All-fiber Mode-division-multiplexed Recirculating-loop Transmission System with Ultralow-cost MIMO Algorithm

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***Abstract*—We experimentally demonstrate an all-fiber few-mode recirculating loop system (AF-FMRLS) with the ultralow-cost transfer-learning multi-input and multi-output (TL-MIMO) equalizers. 20 round trips were tested with the training-cost reduction up to 66.7% to 100%.**

Keywords*—*mode division multiplexing (MDM), multi-input and multi-output (MIMO), few-mode fiber (FMF), recirculating loop.

I. INTRODUCTION

Mode-division multiplexing (MDM) technology carried by few-mode fiber (FMF) has been considered as the most promising candidate to meet the ultra-huge capacity requirements in the next-generation optic-fiber communication network. Spatial modes conversion, multiplexing and demultiplexing are the key and representative functions in MDM that determine the system performance [1-4]. The mode (de)multiplexers have been proposed to realize the functions based on different schemes, such as spatial light modulator [5], on-chip [6] and photonic lantern (PL) [7]. The all-fiber MDM transmission system deployed with PLs is attractive in terms of simple operation and easy implementation, but causes larger crosstalk between spatial modes [8]. In short- and medium-distance MDM system, the stronger crosstalk is not favorable, which not only increases the computational complexity of the multi-input and multi-output (MIMO) equalization algorithm, but also degrades the transmission performance [1-3].Therefore, in order to reduce the crosstalk strength caused by the mode coupling and subsequently induced algorithm costs, we proposed two optimization schemes. First, because the mode coupling is weaker between the modes with larger effective refractive index difference [9], we selected them as channels in FMF to reduce the crosstalk. On the other hand, we introduced the transfer learning (TL) method from the machine learning field to the MIMO module. Faster convergence could be achieved with the less training-costs by transferring the well-trained equalizer parameters.

In this paper, we have built an all-fiber few-mode recirculating loop system (AF-FMRLS) based on 10 km six-mode fiber, i.e., LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b} and LP_{02}. To ensure sufficient effective refractive index difference, we selected the LP_{01}, LP_{21a} and LP_{02} modes as the spatial channels. In addition, we proposed the TL-MIMO algorithm that transfers the well-trained parameters to other groups of data to reduce the training cost. Experimental results demonstrate the bit-error-rate (BER) results of up to 20 round trips are less than the 20% soft-decision forward error correction (SD-FEC) threshold. Furthermore, during the loop transmission, the training cost has been reduced by at least 66.7% or even without further training when the proposed TL-MIMO algorithm applied.

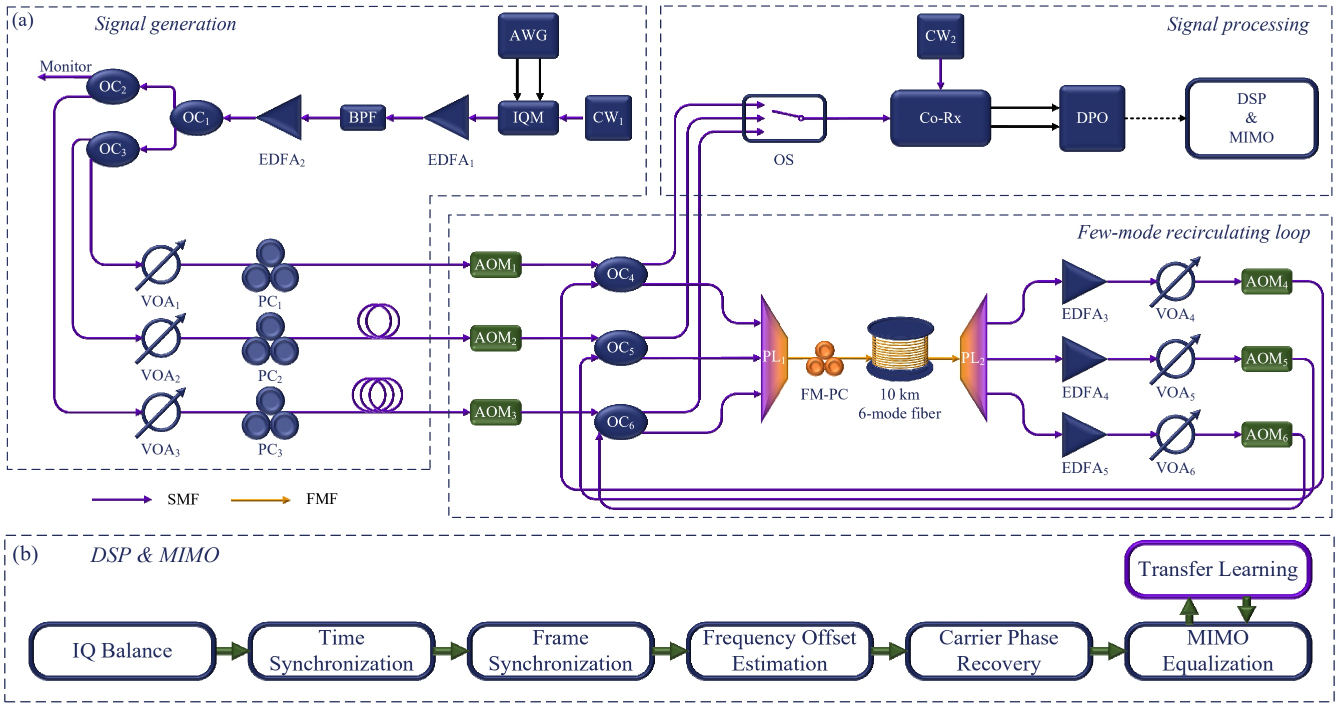

Fig. 1. (a) Experimental setup of AF-FRLS; (b) algorithm flow in DSP module.

II. Experimental setup and TL-MIMO

The AF-FMRLS consists of signal generation unit, few-mode recirculating loop unit and signal processing unit, as shown in Fig. 1 (a). In signal generation unit, the 10 Gbit/s quadrature phase shift keying (QPSK) signal was modulated by the IQ modulator (IQM), which was driven by the continuous wavelength (CW_1) laser of 1550.3 nm and the arbitrary waveform generator (AWG). The generated QPSK signal was amplified by the two erbium-doped fiber amplifiers (EDFA) in cascade to meet the optical power demand in subsequent transmission. The band pass filter (BPF) between two EDFAs was responsible for filtering the amplified spontaneous emission (ASE) noise out of band to ensure the high degree of polarization (DOP) in the optical signal. Subsequently, the amplified signal was divided into three branches by three 50:50 optical couplers (OC). After passing through their respective variable optical attenuators (VOA), polarization controllers (PC) and delay lines, the signals in three branches were simultaneously injected into the few-mode recirculating loop unit. The few-mode components, i.e., PL_1, PL_2, the few-mode polarization controller (FM-PC) and the YOFC produced 10 km graded-index six-mode fiber were the core of the few-mode recirculating loop unit. Among them, FM-PC was implemented to adjust the mode coupling strength together with the single-mode PCs. To keep low crosstalk between the spatial channels, we considered LP_{01}, LP_{21a} and LP_{02} modes to transmit signals. Therefore, it requires three parallel loop device combinations, each of which contains two acousto-optic modulators (AOM) and a 50:50 OC to control the signal conduction and transmission direction respectively. For each round trip, the signals passing through OCs were injected into the corresponding single-mode ports of PL_1 to be converted to few-mode signals and multiplexed. After the transmission in FMF, they were demultiplexed into single-mode signals again and then restored the power level by EDFAs and VOAs. Meanwhile, the signals of each round trip were sent to the signal processing unit from another output port of OC_4, OC_5 and OC_6. In signal processing unit, the signals in three branches were selected by the optical switch (OS) one by one and detected by the coherent receiver (Co-Rx). Finally, the signals collected by digital phosphor oscilloscope (DPO) were recovered in digital signal processing (DSP) module. Figure 1 (b) depicts the algorithm flow in DSP module. After IQ balance, time and frame synchronization, carrier recovery, the signals were equalized by the FD-LMS algorithm loaded with TL scheme. In FD-LMS, the initializations of the step factor μ, the taps number k and the equalizers W determine the convergence speed and final error of algorithm [10]. Among them, the proper combination of μ and k should be located in a wide range, and W is supposed to be trained with the aid of training data. However, both the location and training require massive computational complexity. In order to achieve fast convergence of the algorithm, we combined FD-LMS algorithm with TL, as depicted in Fig. 2. First, a group of data (including training data and test data) was considered as the source domain, other groups of data were divided into target domain. Secondly, we converged the MIMO parameters in source domain in traditional way. Then, the well-trained parameters in source domain were transferred into the target domain as the initial values. Finally, in the initialized target domain, each group of data could achieve convergence with simple training. Furthermore, we propose two TL-MIMO schemes, namely 'transfer with W' and 'transfer without W'. In the former, the transferred parameters are μ, k, and W. In the later, the only transferred parameters are μ and k.

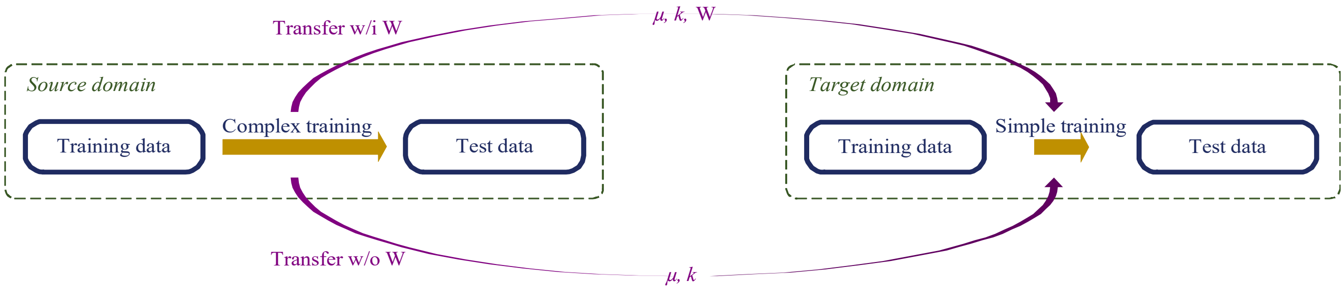

Fig. 2. Principle of TL-MIMO algorithm

III. Results and Discussion

Figure 3 (a) depicts the BER properties of AF-FMRLS versus the round trip with and without TL-MIMO. Each marker represents the average of 25 groups of data. Compared with our previous work [8] (regarding LP_{01}, LP_{11a} and LP_{11b} as channels), the scheme of enlarging the effective refractive index difference increases the maximum round trips up to 20 through reducing mode crosstalk as much as possible. In addition, the BER obtained through TL-MIMO algorithm has only slight deterioration in the whole transmission of 20 round trips, see BER penalty results. In Fig. 3 (b) and (c), we demonstrate the BER histograms of the 1st, 10th and 20th round trips without and with 'TL w/i W' scheme, respectively. It could be found that the BER concentrative state of each round trip is kept well after TL-MIMO. For more detailed results about TL-MIMO, we have plotted the BER results in Fig. 3 (d) ~ (i). Figures 3 (d), (e) and (f) depict the BER curves with the self-recycling times of training data [10] (a method of reducing the required training data) from 0 to 30 with and without TL-MIMO of the 1st, 10th and 20th round trips, respectively. The length of data in each frame was 49152, and the training data length was fixed at 16384. Compared with the BER curves without TL-MIMO, the 'TL w/i W' scheme reduced the self-recycling times by 100%, 75% and 83.33% to achieve the 20% SD-FEC threshold of 2.4×10^{-2}. The curves of 'TL w/o W' scheme indicate that the initial values of equalizers are crucial to the convergence performance of MIMO algorithm. But this scheme still completely avoided the computation of locating μ-k values. Figures 3 (g), (h) and (f) demonstrate the BER properties with the length of training data from 0 to 16384, in which the self-recycling times were set as 30. The length of training data was also greatly reduced by 100%, 80% and 66.7%, corresponding to the 1st, 10th and 20th round trips, respectively. Finally, take the 10th round trip for example, we plot the BER relationship between the self-recycling times and the length of training data without and with TL-MIMO in Fig. 3 (j) and (k). It's found that the colored workable area with the BER less than the FEC threshold was significantly expanded with TL-MIMO algorithm.

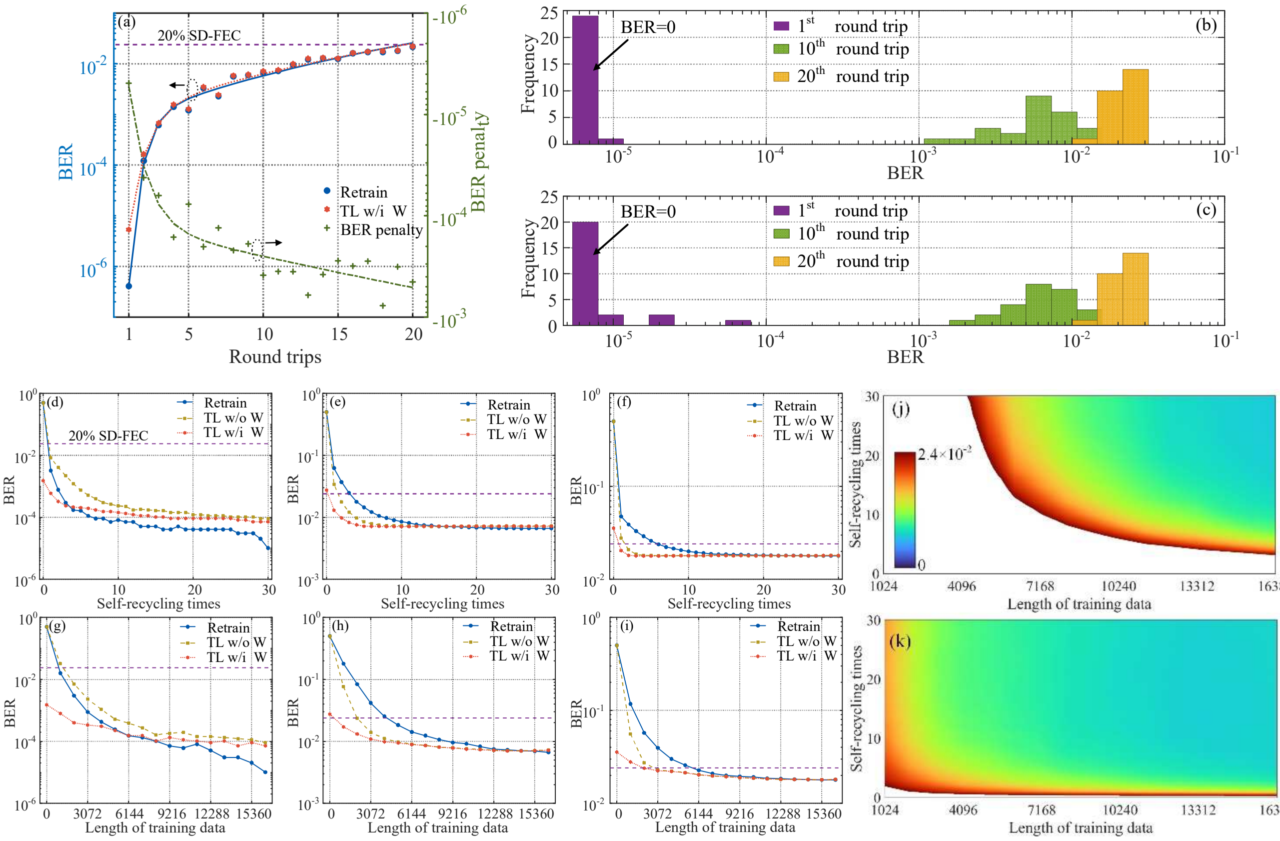

Fig. 3. (a) BER curves on the round trips with and without TL-MIMO; BER histograms (b) without and (c) with TL-MIMO; BER curves on the self-recycling times with different schemes of the (d) 1st, (e) 10th and (f) 20th round trips; BER curves on the length of training data with different schemes of the (g) 1st, (h) 10th and (i) 20th round trips; BER relationships of self-recycling times and training data length (j) without and (k) with TL-MIMO of the 10th round trip.

IV. CONCLUSION

We have built an AF-FMRLS based on 10 km graded-index six-mode fiber. To reduce the crosstalk and consequently MIMO training cost, we considered LP_{01}, LP_{21a} and LP_{02} that have larger effective refractive index difference as channels. And we have applied the TL on MIMO equalization and proposed the TL-MIMO algorithm. Experimental results demonstrated that the maximum valid round trip achieved up to 20 with the weaker crosstalk. In addition, the computational cost reduced by TL-MIMO algorithm achieved up to 100% with slight penalty.

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REFERENCES

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson. “Space-division multiplexing in optical fibres,” Nature Photon, vol. 7, pp. 354–362, 2013.

[2] B. J. Puttnam, G. Rademacher, and R. S. Luís, "Space-division multiplexing for optical fiber communications," Optica, vol. 8, pp. 1186-1203, 2021.

[3] D. Soma, S. Beppu, and N. Yoshikane, *et al*. "High-capacity mode division multiplexing transmission technology," OFC, paper M4B.2, 2022.

[4] F. M. Ferreira, "Linear and nonlinear features of few-mode fibers with partial coupling among groups of quasi-degenerate modes," OFC, paper M3B.4, 2020.

[5] J. Carpenter and T. D. Wilkinson, "All optical mode-multiplexing using holography and multimode fiber couplers," J. Lightwave Technol., vol. 30, pp. 1978-1984, 2012.

[6] Y. Huang, Y. He, and H. Chen, *et al.*, "On-chip mode-division multiplexing transmission with modal crosstalk mitigation employing low-coherence matched detection," J. Lightwave Technol., vol. 39, pp. 2008-2014, 2021.

[7] S. G. Leon-Saval, "The photonic lantern," OFC, paper Tu3J.1, 2017.

[8] T. Zhao, S. Tang, and F. Wen, *et al.*, “Experimental investigation on all-fiber few-mode recirculating loop system (AF-FMRLS),” ACP/IPOC, paper 6493, 2022.

[9] M. Zuo, D. Ge, and Y. Gao, *et al.*, "3-mode real-time MDM transmission using single-mode OTN transceivers over 300 km weakly-coupled FMF," OFC, paper M4B.4, 2022.

[10] T. Zhao, F. Wen, and F. Li, et al., "Noise compensation for a nonlinear six-mode fiber channel through self-recycling training equalizer," OECC, paper M3F.5, 2021.