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Polarization multiplexing and hybrid modulation based bandwidth efficient NG-PON2 coexisting GPON and XG-PON

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The bandwidth efficiency is an important design parameter for the next-generation passive optical network stage 2 (NG-PON2). In this paper, two optical line terminal (OLT) designs based on polarization split state are proposed for NG-PON2. The first method doubles the data rate per wavelength by separate amplitude modulation of both polarization states. Whereas in the second method, differential phase-shift keying (DPSK) modulates another data on each amplitude-modulated state, this approach increases data rate per wavelength by four-folds. The proposed system provides NG-PON2 access while coexisting with a gigabit passive optical network (GPON) and 10 GPON (XG-PON). The proposed system design serves 1024 NG-PON2 next-generation passive optical network stage 2 (ONUs), 128 GPON ONUs, and 128 XG-PON ONUs. The transmission performance of the system is verified by evaluating the (BER) for varied received power. The acceptable bit error rate level of less than 10^{-9} is considered in this work.

Keywords: *next-generation passive optical network stage 2, gigabit passive optical network, 10 gigabit passive optical network, modulation formats, polarization division multiplexing.*

Ocis codes: *060.0060, 060.4250, 060.4510.*

Эффективные мультигигабайтные широкополосные пассивные оптические сети следующего поколения (NG-PON2), использующие поляризационное мультиплексирование и гибридную модуляцию

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Полоса пропускания является важнейшей характеристикой пассивных оптических сетей следующего поколения (the next-generation passive optical network stage 2 (NG-PON2)).

Рассмотрены две конструкции терминала оптической линии (optical line terminal (OLT)) таких сетей, использующие поляризационное разделение. В первой из них скорость передачи данных удваивается посредством раздельной амплитудной модуляции в каналах с различной поляризацией излучения. Вторая конструкция использует дифференциальную фазовую манипуляцию (differential phase-shift keying (DPSK)), обеспечивающую ведение дополнительных данных посредством модуляции в каждом из амплитудно-модулированных сигналов, что приводит к четырёхкратному увеличению скорости передачи данных.

Предложенные системы обеспечивают совместимость сетей NG-PON2 с пассивными оптическими сетями гигабитного и сверхгигабитного классов (gigabit passive optical network (GPON) и 10_GPON (XG-PON)). Системы предложенной конструкции обслуживают 1024 оптических сетевых устройств сетей NG-PON2. Производительность передачи данных системы подтверждена оценкой частоты появления ошибочных битов (BER) для различных значений передаваемой мощности, приняв критериальное допустимое значение BER менее 10^{-9}.

Ключевые слова: *NG-PON 2, GPON, XG-PON, методы модуляции (Modulation Formats), поляризационное мультиплексирование.*

1. INTRODUCTION

The bandwidth demand is increasing for new emerging services like video on demand, high definition television (HDTV), 4K or 8K ultra high definition television (UHDTV), high definition (HD) video gaming, cloud computing, and 5G mobile front haul. Gigabit passive optical network (GPON) serves a data rate of 2.5 Gbps to the subscribers. Globally, at present, the most deployed passive optical network (PON) standard is GPON [1]. However, presently deployed GPON would not be able to support these new emerging services. Ultimately, service providers have to upgrade to the more competent PON systems. 10 gigabit passive optical network (XG-PON) is an immediate remedy for this problem. However, XG-PON can support only the 10 Gbps data rate, which is also not a future proof option. Future access networks should meet the demand for high data rate services. The use of only wavelength division multiplexing (WDM) or time division multiplexing (TDM) is not a suitable solution for providing high speed connectivity. The time and wavelength division hybrid multiplexing is the optimum solution to fulfill the requirements of next-generation services [2,3]. Time and wavelength division multiplexing (TWDM) based next-generation passive optical network stage 2 (NG-PON2) employing centralized light sources, and colorless optical network unit (ONU) is a promising candidate to meet these demands due to its ease of upgradability and high capacity. The technological standards for GPON, XG-PON, and NG-PON2 are shown in table 1. NG-PON2 enables 40 Gbps or 80 Gbps services by the approach of wavelength stacking and TWDM technique. If already deployed PON infrastructure would be for NG-PON2 upgrade, then the up gradation cost will be minimum, and the already deployed GPON/XG-PON system can stay functional. Therefore, the coexistence of the NG-PON2 with legacy PON systems is desirable.

In the context of this, K.A. Mat Sharif et.al have demonstrated a network in which XGS-PON (Symmetric XG-PON) and GPON coexists on the shared infrastructure. The acceptable performance for both the PON services was observed for the 15 Km fiber range [7].

Even with the coexistence, further enhancement of bandwidth efficiency is desired. Polarization of light is one of the fundamental properties of optical signals, which is being analyzed since the beginning of optical transmission systems. Polarization division multiplexing (PDM) is the right candidate to enhance the bandwidth efficiency and for an increase in data rate per wavelength. In PDM, multiple data streams can be transmitted on more than one polarization state of the same optical signal. Hence, the data rate per wavelength increases, which leads to bandwidth efficiency. With the use of orthogonal polarization states, the capacity of the optical

Table 1. GPON, XG-PON, and NG-PON2 Technologies

	GPON	XG-PON	NG-PON2
ITU-Standardization	G.984 (2003) [4]	G.987 (2010) [5]	G.989 (2015) [6]
Bandwidth (DS/US) Gbps	2.5/1.25	10/2	40/10
Splitting ratio	Up to 1:64	Up to 1:128	
Coexistence	–	With GPON	

link doubles without the need for a new optical source [8]. Nada Badraoui et.al presented a method of modulating both polarization states in a single channel point-to-point link. On one polarization, they modulated a 1 Gbps data rate using 16 quadrature amplitude modulation (QAM), and on the second polarization, 1 Gbps data is modulated using 64 QAM format [9].

Fei Xiong et.al presented a polarization multiplexing based 2.5-Gb/s symmetric WDM-PON. They proposed the method of re-modulation for the upstream. The presented system provides point-to-point and multicast services exploiting polarization multiplexing. They observed acceptable results with amplitude-shift keying (ASK) modulation format for a fiber length of 26 Km [10]. Qinghai Huang et al. presented a polarization multiplexing based WDM-PON architecture for supporting 10 Gbps point-to-point and 10 Gbps multicast data. Out of the two orthogonal polarization states, one is used for transmission of point-to-point data and another for multicast data. They experimentally verified the feasibility of the proposed method [11]. Hyun-Do Jung et.al demonstrated WDM PON based on the polarization multiplexing technique utilizing two orthogonal polarization states of a single laser source. One polarization state was utilized for transmitting 10 Gbps downstream data, and another modulation state was transmitted unmodulated from OLT. The unmodulated polarization state was re-modulated with a 10 Gbps data rate from the ONU to produce the upstream data stream. In their work, the ONU presented is polarization insensitive and colorless [12].

Li Tan et al. presented transmitter design for WDM-PON, where two orthogonal polarization states of a single laser at OLT are used for both downstream and upstream. In their method, 10 Gbps downstream data is modulated on the X-polarization state, and the Y-polarization state is transmitted unmodulated from OLT. The Y-Polarization state is modulated from the ONU and is used for the upstream data transmission with a 2.5 Gbps data rate [13].

From the previous works, it is observed that polarization multiplexing is restricted to WDM-PON with a limited data rate. The work can be extended for higher data rate NG-PON2. In this paper, we have proposed bandwidth-efficient polarization multiplexing based OLT designs for 80 Gbps NG-PON2. After that, the performance of the proposed system is investigated for NG-PON2 coexisting with GPON and XG-PON.

The paper is organized into four parts. The related literature and introduction are presented in the first section. The system setups and obtained results are discussed in the second section. The results and discussion is reported in the third section. The conclusions are made in the fourth section. The list of references to the cited sources is at the end of the paper.

2. SYSTEM SETUP OF BANDWIDTH-EFFICIENT NG-PON2 COEXISTING WITH GPON AND XG-PON

The simulation architecture of coexisting NG-PON2 with GPON and XG-PON is shown in Fig. 1, the description of components is given in table 2. Here, the PDM technique is applied only to the NG-PON2 system not for GPON and XG-PON.

In the central office (CO), the individual transmitters of GPON and XG-PON are stacked together with four transmitters of NG-PON2. The wavelengths for the transmitters are assigned according to the dedicated wavelength plans proposed by ITU-T standards. Erbium doped amplifier (EDFA) is put in use to amplify XG-PON and NG-PON2 downstream signals. For the remote pumping of EDFA, a pump of 980 nm wavelength is placed in OLT so that the system remains passive. At the remote node (RN), each wavelength of NG-PON2 is split into two

Table 2. Desciption of Components Used in Simulation Setup

DM	Drop Multiplexer
PS	Polarization splitter
SP	Splitter
NG-PON2 ONU	ONU of NG-PON2
XG-PON ONU	ONU of XG-PON
GPON ONU	ONU of GPON
AWG	Array Waveguide Grating
λg	GPON Wavelength: 1490 nm
λxg	XG-PON Wavelength: 1575 nm
λp	Pump wavelength: 980 nm
λ_1–λ_4	NG-PON2 Wavelengths 1596, 1596.8, 1597.6, 1598.4 nm
Fiber Length	20 Km

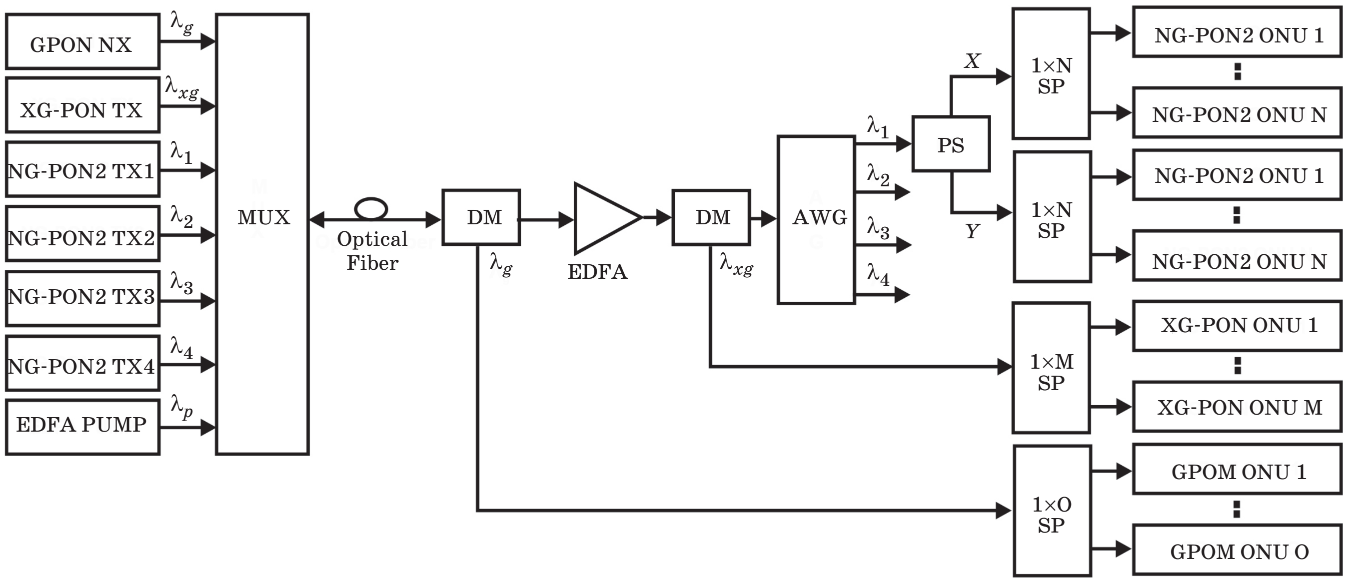

Fig. 1. Coexisting GPON, XG-PON, and NG-PON2 system setup with polarization splitting.

polarization states (X and Y) then each polarization state is used to serve a different set of ONUs. $1{\times}N$ splitter splits the power of each polarization state where N is 128. Therefore, a single downstream wavelength of NG-PON2 is serving 256 ONUs, and a total of 1024 ONUs are considered.

Similarly, the optical power of wavelengths dedicated to GPON and XG-PON is divided into M and O parts by $1{\times}M$ and $1{\times}O$ splitters, respectively. With this, the proposed system is supporting 128 GPON ONUs and 128 XG-PON ONUs.

To utilize Y-polarization along with the X-polarization of OLT laser, we are proposing two methods for NG-PON2 OLT downstream transmitter design, which are based on the polarization division multiplexing (PDM). The followings are the proposed OLT designs.

1. NG-PON2 transmitter using amplitude modulated (AM) orthogonal polarization states.

2. NG-PON2 transmitter using hybrid modulated (AM + DPSK) orthogonal polarization states.

2.1. NG-PON2 transmitter using amplitude modulated (AM) orthogonal polarization states

To utilize the Y-polarization state along with the X-polarization state, we have proposed the OLT transmitter, as shown in Fig. 2. A data stream of 10 Gbps is modulated on each polarization state using AM. Hence, on each downstream wavelength, the 20 Gbps data rate is transmitted.

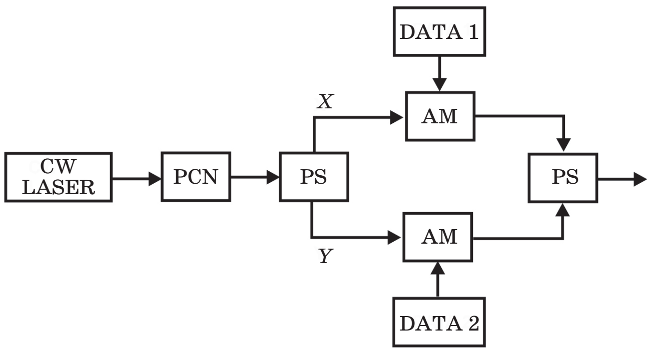

Fig. 2. Proposed transmitter design using amplitude-modulated orthogonal polarization states.

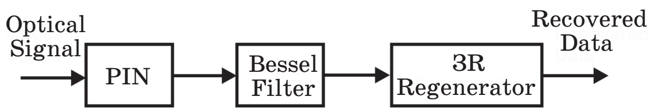

Fig. 3. Direct detection NG-PON2 receiver.

At the downstream receiver, a direct detection method is used to extract the information modulated on amplitude, as shown in Fig. 3.

2.2. NG-PON2 transmitter using hybrid modulated (AM+DPSK) orthogonal polarization

In the previous section, a method of amplitude modulating orthogonal polarization states with downstream data is presented. The data rate per polarization state is further increased by additional DPSK modulation of 10 Gbps data over an already amplitude modulated signal. In this work, a method of hybrid modulation of 10 Gbps using amplitude modulation and 10 Gbps using DPSK on each polarization state has been presented. The phase modulation used is RZ-DPSK (return to zero DPSK). Figure 4 shows the proposed transmitter design of NG-PON2 OLT based on hybrid modulation (AM + DPSK) on orthogonal polarization states.

In the proposed transmitter architecture, the laser light is split into *X* and *Y* polarization states. Two data streams of 10 Gbps each are modulated on the *X*-polarization state using AM and DPSK. Similarly, the other two data streams of 10 Gbps each are modulated on the *Y*-polarization state. After modulation, both polarization states are combined by using a power combiner (PC). Therefore, one wavelength carries a 40 Gbps data rate, which is the minimum required data rate for NG-PON2. With two such stacked NG-PON2 transmitters, 80 Gbps NG-PON2 service can be provided.

The presented technique has the advantage of pay as you grow approach as out of the four data streams per wavelength, one or more data stream can be made operational as per the requirements. In conventional NG-PON2 systems, 40 Gbps and 80 Gbps services are feasible by using four or eight OLT transmitters, respectively. Whereas with the proposed scheme, a full 40 Gbps service can be provided by using a single OLT transmitter, and 80 Gbps NG-PON service can be realized using two OLT transmitters. This suggests the bandwidth efficiency of the proposed OLT design based on PDM and hybrid modulation format. Figure 5 and Fig. 3 show the receiver architectures for NG-PON2 ONUs. The receiver shown in Fig. 5 is for extracting the information modulated over the phase of light.

Also, the direct detection technique is used for information extraction from the amplitude of the signals. Any NG-PON2 ONU receiver can have one or both of these capabilities as per the requirements of the data rate.

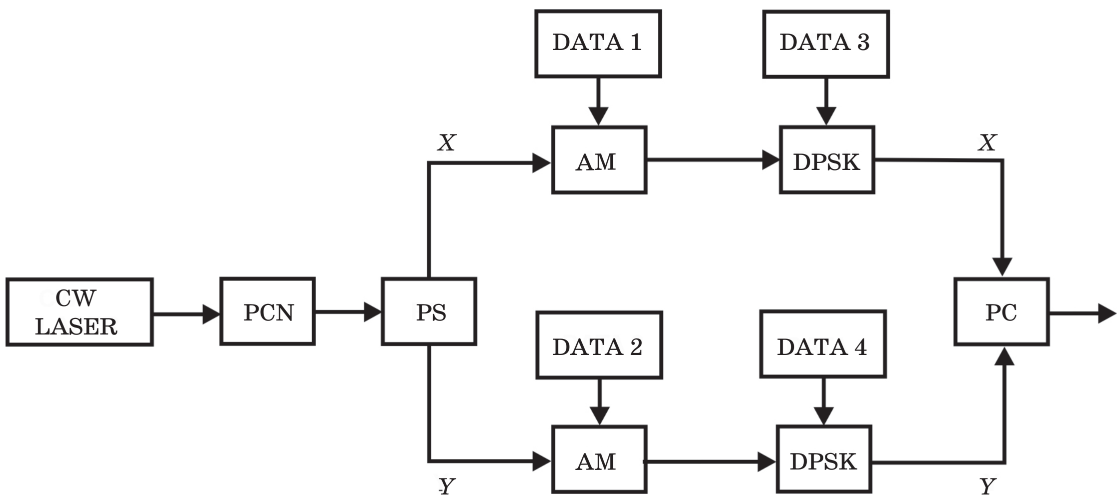

Fig. 4. Transmitter design using PDM and hybrid modulation (AM+DPSK).

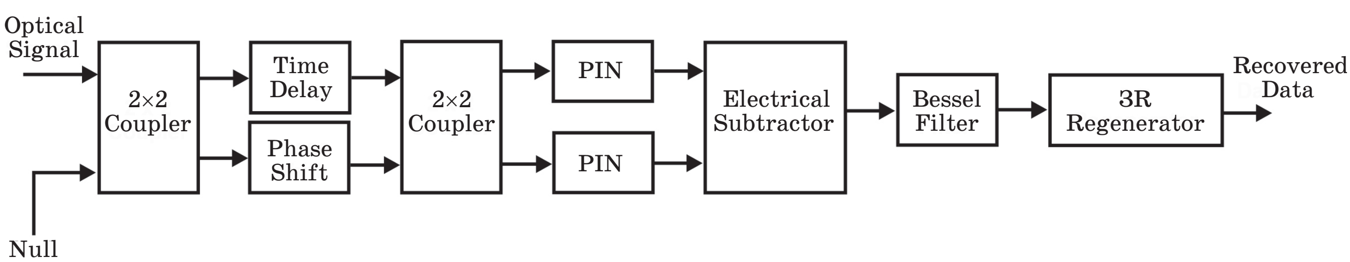

Fig. 5. ONU receiver design for the detection of information modulated on phase.

3. RESULTS AND DISCUSSION

Figure 6 shows the graphical representation of BER vs. received power at the ONUs operating at *X*-polarization and *Y*-polarization states.

The performance is almost similar for both the polarization states. For power exceeding –20 dB, the observed BER is found to be acceptable (less than 10^{-9}) for both states. At 21 dB received power BER is acceptable only for ONU operating at *Y*-polarization state. The BER is not acceptable in both the cases below –21 dB received power.

Simultaneous modulation of data on both amplitude and phase on each polarization state is not feasible if the modulation index of amplitude modulation is fixed to 1 (maximum). So the modulation index of 0.3 has been selected to implement DPSK modulation on the amplitude modulated optical signal. Modulation index value 0.3 is chosen after analyzing the effect of modulation index on the Q-factor of received AM and DPSK data. Figure 7 shows the variation of Q-factor as the function of the modulation index for AM and DPSK.

It is well known that the performance in the case of amplitude modulation improves if the modulation index increases. A similar trend is shown in Fig. 7 for AM data. However, as the modulation index increases, the information on the phase starts to deteriorate. Hence, the modulation index should be chosen such that the performance of both AM and DPSK remains acceptable. Modulation index 0.3 is deliberately chosen because, at this value, the Q-factor for both AM and DPSK is almost equal (around 10 dB) and is acceptable.

Figure 8 shows the BER versus received power for NG-PON2 downstream. The BER increases as the received power decrease in all the considered cases. From the graph, it is observed that the information modulated on the phase can be received at relatively lower power as compared to information modulated over amplitude. An acceptable BER less than 10^{-9} has been observed for received power exceeding –21 dB for DPSK modulated data on both *X*- and *Y*-polarization states. However, due to the reduced modulation

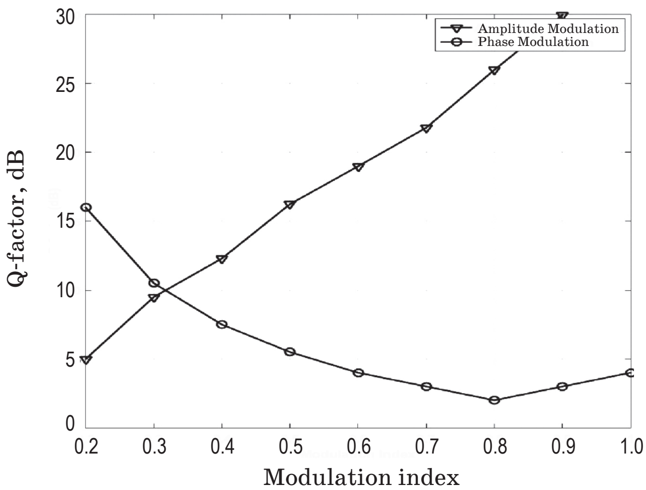

Fig. 7. Q-factor variation as the function of the modulation index for amplitude modulation and phase modulation.

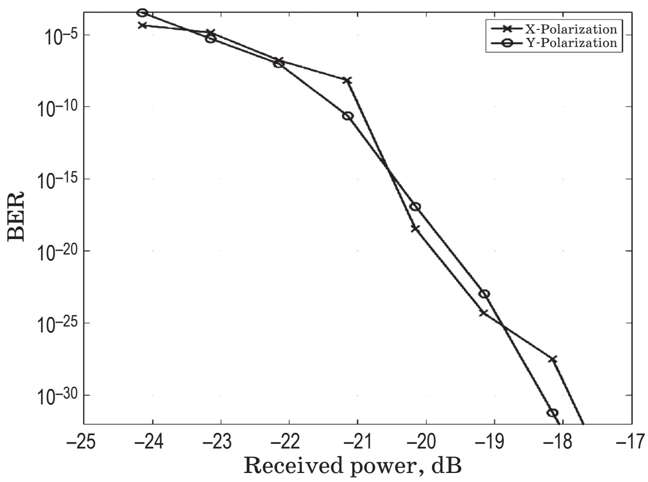

Fig. 6. Downstream BER vs. received power in case of amplitude modulated orthogonal polarization states based NG-PON2.

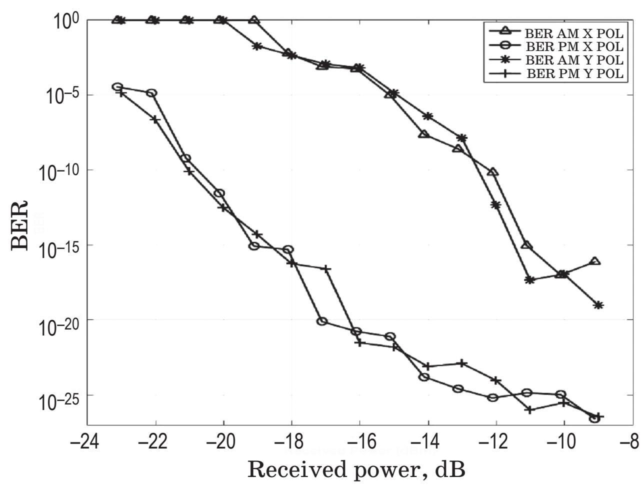

Fig. 8. NG-PON2 Downstream BER versus received power in case of hybrid modulation on orthogonal polarizations.

index, the information modulated on amplitude deteriorates much with the decrease in received power. The BER less than 10^{-9} has been observed for amplitude modulation on both polarization states for power exceeding –12 dB.

Figure 9 shows BER as a function for received power in the case of GPON downstream. The plot shows that the GPON ONU receives data correctly (BER < 10^{-9}) for above –20 dB received power. Below –20 dB received power. The GPON ONU is unable to recover downstream information correctly.

Figure 10 shows the BER for varied received power in the case of XG-PON ONU. In this case, ONU receives downstream data with BER < 10^{-9} for power above –17 dB. For lower received power, the BER is unacceptable.

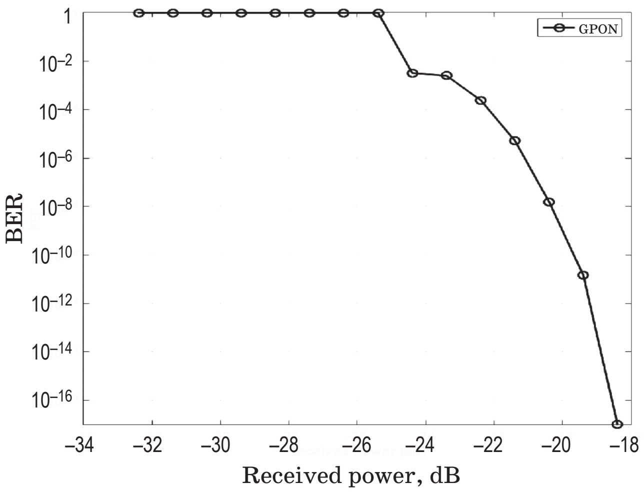

Fig. 9. BER vs. Received power for GPON.

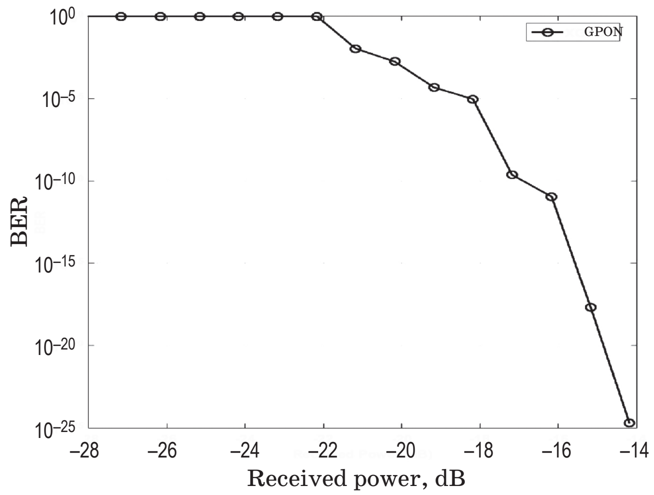

Fig. 10. BER vs. received power for XG-PON.

4. CONCLUSIONS

Due to exponentially increasing data demand, the already deployed GPON/XG-PON is unable to fulfill future demands. NG-PON2 is the future proof solution to this problem. However, in NG-PON2 the bandwidth efficiency enhancement is desirable. In this work, the performance of the NG-PON2 coexisting with GPON and XG-PON has been evaluated in terms of BER for varied received power. In the system design, a total of 1024 NG-PON2 ONUs, 128 GPON ONUs, and 128 XG-PON ONUs are being served over a 20 km long single-mode fiber. Two transmitter design methods are proposed for NG-PON2 based on polarization division multiplexing to enhance the system bandwidth efficiency. In the first method, both the orthogonal polarization states are modulated by AM. It has been observed that the performance is almost similar for both the polarization states. When power exceeds –20 dB, the observed BER is found to be acceptable less than 10^{-9} for both states. At –21 dB received power, BER is acceptable only for ONU operating at *Y*-polarization state. BER is not acceptable in both the cases when received power below –21 dB. The bandwidth efficiency is further improved in the second method by modulating additional data streams using DPSK on amplitude-modulated polarization states. The optimum modulation index of 0.3 is found for amplitude modulation to modulate information on the phase. The information modulated on the phase can be received at relatively lower power as compared to information modulated over amplitude. An acceptable BER < 10^{-9} has been observed for received power exceeding –21 dB for DPSK modulated data on both X and Y-polarization states. However, the information modulated on amplitude deteriorates much with the decrease in received power due to the reduced modulation index. The BER < 10^{-9} has been observed for amplitude modulation on both polarization states for power exceeding –12 dB. Acceptable performance has been observed in both cases proving the feasibility of the schemes. The GPON ONU receives data correctly (BER < 10^{-9}) for above –20 dB received power. The GPON ONU is unable to recover downstream information correctly below –20 dB received power. The performance of XG-PON has also been observed in terms of BER for varied received power. In this case, ONU receives downstream data with BER < 10^{-9} for power above –17 dB, and the BER is unacceptable for lower received power.

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