Randomly-Coupled/Weakly-coupled MCF Long-haul Transmission with Unified FIFO-less Weakly Coupled MCF EDFA

Hui Yan
Huawei Technologies Co., Ltd.
Shenzhen, China
hui.yan@huawei.com

Shuai Yuan
Huawei Technologies Co., Ltd.
Shenzhen, China
yuanshuai27@huawei.com

Yongfu Wang
Huawei Technologies Co., Ltd.
Shenzhen, China
wangyongfu@huawei.com

Guorui Zhang
Huawei Technologies Co., Ltd.
Shenzhen, China
zhangguorui4@huawei.com

Wendou Zhang
Huawei Technologies Co., Ltd.
Peng Cheng Laboratory
Shenzhen, China
zhangwendou@huawei.com

Wenwei Xu*
Huawei Technologies Co., Ltd.
Peng Cheng Laboratory
Shenzhen, China
xuwenwei@huawei.com

***Abstract*—A unified amplification structure based on FIFO-less weakly coupled MCF EDFA over randomly and weakly coupled 4-core MCF long-haul transmission is first experimentally demonstrated. The advantage of integrated EDFA is discussed.**

Keywords—MCF, Randomly Coupled, Weakly Coupled, FIFO-less, Weakly Coupled MCF EDFA, 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]. Weakly-coupled multi-core fiber (WC MCF) and randomly-coupled multi-core fiber (RC MCF) are widely studied. Due to the relatively independent channels and the compatibility of transceiver modules with single-mode transmission equipment, WC MCF is expected to be deployed in submarine cable systems in the near future [2]. RC MCFs have the potential to support higher capacity and lower nonlinearity [3], thanks to the higher core density and randomly inter-core coupling effects.

A lot of research has been carried out on amplifiers used in WC MCF. Initially, FIFO-involved single core amplification architectures using single-mode amplifiers were applied to both types of fibers. The WC MCF transmission has good compatibility, but the FIFO introduces additional loss. The performance over the RC MCF is greatly limited by the MDL due to gain differences and the Group Delay Spread (GDS) due to differences of pigtail length between individual amplifiers. Later, prototype of integrated amplifier based on weakly-coupled multi-core Erbium-doped fiber (MC EDF), single-mode passive component and FIFO was developed. This quasi-integrated amplifier can provide approximately the homogeneous gain spectrum and transmission delay between spatial paths, which is helpful for the channel performance consistency and application of spatial super channel. Recently, FIFO-less integrated amplifiers have been put on the agenda. The link insertion loss may benefit from this architecture.

The amplification mechanism of RC MCF transmission experiments is still using FIFO-involved single core amplifiers and variable optical delay lines. Because of the limited random coupling, low mode dependent gain (MDG) is difficult to achieve based on randomly-coupled MC EDF. Moreover, passive components with RC MCF pigtail are complex to manufacture and test. Considering that the optical signal amplification over RC MCF transmission is independently related to the coupling characteristics of the MC EDF, inheriting mature technologies, and simplifying O&M, it is possible to develop the unified WC EDFA to fit for RC MCF and WC MCF.

In this paper, FIFO-less weakly-coupled multi-core amplifiers are introduced to fit for both weakly-coupled MCF transmission, and randomly-coupled MCF transmission with additional component of core pitch adapter (CPA) . The 110 Tb/s, 2412 km RC MCF transmission and 2096 km WC MCF transmission are achieved with the probability shaping PDM 16-QAM.

II. KEY DEVICE AND MODULE

The transmission fiber is a 4-core RC MCF and WC RCF with standard cladding diameter. For RC MCF, the core pitch

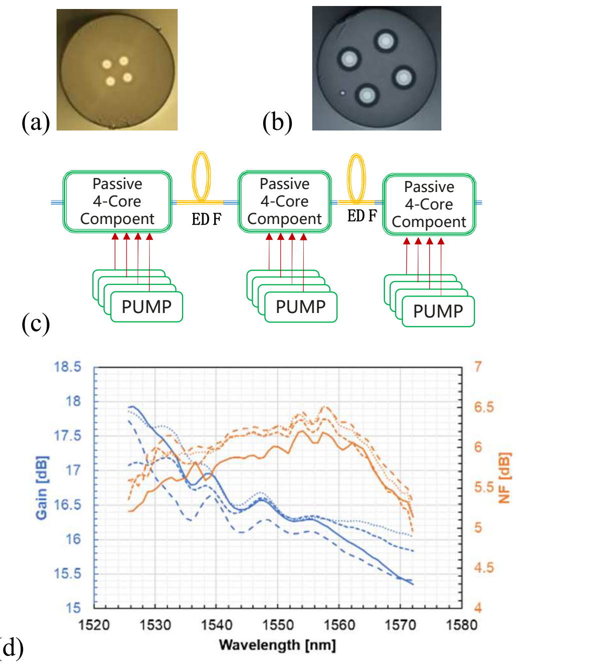


Fig. 1. (a) and (b) are cross section of each side of CPA. (c) Structure of WC MCF 4-Core EDFA. (d) Gain and NF spectrum of WC MCF 4-Core EDFA.

is 20 μm, with the effective area 112μm^2. The typical attenuation coefficient is 0.158 dB/km at 1550 nm. For WC MCF, the core pitch is 43 μm, with the effective area 70 μm^2. The typical attenuation coefficient is around 0.187 dB/km at 1550 nm with trench-assisted Germanium-doped cores.

The function of CPA is to bridge 20 μm core pitch of RC MCF transmission link to 43 μm core pitch WC MCF EDFA, with an effective area of about 80 μm^2 on both sides. By utilizing tapering technique, including both the reverse tapering and the down-tapering schemes, the WC MCF and RC MCF is reshaped to match spacing and mode field with loss of around 0.75 dB [4]. The cross sections of each side of CPA are shown in Fig. 1(a) and (b).

Re-circulating loop is used to construct the long-haul transmission link. For RC MCF transmission, the 120.6 km link contains, two spans of RC MCF with almost same length, two pairs of CPAs, three MCF EDFAs. Fan-In/Fan-out is used to connect single mode path both transmitter and receiver. For WC MCF transmission, the 299.5 km link contains five spans of WC MCF, five MCF EDFAs. The variable optical delay line (VODL), optical equalizer (OEQ), acoustic optical modulator (AOM) and 10:90 coupler was 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.

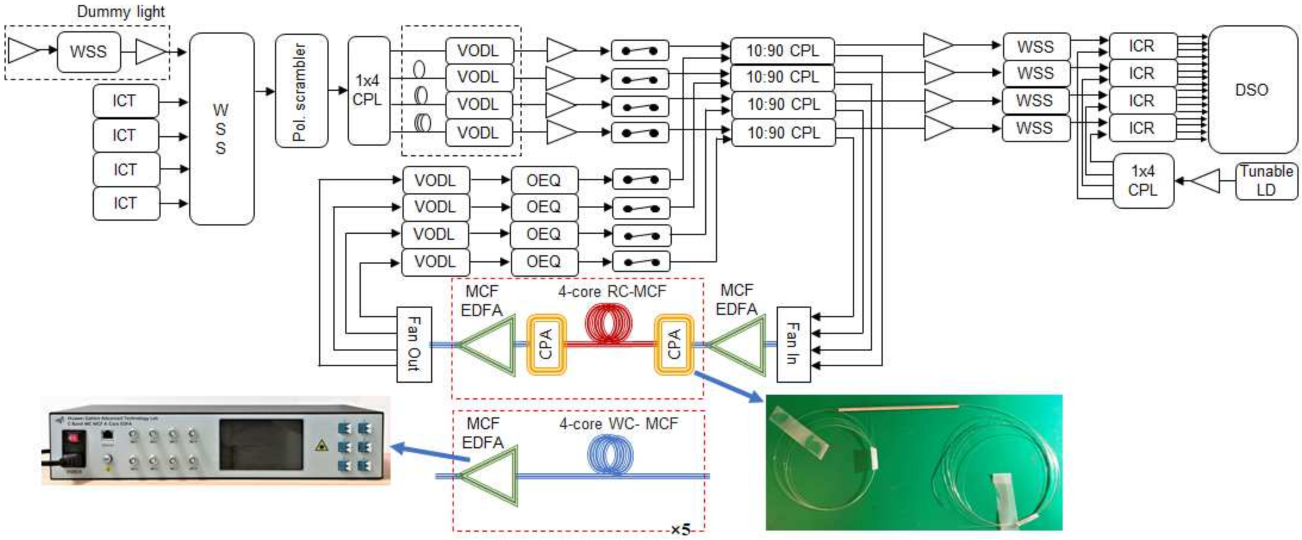


Fig. 2. Experiment Setup Diagram

The appearance of FIFO-less WC 4-core MCF EDFA utilizing core-pumped configuration is shown in Fig. 1(c). 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(d). The gain is set to match the corresponding span loss, and the maximum NF of all cores is 6.4 dB. The maximum gain difference in any spatial channel is lower than 0.7 dB. The maximum output power of each core is up to 22.5 dBm.

III. Experiment Setup

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

At the transmitter side, the data stream was come from commercial transponders hardware and combed ASE dummy light. The 39.87-GBaud PS-PDM-16QAM 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.

At the receiver side, the four sets of frequency under test were 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).

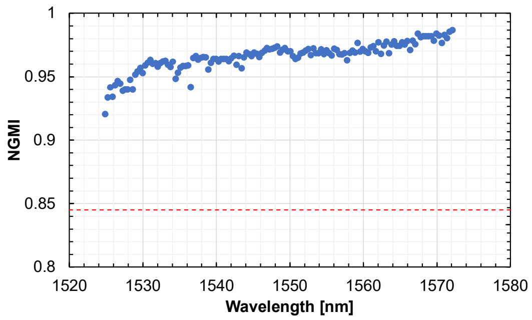
The received signal was processed with offline DSP. In the DSP, the samples from DSO were normalized and resampled with oversampling rate of 1.25. Then, carrier frequency recovery, chromatic dispersion compensation and matched filtering were performed. After frame synchronization, a least mean square (LMS) algorithm based adaptive 8x8 MIMO equalizer in the frequency domain was used to compensate for modal coupling and modal dispersion. The complex MIMO coefficients were first converged with data-aided mode, then switch to decision-direction mode. Carrier phase recovery was based on pilot symbols, and two pilot symbol intervals 32 symbols. Finally, the normalized general mutual information (NGMI) of 8 paths (2 polarizations × 4 cores) was calculated.

IV. Experiment Results

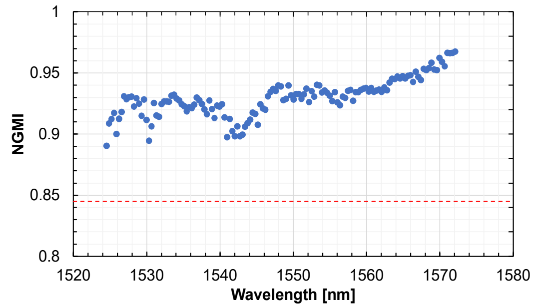
To evaluate the system performance, the averaged normalized general mutual information (NGMI) of 39.87-GBaud CS3.5 PDM-16QAM signal after 2412 km 4-core RC MCF and 2096 km 4-core WC MCF transmission, were measured firstly, and shown in Fig. 3 (a) and (b). In this experiment, the NGMI was averaged over 8 paths, assumed applying spatial super-channel. Referenced to [5], the NGMI threshold of a 25%-overhead soft-decision FEC was set to

0.845. The averaged NGMIs of all WDM channels exceed the NGMI threshold, and some budgets were remained to deal with the performance fluctuation due to MDL or PDL in the systems. Considering 3.5% overhead of the frame, the total capacity is 110 Tb/s (39.87Gbaud x 3.5 bit/symbol x 2 polarizations x 4 cores x 137 WDM channels x 0.75 x 0.965).

Next, the stabilities of two transmission systems were

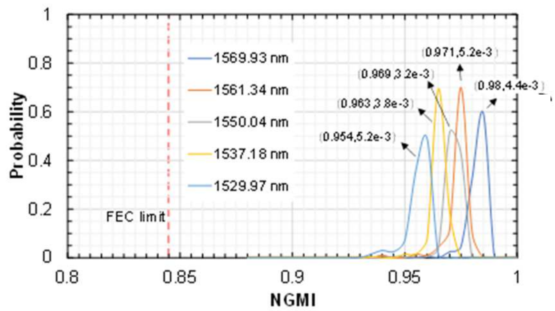


(a)

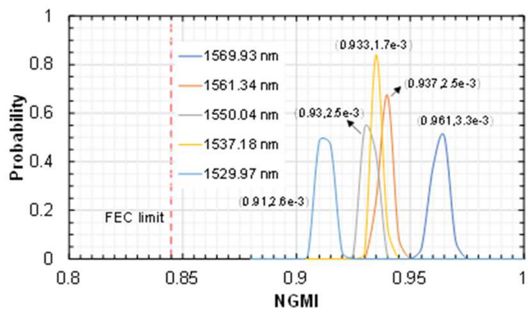


(b)

Fig. 3 Averaged NGMI for 137 super-channels after (a)2412 km RC MCF and (b)2096 km WC MCF transmission.



(a)

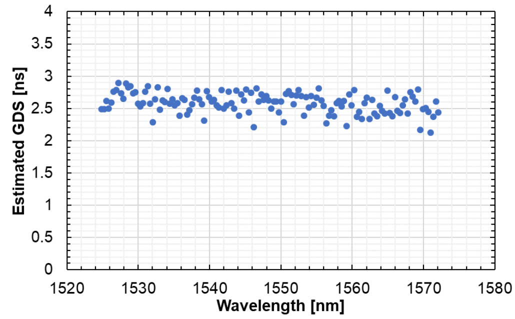


(b)

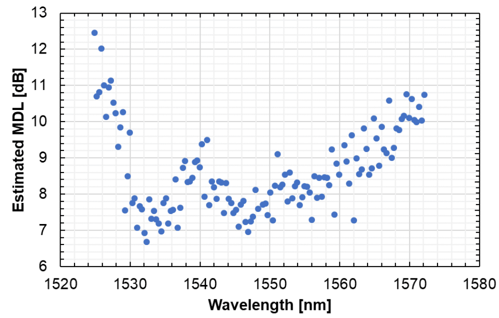
Fig. 4 Average NGMI probabilities of 5 spatial super-channels after (a)2412 km RC MCF and (b)2096 km WC MCF transmission. RC MCF and (b)2096 km WC MCF transmission

inspected. Figure 4 (a) and (b) show the calculated averaged NGMI probabilities distributions of 5 spatial super-channels at typical wavelength over RC MCF and WC MCF transmission, respectively. Each probability distribution was calculated according to 200 groups offline data samples captured in 2.8 hours. The average value and standard deviation of each data group is shown in the bracket. The averaged NGMI at all tested wavelength was larger than 0.9, while trailing in the probability distributions of RC-MCF was observed.

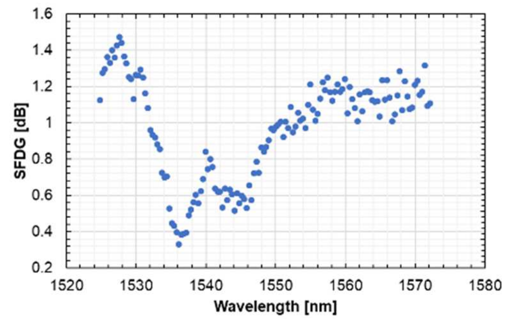
For the RC MCF transmission system, the accumulative



(a)



(b)



(c)

Fig. 5 Estimated (a) GDS and (b) MDL of 137 WDM channels after 2412 km RC-MCF transmission, (c) sum of SFDG in one loop

GDSs of 137 channels were estimated by least square method based on transmitted and received data, shown in Fig. 5(a). This average value is approximately 2.6 ns at 1550 nm, which is very close to 2.52 ns (the MCF GDS estimated from the SMD value). This reveals the potential for a FIFO-less MCF EDFA to reduce GDS accumulation in RC MCF transfers compared to single mode amplification using FIFOs [6].

Finally, The MDLs of 137 WDM channels over RC MCF transmission were estimated by using the maximum and minimum singular values calculated from the 8x8 MIMO equalizer coefficients matrix. The MDL is greatly affected by the gain consistency of the same frequency on different spatial paths of the amplifier. We define the spatial frequency dependent gain (SFDG) to describe this effect. As shown in Figure 5 (b) and (c), the MDL from DSP, and the sum of SFDG of the first two integrated amplifiers are positively correlated. Compared with single core amplifiers, integrated amplifiers have potential to achieve better SFDG, which helpful to improves the transmission distance.

V. Conclusion

The unified weakly coupled 4-core EDFAs to achieve 110 Tb/s capacity beyond 2000 km FIFO-free transmission over the randomly-coupled 4-core MCF and the weakly-coupled 4-core MCF was firstly experimentally demonstrated. Core pitch adapter is introduced to bridge the RC MCF and WC EDFA. Compared with FIFO-involved single core amplification architecture, GDS and MDL performance in the randomly-coupled transmission system was improved.

References

[1] Peter J. Winzer and David T. Neilson, "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade," J. Lightwave Technol. 35, 1099-1115, 2017.

[2] H. Takeshita et al., "Demonstration of Uncoupled 4-Core Multicore Fiber in Submarine Cable Prototype with Integrated Multicore EDFA," in Journal of Lightwave Technology, 2022.

[3] R. Ryf et al., "Coupled-Core Transmission Over 7-Core Fiber," 2019 Optical Fiber Communications Conference and Exhibition (OFC), 2019, pp. 1-3.

[4] R. Yu et al., "Robust Mode Matching between Structurally Dissimilar Optical Fiber Waveguides", ACS Photonics, 8(3), 857-863, 2021.

[5] J. Cho et al., "Trans-Atlantic Field Trial Using High Spectral Efficiency Probabilistically Shaped 64-QAM and Single-Carrier Real-Time 250-Gb/s 16-QAM," in Journal of Lightwave Technology, vol. 36, no. 1, pp. 103-113, 1 Jan.1, 2018.

[6] S. Beppu, D. Soma, N. Yoshikane and T. Tsuritani, "Transoceanic MIMO transmission with coupled-core multicore fibers," 2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC), 2022, pp. 01-03.