56.3 Tb/s × 6030 km Transmission over Randomly Coupled MCF with FIFO-less Weakly-Coupled MCF EDFA

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***Abstract*—A randomly coupled 4-core MCF 6030-km transmission with FIFO-less weakly-coupled MCF EDFA is first experimentally demonstrated. 115.4Gb/s net-rate PDM-QPSK signals with error-free transmission are realized in 122 of 137 channels over the entire super-C band.**

Keywords—randomly-coupled multi-core fiber, weakly-coupled MCF EDFA, SDM transmission

I. Introduction

Growing efforts on the system transmission capacity have been made to approaching Shannon limit. Among which, space-division multiplexing (SDM) is considered one of the most promising solutions [1]. There are two fiber candidates for SDM transmission, the weakly coupled multicore fiber (WC MCF) and the randomly multicore fiber (RC MCF). The WC MCF has be focused in submarine system [2], because of compatibility with single mode transmission equipment. The RC MCF potential support higher capacity and lower nonlinearity [3], but the MIMO complexity and mode dependent loss or mode dependent gain (MDL/MDG) largely limit the progress of deployment. In transmission systems, the MDL is mainly accumulated from the amplifiers when the parallel single-core amplification adopted. Different single-core amplifier modules hardly provide the same gain spectrum, which leads to output power difference in a specific wavelength and consequently the MDG. The single-core amplification also results in group delay spread (GDS), as the skew will be introduced by different fiber length inside different module, when randomly coupling mechanism works in RC MCF, the GDS will be enhanced. This means the increase of MIMO complexity.

As MCF Erbium-doped fiber amplifier (EDFA) with multicore EDF has potential to provide the almost same gain spectrum and skew between different cores, many researches utilizing randomly coupled multicore EDF have been reported to RC MCF transmission. However, RC MCF components are complex to manufacture and test. Furthermore, MDG of RC MCF EDFA is hard to achieve a better value due to limited random coupling in RC EDF [4]. Utilizing WC MCF components and corresponding EDF is beneficial to get small MDL, easier to reach mass production level.

In this paper, a RC MCF transmission with FIFO-less WC MCF EDFA was performed, achieving an error-free capacity of 56.3 Tbit/s over 6030 km loop transmission link. The evaluated GDS of the transmission system is around 4.45 ns, which is close to that of RC MCF transmission fiber. The MDL among error-free channels are between 9.6 dB and 15.3 dB.

II. Key Device and Module

A. Randomly Coupled 4-Core MCF

The transmission fiber used in the experiment bench is a 4-core RC MCF with standard cladding diameter, and the cross section is shown in Fig. 1(a). The core pitch is 20 μm, with the effective area 112 μm^2. The typical attenuation coefficient is 0.158 dB/km at 1550 nm. The fibers with total length of 120.6 km are almost equally divided into two spans. A core pitch adapter (CPA) is connected to bridge core pitch from 20 μm to 43 μm between transmission link and WC MCF EDFA. The cross sections of each side of CPA are shown in Fig. 1(b) and (c).

B. Weakly Coupled 4-Core EDFA

The appearance of FIFO-less WC 4-core MCF EDFA utilizing core-pumped configuration is shown in Fig. 1(d). The total XT between any two cores is lower than -42 dB. The gain and noise figure (NF) of one MCF EDFA is shown in Fig. 1(e). The gain is set to match the corresponding span loss, and the maximum NF of all cores is 6.4 dB. The maximum spatial frequency dependent gain is lower than 0.7 dB. The maximum output power of each core is up to 22.5 dBm.

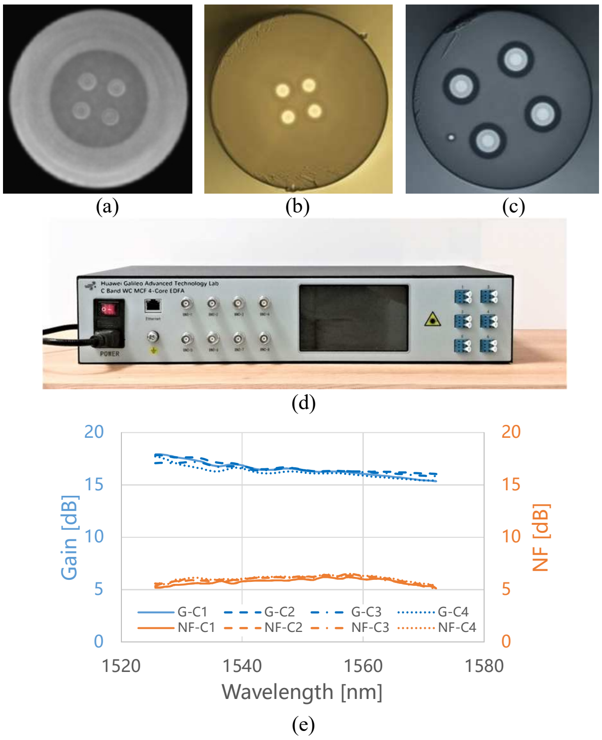

Fig. 1. (a) Cross section of RC MCF. (b) and (c) are cross section of each side of CPA. (d) Appearance photo of WC MCF 4-Core EDFA. (e) Gain and NF spectrum of WC MCF 4-Core EDFA.

III. Experiment Setup

The re-circulating loop experiment setup diagram is shown in Fig. 2.

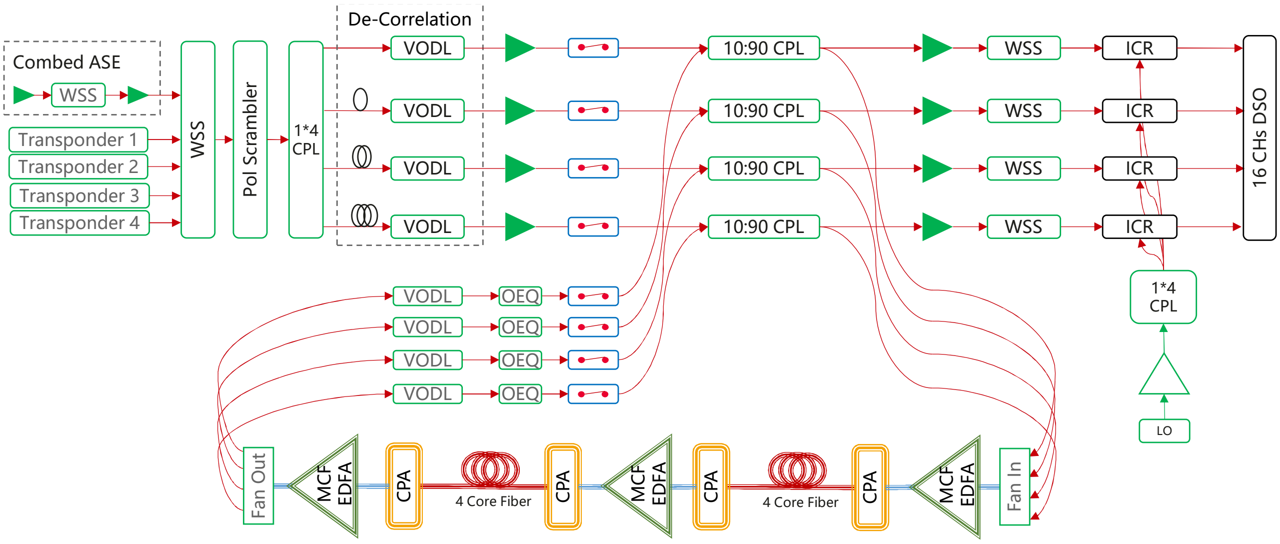

Fig. 2. Experiment Setup Diagram

At the transmitter side, the data stream was come from commercial transponders hardware and combed ASE dummy light. The 40-Gbaud PDM-QPSK signals with a roll-off factor of 0.1, were generated by replacing the data of transponder memory, were put into a frequency slot of 43.75 GHz channel spacing. The combed ASE dummy light used to emulate the real signals loading, was produced by an optical amplifier, and filtered by a WSS to build the combed dummy signal with a channel spacing of 43.75 GHz. The WSS combined 137-channel into WDM signals. In testing procedure, the transceiver group was slid in whole 137 channels to examine the performance of every channel, with the consistent power spectrum density. After 60 Hz polarization scrambling, the WDM signals is split into four copies by splitter, and de-correlation with fixed and variable delay lines, in order to emulate the SDM signals.

Re-circulating loop is used to construct the long-haul transmission link. The 120.6 km transmission link contains, two spans of RC MCF with almost same length, two pairs of CPA, three MCF EDFAs, Fan-In/Fan-out to connect single mode path both transmitter and receiver. The variable optical delay line (VODL), optical equalizer (OEQ), acoustic optical modulator (AOM) and 10:90 coupler are used to expand the transmission link into a loop system. The loop gain spectrum was controlled by OEQ, to ensure the optical power consistence at Fan-In of every specific loop. VODLs are used to compensate for the skew difference introduced by OEQ, AOM and patch cords.

At the receiver side, the channel under test of four sets was filtered by corresponding WSS, and then injected into four integrated coherent receivers (ICR) to convert the optical signals into electrical ones with four copies of local oscillator (LO). The electrical signals was captured by 16-channel digital storage oscilloscope (DSO).

The received signal was processed with offline DSP. In the DSP, the samples from DSO were normalized and resampled with 1.25-fold oversampling rate firstly. Then, carrier frequency recovery, chromatic dispersion compensation and matched filtering were performed. After frame synchronization, a least mean square (LMS) algorithm based adaptive 8x8 MIMO with two stages of phase lock loop was used to compensate for modal coupling, modal dispersion and phase noise. The 421-taps complex MIMO coefficients were first converged with data-aided mode, then switch to decision-direction mode. Finally, the bit error rate (BER) of four cores was calculated and converted to Q factor.

IV. Experiment Result

The 137-channel pre-FEC Q facotrs of 40-Gbaud PDM-QPSK after 6030-km transmission is shown in Fig. 3(a). In this experiment, a soft-decision FEC with 25.5% overhead was assumed, corresponding to 4.5 dB pre-FEC Q limit [5]. Q factors of 122 channels are higher than 4.95 dB, which means there is enough margin for these channels to archive error free after FEC decoding even with 1.5 dB performance fluctuation introduced by MDL or other distortions.

The accumulated GDS of 137 channels were evaluated based on the received data, shown in Fig. 3(b). The value are around 4.45 ns, very close to 4ns (the MCF GDS estimated based on the SMD value). Additional 63 picosecond skew was introduced by MCF EDFAs, CPAs, and other single mode components in the loop. This disclose the FIFO-less MCF EDFA has potential to decease the GDS accumulation in RC MCF transmission, compared with the single-core amplification with FIFO [6].

The MDL distribution of 137 channels are shown in Fig. 3(c). Most of MDL value are lower than 15 dB. Compare with the single-core amplification scheme, 2040 km transmission will accumulate 11~15 dB MDL with 3-core RC MCF transmission [7].

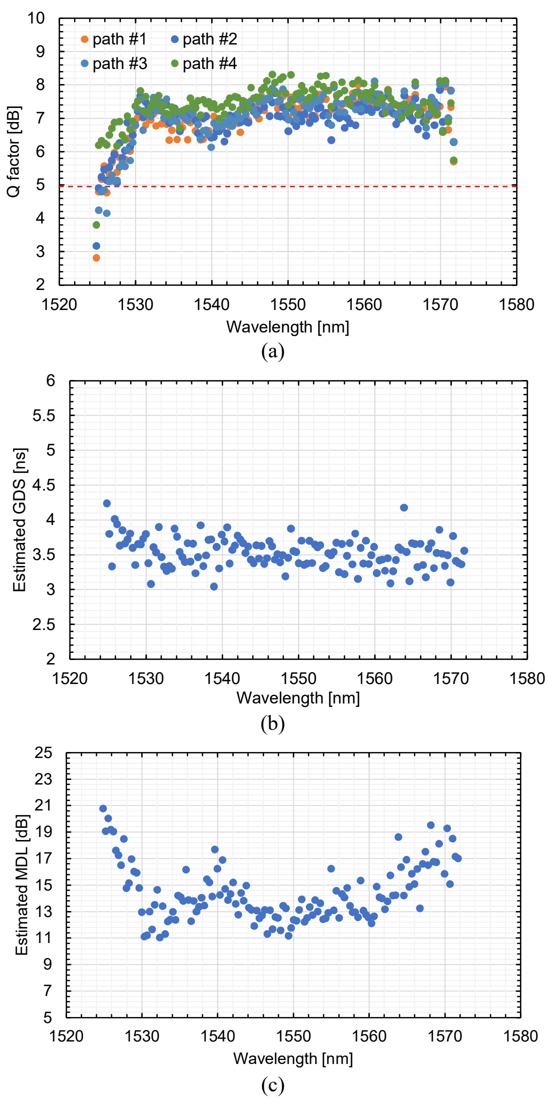

Fig. 3. The Q factors, GDS and MDL value after 6030-km 40-Gbaud PDM-QPSK transmission.

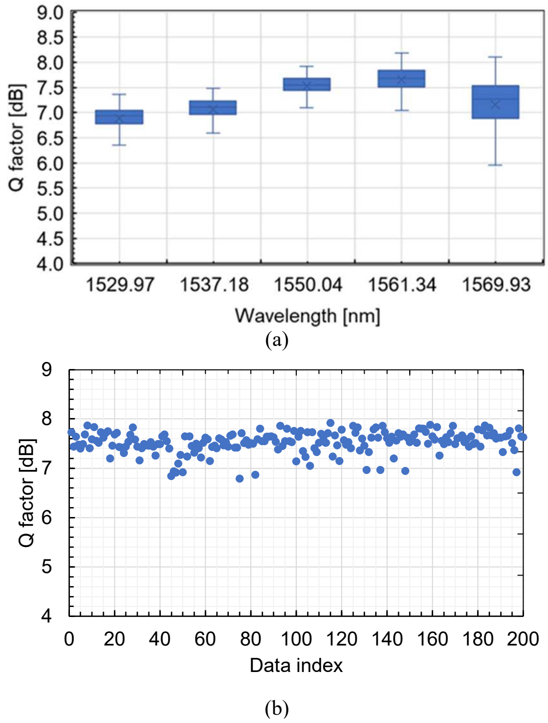

Fig. 4. (a) The Q factors distribution of 200 sets consecutive received data in different frequency; (b) The time evolution of Q factors in 191.44 THz.

The Q factors fluctuation introduced by MDL, will enhance the out-of-bounds probability. 200 sets received data in some specific channels with 50 seconds time interval were captured to investigate this fluctuation, shown in Fig. 4(a). All Q factors were higher than 6 dB, beyond the threshold of soft-decision FEC. In Fig. 4(b), the time evolution of Q factors in frequency 191.44 THz is shown.

V. Conclusion

A 56.3 Tbit/s 6030-km off-line FIFO-less transmission over randomly coupled 4-core MCF with weakly coupled 4-core MCF EDFA was first experimentally demonstrated. The system GDS is benefit from the FIFO-less MCF amplification construction, additional 63 picosecond GDS was introduced in the loop except the RC MCFs. And the 15 dB maximum MDL is investigated after 6030-km transmission, compared with almost same MDL value after 2040-km transmission in single-core amplification. The BER fluctuation is also evaluated, indicates limited out-of-bound probability in 15 dB MDL.

This work shows the feasibility of RC MCF transmission with WC MCF EDFA by CPA module bridging, and the benefits for system GDS and MDL.

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