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An Asymmetric High Serial Rate TDM-PON with Single Carrier $25\,\mathrm{Gb/s}$ upstream and $50\,\mathrm{Gb/s}$ downstream

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***Abstract*—We report a 2:1 rate asymmetric high serial rate TDM-PON with single carrier $25\,\mathrm{Gb/s}$ upstream and $50\,\mathrm{Gb/s}$ downstream. In the upstream, we present a first $25\,\mathrm{Gb/s}$ 3-level modulated BM-RX employing a $^1/_4$-rate linear BM APD-TIA and a custom decoder IC. We successfully demonstrated burst-mode sensitivity of $-20.4\,\mathrm{dBm}$ with $18\,\mathrm{dB}$ dynamic burst-to-burst for $25\,\mathrm{Gb/s}$ upstream links. In another direction, a downstream in upper O-band is proposed and demonstrated with 3-level duo-binary modulation at $50\,\mathrm{Gb/s}$ in real-time. The upstream and downstream transmission experiments show that the proposed asymmetric $50\,\mathrm{G}/25\,\mathrm{G}$ high serial rate TDM-PON can support $\geq$32 users while covering more than $20\,\mathrm{km}$ reach.**

***Index Terms*—TDM-PONs, high serial rate PONs, burst-mode receiver, BM-RX, 3-level duo-binary**

I. Introduction

ACCESS network infrastructure plays a key role in fulfilling the ever-increasing traffic demand and emerging service requirement. Among those solutions, passive optical networks (PONs) are being widely recognized as the most cost-effective technology for access networks. Various time division multiplexing PON (TDM-PON) standards, e.g. GPON and GE-PON, have been proposed by two standard bodies, international telecommunications union (ITU) and institute of electrical and electronics engineers (IEEE) respectively. Both standardization efforts were recently endorsed by the concurrent development of innovative downstream/upstream physical media dependent (PMD) keystone components up to a line rate of $10\,\mathrm{Gb/s}$.

Due to technology and cost challenges associated with further increasing the serial date rate, current NG-PON2 [1] standard from ITU focuses the development on a time and wavelength division multiplexed (TWDM) PON, i.e., by basically stacking $10\,\mathrm{Gb/s}$ XG-PONs [2] at 4 or 8 wavelengths. Still, a low-cost single-wavelength upstream beyond $10\,\mathrm{Gb/s}$ has the potential to serve as a per-wavelength upgrade path for NG-PON2, in line with recent research on high serial rate downstream for PONs [3][4][5]. However, most of the high serial rate TDM-PON research up to now has focused on downstream-only transmission in C-band, also requiring costly dispersion compensation elements or digital signal processing (DSP) in offline processing.

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This paper is an invited extension of our work presented in OFC 2015 [6]. Section II describes the proposed 2:1 rate asymmetric high serial rate TDM-PON with single carrier $25\,\mathrm{Gb/s}$ upstream and $50\,\mathrm{Gb/s}$ downstream. In Section III, we present a $25\,\mathrm{Gb/s}$ 3-level modulated burst-mode receiver (BM-RX) for high serial rate TDM-PONs. The proposed $25\,\mathrm{Gb/s}$ BM-RX relaxes the bandwidth requirement on optical components, esp. the high-speed APDs, and can support a high loss budget of more than $25\,\mathrm{dB}$ in the upstream.

Section IV reports more details on the PON downstream. In downstream direction, we proposed a $50\,\mathrm{Gb/s}$ 3-level duo-binary downstream in upper O-band ($1330\,\mathrm{nm}$ to $1360\,\mathrm{nm}$) for a 2:1 rate asymmetric PON configuration. With a linear downstream optical receiver and the 3-level duo-binary decoder IC, real-time measurement at $50\,\mathrm{Gb/s}$ were performed and a loss budget margin of $17.8\,\mathrm{dB}$ ($\geq$32-way power split) has been achieved with $21\,\mathrm{km}$ fiber for downstream direction. The possibility of applying bit-interleaving (BI) protocol to $50\,\mathrm{Gb/s}$ 3-level downstream has been discussed as well. Finally Section V concludes the paper.

II. Proposed high serial rate TDM-PON

The concept of the proposed high serial rate TDM-PON is shown in Fig. 1. Multiple optical network units (ONUs) at the customer sides share the fiber plant and an optical line terminal (OLT) located at the central office.

Because the bandwidth demanding of common high rate services (e.g. digital broadcasting, video on demand (VOD), files downloading, etc) are asymmetric, the proposed TDM-PON has asymmetric high serial upstream/downstream rates: single carrier $25\,\mathrm{Gb/s}$ upstream and $50\,\mathrm{Gb/s}$ downstream. In upstream, we propose a $25\,\mathrm{Gb/s}$ 3-level modulated burst-mode transmission, which relaxes the bandwidth requirement and enables the possibility of using widely available $10\,\mathrm{Gb/s}$ APDs. Instead of using non-return to zero (NRZ) format, 3-level BM detection is proposed by employing a $^1/_4$-rate avalanch photo-diode (APD)-based linear BM transimpedance amplifier (TIA) and a custom duo-binary decoder chip. Also, we assume that upstream could re-use O-band as multi-rate BM-RXs have been previously demonstrated from different research groups [7][8][9].

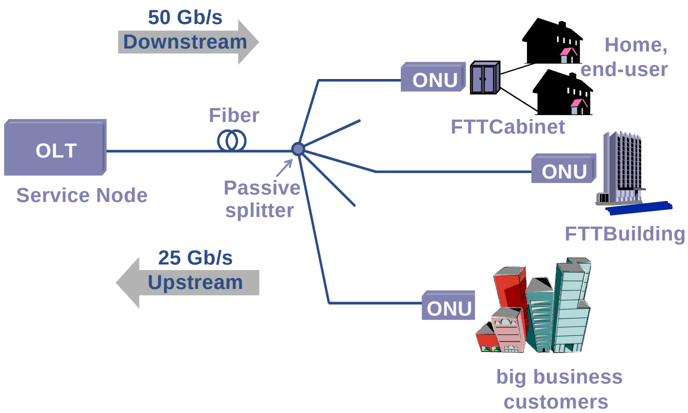

Fig. 1. Proposed asymmetric high serial rate TDM-PON

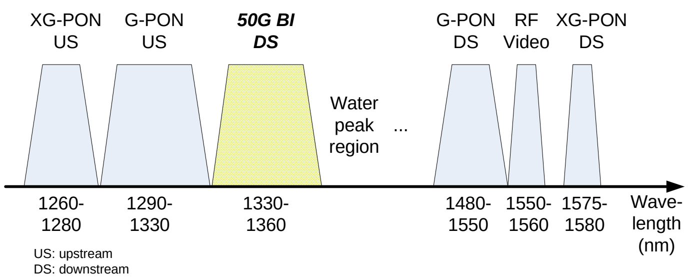

Fig. 2. Proposed 50Gb/s downstream wavelength arrangement

In downstream, in order to upgrade the line rate from current $10\,\mathrm{Gb/s}$ to a single-carrier $50\,\mathrm{Gb/s}$, several technical challenges at 5x higher rate need to be addressed, such as high-speed electronics, the need for more optical power to maintain signal-to-noise ratio (SNR), and increasing chromatic dispersion (CD) tolerance. To alleviate the CD penalty and component speed requirement, we propose a 3-level duo-binary modulation scheme operating in upper O-band ($1330\,\mathrm{nm}$ to $1360\,\mathrm{nm}$) for the $50\,\mathrm{Gb/s}$ downstream. As shown in Fig. 2, the proposed wavelength band fits well with the assigned wavelength bands of (X)G-PON upstream and downstream, allowing backward compatibility with the existing PON systems. In the experiment, because APDs with high bandwidth are not yet commercially available for $50\,\mathrm{Gb/s}$, we could use a semiconductor optical amplifier (SOA) with a PIN receiver at the ONU for this wavelength range. The compact size and integrability of the SOA [10] makes it a suitable candidate for the use as optical preamplifiers in ONU. The proposed downstream scheme reduces the downstream channel bandwidth requirement to $\sim 15\,\mathrm{GHz}$. Unlike optical duo-binary modulation (ODB) [11], this enables a lower-bandwidth SOA-PIN receiver employed at the ONU, reducing the cost and power consumption. As shown by the simulation in [3], the narrowed bandwidth can further improve the CD tolerance and receiver sensitivity of the high serial rate downstream.

III. $25\,\mathrm{Gb/s}$ PON UPSTREAM WITH 3-LEVEL MODULATED BM-RX

In parallel with the PON standardization evolution in ITU and IEEE, upstream BM-RX, the most critical PMD component of PON systems, have been recently developed up to $10\,\mathrm{Gb/s}$ [12][13]. Further increase in upstream data rate becomes challenging due to limitations in the availability, cost and performance of optical components. For instance, while APDs have been used extensively in $10\,\mathrm{G}$-class PONs to improve the receiver sensitivity, high-speed $25\,\mathrm{Gb/s}$ APD devices are still not widely available as low-cost $10\,\mathrm{Gb/s}$ APDs. Therefore, we proposed a 3-level BM detection scheme by employing a $1/4$-rate APD-based linear BM-TIA and a custom duo-binary decoder chip. The proposed $25\,\mathrm{Gb/s}$ BM-RX relaxes the bandwidth requirement on the optical components and permits a better transmission performance compared to a bandwidth-limited NRZ upstream.

A. $25\,\mathrm{Gb/s}$ *3-level modulated BM-RX*

Figure 3 shows the block diagram of the proposed $25\,\mathrm{Gb/s}$ BM-RX. The BM-RX consists of two blocks: a linear BM APD-TIA and a 3-level duo-binary decoder IC. Both blocks were designed and fabricated in a $0.13\,\mu\mathrm{m}$ SiGe BiCMOS process. The linear BM-TIA is based on the design in [14] but with a trans-impedance gain adapted for the decoder IC and a fine-tuned bandwidth (one-fourth of the upstream data rate). The $1/4$-rate small-signal bandwidth and linear operation are required for optimal 3-level signal generation. The linear BM-TIA consists of a core TIA TIAc, a dummy TIA TIAd, a variable gain amplifier (VGA), and a linear output stage. At the start of each burst, the automatic gain control (AGC) senses the output amplitude of the TIAc core and set its transimpedance gain within $10\,\mathrm{ns}$. The linear BM-TIA also performs a fast offset compensation process. This minimizes the DC offset in the output 3-level signal, and helps reduce the settling time of the decoder IC. The output of the linear BM-TIA is a 3-level current-mode signal and ac-coupled to the 3-level decoder IC.

The subsequent custom decoder IC combines a 3-level signal decoding function and a 1 to 4 deserializer. It first amplifies the input signal linearly to partly compensate the internal loss of the RF splitter. After the splitter the upper and lower eyes are separated and amplified to their logic levels by two limiting amplifiers (LA), with two different threshold levels V_{TH1} and V_{TH2}. No automatic threshold feedback has been realized in this first version decoder IC, so a manual threshold control was implemented instead. The upper and lower logic signals then enter a high-speed digital XOR gate to regenerate the data in NRZ format. Finally the received NRZ data is deserialized into 4 current model logic (CML) outputs for interfacing with lower-speed components off-chip, e.g. FPGAs.

B. *Upstream experimental setup and results*

The performance of the 3-level APD BM-RX was evaluated using the $25\,\mathrm{Gb/s}$ experimental set-up as shown in Fig. 4. Two $1.3\,\mu\mathrm{m}$ burst-mode transmitters (BM-TXs) named TX #1

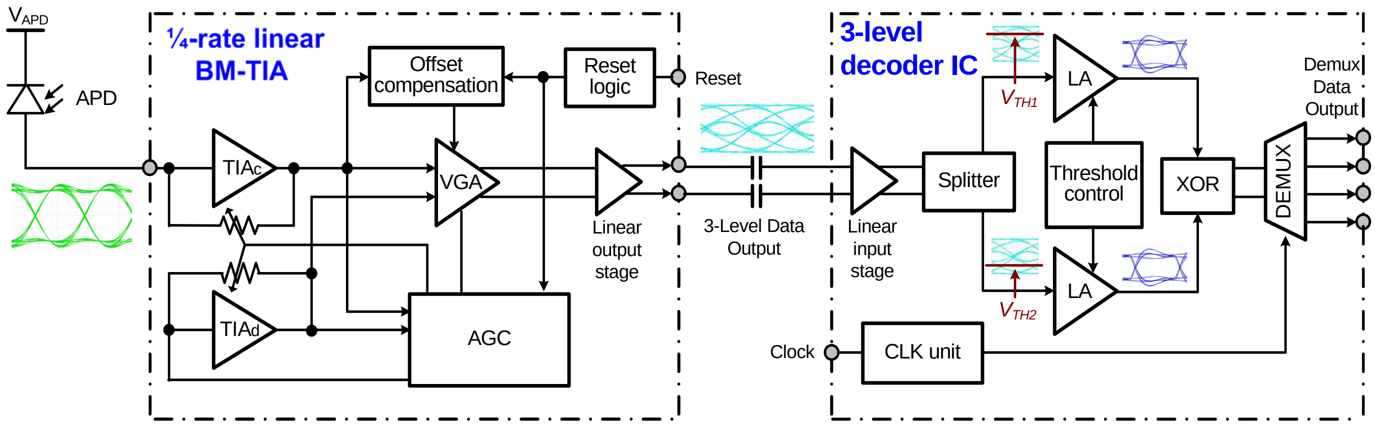

Fig. 3. Block diagram of the 25 Gb/s 3-level modulated BM-RX

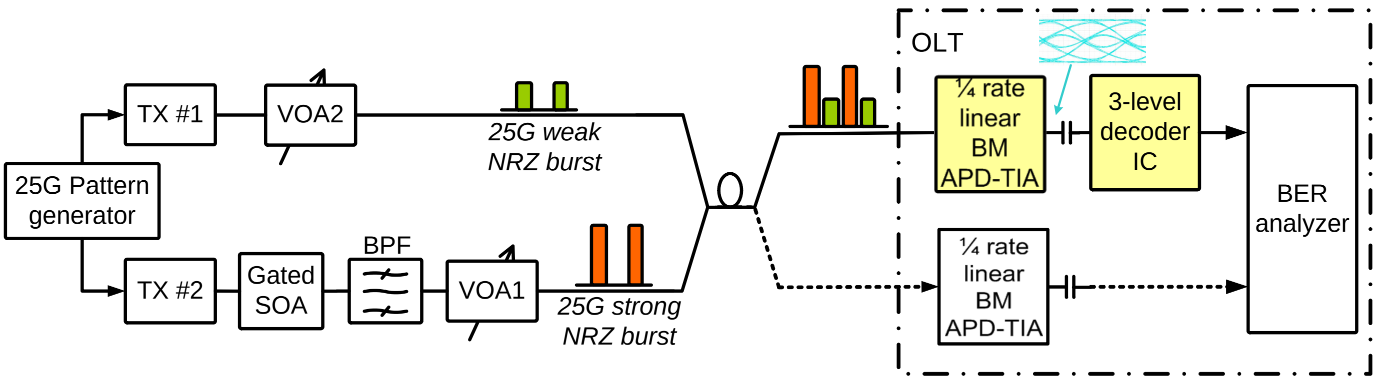

Fig. 4. Upstream experimental setup

and TX #2, are alternately sending burst packets. The BM-TX consists of a 1310 nm electro-absorption modulated laser (EML), a RF amplifier with a 20 GHz low-pass filter and a switching SOA. The switching SOA circuit is designed for fast burst operation and turn-on/turn-off time is $\sim$5 ns. At the OLT, the linear BM APD-TIA was integrated with the 3-level decoder IC and the upstream BER was measured at one of the 4 CML output channels at 6.25 Gb/s. Finally two branches of BM-TXs were built to emulate the worst TDMA scenario: a strong burst followed by a weak burst with a short guard time. The output optical power of the two BM-TXs can be adjusted by two variable optical attenuators (VOAs), namely VOA #1 and VOA #2 for respectively TX #1 and TX #2. A gated semiconductor optical amplifier (SOA) was used to increase the optical output power of the TX #2 to +5dBm, in order to generate a sufficiently large loud/soft ratio for this experiment. A 10 nm coarse wavelength division multiplexing (CWDM) filter was used to remove out-of-band amplified spontaneous emission (ASE) noise from the SOA. The two TX outputs are combined by a 2x2 splitter, and fed to the BM-RX.

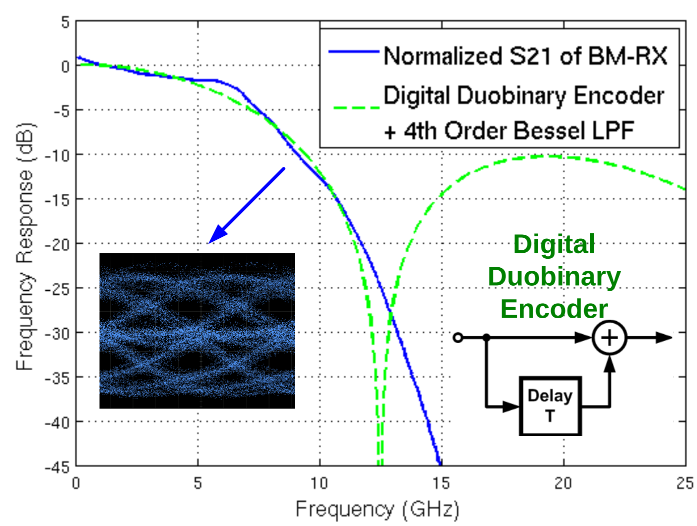

Fig. 5. Measured BM-RX RF frequency response compared with ideal duobinary generation filter

To generate 3-level modulation, the linear BM-TIA should have a bandwidth of roughly one-fourth of the data rate, i.e., $\sim$6.25 GHz for 25 Gb/s. We measured the differential O/E response of the linear BM APD-TIA assembly with a lightwave analyzer and it shows a 3 dB bandwidth of 6.7 GHz. The measured BM-TIA S21 response is plotted in Fig. 5, together with simulated frequency response of cascading a digital duobinary encoder and a 4th-order half-rate Bessel low-pass filter (LPF). Both frequency responses agree nicely in the roll-off shape up to the Nyquist frequency. The measured 25 Gb/s eye-diagram (Fig. 5) at the output of the BM-TIA shows clearly the 3-level signal with two open eyes. Fig. 6(a)

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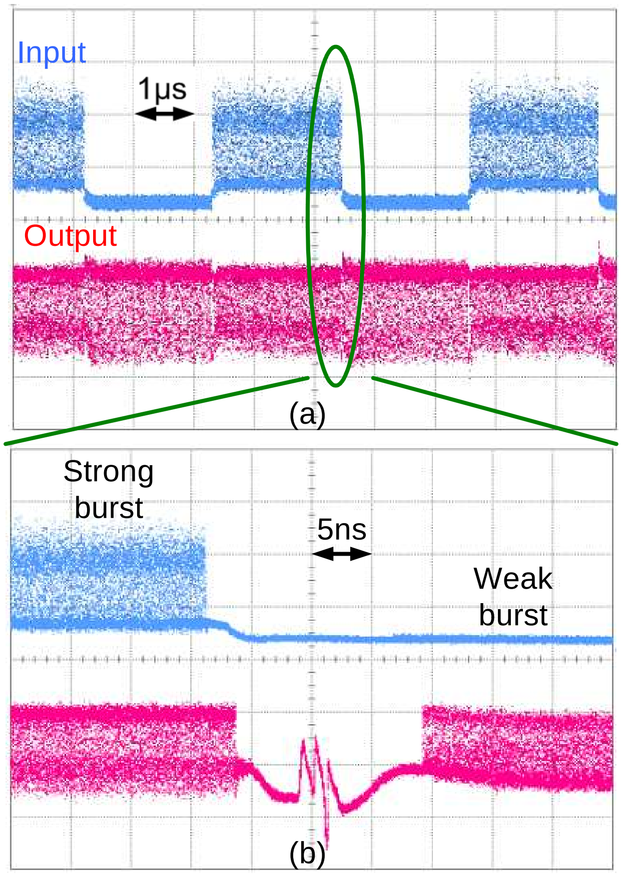

Fig. 6. (a) Input and output waveforms of the BM APD-TIA (b) waveforms within zoomed-in time scale

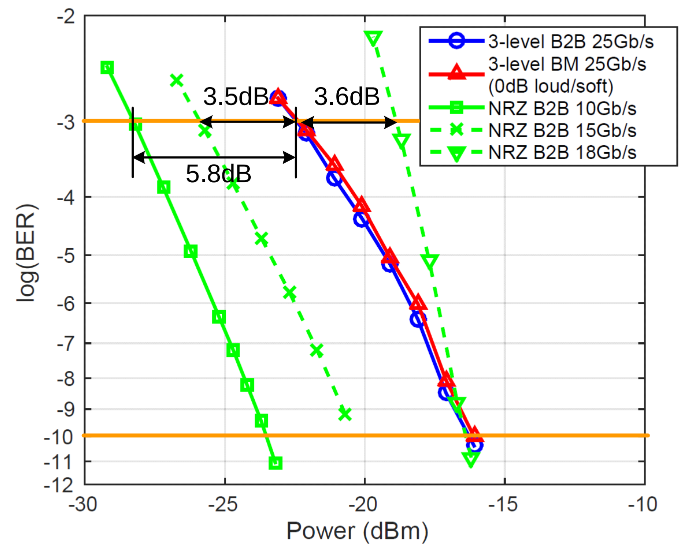

Fig. 7. Comparison of B2B BER between NRZ and 25 Gb/s 3-level modulation

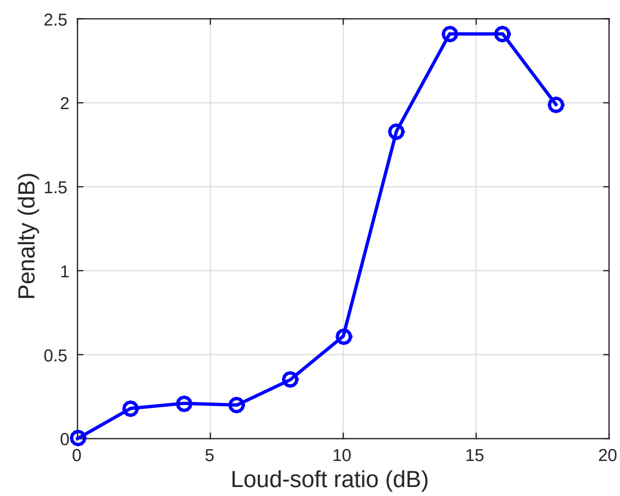

Fig. 8. BM loud-soft penalty of 25 Gb/s 3-level modulation

shows the measured received bursts and the output signal of the BM APD-TIA. The applied $25\,\mathrm{Gb/s}$ burst packets consist of a $245\,\mathrm{ns}$ preamble and a $1800\,\mathrm{ns}$ payload. Due to the limitation of the current setup (without duobinary precoder), 2^7-1 pseudo random bit sequence (PRBS) patterns was used. The guard time between bursts is set to $15\,\mathrm{ns}$. As shown in Fig. 6(b) the received weak burst following a strong burst has been recovered within $\sim 10\,\mathrm{ns}$.

The measured B2B and BM BER curves are presented in Fig. 7. The APD multiplication factor M was set to ~ 7. The linear BM APD-TIA was initially characterized with a NRZ signal in a back-to-back (B2B) configuration for various data rates. The BM APD-TIA cannot directly support $25\,\mathrm{Gb/s}$ NRZ without equalization. We measured the BER curves for $10\,\mathrm{Gb/s}$, $15\,\mathrm{Gb/s}$ and $18\,\mathrm{Gb/s}$ NRZ, and we found that there was $\sim 9.4\,\mathrm{dB}$ penalty at $18\,\mathrm{Gb/s}$ with respect to the $10\,\mathrm{Gb/s}$ case for a pre-FEC BER of 1×10^{-3}. We then measured the BER performance of the proposed 3-level modulation in both B2B and BM scenarios. The measured $25\,\mathrm{Gb/s}$ B2B sensitivity at a pre-FEC BER of 1×10^{-3} is $-22.4\,\mathrm{dBm}$ and the sensitivity at a BER of 1×10^{-10} is $-16.3\,\mathrm{dBm}$. We took the pre-FEC threshold of $\sim 1\times10^{-3}$ as the reference because FEC coding is mandatory in NG-PON2 systems in order to maintain its compatibility with existing ODNs. With respect to $18\,\mathrm{Gb/s}$ NRZ transmission, the $25\,\mathrm{Gb/s}$ 3-level detection experiences a sensitivity improvement of $3.6\,\mathrm{dB}$, which is primarily explained by the reduced $18\,\mathrm{Gb/s}$ NRZ eye openings due to the higher bandwidth requirement. Finally, with two branches of BM-TXs, the BM-RX sensitivity measured on the weak packet emitted by BM-TX #1 was $-22.4\,\mathrm{dBm}$ with a static optical power level ($0\,\mathrm{dB}$ loud/soft). The BM-RX was also assessed in different loud/soft ratios and the measured BM-RX penalties due to the preceding loud burst are shown in Fig. 8. There was $\leq 0.6\,\mathrm{dB}$ penalty for a loud/soft ratio up to $10\,\mathrm{dB}$. The BM penalty was $2\,\mathrm{dB}$ for the maximum loud/soft ratio of $18\,\mathrm{dB}$. The bend of the penalty for very large loud/soft ratios may attribute to the reduced BM-TIA gain in this case (controlled by the AGC circuit), exerting less influence to the weak burst followed. We also measured the proposed 3-level upstream performance with various length of fiber up to $31\,\mathrm{km}$, and there was no noticeable power penalty observed.

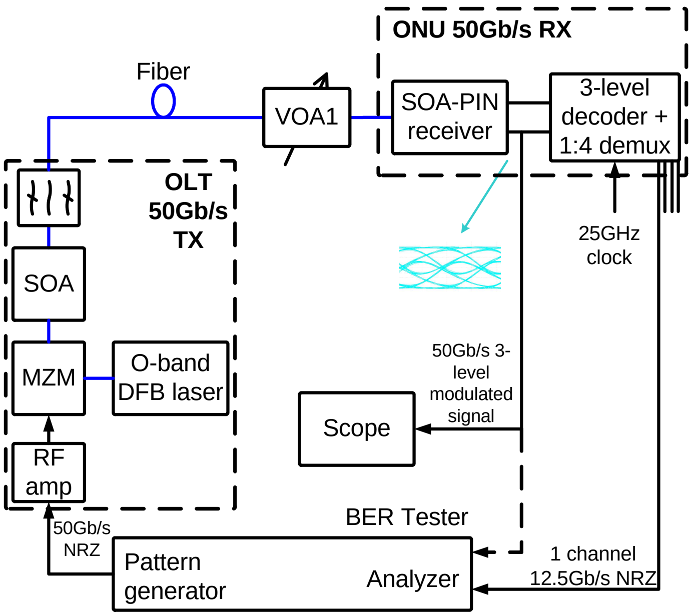

Fig. 9. Downstream experimental setup

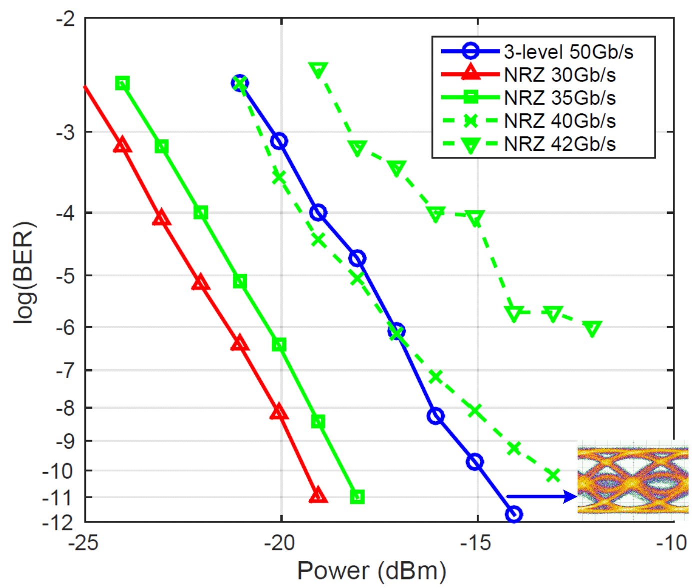

Fig. 10. Downstream BER measurement results in B2B configuration (the figure inset is the $50\,\mathrm{Gb/s}$ 3-level duo-binary eye-diagram measured at the SOA-PIN Rx output)

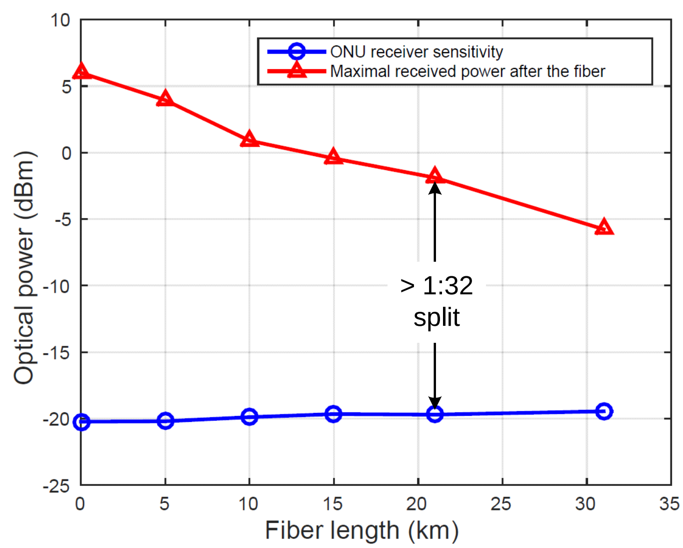

Fig. 11. $50\,\mathrm{Gb/s}$ 3-level duo-binary downstream transmission performance over optical fiber

IV. Single carrier $50\,\mathrm{Gb/s}$ PON downstream

A. Downstream experimental setup and results

The downstream experimental setup, as shown in Fig. 9, consists of an OLT 50Gb/s TX, transmission fiber, an VOA and an ONU 50Gb/s 3-level duo-binary RX. The OLT downstream TX employed an O-band LiNbO3 intensity Mach-Zehnder modulator (MZM), which was driven by an RF amplifier with a $50\,\mathrm{Gb/s}$ 2^7-1 PRBS NRZ signal. A $1335\,\mathrm{nm}$ continuous-wave laser was connected to the input of the MZM. At the output of the MZM, we used an SOA to boost the lauched TX output power to +6 dBm and a CWDM filter was also used to remove out-of-band ASE noise from the SOA. In the ONU, an SOA-preamplified PIN-RX has been used as the front-end for the 3-level decoder IC. The PIN-RX is a $25\,\mathrm{Gb/s}$ to $40\,\mathrm{Gb/s}$ linear optical receiver with configurable transimpedance gain and bandwidth [15][16]. It has been configured to $\sim$20 GHz operational mode in the downstream experiments. After 3-level duo-binary decoding, one of the 4 de-multiplexed outputs at $12.5\,\mathrm{Gb/s}$ was fed into a BER analyzer for real-time BER measurement. As bit errors are randomly distributed in the downstream received data, this BER performance is virtually identical among 4 de-multiplexed outputs.

To compare the performance, we first evaluateed the BER in B2B configuration for both NRZ and proposed 3-level duo-binary modulation. Fig. 10 shows the measured BER curves for $30\,\mathrm{Gb/s}$ NRZ, $35\,\mathrm{Gb/s}$ NRZ, $40\,\mathrm{Gb/s}$ NRZ, $42\,\mathrm{Gb/s}$ NRZ, and $50\,\mathrm{Gb/s}$ 3-level duo-binary. The optical power shown here is measured at the input of the SOA-PIN Rx (after the VOA). As shown in Fig. 10, NRZ signaling works relatively well when the downstream rate is less than $35\,\mathrm{Gb/s}$. For higher rate NRZ, we noted a decreased performance due to the inter-symbol interference (ISI), which introduces a large penalty of $3.4\,\mathrm{dB}$ at $40\,\mathrm{Gb/s}$ with respect to the $35\,\mathrm{Gb/s}$ case for a pre-FEC BER of 1×10^{-3}. Furthermore, a BER floor appeared at around 1×10^{-6} for the $42\,\mathrm{Gb/s}$ NRZ case, and above $44\,\mathrm{Gb/s}$ we could not reach BER threshold of 1×10^{-3}. On the other hand, we were able to receive the downstream at $50\,\mathrm{Gb/s}$ by employing 3-level duo-binary downstream scheme. The measured receiver sensitivity at BER=1×10^{-3} was $-20.2\,\mathrm{dBm}$ and obtained BER performance was comparable to the results of $40\,\mathrm{Gb/s}$ NRZ.

Next, we have transmitted the $50\,\mathrm{Gb/s}$ 3-level duo-binary over various fibers up to $31\,\mathrm{km}$ to evaluate the downstream transmission performance. Fig. 11 shows the measured sensitivity at BER=1×10^{-3} versus different fiber lengths. Maximal power penalty of $0.8\,\mathrm{dB}$ penalty was found with $31\,\mathrm{km}$ standard single-mode fiber (SSMF) in the transmission experiments. We also plotted the measured maximal input power at the input of the SOA-PIN Rx in Fig. 11. For $21\,\mathrm{km}$

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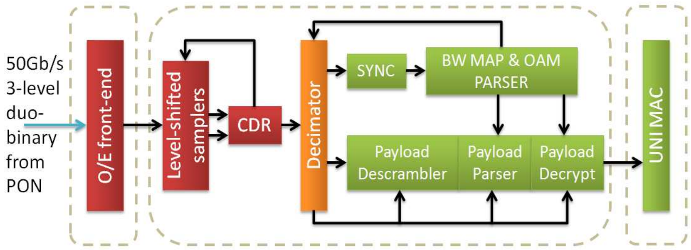

Fig. 12. Conceptual illustration of an ONU receiver supporting 3-level duo-binary and bit-interleaving protocol

transmission distance, the resulting optical power margin of $17.8\,\mathrm{dBm}$ is more than enough for supporting 1:32 split in ODNs.

B. Bit-interleaving protocol in downstream

One important practical issue for high serial rate PON downstream is the power consumption of the ONU. Traditionally, to support a higher instantaneous bandwidth demand, service providers are forced to upgrade their networks with higher capacity equipment. However power consumption of a conventional network element is directly proportional to its line rate and capacity, therefore, higher capacity line cards/equipment will inevitably consume more power. The use of a sleep-mode protocol [17] may help alleviate the problem, but it incurs additional network latency and packet delay.

Considering the vast amount of subscribers, power consumption reduction in the ONU is of major importance, esp. for high rate TDM-PONs. As reported previously [18], a clock-and-data recovery (CDR) IC implementing bit-interleaving (BI) protocol offers unique benefits for lowering the power consumption of a ONU by an order of magnitude. To support a higher serial rate PON downstream, [19] describes the extended architecture and circuit building blocks of the BI-CDR to upgrade the bit-interleaving downstream to 4x higher rate for NRZ signal.

Our future research will study how to combine the 3-level duo-binary and bit-interleaving protocol for the proposed $50\,\mathrm{Gb/s}$ downstream. One conceptual block-diagram of such ONU receivers is illustrated in Fig. 12. In this diagram, the required 3-level duo-binary decoding function is naturally integrated into a BI-CDR IC. The level-shift samplers will sample the incoming 3-level duo-binary signal with different threshold levels. The sampled edge and bit will enter the CDR logic which in turn controls the sampling phase. In every frame period, the 3-level BiCDR decimates and offsets the downstream payload reception based on the BI header information. After the decimator, the throughput of the data will be effectively reduced. Only a small portion of the ONU (colored red in Fig. 12), such as the opto-electrical (O/E) front-end, the level-shifted sampler and the CDR blocks, operates at the aggregated downstream line-rate. Meanwhile, the remaining building blocks can operate at a much lower user rate, allowing substantial power reduction in $50\,\mathrm{Gb/s}$ 3-level duo-binary ONUs.

V. CONCLUSIONS

We presented, for the first time, a 2:1 rate asymmetric high serial rate TDM-PON with single carrier $25\,\mathrm{Gb/s}$ upstream and $50\,\mathrm{Gb/s}$ downstream. Using a low-cost $1/4$-rate linear BM APD-TIA and a custom decoder IC, the $25\,\mathrm{Gb/s}$ OLT BM-RX achieved an excellent RX sensitivity of $-22.4\,\mathrm{dBm}$ without optical pre-amplifier or power-hungry DSP. In the worst case of $18\,\mathrm{dB}$ power difference between strong and weak bursts, we successfully demonstrated BM sensitivity of $-20.4\,\mathrm{dBm}$ and a loss budget of 25.0 dB. In addition, we proposed and demonstrated a $50\,\mathrm{Gb/s}$ 3-level duo-binary downstream in upper O-band for a 2:1 rate asymmetric PON configuration. A downstream loss budget of $26.2\,\mathrm{dB}$ has been achieved in back-to-back and $50\,\mathrm{Gb/s}$ downstream transmission with $31\,\mathrm{km}$ SSMF was successfully demonstrated in real-time.

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REFERENCES

[1] ITU-T G.989.1, "40-Gigabit-capable passive optical networks (NG-PON2): General requirements," 2013.

[2] ITU-T G.987.2, "10-Gigabit-Capable Passive Optical Networks (XG-PON): Physical Media Dependent (PMD) Layer Specification)," 2010.

[3] X. Yin, X. Qiu, G. Torfs, C. Van Praet, R. Vaernewyck, A. Vyncke, J. Verbrugghe, B. Moeneclaey, M. Ruffini, D. Payne, and J. Bauwelinck, "Performance evaluation of single carrier 40-Gbit/s downstream for long-reach passive optical networks," in *2014 International Conference on Optical Network Design and Modeling*, May 2014, pp. 162–167.

[4] D. van Veen, V. Houtsma, A. Gnauck, and P. Iannone, "40-Gb/s TDM-PON over 42 km with 64-way power split using a binary direct detection receiver," in *2014 European Conference on Optical Communication (ECOC)*. IEEE, 2014, pp. 1–3.

[5] V. Houtsma, D. van Veen, A. Gnauck, and P. Iannone, "APD-Based DuoBinary Direct Detection Receivers for 40 Gbps TDM-PON," in *Optical Fiber Communication Conference*. Optical Society of America, 2015, p. Th4H.1.

[6] X. Yin, J. Verbist, T. D. Keulenaer, B. Moeneclaey, J. Verbrugghe, X. Z. Qiu, and J. Bauwelinck, "25Gb/s 3-level Burst-Mode Receiver for High Serial Rate TDM-PONs," in *Optical Fiber Communication Conference*. Optical Society of America, 2015, p. Th4H.2.

[7] K. Hara, S. Kimura, H. Nakamura, N. Yoshimoto, and H. Hadama, "1.25/10.3-Gbit/s dual-rate burst-mode receiver with automatic bit-rate discrimination circuit for coexisting PON systems," in *2010 9th International Conference on Optical Internet (COIN)*, July 2010, pp. 1–3.

[8] J. Nakagawa, M. Noda, N. Suzuki, S. Yoshima, K. Nakura, and M. Nogami, "Demonstration of 10G-EPON and GE-PON Coexisting System Employing Dual-Rate Burst-Mode 3R Transceiver," *IEEE Photonics Technology Letters*, vol. 22, no. 24, pp. 1841–1843, Dec 2010.

[9] X. Yin, X.-Z. Qiu, J. Gillis, J. Put, J. Verbrugghe, J. Bauwelinck, J. Vandewege, H. Krimmel, D. van Veen, P. Vetter, and F. Chang, "Experiments on a 10 Gb/s fast-settling high-sensitivity burst-mode receiver with on-chip auto-reset for 10G-GPONs [Invited]," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 4, no. 11, pp. B68–B76, Nov 2012.

[10] C. Caillaud, P. Chanclou, F. Blache, P. Angelini, B. Duval, P. Charbonnier, D. Lanteri, G. Glastre, and M. Achouche, "Integrated SOA-PIN Detector for High-Speed Short Reach Applications," *Journal of Lightwave Technology*, vol. 33, no. 8, pp. 1596–1601, April 2015.

[11] K. Yonenaga and S. Kuwano, "Dispersion-tolerant optical transmission system using duobinary transmitter and binary receiver," *Lightwave Technology, Journal of*, vol. 15, no. 8, pp. 1530–1537, Aug 1997.

[12] M. Noda, N. Suzuki, S. Yoshima, M. Nogami, and J. Nakagawa, "Technology progress of high-speed burst-mode 3R receiver for PON applications," in *Optical Fiber Communication Conference*. Optical Society of America, 2012, p. OTh4G.6.

[13] X.-Z. Qiu, X. Yin, J. Verbrugghe, B. Moeneclaey, A. Vyncke, C. V. Praet, G. Torfs, J. Bauwelinck, and J. Vandewege, "Fast Synchronization 3R Burst-Mode Receivers for Passive Optical Networks," *J. Lightwave Technol.*, vol. 32, no. 4, pp. 644–659, Feb 2014.

[14] X. Yin, B. Moeneclaey, X.-Z. Qiu, J. Verbrugghe, K. Verheyen, J. Bauwelinck, J. Vandewege, M. Achouche, and Y. Chang, "A 10Gb/s APD-based linear burst-mode receiver with 31dB dynamic range for reach-extended PON systems," *Opt. Express*, vol. 20, no. 26, pp. B462–B469, Dec 2012.

[15] B. Moeneclaey, J. Verbrugghe, F. Blache, M. Goix, D. Lanteri, B. Duval, M. Achouche, J. Bauwelinck, and X. Yin, "A 40-Gb/s Transimpedance Amplifier for Optical Links," *IEEE Photonics Technology Letters*, vol. 27, no. 13, pp. 1375–1378, July 2015.

[16] B. Moeneclaey, G. Kanakis, J. Verbrugghe, N. Iliadis, W. Soenen, D. Kalavrouziotis, C. Spatharakis, S. Dris, X. Yin, P. Bakopoulos, E. Mentovich, H. Avramopoulos, and J. Bauwelinck, "A 64 Gb/s PAM-4 linear optical receiver," in *Optical Fiber Communications Conference and Exhibition (OFC), 2015*, March 2015, pp. 1–3.

[17] P. Vetter, D. Suvakovic, H. Chow, P. Anthapadmanabhan, K. Kanonakis, K.-L. Lee, F. Saliou, X. Yin, and B. Lannoo, "Energy-efficiency improvements for optical access," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 136–144, April 2014.

[18] C. Van Praet, G. Torfs, Z. Li, X. Yin, D. Suvakovic, H. Chow, X.-Z. Qiu, and P. Vetter, "10 Gbit/s bit interleaving CDR for low-power PON," *Electronics Letters*, vol. 48, no. 21, pp. 1361–1363, October 2012.

[19] A. Vyncke, C. Van Praet, M. Verbeke, D. A. Duque, D. Suvakovic, H. Chow, G. Torfs, and X. Yin, "The 40 Gbps Cascaded Bit-interleaving PON," *Optical Fiber Technology*, accepted for publication, 2015.

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