A Comparative Study of SPM, XPM in Er-Yb Co-doped Fiber

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Abstract – Optical fiber communication has been the most versatile and revolutionary medium of communication that has helped in connecting millions of people across the globe. These traits have seen tremendous development in the sector of optical fiber communication. There are now many desired qualities that are expected out of an optical fiber communication like large transmission capacity and a lesser amount of losses. Communication systems operating with higher transmission rates have found an essential role of non-linear fiber optics. The behaviour of light in non-linear media is dealt with non-linear optics. Cross-Phase Modulation (XPM) and Self-Phase Modulation (SPM) are a few non-linearities occurring in the optical fiber. Non-linear effects reduce the performances of optical fibers. In this paper, a comparative study of non-linear effects in Er-Yb co-doped Fiber are reviewed using simulation and the results are compared with optical systems utilizing normal fiber. Benefits of utilizing Er-Yb fiber has been demonstrated by analysing effective systems comprising the Er-Yb co-doped fiber and their ability to mitigate the non-linearities.

Keywords: Er-Yb, SPM, XPM, Q-Factor.

1. INTRODUCTION

Erbium (Er)-doped optical fiber amplifiers (EDFA) rapid development in the 1550-nm band has caused different Er and ytterbium (Yb)-doped (EYDFAs) and 1550-nm EDFAs optical fiber amplifiers to experience sensational improvements [1]. In specific, for high energy applications EYDFAs are vital, counting long-distance optical communications [2]. As of late, EYDFAs have moreover been utilized in modern specialized areas, such as ultra-high-repetition-rate beat sources [3]. EYDFs co-doped with Yb attains several superiorities over EDFs with benefits such as unextinguished higher Er concentration and significantly a bandwidth and a greater absorption intensity around 980 nm. High-power cladding-pumped optical fiber amplifiers utilizing multimode laser diodes utilize the properties of EYDFs [4]. Various stages of energy levels associated with Er-Yb system is shown through a model in Figure 1. Yb ions in an EYDF are excited to the $^2F_{5/2}$ state by pumping light in 800-1,000 nm. Due to the energy transfer from the Yb ions, while they regress to the $^2F_{7/2}$ state, $^4I_{11/2}$ state is achieved by Er ions due to excitation. To make a transition to $^4I_{13/2}$, a non-radiative process is utilized by the Er ions that were excited to the $^4I_{11/2}$, forming a population inversion between the states of $^4I_{13/2}$ and $^4I_{15/2}$. Stimulated emission causes the amplification of the incident optical signal. Having low solubility towards a silica host and having same ionic radius, Yb ions, as well as Er ions, cluster together. In this manner, the separation between Yb ions and Er ions is decreased and the transfer of energy continues with a greatly efficient manner [5].

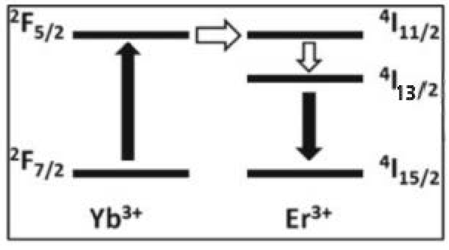

Fig.1. Energy Levels in Er-Yb System

There have been various works done in investigating and mitigating Non-linear effects. Authors in [6-8] have been able to able to mitigate the Non-linearities using various methods. The methodologies adopted by the Authors in [6] is using a regenerative system based on SPM with a bandwidth of 10 Gb/s, Authors in [7] have developed a regenerative system based on HNLF, Authors in [8] utilized multimode non-linear fiber with a numerical approach. The work done by these authors has led us to study the benefits of utilizing a system comprising of Er-Yb Fiber to overcome the issues developed in the above works. We have investigated the properties Er-Yb fiber by comparing it with other similar systems consisting only a normal fiber for transmission. The issues were poor Q-factor in [6], the limited data rate in [6-8].

To study the benefits of using the Er-Yb fiber, we have performed a comparative study, analysing the quality factor and data rates of an optical communication system containing Er-Yb fiber to the optical systems proposed by authors in [18-19]. The findings observed during the comparison will help overcome the shortcomings of the above works, thus providing a simple yet more efficient system to mitigate non-linearities with the use of Er-Yb Co-doped Fiber.

The paper further discusses the origin of non-linearity and continues to talk about SPM in section 2 and about XPM in section 3. The simulation setup and its properties are discussed in section 4. The results and analysis are presented in section 5, and the conclusion is given in section 6.

Non-linearity in its preliminary stage has its origin due to the impact of an applied field on anharmonic motion of bounded electrons. The total polarization P gets affected due to the effect of this anharmonic motion, electric dipoles induce the P and its value is not linear but sums up additionally as a general relation given by

$$P = \varepsilon_0 \chi^{(1)} E1 + \varepsilon_0 \chi^{(2)} E2 + \varepsilon_0 \chi^{(3)} E3 + \cdot \ \cdot \qquad \text{......(1)}$$

Where χ (l) (l = 1, 2...) is l^{th} order susceptibility and permittivity of vacuum is given by ε_0. The linear susceptibility $\chi^{(1)}$ provides the dominant contribution to P. For sum-frequency generation and second harmonic generation, the second-order susceptibility $\chi^{(2)}$ is responsible. $\chi^{(2)}$ vanishes for a symmetrical molecule like silica. Therefore, the second-order non-linear refractive effects are not exhibited by optical fibers. For non-linear effects in fibers of the lowest-order, the third-order susceptibility χ (3) is responsible [9]. Er-Yb fiber has been selected to analyse due to its high efficiency, low noise [10], and cost-effectiveness [11]. Values of Non-linearities must be kept as low as possible for effective communication [12].

2. SELF-PHASE MODULATION

The intensity-dependent phase transition of the fiber is triggered by the intensity-dependent refractive index [13]. Kerr non-linearities for the propagating light pulse through the fiber devise a separate phase transmission for the pulse height relative to the leading and trailing ends of the light pulse. Such an effect that causes modifications to the pulse spectrum is known as SPM. A time-varying frequency is created by the time-varying phase due to the instantaneous frequency of a wave, which is the time derivative of its phase. Therefore, SPM is responsible for alteration and broadening of the frequency spectrum of the pulse. Dispersion-like effects are produced due to the spectral broadening caused by SPM which limits the rates of transmission in some of the optical communication systems of long-haul category, depending on its chromatic dispersion and type of fiber used [14]. A time-varying refractive index is caused due to the variation in intensity rises and falls as the pulse goes past at any single point in the fiber, while the optical pulse propagates through the fiber. Non-linear phase shift which varies with time is caused due to the temporally varying index change. The optical field phase changes is given by [15]

$$\phi = (n + n_2 |E|^2)\, k_{02} L \qquad \text{......(2)}$$

Where the linear refractive index is denoted by n and n_2 indicates the non-linear refractive index of the fiber. ($|E|^2$is the optical signal intensity). Free-space wave number is denoted by k_0 and contains the value of $2\pi/\lambda$, λ is the optical signal wavelength and L denotes the fiber length [15]. Intensity dependence of phase fluctuations causes different phase shifts in different parts of the pulse leading to frequency chirping. Frequency shift in the upper side is produced in the leading edge of the optical pulse whereas the frequency shift in the lower side is produced in the trailing edge. Therefore, the major effect of SPM is to broaden the pulse spectrum, having the temporal shape untouched. In high-transmitted power systems, the SPM effects are more pronounced because the effect of chirping is proportional to signal power transmitted [16].

An Induced phase shift in SPM is proportional to the intensity, occurring due to the non-linear refractive index value [17]. The formula between refractive index and intensity can be described as:

$$\Delta_n = n_2 I(t) \qquad \text{...... (3)}$$

Where the non-linear index is denoted by n_2 and optical intensity is denoted by *I(t)*. The pulse phase is given by:

$$\phi(t) = \omega_0 t - kx = \omega_0 t - \frac{2\pi}{\lambda_0} n(I) L \qquad \text{......(4)}$$

Here, *L* is the propagated distance by the pulse, the carrier frequency is given by ω_0 is the and λ_0 denotes the wavelength of the pulse [17].

3. CROSS-PHASE MODULATION

Effects of XPM and SPM are related. Distinguishable and overlapping pulses with different wavelengths or polarizations are involved in this case. In this case phase modulation of the overlapping pulse(s) is caused due to the intensity variations of one pulse that modulates fibre's refractive index. This modulation of phase in SPM converts into modulation in frequency that broadens the spectrum of the pulse. XPM is therefore displayed as a mechanism of crosstalk between channels. This occurs when the dispersive optical fibre undergoes intensity modulation during transmission or when phase encoding is used. With the increase in the number of channels, the strength of XPM increases. Decreasing the channel spacing also increases the strength of XPM. Nevertheless, there is no exchange of energy among channels, which differentiates the effect from other crosstalk processes in which signal power increase in one channel arises only through a power reduction in another. It can be inferred that the overall intensity is the square of the number of two electric field amplitudes, which makes the total strength of XPM twice that of SPM. This influence is diminished as pulses with different wavelengths or polarizations are typically not balanced by group velocity and thus overlap is not preserved [14]. The shift for the *i*th channel in an *N*-channel transmission system can be given as [16],

$$\phi^{i}_{nl} = (P_i + 2\sum_{n\neq i}^{N} Pi)\, k_{nl}\, L_{eff} \qquad \text{......(5)}$$

The above equation contains a factor 2, which has its origin in the form of non-linear susceptibility and indicates for the same amount of power the XPM is twice as effective as SPM. The first term and the second term in the above equation represents the contribution of SPM and XPM respectively. It can be inferred that XPM is effective only when the interacting signals superimpose in time [15]. Total non-linear phase shift in a fiber of length L [17]:

$$\phi_{NL} = \left(\frac{2\pi}{\lambda}\right) n_2 (|I_1|^2 + b|I_2|^2) \qquad \text{......(6)}$$

4. SIMULATION SETUP OF SYSTEM

OptiSystem 09 simulation software platform has been utilized to study the various parameters responsible for surging SPM and XPM effects [18]. Authors in [19] have also utilized OptiSystem to study non-linearities in fiber. A system to study SPM analysis has been created and portrayed in fig. 2. The system operates at a wavelength of 1550 nm. The power provided to the input is varied from 10 dBm to 20 dBm. The length of fiber is assumed to be 100 km. The transmission rate is fixed at 10Gb/s. The Er-Yb fiber length is set at 1 m and a pump laser is used to amplify the signal and improve efficiency. SPM effect is introduced in the fiber. Analysis to find the Eye-Diagram is done through Bit-Error-Rate (BER) analyzer to devise the Q-factor that determines the distortion in the signal. Photodetector PIN, low pass Bessel filter (LPBF) with cut off frequency set at 0.65 * bit rate and BER analyzer constitute the receiver section.

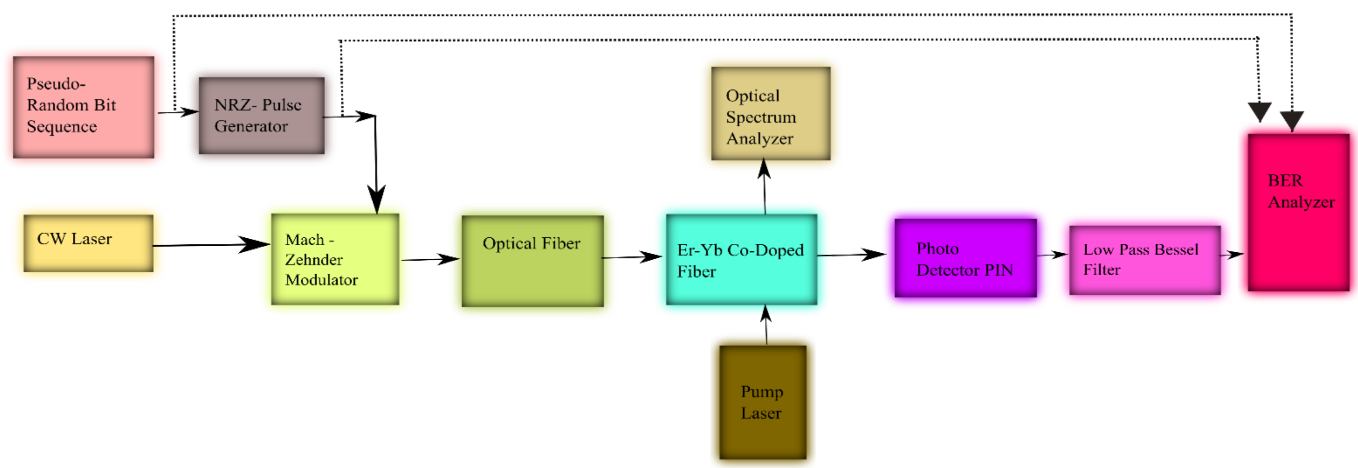

Fig. 2. SPM Simulation Setup

Table 1
Important Parameters and their values pertaining to the SPM system

Parameter	Value
Bitrate	10e+009 Bits/s
Length of Optical Fiber	100 kilometres
Length of Er-Yb Co-doped Fiber	1 metre
Core-radius of Er-Yb Co-doped Fiber	2 micrometres
Doping-radius of Er-Yb Co-doped Fiber	2 micrometres
Er-ion density of Er-Yb Co-doped Fiber	51.4e+024 m-3
Yb-ion density of Er-Yb Co-doped Fiber	620e+024 m-3
Er metastable lifetime	10 milliseconds
Yb metastable lifetime	1.5 milliseconds
Low Pass Bessel Filter cut-off-frequency	0.65* bitrate

WDM system consisting of two-channels has been utilized to analyze the effects of XPM and it is shown in Fig. 3. To generate signals in the system two optical gaussian pulse generators and two user-defined bit sequence generators are used. Multiplexing of two signals over a single channel is done with the help of an ideal multiplexer. Signal after the process of multiplexing is further passed to the fiber and passed through EYDF. The length of the EYDF is set at 1m. The length of optical fiber is assumed to be as 50 Km. BER Analyzer is used to obtain Q-Factor for the assumed signal. Photodetector PIN, LPBF with the cut off frequency set at 0.70 * (bit rate), BER analyzer and 3R regenerator constitute the receiver section.

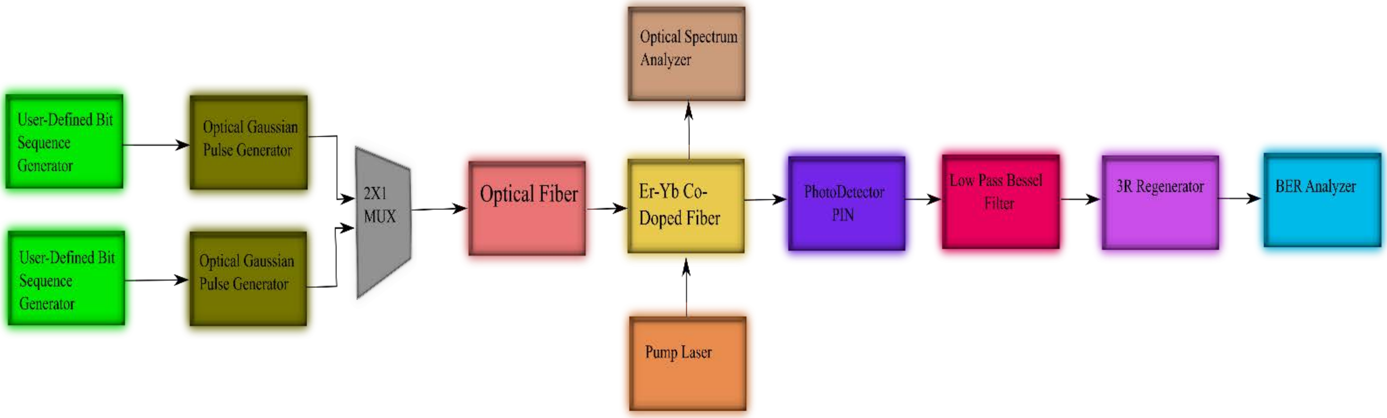

Fig. 3. XPM Simulation Setup

Table 2
Important Parameters and their values of the XPM system

Parameter	Value
Length of Optical Fiber	50 kilometres
Length of Er-Yb Co-doped Fiber	1 metre
Core-radius of Er-Yb Co-doped Fiber	2 micrometres
Doping-radius of Er-Yb Co-doped Fiber	2 micrometres
Er-ion density of Er-Yb Co-doped Fiber	51.4e+024 m-3
Yb-ion density of Er-Yb Co-doped Fiber	620e+024 m-3
Er metastable lifetime	10 milliseconds
Yb metastable lifetime	1.5 milliseconds
Low Pass Bessel Filter cut-off-frequency	0.70* bitrate

5. RESULTS AND ANALYSIS

In this part, the analysis of the effects of SPM and XPM on the fiber is shown. Input power and transmission rates are a few parameters that have been changed over time to provide conclusive evidence of the effects on the fiber.

1. *Eye-Diagram Analysis of Self-phase Modulation*

Marvin and Pratheesh [18] have demonstrated a simulation based on optical fibre to analyse the SPM effect and have obtained various values of Q-factor by varying the input power of the source. They varied the power from 10 to 20 dBm and found that the Q-factor completely vanished at 20 dBm power input [18].
Here we have analysed the Q-Factor by varying powers from 10 dBm to 20 dBm and have obtained the results. Initially, the input power is set at 10dBm and 15dBm.

The output optical signals associated are shown in fig. 4. respectively.

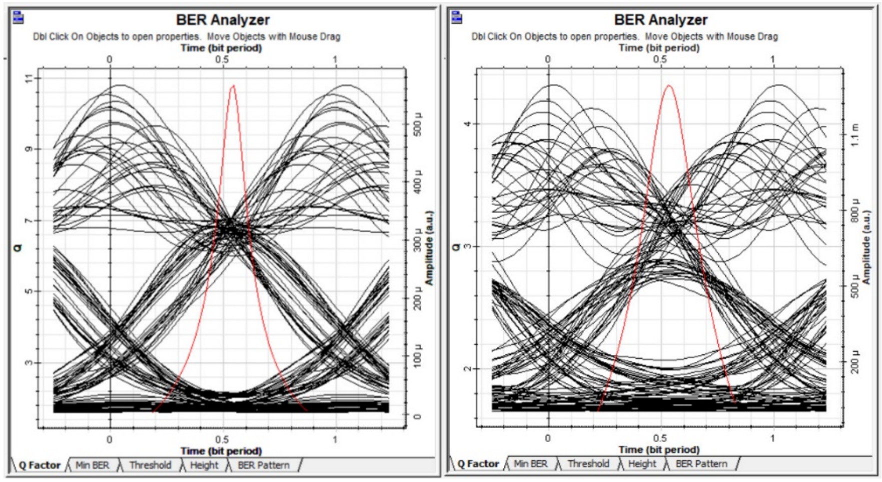

Fig. 4. Eye-Diagrams for SPM at 10 dBm and 15dBm Input

Now, we vary the input power from 17dBm to 20dBm. The output optical signals associated are shown in fig. 5 respectively.

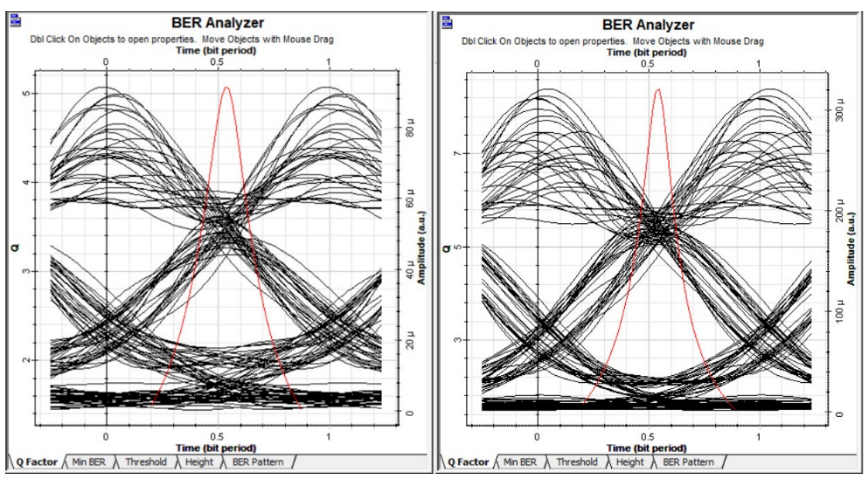

Fig. 5. Eye-Diagrams for SPM at 17 dBm and 20 dBm Input

We observed that the Q-factor at 10dBm power input was 5.06 and at 15 dBm power input was 8.38. When the power input was increased to 17 dBm, the Q-factor increased to 10.79 and at 20 dBm power input decreased to 4.31. The Er-Yb Fiber is well able to compensate SPM at lower power inputs. Table.3 gives the values of parameters related to Eye-Diagram. At higher power input rates, the eye-opening decreases, thus SPM grows and depletes the signal. The Er-Yb gave a Q- Factor of 4.31 at 20 dBm input, whereas the Q-factor in the normal fiber vanished to null [18]. The comparative results have been demonstrated through Fig.6. indicating viable transmission quality in case of Er-Yb fiber. The Er-Yb system generates better Q-Factor for higher input power conditions, whereas in case of a system in [18] the Q-Factor deteriorates and vanishes to null. As a point of benefit, the system with Er-Yb at 20dBm input power manages to provide transmission quality but the other system completely fails. Thus Er-Yb has better operating conditions.

Table 3: -

Eye-Diagram Parametric Values (SPM)

Parameter	10dBm	15dBm	17dBm	20dBm
Max. Q. Factor	5.06	8.38	10.79	4.32
Min.Ber	2.02815e-007	2.4637e-017	1.64342e-027	7.45267e-006
Eye Height	1.79711e-005	$107*10^{-6}$	$214*10^{-6}$	$196*10^{-6}$
Threshold	3.08781e-005	9.16885e-005	$118*10^{-6}$	$291*10^{-6}$
Decision Inst.	0.53	0.55	0.55	0.53

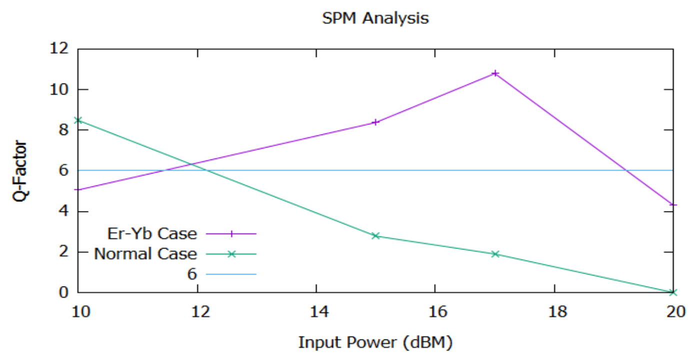

Fig.6. Comparative study of SPM

2. *XPM Analysis by Eye-Diagram*

A. Based on Varying Transmission Rates

In this section for simulation, the rate of transmission is altered from 10 Gb/s to 40Gb/s, to analyse the effect of XPM on varying transmission rates. The Q-factor is considered to determine the strength of the signal.

Initially, the input transmission rate is set at 10 Gb/s and 20Gb/s. The corresponding output Eye-Diagrams are portrayed in fig. 7. respectively.

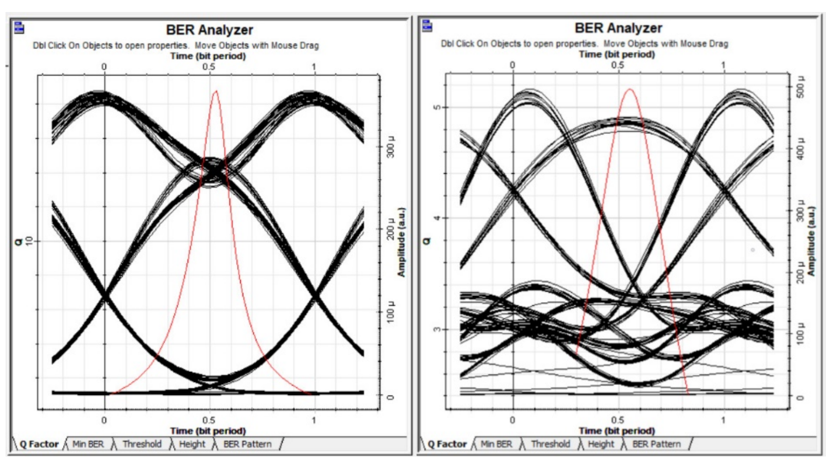

Fig. 7. Eye-Diagrams for XPM at 10 and 20 Gb/s Input

Now, the input transmission rate to the fiber is varied from 30Gb/s to 40Gb/s. The corresponding Eye-Diagrams are portrayed in fig. 8. respectively. The parametric values of the Eye-Diagram are shown in Table.4.

The Q-factor obtained at 10, 20, 30 and 40 Gb/s are 18.78, 5.16, 3.7, and 5.4. This data is shown through Fig. 9 indicating a decrease in Q-Factor but the rate of decrease is slower in this fiber which also increases slightly at the end, which becomes evident that the Er-Yb supports higher transmission rates. Thus Er-Yb can give good quality factor at various transmission rates and has better-compensating ability as compared to normal fiber [19].

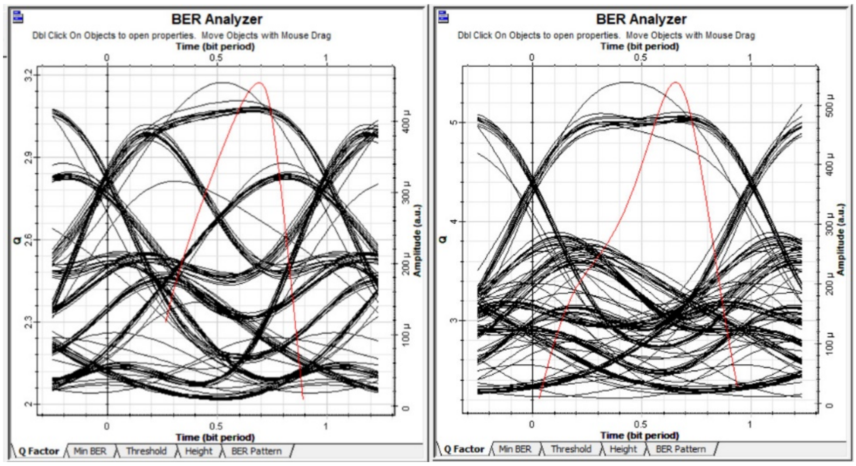

Fig. 8. Eye-Diagrams for XPM at 30 and 40 Gb/s Input

Table 4: -

Eye-Diagram Parametric Values (XPM)

Parameter	10Gb/s	20Gb/s	30Gb/s	40Gb/s
Max. Q. Factor	18.79	5.17	3.18	5.4
Min.Ber	$4.94205e^{-079}$	$1.22285e^{-017}$	$752*10^{-6}$	$2.95298e^{-008}$
Eye Height	$216*10^{-6}$	$139*10^{-6}$	$1.59369e^{-005}$	$160*10^{-6}$
Threshold	$125*10^{-6}$	$411*10^{-5}$	$402*10^{-6}$	$400*10^{-6}$
Decision Inst.	0.53	0.55	0.68	0.66

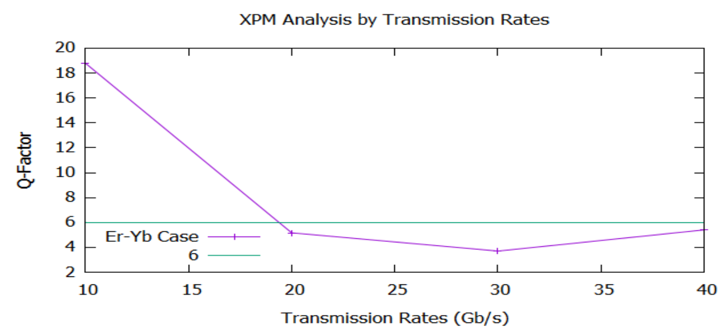

Fig.9. Study of XPM by Transmission rates

B. Based on Varying Input Power

Bhusari, Deshmukh, and Jagdale [19] have demonstrated a simulation based on optic fiber, to analyse XPM effects and have obtained various values of Q-factor by varying the input power of the source from 0 dBm to 12dBm. They found that that the Q-factor decreased from 4.7 to 2.7, causing degradation of the input signal [19].

Here we have analysed the Q-Factor by varying powers from 0 dBm to 20 dBm and have obtained the results. Initially, the input power is set at 0dBm and 5dBm.
The output optical signals associated are shown in fig. 10. respectively.

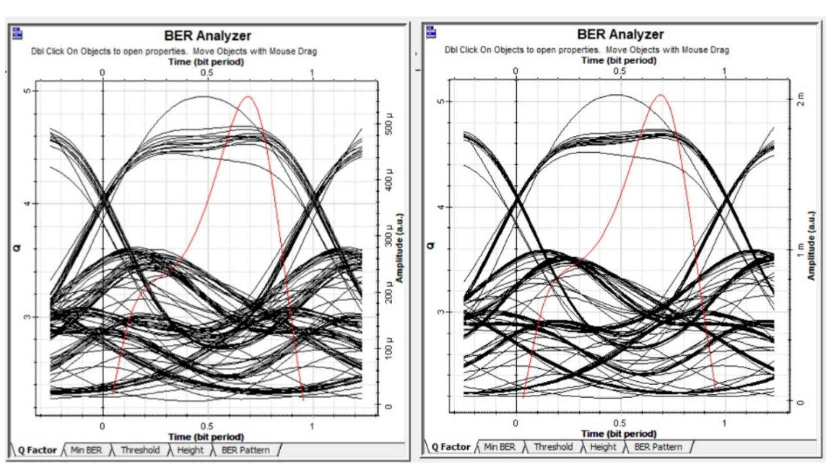

Fig. 10. Eye-Diagrams for XPM at 0 dBm and 5dBm Input

Now, the power given to the input of the fiber is varied from 10dBm to 20dBm. The corresponding Eye-Diagrams are shown in fig. 11. Respectively.

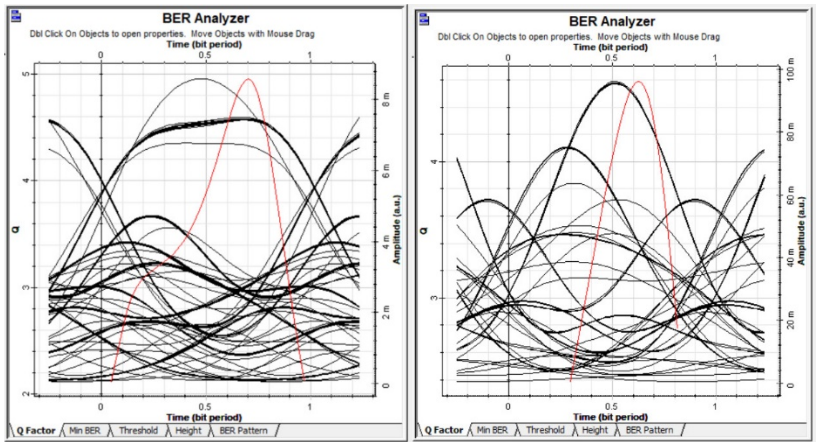

Fig. 11. Eye-Diagrams for XPM at 10dBm and 20dBm Input

Here despite varying power inputs, the Q-factor constantly stays around 5 and decreases slightly at the end. Fig.12. indicates the comparative plot between the considered systems. The Er-Yb fiber generates higher quality signals having better Q-Factor than the system in [19] Thus, Er-Yb fiber can give better results as compared to normal fiber utilized in [19]. The parametric values of the Eye-Diagram are shown in Table.4.

Table 5: -

Eye-Diagram Parametric Values (XPM)

Parameter	0dBm	5dBm	10dBm	20dBm
Max. Q. Factor	4.95	5.06	4.95	4.5
Min.Ber	3.28823e-079	1.91865e-017	3.37875e-007	2.10913e-006
Eye Height	$140*10^{-6}$	$543*10^{-6}$	$222*10^{-6}$	$236*10^{-6}$
Threshold	$387*10^{-6}$	$1458*10^{-5}$	$6287*10^{-6}$	$8594*10^{-5}$
Decision Inst.	0.68	0.68	0.70	0.62

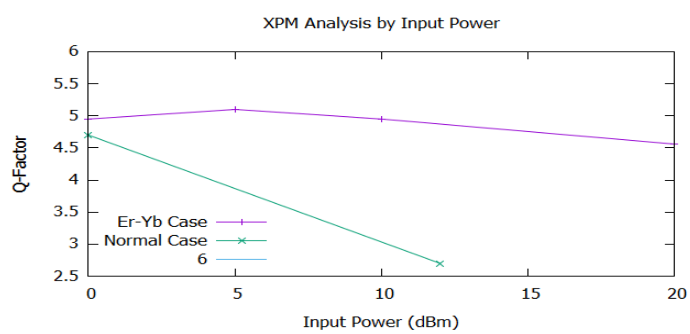

Fig.12. Comparative study of XPM by Input Power

6. CONCLUSION

Mitigation of Non-linearities has been effectively shown to be achieved with optical communication systems comprising of Er-Yb fiber, generating good Q-Factor which provides a higher quality of the signal. Non-linear effects in Er-Yb co-doped fiber is relatively lower than the normal fiber and it can mitigate the non-linearities to a better extent. Systems capacity and signal quality is reduced by SPM and XPM affect. SPM grows and drains the signal at a comparatively lower rate when input power is increased. XPM also performs a similar slower degradation of signal. Thus, Er-Yb co-doped fiber may be adopted if signal quality required is of eminent importance. The study can be further extended by analysing the effects of different input signal waveforms on the fiber and studying the nature of four-wave mixing on the fiber.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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