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Spectral variations in supercontinuum pulse propagation

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ABSTRACT

In this paper, we have used the general nonlinear Schrödinger equation (GNLSE) to study the spectral evolution of a short light pulse propagating through an optical fiber. The equation includes the main factors affecting its propagation through the fibre, involving the linear and nonlinear dispersive characteristics. We find the asymmetry feature of the spectrum due to the Raman Effect. The first order group velocity dispersion sets in after a finite propagation length. We have systematically studied the evolution of the pulse through in a nonlinear medium.

Key words: Supercontinuum Generation, Nonlinear Schrödinger Equation, Self Phase Modulation, Raman Scattering, Self Frequency Shift

INTRODUCTION

The generation and development of supercontinuum (SC) light sources has been an active research field within the last decade. Its generation, in controlled conditions, has been used for developing various new technologies. Among the many interesting applications which have been initiated by this new light sources include, optical coherence tomography (Hartl et al., 2001; Hsiung et al., 2004), frequency metrology(Jones et al., 2000; Ranka, Windeler, & Stentz, 2000; Ye, Schnatz, & Hollberg, 2003), fluorescence lifetime imaging (Dunsby et al., 2004), optical communication (Morioka, Mori, & Saruwatari, 1993; Morioka et al., 1996) and gas sensing (Delbarre & Tassou, 2000; Ere-Tassou, Przygodzki, Fertein, & Delbarre, 2003; Sanders, 2002).

Apart from the above stated applications, the physical processes occurring in the generation of this light source can be a useful and interesting research topic for nonlinear optics. Thus, it is important to analyze the factors affecting the various nonlinear processes such as diffraction, self-phase modulation, group velocity dispersion and Raman processes.

PULSE PROPAGATION EQUATION

To understand the behavior of short light pulses, through an optical fiber, the nonlinear Schrödinger equation needs to be solved. For a fiber, assuming no losses, the nonlinear Schrödinger equation written below governs the properties of light when propagating through an optical fiber (Hasegawa & Tappert, 1973)

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=i\gamma|A|^2 A \qquad (1)$$

In Eq. (1), A is the complex field envelope, β2 and β3 are the second and third order dispersion parameters respectively, z is the distance and γ is the nonlinear parameter. The time t here is the retarded time given by t = t' – z/vg ≡ t' – β1z, where t' is the normal physical time and vg is the group velocity. However, if the assumption of no losses is being avoided, a parameter α, representing the fiber losses, can be included in the equation as written below(Agrawal, 2000).

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}+\frac{\alpha}{2}A=i\gamma|A|^2 A \qquad (2)$$

The Eq. (2) is modified to describe a more realistic picture of propagation, by including higher order nonlinear terms such as the stimulated Raman scattering (SRS) effect, self phase modulation (SPM) and the self steepening effects. For pulses with broader spectrum (i.e. > 0.1 THz), the low-frequency components can be amplified by transfer of energy from the high frequency components of the same pulse. This is known as intrapulse (Stokes) Raman scattering (IRS). Due to IRS, the spectrum can shift to the red-side during propagation.

This phenomenon is known as self frequency shift (Agrawal, 2000). The inclusion of these effects modifies the Eq. (2) as

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}+\frac{\alpha}{2}A = i\gamma\left(1+\frac{i}{\omega}\frac{\partial}{\partial t}\right)\left(A(z,t)\int_0^\infty R(t')\left|A(z,t-t')\right|^2 dt'\right) \qquad (3)$$

Eq. (3) is the typical nonlinear Schrödinger equation which includes the main factors that affect light propagation through an optical fiber. It will be solved numerically to study the physical effects of each term on the temporal and spectral evolutions of the supercontinuum light.

THEORETICAL MODELLING

In Eq.(3), the quantity $R(t')$ is given by $R(t') = (1-f_R)\delta(t) + f_R h_R(t)$ where f_R is the fractional contribution to the delayed Raman response and h_R is the Raman response function given as

$$h_R(t) = \frac{\tau_1^{\,2}+\tau_2^{\,2}}{\tau_1\tau_2^{\,2}} e^{-t/\tau_2}\sin(t/\tau_1) \qquad (4)$$

where τ1 and τ2 are two parameters that can be adjusted for providing a better fit to the real Raman gain spectrum. Their respective values are 12.2 fs and 32 fs (Blow & Wood, 1989). In this paper, we focus on slowly evolving pulse, with the pulse duration between 5 ps and 10 fs such that the Raman and self-steepening terms in Eq. (3) can be approximated by

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}+\frac{\alpha}{2}A = i\gamma\left(|A|^2 A+\frac{i}{\omega_0}\frac{\partial}{\partial t}\left(|A|^2 A\right)-T_R A\frac{\partial |A|^2}{\partial t}\right) \qquad (5)$$

In Eq. (5), TR is the first moment of the nonlinear response function that is given by

$$T_R \equiv \int_0^\infty tR(t)dt$$

For the simulation, the parameters were chosen to give appropriate pictures for studying how supercontinuum light evolves through an optical fiber. The fractional contribution to Raman response (fR) was taken as 0.18 (Hilligsøe, Paulsen, Thøgersen, Keiding, & Larsen, 2003). The input pulses were centered at 835nm.

RESULTS AND DISCUSSION

The simulations are performed by numerically solving Eq. 5 using the split-step transform method. The results enable us to show the basic characteristics of supercontinuum light through an optical fiber. Varying the input power from 2kW to 8kW, the pulse is spectrally broadened, generating more new frequencies. This effect is mainly due to the SPM and IRS as the input power provides higher energy. Figs. (1) ,(2). To investigate the effect of Raman scattering, simulations were carried out by comparing the result of setting the Raman term (TR) to zero and the result of including this term while other parameters were kept unchanged. In the absence of this term, the output in the time and frequency domain show symmetrical profiles Figs. (3). However, the presence of this term produces profiles with asymmetry, uneven peaks and frequency broadening Fig. (4). The broadening is the effect of SPM, and will occur till the phase becomes matched to the initial pulse (Hilligsøe, 2005). Uneven peaks are the effect of self steepening. The effect of group velocity dispersion (GVD) is also investigated. The term responsible for this effect is β2. Increasing this parameter in the anomalous dispersion regime (i.e. β2 < 0), compressed the spectrum. Figs. (5), (6). However, for normal dispersion (i.e. β2 > 0), the spectrum broadens. All these results are qualitatively in accordance with existing theory behind supercontinuum generation. However the 3D plots in Figs. 5 and 6 provide useful insight of how the spectrum changes with propagation distance. Apparently, there is a minimum distance for the onset of group velocity dispersion for any value of anomalous dispersion, β3.

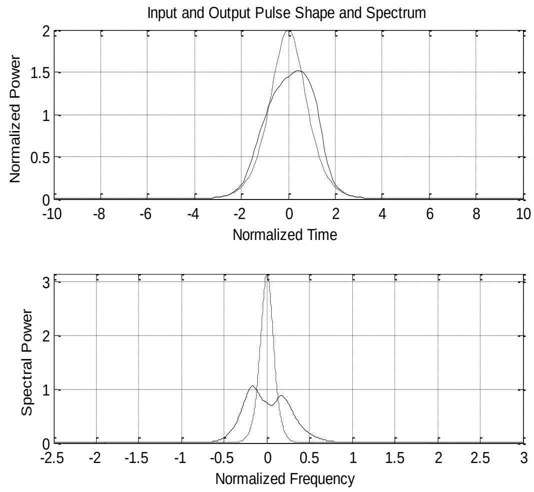

Figure.1. Temporal and spectral profiles of the SC at propagation length = 15cm. We use input power.P_0=2kW, β_2 = -11.830×10^{-3} ps^2/m, β_3 = 8.1038×10^{-8} ps^3/m, and γ = 0.11 $(Wm)^{-1}$

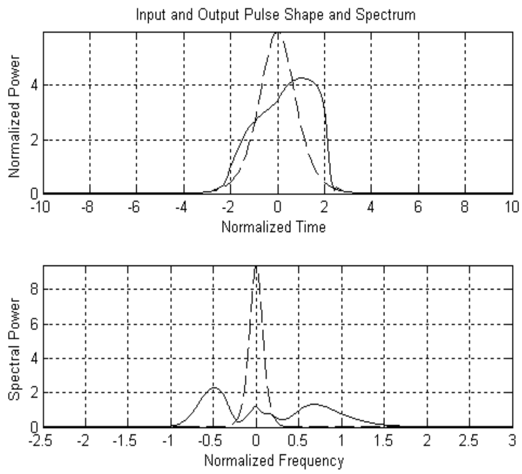

Figure.2. The effect of higher input power on SC, with P_0=6kW. Other parameters are the same as in Fig.1.

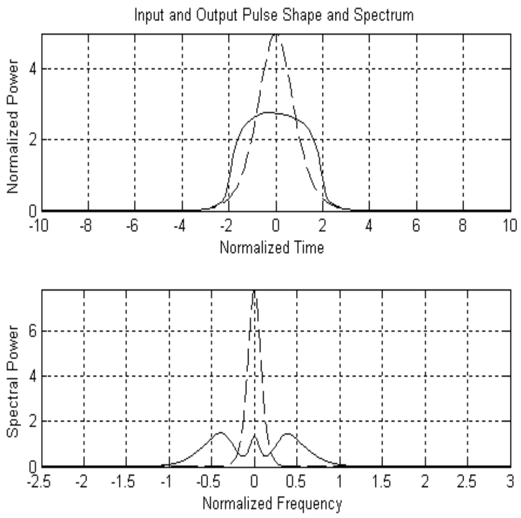

Figure.3. Investigating the effect of Raman response.(Raman term *not included* in simulation). P_0=5kW, β_2 = -11.830e-3 ps^2/m, β_3 = 8.1038e-8 ps^3/m, propagation length = 15cm and γ = 0.11 $(Wm)^{-1}$.

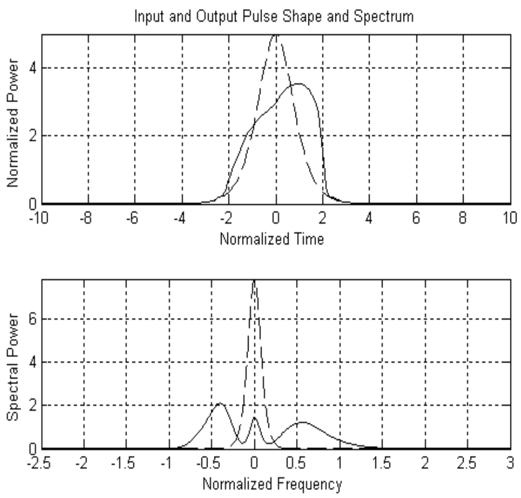

Figure.4. Investigating the effect of Raman response.(Raman term *included* in simulation). All parameters are the same as in Fig. 3.

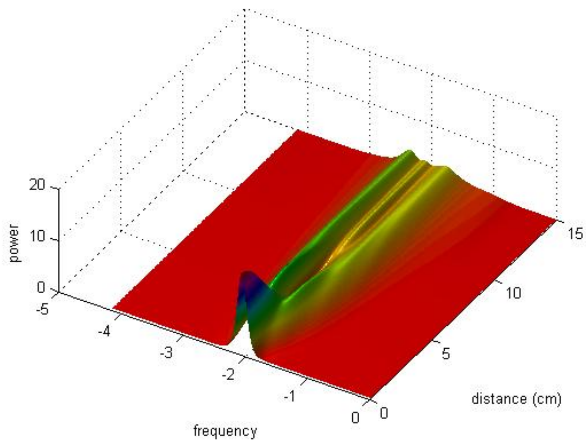

Figure.5. Investigating the effect of the group velocity dispersion (GVD). P_0=10kW, β_2 = -0.06 ps^2/m, β_3 = 0, propagation length = 15cm and γ = 0.1 $(Wm)^{-1}$

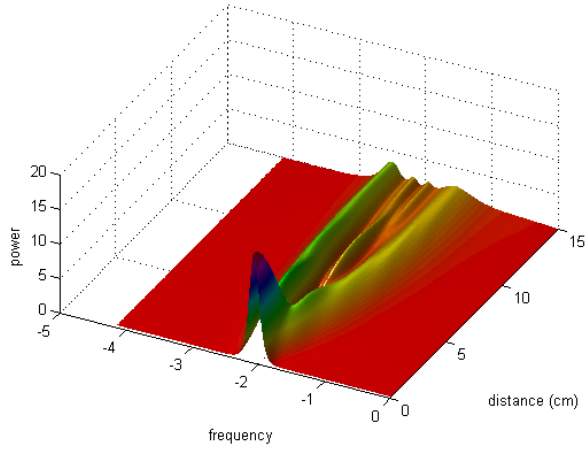

Figure 6. Investigating the effect on SC from the group velocity dispersion (GVD), here using β_2 = - 0.02 ps^2/m. Other parameters are the same as in Fig. 5.

CONCLUSION

In this paper, we have investigated the spatial and spectral properties of supercontinuum generation pumped by femtosecond laser pulses through an optical fiber in the anomalous dispersion regime (i.e. $\beta_2 < 0$).

The results investigated include the effect of varying the input power (P_0), the effect of the Raman response term and the effect on varying the group velocity dispersion (GVD) parameter (β_2). The results agree with the theoretical explanations given in various texts (Agrawal, 2000; Blow & Wood, 1989; Hilligsøe et al., 2003). The simulations have been quite helpful for understanding the most basic and fundamental characteristics of supercontinuum generation.

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