Analysis and mitigation of XPM crosstalk in the scenario of mixed line rates for next generation access networks

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In this paper, we analyzed Cross Phase Modulation (XPM) crosstalk in bidirectional Passive Optical Networks. The proposed network is designed for Mixed Line Rates (MLRs) i.e. 10/ 20/ 40 Gbps to meet the requirement of high volume of heterogenic traffic. Further, the investigation is focused on uniform channel spacing and mixed channel spacing for MLRs. Various multidimensional results are presented to highlight and evaluate the impact of XPM in term of carrier to noise ratio (CNR), input power, received output power and BER. It is depicted that mixed channel spacing for MLRs performs better than conventional uniform channel spacing. It is also investigated that the effect of XPM on the system performance can be minimized with an optimal launch power.

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1. Introduction

The volume of the demand of traffic in the next generation access networks brings up various design issues for supporting high data rate, large data bandwidth, enhanced security and scalability for the future applications [1, 2]. Hybrid Passive Optical Networks (PONs) with different multiplexing techniques like Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM) and Code Division Multiple Access (CDMA) etc. are shown as a prominent solution to provide a cost-effective and scalable network to prop up the rising heterogeneity of traffic demands by having Mixed Line Rates (MLRs) over number of channels for all the end subscribers [3-5]. Due to propagation of number of channels in the same fiber and the increase in the channel bit rate, nonlinear impairments dominate the performance.

Monika et al. [2] reported Four Wave Mixing (FWM) in optical communication system for different number of input channels (2, 4, 6, 8, 12) using various values of uniform channel spacing i.e. 6.25 GHz, 12.5 GHz, 25 GHz, 40 GHz, 50 GHz with input channels. Wei Ji et al. [6] introduced a WDM-RoF-PON based linearly polarized dual-wavelength fiber laser and CSRZ-DPSK modulation without making any major changes in its infrastructure. Naresh Kumar et al. [7] evaluated WDM network with different modulation frequencies, transmission lengths and optical powers for variety of fiber for XPM-induced crosstalk at Single Mode Fiber (SMF), dispersion compensation fiber (DCF), True Wave Fiber (TWF), True Wave-Reduced Slope Fiber (TW-RSF) and Large Effective Area Fiber (LEAF). Various results were shown that, in Cross Phase Modulation (XPM) as the dispersion and effective area of fiber decreases, crosstalk increases with increase in modulation frequencies, transmission distaces. R. Goyal et al. [8] analyzed the performance of a hybrid (WDM/TDM) PON system for triple play services (video, voice and data) up to a distance of 28 km to 128 ONUs.

As per the literature survey, various architectures of PON have been investigated [2, 6, 8]. But the necessity of heterogeneities in the data rate and channel spacing is not achieved yet. In this paper, we have extended our previous work [8] and proposed a network with multi data rates at different channel spacing which have better results than conventional uniform channel spacing networks. Through this model, we can provide a flexible network to the end users in terms of data rate, bandwidth, channel spacing etc. as per their demand.

This paper focuses on the analysis of nonlinear crosstalk caused by XPM in PONs for MLRs i.e. 10/ 20/ 40 Gbps. Further, the two schemes (i) uniform channel spacing, (ii) mixed channel spacing for MLRs are discussed for the proposed network. The paper is organized into four sections. In section 1, introduction to PON is reported. Theoretical analysis of crosstalk due to XPM is studied in section 2. The proposed system setup is described in section 3. In section 4, results have been discussed for different non linear effects with carrier to noise ratio (CNR), input power, received output power, BER, number of ONUs. Finally, in section 5, conclusion is made.

2. Theoretical analysis

To improve the system performance, it is important to analyze the nonlinear effects (like Kerr nonlinearities) in optical network. These effects rise to interference, losses, distortion and degradation of the output signals. In this paper, we have discussed the effect of XPM crosstalk on the network. The XPM is the result of phase inflection of the optical field originated by another optical signal propagating within the same fiber and can be analyzed using Non Linear Schrodinger Equation (NLSE). Considering an optical signal A (t, z) propagating in the fiber [9, 10]:

$$\frac{\partial A(t,z)}{\partial z} + \frac{\alpha_1}{2} A_1(t,z) + \frac{i}{2}\beta_{21}\frac{\partial^2 A_1(t,z)}{\partial T^2} - \frac{1}{6}\frac{i\beta_{31}\,\partial^3 A_1(t,z)}{\partial T^3} = i\gamma[9|A_1|^2|A_2|^2|A_3|^2]A_1(t,z) + \Psi_\omega \tag{1}$$

Where β_{in} is dispersion parameter, α_n is the optical attenuation in the nth channel and (γ) is the channel's non linearity coefficient and γ can be represented as

$$\gamma = \frac{2\pi n_2}{\lambda_2 A_{eff}} \tag{2}$$

Where A_{eff} is the effective area, λ is the optical signal wavelength and n_2 is non linear refractive index. The effect of inter channel crosstalk; we can express the equation (1) as [7]:

$$\frac{\partial A(t,z)}{\partial z} = -\frac{\alpha_1}{2} A_1(t,z) - \frac{i}{2}\beta_{21}\frac{\partial^2 A_1(t,z)}{\partial T^2} + \frac{1}{6}\frac{i\beta_{31}\partial^3 A_1(t,z)}{\partial T^3} + i\gamma[9|A_1|^2|A_2|^2|A_3|^2]A_1(t,z) + \Psi_\omega \tag{3}$$

For representing the above equation in frequency domain, we can written it as:

$$\frac{\partial A(\omega,z)}{\partial z} = \left(\frac{\alpha_1}{2} + \frac{i}{2}\right) - \frac{i\omega^3\beta_{31}}{6} + \frac{in_2\omega_o}{cA_{eff}}[9P(\omega,0)e^{-\alpha L}]A_1(\omega,z) \tag{4}$$

Where A(ω,z) represents the Fourier Transform of A(t,z) and P(ω,o) represents the power spectrum of the pump signal. The first term of RHS of the equation represents the attenuation in the fiber and linear phase delay. The second accounts for phase modulation by the pump signal. The third term represents the phase noise to intensity noise conversion at the end of the fiber z = L. The XPM in the terms of crosstalk power can be expressed as

$$P(\omega,L) = 4\,\gamma\,P_j(0)e^{-\alpha Lz}\left[\int_0^L 9P(\omega,0).\,e^{-\alpha L}\,x\,\left\{\frac{\sin(\beta\omega^2/2)}{\alpha+j\beta\Delta\lambda\omega}\right\}\right] \tag{5}$$

Where wavelength spacing ($\Delta\lambda$) can be expressed as

$$\Delta\lambda = \Delta\omega\lambda^2/c \tag{6}$$

The final solution of the equation (5) can be expressed as:

$$|\,P(\omega,L)\,| = 8\pi\gamma P_j(o)P_k(\omega)\,e^{-\alpha L}\left\{\frac{\sin(\beta\omega^2/2)}{\beta\Delta\lambda\omega}\right\} \tag{7}$$

The calculated results are shown in Table 1 and 2 in the result and discussion section with simulative results.

3. System setup

The schematic of the proposed network is shown in Fig. 1. In this system, three CW laser sources (tuned at 1310 nm, 1490 nm and 1550 nm wavelength) modulation with different Pseudo Random Data Sequence (PRBS) sequence with the speed of 10, 20 and 40 Gbps are employed at the Optical Line Terminal (OLT) end, respectively. Non Return to Zero (NRZ) format is used as line coding which is further modulated by Mach-Zehnder Modulator (MZM) with 30 dB extinction ratio. The signals are combined through WDM multiplexer and transmit to the fiber link (with 0.2 dB/km attenuation and 16.75 ps/nm/km dispersion). PIN photodiode (1A/W responsivity, zero ampere dark current, and thermal noise of $10^{-11}\ A/\sqrt{Hz}$) with Bessel filter are used to detect the upstream data through demultiplexer. Different passive splitters and combiners (with coupling factor of 0.50) are used for transmitting the considered wavelengths to used number of ONUs.

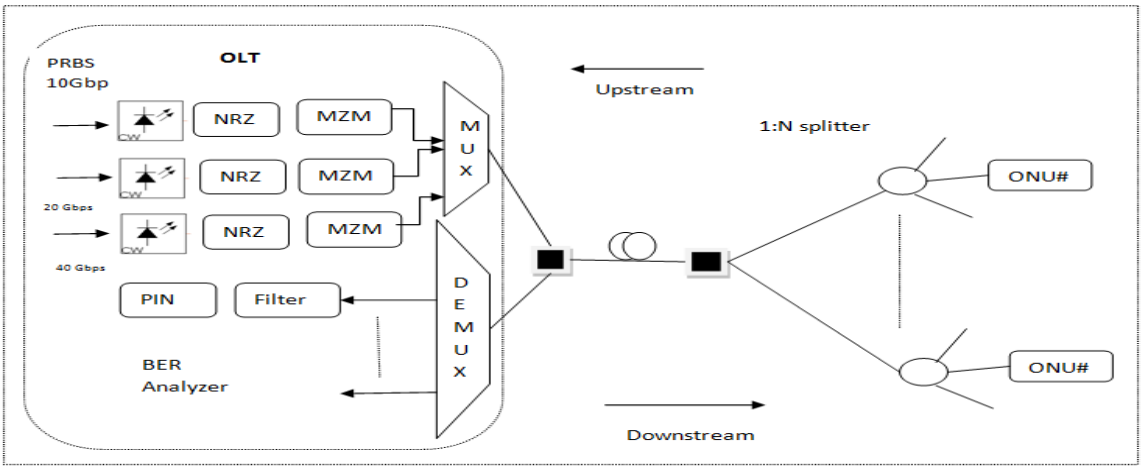

Fig. 1. Schematic of proposed bidirectional-PON system

For upstream transmission, PRBS at 2.5 Gbps data rate with NRZ coder and CW laser source (890 nm wavelength) is used and the signal is recovered with PIN photodiode at the ONU end. The setup is simulated in VPI 8.6 software and results have been discussed in the next section.

4. Result and discussion

The system is investigated for nonlinear crosstalk caused by XPM with MLRs i.e. 10/ 20/ 40 Gbps for uniform channel spacing (at 50 GHz) and mixed channel spacing (at 20, 50 & 100 GHz w. r. t. 10, 20 & 40 Gbps respectively). CNR Vs Input Power for Mixed Line Rates at uniform spacing (in 2D and 3D) is shown in Fig. 2.

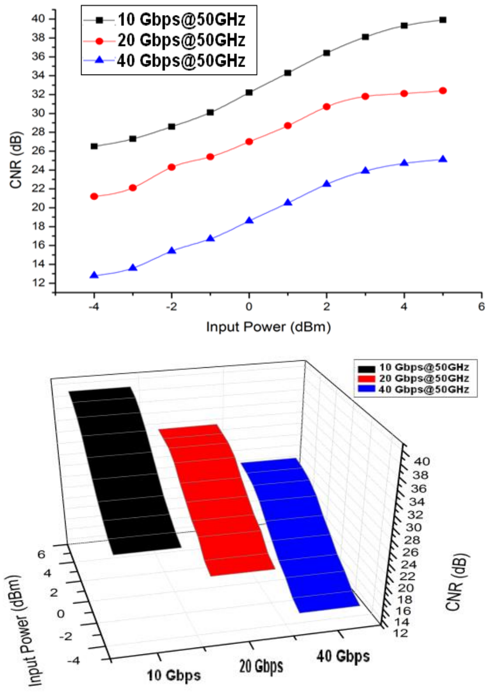

Fig. 2. CNR Vs Input Power for Mixed Line Rates at uniform spacing in 2D and 3D

The system is simulated at 50 GHz channel spacing for all line rates. The CNR of 26.5 to 39.9 dB, 21.2 to 32.4 dB and 12.8 to 25.1 dB is observed with 10, 20 and 40 Gbps of speed respectively. CNR Vs Input Power for Mixed Line Rates at mixed spacing, as also shown in Fig. 3.

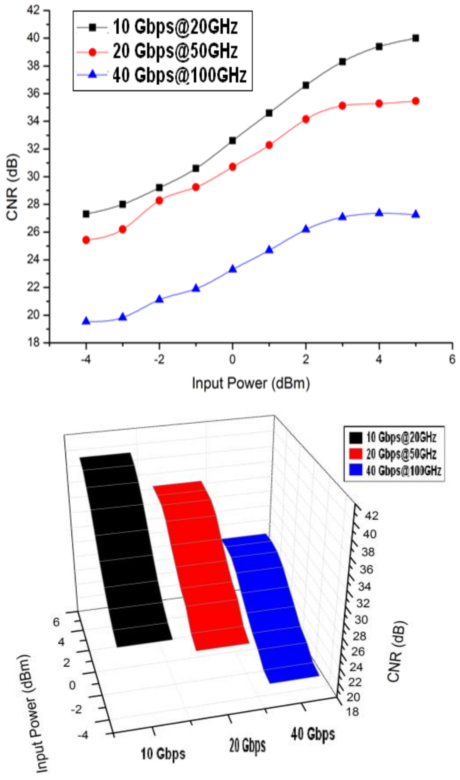

Fig. 3. CNR Vs Input Power for Mixed Line Rates at mixed spacing in 2D and 3D

Further, the setup is simulated at 20 GHz, 50 GHz and 100 GHz channel spacing for 10 Gbps, 20 Gbps and 40 Gbps line rates respectively. The CNR of 27.3 to 40 dB, 25.43 to 35.46 dB and 19.54 to 27.25 dB with 10, 20 and 40 Gbps is observed due to induced XPM respectively. It is evident that the system performance is improved by using mixed channel spacing instead of uniform channel spacing. The calculated CNR for different line rates with uniform and mixed spacing with respect to input power is given in Table 1.

Table 1. CNR for Mixed line rates with uniform and mixed spacing Vs Input Power

Input Power (dBm)	CNR at Uniform Channel Spacing (dB)			CNR at Mixed Channel Spacing (dB)		
	10 Gbps @ 50 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 50 Ghz	10 Gbps @ 20 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 100 Ghz
-4	26.5	21.2	12.8	27.3	25.43	19.54
-3	27.3	22.1	13.6	28	26.2	19.83
-2	28.6	24.3	15.4	29.2	28.27	21.12
-1	30.1	25.4	16.7	30.6	29.24	21.91
0	32.2	27	18.6	32.6	30.71	23.3
1	34.3	28.7	20.5	34.6	32.28	24.69
2	36.4	30.7	22.5	36.6	34.15	26.18
3	38.1	31.8	23.9	38.3	35.12	27.07
4	39.3	32.1	24.7	39.4	35.29	27.36
5	39.9	32.4	25.1	40	35.46	27.25

Received Output Power Vs Input Power for Mixed Line Rates at uniform spacing (in 2D and 3D) is shown in Fig. 4.

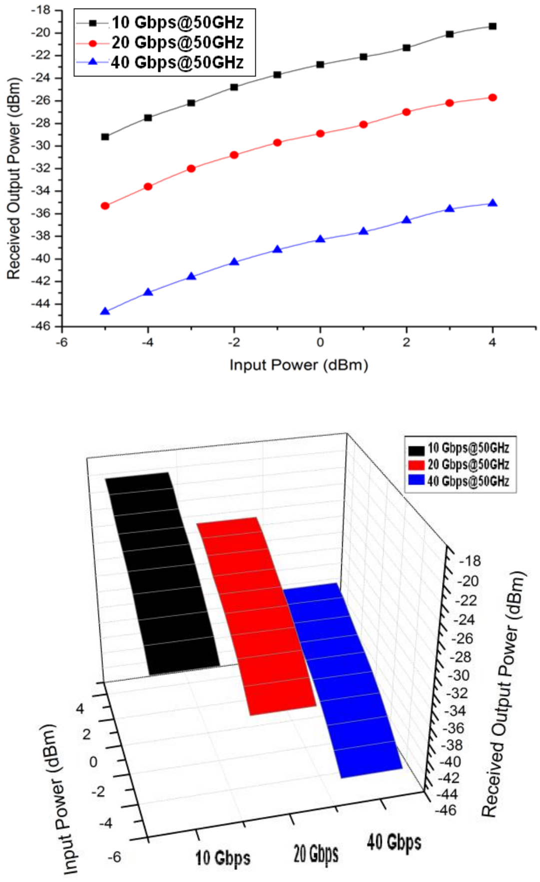

Fig. 4. Received Output Power Vs Input Power for Mixed Line Rates at uniform spacing in 2D and 3D

It is observed that the received output power increases due to increase in the input power. The Output power varies from (-29.1 to -18.6) dBm with 10 Gbps, from (-32.2 to -21.4) dBm with 20 Gbps and (-42.5 to -28.3) dBm with 40 Gbps at uniform channel spacing i.e. at 50 GHz. It is also observed that received output power is degrade with the increase in line rates. Received Output Power Vs Input Power for Mixed Line Rates at mixed channel spacing (in 2D and 3D) is shown in Fig. 5.

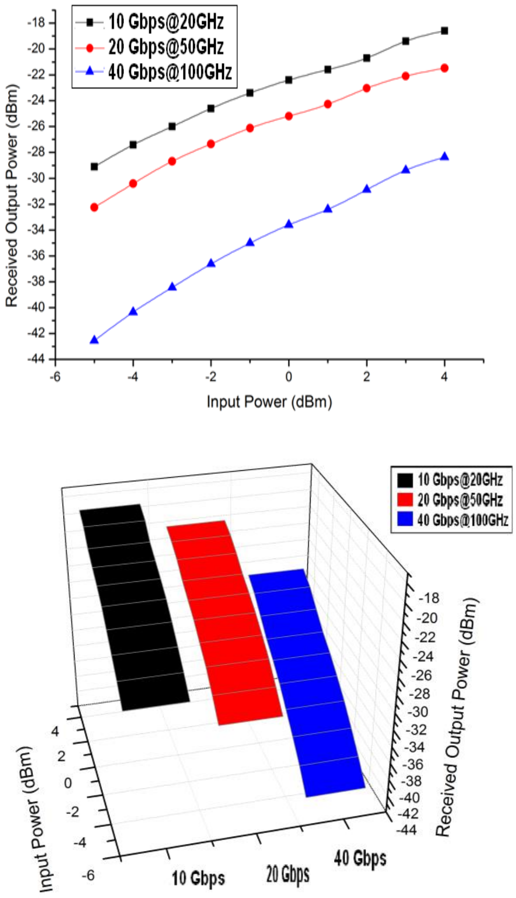

Fig. 5. Received Output Power Vs Input Power for Mixed Line Rates at mixed channel spacing in 2D and 3D

The Output power varies from (-29.2 to -19.4) dBm with 10 Gbps, from (-35.3 to -25.7) dBm with 20 Gbps and (-44.7 to -35.1) dBm with 40 Gbps at 20 GHz, 50 GHz and 100 GHz channel spacing due to induced XPM respectively. The calculated output power for different line rates with uniform and mixed spacing with respect to input power is given in Table 2.

Table 2. O/P Power for Mixed line rates with uniform and mixed spacing Vs Input Power

Input Power (dBm)	O/P Power at Uniform Channel Spacing (dBm)			O/P Power at Mixed Channel Spacing (dBm)		
	10 Gbps @ 50 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 50 Ghz	10 Gbps @ 20 Ghz	20 Gbps @ 50 Ghz	40 Gbps @ 100 Ghz
-5	-29.2	-35.3	-44.7	-29.1	-32.24	-42.55
-4	-27.5	-33.6	-43	-27.4	-30.41	-40.34
-3	-26.2	-32	-41.6	-26	-28.68	-38.43
-2	-24.8	-30.8	-40.3	-24.6	-27.35	-36.62
-1	-23.7	-29.7	-39.2	-23.4	-26.12	-35.01
0	-22.8	-28.9	-38.3	-22.4	-25.19	-33.6
1	-22.1	-28.1	-37.6	-21.6	-24.26	-32.39
2	-21.3	-27	-36.6	-20.7	-23.03	-30.88
3	-20.1	-26.2	-35.6	-19.4	-22.1	-29.37
4	-19.4	-25.7	-35.1	-18.6	-21.47	-28.36

It is evident that the received output power increases at mixed channel spacing instead of uniform channel spacing. It is also observed that received output power is increasing with the increase in input power. BER Vs Input Power for Mixed Line Rates at uniform spacing is shown in Fig. 6.

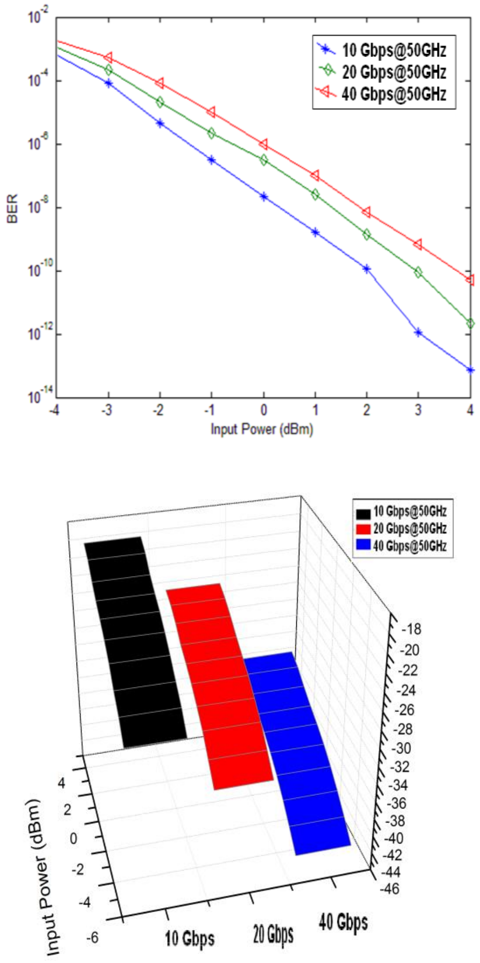

Fig. 6. BER Vs Input Power for Mixed Line Rates at uniform spacing in 2D and 3D

The BER is observed for the system by simulating at 50 GHz channel spacing for all line rates. BER of (7.4×10^{-14} to 6.1×10^{-4}) with 10 Gbps, from (2.1×10^{-12}) to 1.1×10^{-3}) with 20 Gbps and from (4.9×10^{-11} to 1.8×10^{-3}) with 40 Gbps is achieved due to induced XPM respectively. It is also shown that BER decreases with the increase in input power. BER Vs Input Power for Mixed Line Rates at mixed channel spacing is shown in Fig. 7.

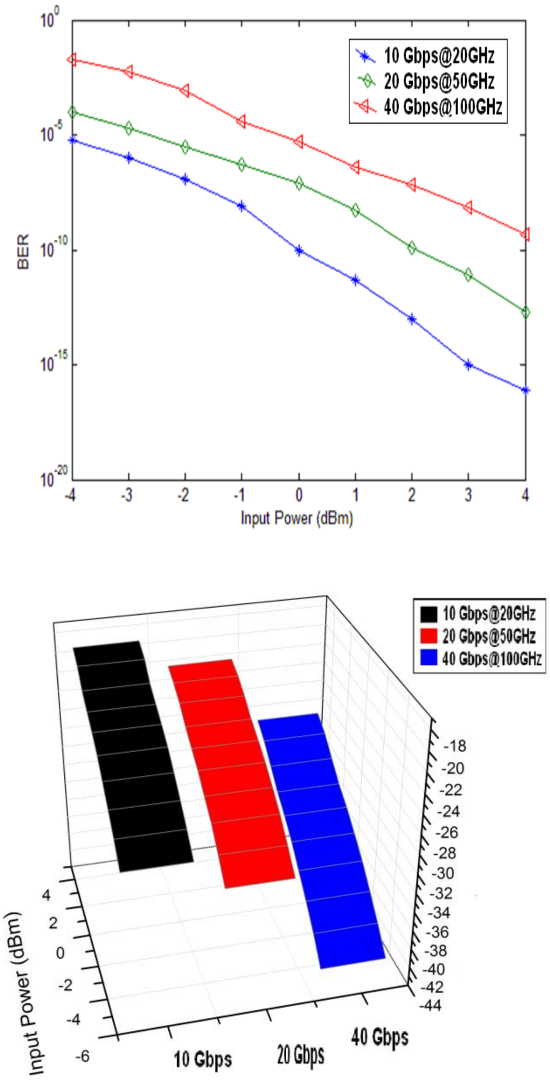

Fig. 7. BER Vs Input Power for Mixed Line Rates at mixed channel spacing in 2D and 3D

The BER is observed for the system by simulating at 20 GHz, 50 GHz and 100 GHz channel spacing for 10 Gbps, 20 Gbps and 40 Gbps line rates respectively. BER of (7.3×10^{-17} to 6×10^{-6}) with 10 Gbps, from (2×10^{-13} to 1×10^{-4}) with 20 Gbps and from (5×10^{-10} to 2×10^{-2}) with 40 Gbps is achieved due to induced XPM respectively [11]. It is also shown that BER decreases with the increase in input power. It is evident that the system gives better performance in terms of BER at mixed channel spacing instead of uniform channel spacing.

5. Conclusions

In this paper, we have investigated bidirectional passive optical network for non linear effect induced by XPM at 20 GHz, 50 GHz and 100 GHz channel spacing for 10 Gbps, 20 Gbps and 40 Gbps line rates respectively. Further, the approach of different data rates to different users is implemented to reach the high bandwidth requirement of next generation networks. Two schemes viz. uniform channel spacing (50 GHz channel spacing to all data rates and users) and mixed channel spacing (20 GHz for 10 Gbps, 50 GHz for 20 Gbps and 100 GHz for 40 Gbps) are discussed and analyzed. Various results of CNR, input power, received output power and BER in 2D and 3D are shown with the impact of XPM. It is found that mixed channel spacing scheme shown better results than conventional uniform channel spacing.

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