Investigation on All-Fiber FM-EDFA Performance in Recirculating-Loop Transmission System

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***Abstract*—We investigated differential mode power (DMP) of the all-fiber few-mode recirculating-loop system composed of a three-mode erbium-doped fiber amplifier (3M-EDFA) and 12km-long three-mode fiber. The DMP is less than 4.05dB after passing through 17 round-trips.**

***Keywords*—few-mode erbium-doped fiber amplifier (FM-EDFA), mode division multiplexing (MDM), few-mode fiber (FMF), recirculating loop.**

I. Introduction

In the past half century, the informatization level of human society has a unprecedented development, which is inseparable from the rapid development of communication technology. At present, the data rate of single-mode optical fiber communication system is about to reach the nonlinear Shannon limit, and mode division multiplexing (MDM) technology is considered to be an effective solution to expand the transmission channel capacity, which can increase the optical fiber transmission capacity from Tbit/s to Pbit/s [1-4]. In MDM systems, few-mode fibers (FMFs) or multi-mode fibers act as the transmission medium, and the new multiplexing dimension can exponentially expand the transmission capacity compared with standard single-mode fiber (SSMF) systems. Few-mode erbium-doped fiber amplifier (FM-EDFA) has also the ability to simultaneously amplify multiple mode signals for long-distance MDM transmission. The amplification principle of FM-EDFAs is the same as that of single-mode EDFAs [5]. In order to validate the transmission performance of long-distance MDM systems at low cost, a recirculating loop is often used in laboratories [6-8]. Differential mode power (DMP) is one of the important parameters for a few-mode recirculating loop system, which is defined as the maximum power difference between the signal modes at the same input power. The increase of DMP will enlarge the differential mode gain (DMG) of FM-EDFA and consequently leads to the deterioration of the system performance, for example, shortening transmission distance and increasing the complexity of the multiple input multiple output (MIMO) algorithm for signal demodulation [9].

In this paper, we built up an all-fiber three-mode recirculating loop system based on a section of 12km-long graded-index three-mode fiber and the FM-EDFA with few-mode isolator and wavelength division multiplexers (FM-IWDMs). The DMP performance of the recirculating loop system is measured and investigated by means of the photoelectric detector (PD). The DMP output from the loop system with 17 round trips is less than 4.05dB and the optical power attenuation value of each round trip is 6.77dB.

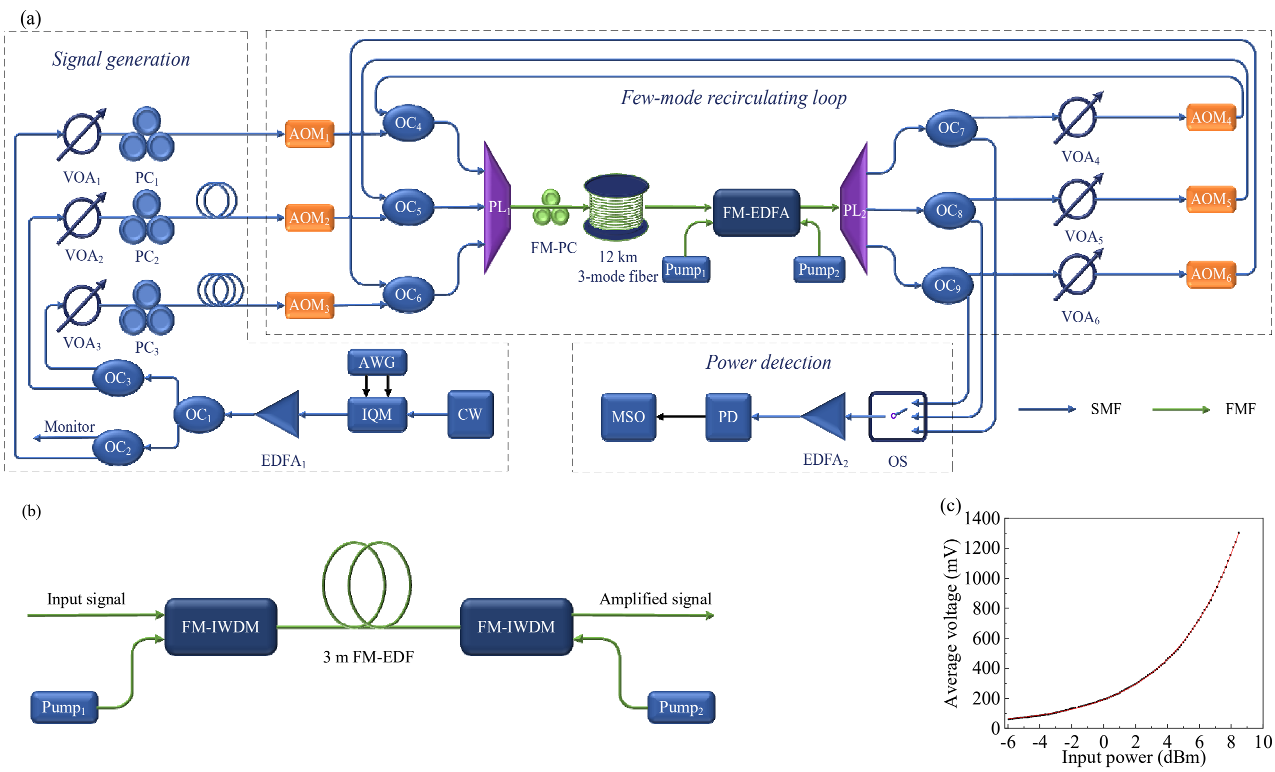

Fig. 1. (a) Experimental setup of all-fiber three-mode recirculating loop; (b) The schematic diagram of the IWDM-based FM-EDFA; (c) The measured curve on optical-to-electronic conversion.

II. EXPERIMENTAL SETUP

Fig. 1 (a) illustrates the experimental setup of the all-fiber three-mode recirculating loop system, composed of three units as follows: the signal generation unit, the few-mode recirculating loop unit, and the power detection unit.

In the signal generation unit, a 10Gbit/s quadrature phase shift keying (QPSK) signal from the arbitrary waveform generator (AWG) is modulated onto a continuous wave (CW) with the wavelength of 1550.3 nm by the in-phase/quadrature modulator (IQM). This generated signal is then amplified by $EDFA_1$ to meet the optical power requirements for the subsequent transmission. The amplified signal is divided into three branches using three 50:50 optical couplers (OCs), each of which passes through the corresponding variable optical attenuator (VOA), polarization controller (PC), and delay line. The delay line is used to eliminate the signal correlation between the branches, while the VOAs and PCs are used to regulate the optical power and polarization state, respectively.

To implement the recirculating transmission of each signal mode in the FMF, three parallel loops are established and each consists of two acousto-optic modulators (AOM) and a 50:50 OC for switching the recirculating signals. The recirculating signals are injected to the few-mode link by $OC_{4\sim6}$, respectively. During each round trip, the photonic lantern (PL_1) is used to excite the few-mode signals of LP_{01}, LP_{11a}, and LP_{11b} modes. The few-mode polarization controller (FM-PC) is utilized to align the mode axis. After passing through the 12km-long graded-index three-mode fiber manufactured by YOFC [10], the power level is restored by the FM-EDFA and then demultiplexed into single-mode signals again. Fig. 1 (b) demonstrates the schematic diagram of the IWDM-based FM-EDFA. At the same time, the mode signals of each round trip are sent to the power detection unit via the 1:99 $OC_{7\sim9}$.

Three signals from the few-mode recirculating loop unit are detected by the PD and then collected by the mixed signal oscilloscope (MSO). In the power detection unit, the optical switch (OS) in front of $EDFA_2$ is used to choose the mode signal under test. Since the signal takes 60μs to complete one round trip in the loop system, it is impossible to measure the output optical power of each round trip by the optical power meter in such a short time. Therefore, we apply the PD for measurement, which is more sensitive than the optical power meter. $EDFA_2$ stably works at the automatic gain control (AGC) mode to ensure the measurement accuracy. Fig. 1 (c) depicts the measured relationship between the output electrical voltage and the input optical power. The fitting curve is given as follows:

$$P_e = 167.18e^{\frac{P_o}{4.17}} + 23.74 \tag{1}$$

where P_e is the average voltage collected by the MSO and P_o is the optical power injected into the PD.

III. RESULTS AND DISCUSSION

The experimental results are demonstrated in Fig. 2. First, we determine the combination of pump mode and power to minimize the DMP. In the experiment, only the forward and backward pumping modes of LP_{01}, LP_{11a} and LP_{11b} are considered. As shown in Fig. 2 (f), for the case of backward LP_{11b} pumping, there is a minimum DMP of less than 3dB with larger modal gain at the pump power of 29.3dBm. Under this case, we measure the average voltages of three modes for each round trip according to Eq. (1). The calculated optical power and DMP for each round trip are depicted in Fig. 3. The markers in the figure represent the average value of 10 independent measured results for accuracy. It can be seen that the optical power curves for LP_{01}, LP_{11a} and LP_{11b} signals have a similar trend with the recirculating count. From Fig. 3, the DMP for the 1st round trip is 3.19dB, and the maximum of 4.05dB occurs at the 11th round trip. Then, the DMP from the 7th to 17th round trip is around 4.05dB. The disequilibrium of modal power is mainly associated with the large DMG of the FM-EDFA, dependent on the input mode power.

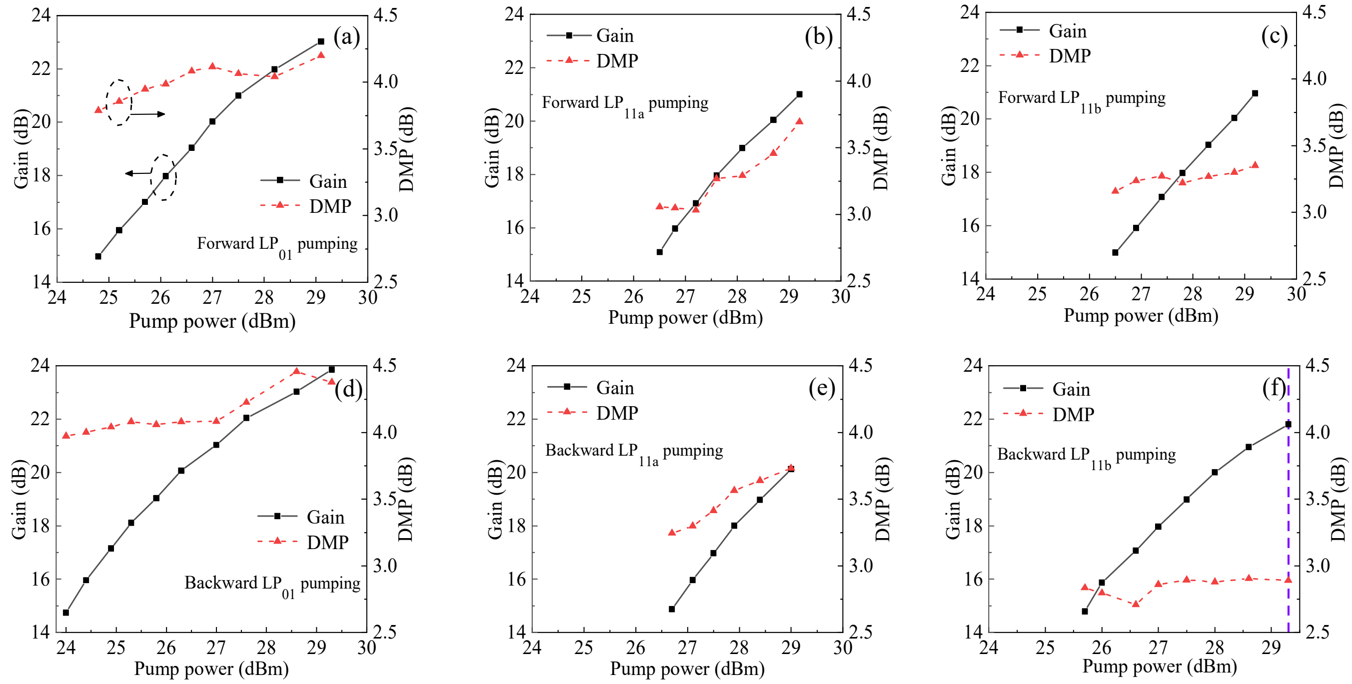

Fig. 2. Modal gain and DMP curves of the FM-EDFA under (a)~(c) forward and (d)~(f) backward pumping cases.

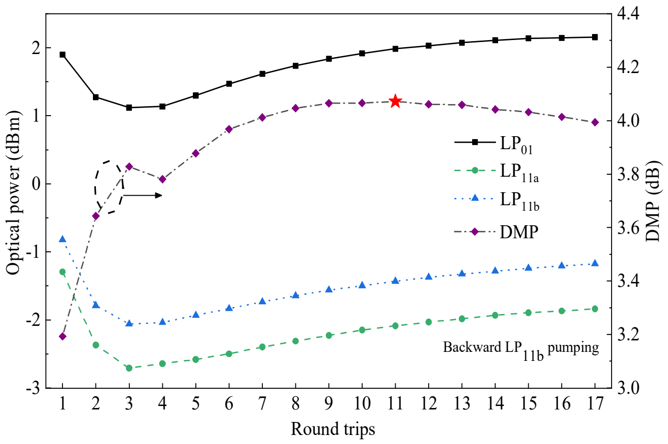

Fig. 3. Optical power and DMP of each round trip under backward LP_{11b} pumping case with the pump power of 29.3dBm.

IV. Conclusion

We measure the DMP of the IWDM-based FM-EDFA under forward or backward pumping cases with different modes, and the backward LP_{11b} pumping case has the minimum DMP of less than 3dB at the pump power of 29.3dBm, corresponding to the 22dB modal gain. In addition, an all-fiber few-mode recirculating loop system with the FM-EDFA is built up and the DMP of each round trip is measured by means of the PD. The results show that the DMP of the recirculating loop system is always kept below 4.05dB within 17 round trips, corresponding to the FMF transmission distance of 204km. The total optical power attenuation value of 17 round trips is 115dB.

Acknowledgment

This work has been supported by the National Key R&D Program of China (2018YFB1801001 and 2018YFB1801003) and the National Natural Science Foundation of China (62171078).

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