Analysis of cross phase modulation in fiber Raman amplifiers for broadband optical communications system

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In this paper, we have investigated cross phase modulation (XPM) effect by copropagating two channels having wavelength of 1550.1 nm and 1550.4 nm with backward pumped fiber Raman amplifier (FRA). The cross phase modulation (XPM) effect has been analyzed by changing various parameters of FRA. It is proposed that XPM increases with increase in input signal as well as pump signal power. XPM is also analyzed for different values of Raman fiber lengths and bit rates and we have achieved that the optimum value of bit rate for which the XPM is minimum for this channel spacing at 10 Gbps.

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1. Introduction

A technique of simultaneous transmission of multiple signals having properly spaced peak emission wavelength originated from different light source through a single optical fiber link is known as wavelength division multiplexing (WDM) technique [1-3]. So, the utilization of different channels over the single fiber gives exceptionally high data rate transmission capacity. Huge increment in available bandwidth without increase in the fiber length is one of the main advantage of this technique [4-6]. Because of their broadband, FRA's are utilized for the amplification of multiple channels simultaneously. The simultaneous transmission of multiple information bearing light signals over the multiple channels of single mode fiber (SMF) results the nonlinear interaction between multiple channels which limits the performance of dense wavelength division multiplexing (DWDM) systems. The nonlinear variation in the refractive index depending upon the intensity of light signals is one of the major parameter which describes the nonlinear interaction between multiple optical channels. This nonlinear interaction results the number of variations in the parameters of signals like self-phase modulation (SPM), cross phase modulation (XPM) [7]. In DWDM systems, adjacent channels may be spaced by tens of nanometer. At such channel spacing, the XPM coefficient may significantly change because of Raman contribution in the nonlinear coefficient [8]. The extent of frequency deviation depends on the wavelength spacing of two adjacent channels, fiber material and the state of polarization of signals. So there is a need of optimizing the fiber Raman amplifier (FRA) in terms of XPM by considering different parameters of FRA.

Number of researchers had provided the various number of solution for XPM in WDM system by the use of FRAs. Souza *et al.* [9] combines the effect of XPM and SRS in mono-mode optical fiber for the simultaneous compression and amplification of low intensity signal pulses. Chan *et al.* [10] proposed a technique to generate ultra-short solitons by the use of XPM and SRS in fiber by co-propagation of CW light with the train of intense pump pulses inside optical fiber. Martinez-Rios *et al.* [11] considers the different symmetry rules that governs the Raman and Kerr nonlinearity and derive the equation for coupled-amplitude which describes the XPM and SPM in non-polarization preserving fiber. Wang *et al.* [12] investigated the enhancement in Raman gain for regenerative all-optical XPM wavelength converter and shows that Raman gain increases the wavelength conversion efficiency by 21 dB at the bit-rate of 80 Gbps having 600 mW of Raman pump power with 1Km of optical fiber. Singh *et al.* [13] presented a theoretical model for crosstalk in WDM systems because of cross phase saturation in semiconductor optical amplifiers (SOAs). By the use of differential phase shift modulation format, this model is used to study the effect of cross phase noise the performance of SOA operating in saturation region for WDM system. They have studied the impact of penalty and cross phase noise imposed on multichannel WDM links for different parameters of

SOAs with the variation in transmission distance. Peleg *et al.* [14] demonstrated that the interplay between induced position shift due to XPM and Raman induced crosstalk are the major causes for error generation at intermediate distance. Till date, no researcher has discussed and analyzed the effect of XPM in Raman fiber amplifier.

In this paper, we analyzed the XPM in FRAs by the variation in different parameters of FRA. For estimating XPM, the light signals having wavelength 1550.4 nm and 1550.1 nm co-propagate through Raman fiber. The effect on XPM by the variation in bit rate is also studied and then obtain the optimum results.

2. XPM Analysis in optical amplifiers

The XPM can be analyzed by the following theoretical model [15]. All the materials including silica behave nonlinearly under the influence of high light intensity and the refractive index varies with intensity. The physical origin of refractive index variation laid in the harmonic behavior of electrons in the medium under the influence of optical field, results because of nonlinear susceptibility. When we include nonlinear refractive index, the indices of core cladding of optical fiber can be modified as

$$n_j' = n_j + \bar{n}_2 (P/A_{eff}), \quad j = 1, 2, \tag{1}$$

where, $\bar{n}_2$ is the nonlinear-index coefficient, P is the optical power, and A_{eff} is the effective mode area. The numerical value of $\bar{n}_2$ depends on the material used for core and for silica fibers it is approximately 2.6×10^{-20} m^2 /W.

If first-order perturbation theory is used to investigate the effect of nonlinear part of refractive index in equation (1) on the fiber modes, we observe that there is no effect on the shape of mode but propagation constant (β') become dependent on the power which is given as

$$\beta' = \beta + k_0 \bar{n}_2 P/A_{eff} \equiv \beta + \gamma P \tag{2}$$

where, $\gamma = 2\pi \bar{n}_2 P/(A_{eff}\lambda)$ is a nonlinear coefficient whose value lay between 1 to 5 W^{-1}/km and depends on effective area (A_{eff}) and the wavelength (λ). Also, the optical phase increases linearly with $\mathcal{Z}$. The variation in phase because of γ can be calculated as

$$\Phi_{NL} = \int_0^L (\beta' - \beta) d\mathcal{Z}\mathcal{z} = \int_0^L \gamma P(\mathcal{Z}) d\mathcal{Z}\mathcal{z} = \gamma P_{in} L_{eff} \tag{3}$$

where $P(\mathcal{Z}) = P_{in} exp(-\alpha \mathcal{Z}\mathcal{z})$ (4)

The fiber losses and effective fiber length L_{eff} is given as

$$L_{eff} = [1 - exp(-\alpha L)]/\alpha \ , \tag{5}$$

where, α represents the fiber losses. In equation (3), P_{in} depends on time which makes Φ_{NL} a time dependent parameter. As the nonlinear phase modulation of an optical signal is induced because of its own intensity variation so this phenomenon of phase variation is known as self-phase modulation (SPM), and Φ_{NL} should be very less than 1 to decrease the effect of SPM in optical system.

In equation (1) the dependency of refractive index on optical field intensity also give rises to the another nonlinearity known as cross phase modulation (XPM).It comes into the picture when multiple optical signals co-propagate though single fiber by the use of WDM technique. In these systems, the phase shift does not depend on the intensity of signal itself only but also on the intensity signals propagating simultaneously. The phase shift in the i^{th} channel can be calculated as

$$\Phi_i^{NL} = \gamma L_{eff} (P_i + 2 \textstyle\sum_{m \neq i} P_m) \tag{6}$$

The sum in the equation (6) extends over the co-propagating signals except the signal itself for whom the phase shift we are calculating. In equation (6), the factor 2 originate from the nonlinear susceptibility and shows that the effect of XPM on the phase of signal is two times effective as compared to the SPM for same amount of power. It can be concluded that the net phase shift depends on the total power of signals co-propagating through the fiber and vary from bit to bit as depending on the bit pattern of the signals. For the worst case, when all the signals carry optical logic high *i.e.* 1, the nonlinear phase shift can be calculated as

$$\Phi_j^{NL} = (\gamma/\alpha)(2M - 1)P_j \tag{7}$$

where, α is attenuation constant, M is the number propagating channel in optical fiber, P_j is the power of j^{th} channel. The phase shift induced because of XPM can occur only when WDM system when two or more pulses overlap each other in term of time. In general, pulses from two different channels will not remain superimposed because of different group velocity dispersion (GVD). Because of short overlap period of time in widely spread channels, the effect of XPM is virtually negligible.

3. System setup

The Raman induced XPM occurs in multichannel system needs to reduce for the optimization of FRA structure. Fig. 1 shows the block diagram for simulation setup.

A silica FRA pumped at the 1451.2 nm wavelength with 1000 mW pump power in counter propagating mode is designed. The pump attenuation is kept at 0.2 dB/km. A CW Lorentzian light source with varying input power provide the continuous optical carrier signal to the phase modulator. The phase modulator modulates the optical signal carrier signal according the data signal received from filtered RZ formatted data signal. The bandwidth for designed setup is from 190.95 THz to 195.94 THz. All the operations performed at the bit rate of 10 Gbps. The impact of XPM in FRAs is evaluated by co-propagating two optical signal through 10 Km of Raman fiber. All the Simulations are carried out by keeping channel 1 and channel 2 at the wavelength of 1550.1 nm and 1550.4 nm respectively. The line-width of both the signal is 5 MHz. The simulations are carried out for the input power level from -2.5 dBm to 2.5 dBm.

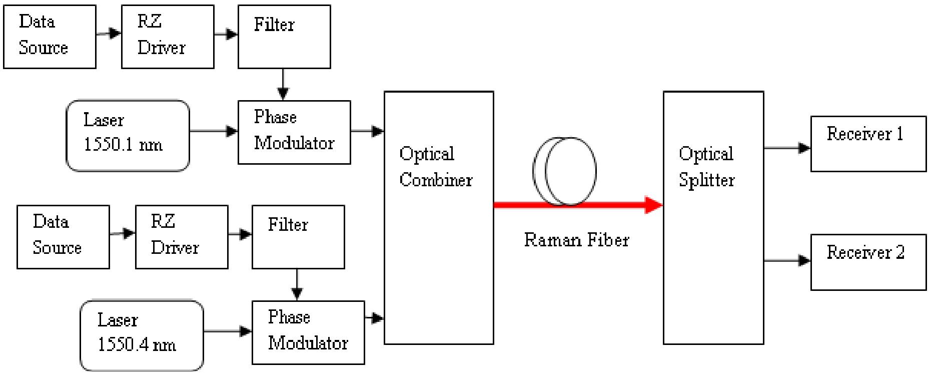


Fig. 1. Simulation setup for XPM

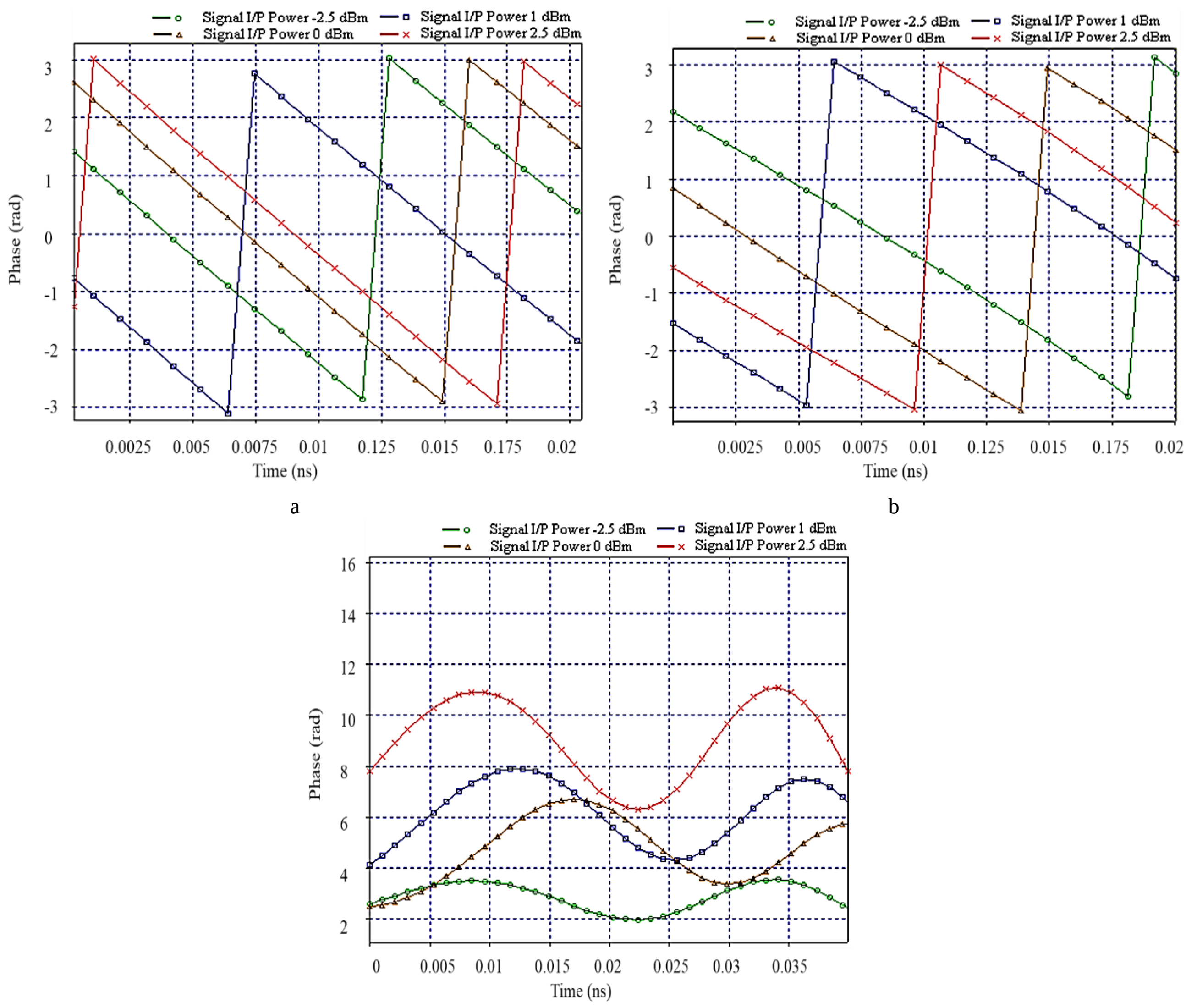


Fig. 2. (a) Plot of input phase versus time (b) plot of output phase versus time (c) plot of output power versus time for different signal input powers

Fig. 2 shows the variation in the phase of the channel with respect to time in presence of other channel. Here, the output phase plot can be compared with the input phase for different signal input power. It is observed that phase noise is minimum for 1 dBm input signal power, the phase noise is minimum. We observe the maximum phase noise if the input power is increased beyond this value to 2.5 dBm, and output is completely out of phase with the input. It is due to the fact that for signal input power of more than 1 dBm, saturation of power occurs by large amounts. The results show good agreement with the above analysis in equation (3).

Further, phase noise for signal input power of -2.5 dBm is also more. As can be seen from Fig. 2 (c), the power penalty is more for this low signal input power of -2.5 dBm. So the optimum input power to be applied here comes out to be 1 dBm.

4. XPM as a function of Raman fiber length

The phase shift occurring in the output signal is also a function of the length of Raman fiber. Simulation is carried out for the different values of the length of Raman fiber lie in between 10 km to 25 km for an optimum value of signal input power of 1 dBm obtained from the Section 3. The phase noise variation with time because of fiber length is shown in Fig. 3 (a) and 3 (b). The input phase for all values of length is same and the output phase obtained for different Raman fiber lengths is compared with this input phase. It is observed that the output shows a good phase relation with the input for 10 Km Raman fiber. The phase noise increases for higher values of Raman fiber length. The results show good agreement with the above analysis in equation (6).

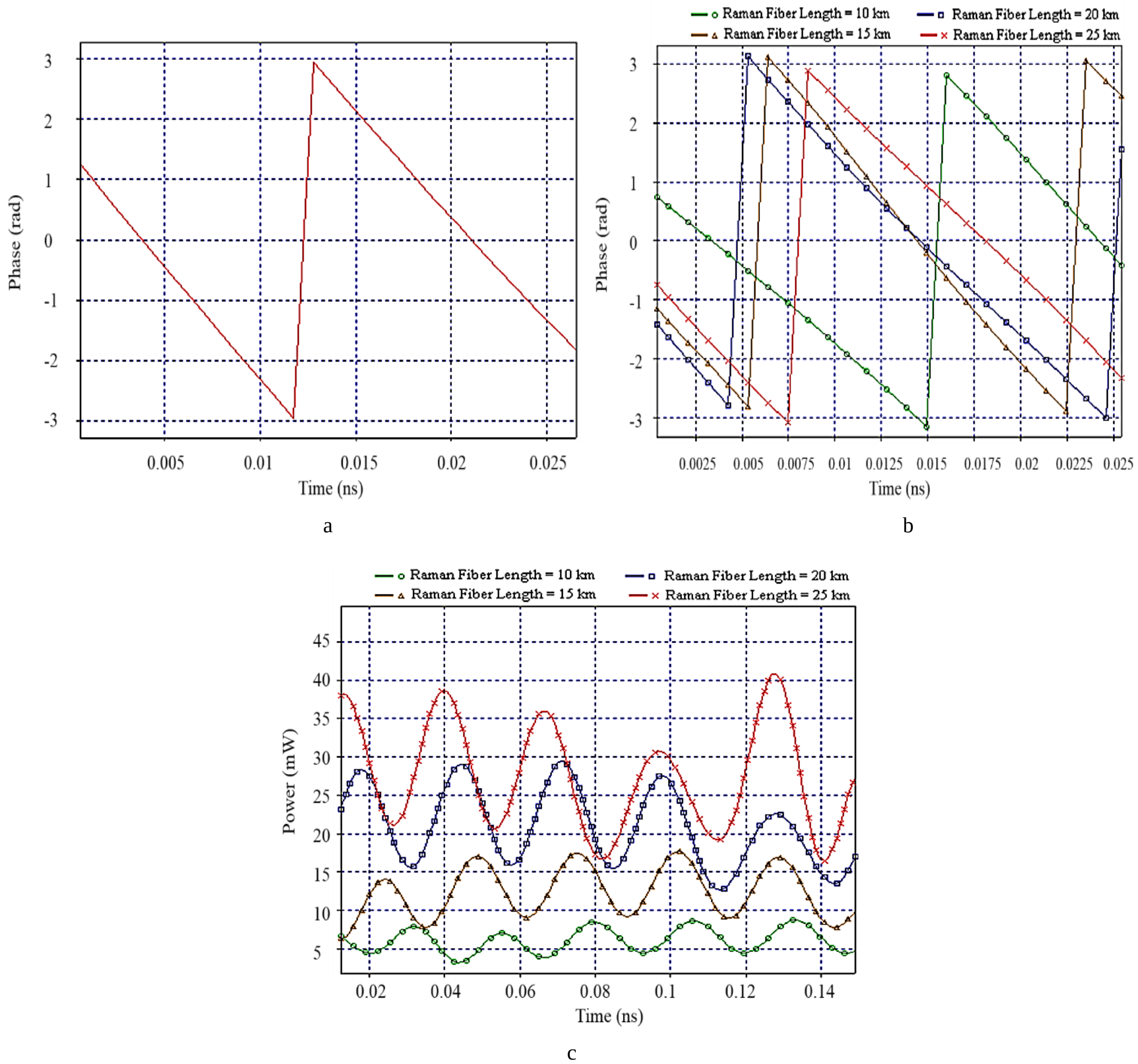
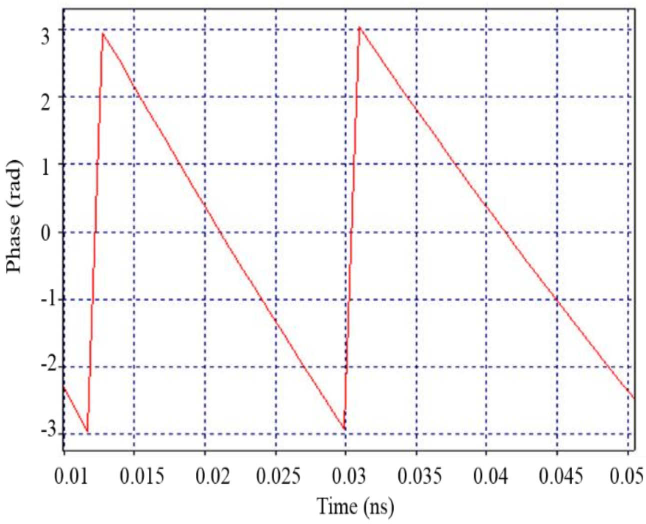


Fig. 3. (a) Plot of input phase versus time (b) plot of output phase versus time (c) plot of output power versus time for different values of Raman fiber length

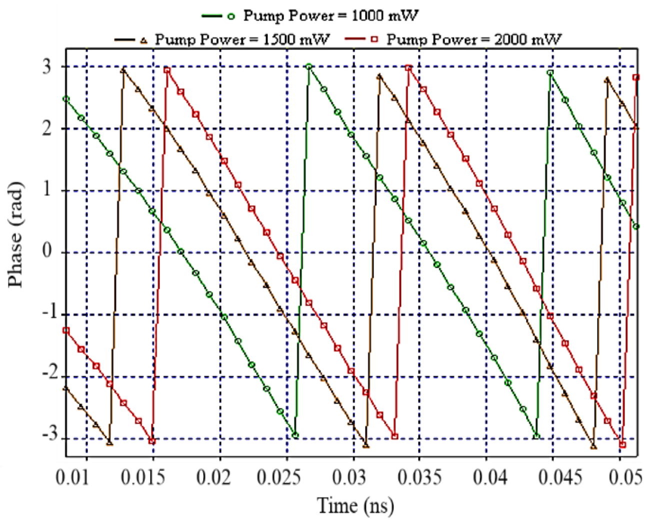
As can be seen from Fig. 3 c, the variation in output power increases with increase in the length Raman fiber but this increase in power is not uniform for all values of length of Raman fiber. For the value of 10 km, the power versus time curve is uniform, but power variation becomes random with increase in length. For the length of 25 km, the power fluctuations are very high showing high noise levels in the output. So, 10 Km is the optimum length of Raman fiber and above this length power fluctuation arises.

5. Effect of injected pump power on XPM

In fiber Raman amplifiers, the performance of the system greatly depends on the value of injected pump power in the fiber. Here, in this work, the pump power is varied from the values of 1000 mW to 2000 mW and their effect on XPM is analyzed. The phase noise variation vs time due to injected pump power is shown in Fig. 4 (a) (input phase) and 4 (b) (output phase). The input phase for all values of pump power is same and it is compared with the output phase obtained for different values of pump power ranging from 1000 mW to 2000 mW. It is observed that the output shows a good phase relation with the input for the injected pump power of 1500 mW. Above the value of 1500 mW, the phase noise increases. It is due to pump depletion noise which is high for higher values of pump power. It is observed from the Fig. 4 (c), that if we decrease the pump power to 1000 mW, we get huge power penalty. For high values of pump power (2000 mW), the variation in power vs time becomes random and power fluctuations are observed. It is due to high pump depletion noise levels in the output which increase with increase in injected pump power in the Raman fiber. So, the optimum value of injected pump power from this work comes out to be 1500 mW as above this value, power fluctuations ariseand below this value huge power penalty occurs.



a



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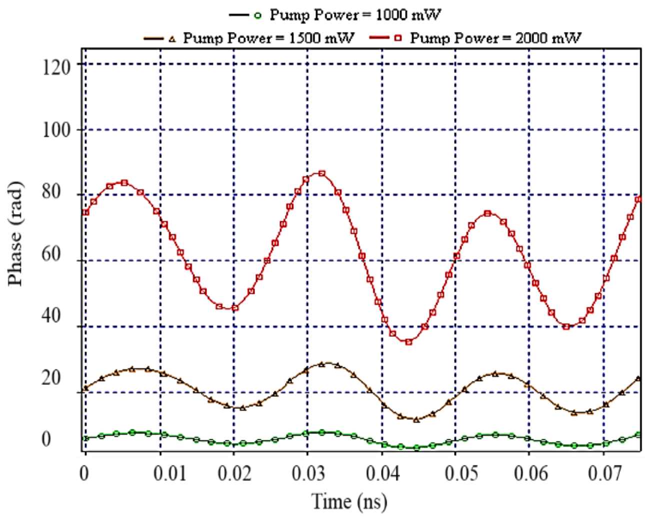
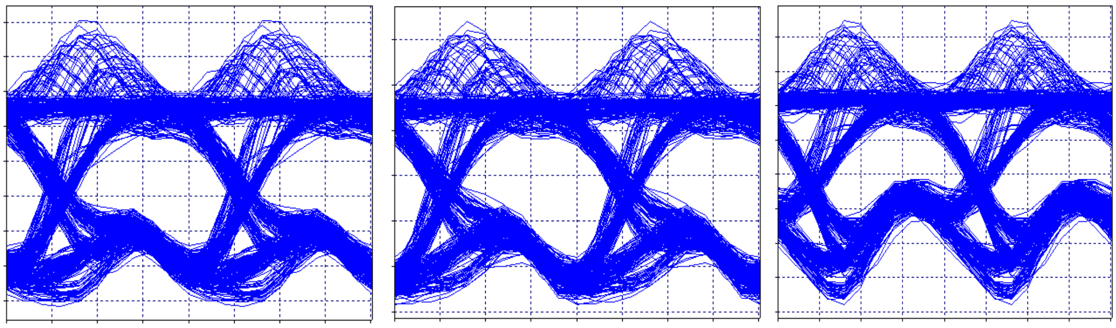


c

Fig. 4. (a) Plot of input phase versus time (b) plot of output phase versus time (c) plot of output power versus time for different values of injected pump power

Fig. 5 shows the eye diagrams for different pump powers. It is observed from the eye diagrams that for injected pump power of 1500 mW, the output signal has maximum quality factor of 19.61 dB. If pump power is increased or decreased, the quality of the signal deteriorates justifying the optimum value of pump power as 1500 mW stated in the last section.



(a) Q = 18.26 dB (b) Q = 19.61 dB (c) Q = 19.61 dB

Fig. 5. Eye diagrams for pump powers (a) 1000 mW (b) 1500 mW (c) 2000 mW

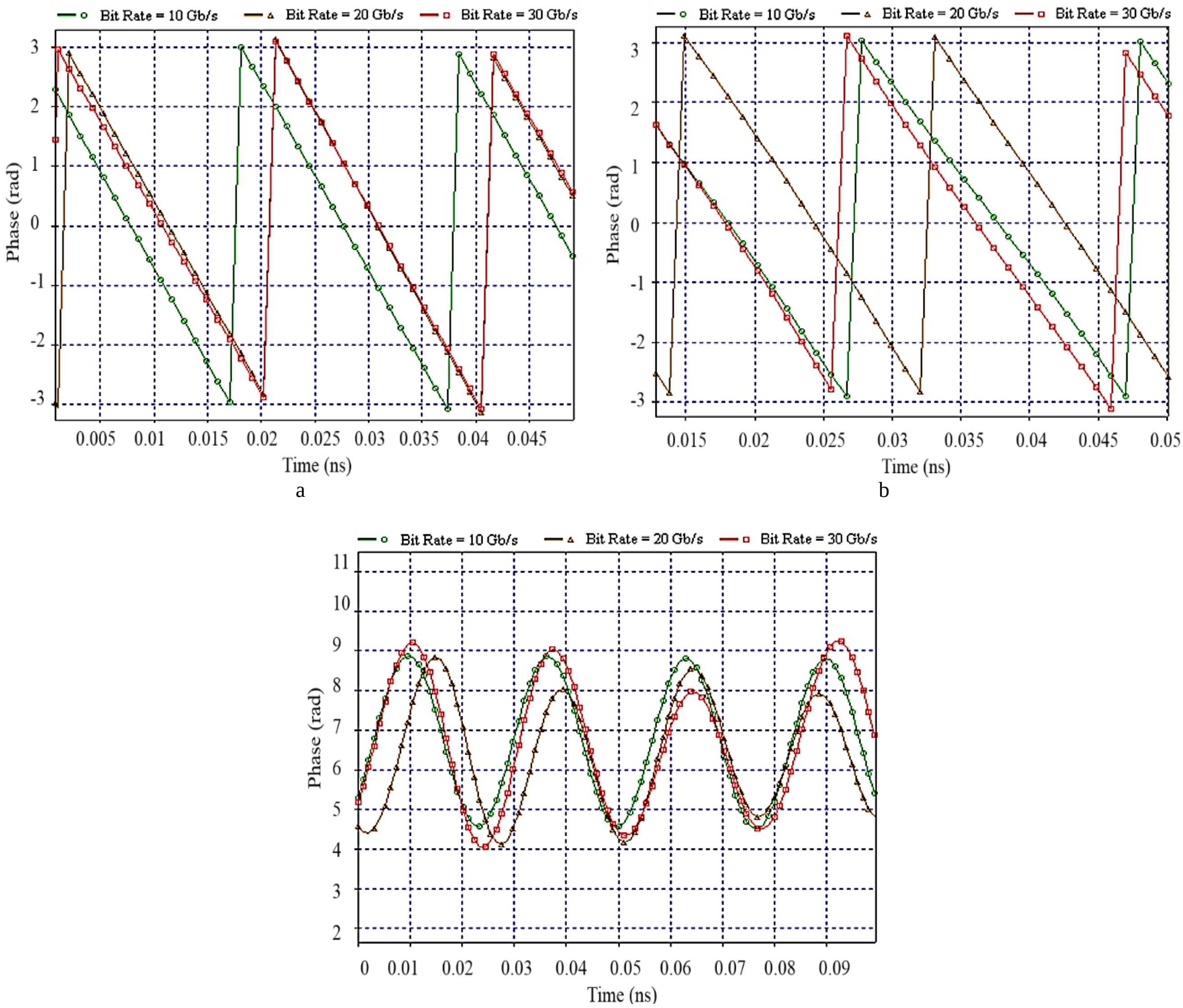


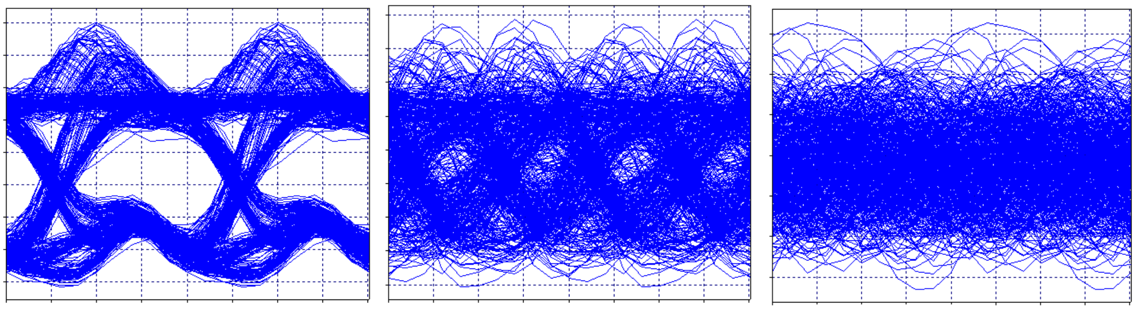
Fig. 6. (a) Plot of input phase versus time (b) plot of output phase versus time (c) plot of output power versus time at different bit rates

6. XPM as a function of bit rate of the applied signal

Bindal et al. [16] had shown that signal quality gets distorted at higher bit rates in FRAs and the optimum value of the channel spacing for high Q-factor get increases. They had concluded that, the bit rate of signals affect the optimum channel spacing between the signals co-propagating through same Raman fiber. So, for Higher bit rate, more channel spacing will be required to get high Q-factor. Proceeding in the same direction, effect of bit rate of the signal on XPM is also analyzed. For this, all the simulation are carried out by varying the bit rate of the data signals from 10 Gbps to 30 Gbps and keeping all the other parameters constant.

Fig. 6 (a) and (b) shows the input and output phase noise variation with respect to the time for different bit rates. It is observed that the output shows a good phase relation with the input at bit rate of 10 Gbps.

Above the value of 10 Gbps, the phase noise increases. It is due to strong crosstalk occurring between channels at high bit rates. So, the optimum value of bit rate for channel spacing of 37.4 GHz comes out to be 10 Gbps. if we want to work at high bit rates, we must increase the spacing between channels. It justifies the statement made in [11]. Further, from the Fig. 6. (c), it is observed that at high bit rates, the variation in power vs time becomes random and power fluctuations are observed. To make the statement made above clearer, the eye diagrams for different bit rates have been taken which is shown in Fig. 7.



(a) Q = 17.44 dB (b) Q = 6.7 dB (c) Q = 6.02 dB

Fig. 7. Eye diagrams for bit rates (a) 10 Gb/s (b) 20 Gb/s (c) 30 Gb/s

It can be seen from the eye diagrams that for the channel spacing of 37.4 GHz, at bit rate of 10 Gbps, the quality factor of value 17.44 dB is obtained. But, as bit rate is increased to a value of 20 Gb/s, the quality factor deteriorates badly and it has a value of 6.7 dB only. This value drops further to 6.02 dB at bit rate of 30 Gb/s.it means for a channel spacing of 37.4 GHz used in this work, the signal cannot be propagated at bit rates more than 10 Gb/s.

7. Conclusions

It has been concluded that XPM increases with increase in input signal and output signal power as well as the length of Raman fiber in FRA. The maximum operating bit rate will also get limit depends on the channel spacing between two adjacent copropagating channels with minimum XPM. At high bit rate Q-factor of signal decrease down drastically.

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