Physical Media Dependent Prototype for 10-Gigabit-Capable PON OLT

Jongdeog Kim, Jong Jin Lee, Seihyoung Lee, and Young-Sun Kim

In this work, we study the physical layer solutions for 10-gigabit-capable passive optical networks (PONs), particularly for an optical link terminal (OLT) including a 10-Gbit/s electroabsorption modulated laser (EML) and a 2.5-Gbit/s burst mode receiver (BM-Rx) in a novel bidirectional optical subassembly (BOSA). As unique features, a bidirectional mini-flat package and a 9-pin TO package are developed for a 10-gigabit-capable PON OLT BOSA composed of a 1,577-nm EML and a 1,270-nm avalanche photodiode BM-Rx, including a single-chip burst mode integrated circuit that is integrated with a transimpedance and limiting amplifier. In the developed prototype, the 10-Gbit/s transmitter and 2.5-Gbit/s receiver characteristics are evaluated and compared with the physical media dependent (PMD) specifications in ITU-T G.987.2 for XG-PON1. By conducting the 10-Gbit/s downstream and 2.5-Gbit/s upstream transmission experiments, we verify that the developed 10-gigabit-capable PON PMD prototype can operate for extended network coverage of up to a 40-km fiber reach.

Keywords: 10-gigabit-capable passive optical networks, optical link terminal, bidirectional optical subassembly, physical media dependent.

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I. Introduction

The evolution of passive optical networks (PONs) has undergone various stages since a pioneering work by British Telecom was released in the late 1980s that introduced the telephony PON (TPON) [1]. An early study for international standardization also began in 1995 by the Full Service Access Network (FSAN) working group, formed by major telecommunications service providers and system vendors to work on fiber-to-the-home architectures. The first-generation PON has been referred to as the asynchronous transfer mode PON (APON), with the initial ITU-T G.983 standards, or as the broadband PON (BPON), with the final version of the ITU-T G.983 standards for further improvements, providing a typical downstream bandwidth of 622 Mbit/s and an upstream bandwidth of 155 Mbit/s. In the 2000s, the gigabit-capable PON (GPON) using the ITU-T G.984 standards began supporting 2.5-Gbit/s downstream and 1.25-Gbit/s upstream bandwidths with relatively strict specifications for high bandwidth efficiency. In addition, the Ethernet PON (EPON) using the IEEE 802.3ah standards began supporting symmetric 1.25-Gbit/s bandwidths in both directions with relatively simple specifications. Both GPONs and EPONs are now being widely deployed across the globe. In the late 2000s, to solve future bandwidth bottlenecks for subscribers and increase network coverage, the next-generation PONs (NG-PONs) [2], [3] were studied by FSAN/ITU-T and IEEE (Fig. 1). The IEEE 802.3av standards for the 10-Gbit/s EPON (10G-EPON) [4] were specified to support a 10-Gbit/s downstream bandwidth and a 10-Gbit/s or 1.25-Gbit/s upstream bandwidth, and the ITU-T G.987 standards for the 10-gigabit-capable PON (XG-PON) [5] were specified to support 10-Gbit/s downstream and 2.5-Gbit/s upstream bandwidths (XG-PON1), with no

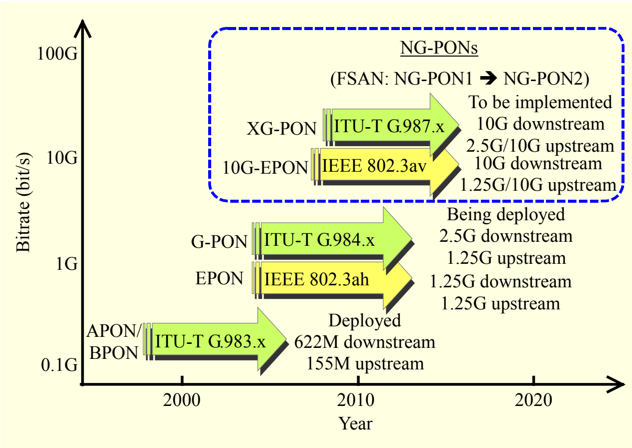

Fig. 1. Evolution of PONs.

specifications yet for symmetric 10-Gbit/s bandwidths (XG-PON2).

Compared to the IEEE standard PONs supporting a 20-km fiber distance, the XG-PON1 has been specified to increase the network coverage for an extended reach of 40 km. ITU-T G.984.6 was specified to increase the overall fiber length and the splitting ratio of the legacy G-PON in 2008 [6], and an active extension node in the middle of the optical network has been studied in several ways to implement an optical reach extender, such as in [7]. In the XG-PON1 for 40 km, however, an entirely "passive" extended PON scheme is desired for simple reach extension as well as a cost-effective high-splitting ratio.

In this paper, we present a novel bidirectional optical subassembly (BOSA) for an XG-PON1 optical line terminal (OLT) system, which consists of a 10-Gbit/s electroabsorption modulated laser (EML) and a 2.5-Gbit/s burst mode (BM) receiver (Rx). The developed prototype is composed of a 1,577-nm EML and a 1,270-nm avalanche photodiode (APD) BM-Rx within a uniquely designed bidirectional mini-flat package and 9-pin TO package. The XG-PON1 physical media dependent (PMD) requirements are first briefly summarized, and the features and characteristics of the developed XG-PON OLT PMD prototypes are then introduced in detail. Finally, the optical transmission performances for 10-Gbit/s downstream and 2.5-Gbit/s upstream links of up to 40 km are reported.

II. XG-PON1 PMD Requirements

1. PMD Functional Blocks

Figure 2 illustrates the functional block diagram of bidirectional OLT and optical network unit (ONU) transceivers with optical and media access control (MAC) signal interfaces in general PON applications. For a central office application

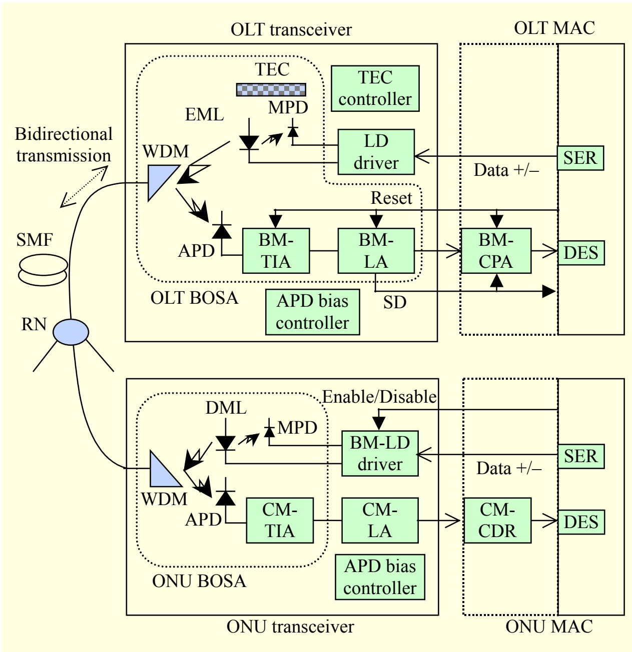

Fig. 2. OLT and ONU PMD functional blocks and interfaces.

requiring a relatively high performance, an OLT transceiver consists of a continuous mode (CM) transmitter (Tx) part and a BM-Rx part with a wavelength division multiplexing (WDM) part for bidirectional optical communication through single mode fiber (SMF). As a main functional block, the OLT Tx part includes a laser diode (LD), that is, an EML, a monitor photodiode (MPD), an LD driver, a thermoelectric cooler (TEC), and a TEC controller, and the OLT Rx part includes an APD, a transimpedance amplifier (TIA), a limiting amplifier (LA), and an APD bias controller. The OLT MAC transmits downstream data to the OLT Tx and receives upstream data from the BM-Rx through a BM clock-phase aligner (BM-CPA). In an XG-PON1 with strict BM overhead timing specifications, the OLT MAC should provide a reset signal to BM-Rx for initialization during the guard time before receiving a BM data packet from an ONU and can receive a signal detect (SD) signal from the BM-Rx to recognize the cleared BM signal duration [8].

For the user site application, the ONU transceiver for the XG-PON1 consists of a BM-Tx part with a direct-modulated laser (DML) and a BM-LD driver, and a CM-Rx part with an APD, a TIA, an LA, and an APD controller, which has a relatively simple and cost-effective structure. An ONU MAC should control the turn on/off ONT Tx using an enable/disable signal, which allows the optical power to be launched only within the proper BM operation timing.

2. XG-PON1 PMD Specifications

Since we target the development of PMD prototypes for

Table 1. ODN and optical interface parameters.

ODN parameter		
Maximum fiber distance	40 km	
Bidirectional transmission	1-fiber WDM	
Optical interface parameter	Downstream	Upstream
Bitrate	9.95328 Gbit/s	2.48832 Gbit/s
Wavelength	1,575 nm to 1,580 nm	1,260 nm to 1,280 nm
ER	> 8.2 dB	> 8.2 dB
BER reference level	1E-3	1E-4
Optical path penalty	< 1.0 dB	< 0.5 dB

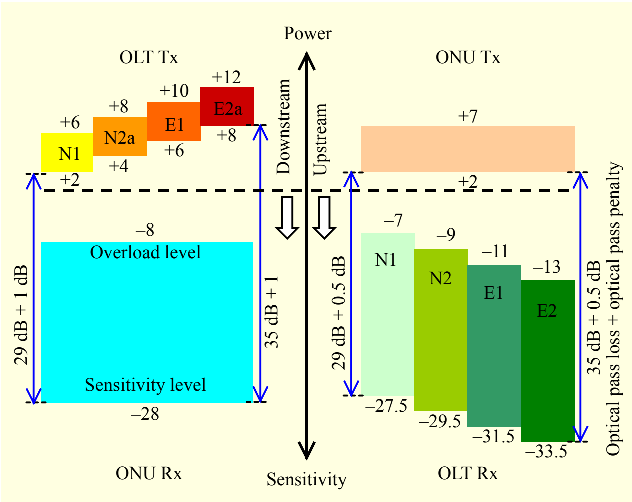

Fig. 3. Power budget requirements in ITU-T G.987.2.

XG-PON1, particularly those capable of extended class application in ITU-T G.987.2, the required main PMD specifications are described in Table 1 and Fig. 3 for an optical distributed network (ODN) and optical interface parameters. The 10-Gbit/s downstream and 2.5-Gbit/s upstream signals need to be transmitted over 1-577-nm and 1,270-nm center wavelengths, respectively, and the required extinction ratios (ERs) of the Tx are larger than 8.2 dB. The optical path penalties, mainly by the worst-case optical dispersion, are allowed to be less than 1.0 dB for downstream links and 0.5 dB for upstream links of up to 40 km. Employing forward error collection based on Reed-Solomon (RS) codes, RS (248,216) and RS (248, 232) [5], 1E-3 and 1E-4 with bit error rate (BER) reference levels are defined for the downstream and upstream directions,

In the XG-PON1 power budget requirements, the two nominal classes, N1 and N2, and two extended classes, E1 and E2, are specified to overcome the optical pass losses of 29 dB, 31 dB, 33 dB, and 35 dB with the allowed optical pass penalty in both directions, as shown in Fig. 4. For the OLT Rx and ONU Rx, all specified sensitivities are based on the use of APD at each bitrate, and the N2a and E2a classes for OLT Tx are defined to distinguish them from N2b and N2b classes, assuming the use of a Pin-PD in an ONU transceiver, which is not described herein.

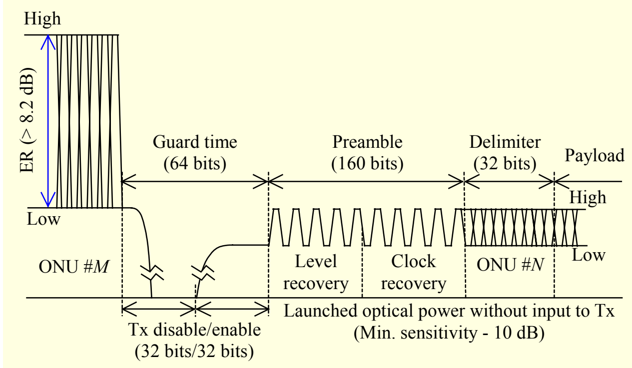

Fig. 4. BM overhead timing and ONU power levels.

Figure 4 shows the allocated BM overhead times for XG-PON1 OLT functions, which are the objective values for a more efficient implementation with optimized components. During a guard time of 64 bits, the previous ONU Tx should be disabled within 32 bits to a lower power level than the minimum sensitivity of below 10 dB, and the following ONU should be enabled within 32 bits to achieve a low-level launched optical power.

3. Small-Form Factor Assembly

To meet requirements for XG-PON specifications and multisource agreement (MSA) packages for 10-Gbit small form factor pluggable modules, such as the XFP [9] and the SFP+ [10], the OLT transceiver is the most difficult PMD part to be implemented, especially for the extended class specification of the XG-PON1. Based on the current performances of the optoelectronics, the E1 and E2 class specifications are difficult to achieve with a cooled EML and a BM-Rx for a bidirectional transmission within an XFP package. A compact OLT BOSA with multifunctional integrations will help simplify the implementation of an XG-PON1 OLT transceiver in a smaller MSA package [11], which provides a better chance to increase the number of OLT ports per rack system.

III. XG-PON1 OLT PMD Prototypes

1. 2.5-Gbit/s Burst Mode Receiver

For a received upstream signal with variations in burst-to-

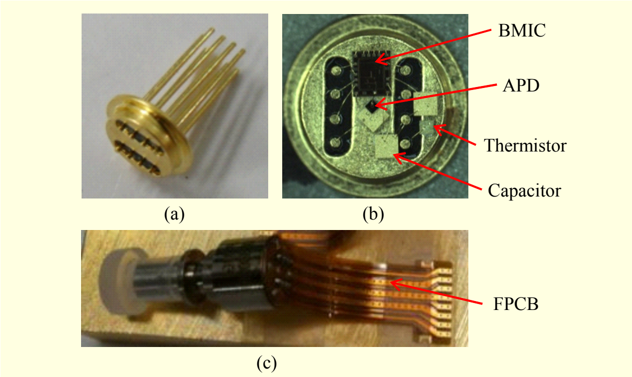

Fig. 5. (a) 8P/9L TO-46 package, (b) BM-Rx subassembly, and (c) 2.5G BM-Rx ROSA module.

burst magnitude and phase, a BM-Rx performs amplitude recovery within an objective preamble time of 160 bits. A single-chip BM integrated circuit (IC) with TIA and LA is developed based on a 0.18-μm SiGe BiCMOS process [12] and assembled with an APD on a uniquely developed 8-pin or 9-lead (8P/9L) TO-46 package, as shown in Figs. 5(a) and 5(b).

The multisignal interfaces including two differential line pairs, a power supply, an APD bias, a reset, an SD, and a thermistor can be supported by the 8P/9L TO-46 package, which is designed for high-speed operation of up to a 10-Gbit/s bitrate. Using the BM-Rx subassembly, we develop a stand-alone 2.5 BM-Rx receiver optical subassembly (ROSA) module, as shown in Fig. 5(c), and an XG-PON1 OLT BOSA module, as shown in Fig. 6. For a ROSA module, the BM-Rx subassembly is first assembled with a ball lens cap using an electric welding method for hermetic sealing and optical collimating and then assembled with an LC-receptacle using a laser welding method for the optical interface. For a BOSA module, the BM-Rx subassembly is sealed with a window glass cap via electric welding and assembled with a blocking filter for a 1,577-nm wavelength on the glass window.

2. XG-PON1 OLT BOSA Module

Figure 6 shows a BOSA module composed of a 10-Gbit/s EML Tx and 2.5-Gbit/s BM-Rx to satisfy the XG-PON1 OLT requirements. Using a uniquely designed bidirectional mini-flat package [13], compatible with a standard 10-Gbit/s miniature device (XMD) MSA, the EML Tx and BM-Rx are fully integrated in a miniature component for bidirectional transmission through a single core of SMF. As shown in Fig. 6(a), a 10-Gbit/s EML subassembly is first assembled in a bidirectional mini-flat package, which consists of a 10G EML submount assembly with a collimating lens and a single-stage optical isolator on a TEC, a 45° WDM filter for 1,270-nm reflection and 1,577-nm transmission, and a focusing lens for a

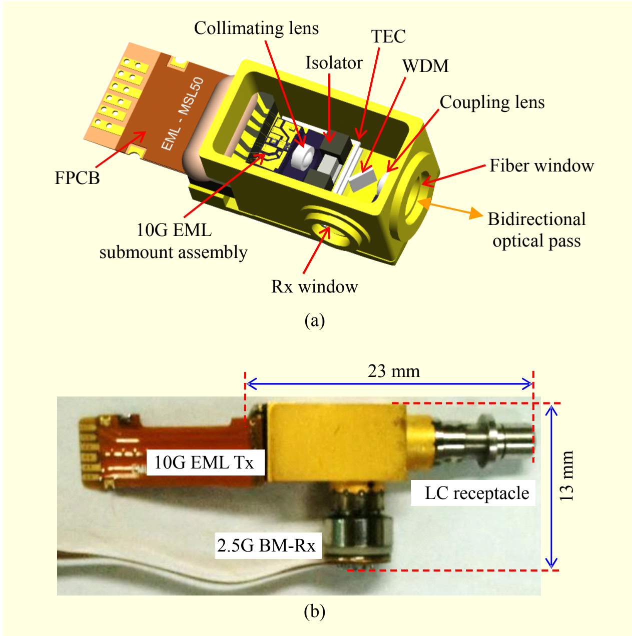

Fig. 6. (a) 10-Gbit/s EML assembly in bidirectional mini-flat package and (b) XG-PON1 OLT BOSA module.

bidirectional transmitted and received optical beam. The 10G EML submount assembly is composed of an EML chip, an MPD, a thermistor, and a 1-mm diameter collimating micro aspheric lens on a silicon optical bench (SiOB) with a 10-Gbit/s single-ended microstrip transmission line and a V-groove for lens assembly.

A BM-Rx subassembly with a window glass cap and blocking filter is aligned and assembled with an aspheric lens on the Rx window of the 10-Gbit/s EML subassembly in a bidirectional mini-flat package using a laser-based welding method. The LC-receptacle for an optical interface is also aligned and assembled on the fiber window using a laser-based welding method. As shown in Fig. 6(b), the length and width of the developed XG-PON1 OLT BOSA module are 23 mm and 13 mm, respectively, which can be used in the XFP module with an 18.35-mm width and compared to an SFP+ module with a 13.55-mm width.

Some XFP transceivers for XG-PON1 OLT have recently been available on the market, but all products are still under development to be fully compatible with the ITU-T G.987 N class, to the best of our knowledge. As shown in our prior article [14], developed with the separated Tx and Rx subassembly sections including a BMIC with relatively high sensitivity and low overload characteristics without an on-chip SD function, the XFP transceiver can be integrated with more functions, such as a clock and data recovery or an external SD generation on a planar circuit board. Thus, such a miniature XG-PON1 OLT BOSA module will give more opportunity for an XFP module with more functions. Furthermore, as future work, the aspheric lens on the Rx window for BM-Rx coupling can be embedded in the Rx window in the same fashion as the coupling lens in the 10-Gbit/s EML subassembly, as shown in Fig. 6, which means the miniature BOSA module can then be adopted within a 13.55-mm width SFP+ module.

IV. Experiment Results

1. 10-Gbit/s EML Transmitter

A. Performance Optimization by Operation Condition

An EML chip is integrated with an LD and a modulator on an InP substrate. For a 10-Gbit/s optical transmission, the modulator is driven by a peak-to-peak modulation bias (V_{PP}) at a modulator reverse bias voltage (V_{MOD}) combined through a bias-tee, while the LD is biased at a constant current for a continuous optical output. Since the overall performances of the EML are critically dependent on the operation conditions of the EML, that is, V_{PP}, V_{MOD}, LD operation current, and the EML temperature, the correlation between the operation conditions must be studied to achieve the desired target performances between the output power, jitter, and ER. As shown in Fig. 7, lower jitters and higher ERs can be archived with a relatively higher V_{MOD} condition at a fixed operation LD current and temperature, but the output powers are proportionally decreased. Herein, we present the average output power and peak-to-peak jitter in the modulated optical output of an EML. In this study, an optimum V_{PP} condition of 1.8 V is chosen for a higher ER without a remarkable affect on the jitter characteristics. The lower LD current is beneficial for a relatively high ER and lower power consumption, but there are penalties in terms of the output power and jitter characteristics, which can be seen in the two dashed lines for 100 mA and 60 mA at 35ºC in Fig. 7. With an increase in the EML temperature, the ER performance can be improved with a decrease in output power.

As a result, with a combined operation condition for an LD current of 100 mA, the EML temperature of 35ºC, V_{PP} of 1.8 V, and V_{MOD} of 0.8 V (Condition 1), we can achieve an optimum performance with an output power of 6 dBm, ER of 7.3 dB, jitter of 19 ps, and eye-crossing of 53%. Otherwise, with an increased V_{MOD} to 1 V from Condition 1 (Condition 2), an ER of 8.3 dB and an output power of 5.3 dBm can be achieved. Thus, unfortunately, this 10-Gbit/s EML Tx can meet only one of the required power and ER specifications. In addition, we measure the TEC power consumption of the BOSA for the EML operation in Condition 1 over the ambient temperature range from 0ºC to 75ºC, and the maximum power consumption is less than 1 W at 75ºC.

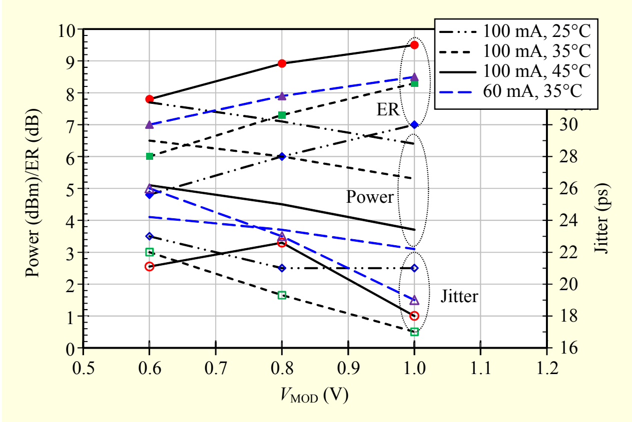

Fig. 7. Characteristics of 10-Gbit/s EML vs. modulation bias, operation current, and temperature.

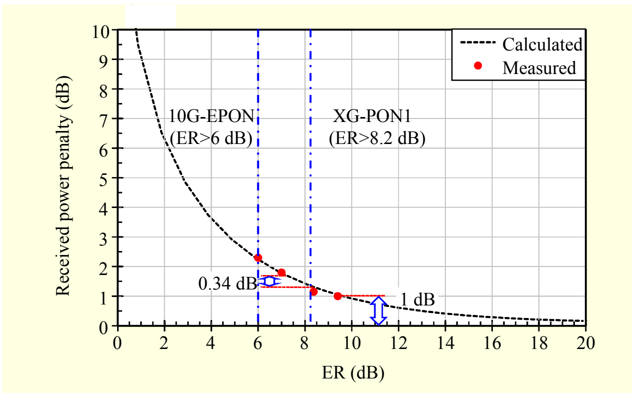

Fig. 8. Received power penalty vs. ER.

B. Received Power Penalty by Extinction Ratio

For a further beneficial selection between the power and ER, we conduct a study on the received power penalty from the ER, as shown in Fig. 8. In binary digital communications, the ER is often expressed as a logarithmic ratio (dB) between the binary "1" and "0" power levels, P_1 and P_0, which are expressed as ER = 10 log10 (P_1/P_0). From certain equations for the bit error probability and optimum decision threshold in Rx [15], the received power penalty based on a finite ER for an infinite ER with an ideal "0" power level can be induced in dB:

$$\delta_{ER}\,(\mathrm{dB}) = 10\log\left[\left(10^{ER/10}+1\right)/\left(10^{ER/10}-1\right)\right].$$

We also measure the differences in BER performances of Rx for a few ER values with arbitrarily selected operation conditions, which are compared using a simulated power penalty graph, which is adjusted to 1 dB for a compensation of the expected power penalty between the largest ER of 9.4 in the measurement and an infinite ER, as shown in Fig. 8. Based on the simulated results, the received power penalty of about 0.34 dB is expected, owing to an ER difference of between

7.3 dB and 8.3 dB. Thus, we can expect a relatively larger performance margin with Condition 1 compared to Condition 2 since the EML powers in both conditions exhibit a difference of 0.7 dB.

2. 2.5-Gbit/s APD Burst Mode Receiver

A. Burst Mode Overhead Timing Characteristics

Figure 9 shows the worst-case scenario of the overhead timing characteristics in greater than 5 BM-Rx ROSA modules, which exhibit electrical output waveforms of BM-Rx for the received optical inputs from two ONU transceivers for a 1,270-nm wavelength. As shown in Fig. 4, a guard time of 64 bits corresponding to 25.6 ns is allowed between the two ONUs for the objective overhead timing specifications. With a preamble length of 128 bits by the setting limitation in ParBERT, a settling time of 25 ns is observed as the worst-case result, which is dependent on the input power [12]. Thus, the recovered preamble signal of a minimum of 95 bits can be provided to the BM-CPA for the clock and phase locking. Considering an additional cable pass delay of about 4 ns in a data signal compared with the reset and SD signals, the rising and falling edge of the SD signal are within 1 ns and 3 ns from the start of the preamble and reset signals, respectively.

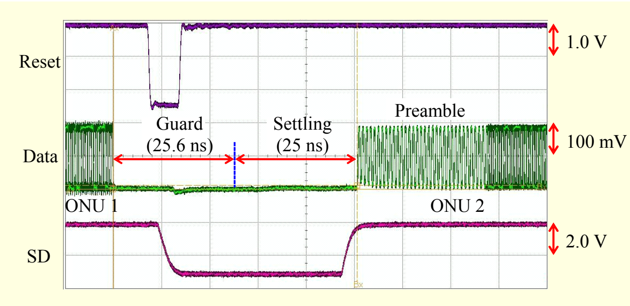

Fig. 9. Timing characteristics of single-chip BM-Rx.

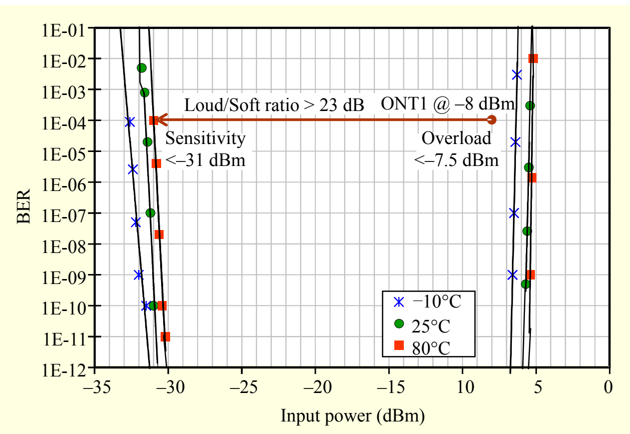

Fig. 10. B2B BER performances of 2.5-Gbit/s BM-Rx over operation temperatures of –10ºC to 80ºC.

B. BER Performances over Temperatures

We investigate the BER performances of an APD BM-Rx over the operation temperatures of –10ºC to 80ºC, as shown in Fig. 10. The roughly controlled APD bias is 52 V for –10ºC and 25ºC and 61 V for 85ºC. ONU 1 and ONU 2 are sequentially transmitted for a BM upstream input into a 2.5-Gbit/s BM-Rx module. While the received input power from ONU 1 is fixed at –8 dBm, the input powers of ONU 2 are varied to measure the BER performances from the overload to the sensitivity levels. In the result for the 1E-4 BER reference level, the dynamic range of BM-Rx for the input power range of ONU 2 is maintained at almost 26 dB, and the loud and soft ratio between the two ONUs is larger than 23 dB for the overall temperature range.

3. Optical Transmission Performances in ODN

A. 10-Gbit/s Downstream Link

The optical transmission performances for up to a 40-km link distance, as well as a back-to-back (B2B) link, are evaluated for the newly developed novel XG-PON1 OLT BOSA module. For a 10-Gbit/s downstream transmission, the 1,577-nm EML Tx at Condition 1 is operated for an output power of 6 dBm and ER of 7.3 dB, and the BER performance of a 10-Gbit/s APD Rx for the received power at a B2B link and 40-km link distance are measured, as shown in Fig. 11. At the 1E-3 BER reference level, the sensitivities are –30.5 dBm and –29 dBm for a B2B link and 40-km distance, respectively, which means a dispersion penalty of about 1.5 dB. In the results of this experiment, the dispersion penalty and ER are somewhat out of the specifications in Table 1, but the output power of the OLT Tx and the sensitivity of the ONU Rx are sufficient enough to satisfy the 10-Gbit/s downstream power budget for the E1 class, as shown in Fig. 3.

B. 2.5-Gbit/s Upstream Link

The 2.5-Gbit/s upstream transmission characteristics are evaluated based on the BER performance of BM-Rx at a B2B link and 40-km link distance. In particular, the crosstalk penalty of BM-Rx from the EML Tx in the XG-PON1 OLT BOSA module is measured from the BER performances in the B2B transmissions while turning the EML Tx on and off. In the optical transmission experiments, a 1,270-nm DML Tx is operated for a continuous 2.5-Gbit/s bit-stream to measure the BER characteristics without the use of a BM-CPA after a long fiber transmission, which results in a performance with better sensitivity compared to the BM operation, as shown in Figs. 10

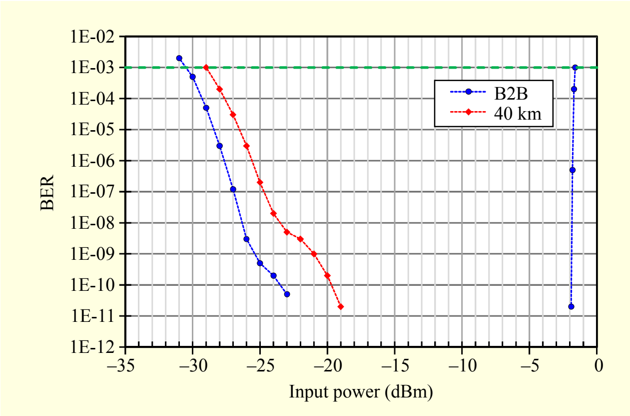

Fig. 11. 10-Gbit/s downstream transmission performances at B2B and 40-km link distance.

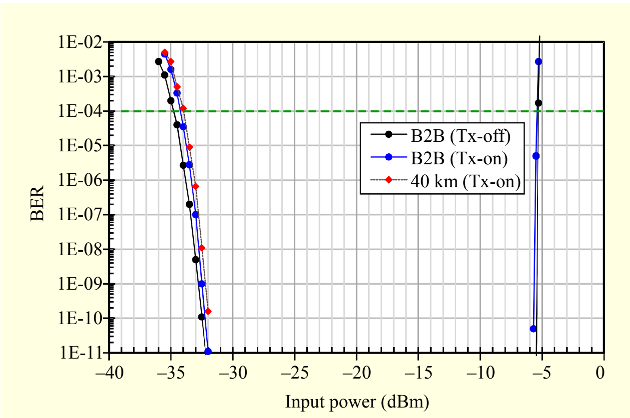

Fig. 12. 2.5-Gbit/s upstream transmission performances at B2B and 40-km link distance.

and 12.

At the 1E-4 BER reference level, the sensitivities of BM-Rx are –34.8 dBm, –34.2 dBm, and –34 dBm for B2B (Tx-off), B2B (Tx-on), and 40-km (Tx-on) transmissions, respectively. Thus, the crosstalk penalty of BM-Rx by the 10-Gbit/s EML Tx is 0.6 dB, which confirms the low optical and electrical noise effect between the BM-Rx and the EML Tx in a BOSA module. The dispersion penalty of up to 40 km is only 0.2 dB since the dispersion coefficient of SMF at a 1,270-nm wavelength is much lower than that at a 1,577-nm wavelength, and the inter-symbol interference also is smaller at a lower bitrate. With an ONU Tx power of more than 2 dBm, the sensitivity performances of the 2.5-Gbit/s BM-Rx confirms that the upstream power budget for the E1 class can be satisfied to overcome an optical pass loss of 33 dB and an optical pass penalty of 0.5 dB.

V. Conclusion

In this paper, we introduced overviews of the XG-PON1 OLT PMD requirements and specifications, a bidirectional miniature prototype of an XG-PON1 OLT BOSA module, and performance optimizations and evaluations of the developed BOSA prototype including a 10-Gbit/s EML Tx and a 2.5-Gbit/s BM-Rx. Using uniquely developed 8P/9L TO-46 and 10-Gbit/s miniature bidirectional mini-flat packages and a single-chip BMIC, the XG-PON1 OLT BOSA module is composed of a 1,577-nm EML Tx and a 1,270-nm APD BM-Rx. The 10-Gbit/s Tx and 2.5-Gbit/s Rx characteristics were evaluated and compared with the PMD specifications of ITU-T G.987.2 for the XG-PON1. By conducting 10-Gbit/s downstream and 2.5-Gbit/s upstream transmission experiments, we verified that the developed 10-gigabit-capable PON PMD prototype can support a power budget of E1 class for up to a 40-km fiber reach, although the ER of 7.3 dB should be further improved to ensure an optical path penalty of less than 1 dB. We believe that the miniature XG-PON1 OLT BOSA module can be adopted with a sufficient space margin into the XFP transceiver, and performances for the ITU-T G.987 ODN parameters from the N1 class to the E1 class can be achieved using the commercial 10-Gbit/s EML and the developed 2.5-Gbit/s BM-Rx devices in the miniature BOSA module.

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