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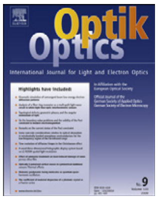

Impact of fibre nonlinearities in optical DWDM transmission systems at different data rates

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ABSTRACT

The impact of major fibre nonlinearities, like stimulated Raman scattering (SRS) and four wave mixing (FWM), in cascaded amplifier dense wavelength division multiplexing (DWDM) transmission system, has been studied at different data rates. SRS has been calculated considering pulse walk off effect. Analysis has been carried out to evaluate signal to noise ratio (SNR) considering the combined effect of SRS and FWM in the presence of amplified spontaneous emission (ASE) noise to achieve minimum noise at different data rates.

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1. Introduction

The current generation of lightwave systems benefit from increased transmission distance by using optical amplification and increased capacity by using wavelength division multiplexing (WDM) technology [1,2]. The emergence of efficient and powerful broadband optical amplifiers, in particular the erbium-doped fibre amplifier (EDFA), has more than anything spurred the enormous increase in capacity and reach in telecommunication networks, in recent years [3]. The large gain bandwidth of these amplifiers has enabled wavelength division multiplexed (WDM) technology, which is used to increase the single fibre capacity by adding many parallel channels positioned side-by-side on a wavelength grid. In particular, dense WDM (DWDM) technology provides the greatest network flexibility with reduced complexity of the control system [4]. DWDM is a technology that uses multiple wavelengths to transport a vast number of separate channels at high data rates.

The reach of present systems is limited by the noise contributed by the used amplifiers, combined with nonlinear effects from transmission [5]. It can be concluded from literature that in a multi-channel system, the effect of fibre nonlinearities should be addressed more properly. The two conventional limiting factors in designing optical communication systems, namely, fibre loss and dispersion, are relatively well understood, and can be easily overcome by optical amplifiers and dispersion compensation but fibre nonlinearities have not been fully analyzed and understood despite a rich collection of literature dealing with fibre nonlinearities [6–14]. Therefore, it is crucial to understand the effects of fibre nonlinearities in DWDM systems.

Authors [15] have earlier studied the combined effect of SRS and FWM in the presence of amplified spontaneous noise (ASE) noise at low data rate that is 2.5 Gbps. The variation of signal to noise ratio (SNR) with respect to inter-amplifier separation, system length and inter-channel separation had been shown graphically. This paper describes the further work to study the combined effect of fibre nonlinearities at different data rates viz 2.5, 10 and 40 Gbps.

The key objective of our work is to do theoretical investigations to study the impact of fibre nonlinearities at different data rates. Keeping in view the findings of the literature [6–9], stimulated Raman scattering (SRS) and four wave mixing (FWM) have been considered as main nonlinearities in our study on non-zero dispersion shifted fibre (NZDSF) at different data rates such as 2.5, 10 and 40 Gbps. The novelty of our work is that SRS has been calculated considering pulse walk off effect and hence the calculation is exact and without any assumption.

2. Limitations due to fibre nonlinearities and ASE noise

The detailed information about the fibre nonlinearities and ASE noise is available in the literature [6–8,13–19]. Effect of SRS considering pulse walk off effect, FWM and ASE on system performance is briefly discussed below.

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2.1. Stimulated Raman scattering (SRS)

Singh and Hudiara [16] have given model to calculate SRS without any assumptions ignoring walk off effects. Modified power due to SRS is given by [16]

$$\begin{aligned} &Pm[k]=Pt[k]-Pt[k]\sum_{i=k+1}^{N}D[k,j]+\sum_{j=1}^{k-1}(Pt[j]D[j,k]) \\ &\text{for}\quad k=1,2,3\cdots N \qquad (1) \\ &D[k,i]=0\quad \text{for } i>N \\ &D[j,k]=0\quad \text{for } k=1 \end{aligned}$$

$$\left.\begin{aligned} &D[i,j]=\left(\frac{\lambda j}{\lambda i}\right)Pt[j]\left\{(fi-fj)/1.5\times10^{13}\right\}g_{r\max}\left\{Le(\lambda j)\times10^{5}/b\times Ae\right\} \\ &\text{for}\quad (fi-fj)\le 1.5\times10^{13}\,\text{Hz and } j>i \\ &D[i,j]=0 \\ &\text{for}\quad (fi-fj)>1.5\times10^{13}\,\text{Hz and } j\le i \end{aligned}\right\} \qquad (2)$$

In Eq. (1), first term gives the total power transmitted to the kth channel, second term gives the total power depleted from the kth channel by the higher wavelength channels and third term indicates the total power received by the kth channel from the lower wavelength channels. The term D denotes the fractional power lost and given by Eq. (2).

In Eq. (2), $g_{r\max}$ is peak Raman gain coefficient (cm/W); λj, λi are the wavelengths (nm) of jth and ith channels; fi, fj are the centre frequencies (Hz) of the ith and jth channels; and $(fi–fj)$ refers to the inter-channel separation, Ae is effective core area of optical fibre in cm^2, $L_e(\lambda j)$ is wavelength dependent effective length and value of b varies from 1 to 2 depending upon the polarization state of the signals.

2.1.1. Pulse walk off effect

When pulses in each channel travel at different group velocities due to dispersion, the pulses slide past each other while propagating. When the faster travelling pulse has completely walked through the slower travelling pulse, the crosstalk effect becomes negligible. The relative transmission distance for two pulses in different channels to collide with each other is called the walk off distance, L_w[17]:

$$L_w=\frac{T_0}{\left|v_g^{-1}(\lambda_1)-v_g^{-1}(\lambda_2)\right|}\approx\frac{T_0}{|D\Delta\lambda|} \qquad (3)$$

where T_0 is the pulse width, v_g is the group velocity, λ_1, λ_2 are the centre wavelength of the two channels, D is the dispersion coefficient and $\Delta\lambda=(\lambda_1–\lambda_2)$.

When dispersion is significant, the walk off distance is relatively short, and the interaction between the pulses will not be significant. When pulses are used, the Raman interaction decreases because the pump and stokes pulses separate as they propagate at different group velocities. Energy transfer between two pulses occurs only when they spatially overlap. The pulse walk off phenomenon has the effect of reducing the interaction length L_{eff} to the propagation distance over which one pulse passes through the other. The most important feature is the group velocity mismatch that limits the SRS process to a duration during which the pump and Raman pulses overlap [17]. The walk off length can be written as

$$L_w=\frac{T_0}{\left|v_{gp}^{-1}-v_{gs}^{-1}\right|} \qquad (4)$$

where T_0 is the duration of pump pulse, v_{gp} is the group velocity of pump and v_{gs} is the group velocity of stokes.

2.2. Four wave mixing (FWM)

FWM power generated at the frequency f_{ijk} is (assuming equal signal power P launched in all the wavelength channels) given by [18]

$$P(f_{ijk})=k^2P^3e^{-aL}\left[\{(M+1)L_e\}/A_e\right]^2\eta_{ijk}d_{ijk}^2 \qquad (5)$$

where $k=32^3X/n^2c\lambda$

$$\begin{aligned} \eta_{ijk}=&\left[\alpha^2/\left(\alpha^2+\Delta\beta_{ijk}^2\right)\right] \\ &\times\left[1+\{4e^{-aL}/(1-e^{-aL})\}^2\right]\sin^2\left(\Delta\beta_{ijk}L/2\right) \end{aligned} \qquad (6)$$

$$\Delta\beta_{ijk}=(2\pi\lambda^2/c)(|f_i-f_k|\cdot|f_j-f_k|)\left\{D+dD/d\lambda(\lambda^2/2c)(|f_i-f_k|+|f_j-f_k|)\right\} \qquad (7)$$

where n is refractive index of the fibre, λ is centre wavelength, X is third order nonlinear electric susceptibility, P is power injected in the channel, a is fibre attenuation coefficient in db/km, M is number of amplifiers, L is the system length, Ae is effective area of fibre, d_{ijk} is degeneracy factor, η_{ijk} is FWM efficiency, c is the velocity of light, $\Delta\beta_{ijk}$ is phase mismatch factor, D is fibre chromatic dispersion coefficient, α is fibre attenuation coefficient in nepers given by $a/4.343$, f_i, f_j, f_k are frequencies of three co-propagating channels and the term $f_j–f_k$ refers to the inter-channel separation between two consecutive channels.

Le is effective system length given by

$$L_e=(1-\exp(-\alpha L))/\alpha \qquad (8)$$

2.3. ASE noise

Chraplyvy [19] gave expression for calculation of noise power due to ASE:

$$Pas=2n_{sp}(G-1)hfB_0M \qquad (9)$$

where h is plank's constant (6.63×10^{-34} J s), f is centre frequency, G is gain of amplifier, B_0 is equivalent rectangular optical bandwidth in Hz, n_{sp} is population inversion parameter, and M is number of amplifiers.

3. Methodology

A program was written in the Matlab to determine the values of SRS, FWM and ASE as per the mathematical relations given in the literature and hence to calculate SNR as per the following relation:

$$\text{Signal to noise ratio (SNR)}=(\text{modified signal due to SRS})/(\text{FWM noise}+\text{ASE noise}) \qquad (10)$$

The SRS has been calculated both ways, considering pulse walk off effect and without considering pulse walk off effect. The SNR was calculated for different data rates and plotted with respect to wavelength. Further, a minimum value of SNR corresponding to the worst affected channel was considered. Subsequently, the SNR was calculated for the different values of the inter-amplifier

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