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Analytical investigations on crosstalk in fiber Raman amplification for WDM systems

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Abstract

In this paper, the analytical investigations for the crosstalk in fiber amplification for WDM channels have been reported. The crosstalk between WDM channels with external Raman amplification including second-order dispersion terms has been investigated. It has been shown that the higher-order dispersion severely degrades the performance of optical communication systems. To ensure small crosstalk, the signal gain and the injected pump power should be limited to the value well below the threshold of Raman amplification. Analytical formula for signal interference ratio (SIR) and gain in fiber Raman amplifier including the impact of second-order dispersion terms for WDM systems has been derived at different wavelengths. It has also been shown that there is increase in crosstalk due to second-order dispersion.

Keywords: WDM—Wavelength Division Multiplexing; SIR—Signal Interference Ratio; SRS—Stimulated Raman Scattering; Raman amplifiers; Crosstalk

1. Introduction

Optical amplification by stimulated Raman scattering in a single-mode fiber find wide range of applications in optical communication systems. Raman amplifier is used as a preamplifier before the signal is detected at the receiver. Because of their broadband, Raman amplifiers are used to amplify several channels simultaneously in a WDM light wave system, but a high-power laser is required for pumping. The same Raman gain that is beneficial for making fiber amplifiers and lasers is also detrimental for WDM systems, because a short wave length channel can act as a pump for longer wavelength channels and thus transfer part of the pulse energy to neighboring channels. This can cause Raman-induced cross-talk among channels and can affect the system performance considerably [1–13].

One major application is for optical amplification in WDM systems because the bandwidth of the Raman amplifiers can be large enough to accommodate two or more WDM channels and the use of de-multiplexing and multiplexing in each repeater can be avoided. Therefore, various behaviors of Raman amplifiers for WDM system are to be investigated under different assumptions. Also at higher bit rates, dispersion plays

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an important role to degrade the overall performance of light wave systems because different components of signal/pulse arrive at the receiver at different times.

In this paper, we investigate the cross-talk between WDM channel with external Raman amplification by calculating signal interference ratio (SIR) and signal gain by considering second-order dispersion terms.

2. Analysis

The differential equations governing Raman amplifications for two WDM channels system [3–5] can be described as

$$\frac{\partial S_1(z,t)}{\partial z}+\frac{1}{V_g}\frac{\partial S_1(z,t)}{\partial t}+\frac{\beta_2}{2}\frac{\partial^2 S_1(z,t)}{\partial t^2} = \left(\frac{g}{A}P(z,t)-\alpha_g\right)S_1(z,t) \tag{1}$$

$$\frac{\partial S_2(z,t)}{\partial z}+\frac{1}{V_g}\frac{\partial S_2(z,t)}{\partial t}+\frac{\beta_2}{2}\frac{\partial^2 S_2(z,t)}{\partial t^2} = \left(\frac{g}{A}P(z,t)-\alpha_g\right)S_2(z,t) \tag{2}$$

$$\frac{\partial P(z,t)}{\partial z}+\frac{1}{V_p}\frac{\partial P(z,t)}{\partial t}+\frac{\beta_2}{2}\frac{\partial^2 P(z,t)}{\partial t^2} = \left[-\frac{g}{A\lambda_p}(\lambda_1 S_1+\lambda_1 S_2)-\alpha_p\right]P(z,t) \tag{3}$$

It is assumed that two channels have different wavelength λ_1 and λ_2 and both signals and the pump have the same effective core area A. $S_1(z,t)$, $S_2(z,t)$ and $P(z,t)$ are the signal powers of two channels and pump power with pump and group velocities V_g and V_p along $+z$ direction, respectively. λ_p is the wavelength of pump. 'g' is the Raman gain constant. α_g and α_p are fiber losses at the signal and pump wavelength, respectively.

The initial power is the powers given at $z=0$ as follows:

$$S_1(z,t)=S_{10}(t) \tag{4}$$

$$S_2(z,t)=S_{20}(t) \tag{5}$$

$$P(z,t)=P_0(t) \tag{6}$$

$S_{10}(t)$ and $S_{20}(t)$ may be series of pulses. P_0 is the steady injected power. Usually, they are much larger than the spontaneous emission power. In order to solve (1) and (2), we assume that

$$\alpha_g=\alpha_p=\alpha \tag{7}$$

$$V_g=V_p=V \tag{8}$$

$$P_0 \geqslant S_{10}(t)+S_{20}(t) \tag{9}$$

The first assumption in Eq. (7) is true around the 1.5-μm wavelength region in extremely low-loss fibers. The second (Eq. (8)) will affect our conclusion a little, which will be discussed later. Eq. (9) is valid for practical systems. Substituting $S_1(z,t)=S_1$, $S_2(z,t)=S_2$ and $P(z,t)=P$.

After considering the above assumptions in Eqs. (1)–(3), the equations are written as

$$\frac{\lambda_1\partial S_1}{\partial z}+\frac{\lambda_1}{V}\frac{\partial S_1}{\partial t}+\frac{\beta_2\lambda_1}{2}\frac{\partial^2 S_1}{\partial t^2}=\left(\frac{gP}{A}-\alpha\right)\lambda_1 S_1 \tag{10}$$

$$\frac{\lambda_2\partial S_2}{\partial z}+\frac{\lambda_2}{V}\frac{\partial S_2}{\partial t}+\frac{\beta_2\lambda_2}{2}\frac{\partial^2 S_2}{\partial t^2}=\left(\frac{gP}{A}-\alpha\right)\lambda_2 S_2 \tag{11}$$

$$\frac{\partial P}{\partial z}+\frac{1}{V}\frac{\partial P}{\partial t}+\frac{\beta_2}{2}\frac{\partial^2 P}{\partial t^2}=\left(-\frac{gS}{A\lambda_P}-\alpha\right)P \tag{12}$$

To characterize the degradation, the SIR has been chosen and is defined as

$$\mathrm{SIR1(dB)}=10\log_{10}\frac{S_1(L)}{|I_2|},\ \mathit{S}\mathrm{IR2(dB)}=10\log_{10}\frac{S_2(L)}{|I_2|}$$

Here, SIR1 and SIR2 are SIRs of channels 1 and 2, respectively. $S_1(L)$ and $S_2(L)$ are the output power of two channels and 'L' is the fiber length. I_1 is the cross-talk power in channel 1 from channel 2 and I_2 denotes the reverse.

These are defined as

$$I_1=S_1(L)\big|S_{20}=0-S_1(L)\big|S_{20}>0$$

$$I_2=S_2(L)\big|S_{10}=0-S_2(L)\big|_{S10}>0$$

$$I_1=S_1(L)\big|S_{20}=0-S_1(L)\big|S_{20}>0$$

It has been assumed that both channels have equal optical power injected into the fiber in the following discussion.

Let $S_{10}=S_{20}=S_0$. After simplication, we obtain SIR as

$$\Rightarrow \mathrm{SIR(db)} = 10\log_{10}\left[\frac{e^{\psi_1}(L)\{1-e^A-\tau e^{[A+\psi_1(L)]}+\tau e^{[A+\psi_1(L)]}+\tau^2 e^{2[A+\psi_1(L)]}\}}{1+\tau e^{\psi_1}(L)}\right]\times\left[\frac{1+\tau e^{\psi(L)}}{e^{\psi(L)}}\right]$$

$$\Rightarrow \mathrm{SIR(db)} = 10\log_{10}\left[e^{\psi_1[(L)-\psi(L)]}\left\{\frac{1+\tau e^{\psi(L)}}{1+\tau e^{\psi_1(L)}}\right\}\times\left\{1-e^A-\tau e^{[A+\psi_1(L)]}+\tau e^{[A+\psi_1(L)]}+\tau^2 e^{2[A+\psi_1(L)]}\right\}\right] \tag{13}$$

$$\text{Gain or } G(\mathrm{db})=10\log_{10}\left[\frac{S_2(L)}{S_{20}e\times\rho(-\alpha L)}\right]$$

$$S_2(L)=\frac{\lambda_2 C_0 e^{[\psi(L)+\alpha(L)]}}{1+\tau e^{\psi(L)}}$$

where$\Psi(L)$ is an overlap factor that takes into account the relative separation between the two pulses along the fiber

$$\psi(L)=\left(\frac{vC_0}{L+v^2C_0}\right)\left[v\log\frac{(\lambda_1+\lambda_2)S_0}{\gamma P(0)}-\frac{C_1L}{v}-\frac{1}{\alpha^2V}(1-\mathrm{e}^{-\alpha L})\right]$$

$$\Rightarrow G(\mathrm{db})=10\log_{10}\left\{\frac{\lambda_2C_0\mathrm{e}^{[\psi(L)-\alpha L]}}{1+\tau\mathrm{e}^{\psi(L)}}\times\frac{1}{S_0\mathrm{e}^{-\alpha L}}\right\} \tag{14}$$

3. Results and discussion

An attractive feature of Raman amplification is related to their broad band width. It can be used to amplify several channels simultaneously in a WDM lightwave system. Normally, SIR should be better than a given figure of 30 dB for good S/N performance. It is also clear that SIR is deteriorated by the high gain and thus there is an actual signal gain limitation for a given SIR.

In this paper, the values of various parameters are taken as $A=6.4\times10^{-11}\,\mathrm{cm}^2$, $\alpha_\mathrm{g}=\alpha_\mathrm{p}=0.2\,\mathrm{dB/km}$, $\lambda_\mathrm{p}=1.60\,\mu\mathrm{m}$, $\lambda_\mathrm{g}=1.49\,\mu\mathrm{m}$ and $g=0.8\times\gamma\times10^{-11}\,\mathrm{cm/W}$. γ is the polarization factor and takes the value of 0.5 for ordinary single-mode fibers.

Figs. 1–3 show SIR versus the injected pump power for different injected signal powers of −500 dBm, −400 dBm and −30 dBm, respectively. It is clear from the figure that SIR decreases exponentially with pump power in the linear region. For Fig. (1), SIR is 30 dB for pump power of 15 dBm for injected signal power of −50 dBm, which reduces to about 3 dB for pump power of 40 dBm. In Fig. (2), SIR is 30 dB for pump power of 4 dBm and reduces to 3 dB when pump power becomes 30 dBm for injected signal power of −40 dBm. But SIR decreases to 3 dB when pump power becomes 20 dBm for a reduced injected signal power of −30 dBm as shown in Fig. (2).

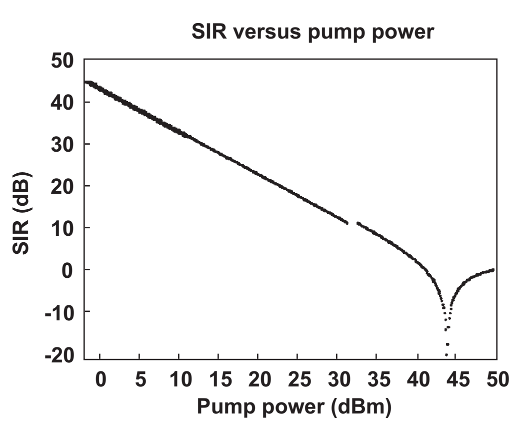

Fig. 1. SIR (dB) versus injected pump power (dBm) with injected signal power ($S_0=-50\,\mathrm{dBm}$) at 400 km, $\lambda_1=1510$ nm and $\lambda_2=1512$ nm.

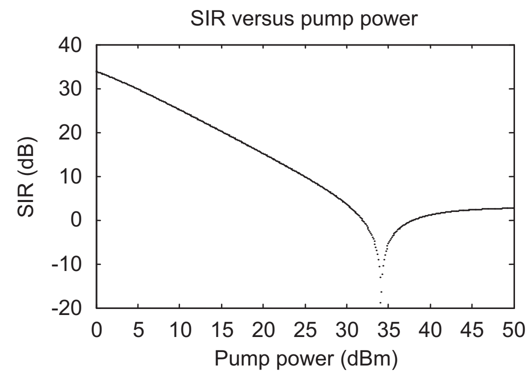

Fig. 2. SIR (dB) versus injected pump power (dBm) with injected signal power ($S_0=-40\,\mathrm{dBm}$) at 400 km, $\lambda_1=1510$ nm and $\lambda_2=1512$ nm.

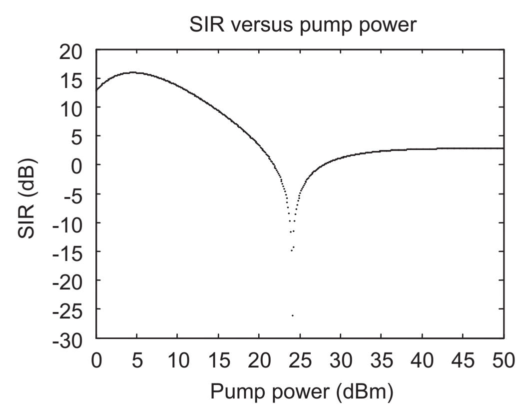

Fig. 3. SIR (dB) versus injected pump power (dBm) with injected signal power ($S_0=-30\,\mathrm{dBm}$) at 400 km, $\lambda_1=1510$ nm and $\lambda_2=1512$ nm.

Thus, the addition of second-order dispersion term has made SIR curves steeper i.e. SIR decreases sharply with pump power than the variation of SIR with pump power considered without second-order dispersion term [3].

4. Conclusion

From the analysis, it is clear that crosstalk between channels exists in Raman amplification for WDM systems and this is measured by SIR. The analytical formula has been derived and it has been shown that acceptable large crosstalk may occur even though the amplifier works in the pump depletion region. To ensure high SIR the signal gain and the injected pump power must be restricted below the threshold values.

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