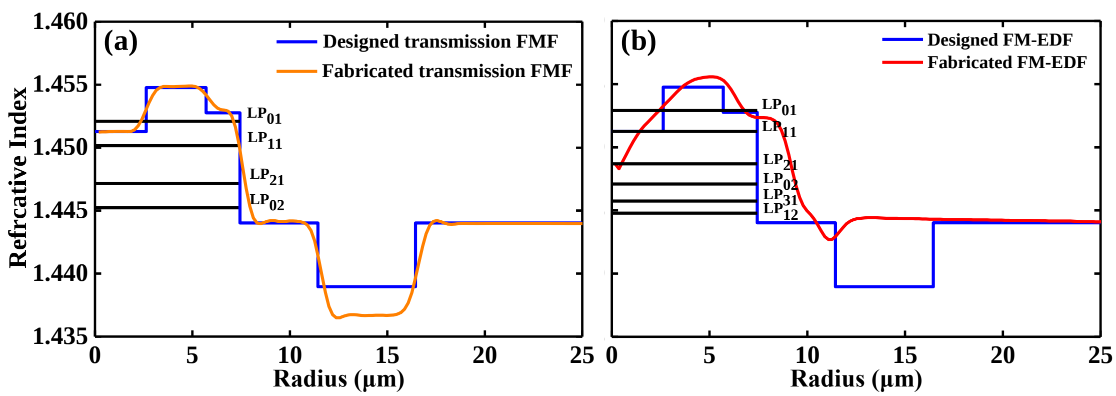

Fig. 1. (a) Index profiles of designed and fabricated transmission FMF. (b) Index profiles of designed and fabricated FM-EDF.

There are three important issues for the realization of the FM-EDFA to achieve low modal crosstalk [5]. First, similar waveguide structure should be adopted for both transmission FMF and FM-EDF to avoid coupling crosstalk induced by mode field mismatching. Second, the insertion of few-mode wavelength-division multiplexer (FM-WMUX) for pump/signal combination should have low modal crosstalk. Finally, modal crosstalk at all splicing points in the FM-EDFA should be examined especially for the junction between the transmission FMF and FM-EDF.

Fig. 1 (a) illustrates the designed and fabricated index profiles of a weakly-coupled transmission MRC-FMF. The refractive index difference (Δn) of the core and cladding is 0.6%. The minimum effective index difference ($\min|\Delta n_{eff}|$) of the fabricated FMF is 1.89×10^{-3}, lying between LP_{21} mode and LP_{02} mode. The propagation loss (PL) of 4 LP modes is all lower than 0.227 dB/km. Fig. 1(b) shows the designed and fabricated index profiles of the FM-EDF adopting similar waveguide structure. The fabricated FM-EDF by MCVD processing supports 6 LP mods and the Er doping concentration in the core ranges from 1.1 to 2.7×10^{25} m^{-3}. The $\min|\Delta n_{eff}|$ among LP_{01}, LP_{11}, LP_{21} and LP_{02} modes of the FM-EDF is 1.35×10^{-3}, which is large enough to avoid modal crosstalk during FM-EDF transmission. Although there is some difference between the index profiles of the two fibers, the coupling crosstalk for all the 4 LP modes could be neglected with proper center alignment according to our simulation results.

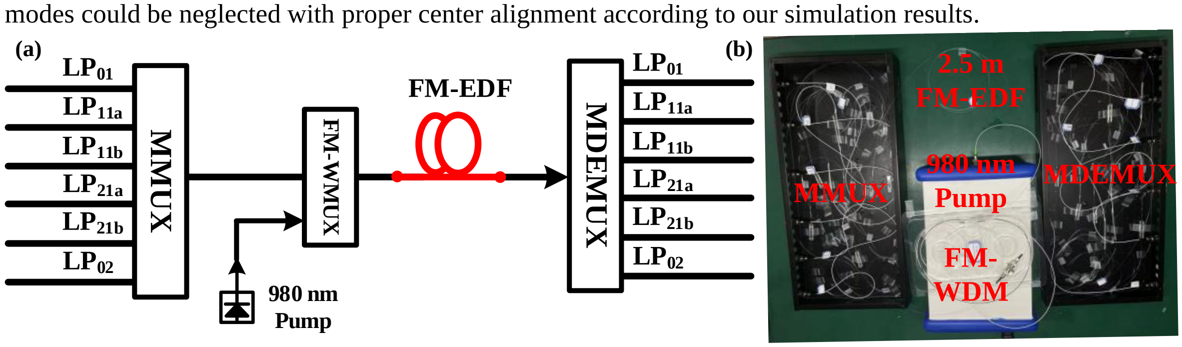

Fig. 2. (a) Experimental setup for 4-LP-mode FM-EDFA. (b) Picture of the experimental setup.

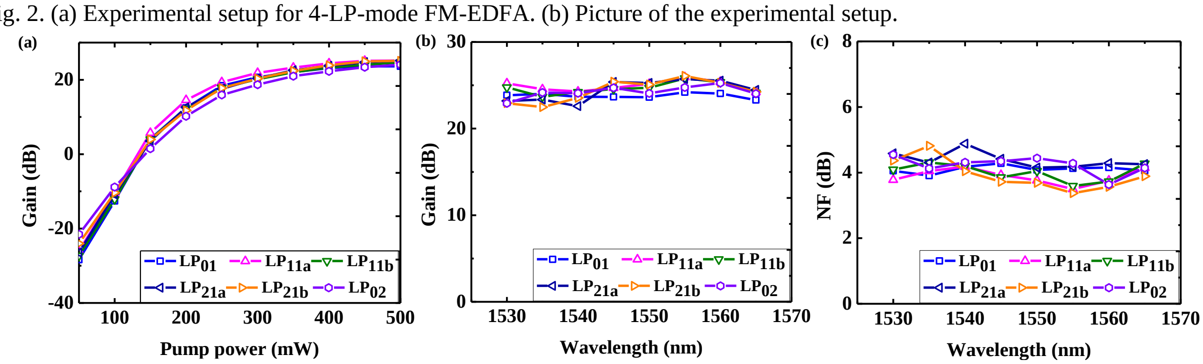

Fig. 3. (a) Gain versus powers of LP_{01} mode pump. (b) Gain spectrum at the C band. (c) NFs at the C band.

Figure 2 (a) shows the experimental setup for characteristics measurement of the fabricated FM-EDFA. Lights from multiple external cavity laser (ECL) sources are generated and multiplexed into different LP modes in the transmission FMFs by the MMUX. The MMUX and MDEMUX consisting of multiple MSCs are fabricated by side-polishing processing [6]. The maximum back-to-back IL and modal crosstalk are 4.53 dB and -17.32 dB, respectively. The 980-nm single-mode pump lights and few-mode signal lights are combined by the FM-WMUX, which is realized by similar method to achieve low modal crosstalk [7]. The optimized length of the FM-EDF is 2.5 m. The modal crosstalk for the 4-LP-mode FM-EDFA is measured utilizing the optical spectrum analyzer (OSA, Yokogawa, AQ6390C). For the measurement of modal crosstalk for the FM-EDFA, lights from 6 ECLs with 1 nm spacing are simultaneously injected, and the optical spectra are measurement at all the output ports of the FM-EDFA by the OSA. The measured maximum modal crosstalk is -11.42 dB.

The measured gain characteristics of the fabricated FM-EDFA versus the powers of LP_{01} mode pump is measured utilizing the OSA, as shown in Fig.3 (a). The input power is set to -15 dBm for each mode at 1550 nm. We can see that the maximum modal gain is 25.26 dB. The gain spectra and NFs at the C band are shown in Fig. 3(b-c). The maximum DMG is 1.16 dB and the NFs range from about 3 to 5 dB.

3. Experimental setup and results of WDM-MDM transmission with the FM-EDFA

The experimental setup for the weakly-coupled MDM transmission is shown in Fig. 4. At the transmitter side, the 4-λ-WDM signals with 100-GHz channel spacing are generated by 4 ECLs. An arbitrary waveform generator (AWG) and a single-polarization IQ-modulator are utilized to generate 28-GBaud single-polarization DQPSK baseband signal. The polarization division multiplexing is emulated by an emulator consisting of a polarization-maintaining coupler (PM-OC), a tunable optical delay line (TODL), and a polarization beam combiner (PBC). The DP-DQPSK signal is further split into six branches utilizing fiber delay lines with different lengths. After FMF transmission, the MDM signals are amplified by FM-DEFA and then launched into another 60-km FMF. At the receiver, signals after transmission are received by a polarization diversity receiver. Electrical waveforms are captured by a real-time digital storage oscilloscope (DSO), and then are processed offline. A time-division-multiplexed (TDM) scheme is utilized to receive the degenerate LP_{11} or LP_{21} modes [8]. 2×2 MIMO-DSP is performed for LP_{01} and LP_{02} modes, while 4×4 MIMO-DSP is performed for LP_{11} and LP_{21} modes.

The weakly-coupled MDM transmission performance is measured. The Q^2-factors for simultaneous $LP_{01}/LP_{11}/LP_{21}/LP_{02}$ MDM-WDM transmission are shown in Fig. 5(a). The Q^2-factor threshold is set to 6.25 dB for 20%-overhead FEC [9]. The Q^2-factors versus wavelengths for MDM transmission at the C band are shown in in Fig. 5(b). We can see that there is a large margin between the Q^2-factors and the FEC threshold, which indicates that the proposed FM-EDFA could support multiple-span weakly-coupled MDM transmission.

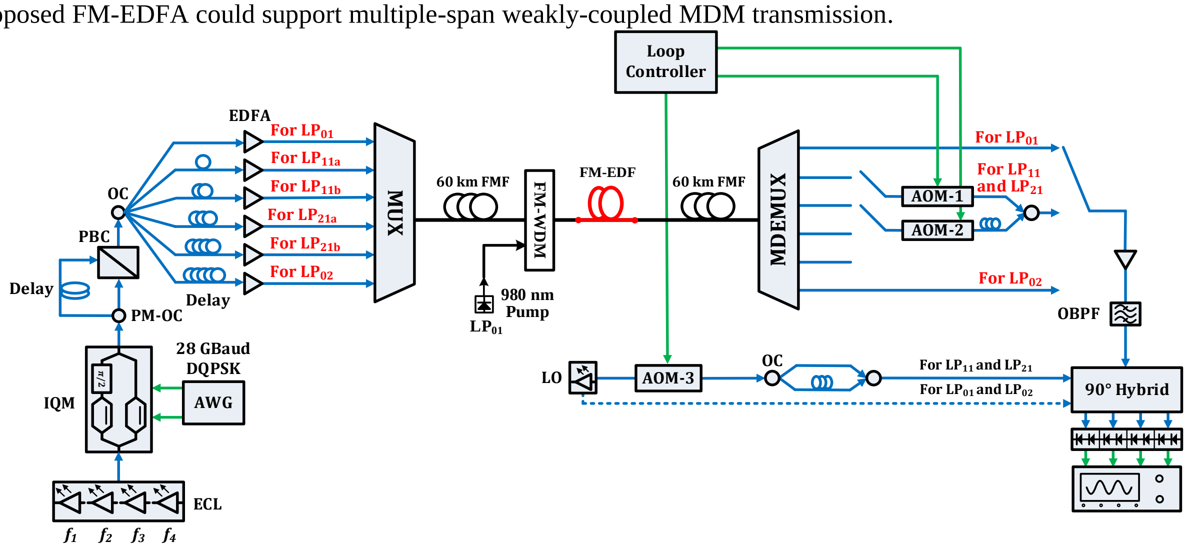

Fig. 4. Experimental setup of weakly-coupled MDM transmission with FM-EDFA.

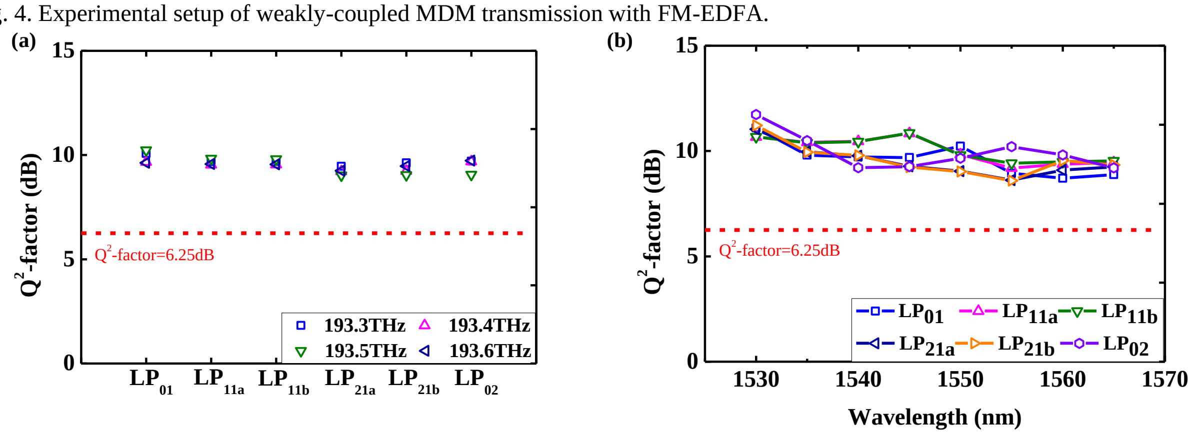

Fig. 5. (a) The Q^2-factors of 4-LP-mode MDM-WDM transmission over 60+60 km FMF. (b) The Q^2-factors versus wavelengths for MDM transmission at the C band.

4. Conclusions

A 4-LP-mode FM-EDFA supporting weakly-coupled MDM transmission is designed and fabricated, based on which 60+60 km simultaneous $LP_{01}/LP_{11}LP_{21}/LP_{02}$ MDM transmission is successfully demonstrated. The large Q^2-factor performance margin shows that it could support multiple-span weakly-coupled MDM transmission. *This work is supported in part by NSFC (U20A20160 and 62101009) and Pengcheng Zili Project (PCL2023AS2-4).*

5. References

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