Performance Evaluation of Symmetric 8 × 10 Gbps TWDM-PON Incorporating Polarization Division Multiplexed Modulation Techniques Under Fiber-Impairments

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Abstract

Today's access networks are in high demand to fulfill the high bandwidth requirement because of extensive improvement in high transmission rate applications for cloud computing, big data analytics, and other next-generation 5G smart applications. This exponential growth of high capacity and broadband access technologies comprise an essential trend in the development of a passive optical network (PON) access network. In this paper, 80/80 Gbps time wavelength division multiplexing PON (TWDM-PON) incorporating polarization division multiplexing (PDM) based Mach–Zehnder modulator (MZM) and electroabsorption modulator (EAM) techniques have been proposed. The performance of the system consisting of different polarized multiplexed modulation techniques is investigated in both downstream and upstream data transmission for variable transmission distance and received optical power in terms of bit error rate (BER), eye diagrams, power budget (PB) and receiver sensitivity. The results show that the 4 × 20/20 Gbps PDM-EAM modulated signals over 100 km fiber distance at −60 dBm RS and 70 dB PB are successfully transmitted under fiber non-linearities. The proposed TWDM-PON system provides a next-generation long-reach access network from urban to rural areas.

Keywords TWDM-PON · PDM · MZM · EAM

1 Introduction

Network operators persist to find solutions to enhance the optical access networks (OANs) capacity to satisfy the ever-growing bandwidth demands, urged by bandwidth-hungry services like high-definition (HD) video, entertainment and Internet of things (IoTs).

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Fiber-to-the-home/business/premise/building (FTTx) is extensively regarded as the only access network capable of fulfilling this demand. For this, a passive optical network (PON) is considered as the most promising access network architecture which employs merely passive splitters/combiners in the remote node (RN) to offer cost-effective, simple and broadband access to the end-users. [1–3] Recent PON FTTx technologies like 10 Gigabit-PON (10GPON), 10 Gigabit Ethernet-PON (10GEPON) uses either wavelength or time-division multiplexing (TDM) and the currently stated next-generation PON stage 2 (NG-PON2) providing at least 40 Gbps network capacity. Time-wavelength division multiplexing PON (TWDM-PON) has been chosen as the key solution for NG-PON2 because of its attractive advantages such as mature, simple, "pay-as-you-grow" and backward compatible architecture. [4–6] To further enhance the transmission capacity of the OANs, various multiplexing techniques are widely used in the PON networks nowadays such as wavelength division multiplexing (WDM), [7] TDM, [8] orthogonal frequency division multiplexing (OFDM) [9] and the latest polarization division multiplexing (PDM). The widespread PDM has been utilized in the backhaul network to double the transmission capacity without degrading the network energy efficiency [10]. High transmission rate of 40 Gbps was demonstrated with the usage of PDM-on–off keying (OOK) modulation in WDM-PON over 80 km fiber distance. [11] Zhang J. et al. successfully demonstrated the 200 Gbps PDM-pulse amplitude modulation (PAM) PON system over a 20 km transmission distance [12]. Mun KH et al. proposed and experimentally tested the 1.35 Gbps coherent PON and intermediate frequency over fiber (IFoF) access network based on differential amplitude and phase-shift keying OFDM (DAPSK-OFDM) over 20 km fiber [13]. Elmagzoub MA successfully demonstrated the NG-PON based RoF-PON system using PDM 16-quadrature amplitude modulation multiple-input–multiple-output 40/10 Gbps (16-QAM MIMO) signals' transmission over 20 km fiber distance. [14] Also, to address the both fiber dispersion and transreceiver bandwidth capability, different modulation along with MZM modulators are used extensively [15–18]. However, as far as we know, there is no previous work on the TWDM-PON incorporating MZM/EAM modulation techniques.

In this work, we proposed and investigate the performance of $4 \times 20/20$ Gbps TWDM-PON employing PDM-Mach Zehnder modulator (MZM) and electroabsorption modulator (EAM) techniques for both downstream and upstream data transmission for a long-reach access network under fiber non-linearities. The significance of this work is to select a technology that offers high capacity per transmission wavelength, enhanced spectral efficiency, steady and easy up-gradation for upcoming 5G networks to tackles customers' needs. This paper is organized as-Sect. 2 presents the concept and system architecture. Section 3 discusses the results and discussion followed by a conclusion in Sect. 4.

2 Concept and System Architecture

Figure 1 depicts a point-to-multipoint architecture of NG-PON2 based TWDM-PON for multiple subscribers. Installed by a service provider at the central office (CO), an optical line terminal (OLT) distributes a WDM (in downstream) and TDM signals (in upstream) through an optical distribution network (ODN). ODN consists of an optical fiber and passive splitter/combiners, which integrates the backhaul and access span up to 100 km. The optical network units (ONUs) positioned at the premise/business/buildings/home receives the sent signals and offer bandwidth to each mobile or fixed user supported by the network [19–21]. Here, in OLT, four pairs of continuous wave (CW) wavelengths ({1596, 1527.2},
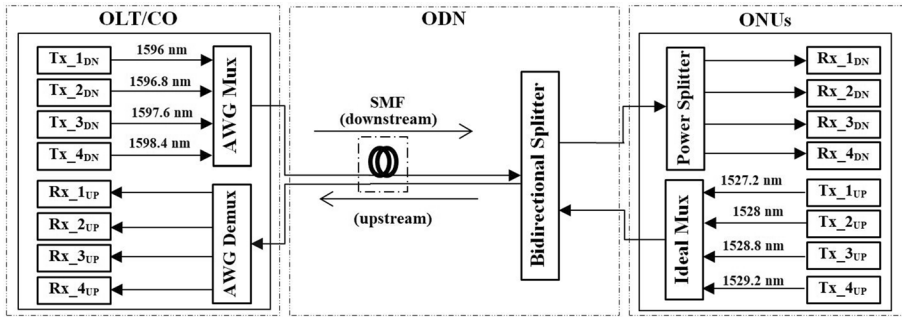
Fig. 1 Schematic of PDM based bidirectional 4×20/20 Gbps TWDM-PON incorporating MZM/EAM modulation techniques

{1596.8, 1528}, {1597.6, 1528.8} and {1598.4, 1529.2}) in nm having 0.8 nm of channel spacing used for downstream (Tx$_{DN}$) and upstream (Tx$_{UP}$) transmission in the system.

Figure 2 presents the architecture of TWDM-PON (1:8 splitting ratio) incorporating PDM-MZM/EAM modulation schemes which are analysed using OptiSystem v16.0 simulation software. Four independent downstream TWDM channels (based on ITU grid) having a range of 1596–1598.4 nm with channel spacing of 0.8 nm are transmitted by using four continuous wave (CW) lasers. Each CW laser with input power (P$_{in}$) of 10 dBm generates the two downstream MZM/EAM modulated polarized channels at 0° and 90° hence offers double transmission capacity [22–24]. Likewise, four polarised channels are generated by four different upstream TWDM channels (each P$_{in}$ = 10 dBm) in the range 1527.2–1529.6 nm (channel spacing = 0.8 nm).

As shown in Fig. 2a, full-duplex TWDM-PON architecture consists of four downstream and four upstream transmitters together with receivers to serve 64 ONUs. In each transmitter, a forked CW laser output is driven by two separate pseudo-random bit sequence (PRBS) generators to generate aggregate 20 Gbps information using the corresponding non-return to zero (NRZ) line coding schemes and two MZM (30 dB extinction ratio) or EAM modulators [25–27]. A MZ modulator's behaviour can be described as

$$E_{out}(t) = E_{in}(t) \cdot \cos\left(\Delta\theta(t)\right) \cdot \exp(j - \Delta\varphi(t)) \tag{1}$$

where $\Delta\theta$ means phase difference two branches of MZM which is described as

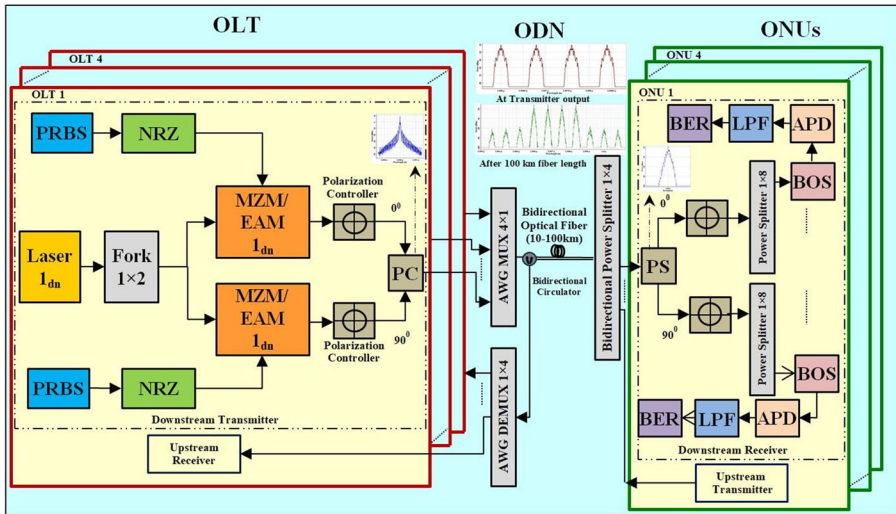$$\Delta\theta(t) = \frac{\pi}{2}.(0.5 - ER \cdot (Modulation(t) - 0.5)) \tag{2}$$

where *Modulation(t)* presents the electrical input signal and the parameter *ER* is given as

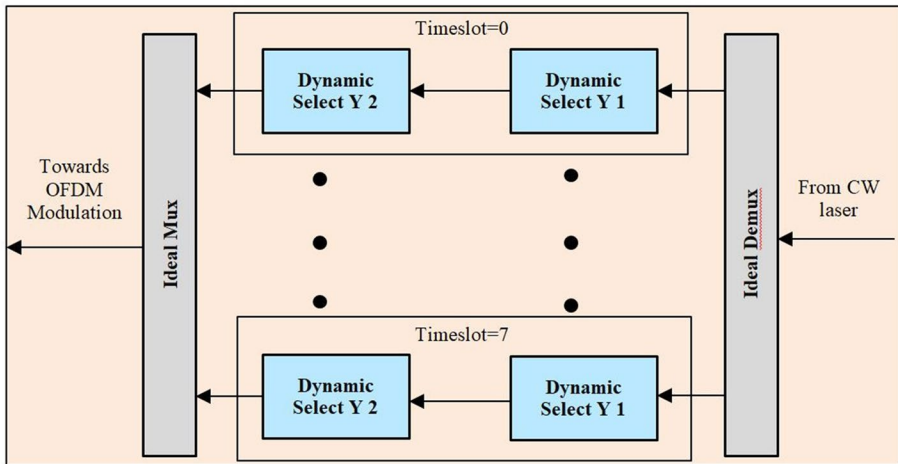$$ER = 1 - \frac{4}{\pi} \cdot \arctan\left(\frac{1}{\sqrt{extrat}}\right) \tag{3}$$

where *extrat* presents the extinction ratio.

Also, the signal phase change, $\Delta\varphi(t)$ is given as

$$\Delta\varphi(t) = SC \cdot \Delta\theta(t).(1 + SF)/(1 + SF) \tag{4}$$

(a)

(b)

Fig. 2 Schematic of **a** bidirectional TWDM-PON incorporating PDM-MZM/EAM modulation techniques and **b** upstream time switch section

where signal chrip (*SC*) values are − 1 and + 1 means negative *SC* is true and negative *SC* is false, *SF* means symmetry factor. However, for an EA modulator, the output signal response to an applied voltage is given as

$$E(V) = \sqrt{I(V)} \cdot \exp \cdot \left(j\frac{1}{2} \int \alpha_m(V) dln(I(V)) \right) \tag{5}$$

where $I(V)$ means signal voltage-dependent intensity, α_m is the absorption parameter on the applied voltage, V.

After that two polarized channels are generated using two polarization controllers with azimuth equal to 0^0 and 90^0 and combined by a linear polarized polarization combiner (PC) for incoming modulated data. For downstream transmission, all four multiplexed channels using an array-waveguide grating (AWG) multiplexer, transmitted through a bidirectional fiber (having 0.2 dB/km attenuation and 0.5 ps/nm^2/k dispersion slope) for the long-reach communication. Further, the incoming data signals from fiber are distributed to different ONUs using a 1×4 bidirectional power splitter. Each ONU consists of a polarization splitter (PS) to split the signal power at 0^0 and 90^0 azimuths with two polarization controllers and fed into two 1×8 power splitters. For the reception, the polarized output is delivered to a Bessel optical filter (BOS) to pass the required signal followed by an avalanche photo-diode (APD) to convert the optical signal to electrical signal, a low pass filter (LPF) and a bit error rate (BER) analyzer. In the same way, the upstream 80 Gbps TWDM MZM/EAM modulated polarized channels transmitted from ONUs to OLT. Besides this as shown in Fig. 2b, each upstream wavelength utilizes dual cascaded dynamic Y selectors at Ts_1 and Ts_2 switching time having Timeslot (*TS*), Sequence Length (*SL*), and Time window (*TW*) values of 0–7, 128, and 1.28×10^{-08} s respectively, to transfer the data to *N* users are given as [28–30]

$$Ts_1 = TS\left(\frac{1}{\text{Bit rate}}\right)\left(\frac{SL}{N}\right) \tag{6}$$

and

$$Ts_2 = Ts_1 + \left(\frac{TW}{N}\right) \tag{7}$$

After passing the upstream data from the fiber, the received signals are detected by using BOS, APD, LPF and buffer selector to choose the received data related to a particular iteration. BER analyzer is used to analyze the performance of the system in the form of BER and eye diagrams. Figure 3 shows the simulation setup of the proposed system in Optisystem.
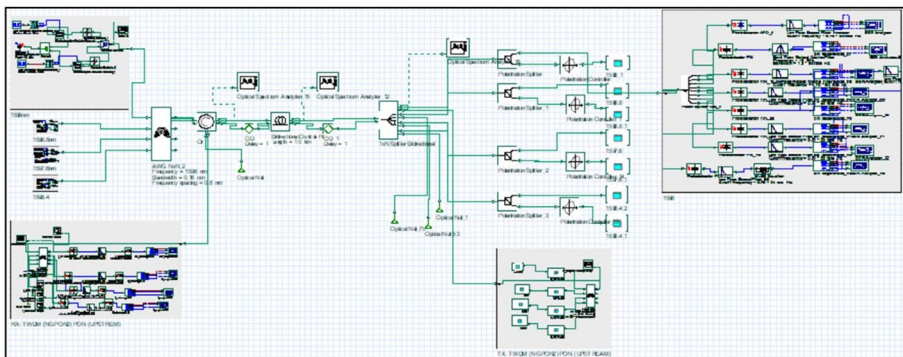

Fig. 3 Simulation setup for bidirectional TWDM-PON incorporating PDM-MZM/EAM modulation techniques

3 Results and Discussion

In this work, the proposed system is investigated in terms of variable fiber length (20–100 km) and received optical power (ROP) along with eye diagrams considering 1 A/W responsivity, 10 nA dark current, 1×10^{-22} W/Hz thermal noise, shot noise and fiber nonlinearities for two MZM and EAM modulators in downstream and upstream directions. Figure 4a, b present the optical spectra for PDM-PON signals in downstream and upstream directions respectively, which are obtained from an optical spectrum analyzer at 10 dBm input power for $4 \times 20/20$ Gbps TWDM-PON system.

Figure 5a, b present the performance of the system employing MZM and EAM modulators in term of BER of the four downstream (1596, 1596.8, 1597.6 and 1598.4 nm) and four upstream (1527.2, 1528, 1528.8 and 1529.6 nm) channels as per increasing fiber length. It can be noted that as the fiber length increases, the BER of the signal increases for both downstream and upstream channels and hence the system performance decreases. Also, upstream channels perform better than downstream channels. Besides this, EAM modulated signals show preferable performance as compared to MZM modulated signals as EAM offers reduced chirp and higher bandwidth than the MZM modulator. From Fig. 5a the results obtained demonstrate a faithful downstream transmission of 80 Gbps information over a transmission distance of approx. 55 and 65 km for MZM and EAM modulators respectively with a minimum acceptable BER of 10^{-9}. Similarly, as observed from Fig. 5b, the maximum achievable transmission ranges for upstream MZM and EAM modulated signals (at 1528.8 nm) are 85 and 100 km respectively.

Again from Fig. 5c, d, it is clear that with an increase in ROP the BER decreases and hence performance of the system increases over 40 km distance at 80/80 Gbps data rate. The results show the supreme performance of EAM modulated signals for both downstream and upstream transmission having maximum ROP of − 11 and − 52 dBm respectively. The comparative performance of downstream/upstream channels employing
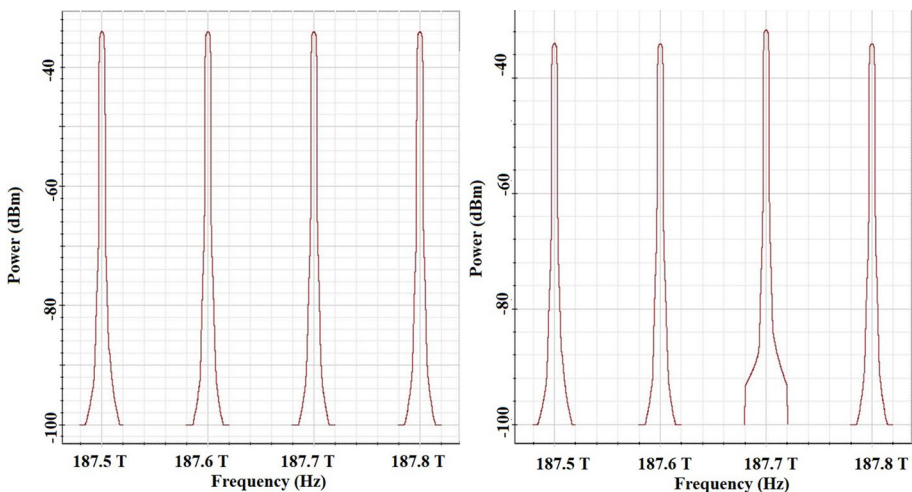

Fig. 4 The optical spectra of OFDM signals in **a** downstream and **b** upstream direction
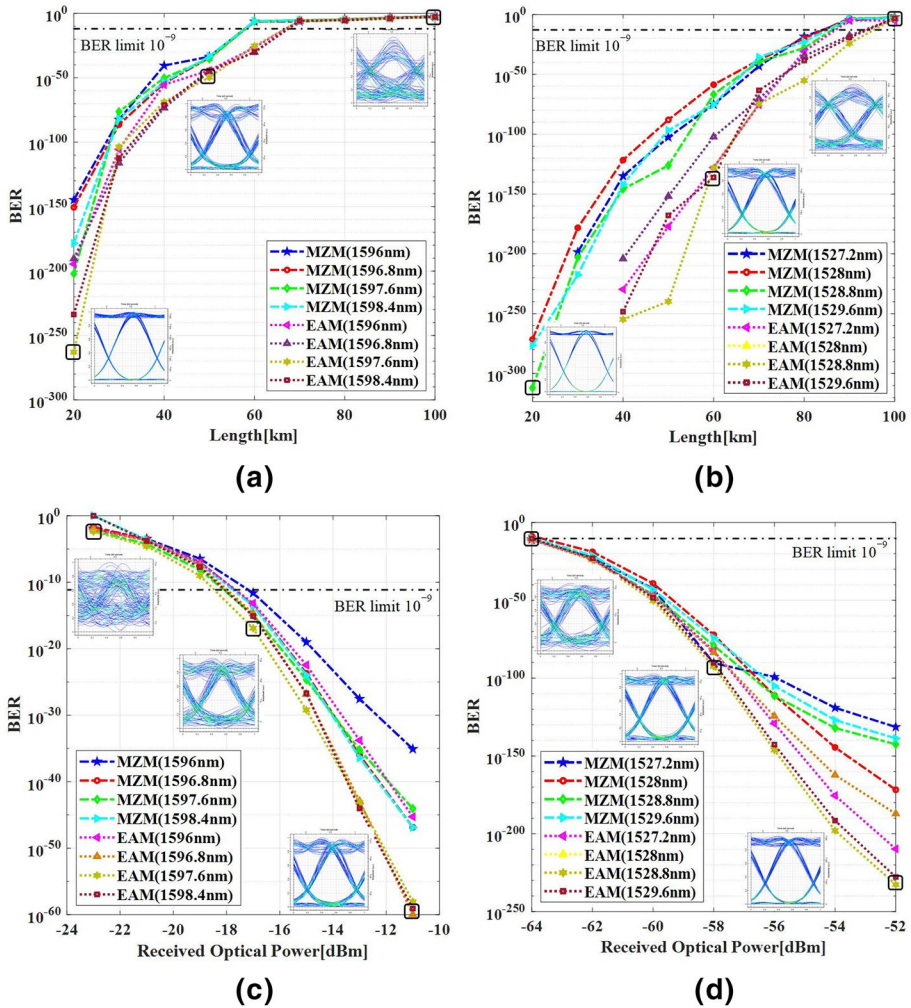
Fig. 5 BER vs length for **a** downstream channels, **b** upstream channels, BER vs ROP over 40 km distance for **c** downstream channels and **d** upstream channels employing MZM/EAM modulators. Insects: corresponding EAM modulation eye diagrams

MZM and EAM modulators for varying received optical power and varied fiber transmission distance are summarized in Tables 1, 2, 3 and 4.

The above-reported results in Tables 1, 2, 3 and 4 show that EAM shows better performance in terms of high Q-Factor with optimum received optical power values over standard 40 km fiber distance and also perform better over long-reach up to 100 km than MZM in the proposed system. Figure 5 also presents the eye diagrams of the proposed TWDM-PON system that shows the distortions in the eye diagrams (high eye closure) of the received signals increases with increasing link range and decrease in received optical power. Figure 6a–k show the optical spectra of the proposed system which consist of four downstream channels having 10 dBm input power and FWM wavelengths. The total number of FWM wavelengths for four channels are 24 as given in [31].

Table 1 Comparative performance of downstream channels employing MZM and EAM modulators for varying received optical power over 40 km transmission distance

Downstream channel (nm)	MZM				EAM			
	Q-factor				Q-factor			
	− 11 dBm	− 15 dBm	− 19 dBm	− 23 dBm	− 11 dBm	− 15 dBm	− 19 dBm	− 23 dBm
1596	12.43	9.01	4.95	2.23	14.18	9.84	5.22	2.31
1596.8	14.44	10.13	5.18	1.93	16.39	10.81	5.38	2.31
1597.6	13.98	10.34	5.65	2.52	16.11	11.30	6.00	2.62
1598.4	14.44	10.10	5.28	0	16.26	10.78	5.48	0

Table 2 Comparative performance of upstream channels employing MZM and EAM modulators for varying received optical power over 40 km transmission distance

Upstream channel (nm)	MZM				EAM			
	Q-factor				Q-factor			
	− 52 dBm	− 56 dBm	− 60 dBm	− 64 dBm	− 52 dBm	− 56 dBm	− 60 dBm	− 64 dBm
1527.2	24.42	21.19	13.73	6.61	30.93	24.22	14.44	6.75
1528	27.96	22.43	13.16	5.84	29.20	23.75	14.59	6.69
1528.8	25.45	22.46	14.36	6.63	32.58	25.78	14.96	6.70
1529.2	25.11	21.80	13.83	6.30	32.24	25.46	14.68	6.48

Table 3 Comparative performance of downstream channels employing MZM and EAM modulators for varying transmission distance

Downstream channel (nm)	MZM				EAM			
	Q-factor				Q-factor			
	10 km	40 km	70 km	100 km	10 km	40 km	70 km	100 km
1596	42.82	13.39	4.35	2.53	46.07	15.72	4.58	2.57
1596 0.8	42.15	15.56	4.51	2.99	42.34	18.16	4.73	3.05
1597.6	48.24	14.95	4.42	2.75	52.48	17.57	4.58	2.80
1598.4	49.76	15.46	4.44	3.03	52.88	17.89	4.61	3.07

Figure 6a shows the original signals at transmitter side having 10 dBm power and no FWM wavelengths. However, in Fig. 6b–k the spectrum for both EAM and MZM from 20 to 100 km reach containing original pulses and FWM wavelengths having Q-factor of 6. From this it is clear that EAM shows better performance than MZM over long-reach and high-speed TWDM-PON system. Further, Table 5 strengthens the above

Table 4 Comparative performance of upstream channels employing MZM and EAM modulators for varying transmission distance

Upstream channel (nm)	MZM				EAM			
	Q-factor				Q-factor			
	10 km	40 km	70 km	100 km	10 km	40 km	70 km	100 km
1527.2	48.22	24.76	13.84	4.28	52.47	32.37	18.42	4.39
1528	41.74	23.49	12.97	3.13	44.74	30.50	17.82	3.20
1528.8	41.95	25.75	13.23	3.20	45.93	34.11	18.33	3.27
1529.2	42.49	25.40	12.53	3.15	45.30	33.67	16.87	3.22

discussions. Table 1 depicts the comparative analysis of MZM and EAM modulated signal for downstream and upstream channels in terms of fiber distance, power budget (*PB*) and receiver sensitivity (*RS*) as follows [4]

$$PB = \text{Transmitted power} - RS \qquad (8)$$

Also, the comparative performance of the proposed work shows the notable enhancement than the recent work where the maximum attained high capacity is 20 [10], 20, [28] and 40 Gbps, [11] over 100, 130 and 80 km fiber distance respectively.

4 Conclusion

In this paper, NG-PON2 based symmetric and full-duplex 80 Gbps TWDM-PON incorporating PDM-MZM/ EAM modulation techniques have been proposed and analysed for long-reach and high-speed applications. The performance of the system is investigated for downstream and upstream polarized multiplexed modulated channels and it is concluded that upstream channels perform better than downstream channels. Also, the results reveal the better performance of PDM-EAM modulation signals as compared to PDM-MZM signals and provide a successful transmission range 10–100 km under 10^{-9} BER limit at 80 Gbps transmission rate. Moreover, a high received optical power of − 11 dBm, 70 dB power budget and − 60 dBm receiver sensitivity is obtained without using any amplifier under the impact of fiber impairments and noise. Thence, the TWDM-PON incorporating EAM-PDM modulation technique can improve the usage of fiber link in fixed and mobile broadband FTTx and high-speed wide area networks.
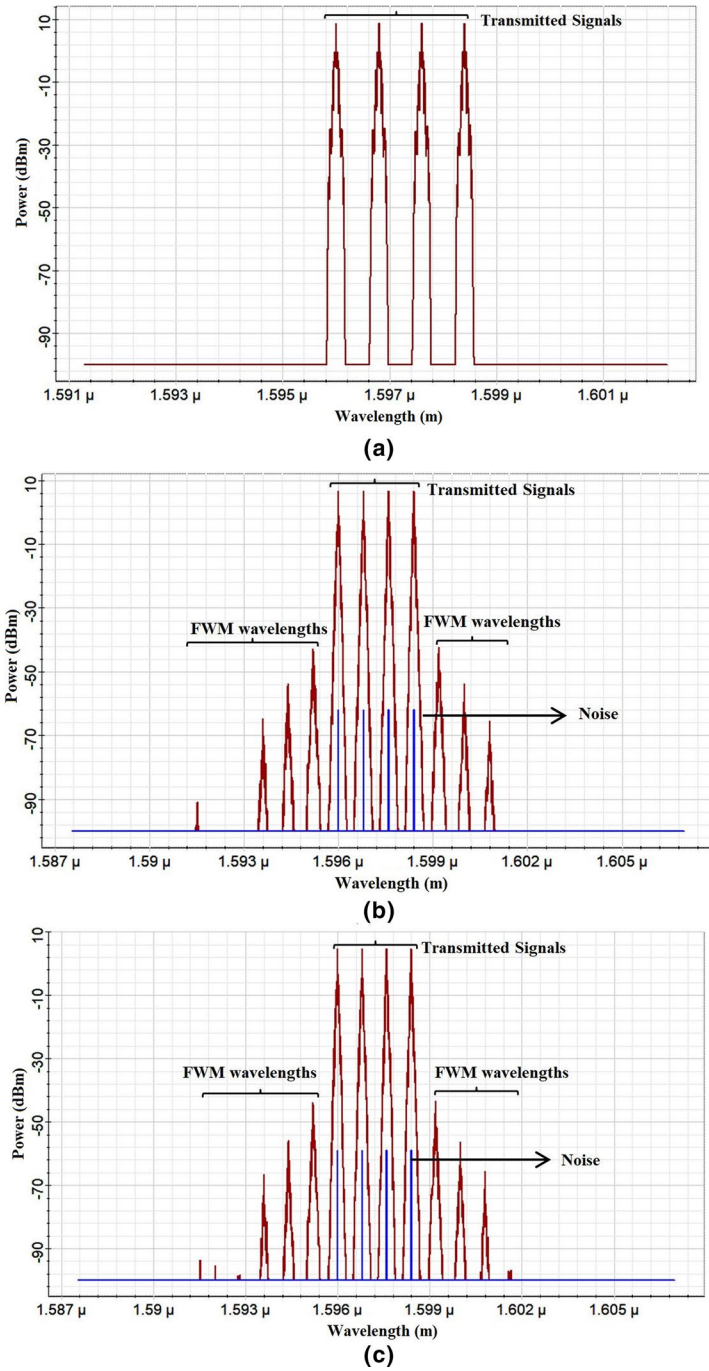
Fig. 6 Optical spectrum of **a** transmitted signal, after 20 km for **b** EAM, **c** MZM; after 40 km for **d** EAM, **e** MZM; after 60 km for **f** EAM, **g** MZM, after 80 km for **h** EAM, **i** MZM; after 100 km for **j** EAM and **k** MZM
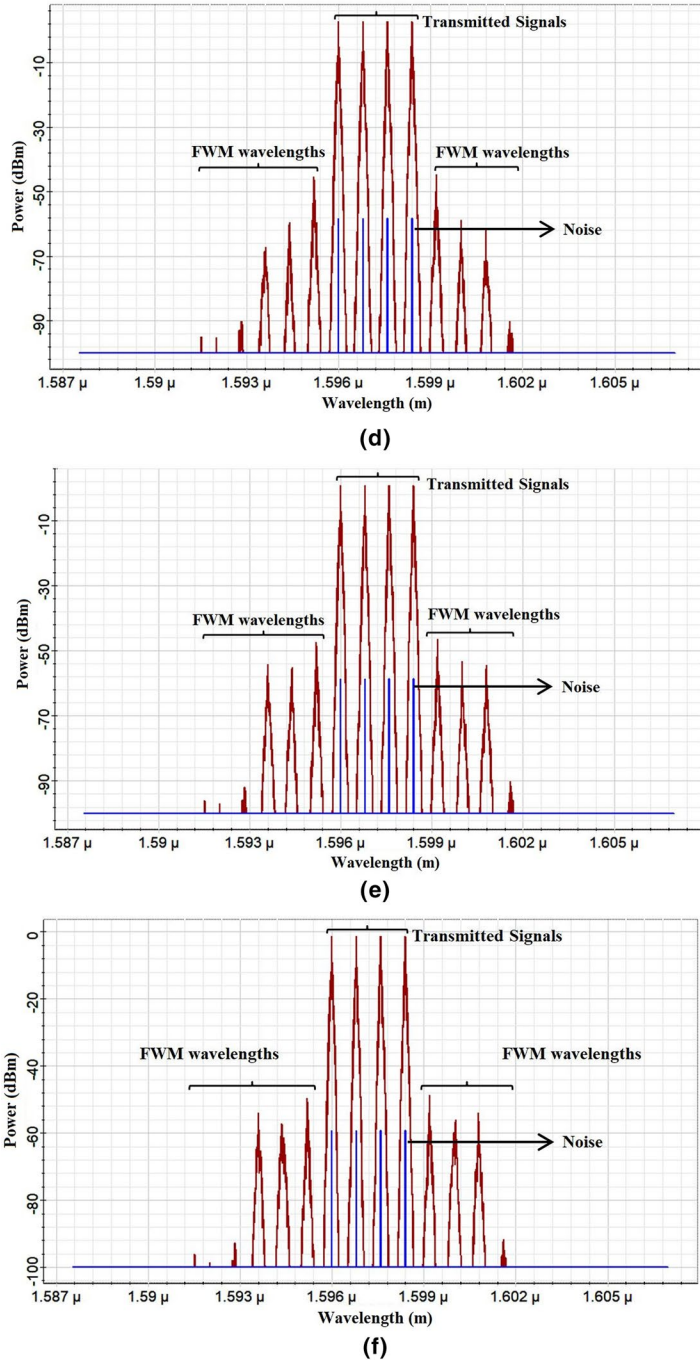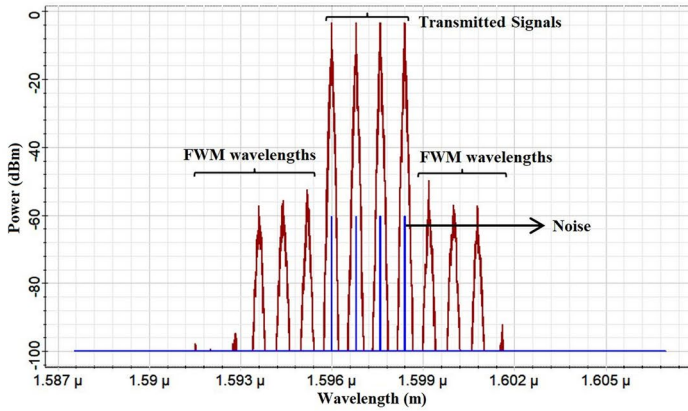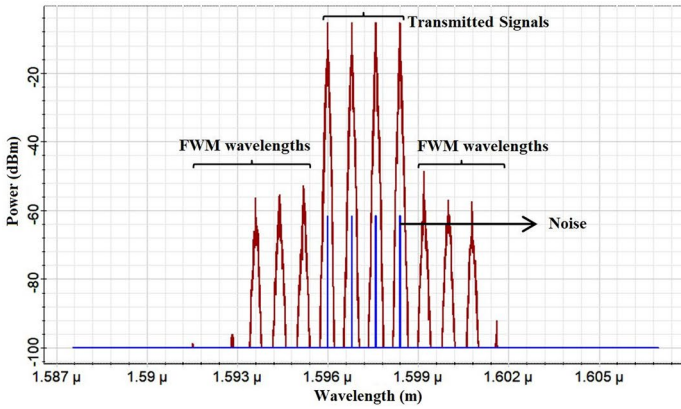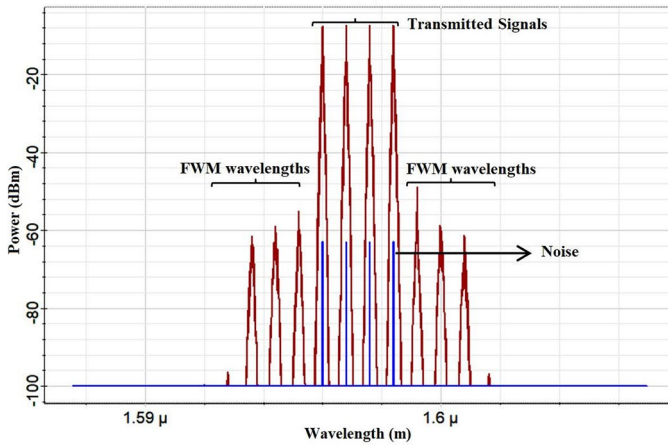
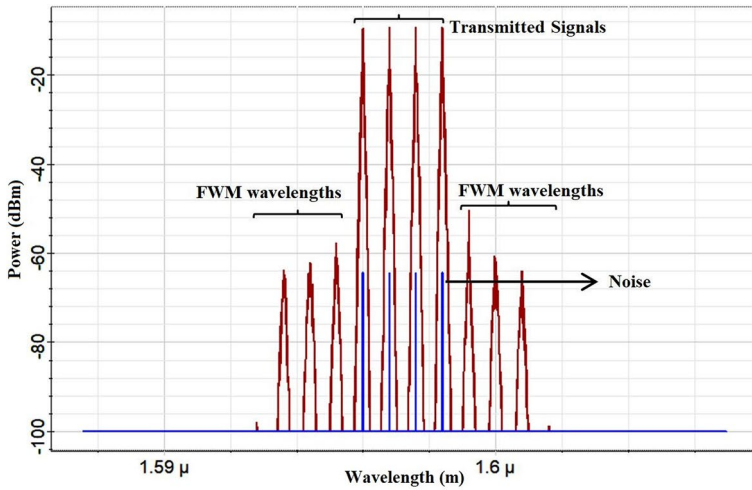**Fig. 6** (continued)

(g)

(h)
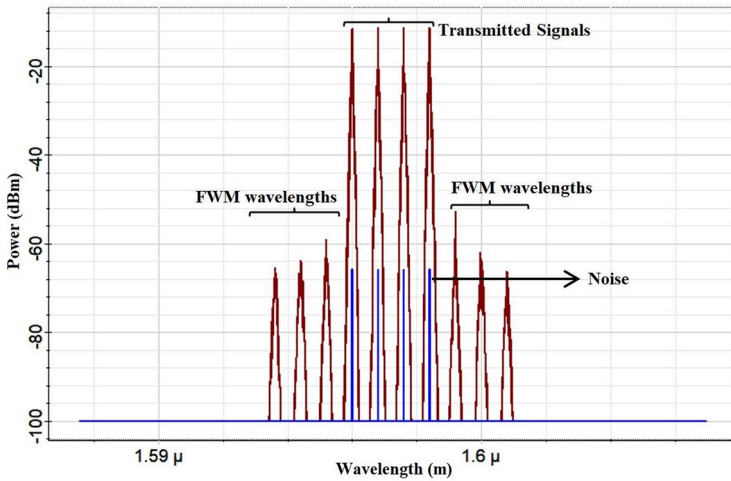

(i)

Fig. 6 (continued)

(j)

(k)

Fig. 6 (continued)

Table 5 Comparative analysis of MZM and EAM modulators for downstream and upstream channels

Channels	MZM		EAM	
	PB (dB)	RS (dBm)	PB (dB)	RS (dBm)
Downstream (1596–1598.4 nm)	22	− 12	25	− 15
Upstream (1527.2–1529.6 nm)	67	− 57	70	− 60

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