# Parametric Analysis of Fiber Non-Linearity in Optical systems

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***Abstract*- With the advent of technology Wavelength Division Multiplexing (WDM) is always an area of interest in the field of optical communication. When combined with Erbium Doped Fiber Amplifier (EDFA), it provides high data transmission rate and low attenuation. But due to fiber non-linearity such as Self Phase Modulation (SPM) and Cross Phase Modulation (XPM) the system performance has degraded. This non-linearity depends on different parameters of an optical system such as channel spacing, power of the channel and length of the fiber section. The degradation can be seen in terms of phase deviation and Bit Error Rate (BER) performance. Even after dispersion compensation at the fiber end, residual pulse broadening still exists due to cross talk penalty.**

**Keyword- EDFA, residual pulse broadening, SPM, XPM, WDM.**

## I. INTRODUCTION

With the evolution of new technology, WDM plays a major role in the field of fibre optic communication. It provides multiplexing of multiple carrier signals on a single fibre by using different wavelength of optical sources, each of which carry a different signal. It offers higher transmission rate and information capacity to carry across the fibre end. WDM techniques when combined with EDFA are essential for realizing high capacity light wave transmission and flexible optical networks. EDFAs are the most important fibre amplifiers in the long-range optical fibre communications because of its low attenuation and efficient amplification. With the development of amplifiers, the attenuation in a signal has reduced to large extent but a major problem arises due to fibre non-linearity which has degraded the overall efficiency of a WDM system.

Non- linearities in fibre result from the interaction between several optical fields simultaneously present in the fibre and may also involve acoustic waves or molecular vibrations. These can be classified into two categories. The first set includes scattering effects in the fibre medium that occur due to the interaction of light waves with phonons (molecular vibrations) in the silica medium. The two main effects in this category are Stimulated Brillion Scattering (SBS) and Stimulated Raman Scattering (SRS). The second set occurs because of the dependence of refractive index on optical power called Kerr effect. SBS can be viewed as scattering of the pump wave from this acoustic wave generated by an oscillating electric field, resulting in creation of a new wave at the pump frequency. SRS on the other hand, causes a power transfer from shorter wavelength channels to longer wavelength channels which primarily affects the power distribution of the input data channels and leads to channel- to- channel crosstalk [1]-[3].

The Kerr effect occurs because of electrical perturbation of the refractive index of a material as the electric field of the light itself causes a symmetry breaking in the refractive index of the material. Thus, the refractive index becomes: $n(I) = n + n_2(I)$ in the direction of the electric field, where $n$ is the refractive index of fibre, $I$ is the intensity and $n_2$ is the non- linearity coefficient. This gives rise to self phase modulation (SPM), cross phase modulation (XPM) and four waves mixing.

Self phase modulation (SPM) which arises because the refractive index of the fibre has an intensity dependent component causes an induced phase shift that is proportional to intensity of the pulse. Different parts of the pulse therefore undergoes different phase shifts, giving rise to chirping of pulses, which in turn enhances pulse broadening effects of chromatic dispersion. At a zero dispersion wavelength, SPM leads to amplitude modulation of pulse [4].

In future long-span, high-channel-count WDM systems, XPM will be one of the severe obstacles to error free transmission. In many cases, the impairments caused by XPM can be categorized into two separate effects: intensity distortion and timing jitter. When examining the distorted eye at the receiver, intensity distortion manifests itself as a broadening of the upper rail corresponding to the transmission of “ones”. Timing jitter, on the other hand, appears as broadening of the edges of the eye corresponding to transitions between “ones” and “zeros.” Timing jitter in the probe channel results from the frequency shifted components propagating at slightly different velocities due to fibre dispersion. XPM depends upon several parameters of a WDM system such as channel spacing, fibre length, and power of the channel. Variation in any parameter induces crosstalk penalties in the system [5] - [8].

Section II describes the theoretical analysis of non- linearity such as SPM and XPM, Section III presents the results and discussions and Section IV draws the final conclusions.

## II. THEORETICAL ANALYSIS

The theoretical analysis begins with the nonlinear wave propagation equation [9]. Consider the pump and probe optical signals, $A_m(t,z)$ and $A_c(t,z)$, co- propagating in the same optical fibre. The evolution of the pump and probe wave can be described by:

$$\frac{\partial A_m(t,z)}{\partial z} = -\frac{\alpha}{2} A_m(t,z) - \frac{1}{v_m}\frac{\partial A_m}{\partial t} - i\frac{\beta_2}{2}\frac{\partial^2 A_m}{\partial t^2} + i\gamma_m P_m(t,z) A_m(t,z) + 2i\gamma_m P_c(t - z/v_c, z) A_m(t,z) \tag{1}$$

$$\frac{\partial A_c(t,z)}{\partial z} = -\frac{\alpha}{2} A_c(t,z) - \frac{1}{v_c}\frac{\partial A_c}{\partial t} - i\frac{\beta_2}{2}\frac{\partial^2 A_c}{\partial t^2} + i\gamma_c P_c(t,z) A_c(t,z) + 2i\gamma_c P_m(t - z/v_m, z) A_c(t,z) \tag{2}$$

where $\alpha$ is the attenuation coefficient of the fibre, $\beta_2$ is the fibre chromatic dispersion parameter, $\gamma_c = 2\pi n_2 / (\lambda_c A_{eff})$ is the nonlinear coefficient, $n_2$ is the nonlinear refractive index, $\lambda_c$ and $\lambda_m$ are the probe and the pump signal wavelengths, $A_{eff}$ is the effective fibre core area, $P_m = |A_m|^2$ and $P_c = |A_c|^2$ are optical powers of the pump and probe, respectively. Due to chromatic dispersion, the pump and the probe waves travel at different speed and this difference is taken into account in the calculation of XPM because it introduces walk-off between the two waves. $v_m$ and $v_c$ are used to represent the group velocities of pump and probe channel respectively.

On the RHS of (1),(2), the first term introduces attenuation, the second term is for linear phase delay, the third term accounts for chromatic dispersion, the fourth term is responsible for SPM and the fifth term is the XPM in the probe signal induced by the pump signal. In order to simplify the analysis and focus on the effect of XPM induced inter-channel crosstalk, the interaction between SPM and XPM is neglected and assumed that these two act independently. The probe signal is considered to be operated in continuous wave (CW), whereas the pump signal is modulated with a sinusoidal wave at a frequency. The effect of SPM for both the probe and the pump channels are neglected in this XPM calculation. This approximation is valid as long as the pump signal waveform is not appreciably changed by the SPM induced distortion before its optical power is significantly reduced by the fibre attenuation. Under this approximation, the fourth term on the RHS of (1),(2), is neglected in the XPM evaluation. XPM induced crosstalk involves the phase modulation generation through the nonlinear Kerr effect followed by the phase-noise to intensity noise conversion through fibre dispersion. The received power at the end of the fibre contains XPM induced crosstalk as well as the attenuated signal power. Therefore, the probe output optical power with XPM-induced crosstalk in the time domain takes the form.

$$P_{cm}(t, L_s) = P_c(L_s) + \Delta s_{cm}(t, L_s) \tag{3}$$

Where $\Delta s_{cm}(t, L_s)$ is the XPM induced crosstalk power in time domain and $P_c(L_s)$ is the probe output at the end of the fibre without XPM. $\Delta s_{cm}(t, L_s)$ has a zero mean. The original CW probe is intensity modulated by the pump through the XPM process. After a series of derivations and approximations, the XPM induced optical power spectral density in the probe channel for an N-span system:

$$\Delta P_{cm}(f_c, L_s) = \left| \sum_{i=1}^{N} \left\{ 4\gamma_2 P_c^{(i)}(f_c, 0) \exp\left[ i f_c \sum_{n=1}^{i-1} d_{cm}^{(n)} L_s^{(n)} \right] \frac{\sin\left[ f_c^2 \sum_{n=i}^{N} \beta_{22}^{(N)} L_s^{(n)} \right]}{\alpha - i f_c d_{cm}^{(i)}} \right\} \right| P(L_s) \tag{4}$$

where, $L_s = \sum_{n=1}^{N} L^{(n)}$ is the total fibre length in the system, $L^{(n)}$ and $\beta^{(n)}$ are fibre length and dispersion of the nth span [where $L^{(0)} = 0$], $P_c^{(i)}(f_c, 0)$ is the power spectral density of pump wave at the input of the $i^{th}$ span and $d_{cm}^{(i)}$ is the relative walk-off between two channels in the $n^{th}$ span, [$d_{cm}^{(0)} = 0$]. Using a linear approximation, the walk-off $d_{cm}$ can be expressed as $d_{cm} = D\Delta\lambda_{cm}$, where $D = -(2\pi c/\lambda^2)\beta$ is the fibre dispersion coefficient, $\Delta\lambda_{cm}$ and $\lambda$ are, the wavelength spacing and average wavelength between the probe and pump, respectively, and $c$ is the velocity of light. For a dispersion slope fibre, we can determine $D(\lambda)$ for a particular operating wavelength, $\lambda$ from its dispersion slope $S_0$ and zero dispersion wavelength $\lambda_0$, using $D(\lambda)=(S_0/4)\lambda[1-(\lambda_0/\lambda)^4]$

The basic difference between XPM and SPM is the channel spacing. By putting channel spacing $\Delta\lambda_{cm}=0$ in the equation of XPM and replacing the multiplication term 5 by 2, SPM induced optical power spectral density for an N-span system is found to be,

$$\Delta P_{cc}(f_c,L_s)=|\sum_{i=1}^{N}\{2\gamma_2 P_c^{(i)}(f_c,0)\frac{\sin[f_c^2\sum_{n=i}^{N}\beta_{22}^{(n)}L_s^{(n)}]}{\alpha}\}|P(L_s) \tag{5}$$

Where, $P_c^{(i)}(f_c,0)$ is the PSD of the probe signal itself at the input of the $i^{th}$ span.

## III. EXPERIMENTAL SETUP AND DISCUSSION OF RESULTS

In this section, study and simulation of different parameters of an optical system which results in SPM and XPM have been analysed. Here, simulations of 1-channel and 2-channel optical system have been done. The central wavelength and channel power is set as 1550nm and 6.98dBm respectively across different fibre length. The channels are modulated at a data rate of 10 Gbps.

### *A. Analysis of SPM*

Here, a laser source of power 6.98dBm and wavelength of 1550.12 nm is taken into consideration for a single channel optical system. Length of each of the 2-fibre spans is taken as 50 km. At the transmitter side, the data source is in NRZ format at a bit rate of 10 Gbps. A sine square amplitude modulator with 3 dB excess loss is used. The PIN photo detector at the receiver converts the incoming optical signal to electrical signal. Optical probes are used for measuring the instantaneous phase deviation at both input and output. The schematic setup and the phase deviations at the transmitter and receiver side are shown below.

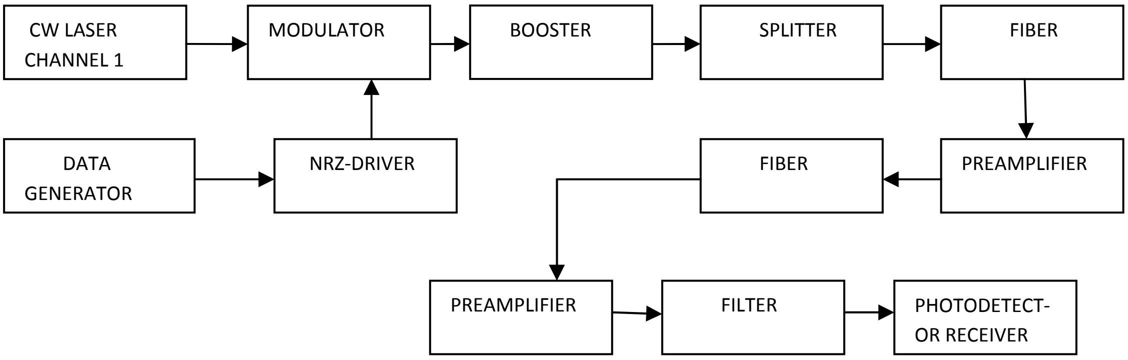


Fig. 1 Block diagram for a single channel optical system

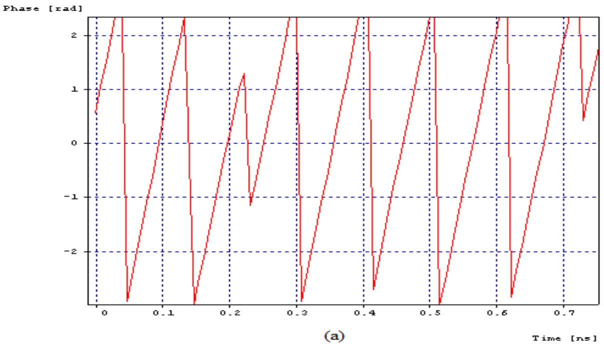


Fig. 2 (a) Input phase deviation

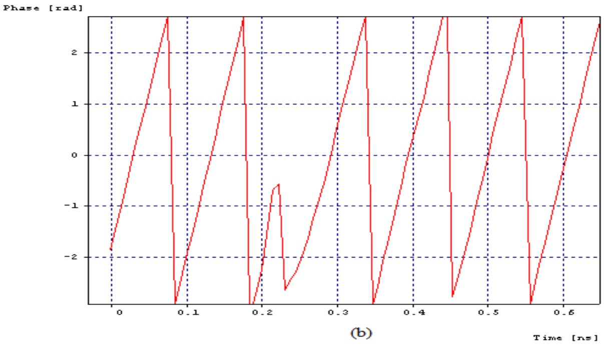


Fig.2 (b) Output phase deviation

As seen from Fig. 2 (a) and (b), there is a forward shift in phase at the receiver side with respect to the transmitter side. At the input section, for the time duration of 0 to 0.1 ns, there is a phase shift from 2 rad/s to -2 rad/s and then to 0 rad/s. However, at the output section, for the same duration, only a phase shift from 2 rad/s to -2 rad/s can be observed. The shift back to 0 rad/s is shifted to the interval 0.1 rad/s to 0.2 rad/s. This phase shift is induced due to the effect of SPM in the fibre section.

### *B. Parametric Analysis of XPM*

A WDM system consisting of two channels have been simulated and reported here. First channel is taken as pump (which modulates transmitted data from laser diode) of wavelength 1549.712 nm and second channel as probe (low power continuous wave) of wavelength 1550.12021 nm , over 2- fibre spans. The transmitter section consists of laser source, data source which is NRZ at 10 Gbps and a Mach-Zehnder modulator for each of the 2-channels. Ideal Braggs grating is used for compensating the dispersion. Here, XPM dependent different parameters such as fibre length, power of the channels, broadening of pulses are varied and its effect on an optical system has been studied.

#### *1. Residual Pulse Broadening*

Here, both pump and pump power are set to 6.98 dBm and fibre spans of 50 km are considered. First, the pulse width is measured at the transmitter side before the fibre section. It is found to be 0.24 ns as indicated by the underline portion in the Fig. 3. Next, the pulse width is measures after the fibre section without including the fibre grating (no dispersion compensation). Here, the pulse width is observed to be $P_1$=0.413856ns. Further, the simulation is carried out by including the grating section (dispersion compensated) having dispersion $800\,psnm^{-1}$ (16 ps/nm/km×50km). The pulse width is now found to be: $P_2$=0.34406ns. Therefore, the residual pulse broadening is found to be: $P_1$-$P_2$=0.0659ns.Thus it can be inferred that after compensating the dispersion there is broadening of pulses which is mainly due to XPM in the fibre section.

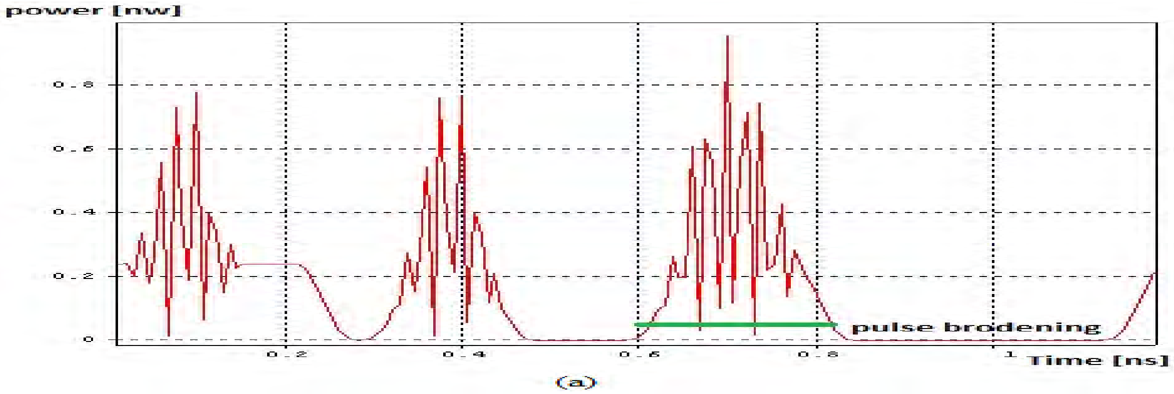


Fig. 3 (a) Pulse broadening at the transmitter before the fibre section

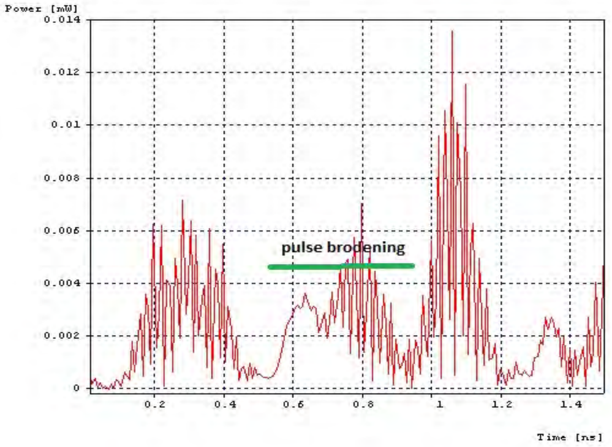
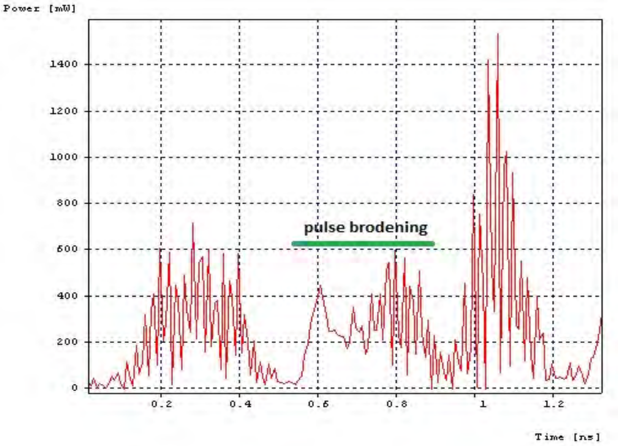


Fig. 3 (b) Pulse broadening at the fibre end without dispersion compensation



(c) Pulse broadening with dispersion compensation

#### *2. Variations in Fibre Length*

Here, the simulations are carried out without amplifiers and splitters in 2-channel optical system and link power budget analysis are done. After that, the power of the channels is kept constant and fibre length is varied to study its impact due to XPM. The pump and probe power are set to 6.98 dBm. Link power budget analysis for fibre length, $L = 40$ km is shown below.

Referring Table 1, the power budget, $P_B$ can be calculated as:

$P_B = P_{T_{\min}} - P_{R_{\min}}$ =10.25 dBm

Adding up all the losses, Span loss $P_s$ is obtained as 16.5 dBm. Therefore, the power margin $P_M$ can be computed as:

$P_M = P_B - P_s$ = -6.25 dBm

Since the power margin is negative, amplifiers will be needed for spans including and above 40 km.

TABLE 1.

| PARAMETER | VALUES |
|---|---|
| Transmitted power | -0.576 dBm |
| Received power | -10.83 dBm |
| Attenuation loss | 0.25 dB/km |
| Dispersion Compensation loss | 2 dB |
| SPM/XPM loss | 0.5 dB |
| PMD loss | 0.5 dB |
| SRS/ SBS loss | 0.5 dB |
| Optical Safety and Repair Margin loss | 3 dB |

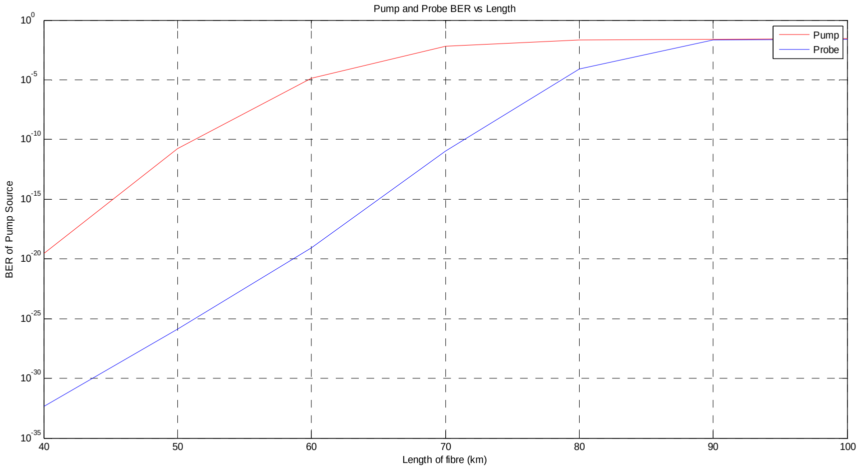


Fig. 4 BER vs fibre length (Km) for pump and probe channel.

Next, BER has been calculated for different fibre spans above 40 km. The pump and probe power has been set to 6.98 dBm. Dispersion is compensated by 16 ps/nm/km and attenuation of 0.25 dB/km is kept across the fibre section. As observed from Fig.4, as the length of the fibre increases, BER increases for both the pump and probe channel. Thus, it can be inferred that as the fibre length increases, larger is the effect of XPM on the system which induces crosstalk penalty, therefore increases bit error swiftly.

### *3. Variation in Power of the channels*

Here, power of the pump and probe channel are varied one at a time keeping the other constant. The channels are modulated at a data rate of 10 Gbps. First, simulations have been done by varying the probe power keeping pump power constant to 6.98 dBm on two fibre spans of 50 km each. It can be inferred from Fig. 5 that with increase in probe power, XPM increases due to cross talk and as a result BER decreases.

Next, simulations have been performed by varying pump power, keeping probe power constant to 6.98 dBm. The corresponding variation in BER is observed. As seen from Fig.6, BER increases as the probe power increases.

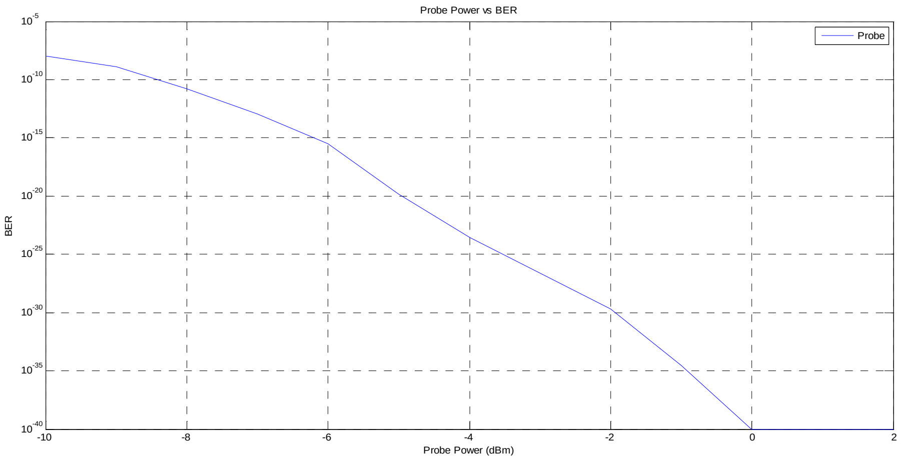


Fig. 5. BER vs. Probe power in dBm (keeping pump power=6.98dBm)

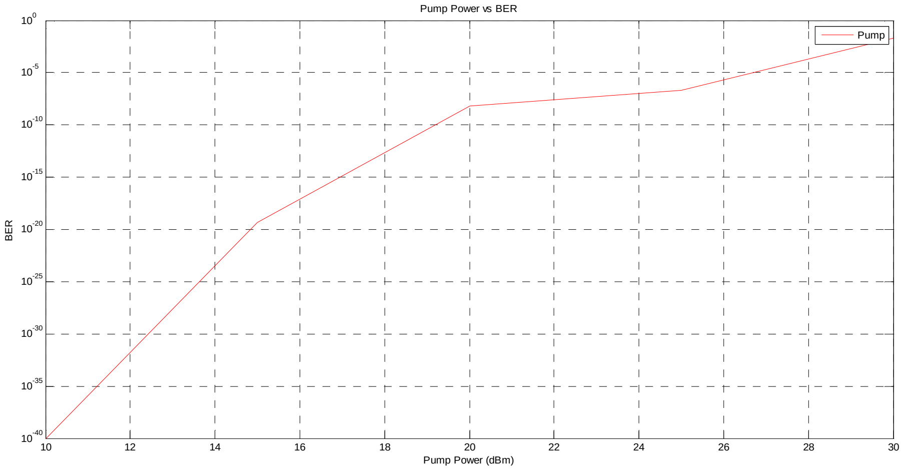


Fig. 6. BER vs. Pump power in dBm (keeping probe power=6.98dBm)

## IV. CONCLUSION

In this paper, a detailed analysis of fibre non-linearity such as SPM and XPM has been presented. It is observed that XPM and SPM induces crosstalk penalty which depends upon various parameter of an optical system. Due to SPM, there is positive phase shift in the receiver section as compared to the transmitter. Varying fibre length has caused increment in BER for both the pump and probe channels. Power of the pump and the probe played a major role in the performance of BER. Therefore, it can be concluded that for designing a WDM system of higher channel capacity and higher data rate more than 10 Gbps, these parameters should be taken into consideration. These should be varied such that the effect of fibre non-linearity on WDM system is reduced.

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