Dynamics of Femtosecond Pulses in the Region of Zero Second Order Dispersion of Single Mode Optical Fibers

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The evolution of femtosecond optical pulses in the region of minimum group velocity dispersion of single mode optical fibers is analyzed numerically, by means of an extended nonlinear Schrodinger equation. Besides spectral fragmentation with formation of femtosecond optical solitons and dispersive waves, the results revealed new features of the pulse evolution owing to the intrapulse stimulated Raman scattering effect.

I. Introduction

It has been shown that solitons also emerge from pulses whose central frequencies straddle the zero dispersion wavelength of an optical fiber[1-4] and in femtosecond ring dye lasers[5,6]. In the process, due to the non-linearity, a portion of the pulse energy is shifted into the region of normal dispersion while the other fraction goes into the anomalous dispersive regime of the propagation medium. As a consequence, solitary and dispersive waves evolve on passage. In an optical fiber, however, only qualitative agreement between theoretical[1,2] and experimental[3,4] results related to the pulse evolution and frequency shift of the solitary waves with pulse amplitude was obtained. The discrepsncies were mainly due to the fact that in the experiment[3,4], femtosecond input pulses were utilized, while in the theory[1,2], a few picosecond input pulsewidths were assumed. The predictions of the nonlinear Schrödinger equation are accurate for picosecond pulses but need to be modified for femtosecond input pulses, as several higher-order nonlinear effects become important for such short pulses. The most important among them is intrapulse stimulated Raman scattering (ISRS)[7-9].

The motivation of this work is to show that, the inclusion of tlie intrapulse stimulated Rarnan scattering term in a generalized nonlinear Schrodinger equation, gives rise to new features for the evolution of femtosecond optical pulses in the region of zero second order dispersion of fibers and also provides much better agreement between theoretical and experimental results current in the literature[1-4].

II. Theory and Results

The propagation of a femtosecond optical pulse envelope with carrier frequency at the zero second order dispersion wavelength in an optical fiber is described by an extended nonlinear Schrodinger equation. By using normalized coordinates one may write it in the form:

$$\frac{\partial U}{\partial \xi} - \frac{1}{6}\frac{\partial^3 U}{\partial T^3} - i|U|^2U + i\tau_R U\frac{\partial |U|^2}{\partial T} = 0, \qquad (1)$$

where U is the normalized pulse envelope amplitude with

$$\xi = |\beta_3|z/T_0^3 \quad \text{and} \quad T = \frac{t-\beta_1 z}{T_0}.$$

The parameter β_1 is given by $1/v_g$ where v_g is the group velocity, β_3 the third order dispersion coefficient, T_0 is the pulse width and $\tau_R = T_R/T_0$ is the intrapulse stimulated Raman scattering parameter. In our calculations, typical parameters were used in eq. (1) such as: $\beta_3 = 0.01$ ps^3/km, $T_{FWHM} \approx 1.76\ T_0 = 150$ fs, $\tau_R = 0.06$ and $n_2 \approx 3.2 \times 10^{-20} m^2/W$. It should be noted that the self-steepening term has not been included in the propagation equation, since it is important only for input pulses much shorter than 100 fs.

Equation (1) has been solved numerically by the Split-Step Fast Fourier transform method, and the results are illustrated in Figs. 1(a) and 1(b) which shows the spectral and temporal evolution of a hyperbolic secant input pulse envelope with $A_0 = 2$, over the range $\xi = 0 - 10$. The input pulse initially develops spectral fragmentation at $\xi = 2$ with a fraction of the input pulse energy shifting into the anomalous dispersive regime (negative frequencies) and the other portion going into the normal dispersion region of the spectrum as shown in Figure 1 (a). In the time domain, the pulses only developed some ultrashort temporal structure on the peak of the input pulse envelope (at $\xi = 2$) as shown in Figure 1(b).

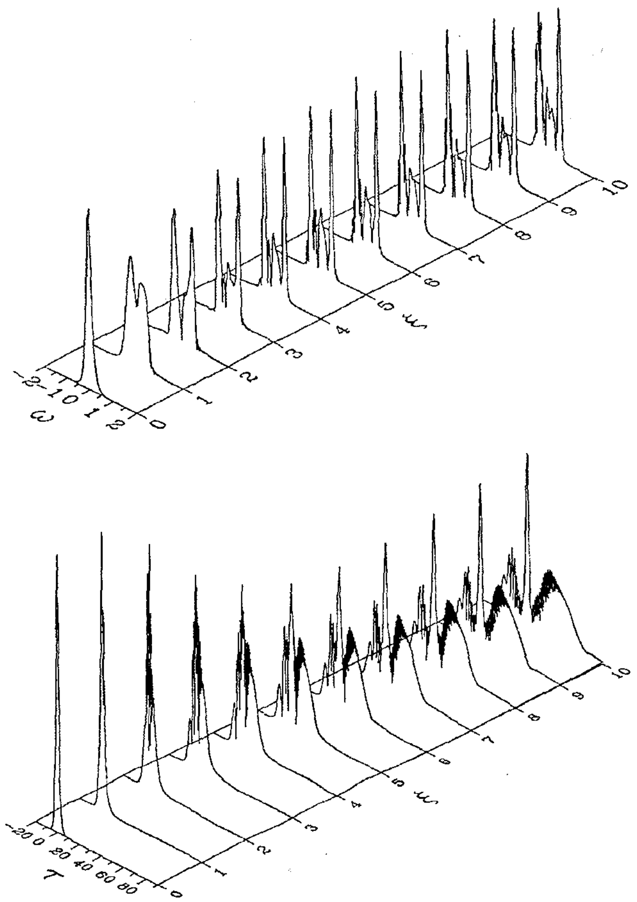

Figure 1: Spectral (a) and temporal (b) evolution of hyperbolic secant input pulse envelope with amplitude $A_0 = 2$. In the plot w is the normalized frequency, τ is the normalized time and ξ is the normalized distance along the fiber.

As the pulse propagatcs, tlie spectral feature settled down into two distinct components on both sides of the minimum dispersion wavelength of the fiber, with the broader component being the one associated with the evolution of a short soliton and the narrower as a dispersive wave. Temporally, this evolution is characterized by the appearence of a delayed, structureless and stable pulse (soliton) and a very boad component related to the dispersive wave generated. It is important to mention that, besides the fact that tlie biggest portion (over 60%) of the input pulse energy lied in the anornalous dispersive region, the centroid of the soliton spectral component shifts rapidly towards longer wavelengths owing to the soliton self-frequency shift effect[7−9].

ln figure (2) we have ploted the frequency shift of the solitons and dispersive wave as a function of incident field amplitude. As one sees, differently from early theoretical reports[1,2] the shift is not linear with field amplitude A_0. As a matter of fact, it presents a behavior similar to the experimental results reported in references [3,4], with the soliton branch agreeing quite well with our calculations. In addition, in references [1,2], it is stated that in a linear approximation the slope of the dispersive wave frequency shift is 1.7 larger than tlie one of the soliton wave, while in our case one may find a 1.3 factor which is in very good agreement with experimental results of references [3 4]. The main reason for this trend is the inclusion of the intrapulse stimulated Raman scattering term in the propagation equation of our calculations, which leads to an additional frequency shift contribution to the solitary wave owing to soliton self-frequency shift effect.

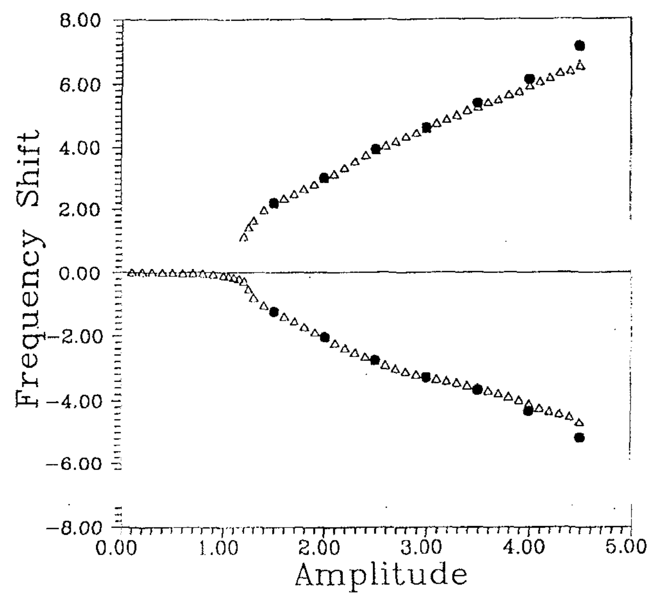

Figure 2: Normalized frequency shift against pulse amplitude at $\xi = 2$. Triangles stand for 150 fs input pulse duration and circles for 100 fs input.

III. Conclusion

In conclusion, we have studied the propagation of femtosecond optical pulses in the region of zero second order dispersion of single mode fibers. The inclusion of the intrapulse stimulated Raman scattering effect in the nonlinear Schrodinger equation led to tlie appearence of new features, when solitary and dispersive waves are involved. The soliton self-frequency shift effect led tlie solitary wave generated to experience a much larger frequency shift into the anomalous dispersive region of the spectrum, as the input power increased. As a consequence a much better agreement between theory and previous experimental reports[3,4] was obtained[10] as far as dispersive and solitary waves frequency shift is concerned.

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