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ASYMMETRIC PULSE DISTORTION DUE TO PULSE WALK-OFF PHENOMENA IN WIDE-BAND DWDM RAMAN AMPLIFICATION SYSTEMS

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Abstract

The performance of wide-band dense wavelength division multiplexed (DWDM) optical communication systems can be degraded by nonlinearities in optical fiber. It has been shown that stimulated Raman scattering (SRS) is the ultimate performance-limiting phenomenon in multichannel optical transmission systems. The performance degradation imposed by stimulated Raman scattering has been previously studied. However, pulse walk-off effect among different channels has been ignored in analyses. To our knowledge there is no treatise which deals with coupled nonlinear equations (with walk-off effect) in case of wide-band WDM Raman amplification systems. In this paper, we investigate the effect of group velocity dispersion on stimulated Raman crosstalk in case of wide-band DWDM transmission systems. We have also provided a scheme to solve the nonlinear-coupled gain equations with pulse walk-off effect. We have tried to gain deeper insight into the functioning of DWDM Raman amplification systems by using the numerical technique called finite difference time domain method. Finally we have provided results of the simulation for some cases. Since pulse walk-off effect is responsible for transient effects in DWDM Raman fiber amplifier (RFA), hence the modeling has also done in this paper to simulate the effect of abrupt channel addition and removal response**.**

Keywords: Fiber nonlinearity, stimulated Raman scattering, group velocity dispersion, pulse walk-off rate among DWDM channels, finite difference time domain method scheme.

1. Introduction

Simulated Raman scattering (SRS) is a nonlinear scattering process. Nonlinear effect in optical fiber can be observed at relatively low power levels [1]-[4]. In spontaneous Raman scattering, incident light is scattered at a down shifted (Stokes-shifted) frequency. This process is strongly dependent on the power of the incident beam, called pump. As pump power increases, the scattering increases until scattered power reaches a threshold level. If pump power is increased beyond this limit, the scattering becomes stimulated and pump rapidly losses its power to the Stokes shifted beam. The pump is said to be depleted due to stimulated Raman scattering. A Raman amplifier uses intrinsic properties of a silica fiber to obtain signal amplification [5]. This means that transmission fibers can be used as a medium for amplification and hence the intrinsic attenuation of data signals transmitted over the fiber can be combated within the fiber. An amplifier, which works on the basis of this principle, is commonly known as a distributed Raman amplifier (DRA). The physical property behind DRAs is called SRS. The Raman gain depends strongly on the pump power and the frequency offset between pump and signal. Generally, Raman gain increases almost linearly with wavelength offset between signal and pump peaking at about 100 nm. The usable gain bandwidth is about 48 nm. The gain band within the wavelength domain can be adjusted by tuning the pump wavelength. Thus, Raman amplification potentially can be achieved in every region of the transmission window of the optical transmission fiber. It only depends on the availability of powerful pump sources at the required wavelengths. In a chromatic type of dispersion, pulses at different wavelengths propagate at different speeds inside a fiber because of a mismatch in their group velocities. This feature leads to a walk-off effect that plays an important role in the description of the nonlinear phenomena involving two or more closely spaced optical pulses. The performance degradation imposed by stimulated Raman scattering (SRS) process has been previously studied in several papers [6]-[19]. However pulse walk off effect among different channels have been ignored in all the analyses mentioned above. Now, with the increasing of the bit rate per channel and the deployment of fibers with relatively high chromatic dispersion, the walk off effects becomes important. Although D. Cotter and A. M. Hill have studied for the first time the effect of group velocity dispersion on stimulated Raman scattering crosstalk with different modulation techniques and line codes [20], however the pulse distortion due to pulse walk-off effect in multichannel transmission systems has not been discussed sofar. If dispersion shifted fibers (DSF's) are employed instead of single mode optical fibers, the group velocity mismatch among different channels may become even insignificant [24]. This is because group velocity dispersion (GVD) at some bands becomes the same, and no walk-off situation can be occurred. Suppose that channels are allocated symmetrically with respect to zero-GVD wavelength. Optical signals propagate with the same propagation velocity and interact with each other for a long distance. Then, pulses are distorted drastically. Moreover, when the channel separation reaches 100 nm, the pulse distortion even become more serious due to the high walk off rate among wide-band DWDM channels. In the future, invented optical amplifiers or Raman amplifiers will be applied for other wavelength band, and the wide-band transmission will be conducted. Therefore, evaluation of pulse distortion taking in to account of group velocity dispersion for such a wide-band is expected. If conventional single mode fibers (SMF's) are employed instead of dispersion shifted fibers, the group velocity mismatch among different channels may become even more significant due to the high dispersion of conventional single mode fiber at $1.55\ \mu m$ hence it can not be neglected for systems with a large number of channels, especially when conventional single mode fiber is employed. The pulse walk-off effect may lead the significant positive chirp for the high frequency channel; hence in the anomalous regime, high frequency channel would suffer very less amount of dispersion. This feature can be exploited to overcome the chromatic dispersion effect in DWDM transmission systems [28].

2. Raman-Gain Equation with Pulse Walk-Off Effect in Dwdm Transmission Systems

In this section we discuss about the DWDM Raman gain equation with pulse walk-off effect. Consider that N channels are launched into the fiber. Lower number of the channel represents a channel at a shorter wavelength (higher frequency). Thus channel 1 is the highest frequency channel and channel N is the lowest frequency channel. A given channel will act as a pump for all the lower frequency (higher-numbered) channels and will lose power to those channels while it will act as a Stokes channel for all the higher frequency (lower-numbered) channels. The equation governing the above process is given by [12]

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_i}\frac{\partial}{\partial t}\right)P_i(z,t)=P_i(z,t)\left[-\alpha_i+\sum_{j=1}^{i-1}g_{ij}\frac{P_j(z,t)}{K_{ij}A_{ij}}-\sum_{j=i+1}^{N}g_{ij}\frac{\lambda_j}{\lambda_i}\frac{P_j(z,t)}{K_{ij}A_{ij}}\right],$$

$$1\le i\le N, \qquad (1)$$

where power of i^{th} channel $P_i(z,t)$ is the function of distance z and time t, α_i is its linear attenuation coefficient, g_{ij} is the Raman gain coefficient in the fiber between channels i and j, λ_i and λ_j are the wavelengths of i^{th} and j^{th} channels, A_{ij} is the effective overlap area of the modes of channel i and j, and K_{ij} is a factor between 1 and 2. The actual value of this factor depends on the relative polarization of the fields of channels i and j. The second term on the left-hand side of eq. (1) indicates that the propagation velocity for each channel $\left(v_i\right)$ is different. Thus, if the channels are used to transmit data, a pulse in one channel may be traveling faster than the pulse in another channel. After a length called the walk-off length [21], the pulses will not interact with each other because they do not occupy the same space within the fiber. Although several papers have been published on SRS crosstalk with the effect of group velocity dispersion (GVD) [19]-[27], however pulse shape distortion due to SRS crosstalk with the effect of pulse walk-off has not been discussed so far. Consider that all channels lie within linear portion of the Raman gain profile and are equally separated in the spectral domain. In addition let us employ the triangular approximation to the Raman gain curve. In this approximation, the Raman gain is assumed to vary linearly with frequency as long as the spectral separation between highest and lowest channel is kept below 13.2 THz [12]. For this assumption, above eq. (1) would become as [16], [17]

$$\frac{dP_n(z,t)}{dz} + \beta_1^n.\frac{dP_n(z,t)}{dt} + \alpha.P_n(z,t) + \left(\frac{g^{'}\Delta f}{2.A_{eff}}\right).P_n(z,t).\sum_{m=1}^{N}\left(m-n\right).P_m(z,t) = 0. \qquad (2)$$

Where $g^{'} = \frac{dg}{df}$ represents the slope of the Raman gain profile, β_1^n represents group velocity term, Δf is the inter channel spacing, and A_{eff} is the effective cross-sectional area of the single-mode fiber. The gain has been divided by 2 to account for polarization averaging. In deriving eq. 2, it was implicitly assumed that $\frac{\lambda_j}{\lambda_i} \approx 1$. In this section we have discussed about the nonlinear-coupled Raman gain equations for N-channels DWDM transmission systems and also discussed about the need to consider the pulse walk- off effect within the analyses. In the next section we have devised an algorithm for solving this set of equations.

3. Simulation Scheme

In this section we apply finite difference time domain method to devise a simulation scheme for the coupled nonlinear Raman gain equations discussed in the second section. Above eq. (2) can be written by finite difference time domain method scheme as [29]-[31]

$$\frac{P_{n,i+1}^{n} - P_{n,i}^{n}}{\Delta z} + \beta_1^n\left[\frac{P_{n,i+1}^{n+1} - P_{n,i+1}^{n-1}}{4.\Delta t} + \frac{P_{n,i}^{n+1} - P_{n,i}^{n-1}}{4.\Delta t}\right] + \alpha\left[\frac{P_{n,i+1}^{n} + P_{n,i}^{n}}{2}\right] + \frac{g^{'}\Delta f}{2.A_{eff}}\left(\sum_{m=1}^{N}\left(m-n\right)P_m\right)\left[\frac{P_{n,i+1}^{n} + P_{n,i}^{n}}{2}\right] = 0. \qquad (3)$$

After rearranging the above equations we get

$$\begin{aligned}
&P_{n,i+1}^{n}\left[1+\frac{\Delta z}{2}\left(\alpha+\frac{g^{'}\Delta f}{2.A_{eff}}\left(\sum_{m=1}^{N}\left(m-n\right)P_{m}\right)\right)\right]\\
&+\frac{\beta_{1}^{n}.\Delta z}{4.\Delta t}P_{n,i+1}^{n+1}-\frac{\beta_{1}^{n}.\Delta z}{4.\Delta t}P_{n,i+1}^{n-1}=P_{n,i}^{n}\left[1-\frac{\Delta z}{2}.\left(\alpha+\frac{g^{'}\Delta f}{2.A_{eff}}\left(\sum_{m=1}^{N}\left(m-n\right)P_{m}\right)\right)\right]\\
&-\frac{\beta_{1}^{n}.\Delta z}{4.\Delta t}P_{n,i}^{n+1}-\frac{\beta_{1}^{n}.\Delta z}{4.\Delta t}P_{n,i}^{n-1}
\end{aligned}\tag{4}$$

A detail of the treatment with this coupled Raman gain equations is given in Appendix. The simulation mythology is used to solve these nonlinear coupled equations forms- (8), (9), (10), (11) and (12) (see Appendix) respectively by taking inverse of matrix M_1 and find the new value of A_{i+1} from eq. (8), put this value of A_{i+1} into matrix M_3 and find the new value of B_{i+1} from eq. (9), put the new found values of A_{i+1} and B_{i+1} into matrix M_5 and find the new value of C_{i+1} from eq. (10), now put the new found values of $A_{i+1,}B_{i+1},C_{i+1}$ into matrix M_7 and find the new value of D_{i+1} from eq. (11), again put the new values of $A_{i+1},B_{i+1},C_{i+1},D_{i+1}$ into matrix M_9 and find the latest value of E_{i+1} from eq. (12). The next step of simulation is to repeat the above mention iteration, once again put the new values of $A_{i+1},B_{i+1},C_{i+1},D_{i+1},E_{i+1}$ into matrix M_1 and find the latest value of A_{i+1}. This whole process is repeated a couple of times. It should be noted that M_1,M_3,M_5,M_7,M_9 are not constant and depends on the values of $A_{i+1},B_{i+1},C_{i+1},D_{i+1},E_{i+1}$ and hence the values of the entries of these all matrices should be updated each time a correction is done in $A_{i+1}.......E_{i+1}$.

In this section of paper we have suitably modeled the equations to make them amenable to numerical methods. Increasing the number of mesh points in time and distance axis, account on simulation time can increase the accuracy of the model.

4. Asymmetric Pulse Distortion Due to Pulse Walk-Off Phenomena

In the previous section we looked at how we can suitably model the equations in the difference form so that they can be solved numerically on a computer. In this section we look at some of the results of these simulations. As an example, let us consider a single mode optical fiber operating at $\lambda = 1.55 \ \ \mu m$. At this wavelength, the fiber attenuation is assumed to be $0.2 \quad dB/km \quad (\alpha = 0.046 \ km^{-1})$ and the Raman gain slope is approximately $\left(g^{'}\right) = 4.9 \times 10^{-18} m/\left(W - GHz\right)$ [17]. In all cases, the effective cross-sectional area of the fiber, is assumed to be $50 \ \ \mu m^{2}$ and the inter channel frequency spacing $100 \ \ GHz$. In addition, group velocity dispersion parameter $\left(\beta_1\right) \approx 4.875 \ \ ns/m \ (1.55 \ \ \mu m)$ has been used for all calculations. In our model, we have considered $10 \ \ ps$ unchirped Gaussian input pulse, pulse walk off rate among DWDM channels is $500 \ \ ps/km$ [20], and hence total walk-off length is $20 \ m$. Moreover we have considered the case of normal dispersion region $\left(\beta_2 > 0\right)$; a longer wavelength pulse travels faster. In case of loss less energy system we have considered $\alpha = 0$ for further analysis to understand the better pulse shape distortion.

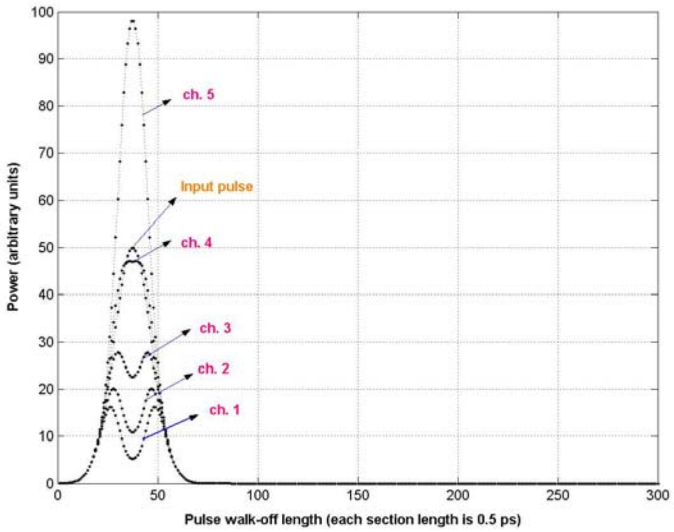

Figure. 1 Pulse distortion, when there is no pulse walk-off among DWDM channels. Pulses are distorted symmetrically.

Situation is discussed when channels are allocated symmetrically with respect to zero GVD wavelength, in this case the pulse walk-off can be ignored for a small group of closely spaced channels. If group velocity dispersion between channels is small or zero, the longer wavelength channels eats the optical power of the pulse in the pump channel for a long time, and the pulse shape of the pump channel is changed. Therefore the pulse distortion in the pump channel is occurred, which is reported in Fig. 1. In Fig. 1, channel-1 work as a pump for other low frequency channels. It is worth mentioning here that pulse distortion of channel-1 and others are symmetric in this case. Hence the prediction of the behaviour of transmitted signal can be done. Usually the crosstalk among the DWDM channels is high in this case because of long interaction length among the channels. Usually large wavelength difference results in large group velocity dispersion.

In this case, pulse distortion even become smaller due to group velocity dispersion, because it acts to reduce the amount of interaction time between different channels [20]. Next we can see the pulse distortion due to moderate to high pulse walk-off effect.

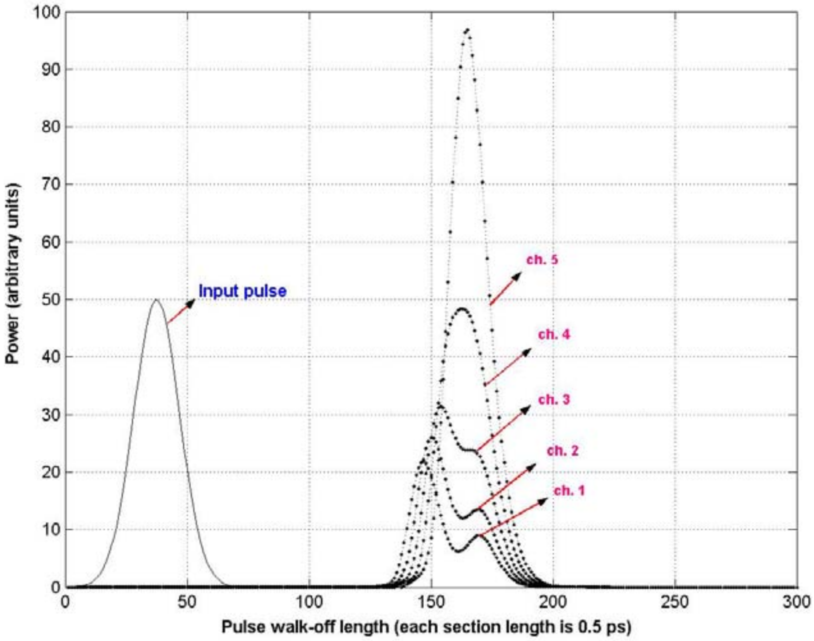

Figure. 2 Pulse distortions, when pulses are just start walking away to each other. There is clearly visualable the severe crosstalk and moderate pulse walk-off effect. Pulses are tends to be asymmetric.

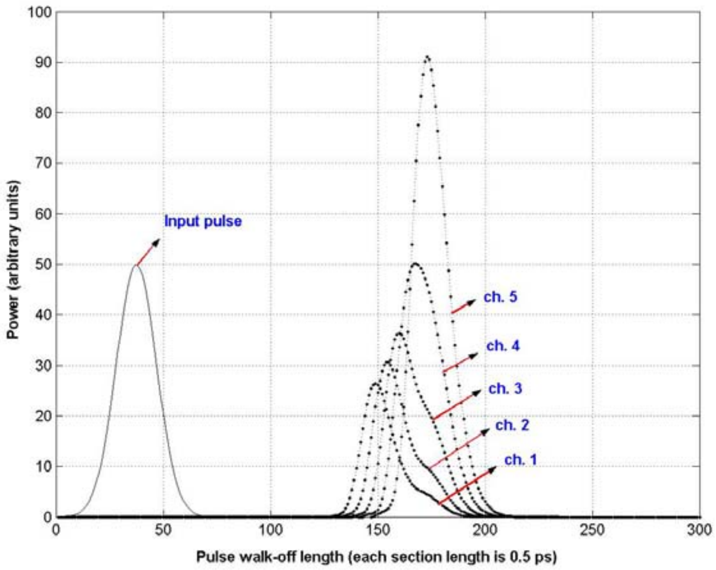

Figure. 2 Asymmetric pulse distortion, when pulses are walking away much longer than above case (severe pulse walk-off effect but moderate crosstalk). There is significant asymmetric pulse distortion.

It is clear from Fig. 2 and Fig. 3, that pulse walk-off phenomena may distort the pulse shape in asymmetric way. So even after transmitting the optical signals for few hundred-kilometer length of fiber, the prediction cannot easily be done about the behaviour of the transmitted signal due to asymmetric pulse distortion. Pulse walk-off effect may reduce the information carrying capacity of WDM transmission systems because of high bit rate per channel, which may distort pulse badly, moreover it will reduce the interaction time of two co propagating signals resultant it may reduce the crosstalk too.

5. Channel addition/removal response: modeling

Now we can easily imposed the boundary conditions into our developed simulation scheme to see the effect of abrupt channel addition and removal response. Fiber Raman amplifier (FRA) are playing a critical role with increasing importance in high speed/long haul wavelength division multiplexed systems as they can provide low noise wide-band optical amplification. Furthermore with the implementation of all optical switching technology, dynamic characteristic of these amplifiers due to abrupt channel add/drop attracts considerable interest. Since the pulse walk-off effect is responsible for transient effect, hence transient is defined as the output signal power response to abrupt input signal power change.

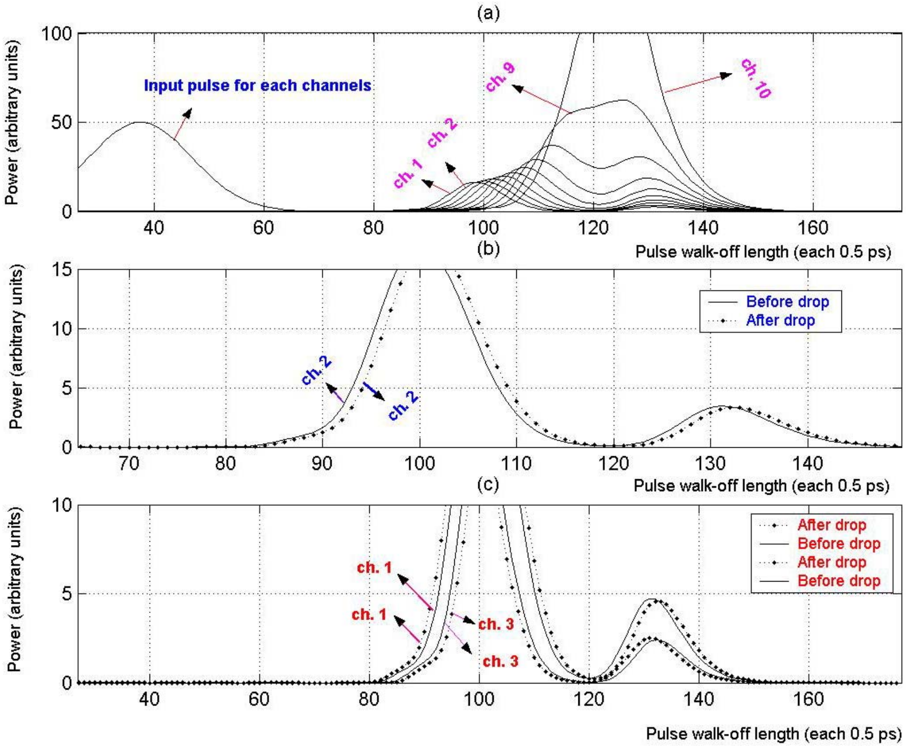

Figure 4
a) There are 10 channels to show the effect of abrupt channel addition and removal response.
b) Performance of channel-2 is checked just before and after dropping of channel-1 at some arbitrary simulation run length.
c) The performances of channel-1 and channel-3 are checked just before and after the dropping of channel-2 at some arbitrary point.

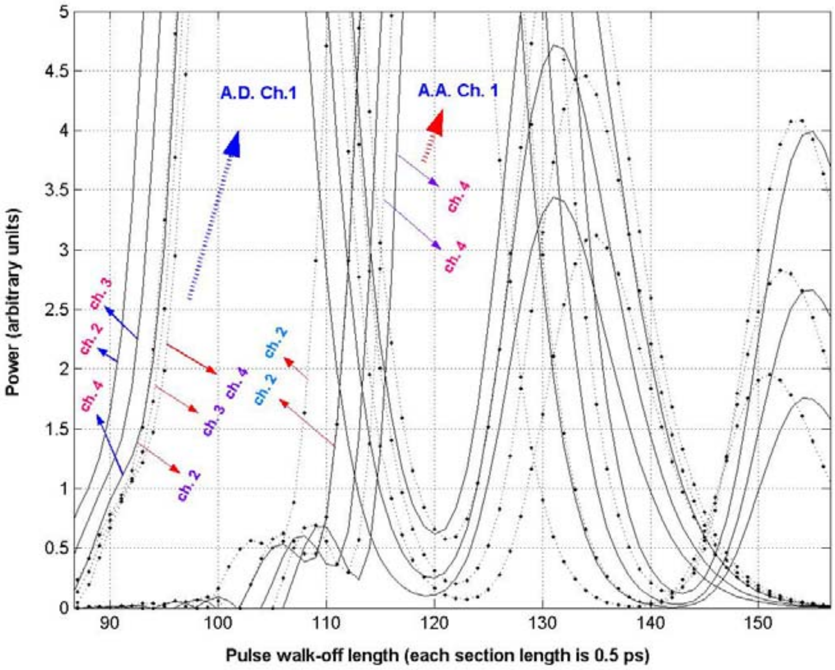

Figure. 5 The performances of channel-2, channel-3 and channel-4 are checked just before and after the dropping and adding of channel-1 at some arbitrary points (A.D. means after drop, A.A. means after add).

In DWDM systems, signal power of surviving channels will change when channel add/drop occur due to gain saturation of the optical amplifier incorporated in the system. Because of all the channels in DWDM Raman amplification systems are coupled to each other, hence addition or removal of channels will tend to perturb channel at other wavelengths that share all or part of the route. In our modeling we have taken 10 DWDM channels, as shown in Fig. 4(a). Our aim is to investigate the sudden channel addition and dropping effect on the other surviving channels [32]-[36]. The performance of channel-2 is checked just after when channel-1 drops at some arbitrary points. As the channel-1 drops, channel-2 will get affected much more than any other channels because it is the nearest one. It is expected that channel-2 will no longer get power from the channel-1; hence the power level of channel-2 will get reduced slightly, which is observed in Fig. 4(b). In the second case, the performances of channel-1 and channel-3 are checked just before and after of channel-2 drops at some arbitrary points. Now it is obvious that at some arbitrary points where channel-2 drops, channel-1 will grow slightly but channel-3 will get depleted slightly, which is observed in Fig. 4 (c). In the third case, the performances of channel-2, channel-3 and channel-4 are checked just before adding and after dropping of channel-1 at some arbitrary points of simulation. It is obvious that just after dropping and adding of channel-1 will leads to perturb the other subsequent channels-2, 3 and 4. Hence channel-2 will be affected more instead of other channels, which is shown in Fig. 5.

Conclusion:

In the literature, the effect of group velocity dispersion on stimulated Raman scattering crosstalk has been studied with different modulation techniques and line codes but no one has studied it by using finite difference time domain method so far. We have developed an algorithm by using finite difference time domain method to tackle the nonlinear Raman gain equations in case of DWDM systems. We have also provided a scheme to solve them with pulse walk-off effect. It has been shown that pulse walk-off phenomena may distort the data asymmetrically; especially in case of wide-band DWDM transmission system is concern. Hence the pulse walk-off effect must be considered into analyses for future invented optical amplifier. It has also shown that large walk-off rate may reduce the crosstalk among DWDM channels. Hence in this way we can at least minimized the crosstalk among the DWDM channels but the only problem is asymmetric pulse distortion, as a consequence lost the useful data. Hence pulse distortion effect due to pulse walk-off phenomena is unpredictable. Data may lose due to walk-off phenomena. Since we have developed a numerical techniques to see the effect of abrupt channel addition and removal response, hence modeling has also been done within the paper.

Appendix

We are assuming that initially there is no field anywhere in the fiber. This initial condition lets enable us to write the difference form eq. (4) in a more compact matrix form, which is shown below

$$X = 1 + \frac{\Delta z}{2}\left[\alpha + \frac{g^{'}\Delta f}{2.A_{eff}}\left\{\sum_{m=1}^{N}(m-n)P_m\right\}\right] \tag{5}$$

$$Y = 1 - \frac{\Delta z}{2}\left[\alpha + \frac{g^{'}\Delta f}{2.A_{eff}}\left\{\sum_{m=1}^{N}(m-n)P_m\right\}\right] \tag{6}$$

$$\begin{bmatrix} X\text{........}\dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{....}0\text{.........} \\ -\dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{....}\dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{.........} \\ 0\text{...................................} \\ \text{...................................} \end{bmatrix} \begin{bmatrix} P_{n,i+1}^1 \\ P_{n,i+1}^1 \\ . \\ . \\ P_{n,i+1}^n \end{bmatrix} = \begin{bmatrix} Y\text{........}-\dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{....}0\text{.........} \\ \dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{....}-\dfrac{\beta_1^n.\Delta z}{4.\Delta t}\text{...........} \\ 0\text{.....................................} \\ \text{...} \end{bmatrix} \begin{bmatrix} P_{n,i}^1 \\ P_{n,i}^1 \\ . \\ . \\ P_{n,i}^n \end{bmatrix}. \tag{7}$$

Split the above eq. (7) for five channels DWDM systems denoted by letters A, B, C, D and E respectively. Let us for channel-1, denote it by matrix M_1, M_2 therefore the equations can be more compactly

written as

$$M_1.A_{i+1} = M_2.A_i \tag{8}$$

similarly for the other channels also

$$M_3.B_{i+1} = M_4.B_i \tag{9}$$

$$M_5.C_{i+1} = M_6.C_i \tag{10}$$

$$M_7.D_{i+1} = M_8.M_i \tag{11}$$

$$M_9.E_{i+1} = M_{10}.E_i\ . \tag{12}$$

Where all of the above ten matrices are tri-diagonal matrices. We can exploit this fact and make efficient routines for inverting these matrices. We note that the equations are still coupled.

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