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100 Gb/s SDM-PON Using Polarization-Diversity Silicon Micro-Ring Resonator Enhanced DML

Fangdi Bao, Yunhong Ding, Toshio Morioka, Leif K. Oxenløwe and Hao Hu

Abstract— **We experimentally demonstrate a bidirectional space-division multiplexing passive optical network (SDM-PON) system by using a commercial directly modulated laser (DML) modulated by a 25 Gb/s NRZ-OOK signal, and followed by a polarization-diversity silicon micro-ring resonator (PolD-MRR) for enhancing the modulation extinction ratio. A multi-core fiber (MCF) with negligible inter-core crosstalk is used for bidirectional transmission, not only increasing the aggregated capacity, but also simplifying the splitting of upstream and downstream and enabling colorless optical network units (ONUs). The capacity of 100 Gb/s for downstream and 75 Gb/s for upstream has been achieved, respectively. In addition, transmission capacity could be further increased by wavelength-division multiplexing (WDM) according to PolD-MRR periodical feature, which might be beneficial for future large-capacity optical access networks.**

***Index Terms*— Passive optical networks, micro-ring resonator, space division multiplexing, polarization diversity.**

I. INTRODUCTION

With the exponential increase of bandwidth demands of optical access networks, passive optical networks (PONs) with large traffic capacity are attracting a lot of attention. Next generation Ethernet PON (NG-EPON) proposed by IEEE 802.3 Ethernet Working Group, suggests 25 Gb/s or 40 Gb/s at single wavelength and an aggregated capacity of 100 Gb/s using wavelength division multiplexing (WDM) [1]. Coherent transmission schemes have also been proposed to increase capacity although cost and complexity of such solutions are the main challenges [2], [3]. The trade-off between capacity and cost should always be considered as subscribers have to pay the cost of PON systems. Commonly, vendors prefer to utilize existing 10G-class optical components for upgrading the serial bit rate in the most economical manner, where several methods have been proposed. Advanced modulation formats such as four-level pulse amplitude modulation (PAM-4), electrical duobinary, optical duobinary were used to realize 25 Gb/s data rate per wavelength using 10G-class devices. PAM-4 is chromatic dispersion tolerant and can be used in intensity modulation and direct detection (IM/DD) systems and can relax the bandwidth requirement of transceivers. However, a linear transceiver is required, resulting in a limited extinction ratio [4]. Electrical duobinary and optical duobinary are also tolerant to dispersion, but the former needs a conversion circuit to demodulate the received signals in the receiver [5]; the latter requires a wide bandwidth Mach-Zehnder modulator (MZM) [6], [7], thus adding cost and complexity of the system. To simplify the system design and control cost in access networks, non-return-to-zero on-off-keying (NRZ-OOK) modulation is still a good candidate for the PON system. In particular, 10G-class directly modulation lasers (DMLs) modulated by 25-Gb/s NRZ-OOK signal have been proposed, however, the main issues of such a modulation scheme have a low extinction ratio. An effective solution achieving 25 Gb/s per wavelength has been demonstrated by using a delay-interferometer with an optical filtering effect to mitigate the impact of dispersion and equalize the frequency response [8]. However, delay-interferometers are usually bulky and not easy to be integrated with other optical components, making them not so attractive for access networks. Alternatively, a micro-ring resonator (MRR) has also been proposed as a candidate to overcome this problem and improve the signal quality [9], [10], although the feasibility of using a polarization-insensitive MRR in high-speed optical access networks has not been investigated so far.

Space-division multiplexing (SDM) has also been proposed as another solution in large capacity PONs as special fibers in terms of design and fabrication have become more mature and commonplace, and with many spatial channels data capacity can be significantly increased in a cost-effective way. Two types of fibers – few mode fibers (FMFs) and multi-core fibers (MCFs) have been used for SDM-PONs [11]-[14]. In our previous research, we have experimentally demonstrated a bidirectional SDM-WDM-PON system with a capacity beyond 100 Gb/s for next generation access networks [14] where the data rate per wavelength was still 10 Gb/s and MZM was also employed.

In this paper, we propose a bidirectional SDM-WDM-PON system based on commercial DMLs [15] modulated by NRZ-OOK at 25 Gbit/s followed by a polarization-diversity

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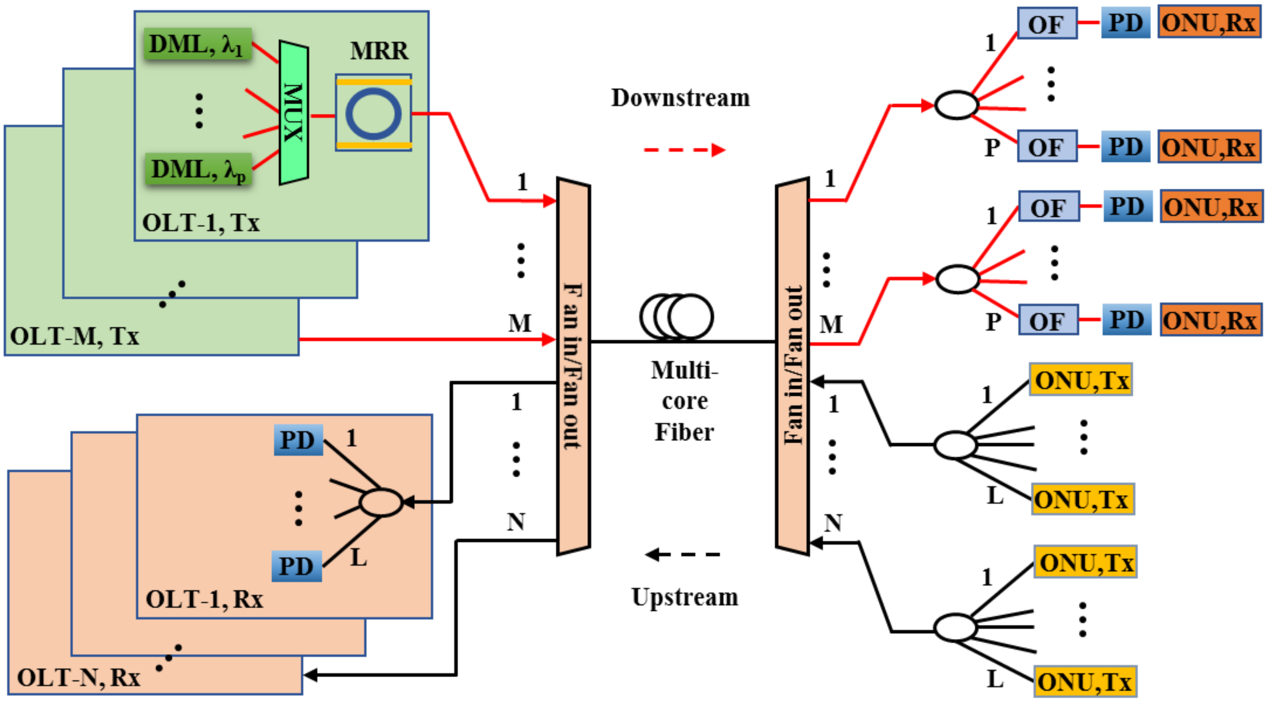

Fig. 1. Proposed SDM-WDM-PON architecture based on DMLs and PolD-MRRs. (DML: directly modulated laser, MRR: micro-ring resonator, OLT: optical line terminal, ONU: optical network unit, OF: optical filter, MUX: multiplexer, PD: photodetector, Rx: receiver, Tx: transmitter.)

silicon micro-ring resonator (PolD-MRR) which can be used to enhance the extinction ratio of the modulated 25 Gb/s signal. In addition, by using a MCF for bidirectional transmission, not only is the transmission capacity increased, but also colorless optical network units (ONUs) can be achieved, allowing the same optical line terminals (OLTs) and OUNs to be employed regardless of wavelengths. Finally, a proof-of-concept experiment is performed with an aggregated capacity of 100 Gb/s for downlink and 75 Gb/s for uplink. Thanks to the compatibility with WDM techniques, the transmission capacity can be further increased. In this experiment, we demonstrate a simple and low-cost SDM-PON based on silicon PolD-MRR using commercial DML without digital signal processing (DSP), electro-optic modulation and advanced modulation formats.

II. ARCHITECTURE OF THE PROPOSED SDM-WDM-PON

The proposed SDM-WDM-PON architecture using DMLs and PolD-MRRs is shown in Fig. 1. 3D waveguide based fan-in/fan-out devices are used for spatial multiplexing and demultiplexing. For the downstream link, each OLT has multiple DMLs at the wavelengths from λ_1 to λp, which are modulated by high-speed NRZ-OOK signals, multiplexed by a WDM multiplexer (MUX) and launched into a silicon PolD-MRR to enhance the modulation extinction ratio. All the signals from a number of OLTs (OLT-1 to OLT-M) are aggregated in parallel and then sent to the M cores of the MCF for downstream. After the transmission over the MCF, signals of each core are split by a power splitter, filtered by an optical filter (OF) and finally detected by a photodetector (PD). Here, M represents the number of OLTs, which also equals the number of cores of MCF for downstream. For the upstream transmission, signals generated by the transmitters (from 1 to L) of ONUs are combined by a coupler and then launched into one of the cores of the MCF. Each ONU has N transmitters to carry a large-capacity signal, which are transmitted through N cores of the MCF for upstream. The received signals in the OLT are directly split and detected by PDs in the form of time-division multiplexing (TDM) method. Here, N denotes the number of cores of MCF for the upstream transmission and L represents

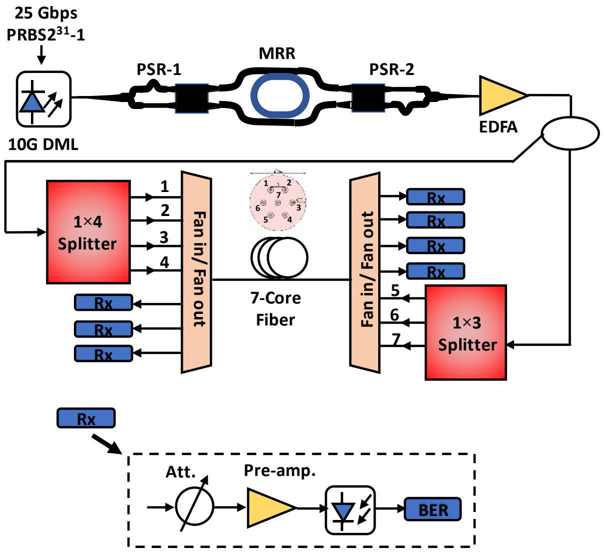

Fig. 2. The schematic experimental setup of the SDM-PON based on DML and PolD-MRR. (DML: directly modulated laser, MRR: micro-ring resonator, PSR: polarization splitters and rotators, EDFA: erbium-doped fiber amplifier, Pre-amp.: pre-amplifier, Rx: receiver, BER: bit error rate, Att.: attenuator.)

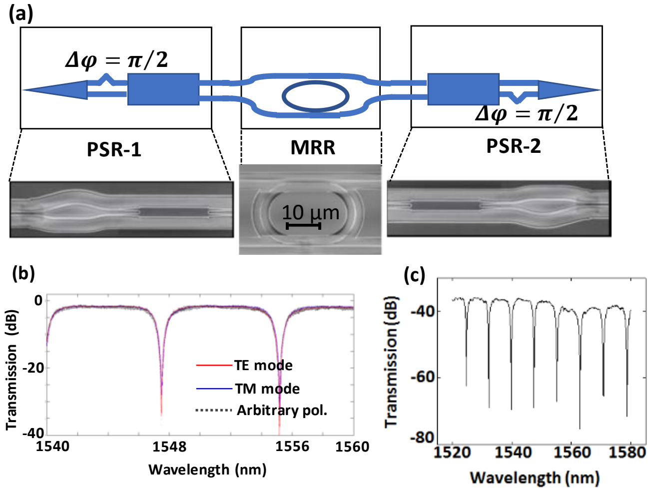

Fig. 3. (a) Scanning electron microscope (SEM) images of the PolD-MRR. (b) measured normalized transmission of the PolD-MRR for TE/TM modes and for arbitrary input polarizations. (c) measured transmission spectrum of the PolD-MRR over 70 nm wavelength range.

the number of transmitters of ONUs allocated to each core. It should be noted that M is larger than N in the proposed asymmetric system. Upstream and downstream signals are transmitted through different cores of the MCF with negligible inter-core crosstalk, which avoids Rayleigh backscattering noise, simplifies the splitting of upstream and downstream and enables colorless ONUs. In addition, there is no dispersion compensation or offline signal processing since the extinction ratio of the signals is improved sufficiently by using the silicon PolD-MRR.

III. EXPERIMENTAL SETUP AND RESULTS

In order to validate the feasibility of the proposed SDM-WDM-PON architecture based on DMLs and PolD-MRRs, we set up an experiment as shown in Fig. 2, in which only one DML is employed for the proof of concept. The system mainly consists of a commercial DML, a PolD-MRR, a 7-core fiber and a 20G PD. The design of the silicon PolD-MRR is shown in Fig. 3(a), consisting of a silicon MRR and two polarization splitters and rotators (PSRs) employed at the input and output of the device [16]-[18]. The PSR consists of a tapered waveguide which is used to convert mode followed by a 2 × 2 multi-mode interference (MMI) through two arms inducing an extra phase difference. As the beam passes through the first PSR, the input polarization TE_0 and TM_0 modes are split and converted into two TE_0 which propagate in the upper and down arms of the silicon MRR. At the output of the silicon MRR, the two beams with TE_0 are combined through the second PSR. Since the second PSR at the output is vertically flipped with respect to the first PSR at the input, a low polarization dependent loss (PDL) is obtained for the whole circuit. Fig. 3 (a) and (b) show the scanning electron microscope (SEM) images of the PolD-MRR and the measured normalized transmission of the PolD-MRR with TE and TM modes, and for arbitrary input polarizations, separately. Fig. 3 (c) illustrates measured transmission spectrum over a 70 nm wavelength range, which has a free spectral range (FSR) of ~800 GHz, allowing potentially WDM operation using multiple DMLs with frequency spacing of ~800 GHz. In the experiment, the measured total loss of the PolD-MRR is 27.8-dB, which consists of ~25 dB insertion loss and 2.8 dB filtering loss. Note that the insertion loss of the PolD-MRR could be reduced to ~2 dB by improving the grating couplers for fiber input and output.

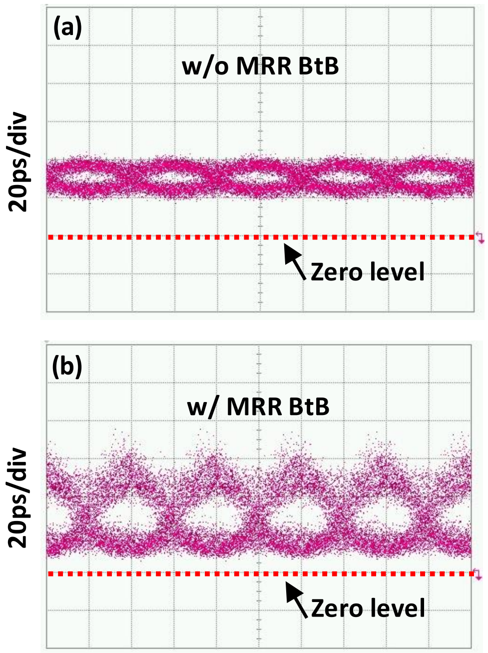

Fig. 4. Eye diagrams of the 25 Gbps OOK signal (a) without PolD-MRR in BtB case, (b) with PolD-MRR in BtB case.

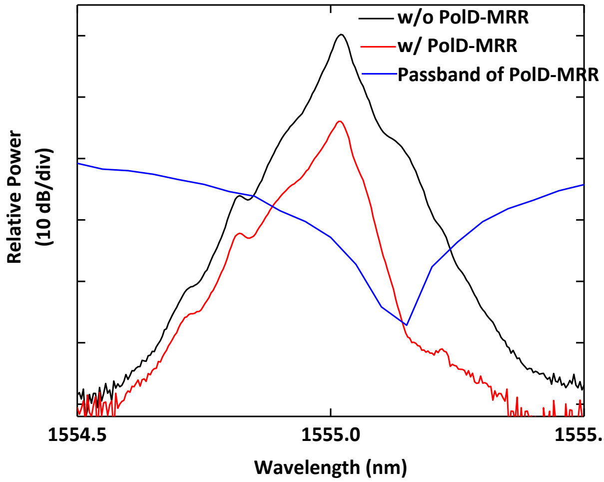

Fig. 5. 25 Gbps OOK signal spectrum with and without PolD-MRR transmission.

The DML with a bias current of 80 mA is on-off keying (OOK) modulated by a 25 Gb/s pseudo-random binary sequence (PRBS, 2^{31}-1), which is centered at 1553.3 nm at room temperature and has a 3 nm tuning range by using a thermal controller. The generated signal is coupled into the silicon PolD-MRR without using a polarization controller to adjust input polarization. At the output of the silicon PolD-MRR, the signal is amplified and split into two parts. One of them acting as downstream signals are split equally and sent into 4 cores of the 7-core fiber. After the 7-core fiber transmission, the signals are received by ONU receivers through the fan-out device and four SMFs. The receiver

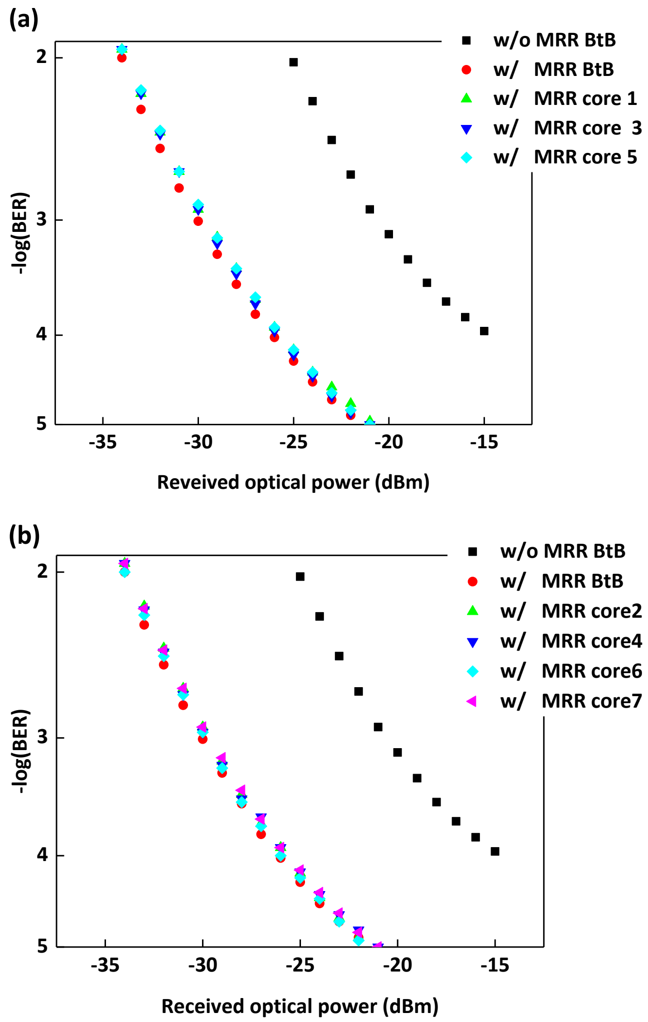

Fig. 6. BER measurement for 25 Gbps OOK signal over 7-core fiber, (a) for upstream, (b) for downstream.

consists of a tunable attenuator, an optical pre-amplifier and a 20G PD for signal detection. Note that the optical pre-amplifier can be removed, when PD is replaced by an avalanche photodiode (APD) [19]. Meanwhile, upstream signals are launched into the remaining 3 cores of the 7-core fiber. After the transmission, the signals are received in the OLT side.

The 7-core fiber used in this experiment is 2-km and has a core diameter of 9 µm, a core pitch of 46.8 µm and cladding diameter of 186.5 µm. The dispersion and dispersion slope per core of 7-core fiber at the wavelength of 1550 nm are around 16.5 ps/km-nm and 0.06 ps/km-nm^2 respectively [20]. By launching the light in the center core and measuring the optical power for each of the 6 outer cores, the crosstalk values from the center core to adjacent outer cores have been obtained. The range of the crosstalk values for 6 outer cores is in between -40 ~ -50 dB at the wavelength from 1525 nm to 1575 nm. The core-averaged inter-core crosstalk is around -45 dB over 2-km at 1550 nm [21]. The MCF has a low inter-core crosstalk and the physical properties of each core of the MCF is similar as that of a standard single mode fiber (SSMF), therefore the receiver sensitivity for the different MCF lengths are also similar as that of the SSMF. For the long-reach transmission some potential solutions could be used such as dispersion compensation or coherent detection.

The fan-in/fan-out device used in the experiment was designed and fabricated to match the mode field characteristics and inter-core spacing of the 7-core fiber. We have measured the insertion losses of the fan-in/fan-out device for core 1 to core 7: 1.45 dB, 2.25 dB, 2.5 dB, 3.05 dB, 1.7 dB, 2.85 dB and 2.3 dB. The insertion losses of the 7-core fan-in/fan-out devices vary, due to mode field mismatch, minor core misalignment and asymmetry. Note that the fan-in/fan-out device loss can be reduced to around 1dB in case free-space device is used.

Fig. 4 shows eye diagrams of the 25 Gb/s signal with and without using the PolD-MRR in the back-to-back (BtB) case. It can be seen, without using the PolD-MRR the eye diagram is almost closed in the BtB case; when the PolD-MRR is used in the system, the eye diagram is significantly opened. This is because a strong optical filtering is generated by the transfer function of the MRR (Fig. 5), suppressing the ‘0’ level of the signal. In addition, the wavelength spacing between the center wavelength of the signal and the resonance of the MRR is optimized for the best performance. We found that the optimal notching point of the MRR is about 0.2 nm to the longer-wavelength side of the signal generated in the DML, as shown in Fig. (5), where the PolD-MRR suppresses the low frequency components (i.e. ‘0’ level) of signals (Fig. 4), thus improving the extinction ratio.

In order to evaluate the performance of the SDM-PON system, we measured the BER performance of bidirectional transmission through the 7-core fiber by using the silicon PolD-MRR, as shown in Fig. 6 (a, b). Without using the PolD-MRR, the BtB sensitivity is -20.4 dBm at a BER of 1×10^{-3}. By using the silicon PolD-MRR, the BtB sensitivity at the BER of 1×10^{-3} is improved to be -30 dBm. It can also be seen that the measured BERs of upstream and downstream are almost identical with the receiver sensitivity of -30 dBm at the BER of 1×10^{-3}, which also confirms a negligible inter-core crosstalk in the 7-core fiber. The signal quality has no obvious degradation after all the 7-core transmission compared to the BtB case.

IV. CONCLUSION

In summary, we have proposed a low-cost bidirectional SDM-WDM-PON architecture using DMLs and a silicon PolD-MRR and in the proof-of-concept experiment we successfully demonstrated the bidirectional PON system with the aggregated capacity of 100 Gb/s for downstream and 75 Gb/s for upstream. By using the silicon PolD-MRR, the extinction ratio is improved, which allows for the transmission of a 25 Gb/s signal using a commercial DML. Since the silicon PolD-MRR has the periodical feature with a FSR of ~800 GHz, it can potentially be used in the SDM-WDM-PON system with ~800 GHz frequency spacing, which could support 5 WDM channels within the telecom C-band and achieve an aggregate capacity of 500 Gb/s for downlink and 375 Gb/s for uplink. In addition, the DMLs and the silicon PolD-MRR could potentially be integrated, resulting in further cost reduction. The 7-core fiber used in this scheme not only increases the capacity but also avoids the Rayleigh backscattering noise and facilitates the ease of splitting upstream and downstream. Therefore, the proposed scheme is an attractive candidate for the future large-capacity low-cost access network.

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V. ACKNOWLEDGMENT

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REFERENCES

[1] IEEE 802.3 Ethernet Working Group, "Feasibility Assessment for the Next Generation of EPON," 2015.

[2] S. Smolorz, H. Rohde, E. Gottwald, D. W. Smith, and A. Poustie, “Demonstration of a Coherent UDWDM-PON with Real-Time Processing,” in Proc. OFC, 2011, pp. PDPD4.

[3] M. Presi, M. Artiglia, and E. Ciaramella, “Electrical filter-based and low-complexity DPSK coherent optical receiver,” Opt. Lett., vol. 39, no. 21, pp. 6301, Nov. 2014.

[4] D. T. van Veen and V. E. Houtsma, “Symmetrical 25-Gb/s TDM-PON with 31.5-dB Optical Power Budget Using Only Off-the-Shelf 10-Gb/s Optical Components,” J. Lightw. Technol., vol. 34, no. 7, pp. 1636–1642, Apr. 2016.

[5] V. Houtsma et al., “APD-Based DuoBinary Direct Detection Receivers for 40 Gbps TDM-PON,” in Proc. OFC, 2015, pp. Th4H.1.

[6] D. T. Van Veen, V. E. Houtsma, A. H. Gnauck, and P. Iannone, “Demonstration of 40-Gb/s TDM-PON over 42-km with 31 dB optical power budget using an APD-based receiver,” J. Light. Technol., vol. 33, no. 8, pp. 1675–1680, 2015.

[7] A. Gnauck, P. Iannone, D. van Veen, and V. Houtsma, “4 × 40-Gb/s TWDM PON downstream transmission over 42 km and 64-way power split using optical duobinary signals and an APD-based receiver,” Opt. Exp., vol. 23, no. 19, pp. 24133, Sep. 2015.

[8] Z. Zhou, M. Bi, S. Xiao, Y. Zhang, and W. Hu, “Experimental demonstration of symmetric 100-Gb/s DML-based TWDM-PON system,” IEEE Photon. Technol. Lett., vol. 27, no. 5, pp. 470–473, 2015.

[9] Y. An et al., “Signal Quality Enhancement of Directly Modulated VCSELs Using a Micro-Ring Resonator Transfer Function,” in Proc. OECC, 2013, pp. ThK3_3.

[10] Q. Zhang, Q. Cao, S. Fu, R. Ji, and L. Zeng, “Compact silicon-based DML Transmitter with Extinction Ratio improved for 40G TWDM PON OLT scenarios,” in Proc. OFC, 2015, pp. Tu3E.7.

[11] B. Li et al., “Experimental demonstration of large capacity WSDM optical access network with multicore fibers and advanced modulation formats,” Opt. Exp., vol. 23, no. 9, pp. 10997, May 2015.

[12] B. Zhu et al., “Seven-core multicore fiber transmissions for passive optical network.,” Opt. Exp., vol. 18, no. 11, pp. 11117–11122, 2010.

[13] R. Asif et al., “Experimental demonstration of 6-mode division multiplexed NG-PON2: Cost effective 40 Gbit/s/spatial-mode access based on 3D laser inscribed photonic lanterns,” in Proc. ECOC, 2015, pp. 10–12.

[14] H. Hu et al., “Bidirectional 120 Gbps SDM-WDM-PON with Colourless ONU using 10 Gbps Optical Components without DSP,” in Proc. OFC, 2016, pp. M3C.1.

[15] F. Da Ros et al., “4-PAM dispersion-uncompensated transmission with micro-ring resonator enhanced 1.55-µm DML,” in Proc. CLEO, 2017, pp. STu1M-5.

[16] H. Hu, Y. Ding, and L. K. Oxenlowe, “Polarization Diversity Silicon Microring Resonator for WDM Add-Drop Filtering,” in Proc. OFC, 2016, pp. Th1K.3.

[17] Y. Ding, B. Huang, H. Ou, F. Da Ros, and C. Peucheret, “Polarization diversity DPSK demodulator on the silicon-on-insulator platform with simple fabrication.,” Opt. Exp., vol. 21, no. 6, pp. 7828–34, 2013.

[18] Y. Ding, H. Ou, and C. Peucheret, “Wideband polarization splitter and rotator with large fabrication tolerance and simple fabrication process,” Opt. Lett., vol. 38, no. 8, pp. 1227, 2013.

[19] J. Wei and E. Giacoumidis, “40 Gb/s/λ optical amplified PAM-4 PON with transmission over 30 km SMF using 10-G Optics and simple DSP,” in Proc. OFC,2017, pp. Tu3G. 3.

[20] B. Zhu et al., “112-Tb/s space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber,” Opt. Exp., vol. 19, no. 17, pp. 16665–16671, Aug. 2011.

[21] Deliverable D2.3 “Report on Development of First Generation MCF and PBGF Fibres” http://www.fp7-cosign.eu/deliverables/