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Demonstration of Real-time Unrepeatered MDM Transmission over 200-km FMF with Commercial 400G System and ROPA

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Abstract *By using LP01 and LP02 in a weakly-coupled double-ring-core FMF, a record real-time unrepeatered MDM transmission over 200-km FMF (54.5dB loss for LP01 and 67.5dB loss for LP02) with 400 Gbps DP-16QAM-PCS commercial system and remote optically pumped amplifiers for the first time. ©2022 The Author(s)*

Introduction

In recent years, spatial division multiplexing (SDM) has gradually attracted the attention from industry. ITU-T Q5/SG15 has already started a draft report TR.sdm on all possible SDM techniques [1]. IEC has also initiated the process of standardizing SDM-related techniques [2]. The now accelerated progress of SDM for practical applications urges both academic and industry to investigate schemes compatible with current commercial systems. Currently, for terrestrial backbone and DCI networks, 100G and 200G have been wildly deployed [3]. As capacity demand grows, 400G is expected to be massively rolled out in 2023. Currently, different 400G approaches have been developed and testified for different applications. 400G based on about 90-GBd dual-polarized 16 quadrature amplitude modulation with probabilistic constellation shaping (DP-16QAM-PCS) shows great performance in both G.652.D and G.654.E. Therefore, we are interested in the possibility for SDM to reach a relatively long transmission distance with commercial 400G systems.

As we know, strongly-coupled SDM techniques, e.g. coupled multi-core fibres (C-MCFs) [4] and strongly-coupled few mode fibres (SC-FMFs) [5], all require massive N×N (N>2) multiple-input-multiple-output (MIMO) to separate signals carried by different spatial channels [6]. However, commercial coherent optical modules are based on polarization division multiplexing (PDM), which requires only 2×2 MIMO. Hence, strongly-coupled SDM techniques are not compatible with current commercial systems, while weakly-coupled SDM techniques, e.g. weakly-coupled MCF (WC-MCFs) [7] and weakly-coupled FMFs (WC-FMFs) [8], do have spatial channels that can adapt 2×2 MIMO. It is also worth noting that fusion splicers used in construction site are normally not able to fuse MCFs. In result, weakly-coupled mode division multiplexing (MDM) based on WC-FMFs might be a rather quick path to SDM commercialization. There have been some reports on weakly-coupled MDM utilizing commercial transceivers [9-10]. A real-time 200 Gb/s × 40 × 2 WDM-MDM transmission over single-span 100-km FMF with 200G DP-16QAM was demonstrated in 2021 [9]. In 2022, a longer 3-mode real-time MDM transmission using 200G QPSK over 300-km weakly-coupled FMF has also been experimented [10]. To the best of our knowledge, there is still no real-time weakly-coupled MDM transmission based on 400G commercial systems. In particular, unrepeatered coherent link without any devices in need of power supply for DCI is one major scheme that requires large capacity. For example, 800G ZR has been initiated in OIF [11]. It is necessary for us to testify the ultimate ability of such systems.

In this paper, we report a successful demonstration of a record real-time unrepeatered MDM transmission over 200-km FMF (54.5dB loss for LP01 and 67.5dB loss for LP02) with 400 Gbps DP-16QAM-PCS commercial system. An overall low-modal-crosstalk 200-km optical path consisting of weakly-coupled double-ring-core FMF (DRC-FMF) and all-fibre mode selective couplers (MSCs) is adopted. Two remote optical power amplifiers (ROFAs) are used for independent amplification of LP01 and LP02. It is the first time that a 400G real-time commercial system running on an MDM link, which proves that smooth upgrade is possible by using weakly-coupled MDM techniques.

Technique Principles

As the cornerstone of our experiment, the DRC-FMF has been reported by Ref. [8], which were fabricated by YOFC in 2018 and 2019. The main innovation of the DRC-FMF is that its two layers of refractive index rings can greatly suppress the strongest modal crosstalk between LP21 and

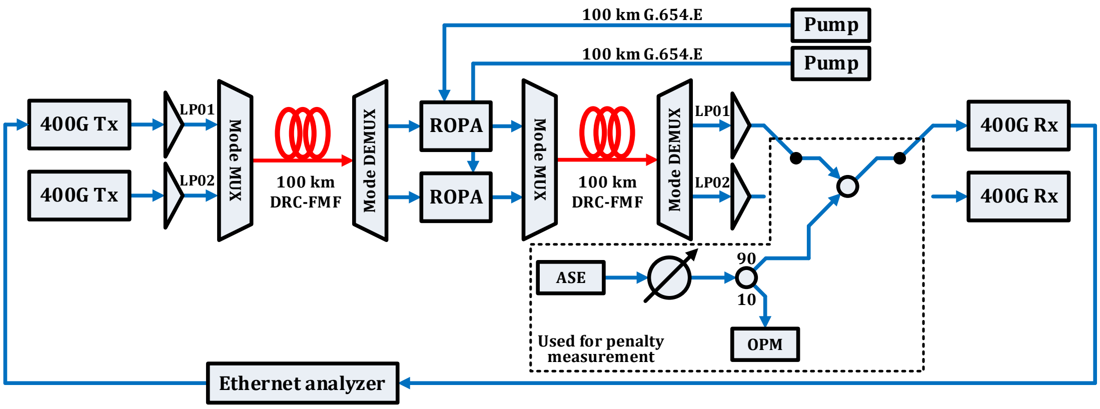

Fig. 1: Experimental setup of real-time 2-LP-mode unrepeated MDM transmission over 200-km FMF with commercial 400G system and ROPAs.

Tab. 1: Attenuations of the DRC-FMF.

	Year	LP01	LP02
Att. Co. (dB/km)	2018	0.230	0.246
	2022	0.265	0.302
MUX/DEMUX+200km Att. (dB)		54.53	67.49

Tab. 2: BTB insertion loss and modal crosstalk matrix of a pair of mode MUX/DEMUX.

Tapered MSC		
Unit: (dB)	**LP01 out**	**LP02 out**
LP01 in	-0.94	-27.18
LP02 in	-35.74	-2.64
Side-polished MSC		
Unit: (dB)	**LP01 out**	**LP02 out**
LP01 in	-0.6	-38.4
LP02 in	-33	-4.4

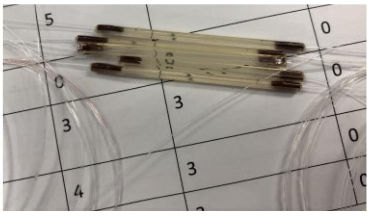

Fig. 2: (a) tapered MSCs; (b) side-polished MSC.

LP02. However, since hydrogen induced loss was not considered in the fabrication of DRC-FMF, the attenuations and other characteristics that related to attenuations for different modes have been greatly changed in the last 3-4 years. As shown in Tab.1, the attenuation coefficient of LP01 deteriorates from 0.230 dB/km to 0.265 dB/km, while the attenuation coefficient of LP02 furtherly deteriorates from 0.246 dB/km to 0.302 dB/km. Combined with mode multiplexer and demultiplexer (MUX/DEMUX), the overall link losses of LP01 and LP02 are measured to be 54.53 dB and 67.49 dB, respectively, which already fall into the category of large span loss. Hence, the performance of our unrepeatered MDM transmission is greatly limited by link loss.

As for mode devices, mode MUX/DEMUXs we used are all cascaded MSCs based on phase matching theory. Because of the shortage of MSCs, in fact two kinds of MSCs are used. One kind is fabricated by heating and tapering parallel SMF and DRC-FMF [12], the other one is fabricated by side-polishing technique [13]. Tapered MSCs are illustrated in Fig. 2. The back-to-back (BTB) insertion loss and modal crosstalk matrix of a pair of mode MUX/DEMUX is shown in Tab. 2. We can see that tapered MSC outperforms side-polished MSC for LP01 in both insertion loss and modal crosstalk, while for LP02 the situation reverses. Despite the differences in insertion loss and modal crosstalk, both MSCs are fully adequate for our experiment. After 200-km DRC-FMF, a pair of MUX/DEMUX based on tapered MSCs and a pair of MUX/DEMUX based on side-polished MSCs, the modal crosstalk from LP01 to LP02 and from LP02 to LP01 are measured to be -11.46 dB and -13.99 dB, respectively.

As descried above, the overall link losses of LP01 and LP02 are very large. For unrepeatered transmission, ROPA and Raman amplification or both are suitable techniques. However, the Raman amplification deeply depends on the transmission fibre. The mechanism of Raman amplification with multiple independent LP modes remains unclear. Thus, we choose ROPA as our solution, and two modes amplified independently in single-mode domain after 100-km transmission, which is helpful to gain control.

Experimental Setup and Results

The experimental setup of the real-time 2-LP-mode unrepeatered MDM transmission over 200-km FMF with commercial 400G system and ROPAs is illustrated in Fig. 2. 2 sets of commercial 400G sub-carrier multiplexing (SCM) DP-16QAM-PCS modems (WaveLogic 5 Exteme, Ciena) with 95 GBd are used as transmitters and receivers for LP01 and LP02, respectively. Data

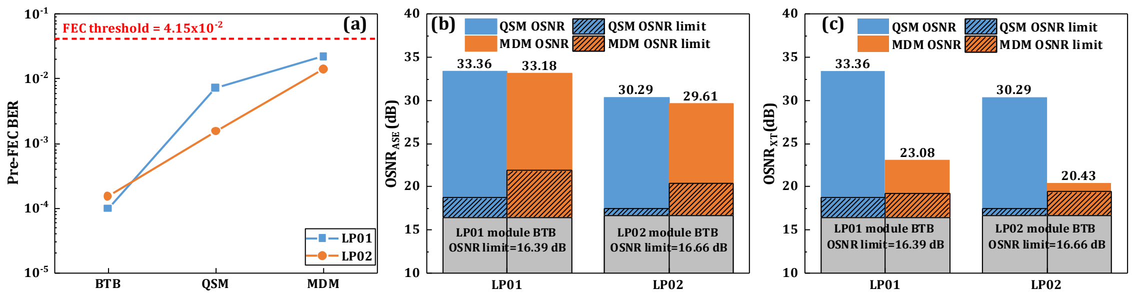

Fig. 3: (a) pre-FEC BERs (b) $OSNR_{ASE}$ and (c) $OSNR_{XT}$ for BTB, QSM and MDM of both LP01 and LP02 modes.

Tab. 3: $OSNR_{ASE}$ and $OSNR_{XT}$ for QSM and MDM of both LP01 and LP02 modes..

Unit: (dB)	$OSNR_{XT}$	$OSNR_{ASE}$	$OSNR_{XT}$ limit	$OSNR_{ASE}$ limit	$OSNR_{XT}$ penalty	$OSNR_{ASE}$ penalty
LP01 MDM	23.08	33.18	19.28	21.92	2.886	5.530
LP02 MDM	20.43	29.61	19.47	20.44	2.807	3.780
LP01 QSM	--	33.36	--	18.76	--	2.369
LP02 QSM	--	30.29	--	17.49	--	0.835

is generated by an ethernet analyser (VIAVI ONT 603), and fed into 400G transceivers by 4 sets of cascaded 100GBASE-LR4 modules at the client side. The central frequencies for both modems are 193.4 THz, near the centre of C-band. Since for each mode, only one channel is activated, wavelength MUX/DEMUX modules are removed to save link budget. The launch power before mode MUX for LP01 is 9.15 dB. For LP02, due to its relatively larger link loss, a launch power of 15.12 dB is adopted to balance the performances of LP01 and LP02. Two ROPAs are placed between the first and second sections of the 200-km FMF link, each of which is driven by a pump placed at the receiver side. Two 100-km G.654.E links are used for transmitting pump lights to the ROPAs. After 200-km FMF transmission, signals are detected by two 400G receivers. Data after decision is fed back to the ethernet analyser by 100GBASE-LR4 again, so that we can know any error happens. An amplifier spontaneous emission (ASE), a variable optical attenuator (VOA), a 90:10 optical coupler (OC), an optical power monitor (OPM) and a switch are combined for penalty measurement of both modes.

MDM transmission and quasi-single-mode (QSM) transmission are carried out. Fig. 3 (a) shows the pre-forward-error-code (pre-FEC) bit error rates (BERs) for BTB, QSM and MDM of both LP01 and LP02 modes. We can see that after 200-km unrepeatered MDM transmission, BERs of LP01 and LP02 are 2.23×10^{-2} and 1.40×10^{-2}, respectively, which are all below the FEC threshold of 4.5×10^{-2}. Fig. 3(b) illustrates the common $OSNR_{ASE}$ calculated by traditional OSNR definition that includes only ASE into noise, as shown in Eq. (1). It is worth noting that the $OSNR_{ASE}$ penalty of LP01 accumulates very fast under QSM transmission. Considering that nonlinear penalty in this distance should be small, we can say that this part of penalty mainly comes from multiple path interference (MPI). And MPI is caused by modal crosstalk coupled back and forth between transmitting mode and other modes. While for LP02, MPI penalty is smaller. Under MDM transmission, the $OSNR_{ASE}$ penalties of LP01 and LP02 increase by 3.16 dB and 2.95 dB, respectively, meaning that the modal crosstalk caused by MDM is close. We can also see that $OSNR_{ASE}$ cannot effectively represent the actual performance due to its artificially high value, so we introduce the concept of $OSNR_{XT}$, which includes measurable modal crosstalk into noise like ASE as shown in Eq. (2). The recalculated $OSNR_{XT}$ values for both two modes are shown in Fig. 3(c). $OSNR_{XT}$ values are closer to $OSNR_{XT}$ limits, showing better consistency with measured BER values. All OSNR values are listed in Tab. 3.

$$OSNR_{ASE} = \frac{S + MPI + XT}{N} \tag{1}$$

$$OSNR_{XT} = \frac{S + MPI}{N + XT} \tag{2}$$

Conclusions

In conclusion, a record real-time unrepeatered MDM transmission over 200-km FMF with 400G DP-16QAM-PCS commercial system and ROPAs is successfully demonstrated for the first time. It proves that smooth upgrade is possible by using weakly-coupled MDM techniques and commercial single-mode 400G systems. OSNR definition should also be reconsidered for MDM transmission in the future.

Acknowledgements

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