Four-Wave Mixing Interactions in the Anomalous Propagation Regime in WDM Optical Communication Systems

D.F. Grosz*, W. A. Arellano and H.L. Fragnito**

Instituto de Física Gleb Wataghin,

Unicamp, Campinas, 13083-970, SP, Brazil

**alan@ifi.unicamp.br*

***hugo@ifi.unicamp.br*

Recebido em 29 de Abril 1998

Modulation Instability is shown to enhance inter-channel Four-Wave Mixing interactions in Wavelength Division Multiplexed optical communication systems leading to a strong modulation of the received power when operating the system in the anomalous propagation regime. This penalty can be as high as 4 dB for realistic system parameters even in the absence of amplifier noise. Our results strongly suggest the convenience of using Non-Zero Dispersion Shifted fiber in the normal propagation regime for WDM optical systems.

Mostramos como efeitos de Instabilidade Modulacional aumentam a penalidade devida às interações de Mistura de Quatro Ondas entre canais em sistemas de comunicação óptica Multiplexados em Comprimento de Onda, conduzindo a uma forte modulação da potência recebida quando o sistema é operado no regime de propagação anômalo. Esta penalidade pode chegar aos 4 dB para parâmetros realistas do sistema. Nossos resultados sugerem fortemente a conveniência do uso de fibra de Dispersão Deslocada Não Nula no regime de propagação normal para sistemas ópticos WDM.

I. Introduction

Wavelength Division Multiplexing (WDM) optical communication systems are presently limited by nonlinear optical effects in the fiber. Four Wave Mixing (FWM) represents the source of greatest power penalty in these systems [1-2]. It is well established that FWM can be greatly reduced using fibers with non-zero group velocity dispersion (GVD) [1]. This consideration has motivated in recent years the design of special fibers (Non-Zero Dispersion Shifted Fibers, NZ-DSF) with small GVD but dipersion parameter D such that $D \neq 0$, so as to reduce FWM while keeping the dispersion within tolerable limits [2]. Presently, various NZ-DSFs are available with positive (anomalous dispersion regime) or negative D (normal dispersion regime), which can be alternated along the link for dispersion management, i.e., in order to have non zero local but nearly zero average dispersion [3]. For a link without dispersion management the NZ-DSF with normal group velocity dispersion (GVD) is generally more convenient than one with anomalous dispersion because in the first there is no modulation instability (MI) that amplifies noise within a given spectral range [4-7].

We demonstrate in the present paper that FWM among WDM channels is enhanced in the same spectral region where MI is expected. This study suggests that MI is a more general phenomenon than previously believed, i.e., it occurs not only between a coherent signal and noise, but also between coherent fields (two or more WDM channels). We present numerical simulations on two-channel WDM systems with parameters so chosen as to clarify how FWM is modified by MI and thus explain why and under what conditions the normal GVD fiber is superior to the anomalous GVD fiber.

Let us first review the main characteristics of modulation instability. In the case of a continuous wave with power P and frequency $\omega_0 0 = 2\pi c/\lambda$, the gain coefficient for noise at frequency w is given by [4]

$$g(\omega-\omega_0) = -\beta_2(\omega-\omega_0)^2\sqrt{\omega_c^2/(\omega-\omega_0)^2-1} \quad (1)$$

This gain vanishes for $|\omega-\omega_0| > \omega_c$ (ω_c is the MI cutoff frequency) and has its maximum $g_{\max} = g(\omega_{MI}) = 2\gamma P$ where the modulation instability ω_{MI} is given by

$$\omega_{MI} = \sqrt{4\pi c\gamma P/\lambda^2|D|} = \omega_c/\sqrt{2}\ . \quad (2)$$

In these equations, $\gamma = \lambda n_2/A_{eff}$ (n_2 is the nonlinear refractive index, A_{eff} is the effective area of the fiber and λ the wavelength (D is the GVD parameter and c the speed of light in vacuum). As the noise is being amplified along the fiber, the original continuous wave evolves into a sequence of pulses. This is the so-called modulation instability effect. It is important to note that MI occurs only if $D > 0$. In the frequency domain, MI can be interpreted as a FWM process between the signal and noise which has a contribution to the phase-mismatch of the interaction $\Delta\kappa$, coming from the Kerr effect. This mismatch is given by [4] .

$$\Delta\kappa = -(2\pi c/\lambda^2)D\Delta\lambda + 2\gamma P. \quad (3)$$

where $\Delta\lambda = \lambda(\omega_0-\omega)/\omega_0$ (i.e. the channel spacing in a WDM system). Extending this concept to a two-channel WDM system, the FWM interaction between channels will be enhanced in a fiber with $D > 0$ when the channel spacing $\Delta\lambda$ is close to ω_{MI} (in wavelength units) and for power levels such that $\Delta\kappa = 0$. As illustrated below, typical system parameters are such that these conditions are easily met.

II. Results

To give an idea of the impact of MI on the power penalty of two-channel WDM systems we present now results of numerical simulations on a fiber with realistic parameters. Results are given in terms of a normalized received power NRP

$$NRP = P(L)/(P_{in}e^{-\alpha a L}), \quad (4)$$

where L is the propagated distance, P_{in} the input power per channel, and a the attenuation coefficient. The NRP represents the received power relative to that that would be received ignoring the nonlinear effects in the fibers.

In Fig. 1 we show the NRP of a two-channel system at 10 Gb/s per channel as a function of channel spacing in wavelength units. The input channel power is $P_{in} =$ 25 mW and for this simulation we compare the NRP in two fibers with identical parameters ($n_2 = 2.3 \times 10^{-16}$ cm^2/W, $\alpha = 0.25$ dB/km, $L = 20$ km, $|D| = 0.15$ ps/nm/km) except for the sign of D. For each channel spacing and for each fiber, the propagation equation (i.e., the Nonlinear Schrödinger Equation with attenuation) was solved using the Split Step Fourier method [4]. Bit patterns on each channel were taken to be identical (to put ourselves in the worst penalty case) and consisted of 64 bit strings in NRZ format. The number of points for the presented simulations was 8192 (providing a 10 nm spectral wide window enough to avoid power aliasing) and we verified that our results depended very slightly on these parameters. We also verified that same results were obtained for RZ format [8].

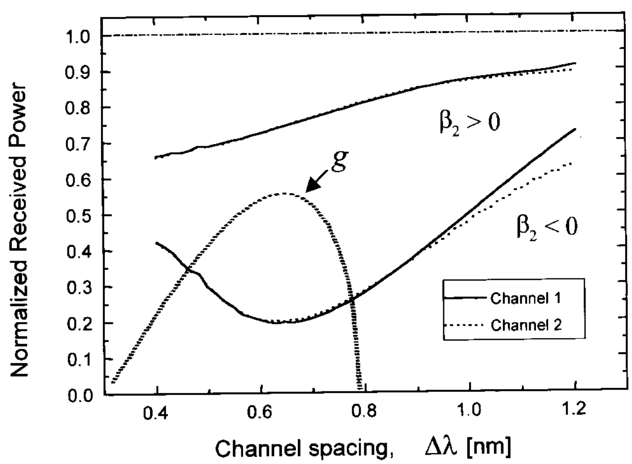

Figure 1. Normalized Received Power as a function of channel spacing (MI gain spectrum g is also shown for comparison).

In the normal propagation regime ($D < 0$) the behavior is that of a "pure" FWM case in long fibers [9] ($1/\alpha$ much larger than the length of the fiber): the channels are monotonically less penalized as the channel spacing is increased. However, in the anomalous propagation regime ($D > 0$) the output power in both channels is greatly reduced. Furthermore, the MI resonance effect near $\Delta\lambda = 0.64$ nm is clearly evidenced. To convince ourselves that this resonance has its origin in the MI effect, we note that if we compute ω_{MI} in (1) using the averaged power along the propagated distance ($\bar{P} = \int_0^L P_{in}e^{-\alpha L}dz/L$) we obtain ω_{MI} corresponding to 0.66 nm, in good agreement with the results in Fig. 1.

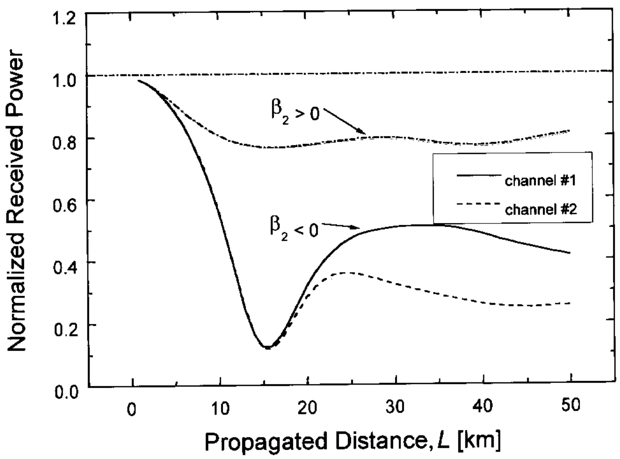

Figure 2: Normalized Received Power as a function of propagated distance.

In Fig.2 we show the normalized received power as a function of propagated distance for a channel spacing of 100 GHz (close to ω_{MI}). The dip near 17 km (one effective length) in the $D > 0$ case corresponds to a power penalty of 6 dB relative to the $D < 0$ case. For short fibers, the energy flows mainly from the signal channels into the FWM sidebands at $2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$. For fibers with $L > \pi/\Delta\kappa$ [9], part of the energy in these sidebands returns to the signal channels, so that the power in the signal channels is slightly recovered. This resembles the FWM oscillations described in [4,9] for the undepleted signal case. In a real system, where depletion takes place, the FWM process is not exactly oscillatory and the energy transferred to the sidebands does not fully return to the signal channels. Eventually, as the power drops due to the fiber attenuation, the cutoff frequency of MI [4] becomes smaller than the channel spacing ($\omega_c < \Delta\omega$) and MI no longer enhances FWM [10]. Finally, for $L >> 1/\alpha$, the system with $D > 0$ is more penalized than in the $D < 0$ case, although by a much smaller amount than for fibers with $L \cong 1/\alpha$. Numerical experiments show that this difference is around 3.5 dB for typical system parameters.

III. Conclusions

We have investigated the interplay among SPM, FWM and MI in a two- channel WDM system. Our results demonstrate that modulation instability induced power penalties are greatly enhanced when operating the system with a channel spacing coinciding with the modulation instability frequency, ω_{MI}. In this case the use of non zero dispersion shifted fibers with slightly negative group velocity dispersion (normal propagation regime, $D < 0$) represents a better choice for WDM transmission systems, leading to smaller power penalties as compared to positive dispersion fibers.

We gratefully acknowledge financial support from CNPq, Fapesp, and Telebrás.

References

1. R. W. Tkach, et.al., "Four-Photon Mixing and High-Speed WDM Systems," J. of Lightwave Technol., vol. **13**, 5 (1995).
2. N. S. Bergano, et.al., "Wavelength Division Multiplexing in Long-Haul Transmission Systems," J. of Lightwave Technol., vol. **14**, 6 (1996).
3. R. A. Saunders, et.al., "System Penalty at 10 Gb/s Due to Modulation Instability and Its Reduction Using Dispersion Compensation," IEEE Photon. Technol. Lett., vol. **9**, 5 (1997).
4. G. P. Agrawal, *Nonlinear Fiber Optics,* 2nd Ed., Academic Press, 1995.
5. R. Hui, et.al., "Nonlinear Amplification of Noise in Fibers with Dispersion and Its Impact in Optically Amplified Systems," IEEE Photon. Technol. Lett., vol. **9**, 3 (1997).
6. R. Hui, et.al., "Noise squeezing due to Kerr effect nonlinearities in optical fibres with negative dispersion," Electron. Lett., vol. **32**, 21 (1996).
7. M. Midrio, et.al., "Reduction of the amplified spontaneous emission noise effect in optical communication systems by means of unusual modulation instability," OFC'97 Techn. Digest, Paper WL40, 1997.
8. D. F. Grosz and H. L. Fragnito, "Pulse Distortion and Induced Penalties Due to Modulation Instability in WDM Systems," Microw. and Opt. Techn. Lett., vol. **19**, 4 (1998).
9. D. Marcuse, et.al., "Effect of Fiber Nonlinearity on Long-Distance Transmission," J. of Lightwave Technol., vol. **9**, no. 1 (1991).
10. D. F. Grosz and H. L. Fragnito, "Power Modulation Due to Modulation Instability Effects in WDM Optical Communication Systems," Microw. and Opt. Techn. Lett., vol. **18**, 4 (1998).