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Impact of Self-Steepening and Stimulated Raman Scattering Effects in a Wavelength Division Multiplexing System

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ABSTRACT: This paper is devoted to the analysis of the impacts of Self-Steepening and Stimulated Raman Scattering effects in a Wavelength Division Multiplexing (WDM) system. To attain this purpose, the Non Linear Schrödinger Equation (NLSE) has been extended to its generalized form in order to take into account higher order dispersion and nonlinearity effects. The numerical approach used is based on the Split Step Fourier (SSF) method due to its faster calculation speed compared to other methods. Our simulations were carried out with Matlab software. The envelope of the wave under consideration has a Gaussian shape of pulse width T_0= 100fs. The results of simulations show that after a given propagation distance, the Self-Steepening effect causes a shift in the amplitude of the pulse with respect to the input signal. This shift becomes increasingly important as the propagation distance increases. It could be explained physically by the dependence of a group velocity on the intensity. The Stimulated Raman Scattering effect has no influence on the temporal profile of the amplitude of a Gaussian pulse, whereas it induces a shift of the output spectrum which increases with the distance. It could be explained by the transfer of energy from the high frequencies to the low frequencies resulting from the interaction between the incident wave and the molecular vibrations of the optical fiber.

KEYWORDS: Fiber optics, WDM, optical nonlinearity, Self-Steepening, Stimulated Raman Scattering

I.INTRODUCTION

The technology of transmission in optical Fiber remains a preferred choice to meet increasing bandwidth demand [1, 2]. Indeed, the optical fiber is a network medium with a useful bandwidth that can exceed 40 THz. Thus, the optical fiber is very effective for the use of the Wavelength Division Multiplexing (WDM) technique, which consists in simultaneously propagating of several wavelengths in a single optical fiber. The total bandwidth being divided by the number of channels centered on the different wavelengths [2]. Nonlinear three-order effects significantly influence WDM transmission systems and distort the transported information [1-5]. The most important of these effects are categorized in Fig.1.

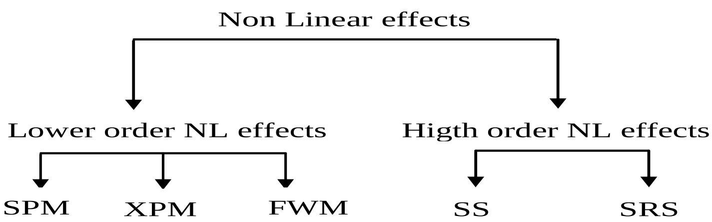

Fig.1: Nonlinear effects in Fiber Optic Systems

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Generally, the works consider only the phenomena resulting from the optical Kerr effect such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM). However, Self-steepening (SS) and stimulated Raman scattering (SRS) phenomena are also two main nonlinear effects that limit the performance of transmission systems in the case of ultra short pulses (order of a few femtoseconds) [2-8]. The first phenomenon results from the dependence of the group velocity on the intensity while the second is due to the interaction between the incident wave and the modes of molecular vibration of the fiber [8, 9]. In addition, our analysis clearly shows that impairments due to SS and SRS effects increase as a function of the number of multiplexed channels. In fact, in a WDM system, the total intensity in the fiber is the sum of the intensities of the multiplexed channels.

In this work, we analyzed the deformation in the shape of Gaussian pulse due to the SRS and SS effects. The theoretical aspects of the SRS and SS effects for a WDM system are developed in Section II. The simulation results are reported in Section III and conclusions are summarized in Section IV.

II.THEORY

The analytical description of the propagation of a pulse in an optical fiber is based on the standard Non Linear Schrödinger Equation (NLSE):

$$\frac{\partial A(z,t)}{\partial Z} + \beta_1 \frac{\partial A(z,t)}{\partial t} + \frac{i}{2}\beta_2 \frac{\partial^2 A(z,t)}{\partial t^2} + \frac{\alpha}{2} A(z,t) = i\gamma |A(z,t)|^2 A(z,t) \quad (1)$$

Where A (z, t) is the complex envelope of the pulse, z is the propagation distance of the pulse, t is the propagation time, β_1 and β_2 are respectively the first and the second order dispersion coefficients, α is the attenuation coefficient, and γ is the nonlinearity coefficient [7].

$$\beta_1 = \frac{1}{v_g}\ ,\ \beta_2 = \frac{\beta_1}{\partial\omega},\ \ \gamma = \frac{\omega_0 n_2}{CA_{eff}} \quad (2)$$

Where v_g is the group velocity and ω_0 is the center frequency of the pulse, n_2 is the refractive index of the fiber, C is the velocity of light in the vacuum, and A_{eff} is the effective area of the fiber.

A.GENERALIZED NONLINEAR SCHRÖDINGER EQUATION (GNLSE)

For the propagation of ultrashort pulses with a small pulse width (T_0<100fs), equation (1) becomes inadequate [10]. It is necessary to add the terms describing the third order dispersion, self-steepening and stimulated Raman scattering effects [7, 10]:

$$\frac{\partial A}{\partial Z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial t^3} + \frac{\alpha}{2} A = i\gamma \left[|A|^2 A + \frac{i}{\omega_0}\frac{\partial(|A|^2 A)}{\partial t} - T_R A \frac{\partial(|A|^2)}{\partial t} \right] \quad (3)$$

Where $A(z,t)$, $\frac{1}{\omega_0}$ is the factor of the term responsible for the SS effect, T_R is the time response relative to the Raman gain: it is the factor of the term responsible of the SRS effect. In the case of the approximation of slowly varying envelope (compared to the optical carrier), it is possible to make a change in the time variable $T = t - \beta_1 z$ so that the pulse propagates in a mobile time reference delayed, evolving at the group velocity $v_g$of the reference frequency ω_0[7,11]. Thus, equation (3) becomes:

$$\frac{\partial A}{\partial Z} + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial T^3} + \frac{\alpha}{2} A = i\gamma \left[|A|^2 A + \frac{i}{\omega_0}\frac{\partial(|A|^2 A)}{\partial T} - T_R A \frac{\partial(|A|^2)}{\partial T} \right] \quad (4)$$

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Using the normalized envelope $U = \frac{A}{\sqrt{P_0}}$ with the normalized distance $\zeta = \frac{z}{L_D}$ and the normalized time variable $\tau = \frac{T}{T_0}$, the propagation equation (4) becomes:

$$\frac{\partial U}{\partial \zeta} + \frac{i}{2}\frac{\partial^2 U}{\partial \tau^2} - \delta_3 \frac{\partial^3 U}{\partial \tau^3} + \frac{\alpha}{2|\beta_2|}U = \frac{L_D}{L_{LN}} i\left[|U|^2 U + is\frac{\partial(|U|^2 U)}{\partial \tau} - \tau_R U \frac{\partial(|U|^2)}{\partial \tau}\right] \quad (5)$$

where

$$\delta_3 = \frac{\beta_3}{6|\beta_2|T_0},\ s = \frac{1}{\omega_0 T_0},\ \tau_R = \frac{T_R}{T_0},\ L_D = \frac{{T_0}^2}{|\beta_2|},\ L_{NL} = \frac{1}{\gamma P_0} \quad (6)$$

P_0 is the peak power of the pulse, T_0 the pulse width, L_D the dispersion length, L_{NL} the nonlinearity length, δ_3 cubic dispersion parameter, s the coefficient of SS effect and τ_R is the coefficient of SRS effect [6, 7, 10]. Since the three parameters δ_3, s and τ_R are inversely proportional to T_0, they would be negligible for the pulse widths T_0> 1Ps, but they are appreciable for femtosecond pulses [7].

B. MODELING A WDM SYSTEM

In a WDM system, the input signal in the fiber is the sum of the input signals of multiple channels [12, 13]. Consider a WDM system with the same channel spacing $\Delta\omega$ constant. Assume that channels are also spaced on both sides of the central channel $A_0(0,t)$, the total complex envelope of the input signal can be written:

$$A_{tot}(0,t) = \sum_{k=-M,k\neq 0}^{M} A_k(0,t)\exp(jk\Delta\omega t) \quad (7)$$

Where $A_k(0,t)$ is the complex amplitude of the input signal for channel k, the total number of channels is 2M. When the amplitude of $A_k(0,t)$ is the same for all channels, and equal to the amplitude of $A_0(0,t)$, then (7) becomes:

$$A_{tot}(0,t) = A_0(0,t)\sum_{k=-M,k\neq 0}^{M} \exp(jk\Delta\omega t) \quad (8)$$

Similarly

$$U_{tot}(0,t) = U_0(0,t)\sum_{k=-M,k\neq 0}^{M} \exp(jk\Delta\omega t) \quad (9)$$

To simulate a WDM system for a given channel number M, the envelope and the normalized envelope of the input signal will be those given by equations (8) and (9) respectively.

III.RESULT AND DISCUSSION

The propagation of the pulse in an optical fiber is described by the NLSE. Indeed this equation does not admit analytical solutions, except for a few specific cases. It is shown that numerical simulation is a necessary approach for understanding nonlinear effects in fiber optic systems. Generally the numerical approach solves problems of the pulse propagation and the most used method is the SSF method [10].

A.THE PHENOMENON OF SELF-STEEPENING (SS)

To better understand the self-steepening effect, we assumed α = 0, $\delta_3 = 0$ and $\tau_R = 0$ in equation (6). Thus the propagation of the pulse is described by:

$$\frac{\partial U}{\partial \zeta} + \frac{i}{2}\frac{\partial^2 U}{\partial \tau^2} = \frac{L_D}{L_{LN}} i\left[|U|^2 U + is\frac{\partial(|U|^2 U)}{\partial \tau}\right] \quad (10)$$

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This equation has been simulated for 32-channel WDM system where the total input signal satisfies the relation (9), with M = 16 and the input signal of each channel has a Gaussian shape, $U(\tau,0) = \exp\left[-\frac{1}{2}\tau^2\right]$.

We have plotted in the following figures the temporal and frequencies variation of the solution of equation (10) in the case where $S = 0.05$, $T_R = 3fs$, $\beta_2 = -3.27\ Ps^2/Km$, $\beta_3 = 0.027\ Ps^3/Km$, $\gamma = 1.3/W.Km$, $\lambda_0 = 1550\ nm$, $P_0 = 25W$, $\zeta = Z'$

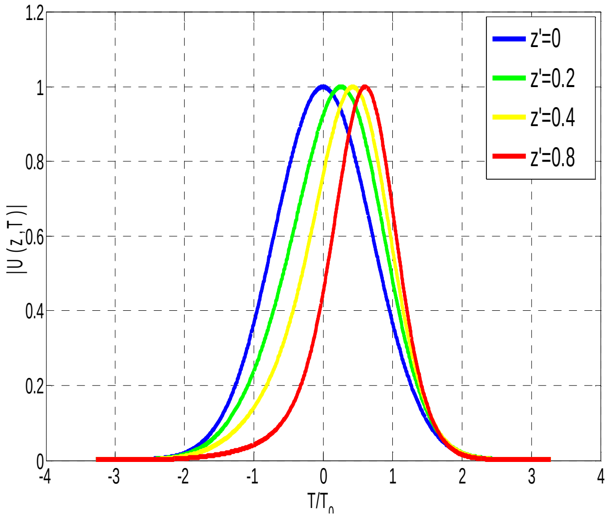


Fig.2 Time profile of a Gaussian-shaped pulse for different z'-values in the presence of the self-steepening effect

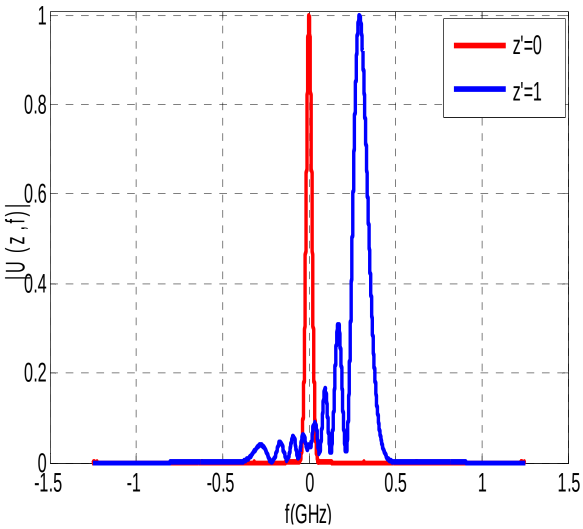
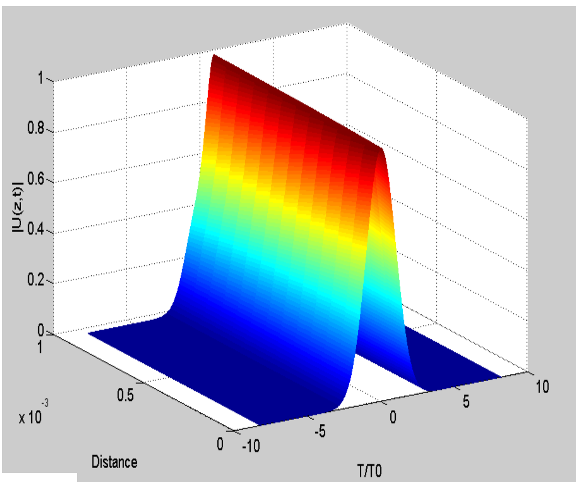
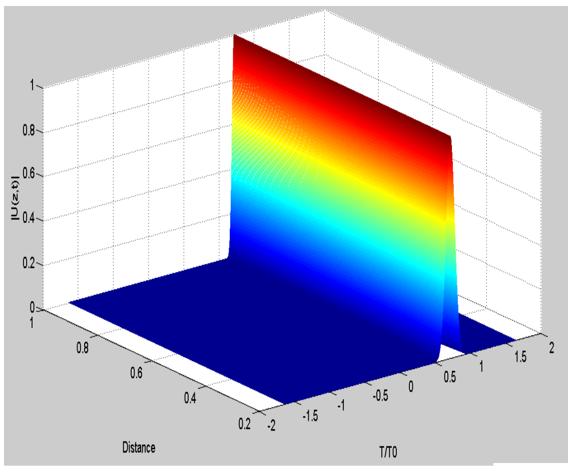


Fig.3 Frequency profile of the pulse in the presence of the self-steepening effect

The result of Fig.2 shows that during its propagation in the fiber, the pulse becomes asymmetric and its peak moves towards the falling front which becomes more and steeper, thus causing a shift of the rising edge. The observed shift of the propagating pulse with respect to the input signal becomes increasingly important as the propagation distance increases. The Fig.4a and Fig.4b show the evolution of the amplitude as a function of time and distance. For small normalized distances the shift of the pulse is insignificant (Fig.4a), whereas for large normalized distances this shift is important and the shift of the rising edge becomes very remarkable (Fig.4b).



(a)



(b)

Fig.4 Pulse shift in the presence of the self-steepening effect for (a) very low z' values and (b) for reasonable z' values

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The Fig.3 is the frequency profile plot for the same parameter values. We can note broadening of the pulse with different frequency components of the pulse. This is a consequence of the dependence of phase velocity on the frequency known as chromatic dispersion.

Physically, these results could be explained by the dependence of the group velocity of the intensity which causes the center of the pulse to move with a speed higher than that of the rising and falling edges of the pulse.

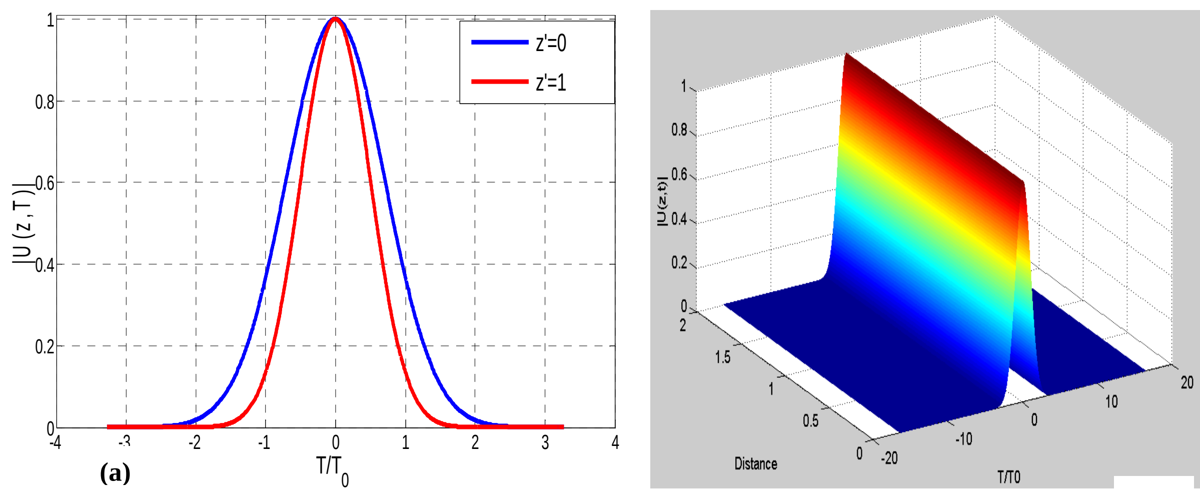
B.THE STIMULATED RAMAN SCATTERING (SRS) PHENOMENON

To better understand the stimulated Raman scattering effect, we assumed α = 0, $\delta_3 = 0$, s = 0 in equation (5). Thus the propagation of the pulse is given by:

$$\frac{\partial U}{\partial \zeta} + \frac{i}{2}\frac{\partial^2 U}{\partial \tau^2} = \frac{L_D}{L_{LN}} i\left[|U|^2 U - \tau_R U \frac{\partial(|U|^2)}{\partial \tau}\right] \tag{11}$$

Equation (11) has been simulated by considering the same system and for parameter values identical to those of SS, in the case where $\tau_R = 0.03$. We have plotted the temporal and frequency variations of the amplitude. The temporal profile of the pulse during its propagation is not modified due to the SRS effect and therefore no shift or a deformation of the output signal with respect to the input signal (Fig.5a and Fig.5b). This can be clearly seen through the term $f(U) = -\tau_R U \frac{\partial(|U|^2)}{\partial \tau}$ of equation (11). The frequency profile shows a shift of spectrum and another small peak (Fig.6a). The pulse has been decomposed into two components which move at different speeds and directions. This is clearly shown in Fig.6b.

Those are the red (low frequency) spectral components and the blue (high frequency) spectral components of the same pulse. It is also important to note that the spectral shift due to SRS effect increases with the propagation distance.



(a) (b)

Fig.5The temporal profile of a Gaussian-shaped pulse in the presence of the stimulated Raman scattering effect in two dimensions (a) and three dimensions (b)

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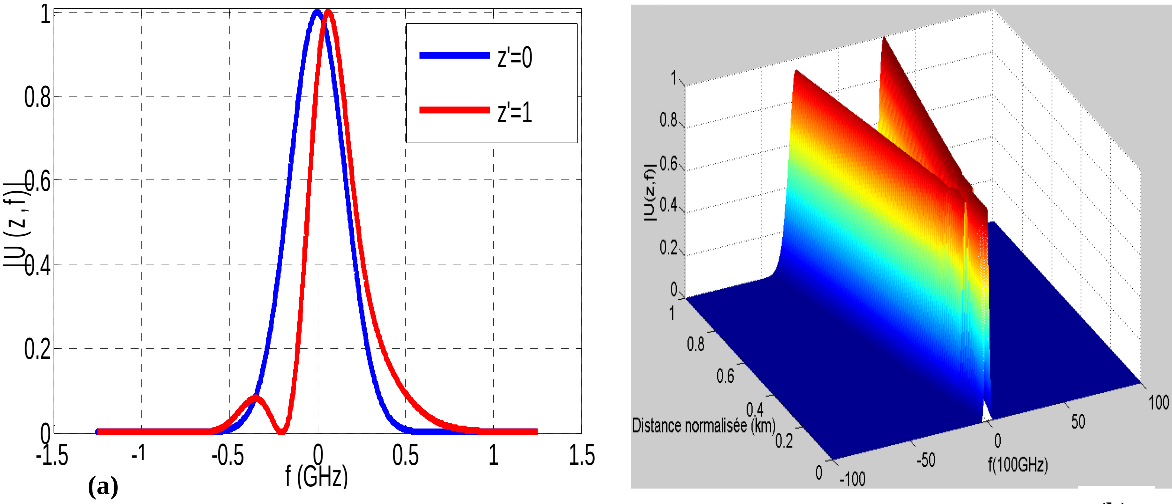

(b)

Fig.6 Frequency profile of a Gaussian-shaped pulse in the presence of the stimulated Raman scattering effect in (a) two dimensions and (b) three dimensions

Physically speaking, when the width of the pulse is very small (less than Picoseconds), its spectral width is so great that the Raman gain can amplify the low frequency components of the pulse with its high frequency components acting in pump. The mechanism can be repeated all along the fiber and the energy of the high frequency components is constantly transmitted to those of low frequencies. This energy transfer leads to a shift of the two groups of the spectral components in two directions

IV.CONCLUSION

In this paper, we analyzed, through a simulation, the impact of two important phenomena in a WDM system. At the end of the simulations, it appears that after a given propagation distance, due to the SS effect, the Gaussian-shaped pulse becomes asymmetric and its peak moves towards the falling edge which becomes increasingly steep, resulting in thus a shift of the rising edge of the pulse. This could be explained by the dependence of the group velocity on the intensity. The time profile of the amplitude of the pulse is always maintained due to the SRS effect while there is a shift between the input and output spectra. This spectral shift which increases with the propagation distance would be due to an energy transfer resulting from the interaction between the incident wave and the molecular vibrations of the optical fiber.

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