Analysis of XPM-induced cross talk in the optical fiber for higher order dispersion with respect to power input to the fiber

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Abstract- **Due to demand of voice, data and multimedia, the services in telecommunications are increasing day by day. The wireless network providers are facing so many problems and it is difficult to provide cost effective and reliable service to each consumer. To deal with these problems, optical fiber communication system was introduced. But when a signal of combined order is transmitted through optical fiber a large amount of distortion is received. The motivation of this work was non-linearity present in the fiber communication that can be compensated by dispersion. So the higher order study needed typical values of parameters of fiber core radius, length of fiber and power attenuation constant. Moreover the study of higher order dispersion for the fiber optic communication system becomes important.**

Keywords- **Broadband; Transmission medium; Nonlinearity; Dispersion; Fiber Optic.**

I. INTRODUCTION

When we transmit a signal through an optical fiber amount of distortion can be seen in received signal. Distortion can be in any communication system but here scenario is different here medium property is also modified when signal propagates. This happens due to presence nonlinear effects because medium property varies so it become very complicated to study, we have to use fresh approach for the propagation of light through fiber optic after a hectic mathematical calculation we reach to a final equation that is called nonlinear Schrödinger equation [1].

This nonlinear Schrödinger equation can be solved by considering two separate cases the first when nonlinearity term is neglected then find solution for the dispersion term, in another case is when nonlinearity is dominating [2].In dispersion regime, the time pulse goes on expanding with distance while nonlinear regime timing pulse remains constant and spectrum goes up and new frequencies goes on getting generated [3]. When multiple signals transmitted together we have to use some special techniques called multiplexing here in optical fiber we use multiplexing like wavelength division multiplexing (WDM) or dense wavelength division multiplexing (DWDM) [4].

It It has been reported in [7] that total effect of Stimulated Raman Scattering (SRS) and cross-phase modulated induced crosstalk (XPM-induced crosstalk) increase exponentially, but some fluctuations are there if we increase the modulation frequency. When signal transmitted through fiber the combined effect of second order (2OD) and third order (3OD) varies as walk off parameters. The Combined effects of SRS-and XPM can be study and explain through this paper further studies can be performed separately for higher order. The equations mentioned bellow are coded and simulated up to sixth order of dispersion (6OD) and combined effect of input power for combined effect of dispersion up to 6th order of dispersion is simulated using MATLAB.

II. THEORETICAL ANALYSIS

A. Dispersion

Dispersion is that the spreading of input optical pulses as it travels down through the fiber, which ends in distortion of the signal. It results in the broadening of optical pulses transmitted on a fiber to such an extent wherever they cause a lot of overlapping with one another that the detection of individual pulses at the receiving end becomes very difficult. The overlapping of pulses ends up in Inter-symbol Interference (ISI) those results in Bit Error Rate (BER) performance. It limits the performance of optical communication systems.

Mathematically, Dispersion can be expressed as:

$$D = \frac{1}{L}\frac{d\tau}{d\lambda} \qquad (1)$$

$$\beta = \beta_0 + (\omega-\omega_0)\frac{d\beta}{d\omega} + \frac{1}{2}(\omega-\omega_0)^2\frac{d^2\beta}{d\omega^2} + \frac{1}{6}(\omega-\omega_0)^3\frac{d^3\beta}{d\omega^3} + \frac{1}{24}(\omega-\omega_0)^4\frac{d^4\beta}{d\omega^4} + \frac{1}{120}(\omega-\omega_0)^5\frac{d^5\beta}{d\omega^5}\ldots \qquad (2)$$

Where τ_0 pulse broadening in ps, λ_d is in nm and L is in

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km. Pulse broadening depends on frequency dependence of propagation constant β that can be expanded in Taylor series around central frequency ω_0 .

B. Nonlinearities in the fiber

When material properties are modified by the signal, it falls in the category is called nonlinear optical fiber. If fiber properties change by the signal then what will happen to the signal propagation? When the signal transmitted through an optical fiber an amount of distortion can be seen in received signal.

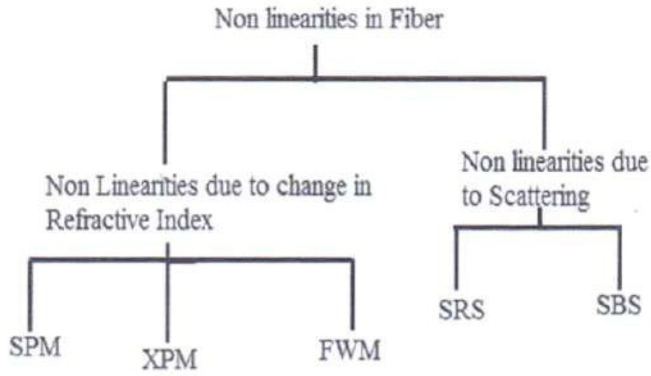

Fig. 1: Nonlinearity in fiber

C. Cross-Phase Modulation (XPM)

In fiber cross-phase modulation come in the feature in multimode fiber as if we consider the simplest case only one pulse is traveling at a time, we found that is the change in phase of propagating pulse at receiver end similar phenomenon takes place if there multiple optical signals transmitted in the fiber at a time. The distortion is received at receiver due to pulse broadening. It is asymmetric because of multiple signals propagating together. It is dependent on power of all pulses.

Expression of phase shift due to nonlinear effects is given as

$$\phi^{i}_{nl} = k_{nl} L_{eff} \left(P_i + 2 \sum_{n \neq i}^{N} P_n \right) \qquad (3)$$

N= N-channel transmission system, n= 1, 2, 3......N

L_{eff}= Effective length of link

k_{nl} = Propagation constant

When we compare XPM and SPM, XPM is advantageous as in XPM channel capacity is twice. SPM occupies total channel capacity for a single signal. XPM is advantageous only when both signals superimposed. If this criterion is not fulfilled there will be adverse effect on system performance.

Let $Aj(t, z)$ and $A_k(t,z)$ are two propagating signals at a time:

$$\frac{\partial A_j(t,z)}{\partial t}+\frac{\alpha}{2}A_j(t,z)+\frac{1}{V_j}\frac{\partial A_j(t,z)}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A_j(t,z)}{\partial t^2}-\frac{i\beta_3}{6}\frac{\partial^3 A_j(t,z)}{\partial t^3}$$
$$-\frac{i\beta_4}{24}\frac{\partial^4 A_j(t,z)}{\partial t^4}+\frac{i\beta_5}{120}\frac{\partial^5 A_j(t,z)}{\partial z^5}-\frac{i\beta_6}{720}\frac{\partial^6 A_j(t,z)}{\partial t^6}=i\gamma\left[2P_k\left(t-d_{jk}z,z\right)\right]A_j(t,z) \qquad (4)$$

α= attenuation coefficient.

$\gamma = 2\pi\eta_2/\lambda_2 A_{eff}$ γ= nonlinear coupling coefficient

Hence

$$\frac{\partial A_j(t,z)}{\partial z}=-\frac{\alpha}{2}A_j(t,z)-\frac{1}{V_j}\frac{\partial A_j(t,z)}{\partial t}-\frac{i\beta_2}{2}\frac{\partial^2 A_j(t,z)}{\partial t^2}+\frac{i\beta_3}{6}\frac{\partial^3 A_j(t,z)}{\partial t^3}+\frac{i\beta_4}{24}\frac{\partial^4 A_j(t,z)}{\partial t^4}-\frac{i\beta_5}{120}\frac{\partial^5 A_j(t,z)}{\partial t^5}$$
$$+\frac{i\beta_6}{720}\frac{\partial^6 A_j(t,z)}{\partial t^6}+i\gamma\left[2P_k\left(t-d_{jk}z,z\right)\right]A_j(t,z) \qquad (5)$$

For solving this equation for dispersion, we should take Fourier transform to convert above equation in the frequency domain so that the higher order of derivation can be converted in the multiplication of frequencies.

$$\frac{\partial A_j(\omega,z)}{\partial z} = -\left(\frac{\alpha}{2}+\frac{1}{V_j}\right)+\frac{i\omega^2\beta_2}{2}-\frac{i\omega^3\beta_3}{6}+\frac{i\omega^4\beta_2}{24}$$
$$-\frac{i\omega^5\beta_5}{120}+i\gamma_j\left[2P_k(\omega,0)e^{i\omega z d_{jk}}e^{-\alpha z}\right]A_j(\omega,z) \qquad (6)$$

For very small fiber length, The XPM caused by the pump signal reduces when we apply the small signal approximation.

$$d\phi_{jk}(\omega,z) = 2\gamma_j P_k(\omega,0)e^{(-\alpha+i\omega d_{jk})z}dz \qquad (7)$$

Now, we focus on the third term of the equation (6). The phase noise to intensity noise conversion in the probe signal is due to this term only. Because of the chromatic dispersion, the Phase noise generated at z = z is now transferred into intensity noise at z=L.

The component of the conversion in the same phase is proportional to the terms given bellow.

$\sin\left[(\omega^2\beta_2(L-z))/2\right], \sin\left[(\omega^3\beta_3(L-z))/6\right], \sin\left[(\omega^4\beta_4(L-z))/24\right],$
$\sin\left[(\omega^5\beta_5(L-z))/120\right]$

Taking all the XPM contributions, whole fiber loss and linear phase delay in consideration, we can deduce final noise intensity at fiber length z=L.

$$\Delta A_j(\omega,L)=-2P_j(0)e^{(-\alpha-(i\omega/V_j))z}\left[\int_0^L 2\gamma_j P_k(\omega,0)e^{(-\alpha-i\omega d_{jk})z}\left[\sin\left[\frac{\omega^2\beta_2(L-z)}{2}\right]\right.\right.$$
$$\left.\left.-\sin\left[\frac{\omega^3\beta_3(L-z)}{6}\right]+\sin\left[\frac{\omega^4\beta_2(L-z)}{24}\right]-\sin\left[\frac{\omega^5\beta_5(L-z)}{120}\right]+\sin\left[\frac{\omega^6\beta_6(L-z)}{720}\right]\right]\right]dz \qquad (8)$$

Now put

$$P_j(L) = P_j(0)e^{-\alpha L}$$

$\Delta A_j(\omega,L)=$

$$P_j(L)e^{(i\omega/V_j)L}2\gamma_j P_k(\omega,0)\left[\left\{\frac{e^{i\omega^2\beta_2 L/2}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^2\beta_2/2)\right]}-\frac{e^{-(i\omega^2\beta_2 L/2)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^2\beta_2/2)\right]}\right\}\right]$$

$$
-\left\{\frac{e^{-(i\omega^3\beta_3 L/6)}-e^{-(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^3\beta_3/6)\right]}-\frac{e^{i\omega^3\beta_3 L/2}-e^{-(\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^3\beta_3/6)\right]}\right\}
$$

$$
+\left\{\frac{e^{i\omega^4\beta_4 L/24}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^4\beta_4/24)\right]}-\frac{e^{-(i\omega^4\beta_4 L/24)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^4\beta_4/24)\right]}\right\}
$$

$$
\left\{\frac{e^{i\omega^6\beta_6 L/720}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^6\beta_6/720)\right]}-\frac{e^{-(i\omega^6\beta_6 L/720)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^6\beta_6/720)\right]}\right\}-\Bigg] \tag{9}
$$

Where P_j (L) is the average optical signal power of the propagating signal at z = L end of fiber. When we assume that EXP ($-\alpha$L) << 1 and modulation frequency is much smaller on spacing between the channels.

The amplitude fluctuation due to the XPM- induced can be written as:

$$
\Delta P_j(\omega, L)=
$$

$$
2\gamma_j P_k(\omega,0)\Bigg[\left\{\frac{e^{i\omega^2\beta_2 L/2}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^2\beta_2/2)\right]}-\frac{e^{-(i\omega^2\beta_2 L/2)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^2\beta_2/2)\right]}\right\}
$$

$$
-\left\{\frac{e^{-(i\omega^3\beta_3 L/6)}-e^{-(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^3\beta_3/6)\right]}-\frac{e^{i\omega^3\beta_3 L/2}-e^{-(\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^3\beta_3/6)\right]}\right\}
$$

$$
+\left\{\frac{e^{i\omega^4\beta_4 L/24}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^4\beta_4/24)\right]}-\frac{e^{-(i\omega^4\beta_4 L/24)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^4\beta_4/24)\right]}\right\}
$$

$$
\left\{\frac{e^{i\omega^6\beta_6 L/720}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})+(i\omega^6\beta_6/720)\right]}-\frac{e^{-(i\omega^6\beta_6 L/720)}-e^{(-\alpha+i\omega d_{jk})L}}{i\left[(\alpha-i\omega d_{jk})-(i\omega^6\beta_6/720)\right]}\right\}\Bigg|^2 \tag{10}
$$

III. SIMULATION AND RESULTS

In calculations, following parameters are assumed as given below Referring to ITU: T recommendation G.653 [ITU].

PARAMETER	VALUE
D	0.5 ps/nm/km
D_1	0.085 ps/nm/km
D_2	0.00025 ps/nm/km
D_3	0.0000025 ps/nm/km
D_4	0.000000025 ps/nm/km
$\Delta\lambda$	4nm
L	50km
n_2	2.68 $e^{-20} m^2/W$
M	0.7
α	0.25dB/km
λ_1	1550nm
λ_2	1552nm

Table 1

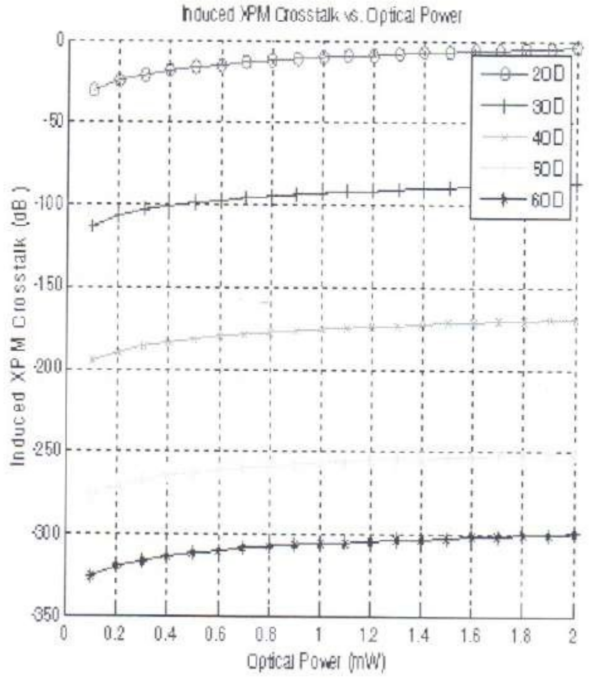

Fig. (2): Simulation result between XPM crosstalk v/s power input at the different higher order.

Fig.:- (2) shows that the XPM crosstalk is (−40 to−20), (−90 to−75), (−180 to−160), (−280 to−255) and (−325 to−300) dB in the presence of 2OD, 3OD, 4OD, 5OD and 6OD at 3GHz Modulation Frequency and 50 km transmission length for variable input power.

By this result, one can deduce that the effect of the different order with the change in input power with fixed length and modulation frequency. As one can see that as order of dispersion is increasing the induced crosstalk is decreasing but all the orders are still significant and must be studied because they are contributing in distortion.

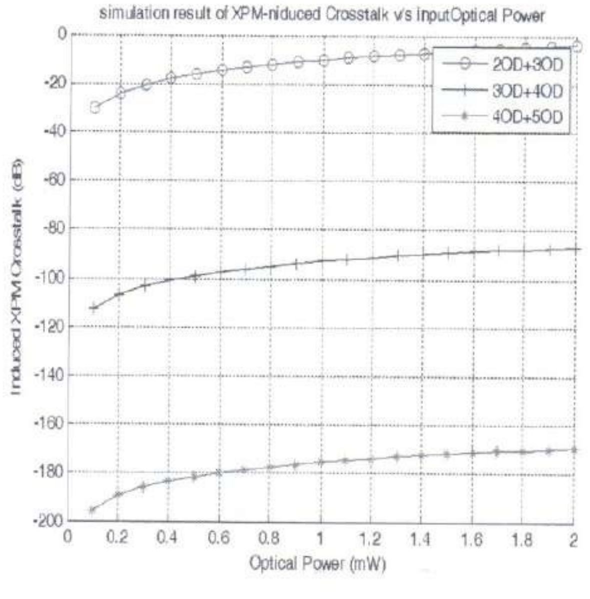

Fig.: (3) Simulation result of XPM crosstalk v/s optical power at different combined order of dispersion.

Fig.(3) shows that the XPM crosstalk is (−38 to−18), (−88 to−73), (−178 to−58) and (−280 to−255) dB in the presence of combined dispersion order like 2OD + 3OD, 3OD + 4OD,4OD + 5OD and 5OD + 6OD at 3GHz Modulation Frequency and 50 km transmission length for variable input power.

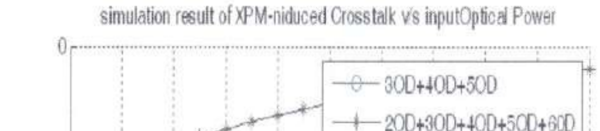

Fig.:- (4): Simulation result between XPM crosstalk versus input power combination of all order.

Fig.:- (4) shows that the XPM crosstalk is (−30 to−5), and (−118to−97) dB in the presence of combined dispersion order like 2OD + 3OD + 4OD + 5OD + 6OD and 3OD + 4OD + 5OD + 6OD at 3GHz Frequency and 50 km Transmission length for variable input optical power.

IV. CONCLUSIONS ·

This paper presents the detailed theoretical and simulation analysis of the influence of higher order dispersion effect (2OD, 3OD, 4OD, 5OD and 6OD) on XPM-induced crosstalk. It is also observed that the higher order dispersion term has the significance in XPM crosstalk. The impact decreases as the order of the dispersion increases.

By this result, one can deduce that the effect of combined order with the change in input power at fixed transmission length and modulation frequency. As one can see that as the order is increasing the induced crosstalk is decreasing but they are still significant and must be studied because they are contributing in distortion. Here also one can see that 2OD + 3OD + 4OD + 5OD + 6OD is most effective than 3OD + 4OD + 5OD + 6OD is contributing but less in extent.

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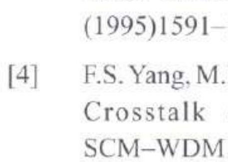

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