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DSP-free single-wavelength 100 Gbps SDM-PON with increased splitting ratio using 10G-class DML

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Abstract: We present beyond 100 Gbps space-division multiplexing passive optical network (SDM-PON) systems using commercial 10G-class directly modulated laser (DML) modulated with 25/28 Gbps data signals, with polarization-diversity micro-ring resonator (PD-MRR) to improve the extinction ratio (ER). A high-count multi-core fiber (HC-MCF) with low-crosstalk (XT) is used in the system, simultaneously increasing the transmission capacity and splitting ratio. Different cores of the HC-MCF are used for upstream (US) and downstream (DS) transmission, avoiding the Rayleigh backscattering noise. Thanks to compatibility with time-division multiplexing (TDM), the splitting ratio could be further increased. In addition, both symmetric and asymmetric SDM-PON architectures are proposed to meet different requirements of users. In the SDM-PON systems, a simple intensity modulation/ directly detection (IM/DD) is applied without digital signal processing (DSP), which may be a promising candidate for future large-capacity and high splitting ratio access networks.

1. Introduction

To meet ever-increasing bandwidth demands in access networks, particularly for emerging services, such as cloud computing, 4K or 8K TV, virtual reality and mobile X-haul for the 5G, high-speed passive optical networks (PONs) have attracted a lot of research interest. A solution of 25G EPON with scalability up to 100G (25G/50G/100G) is being intensively discussed by IEEE 802.3 task force [1]. At the same time, a PON system requires a larger splitting ratio to keep pace with the increasing number of network users [2]. Space-division multiplexing (SDM) has been demonstrated to significantly increase data capacity in optical fiber transmission links [3–6]. Recently, SDM as a promising technique using few mode fibers (FMFs) or multi-core fibers (MCFs) in a PON system has been proposed to increase the transmission capacity and splitting ratio [7–10]. The major challenge to deploy the FMFs in access networks is differential modal dispersion and modal interference. Compared to the FMF, the inter-core crosstalk (XT) of the MCF can be well controlled which makes the system design simpler. Since the cost of deploying an optical fiber underground is much higher than that of the optical fiber itself, the deployment of MCFs is a good option particularly for some newly-built community and enterprises. In addition, directly modulated lasers (DMLs) at high speeds with high output powers are very attractive for PON systems. However, usually DMLs with modulation speeds beyond 10 Gbps suffer from a reduced extinction ratio (ER). Several schemes have been proposed to enhance the ER of the signals [11–14], such as using chirp managed lasers (CMLs), filtering the signal by a delay line interferometer (DLI) or micro-ring resonator (MRR). A silicon based MRR has a small footprint and is compatible with complementary metal-oxide-semiconductor (CMOS) technology allowing

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potential integration with other optical/ electrical devices, which is a promising technique for the cost-effective implementation of compact transmitters for access network applications.

Previously, we have demonstrated a 100 Gbps SDM-WDM-PON using a Mach-Zehnder modulator (MZM) based 10 Gbps transmitter [7]. In this paper, we propose, for the first time, a SDM-PON scheme based on a high-count multi-core fiber (HC-MCF) achieving a high splitting ratio and large transmission capacity at the same time. Instead of using MZM, an off-the-shelf DML modulated with 25/28 Gbps signals is used [14], and the ER is improved by using a polarization-diversity micro-ring resonator (PD-MRR) [15]. SDM-PON with both symmetric and asymmetric architectures are proposed for different scenarios, such as 25/100 Gbps US/DS capacity for residential subscribers and 100/100 Gbps US/DS capacity for enterprises, respectively. A 30-core fiber is used in the proof-of-concept experiment and the signals for downstream (DS) and upstream (US) are distributed in different spatial channels, achieving a bidirectional operation and avoiding the Rayleigh backscattering noise. Compared with the couplers used in a TDM-PON system, the loss of the SDM fan-in/fan-out devices based on 3D-waveguide in the SDM-PON are independent of the number of spatial channels, which is beneficial for the power budget of the PON system.

2. Symmetric 125 Gbps SDM-PON system

2.1. Proposed symmetric SDM-PON architecture

Figure 1 shows an architecture of the proposed SDM-PON with symmetric DS and US transmission over an HC-MCF, which can support $M \times k$ optical network units (ONUs). The HC-MCF is used to increase both splitting ratio ($\times M$) and capacity ($\times i$). Each SDM-OLT has i transmitters and i receivers and the number of optical line terminals (OLTs) are M, which correspond to $2 \times i \times M$ cores of the HC-MCF for bidirectional transmission. In addition to SDM, the proposed architecture is also compatible with conventional TDM, which can distribute the signal using power splitters and k represents the TDM splitting ratio.

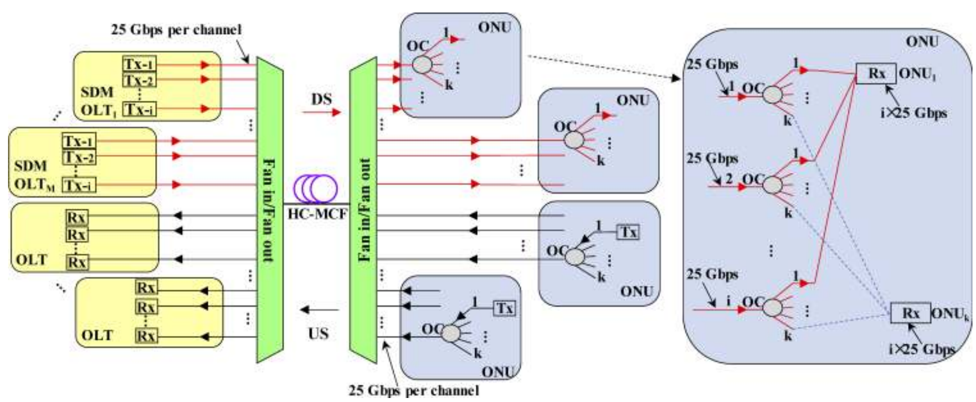

Fig. 1. Architecture of the proposed symmetric SDM-PON. (HC-MCF: high-count multi-core fiber, OLT: optical line terminal, ONU: optical network unit, Tx: transmitter, Rx: receiver, DS: downstream, US: upstream.)

In each ONU there are i SMFs for the DS link, which could be packed as a fiber ribbon for ease of management. The SMFs after the fan-out device can be specified in different lengths to meet differential distance requirements in SDM-PON system. At the same time, the lengths of the fibers at the output of the power splitters can also be adjusted to meet the needs of a small range of different distances. In this case, in order to meet enough power budget for all ONUs, EDFAs (Erbium-doped fiber amplifiers) could be used. Actually, a single multicore EDFA would be a desirable solution since it can simultaneously boost the optical signal power of all the spatial channels of the multi-core fiber [16]. Note that all the transmitters from OLTs or ONUs can share a single multicore EDFA, therefore the cost and power consumption per user can be reduced.

To lower the cost and simplify the system design, the transmitters on both OLTs and ONUs sides are off-the-shelf DMLs, modulated with 25 Gbps NRZ-OOK signals. Since the DML has a limited ER, a PD-MRR is used to reshape the optical spectrum and increase the ER of the signals. Therefore, digital signal processing (DSP) and dispersion compensation are not required in the system. With the low inter-core crosstalk (XT) of the HC-MCF in the proposed architecture, all the SDM channels can be independently transmitted in a single fiber, which makes the system design easier. By using different cores for DS and US, Rayleigh backscattering noise can also be avoided. Each OLT is specified to consist of 5 transmitters and each transmitter works at 25 Gbps, therefore 125 Gbps per ONU can be obtained. Considering the 7% forward error correction (FEC) overhead and a line rate of 125 Gbps, a net rate of 116 Gbps per ONU for both DS and US can be obtained in the symmetric structure after the FEC overhead subtraction. Since the SDM fan-in/fan-out device has a low insertion loss which is independent of the number of SDM channels, the combined loss for the US can be reduced.

2.2. Experimental setup and results

To verify the feasibility of the proposed architecture, a proof-of-concept experiment is performed and the experimental setup is shown in Fig. 2. The DML is NRZ-OOK modulated by a 25 Gbps pseudo-random binary sequence (PRBS of $2^{31}-1$), with a bias at 80 mA and an output power of 7.5 dBm. The central wavelength of the DML is 1553.3 nm with a 3 nm tuning range controlled by a thermal controller. The modulated signal is amplified to 17 dBm and then coupled into a PD-MRR with a random polarization. At the output of the PD-MRR, the signal is amplified and equally split into two parts by a 3-dB coupler. One part is equally split into 15 parts which are decorrelated acting as DS signals and then launched into 15 cores of the 30-core fiber through a fan-in device. After the transmission over the 30-core fiber, the signals are detected by a 20 Gbps receiver. The other part is also equally split into 15 parts which are decorrelated acting as US signals and then transmitted through the remaining 15 cores of the 30-core fiber. The receiver consists of a tunable optical attenuator, an optical pre-amplifier and a 20 Gbps photodiode (PD). Note that, the pre-amplifier can be removed if an avalanche photodiode (APD) is used in the experiment.

Figure 3(a) shows the design and scanning electron microscope (SEM) image of the PD-MRR, which composes of a silicon MRR and two polarization splitters and rotators (PSRs) at both the input and output of the device [15]. The input polarization to TE_0 and TM_0 modes are split and then TM_0 mode is converted into TE_1 mode by the first PSR. The TE_0 beam propagates in the lower arm of the MRR, and the TE_1 beam is converted to TE_0 beam with π phase difference and propagates in the upper arm of the MRR. At the output of the silicon MRR, the two TE_0 beams are combined in the second PSR. The normalized transmission spectra of the PD-MRR with TE/TM modes and for arbitrary input polarizations are measured, as shown in Fig. 3(b). The spectra of 25 Gbps NRZ-OOK signals with and without PD-MRR are shown in Fig. 3(c). Figure 3(d) illustrates a measured transmission spectrum at the wavelength from 1480 nm to 1580 nm, which has a free spectral range (FSR) of ~800 GHz, and therefore it can support a WDM operation utilizing multi-DMLs with a frequency spacing of ~800 GHz. The PD-MRR totally introduces ~26 dB of loss, including 2.4 dB filtering loss and ~24 dB insertion loss. The insertion loss of the PD-MRR is high due to a limited coupling efficiency induced by both the refractive index mismatch and mode mismatch between the fiber and the silicon PD-MRR waveguide. Actually, the insertion loss of the PD-MRR can be significantly reduced down to ~2 dB by optimizing the grating couplers for fiber input and output [17].

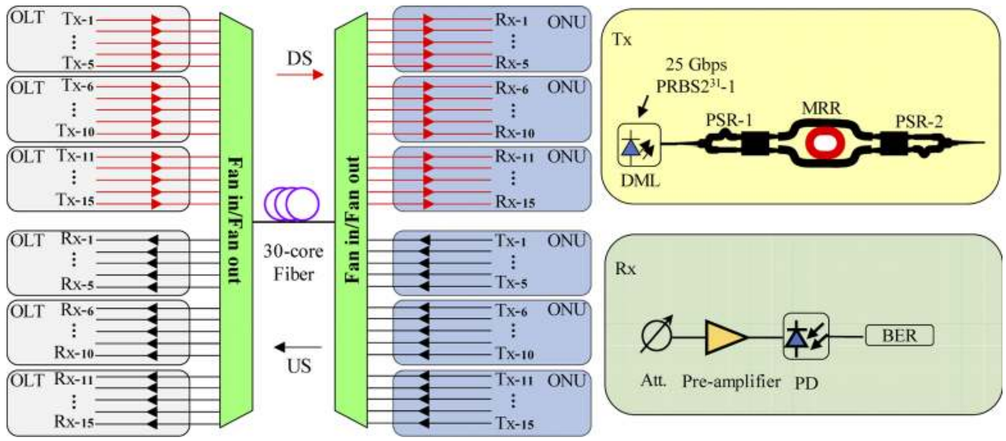

Fig. 2. Experimental setup of symmetric SDM-PON. (DML: directly modulated laser, PSR: polarization splitter and rotator, MRR: micro-ring resonator, PRBS: pseudo-random binary sequence, Att.: attenuator, Tx: transmitter, Rx: receiver, DS: downstream, US: upstream, PD: photodiode, BER: bit error rate.)

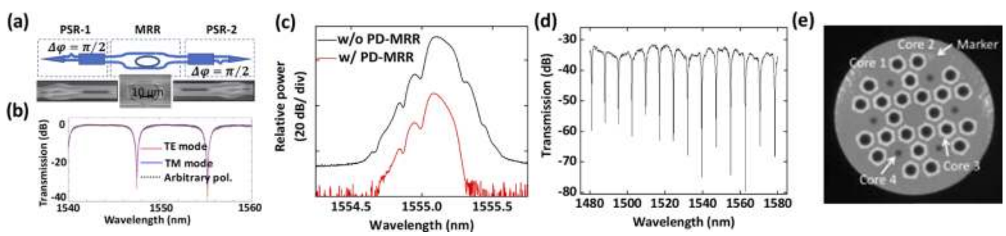

Fig. 3. (a) Scanning electron microscope image; (b) normalized transmission for TE/TM modes and for arbitrary input polarizations; (c) spectra of 25 Gbps OOK signal with/without PD-MRR; (d) measured transmission spectrum; (e) Cross-sectional view of the 30-core fiber.

The heterogeneous 30-core fiber is designed and fabricated with four types of cores, as shown in the Fig. 3(e), achieving a large spatial multiplicity and enabling low XT between adjacent cores [18]. It has a limited cladding diameter of 228 um, A_{eff} of around 80 μm^2 and low XT of below −50 dB at 9.6 km. 3D-waveguide based fan-in/fan-out devices are used for space (de)multiplexing. The entire loss for all cores through fan-in/fan-out devices and the 30-core fiber are within the range 8.7 dB to 14 dB, including transmission loss of the 30-core fiber of 5.4 dB to 6.3 dB. Note that by using a free-space device, the fan-in/fan-out device loss can be reduced to ∼1 dB [19].

Figures 4(a)–4(f) show the eye diagrams of the 25 Gbps NRZ-OOK signals for different cases. Without the PD-MRR, the signal has a low extinction ratio (ER) even in the back to back (B2B) case. Since the transfer function of the PD-MRR has a strong optical filtering effect as shown in Fig. 3(c), “0” level of the signal is suppressed and the ER is improved. As a result, the eye diagram becomes open in the case of using the PD-MRR for both the B2B signal and the signal after the 30-core fiber transmission. In addition, as can be seen in Figs. 5(a) and 5(b), the bit error rate (BER) curves for DS and US are almost the same due to a low inter-crosstalk of 30-core fiber. Without the PD-MRR for US, the receiver sensitivity at a BER of 10^{-3} in B2B case is −28 dBm. By using the PD-MRR, the receiver sensitivity at a BER of 10^{-3} in B2B case is improved to −34.5 dBm; after the 30-core fiber transmission, the power penalty is ∼2.5 dB. The power penalty is mainly due to the dispersion of the multi-core fiber. As the launched power is amplified to 24 dBm before the fan-in device; after the 30-core fiber transmission the receiver sensitivity at a BER of 10^{-3} is around −32 dBm and maximum loss of the fan-in devices for each core is 4.3 dB, therefore a power budget of ∼51 dB at a BER of 10^{-3} is achieved. In order to reduce the cost, the pre-amplifier EDFA can be removed for the receiver. By using an APD, the power budget is ∼45 dB compared to a pre-amplifier PD [20]. Considering the 7% FEC overhead and a line rate of 125 Gbps, a net rate of 116 Gbps for DS and US is obtained for symmetric transmission after the FEC overhead subtraction.

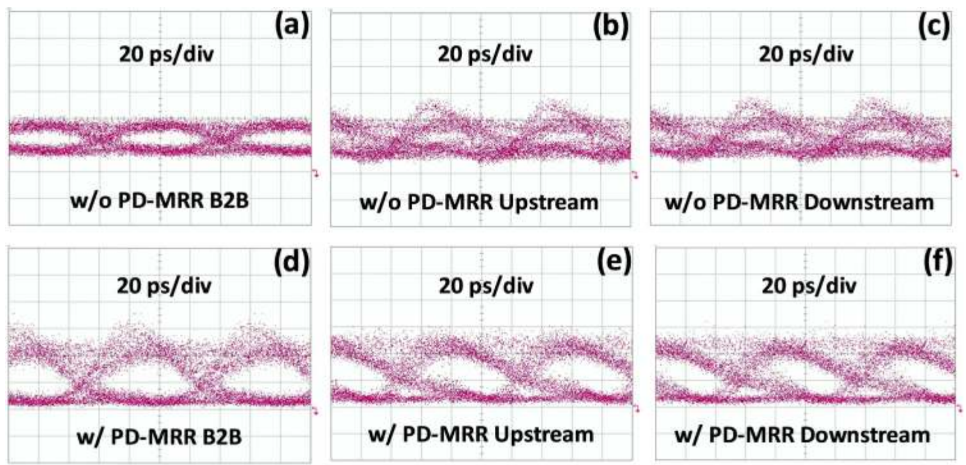

Fig. 4. Eye diagrams of 25 Gbps OOK signal with and without PD-MRR for B2B case (a, d); upstream transmission (b, e); downstream transmission (c, f).

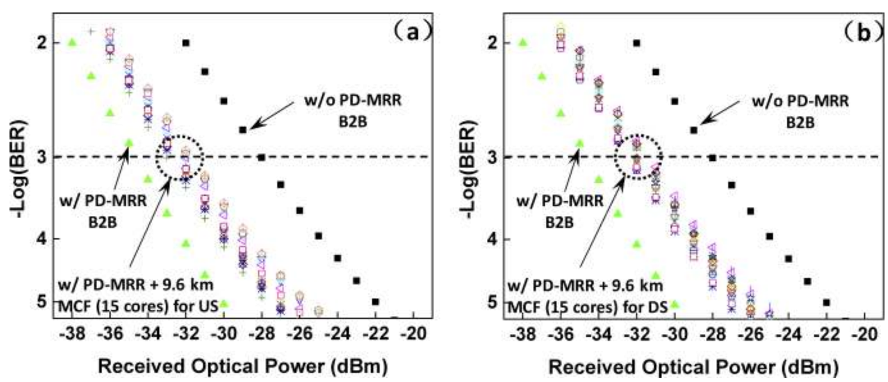

Fig. 5. BERs for 25 Gbps OOK signals over a 9.6-km 30-core fiber (a) for US; (b) for DS. (US: upstream, DS: downstream, PD-MRR: polarization-diversity micro-ring resonator, MCF: multi-core fiber, B2B: back to back.)

3. Asymmetric 112 Gbps SDM-PON system

3.1. Proposed asymmetric 112 Gbps SDM-PON architecture

Figure 6 shows an architecture of the proposed asymmetric SDM-PON based on an HC-MCF. The number of SDM OLTs is M and each SDM OLT has i transmitters, which indicates the number of cores for the DS transmission is $i \times M$. After the transmission over the HC-MCF, the signal can also be split ($\times k$) using power splitters. Thus, this architecture can be compatible with

TDM PON and support $M \times k$ ONUs, simultaneously increasing the transmission capacity ($\times i$) and the splitting ratio ($\times M$) for DS. For the US transmission, the total ONUs are divided into several groups (1 to t), and then transmitted into the corresponding cores of the HC-MCF. Each group has n ONUs and these are combined by a power combiner. Note that, in the ONUs side $t \times n$ should equal to $M \times k$. If $M \times k$ is an integer multiple of n, the number of DS channels matches the number of US channels. Otherwise, the total number of US channels is dependent on n when $M \times k$ is known. In the experiment, the transmitter is modulated by 28 Gbps PRBS of $2^{31}-1$ to explore a higher data rate and i equals to 4, therefore achieving the 112 Gbps transmission capacity per ONU for DS. 20 cores of the 30-core fiber are used for DS and m equals 5, which increase the splitting ratio by a factor of 5.

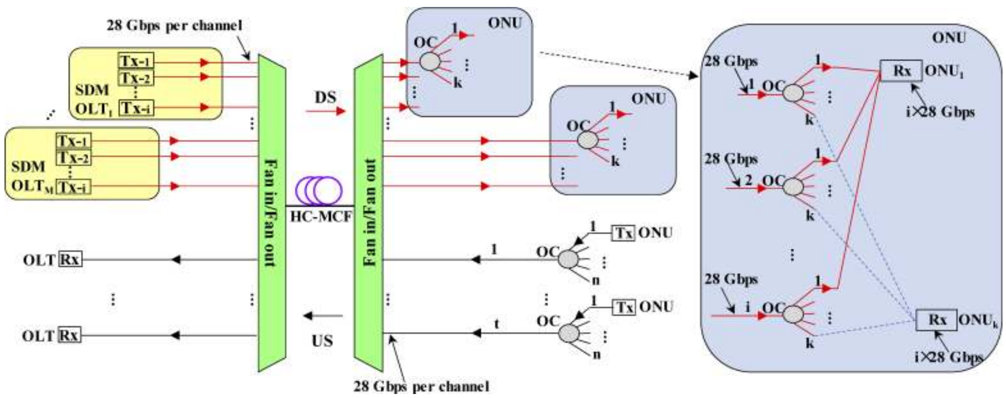

Fig. 6. Architecture of the proposed asymmetric SDM-PON. (HC-MCF: high-count multi-core fiber, OLT: optical line terminal, ONU: optical network unit, Tx: transmitter, Rx: receiver.)

3.2. Experimental setup and results

In order to verify the proposed asymmetric SDM-PON architecture, we perform a proof-of-concept experiment and the experimental setup is shown in Fig. 7. All the experimental devices are identical to those of the above symmetric SDM-PON. The DML is NRZ-OOK modulated with a 28 Gbps PRBS of $2^{31}-1$ and 20 cores of the 30-core fiber are used for DS and the remaining 10 cores are used for US.

Figures 8(a)–8(f) show the eye diagrams of 28 Gbps NRZ-OOK signals for different cases. Comparing the eye diagrams of Fig. 4 and Fig. 8, the eyes of 28 Gbps NRZ-OOK signals with the PD-MRR after 30-core fiber transmission become a bit worse, since a higher modulated speed causes a degraded ER. Through the 30-core fiber transmission, the fiber dispersion causes the signal degradation, as shown in the eye diagrams of Figs. 8(e) and 8(f). Figs. 9(a) and 9(b) show the measured BERs for US and DS. Without using the PD-MRR, the receiver sensitivity at a BER of 10^{-3} is −24.5 dBm in the B2B case; by using the PD- MRR, the receiver sensitivity is improved to be −31 dBm in the B2B case. Thus, the receiver sensitivity is significantly improved by using the PD-MRR. After the 30-core fiber transmission in the case of using the PD-MRR, there is around 2 dB power penalty compared to the B2B case.

We also experimentally investigate the relationship of the receiver sensitivity at a BER of 10^{-3} with different launched power at the input of the fan-in device of the 30-core fiber, in the case of using the PD-MRR to improve the signal quality. The experimental result is shown in Fig. 10. As the launched power at the input of the fan-in device is increased from 18 dBm to 23 dBm, the receiver sensitivity at a BER of 10^{-3} has no obvious change. However, beyond 23 dBm launched power we observed the power penalty for the receiver sensitivity, which is attributed to the fiber

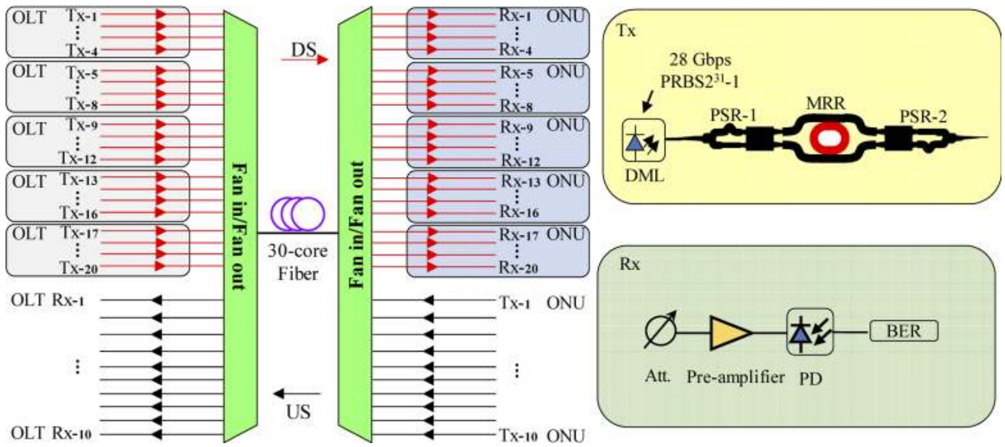

Fig. 7. Experimental setup of asymmetric SDM-PON. (DML: directly modulated laser, PSR: polarization splitter and rotator, MRR: micro-ring resonator, PRBS: pseudo-random binary sequence, Att.: attenuator, Tx: transmitter, Rx: receiver, DS: downstream, US: upstream, PD: photodiode, BER: bit error rate.)

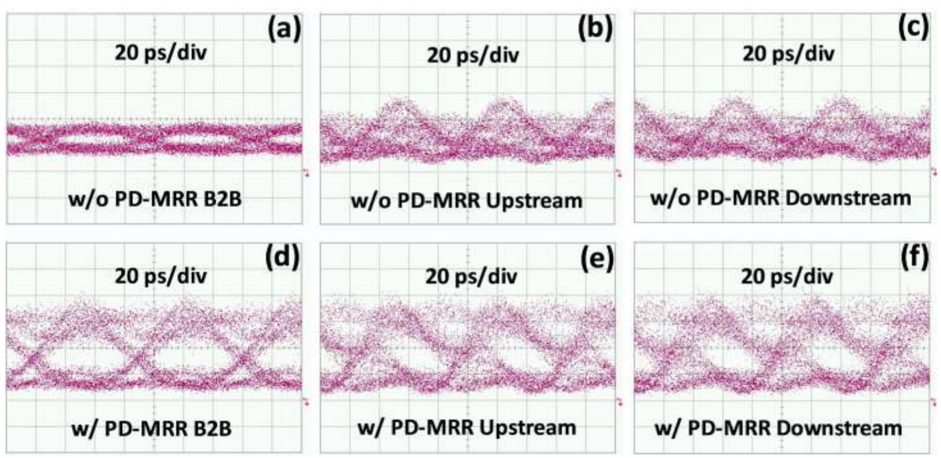

Fig. 8. Eye diagrams of 28 Gbps OOK signal with and without PD-MRR for B2B case (a, d); upstream transmission (b, e); downstream transmission (c, f).

nonlinearity in the 30-core fiber. Therefore, launched power of 23 dBm can be used at the input of the fan-in device. Considering that the maximum loss of the fan-in device is 4.3 dB, the power budget is around 47 dB. If the optical pre-amplifier is replaced by an APD, a power budget of 41 dB will be obtained. Therefore, the launched power could be increased, resulting in a higher power budget through the HC-MCF transmission. In the proposed asymmetric SDM-PON, each OLT consists of 4 transmitters and each transmitter works at 28 Gbps, therefore 112 Gbps per ONU can be obtained. Considering the 7% FEC overhead, a line rate of 112 Gbps, a net rate of 104 Gbps for DS is obtained for DS transmission after the FEC overhead subtraction. As the TDM is used for US, a net rate of 26 Gbps is obtained for US transmission after the FEC overhead.

In both the symmetric and asymmetric SDM-PON experiments, the HC-MCF used in the experiment has a limited fiber length of 9.6 km. Actually, it could be expected to demonstrate the SDM-PON system with much longer distance, since the HC-MCF has a very low inter-core

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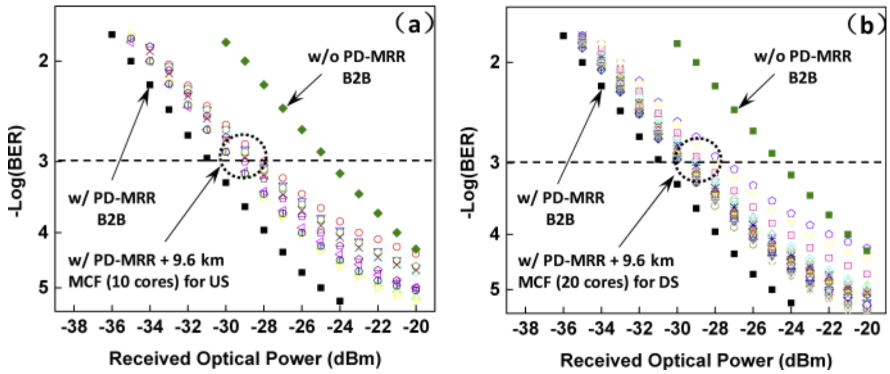

Fig. 9. BERs for 28 Gbps OOK signals over 9.6-km 30-core fiber (a) for US; (b) for DS. (US: upstream, DS: downstream, PD-MRR: polarization-diversity micro-ring resonator, MCF: multi-core fiber, B2B: back to back.)

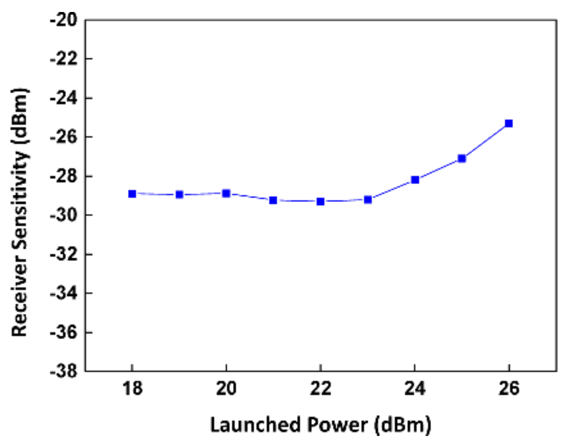

Fig. 10. Receiver sensitivity at a BER of 10^{-3} as a function of launched power before fan-in device with PD-MRR

crosstalk. The main distance limitation is fiber dispersion. The dispersion of HC-MCF is almost identical to standard single mode fiber (SSMF), therefore the expected transmission distance and corresponding solution are also similar as that of the SSMF, such as utilizing advanced modulation techniques or dispersion compensation.

4. Conclusions

To the best of our knowledge, this is the first demonstration of beyond 100 Gbps SDM-PON systems using a commercial 10G-class DML and an HC-MCF without WDM and DSP. The extinction ratio of DML operating at 25/28 Gbps is improved by using the PD-MRR at the transmitter. Symmetric and asymmetric PON architectures have been proposed and demonstrated, which could meet different requirements of users. By using ~10 km, 30-core fiber, the increased transmission capacity (×5) and the enhanced splitting ratio (×3) have been obtained for both DS and US in the symmetric SDM-PON system; and the increased transmission capacity (×4) and the enhanced splitting ratio (×5) have been obtained for DS in the asymmetric SDM-PON system. Since the insertion loss of fan-in/fan-out devices based on 3D-waveguide is independent

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of the number of the spatial channels, the power budget of the proposed SDM-PONs can be significantly increased.

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