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Impact of 2OD and 3OD on SRS- and XPM-induced crosstalk in SCM-WDM optical transmission link

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Abstract

In this paper, the impact of second-order dispersion (2OD), third-order dispersion (3OD) and modulation frequency over stimulated Raman scattering (SRS)- and cross-phase modulation (XPM)-induced crosstalk in sub-carrier-multiplexed (SCM) wavelength division multiplexed (WDM) transmission link has been analyzed. It has been observed that there is significant effect of 2OD, 3OD and modulation frequency on the SRS- and XPM-induced crosstalk in a SCM-WDM transmission link. Here the results for SRS- and XPM-induced crosstalk have been reported with independent and combined higher-order dispersion. It has been observed that XPM-induced crosstalk lies between [−52.8 to −45.3] and [−94.7 to −78.6] dB in the presence of 2OD and 3OD respectively for modulation frequencies varied from 500 MHz to 2.0 GHz, while it is in the range of [−94.4 to −84] and [−128.5 to −117] dB when both SRS and XPM are taken into consideration.

Keywords: Cross-phase modulation (XPM); Stimulated Raman scattering (SRS); Wavelength division multiplexing (WDM) and higher-order dispersion (HOD) coefficients

1. Introduction

Optical transmission systems using sub-carrier-multiplexing (SCM)-wavelength division multiplexing (WDM) techniques are currently being used for CATV transmission systems, backbones for wireless networks and antenna remoting systems. The fiber nonlinearities lead to crosstalks between sub-carriers of different wavelengths traversing simultaneously through the fiber. Signal distortions in intensity-modulated direct-detection WDM systems induced by interaction of cross-phase modulation (XPM) and dispersion were investigated [1]. The spectral characteristics of stimulated Raman scattering (SRS) and XPM in multispan intensity-modulation direct-detection optical systems were found to be strongly dependent on fiber dispersion, optical signal channel spacing and data rates [2–4]. Crosstalk between wavelengths in SCM-WDM optical communication systems has been studied [5]. It has been reported that in a dispersive fiber, crosstalk can be attributed to SRS and XPM combined with group velocity dispersion (GVD).

The effect of SRS on the hybrid WDM system was measured in a two-channel hybrid WDM system [6]. Variance due to XPM and four-wave mixing induced

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intensity distortion were derived based on the Volterra series transfer function method [7]. Study of XPM- and SRS-induced crosstalk noise evolution as well as their interaction along lossy, nonlinear dispersive fiber in a cascaded IM-DD system was performed and found that it comes mainly from adjacent channels [8]. Power impairments and power penalty due to SRS in dispersion-managed fiber links were evaluated [9]. Transmission limitations due to XPM-induced crosstalk in SCM-dense-wavelength-division-multiplexing (DWDM) systems were studied at wavelength spacing of 50 and 100 GHz [10]. XPM was reported as a major performance-limiting effect in high-bit-rate WDM networks with narrow channel spacing [11]. A four-wavelength bi-directional DWDM CATV system used chirped fiber gratings as the dispersion compensation devices to reduce the fiber dispersion and XPM-induced crosstalk simultaneously [12]. In highly dispersive return-to-zero differential phase-shift keying two adjacent channel transmission system, without spectral overlap, the standard deviation of XPM-induced phase shift was reported inversely proportional to the channel separation [13].

If the peak power of the incident waves is more than a threshold level, both SRS and SBS transfer energy from pump pulse to generate stoke pulses which co-propagate along with the pump signal in the same or opposite directions. The two pulses interact with each other through the Raman gain, Brillouin gain and XPM. A similar situation happens when two or more pulses separated by a small frequency, i.e., 100–200 GHz, interact with each other [14]. The intensity-dependent refractive index may further lead to XPM between the transmitted channels. XPM is severe for adjacent SCM-WDM channels with the same dispersion value because this allows long interaction lengths between channels during transmission. SRS further may cause the transfer of energy from one signal to another WDM channel operating at the adjacent frequency leading to crosstalk and power depletion effects. The SRS effect is more dominant for the frequencies, which are adjoining to the transmitted ones. The crosstalk levels obtained to date [15,16] indicated that crosstalk in SCM-WDM systems can easily reach intolerable levels even with two wavelengths.

The work reported in [5] considered the impact of second-order dispersion (2OD) only for SRS- and XPM-induced crosstalk. With the advancement of communication systems, there is a trend of using higher modulation frequencies. So it is necessary to investigate the performance of optical transmission link at higher modulation frequencies including the higher-order dispersion coefficients. This paper extends the work reported in [5] by including 2OD and third-order dispersion (3OD) coefficients independently at different modulation frequencies.

After describing the introduction in Section 1, the expression for modified XPM- and SRS-induced crosstalk has been reported in Section 2 including the impact of higher-order dispersion coefficients. The results and discussion are mentioned in Section 3 and concluding remarks are given in Section 4.

2. Theory

Here the modified analysis has been reported by taking into account higher-order dispersion parameter. This analysis is important for pulse widths $\leqslant 0.1$ ps. The contribution due to higher-order dispersion parameter β has to be included when the pulse width $T_0 < 0.1$ ps. In general, both β_2 and β_3 contribute to pulse broadening. With the advent of time, the optical communication systems are moving towards femto-second region. Therefore, we have analyzed the SRS- and XPM-induced crosstalk for SCM-WDM transmission link by considering higher-order dispersion β_2 and β_3 (2OD and 3OD).

2.1. SRS and XPM-induced crosstalk

Considering two optical waves with identical polarization, co-propagating in single mode fiber and taking two coupled equations describing XPM under slowly varying envelope are given by [5,16]

$$\frac{\partial \xi_1}{\partial z} + \frac{1}{vg_1}\frac{\partial \xi_1}{\partial t} = \left(-\mathrm{j}\gamma U_2 - \frac{\alpha}{2}\right)\xi_1, \tag{1}$$

$$\frac{\partial \xi_2}{\partial z} + \frac{1}{vg_2}\frac{\partial \xi_2}{\partial t} = \left(-\mathrm{j}\gamma U_1 - \frac{\alpha}{2}\right)\xi_2, \tag{2}$$

where $\xi_i(z,t)$, $i = 1, 2$ denote the slowly varying complex field envelope of each wave. γ = nonlinearity coefficient, $|\xi_i|^2 = U_i$ = channel power, z = transmission distance, α = fiber loss coefficient, v_{g_i} = group velocity for transmitted signal at wavelength λ_i. Therefore, optical power at the input of the fiber can be expressed as

$$U_i = U_c[1 + m\cos\omega t], \tag{3}$$

where $i = 1(\lambda_1)$ or $2(\lambda_2)$ and $\lambda_1 > \lambda_2$, U_c is the average optical power, m the modulation index, $\cos\omega t$ the modulating signal and ω the angular frequency.

SRS interaction in the optical fiber can be described by a set of coupled equations

$$\frac{\partial U_1}{\partial z} + \frac{1}{vg_1}\frac{\partial U_1}{\partial t} = (gU_2 - \alpha)U_1, \tag{4}$$

$$\frac{\partial U_2}{\partial z} + \frac{1}{vg_2}\frac{\partial U_2}{\partial t} = (gU_1 - \alpha)U_2, \tag{5}$$

where $g = g_R/A_{eff}$, g_R is the standard Raman coefficient, $A_{eff} = \pi w^2$ effective fiber area, and w the width parameter (depends upon fiber parameters). Typically $A_{eff} = 55\,\mu m^2$.

Solving Eqs. (1) and (2) of electric envelope by neglecting γ for initial conditions, $z=0$ and $t=\tau_1$

$$\xi_1(z,t)=\xi_1(0,\tau_1)\exp(-\alpha z/2). \tag{6}$$

By substituting the results of $\xi_1(z,t)$ in the second coupled equation:

$$\xi_2(z,\tau_2)=\xi_2(0,\tau_2)\exp(-\alpha z/2) \times \exp\left(-2j\gamma\int_0^z U_1(0,\tau_2+d_{jk}z)\right)e^{-\alpha z}\,dz), \tag{7}$$

$$\tau_1=\tau_2+d_{jk}z.$$

Now the phase is given by ϕ

$$\phi=-2\gamma\int_0^z U_1(0,\tau_2+d_{jk}z)e^{-\alpha z}\,dz, \tag{8}$$

$$\xi_2(z,\tau_2)=\xi_2(0,\tau_2)\exp(-\alpha z/2)\exp(-j\phi).$$

Considering GVD and HOD, the phase modulation can be converted into intensity modulation via relation [18–20]:

$$U_2(z,\tau_2)=U_2(0,\tau_2)\left|\left\{1+j\left(\frac{\partial^2\phi}{\partial t^2}+j\left(\frac{\partial\phi}{\partial t}\right)^2\right)F_1+1 +j\left(\frac{\partial^3\phi}{\partial t^3}-3\frac{\partial\phi}{\partial t}\frac{\partial^2\phi}{\partial t^2}-j\left(\frac{\partial\phi}{\partial t}\right)^3\right)F_2\right\}\right|^2, \tag{9}$$

where $F_1=-\beta_2(z/2)$, $F_2=\beta_3(z/6)$, $\beta_2=\partial^2\beta/\partial\omega^2$ and $\beta_3=\partial^3\beta/\partial\omega^3$ where β is phase constant at wavelength λ_2.

Solving Eq. (9) we get

$$U_2(z,\tau_2)=U_2(0,\tau_2)\left\{\left(1-2F_1-6F_2\frac{\partial\phi}{\partial t}\right)\frac{\partial^2\phi}{\partial t^2}\right\}. \tag{10}$$

As the values of β_2^2 and β_3^2 are very small, they are neglected

$$=U_2(0,\tau_2)e^{-\alpha z}\beta_2\frac{\partial^2\phi}{\partial\tau_2^2}-U_2(0,\tau_2)e^{-\alpha z}\beta_3\frac{\partial^3\phi}{\partial\tau_2^3}, \tag{11}$$

$$\frac{\partial U_2(z,\tau_2)}{\partial z}=U_2(z,\tau_2)e^{-\alpha z}\left[\beta_2+\beta_3\frac{\partial\phi}{\partial\tau_2}\right]\frac{\partial^2\phi}{\partial\tau_2^2}. \tag{12}$$

From (12), the effect of β_2 in $\partial U_2(z,\tau_2)/\partial z$ is given by ζ and the effect of β_3 in $\partial U_2(z,\tau_2)/\partial z$ is given by χ. The impacts of 2OD and 3OD have been studied in the following cases 1 and 2.

Case 1. (XPM-induced crosstalk with 2OD)

The XPM-induced crosstalk due to 2OD coefficient is given by

$$\zeta=U_2(0,\tau_2)e^{-\alpha z}\beta_2\frac{\partial^2\phi}{\partial\tau_2^2}. \tag{13}$$

XPM-induced crosstalk due to 2OD at wavelength λ_2 is given by [5,17]

$$XT_{\mathrm{XPM2}}=-\frac{2\beta_2\gamma U_c\omega^2}{(\alpha-j\omega d_{jk})^2}\{(\alpha L-1+e^{-\alpha L}\cos(d_{jk}\omega L)) +j(e^{-\alpha L}\sin(d_{jk}\omega L)-d_{jk}\omega L)\}. \tag{14}$$

Case 2. (XPM-induced crosstalk with 3OD)

XPM-induced crosstalk due to 3OD coefficient is given by

$$\chi=-U_2(0,\tau_2)e^{-\alpha z}\beta_3\frac{\partial^3\phi}{\partial\tau_2^3}=-U_2(0,\tau_2)e^{-\alpha z}\beta_3\left[\frac{\partial\phi}{\partial\tau_2}\frac{\partial^2\phi}{\partial\tau_2^2}\right], \tag{15}$$

$$\chi=-U_2(0,\tau_2)e^{-\alpha z}\beta_3\left[\frac{4\gamma^2U_c^2\omega^3m^2e^{2j\omega\tau_2}}{(\alpha-j\omega d_{jk})^2}(1-e^{-\alpha z}e^{j\omega d_{jk}})^2\right]. \tag{16}$$

Because of attenuation, this incremental change is attenuated by a factor $e^{-\alpha(L-z)}$. The modulation is obtained at the end of fiber by integrating attenuated power over a length of fiber L

$$\int_o^L \partial U_2(z,\tau_2)e^{-\alpha(L-z)}. \tag{17}$$

Effect on modulation due to β_3 is given by integrating Eq. (17),

$$\int_o^L U_2(z,\tau_2)e^{-\alpha z}\beta_3\frac{\partial^3\phi}{\partial\tau_2^3}e^{-\alpha(L-z)}\,dz =U_2(0,\tau_2)\beta_3\left[\frac{4\gamma^2U_c^2\omega^3m^2e^{2j\omega_{jk}}}{(\alpha-j\omega d_{jk})^2}\right]\int_O^L(1-e^{-\alpha z}e^{j\omega d_{jk}})^2e^{-\alpha L}\,dz. \tag{18}$$

The crosstalk in phasor form is obtained by normalizing expression in Eq. (18) by $mP_c e^{-\alpha L}$. The crosstalk due to 3OD parameter at λ_2 is given by

$$XT_{\mathrm{XPM2}}=-\frac{2m\beta_3\gamma^2U_c^2\omega^3}{(\alpha-j\omega d_{jk})^3}(3+2\alpha L+4e^{-\alpha L}e^{jd_{jk}\omega L} -e^{-2\alpha L}e^{j2d_{jk}\omega L}-2Lj\omega d_{jk}), \tag{19}$$

$$XT_{\mathrm{XPM2}}=-\frac{2m\beta_3\gamma^2U_c^2\omega^3}{(\alpha-j\omega d_{jk})^3}\times\left\{\begin{array}{l}(3+2\alpha L+4e^{-\alpha L}\cos(d_{jk}\omega L)-e^{-2\alpha L}\cos(2d_{jk}\omega L))\\ +j(4e^{-\alpha L}\sin(d_{jk}\omega L)-e^{-2\alpha L}\sin(2d_{jk}\omega L)-2d_{jk}\omega L)\end{array}\right\}. \tag{20}$$

Therefore, the modified expression for the total crosstalk due to SRS and XPM can be obtained using the same method reported in [5,17]

$$\mathrm{XTALK_{TOTAL}}=|\mathrm{XT_{XPM}}+\mathrm{XT_{SRS}}|^2. \tag{21}$$

3. Results and discussions

Here, the results have been mentioned for SRS- and XPM-induced crosstalk at various modulation frequencies in the presence of 2OD and 3OD coefficients independently. An effort has been made for the exhaustive investigation to ascertain the impact of HOD coefficients on non-linear crosstalk in SCM-WDM communication systems. The results have been reported by taking values of the various parameters like: $\Delta\lambda = 4\,\text{nm}$, $U_c = 17\,\text{dBm}$, $L = 25\,\text{km}$, $m = 0.7$, $\gamma = 0.00095/m\,W$, $\alpha = 0.22\,\text{dB/km}$, $g = 5.5\times10^{-11}\,\text{W}^{-1}\text{m}^{-1}$, $\lambda_1 = 1546\,\text{nm}$ and $\lambda_2 = 1542\,\text{nm}$.

Fig. 1 indicates the graph between nonlinear crosstalk due to XPM-induced crosstalk and dispersion at different values of modulation frequencies. From the results, it has been observed that the crosstalk increases exponentially with the increase in dispersion and modulation frequency. The value of XPM-induced crosstalk at 500 MHz modulation frequency varies from −58 to −52.5 dB. Further at modulation frequency of 2.0 GHz, it lies in the range of −54.5 to −50 dB. It varies exponentially for lower values of dispersion and sinusoidally beyond a certain limit of dispersion, so one can select the appropriate frequency as well as the value of dispersion or type of fiber whose value of dispersion gives minimum crosstalk. At 2.0 GHz modulation frequency, the XPM-induced crosstalk increases exponentially upto 4 ps/nm/km dispersion and above 4 ps/nm/km, it varies sinusoidally in the range of −46.8 to −45 dB.

Fig. 2(a) shows the graph between XPM-induced crosstalk and 2OD at varied modulation frequency varying from 500 MHz to 2.0 GHz. The value of 2OD is varied from 10 to 30 ps^2/km. From the results, minimum value of XPM-induced crosstalk is obtained at modulation frequencies up to 500 MHz and 2OD coefficient at 10 ps^2/km. The XPM-induced crosstalk increases exponentially at lower frequencies at 500 MHz and lies in the range of −52.8 to −51.6 dB at a value of dispersion coefficient at 10 and 30 ps^2/km, respectively. But at modulation frequencies beyond 500 MHz, the impact of 2OD on XPM-induced crosstalk is sinusoidal and varies in the range of −49.9 to −45.3 dB for 2OD at 10 ps^2/km. So, optical communication can be designed for tolerable XPM-induced talk at an optimum modulation frequency and 2OD.

Fig. 2(b) shows the graph between XPM-induced crosstalk and 3OD at varied values of modulation frequency varying from 500 MHz to 2.0 GHz. The value of 3OD is varied from 0.1 to 1.0 ps^3/km. The graph shows exponential growth in the range of XPM-induced crosstalk varying from [−94.6 to 88.8] dB for a value of 3OD at 0.1 ps^3/km and maximum value of the XPM-induced crosstalk is experienced at higher values of 3OD, i.e., at 1 ps^3/km. It varies in the range of [−84.4 to

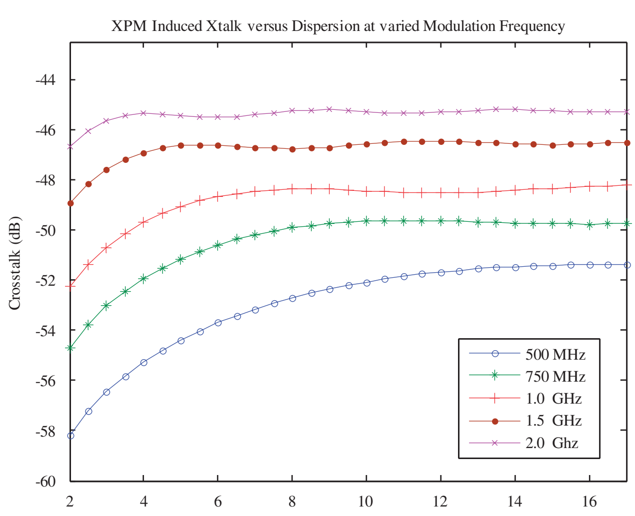
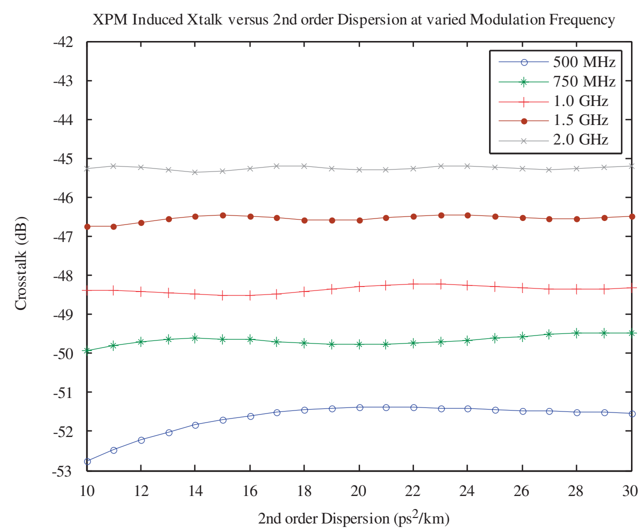


Fig. 1. XPM-induced crosstalk versus dispersion coefficient at varied modulation frequency.



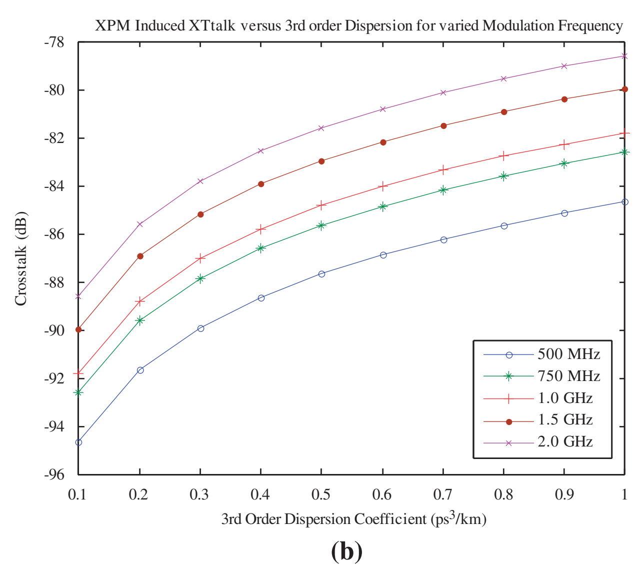


Fig. 2. XPM-induced crosstalk versus (a) 2OD and (b) 3OD coefficient at varied modulation frequency.

−78.8] dB for increasing value of modulation frequency from 500 MHz to 2.0 GHz.

Fig. 3(a) shows the combined effect of SRS- and XPM-induced crosstalk versus dispersion at varied modulation frequency. The value of dispersion is varied from 2 to 17 ps/nm/km. From Fig. 3(a) it has been observed that for 500 MHz modulation frequencies, the SRS- and XPM-induced crosstalk rises exponentially and for modulation frequencies higher than 500 MHz, it varies exponentially for lower values of dispersion and afterwards it varies sinusoidally. For 500 MHz modulation frequency, the value of SRS- and XPM-induced crosstalk rises from −94.4 to −85 dB exponentially. At higher modulation frequencies, the total SRS- and XPM-induced crosstalk increases exponentially up to a certain limit of dispersion and afterwards it varies like a sinusoidal wave. At 2.0 GHz modulation frequency, the minimum value of total crosstalk at −85 dB is observed at a dispersion value of 2.0 ps/nm/km and it increases exponentially up to 4.0 ps/nm/km and beyond this, it varies sinusoidally. For dispersion 17 ps/nm/km, the combined effect of SRS- and XPM-induced crosstalk varies in the range −85 to −84 dB at modulation frequencies of 500 MHz and 2.0 GHz, respectively. Hence communication system can be optimized for minimum value of combined effect of SRS- and XPM-induced crosstalk for a desired operating modulation frequency and dispersion coefficient.

Fig. 3(b) shows the impact of 3OD on total SRS- and XPM-induced crosstalk. The value of 3OD and modulation frequency is varied from 0.1 to 1.0 ps^3/km and 500 MHz to 2.0 GHz, respectively. The graph shows that the total SRS- and XPM-induced crosstalk increases exponentially with increase in 3OD and modulation frequency. For different values of modulation frequency varying from 500 MHz to 2.0 GHz, it increases in the range of −128.5 to −127 dB at 3OD of 0.1 ps^3/km and it rises exponentially up to the range of −118.4 to −117 dB at 1.0 ps^3/km. 3OD.

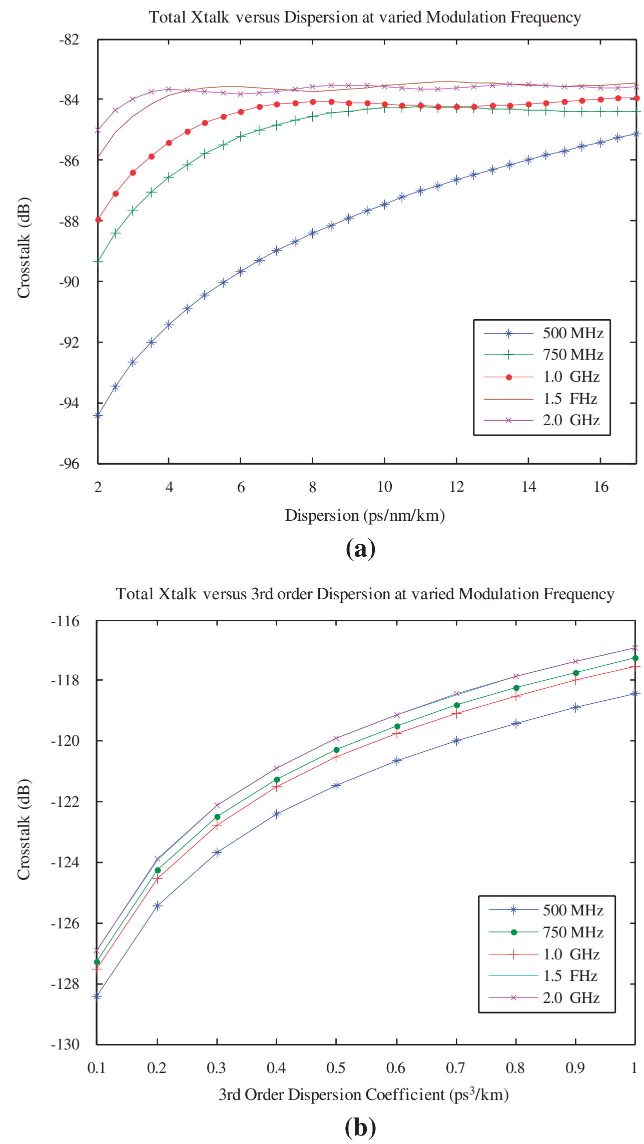


Fig. 3. Total SRS and XPM-induced crosstalk versus (a) dispersion and (b) 3OD coefficient at varied modulation frequency.

4. Conclusions

Here, independent and combined effect of 2OD and 3OD over SRS- and XPM-induced crosstalk in SCM-WDM transmission link has been analyzed at different modulation frequencies varied from 500 MHz to 2 GHz. It has been investigated that there is significant effect of 2OD, 3OD and modulation frequency on the SRS- and XPM-induced crosstalk in SCM-WDM transmission link. It is observed that XPM-induced crosstalk lies between [−52.8 to −45.3] and [−94.7 to −78.6] dB in the presence of 2OD and 3OD respectively for modulation frequencies varying from 500 MHz to 2.0 GHz, while it lies in the range of [−94.4 to −84] and [−128.5 to −117] dB when both SRS and XPM are taken into account.

It has been seen that higher-order dispersion and modulation frequency affect the performance of the SCM-WDM optical communication system. With the increase in dispersion, the SRS- and XPM-induced crosstalk increases exponentially for lower values of modulation frequencies. However, at modulation frequencies beyond 500 MHz, it increases sinusoidally. So, optical communication can be optimized in order to give a minimum value of SRS- and XPM-induced crosstalk at a desired value of dispersion and modulation frequency.

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