Non-linear cross-talk analysis in fiber Raman amplifiers

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Optical non-linearities limit the optical power and information capacity of light-wave systems. These non-linearities introduce different types of frequency and phase distortions, which lead to cross-talk. Various non-linear effects that affect Raman amplification have been discussed and an evaluation of the cross-talk induced due to these effects, has been presented. The maximum input power that can be transmitted in a WDM system without degrading its performance has also been evaluated.

1 Introduction

Since the first low-loss fiber in 1970, fiber-optics emerged from being a laboratory curiosity to constituting a significant portion of the communications and sensors business. Throughout the world, optical cables are carrying plain, old telephone service across land and sea, along with data and video, at rates exceeding several gigabytes per second. Optical fiber communication systems have made dramatic progress over the past years. Both bandwidth and wavelength utilization have significantly improved and continue to do so. Within this decade, dense WDM systems are expected to span the entire low-loss range in silica fibers of 1.2 to 1.7 μm (Ref. 2).

This huge bandwidth will only be accessible, if suitable optical amplifiers are available. EDFAs have some advantages such as, large available power amplification, relatively good, overall power efficiency, small size and small dependence of amplification on optical polarization. EDFAs used in WDM transmission systems are so-called lumped amplifiers in which, the gain is lumped at a point of the transmission line. Such amplifiers are often cascaded to overcome the fibre loss in a communication channel, but, in such system, amplified spontaneous emission (ASE), accumulates to affect the gain and deteriorates the SNR at the receiver. On the other hand, distributed amplifiers, such as, fiber Raman amplifier, retain the optical signal level over a long distance along the transmission line and provides better system performance. Although, it was even before EDFAs that Raman amplifiers were used in experiments, using large scale solid-state lasers. They were not actually deployed in real field systems until recently, when high power diode pump sources became commercially available. Studies on Raman amplifiers have been continually conducted to suggest two critical merits of Raman amplifiers; one is low noise and the other is arbitrary gain band. Raman amplifiers can work at any wavelength as long as the pump wavelength is suitably chosen. The wide wavelength range of pump light in a wide and flat composite gain spectrum of Raman amplifier is suitable for multi-channel systems in the low loss region of light-wave system. In practice, the gain spectrum is flattened by using several pumps at different wavelengths, yielding a super-posed flat gain spectra. In general, such pump beams are also affected by Raman scattering as well, with the WDM channels. This would result in power exchange between WDM channels. The cross-talk in such WDM channels leads to signal degradation due to stimulated Raman scattering (SRS), cross phase modulation (XPM), interaction with group velocity dispersion (GVD), self phase modulation (SPM), four wave mixing (FWM), etc.

In this paper, one of the issues that degrades the performance of Raman amplifiers i.e. channel cross-talk is taken up. In WDM, light at numerous wavelengths is injected into the fiber and the signals at longer wavelengths will be amplified not only by the pump but also by other signals at shorter wavelengths. This is a serious problem in Raman amplifiers. Here, a detailed analysis of the various factors that cause cross-talk in Raman amplifiers pumped in one direction and also bi-directionally
pumped Raman amplifiers has been done. The maximum power that can be transmitted through the fiber without degrading system performance is also estimated.

2 Theory

Stimulated Raman scattering is an important non-linear process that can turn optical fibers into broad-band amplifiers and tunable Raman lasers. Raman scattering can be viewed as modulation of light by molecular vibrations in the silica matrix.

In Raman scattering, a pump photon is annihilated and a Stokes photon is created along with quantum vibrational energy in the scattering molecule. If a probe signal at Stokes frequency is co-injected into Raman active medium, the probe will be amplified at the expense of the pump. The strength of this amplification is exponentially dependent on pump intensity.

\[ P_1(L) = P_0 \exp \left( g L P L \delta \gamma_0 \right) \]  

where \( P \) is the injected pump power, \( A \) is the effective area of propagating waves, \( L \) is the effective fiber length to account for fiber loss, and \( b \) is the relative polarization factor of the amplifier. Effective area is approximated as \( \pi w^2 \) with a mode-field diameter \( w \). The exponential decay of power will be given as:

\[ L_e = \frac{1}{e^{aL}} \]  

where \( L_e \) is the effective length in case of exponential decay of power will be given as:

\[ L_e = \frac{1-e^{-aL}}{a} \]  

The same phenomenon of SRS that is beneficial for making fiber amplifiers is also detrimental to multi-channel communication systems employing wavelength division multiplexing. The reason is that, the short wavelength channel can act as a pump for longer wavelength channels and transfer part of the pulse energy to the neighbouring channels. This leads to Raman-induced cross-talk among channels that can affect the system performance considerably. Channel cross-talk is induced due to various non-linear effects of which SRS, XPM, SPM, FWM and stimulated Brillouin scattering (SBS) are important.

There are two types of Raman amplifiers; discrete Raman amplifier and Distributed Raman amplifier. They differ in two ways: 1) Fiber type and length; 2) Pumping geometry. In both, there is a fundamental design compromise between bandwidth and low noise operation. In discrete Raman amplifier noise figure will be 5-6 dB at shorter wavelengths due to increase in spontaneous emission for the signal wavelength closer to pump wavelength. While for distributed Raman amplifier, it has always an improvement in noise figure.

The Raman gain coefficient increases linearly with pump probe frequency separation up to 500 cm\(^{-1}\) (15000 GHz). This gives us an easy and efficient way for obtaining the Raman gain coefficient profile by using linear and exponential approximations in the respective regions of the spectrum. This model has been used for theoretical estimation of stimulated Raman cross-talk in the multi-wave optical channel. Moreover, since, transmitted optical powers for analog CATV signals carried by the fiber typically need to be in the order of 10 dBm. This high power level induces a variety of fiber non-linear effects leading to system impairment, particularly in WDM systems. Amongst these effects cross-talk due to stimulated Raman scattering\(^6\) (SRS), self-phase modulation, cross-phase modulation (XPM)\(^9\), Brillouin scattering\(^11\) and four wave mixing\(^12\) are predominant.

The total cross-talk due to SRS and XPM is given by\(^11\):

\[ X_{XT} = \frac{P_i^2}{\alpha^2 + d^2} \left[ 1 + g(e^{-(1/\alpha L)} - 1) \right] \frac{D e^{2\Omega \gamma}}{\pi \alpha} \]  

\[ \left[ e^{aL} \cos (dL) - 1 + aL \right] + j \left[ e^{aL} \sin (dL) - dL \right] \]  

where \( P_i \) is the transmitted power per carrier, \( a \) is the fiber-loss coefficient, \( \alpha \) is the fiber Kerr coefficient, \( g \) is the Raman-gain coefficient, \( L \) is the fiber length, \( d = 2\Omega \Omega D \delta \) is the walk-off parameter between the two carriers, \( \Omega \) is the modulation frequency, \( D \) is the chromatic dispersion and \( \delta \) is the wavelength separation between optical channels. The first term is, the SRS cross-talk term and the second and third are XPM terms.

Combining the non-linear effects of the Brillouin scattering and four-wave mixing, the total cross-talk comes out to be:

\[ X_{NT} = \frac{P_i^2}{\alpha^2 + d^2} \left[ 1 + g(e^{-(1/\alpha L)} - 1) \right] \frac{D e^{2\Omega \gamma}}{\pi \alpha} \]  

\[ \left[ e^{aL} \cos (dL) - 1 + aL \right] + j \left[ e^{aL} \sin (dL) - dL \right] \]
\[+\{g_{im} I_p L_a \left( \Gamma - j \Delta \Omega \right) / (\Delta \Omega^2 + \Gamma^2) - \alpha L \} + \{(\eta/P) (1024 \Gamma^4 / n^2 \chi'^{(2)} (\chi_{1111})^2 (L_a/A)^2) \}^F \]

where \(g_{im}\) is the Brillouin-gain coefficient, \(I_p\) is the pump light intensity, \(\Delta \Omega = f_p - f_s\), \(f_p\) is the pump frequency, \(f_s\) is the signal frequency, \(f_{\text{Br}}\) is the frequency of Brillouin-gain, \(\Gamma\) is the acoustic phonon life-time, and \(\chi_{1111}\) is the third-order non-linear susceptibility.

The cross-talk for discrete Raman amplifier (pumped in one direction) was evaluated and the plot of cross-talk versus modulation frequency is obtained. In distributed Raman amplification (DRA), both forward and backward pumping is done. For DRA configuration, it reduces the fiber attenuation and \(\alpha\) must be replaced by some \(\alpha'\) which corresponds to zero, when the Raman-gain cancels out fiber loss. The cross-talk variation with modulation frequency was determined for DRA, using the above equation and typical curves have been obtained.

In this paper, two channel WDM system with signal wavelengths 1542 and 1553 nm, respectively, has been taken into consideration. The transmission fiber is a 25 km long, standard, single-mode fiber (SMF), with \(\alpha = 0.22 \text{ dB/km}\) and \(D = 17 \text{ ps/(nm-km)}\).

Stimulated Raman scattering and stimulated Brillouin scattering pose serious limitations to the input power that can be transmitted through any optical system\(^4\). The critical power that can be transmitted through the system without degrading...
the performance was also evaluated for both the cases. 

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It is clear from Figs 1(a) and (b) that, as modulation frequency increases the cross-talk decreases, more rapidly, in the case of DRA. However, the order of magnitude of cross-talk is lesser in the case of discrete Raman amplifier, which may be attributed to higher attenuation compared with the distributed case.

3 Results and Discussion

Using Eq. (4), the total cross-talk in case of discrete Raman amplifier and distributed Raman amplifier has been numerically estimated as shown in Figs 1(a) and (b).

It is evident that, in discrete Raman amplifier pumped from one end, power will attenuate, as it propagates, giving a lesser cross-talk and hence exponential decrement with modulation frequency will be lesser as compared to the DRA case. In case of DRA, the attenuation factors get reduced, and impose a larger scattering cross-talk.

Fig. 3 — (a) Variation of cross-talk (neglecting SBS) with input power in discrete Raman amplifiers; (b) Variation of cross-talk (neglecting SBS) with input power in distributed Raman amplifiers

Fig. 4 — (a) Variation of cross-talk with input power for different values of wavelength differences between signals for the case of distributed Raman amplifiers; (b) Variation of cross-talk with input power for different values of wavelength differences between signals

In order to find out the maximum input power that can be transmitted without degrading system performance, the variation of cross-talk with input power has been obtained for the case of discrete and distributed Raman amplifiers, taking Brillouin and four-wave mixing cross-talk into consideration. The numerical estimation of cross-talk, using Eq. (4) has been shown in Figs 2(a) and (b).

It may be inferred from Figs 2(a) and (b) that, as the input power increases, the cross-talk level also
increases for both discrete and distributed Raman amplifiers because of a larger power scattering and this sets a limit to the maximum input power that can be transmitted through the system. It can also be seen that, the order of magnitude of cross-talk reaches higher levels, for lower input power levels, in the case of distributed Raman amplifiers, as compared to discrete Raman amplifiers. This is obvious as in case of distributed Raman amplifier, signal level maintains a higher level in the channel which causes more non-linear scattering. This gives a scope that, for a given noise margin, the input power requirement for distributed Raman amplifier will be smaller as compared to discrete Raman amplifier. The study has been extended to see the effect of SRS, XPM and FWM only. These are shown in Figs 3(a) and (b).

It may be concluded from the Figs 3(a) and (b) that, the input power levels that can be transmitted, drastically increase, when cross-talk due to Brillouin scattering is neglected. It is once again seen that, more power can be transmitted in the case of discrete Raman amplifier as compared to distributed Raman amplifiers, since the cross-talk reaches higher levels, for lower input power levels in distributed Raman amplifiers, as compared to discrete Raman amplifiers. It is also clear that, the Brillouin scattering puts a severe constraint towards cross-talk.

Finally, the authors have tried to evaluate the variation of cross-talk with input power, by varying the difference between the wavelengths of the two signals that are transmitted in a two-channel WDM system. They have considered a wider channel spacing to avoid large cross-talk level in the present analysis. However, this is applicable to narrow WDM with wavelength less than 1 nm. The result is shown in Figs 4(a) and (b).

It can be seen from Figs 4(a) and (b) that, as the wavelength difference between the two channels increases, the cross-talk level for a particular input power decreases, for both discrete and distributed Raman amplification. It can also be observed that, in the case of distributed Raman amplifiers, when the wavelength difference approaches closer to zero, there is a sharp increase in the cross-talk level due to larger effective scattering. The graph illustrates that, for low input power, cross-talk is very small and attains a saturated value for a given channel separation. This gives a scope to select the appropriate channel spacing, for a given input power, at a desired cross-talk.

4 Conclusion

In the present analysis, the contributions of SRS, XPM, SBS and FWM towards cross-talk have been analyzed. The theoretical estimations of cross-talk in case of discrete and distributed Raman amplifiers have been presented. The study has also been extended to find the input power limitation, considering the various types of non-linear cross-talk.

It has been verified that, Brillouin scattering is the most dominant effect in inducing cross-talk in a WDM system. This phenomenon dominates in the backward pumping case, thereby, resulting in a higher magnitude cross-talk in distributed Raman amplifier, compared to discrete Raman amplifier where only forward pumping is done. It is also inferred from the study that, the four-wave mixing least affects the channel cross-talk in the WDM systems considered in the present study.

It is observed that, an increase in input power results an increase in the channel cross-talk. This imposes a limit on the maximum input power that can be transmitted through a WDM system. In the absence of Brillouin scattering, the input power levels that can be transmitted, drastically increase for both discrete and distributed Raman amplifier. So, if by some means the Brillouin scattering is eliminated, then larger input powers can be transmitted. It is also inferred that, smaller channel spacing imposes a higher cross-talk, which becomes more severe in DRA system.

References

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