[1]Ghanendra KUMAR, [2]Chakresh KUMAR

PERFORMANCE ANALYSIS OF CROSSTALK INDUCED OPTICAL COMMUNICATION SYSTEM

[1]Department of Electronics and Communication Engineering, National Institute of Technology, New Delhi, INDIA
[2]University School of Information, Communication & Technology, Guru Gobind Singh Indraprastha University, New Delhi, INDIA

Abstract: Cross-phase Modulation and self-phase modulation has some effect on two analog channels propagating in the optical fiber. The motivation behind this work is to compute these effects by studying the interaction between two channels and modulating the components of two channels. Crosstalk between two channels depends on wavelength spacing, sub-carrier frequency and optical power. Crosstalk due to cross-phase modulation depends on channel spacing and dispersion in fiber. The power of the crosstalk created by the received radio frequency and the two channels are calculated in direct identification. Formulations for phase modulation and amplitude are analyzed with the help of SPM and XPM. In this approach, it is assumed that there is no distortion in the pump channel therefore this method computes distortions due to Self-phase modulation, cross-phase modulation and dispersion in both channels.
Keywords: Cross-phase Modulation (XPM), Pump, Self- Phase Modulation (SPM), Probe, Crosstalk, Amplitude Modulation, Phase Modulation

INTRODUCTION

When a number of signals are multiple into a single optical fiber by using different wavelength, an optical effect which is non-linear in nature takes place. In this effect, one wavelength of signal affects the phase of some other wavelength of light due to the kerr effect. This is known as Cross-phase modulation (XPM). This effect is huge and harmful in nature in the presence of dispersion. Probe channel is the channel in which phase modulation is transferred by XPM and similarly pump channel is the channel in which intensity modulation is transferred.

Intensity modulation which is transferred from the pump to probe is calculated in terms of crosstalk. Mathematically, it is the ratio of power of the received radio frequency in probe channel to received radio frequency power in the pump channel in decibels. [1-5]

Crosstalk in optical fiber arises because of the Kerr effect. Therefore, it is necessary to reduce it by using some techniques. These techniques have been used successfully to reduce this interaction between channels. The dispersion-managed system is a system in which a technique is used to reduce the dispersion introduced in the optical fiber, generally, a dispersion slope compensator is used. In these types of dispersion-managed systems, a large difference between group velocity is achieved between two channels which reduce the nonlinearity in phase rotation in a probe over many periods of amplitude modulation [6-8].

In the past work, it is difficult to calculate crosstalk I analog fiber links. In previous work, some expression for crosstalk has been presented. However, in previous researches, it is assumed that there is no distortion in the pump channel during transmission. But it is necessary to take the distortion in the account to compute crosstalk accurately for large frequency in modulation for dispersion-managed systems on which we are working in this work.

One of the techniques to calculate the crosstalk for any system is by using the Schrödinger equation. But, in this paper there is an assumption that modulation depth (modulation index) and the ratio of modulation frequency to the spacing between two channels are very small, therefore, contributing to a linear system of ordinary differential equation. So, crosstalk can be determined by solving differential equations. The linearization helps us in getting characteristics of XPM in dispersion-managed systems [9-10].

ANALYSIS

Let D (z) be the dispersion dependent on z-axis, and our electric field is E that is normalized in order that $|E|^2$ has power units, C is fiber's coefficient that are non-linear & L (z) is the Z dependent loss/gain. So, our equation is

$$\frac{\delta E}{\delta Z} = \frac{j}{2} D(z) \frac{\delta^2 E}{\delta t^2} + jC|E|^2 - \frac{1}{2} L(z) E$$

Let us analyses our equation taking Z varying dispersive and non-linear coefficients by making the transformation

$$q(z,t) = E(z,t) e^{[\frac{1}{2}\int_0^2 L(z')dz\prime]}$$

which yields

$$\frac{\delta q}{\delta Z} = \frac{j}{2} D(z) \frac{\delta^2 q}{\delta t^2} + jF(z) q|q|^2 \qquad (1)$$

where,

$$F(z) = Ce^{[-\int_0^Z L(z')dz\prime]}$$

In our equation (1) we have not included the RAMAN effect since in this paper our main goal is to observe the Kerr effects at larger modulation frequency (>2GHz) and also we know that RAMAN effect plays vital role in lower frequency region only (<2GHz). That's why we haven't counted RAMAN Effect in our equation. Let the signal consists of two adequately separated wavelength channels. Here the term adequately separated implies that demultiplexer doesn't produce any crosstalk in between them. So, the crosstalk (our main focus) comes only from the interaction during the propagation that is non-linear. So,we can write

$$Q`(z,t) = P(z,t) + Q(z,t)e^{(j\Delta\omega t)} \quad (2)$$

Here $\Delta\omega$ is the difference in frequency or spacing between the two channels. Since each channel P and Q are well separated so we can write separate equations for the wavelength channel

$$\frac{\delta P}{\delta Z} = \frac{j}{2}D(z)\frac{\delta^2 P}{\delta t^2} + jF(z)(|P|^2 + 2|Q|^2)P$$

$$\frac{\delta Q}{\delta Z} = \frac{j}{2}D(z)\left\{\frac{\delta^2 Q}{\delta t^2} + 2j\Delta\omega\frac{\delta Q}{\delta t} - \Delta\omega^2 Q\right\} + jF(z)(2|P|^2 + |Q|^2)Q$$

We obtained this equation by putting $q = P + Qe^{j\Delta\omega t}$ into equation (1) and setting $e^{j\Delta\omega t} = 1$. Now, Our main interest is only a small number of radio frequency tones in transmission. We know that RF tones produce electric fields. So the electric field decomposing in our RF tone is obvious. So, let's the decomposition are

$$P(z,t) = \sum_{k=-\infty}^{\infty} \overline{P}k(z)e^{(jk\beta t)}$$

$$Q(z,t) = \sum_{k=-\infty}^{\infty} \overline{Q}k(z)e^{(jk\beta[t-\Delta\omega g(z)])}$$

where $g(z) = \int_0^z D(z')dz'$

Since, Q is $\Delta\omega$ apart from P so decomposition in fourier domain for Q contains the group velocity that is dependent on dispersion that is directly related to the P channel.

CHANNEL'S FOURIER EVOLUTION

We know that in the transmission of either phase modulation or amplitude modulation in the optical field there are three tones in each channel. Two weak sidebands corresponding to modulation and one strong tone that corresponds to the optical carrier. Let's us introduce here an expansion that is a perturbation expansion (a theory in which we conclude an approximate solution to a problem by taking an exact solution to a similar problem) of each channel, which is given as

$$\begin{Bmatrix}\overline{P}K \\ \overline{Q}K\end{Bmatrix} = \begin{Bmatrix}\overline{P}\,0,K \\ \overline{Q}\,0,K\end{Bmatrix} + m\begin{Bmatrix}\overline{P}\,1,K \\ \overline{Q}\,1,K\end{Bmatrix} + O(m^2)$$

Here M is the modulation depth. Our main objective is to make the interaction between channels in linear to the optical carrier. So, let us lower the modulation depth m. Due to small modulation we also need to get derived

Area improvement. So, taking those requirements in mind we assume that $\overline{P}0$ & $\overline{Q}0$ are of unity order and $\overline{P}(+-1)$ & $\overline{Q}(+-1)$ are of Mth order , and all other Fourier components of the channels are of order 2nd order of M or higher. In order to handle the highest interaction between the leading order and optical carrier of the two channels, we should assume that there is no modulation in both channels. So, our intersection equals.

$$\frac{\delta P1,0}{\delta Z} = jF(z)(|P1,0|^3 + 2|Q1,0|^3)P1,0$$

$$\frac{\delta Q1,0}{\delta Z} = -\frac{j}{2}D(z)\Delta\omega^3 Q1,0 + jF(z)(2|P1,0|^3 + |Q1,0|^3)Q1,0$$

By using these equations, we yielded explicit solutions

$P1,0(z) = P1,0(0)e^{j(P1+2P2)n(z)}$

where,

$n(z) = \int_0^Z F(z')dz'$

$P1 = |P1,0(0)|^3$ and

$P2 = |Q1,0(0)|^3$

We assume that there was no loss of generality.

$$\text{So, } P1,0(0) = (P1)^{0.5}$$

and

$$Q1,0(0) = (P2)^{0.5}.$$

Next, let us solve for $P1,\pm1$ and $Q1,\pm1$ by considering the higher order in distortion expansion, O (m), we obtained four equations that are coupled for $P1,\pm1$ and $Q1,\pm1$.

Let us change the variables which simplifies the equations significantly.

$$y1(z) = P1,1\ (z)e^{j\varphi1(z)}$$

$$y2(z) = P'1,-1\ (z)e^{j\varphi2(z)}$$

$$y3(z) = Q1,1\ (z)e^{j\varphi3(z)}$$

$$y4(z) = Q'1,-1\ (z)e^{j\varphi4(z)}$$

when we choose these substitution

$$\varphi1\ (z) = -(P1 + 2P2)n(z) + \Omega\frac{\Delta\omega}{2}g(z)$$

$$\varphi2\ (z) = (P1 + 2P2)n(z) + \Omega\frac{\Delta\omega}{2}g(z)$$

$$\varphi3\ (z) = -(2P1+ P2)n(z) + \frac{1}{2}(\Delta\omega^2 - \Omega\Delta\omega)g(z)$$

$$\varphi4\ (z) = (2P1 + P2)n(z) - \frac{1}{2}(\Delta\omega^2 + \Omega\Delta\omega)g(z)$$

Since, we have changed the variables so we get

$$\frac{dy}{dz} = j\left[\frac{1}{2}D(z)\Omega A + F(z)B\right]y(z) \quad (3)$$

where $Y`(z) = (Y`1, Y`2, Y`3, Y`4)^T$ and here we have taken A and B as constant square matrices of order 4, that are given below

$$A = \begin{pmatrix} -\beta+\Delta\omega & 0 & 0 & 0 \\ 0 & \beta+\Delta\omega & 0 & 1 \\ 1 & 0 & -\beta-\Delta\omega & 0 \\ 0 & 1 & 0 & \beta-\Delta\omega \end{pmatrix}$$

and

$$B = \begin{pmatrix} P1 & P1 & 2(P1P2)^{0.7} & 2(P1P2)^{0.7} \\ -P1 & -P1 & -2(P1P2)^{0.7} & -2(P1P2)^{0.7} \\ 2(P1P2)^{0.7} & 2(P1P2)^{0.7} & P2 & P2 \\ 2(P1P2)^{0.7} & 2(P1P2)^{0.7} & -P2 & -P2 \end{pmatrix}$$

Here we can see that equation 3 is an ordinary differential equation that is a linear system that is also homogeneous. Since these equations are fourth order

ODEs so its solution i.e., quantitative evaluation is far rapid and it will be very useful in parametric studies of the system. Also here in equation (3) there are two explicit terms which separate the effect of power dispersion and fluctuation in the variable coefficients D (z) and F (z).

COMPUTING CROSSTALK BETWEEN SIMPLE WIRES

Crosstalk is the coupling of energy from one wire to other wire when both are parallel to each other and carrying some signal. Coupling of energy takes place through mutual induction and mutual capacitance between two wires.

Due to the mutual induction, current will induce in each wire opposite to the signal current. It is known as Lenz's law. Due to the mutual capacitance, some signal current will pass through this capacitor and producing some error.

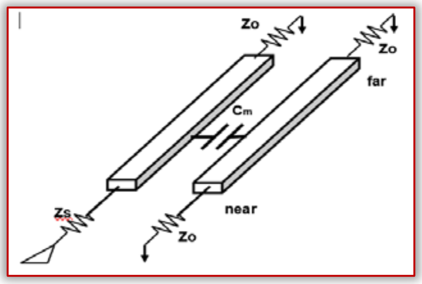


Figure 1. Mutual Capacitance

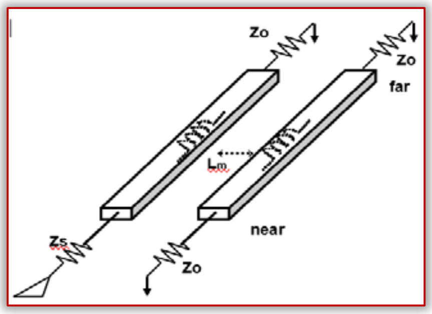


Figure 2. Mutual Inductance

L AND C MATRIX

L and C matrix are the transmission matrices which are to evaluate electrical characteristics and help us to compute crosstalk.

L matrix is known as the Inductance matrix and it is shown in figure 3. C matrix is known as Capacitance matrix and it is shown in figure 4.

$$\begin{bmatrix} L_{11} & L_{12} & \dots & L_{1N} \\ L_{21} & L_{22} & & \\ & & & \\ L_{N1} & & & L_{NN} \end{bmatrix}$$

Figure 3. Inductance matrix

$$\begin{bmatrix} C_{11} & C_{12} & \dots & C_{1N} \\ C_{21} & C_{22} & & \\ & & & \\ C_{N1} & & & C_{NN} \end{bmatrix}$$

Figure 4. Capacitance matrix

In the L matrix L_{11} L_{22} etc. are the self-inductance of line per unit length where L_{xy} is the mutual inductance between line x and line y. In the C matrix C_{11} C_{22} etc. are the self-capacitance of line per unit length and C_{xy} is the mutual capacitance.

With the help of L and C matrices, the crosstalk voltages of the end and far-end can be easily found. Quotes for near end and far end crosstalk amplitude can be written as below:

$$V_{near} = \frac{V_{input}}{4}\left[\frac{L_{12}}{L_{11}} + \frac{C_{12}}{C_{11}}\right] \quad (4)$$

$$V_{far} = \frac{V_{input}(X\sqrt{LC})}{2T_{rise}}\left(\frac{L_{12}}{L_{11}} - \frac{C_{12}}{C_{11}}\right) \quad (5)$$

Where V_{input} is input voltage, X is the length of line and L and C is the values of inductor and capacitor.

COMPUTING CROSSTALK-DIRECT DETECTION

Direct optical transmission systems are characterized by their capability to do "direct detection". It is used by systems which have 10GB/s or lower speed. I a direct detection receiver, the photodetector is sensitive to changes in receiving signal optical power, it cannot extract or get the information of phase or frequency from optical carrier (4).

Crosstalk can be calculated in optical direct transmission at some distance. Therefore, crosstalk is defined as:

$$\text{Crosstalk}(\Omega) = 1010 \log_{10} \frac{\text{RF power of signal 1}}{\text{RF power of signal 2}} \quad (6)$$

Where signal 1 is in probe channel and signal 2 is in the pump channel.

Radio frequency spectrum analyzer is similar to an oscilloscope, but it displays the signal in frequency domain i.e. signals versus frequency. This is helpful to test RF circuits and to get the RF power. Therefore, RF analyzer gives power of the radio frequency that considers probe channel and pump channel by squaring the amplitude and the complex Fourier component of acquired photocurrent in the analyzer of the above channel. The relation between radio frequency power and the optical field is:

$$\text{RF power}(\beta) = R\left|\frac{K}{T}\int_0^T |\mu(z,t)|^2 e^{i\beta t} dt\right|^2 \quad (7)$$

where the radio frequency spectrum analyzer that consider the load resistance and denoted by R, photodetector's responsivity by K and $T = \frac{2\pi}{\beta}$ denotes the time duration of the radio frequency oscillation.

These expressions are used to calculate RF power for probe and pump channel. By using equations 6(a) and 6(b) and above equation for u channel, the RF power is calculated as:

$$\text{Radio frequency power of } \mu\ (\beta) = RRK^2[(|\tilde{\mu}_{-1}|^2 + |\tilde{\mu}_1|^2)|\tilde{\mu}_0|^2 + |\tilde{\mu}_0|^2|\tilde{\mu}_1|^*|\tilde{\mu}_{-1}|^* + |\tilde{\mu}_0|^2\tilde{\mu}_1\tilde{\mu}_{-1}]$$

Similarly, the same expression is for v channel. Finally, RF power of u and v channel is described as:

$$\text{RF power of u } (\Omega) = RK^2m^2P_1|y_1(z) + y_2(z)|^2$$

$$\text{RF power of v}(\Omega) = RK^2m^2P_2|y_3(z) + y_4(z)|^2$$

With the help of the previous two expressions, crosstalk can be calculated by the assumption that v channel is pump channel and u channel is probe channel as:

$$\text{Crosstalk}(\Omega) = 10\log_{10}\left[\frac{|w_1(z)+w_2(z)|^2}{|w_3(z)+w_4(z)|^2}\right]$$

AM AND PM MODE EVOLUTION

Above discussions shows that phase modulation mode of a channel affected by amplitude modulation and phase modulation mode of the same channel and amplitude modulation mode of another channel. But, the amplitude modulation mode affected by the modulation technques that are amplitude and phase modulation of the same channel only. Due to dispersion, amplitude modulation in one channel transfers to phase modulation in another channel and phase modulation in one channel transforms to amplitude modulation in the same channel.

Therefore, crosstalk in direct detection assuming pump and probe channel as a v channel and μ channel respectively is given as:

$$\text{Crosstalk}(\Omega) = 10\log_{10}\left[\frac{P_1|A_u(z)|^2}{P_2|A_v(z)|^2}\right] \quad (8)$$

In direct detection, Crosstalk is zero when AM mode of probe channel is zero and crosstalk is infinity when AM mode of pump channel is zero. It means that direct detection receiver cannot extract information about the phase of the pump channel. When AM mode vanishes, the modulation exists as PM mode. So, A system cannot be designed to work on the frequency at which crosstalk is infinity.

RESULTS

Equations for near-end and far-end voltage:

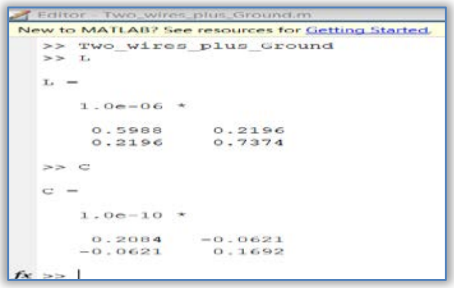
$$V_{near} = \frac{V_{input}}{4}\left[\frac{L_{12}}{L_{11}} + \frac{C_{12}}{C_{11}}\right]$$

$$V_{far} = \frac{V_{input}(X\sqrt{LC})}{2T_{rise}}\left(\frac{L_{12}}{L_{11}} - \frac{C_{12}}{C_{11}}\right)$$

For the two wires the parameters required to calculate the crosstalk are input voltage,self-inductance between wire L_{11}, self-capacitance between wires C_{11}, mutual inductance L_{12}, mutual capacitance C_{12}.

From MATLAB software the distance between wires is 1m and the radius of each wire is 0.1m. The input voltage is 1V and length of the each wire is 2inches and the T_{rise}=100ps.

The L and C matrices given by MATLAB is:



From above The crossstalk voltage is 0.017V at the far and at the end is the crosstalk voltage is 0.004V

CONCLUSION

The work is performed to determine crosstalk induced by cross-phase modulation (XPM) in analog fiber link by solving an ordinary differential equation. Crosstalk between two wires is also calculated with the help of inductance and capacitance matrix. Then, near and far end crosstalk voltages are analyzed. Optical fiber converts Am to PM when direct detection is used. When distortion in the pump channel has neglected the results varies from practical answers where distortion is taken into account tells that distortion in the pump channel cannot be neglected.

References

[1] P.-L. Luo, J. Hu, Y. Feng, L.-B. Wang, and J.-T. Shy, “Doppler-free intermodulated fluorescence spectroscopy of 4He 23P–31,3D transitions at 5 88 nm with a 1-W compact laser system,” Appl. Phys. B, Lasers Opt., vol. 120, no. 2, pp. 279–284, 2015.

[2] J. W. Nicholson et al., “Raman fiber laser with 81 W output power at 1480 nm,” Opt. Lett., vol. 35, no. 18, pp. 3069–3071, 2010.

[3] V. R. Supradeepa and J. W. Nicholson, “Power scaling of high-efficiency 1.5 μm cascaded Raman fiber lasers,” Opt. Lett., vol. 38, no. 14, pp. 2538–2541, 2013.

[4] J. E. Heebner et al., “High brightness, quantum-defect-limited conversion efficiency in cladding-pumped Raman fiber amplifiers and oscillators,” Opt. Express, vol. 18, no. 14, pp. 14705–14716, Jul. 2010.

[5] J. Nilsson, J. Ji, C. A. Codemard, and J. K. Sahu, “Design, performance, and limitations of fibers for cladding-pumped Raman lasers,” Opt. Fiber Technol., vol. 16, no. 6, pp. 428–441, 2010.

[6] J. Ji, C. A. Codemard, and J. Nilsson, “Analysis of spectral bendloss filtering in a cladding-pumped W-type fiber Raman amplifier,” J. Lightw. Technol., vol. 28, no. 15, pp. 2179–2186, 2010.

[7] L. Zhang et al., “Kilowatt ytterbium-Raman fiber laser,” Opt. Express, vol. 22, no. 15, pp. 18483–18489, 2014.

[8] H. Zhang, R. Tao, P. Zhou, X. Wang, and X. Xu, “1.5-kW Yb-Raman combined nonlinear fiber amplifier at 1120 nm,” IEEE Photon. Technol. Lett., vol. 27, no. 6, pp. 628–630, 2015.

[9] T. H. Runcorn, R. T. Murray, E. J. R. Kelleher, S. V. Popov, and J. R. Taylor, “Duration-tunable picosecond source at 560 nm with watt-level average power,” Opt. Lett., vol. 40, no. 13, pp. 3085–3088, 2015.

[10] C. E. Max et al., “Image improvement from a sodium-layer laser guide star adaptive optics system,” Science, vol. 277, no. 5332, pp. 1649–1652, 1997

ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering
ISSN: 2067-3809