200Gb/s Bi-Directional TDM-PON with 29-dB Power Budget

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Abstract *We demonstrate the first 200-Gb/s (100-GBaud PAM-4) TDM-PON using directly modulated lasers and direct detection. We achieve >29-dB link power budget by combining distributed Raman amplification over 21-km fiber and an SOA-based pre-amplifier.*

Introduction

Passive optical networks (PON) are evolving from 1 Gb/s towards 10 Gb/s with IEEE 10G-EPON and ITU-T XG-PON/XGS-PON, and the industry is moving forward to the next-generation PON at higher rates. IEEE 802.3ca has finalized the 25G EPON which supports 25G on a single wavelength and 50G by bonding two wavelengths[1]. The new 25G specification from the 25GS-PON Multi-Source Agreement (MSA) Group[2] has combined IEEE 802.3ca's 25G physical media dependent (PMD) layer with ITU-T's ONU management and control interface (OMCI) and ITU-T XGS-PON's transmission convergence (TC) layer. Meanwhile, ITU-T has decided to offer a higher line rate at 50 Gb/s/λ (Gb/s per wavelength)[3]. At the research level, 100G PON has been demonstrated by both time and time wavelength division multiplexing (TDM[4-5] and TWDM[6]). While stacking more wavelength can always increase the capacity, it is commonly believed TWDM is less economical than TDM in PON due to its higher operational cost for the wavelength management. Therefore, it is desired to develop a TDM-PON for future applications beyond 100 Gb/s.

In the post-50G era, PON will likely leverage the ever-maturing datacenter (DC) ecosystem. Though state-of-the-art DC optics have achieved 100 Gb/s/λ in the product and 200-Gb/s/λ in the lab by a variety of techniques[7-8], the rate of 200-Gb/s has not been demonstrated for non-coherent TDM-PON, as it faces a unique challenge of much higher optical power budget than DC applications. Directly modulated lasers (DMLs) are usually preferred owing to their high output power at a level of 10 dBm. It was not until 2019 when DMLs first achieved the speed of 200 Gb/s[9-10] by much improved bandwidth (BW) beyond 50 GHz. Due to the lack of high responsivity photodiodes (PD) like avalanche PD (APD) with such high BW, a 200-Gb/s non-coherent system inevitably needs certain kinds of optical amplification to meet the power budget. Semiconductor optical amplifiers (SOA) have been considered as a booster or pre-amplifier for 50- and 100- Gb/s PON[4], but it is questionable if it could satisfy the higher OSNR requirement for 200-Gb/s signals. In this paper, we apply a most recently designed DML[11] with >65-GHz BW to a high-speed TDM-PON system. To satisfy the power budget of >29 dB, we propose a hybrid Raman-SOA scheme to provide a high-gain amplification with low optical noise, in which a single Raman[12-13] pump at the optical line terminal (OLT) is shared by the bi-directional (BiDi) PON link. We demonstrate a record line rate of 200-Gb/s for a symmetric TDM-PON over 21-km standard single mode fiber (SSMF) which doubles the previous TDM-PON speed[4-5].

Experiment setup

We use a pair of DMLs for the BiDi transmission. Their 3-dB BW are around 65 GHz and the output power are 9.1 and 8.2 dBm, respectively. At the temperature of 20^{o}C, both lasers operate at the wavelength of around 1313 nm. To detune their wavelengths, we tune the temperature of one laser to 40^{o}C to obtain a wavelength offset of 3.5 nm, which results in a performance imbalance between the lasers. To make a fair performance comparison between downlink (DL) and uplink (UL), we always use the laser at 20^{o}C for the channel under test (CUT). When the other laser is off, we test the uni-directional (UniDi) DL/UL performance; and when it is on, we test the BiDi performance. We use two digital-to-analog converters (DACs) to generate 100-GBaud PAM-4 signals at one sample per symbol (sps). The DACs have 6-bit physical resolution and a 3-dB analog BW of 40 GHz. Each DAC output is boosted by a 55-GHz RF amplifier to drive the DML with an extinction ratio (ER) of around 3 dB.

The DL optical signal is transmitted through a span of 21-km SSMF with 8-dB loss and then a 1:32 passive splitter with 17-dB loss. The UL signal goes through the opposite direction. Two circulators serve as the (de-) multiplexer (MUX) of the BiDi signal which together induce around 1.4-dB insertion loss for both directions. Such loss is *not* counted into the total optical path loss (OPL) according to the PON standard. At the OLT, a WDM coupler injects 386 mW of 1240-nm Raman pump light into the 21-km feeder fiber.

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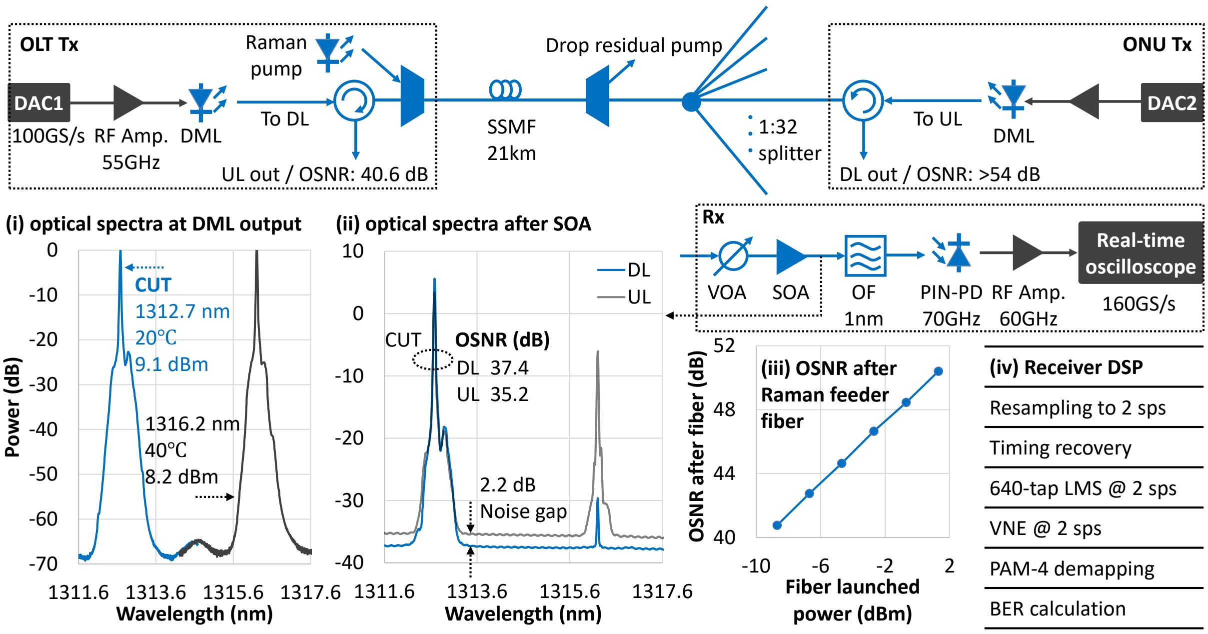

Fig. 1: Experiment setup. OLT: optical line terminal; ONU: optical network unit; DL/UL: downlink/uplink; CUT: channel under test.

The Raman pump is a butterfly-packaged fiber Bragg grating wavelength-stabilized high-power laser diode. The peak on-off Raman gain is 9.5 dB at 1313 nm and has a 1-dB BW of 14.3 nm from 1307.2 nm to 1321.5 nm. The DL signal at 1312.7 nm is amplified by 9.4 dB (co-pumping), and the UL signal at 1316.2 nm is amplified by 9.0 dB (counter-pumping). Residual pump light is rejected by a second WDM coupler at the input to the 1:32 splitter. This single-pump Raman amplification can be configured with minimal dependence of polarization by including a depolarizer at the pump output. However, to maximize the amplification efficiency with the single pump and get sufficient gain, we exclude the depolarizer and fix the state of polarizations for the pump and signals. A more practical setup with polarization diversity could be a higher-power pump with a depolarizer, or dual pumps with polarization combining.

A variable optical attenuator (VOA) is inserted in front of the receiver to adjust the OPL. The received DL or UL signal is amplified by an SOA, followed by a tunable optical filter (OF) to remove the out-of-band noise with a 3-dB BW of 1 nm and a 20-dB BW of 10 nm. The filtered signal is detected by a 70-GHz PIN PD, amplified by a 60-GHz RF driver, and digitized by a 63-GHz real-time oscilloscope at 160-GS/s. The receiver DSP is listed in Fig. 1(iv). To enhance the receiver sensitivity, it is desired to drive the DML harder to get higher ER, which aggravates the transmitter nonlinearity. The hybrid Raman-SOA scheme adds nonlinearity to the optical signal as well. Thus, besides the 640-tap linear equalizer (LE), we use a 3-kernel Volterra nonlinear equalizer (VNE) with the memory length of [32, 32, 16] including $|x|$, $x|x|$ and $x(k)x(k-\tau)$ where $x(k)$ is the k-th sample of x, and τ is the sample delay[14]. Further, we add a 64-state maximum likelihood sequence estimation (MLSE) at 1sps to remove the residual inter-symbol interference (ISI). We use 1e-2 as the BER threshold of hard-decision (HD) forward error correction (FEC) as suggested by PON standards [1-2].

Results

We first bypass the fiber (*i.e.*, without Raman amplification) and test the receiver sensitivity in Fig. 2(a). We choose the SOA bias of either 100 or 140 mA during this sensitivity measurement. The two biases provide similar performance, except for the low received power region where the 140-mA bias achieves slightly lower BER. At the HD-FEC BER limit, the receiver requires -4.6 dBm power without the SOA, and -14.4 dBm power with the SOA as a pre-amplifier. Namely, the SOA improves the power budget by 9.8 dB. Taking into account the CUT laser output power of 9.1 dBm and the insertion loss of 1.4 dB for circulators, the required input of -14.4 dBm for the SOA indicates the link requires an extra stage of amplification with at least 6.9-dB gain to meet 29-dB power budget. Moreover, a margin should be reserved to accommodate other impairments like the OSNR penalty from the amplification, chromatic dispersion and BiDi crosstalk. While it is almost impractical to add a booster amplifier with >7 dB gain for a DML with 10-dBm-class output power, Raman amplification seems to be a proper option which requires only one pump at the OLT shared by the BiDi signals.

Turning on the Raman pump, we characterize the full-system BER as a function of OPL in Fig.

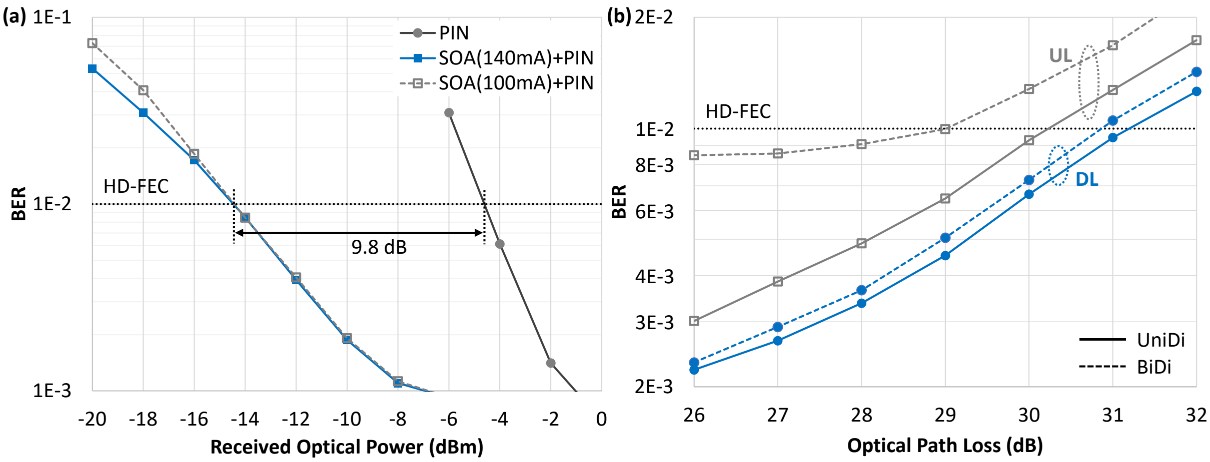

Fig. 2: 200-Gb/s experiment results. (a) Sensitivity for PIN and SOA+PIN receivers. (b) Full-system BER versus OPL.

2(b). We observe two notable phenomena comparing among UniDi/BiDi DL/UL links. First, for both UniDi and BiDi, the DL performs better than the UL, mainly due to their OSNR difference. For the same OPL, the input power to the SOA is identical for both DL and UL signals; however, the launch power to the fiber is much lower for the UL because the UL signal is first attenuated by the 1:32 splitter. The lower launch power degrades the OSNR of distributed Raman amplification. As shown in Fig. 1, the optical noise is almost negligible after the DL signal transmits over the fiber which leads to >54-dB OSNR; in contrast, the OSNR reduces to 40.6 dB for the UL signal after 21-km SSMF. Taking into account the SOA, the OSNR after Raman+SOA is 37.4 dB for DL and 35.2 dB for UL under 29-dB OPL. Second, the UL penalty is more severe than the DL penalty for BiDi with respect to UniDi. We attribute this to the crosstalk of Rayleigh backscattering and a decrease in OSNR caused by Raman gain saturation, both of which adversely affect the UL more than the DL, again due to the substantially lower peak UL signal power in the 21-km fiber relative to the DL. As shown in Fig. 1(ii), the Rayleigh-scattered DL signal is only 11 dB below the UL signal at the output of the SOA, which is suppressed to 28 dB at the OF output (not shown in the figure), as compared to the DL for which the UL signal is more than 35 dB down in Fig. 1(ii) and is >50 dB down after the OF. Another contributor to the disparity in BiDi performance may be the change in OSNR due to Raman gain saturation, which decreases by 0.5 dB at the SOA output (from 35.7 dB to 35.2 dB) for the UL when the DL signal is t urned on. Overall, both the DL and UL achieve the BER below the HD-FEC threshold for the BiDi 200-Gb/s transmissions with 29-dB OPL.

Conclusions

We achieve symmetric line rates of 200 Gb/s in a BiDi TDM-PON by modulating 100-GBaud PAM-4 signals on two DMLs with 10-dBm-class output power. To meet the 29-dB link power budget, we use an SOA-pre-amplified PIN receiver, together with distributed Raman amplification over 21-km SSMF which provides around 9-dB gain.

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