# EFFECTS OF RAMAN SCATTERING AND THIRD ORDER DISPERSION ON SOLITON PROPAGATION IN OPTICAL FIBER

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***Abstract:*** *In this study, the generalized nonlinear Schrödinger equation describing nonlinear wave propagation in optical fiber with all higher order effects such as higher order dispersion, self-phase modulation and Raman scattering is considered. Using the numerical method, the effects of the terms third order dispersion, Raman scattering on evolution of ultrashort pulses are investigated in detail.*

**Keywords:** Raman scattering; Third order dispersion; Soliton.

## 1. INTRODUCTION

The study of nonlinear effects on soliton propagation in Kerr media has become a topic of intense research activities because of its important application in the optical telecommunication [1, 2, 3]. Soliton in optical fibers is possible because of the exact balancing between the group velocity dispersion (GVD) and its counterpart self-phase modulation (SPM). Optical solitons are not only predicted theoretically [1, 4] but they have also been observed experimentally [5, 6]. Some possible applications of solitons such as optical pulse compression, all optical switching, logic devices, etc. have been proposed.

For pulse widths $T_0$ > 10 ps, the soliton dynamics is described by the nonlinear Schrödinger (NLS) equation for a scalar field. However, modeling the propagation of ultrashort pulses (femtosecond pulses having widths $T_0$ <1 ps), the higher order effects in nonlinear media become important, and therefore the governing equation should still include third-order dispersion (TOD) and the self-frequency shift [7,8]. The effect of TOD is significant for fs pulses when the GVD is close to zero [1,6]. The Raman scattering can lead to self-frequency-shift to the long wavelength on the ultrashort optical pulse spectrum, which is termed red-shift. Fundamentally, when a femtosecond pulse propagates in nonlinear dispersion medium, the gain is different at different wavelength and the gain of red part, i. e. the long wavelength, is larger than that of the blue part. So the energy of the blue part is converted into the red part, which leads to the red-shift of pulse in the spectrum.

The effects of Raman scattering on soliton propagation have been presented in [1], however, the combined effect of the dispersion and Raman scattering on soliton propagation in the optical fiber has not been adequately studied. In this work, the generalized nonlinear Schrödinger equation to study propagation of ultrashort optical pulses in the presence of Raman scattering and third - order dispersion effects is used.

## 2. PROPAGATION EQUATION FOR ULTRASHORT PULSES

To investigate the effect of dispersion and Raman scattering on the propagation dynamics of pulse, we use a generalized scalar nonlinear Schrodinger equation (GNLSE) to model the pulse propagation inside the fiber [1].

$$\begin{aligned} i\frac{\partial A(z,t)}{\partial z} + i\beta_1\frac{\partial A(z,t)}{\partial t} - \frac{\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} - \frac{i\beta_3}{6}\frac{\partial^3 A(z,t)}{\partial t^3} + \\ + \gamma\left(\left|A(z,t)\right|^2 A(z,t) - T_R A(z,t)\frac{\partial\left|A(z,t)\right|^2}{\partial t}\right) = 0. \end{aligned} \tag{1}$$

where *A=A(z,t)* is a complex envelop function of optical field. This function varies slowly with time and position z along optical fiber; $\beta_1$, $\beta_2$ and $\beta_3$ are first, second and third-order dispersion factors, respectively; $\gamma$ is nonlinear factor of optical fiber; $\gamma T_R$ term describes Raman scattering effect.

Using the new parameters and variables

$$U(\xi,\tau)=\frac{1}{\sqrt{P_0}}A(z,t),\quad L_D=\frac{\tau_0^2}{|\beta_2|},\quad L_N=\frac{1}{\gamma P_0},\quad N^2=\frac{\tau_0^2\gamma P_0}{|\beta_2|},$$
$$\tau=\frac{t-\beta_1 z}{\tau_0},\quad \xi=\frac{z}{L_D},\quad \delta_3=\frac{\beta_3}{6|\beta_2|\tau_0}, \tag{2}$$

where $L_D$ is the dispersive length, $L_N$ is the nonlinear length, $\tau_0$ is the pulse width and $P_0$ is the peak power of the input pulse. We can rewrite the equation (1) in the normalized form:

$$\frac{\partial U}{\partial \xi}-\beta_2\frac{i}{2}\frac{\partial^2 U}{\partial \tau^2}-\delta_3\frac{\partial^3 U}{\partial \tau^3}=iN^2\left(|U|^2U-\tau_R U\frac{\partial |U|^2}{\partial \tau}\right). \tag{3}$$

In the general case it is very difficult to find analytic solutions of Eq.(3) and no such solution was known until now. For the numerical solution of Eq. (3) we consider the following expression:

$$\frac{\partial U(\xi,\tau)}{\partial \xi}=\left(\hat{L}+\hat{N}\left(U(\xi,\tau)\right)\right)U(\xi,\tau). \tag{4}$$

Here $\hat{L}=\frac{i}{2}\frac{\partial^2}{\partial \tau^2}+\delta_3\frac{\partial^3}{\partial \tau^3}$ is an linear operator containing time derivative, $\hat{N}(U)=iN^2\left(|U|^2-\tau_R\frac{\partial |U|^2}{\partial \tau}\right)$ is a non-linear operator and is a function of $U(\xi,\tau)$.

Equation (4) was solved by using the fourth-order Runge-Kutta method in the interaction picture using the following algorithm [9]:

$$U_1(\xi,\tau)=IFT\left[\exp\left(\frac{\Delta\xi}{2}\hat{L}(\omega)\right)FT\left[U(\xi,\tau)\right]\right]$$
$$K_1=IFT\left[\exp\left(\frac{\Delta\xi}{2}\hat{L}(\omega)\right)FT\left[\Delta\xi\hat{N}U(\xi,\tau)\right]\right];$$
$$K_2=\Delta\xi\hat{N}\left(A_1(\xi,\tau)+K_1/2\right)\left(A_1(\xi,\tau)+K_1/2\right);$$
$$K_3=\Delta\xi\hat{N}\left(A_1(\xi,\tau)+K_2/2\right)\left(A_1(\xi,\tau)+K_2/2\right);$$
$$K_4=\Delta\xi\hat{N}\left(IFT\left\{\exp\left(\frac{\Delta\xi}{2}\hat{L}(\omega)\right)FT\left\{A_1(\xi,\tau)+K_3\right\}\right\}\right)\times$$
$$IFT\left\{\exp\left(\frac{\Delta\xi}{2}\hat{L}(\omega)\right)FT\left\{A_1(\xi,\tau)+K_3\right\}\right\}.$$

We obtain the value of the envelope function in the location $\xi+\Delta\xi$

$$U\left(\xi+\Delta\xi,\tau\right)=IFT\left[\exp\left(\frac{\Delta\xi}{2}\hat{L}\left(\omega\right)\right)FT\left[U_1\left(\xi,\tau\right)+\frac{K_1}{6}+\frac{K_2}{3}+\frac{K_3}{3}\right]\right]+\frac{K_4}{6}. \quad (5)$$

In relations (5), FT and IFT denote the Fourier and inverse Fourier's transforms, respectively. Errors in applying (5) are of orders $\left(\Delta\xi\right)^5$.

## 3. NUMERICAL RESULTS AND DISCUSSION

First, we consider the simplest case, which is to ignore the Raman scattering effect and only pay attention to the third-order dispersion. At this time equation (3) reduces to:

$$\frac{\partial U}{\partial\xi}=\frac{i}{2}\frac{\partial^2 U}{\partial\tau^2}+\delta_3\frac{\partial^3 U}{\partial\tau^3}+i\,N^2\left|U\right|^2 U\,. \quad (6)$$

Our purpose is to examine the influence of third order dispersion on soliton propagation in optical fiber, so first of all we consider the case when the pulse wavelength lies in the vicinity of the zero-dispersion wavelength, the $\beta_3$ term provides the dominant contribution to the dispersive effects. In this case, we can not use abovementioned normalization. To normalize the equation (1), we must choose scaling parameters as follows

$$\xi=\frac{z}{L_D^{'}},\ \ L_D^{'}=\frac{\tau_0^3}{\left|\beta_3\right|},N=\frac{\gamma P_0\tau_0^3}{\left|\beta_3\right|}.$$

and equation (6) is rewritten:

$$\frac{\partial U}{\partial\xi}=sign(\beta_3)\frac{1}{6}\frac{\partial^3 U}{\partial\tau^3}+iN\left|U\right|^2 U. \quad (7)$$

We will consider the propagation of the hyperbolic secant pulse with $\beta_3 = 0.1$ ps$^3$/km. The pulse amplitude of vibration tail which is formed at the back edge of pulse decreases along optical fiber. Numerical calculation shows that the deformation of pulse caused by third-order dispersion at dispersion wavelength equals zero can limit the efficiency of optical fibers information system.

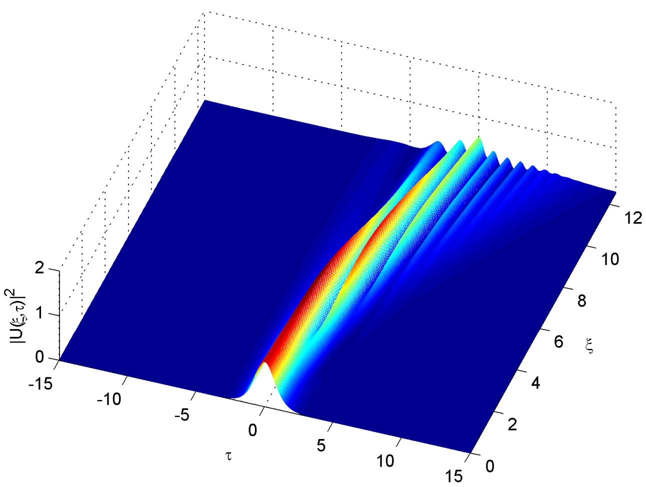


***Figure 1.*** *Propagation of the hyperbolic secant pulse with $\beta_3 = 0.1$ ps$^3$/km over the distance $\xi = 12$.*

As we know, for the ultrashort pulses with the width $\tau_0 \approx 50 fs$ and the carrier wavelength $\lambda_0 \approx 1.55 \mu m,$ the higher-order parameters in (3) during their propagation in the medium $SiO_2$ have the values $\delta_3 \approx 0.03, \tau_R = 0.1$. In this case, the self-shift frequency effect dominates over the TOD and the self- steepening for the pulses with the width of hundred and ten femtoseconds. The self-frequency shift effect is the main cause of the pulse frequency spectrum in the propagation shifted to the low frequency domain. In other words, the medium was "amplified" the longer wavelengths of the pulse [7,8].

For the ultrashort pulses with the width $\tau_0 \approx 50 fs$ . Equation (3) is rewritten:

$$\frac{\partial U}{\partial \xi} = \frac{i}{2}\frac{\partial^2 U}{\partial \tau^2} + i N^2 \left( |U|^2 U - \tau_R U \frac{\partial |U|^2}{\partial \tau} \right). \quad (8)$$

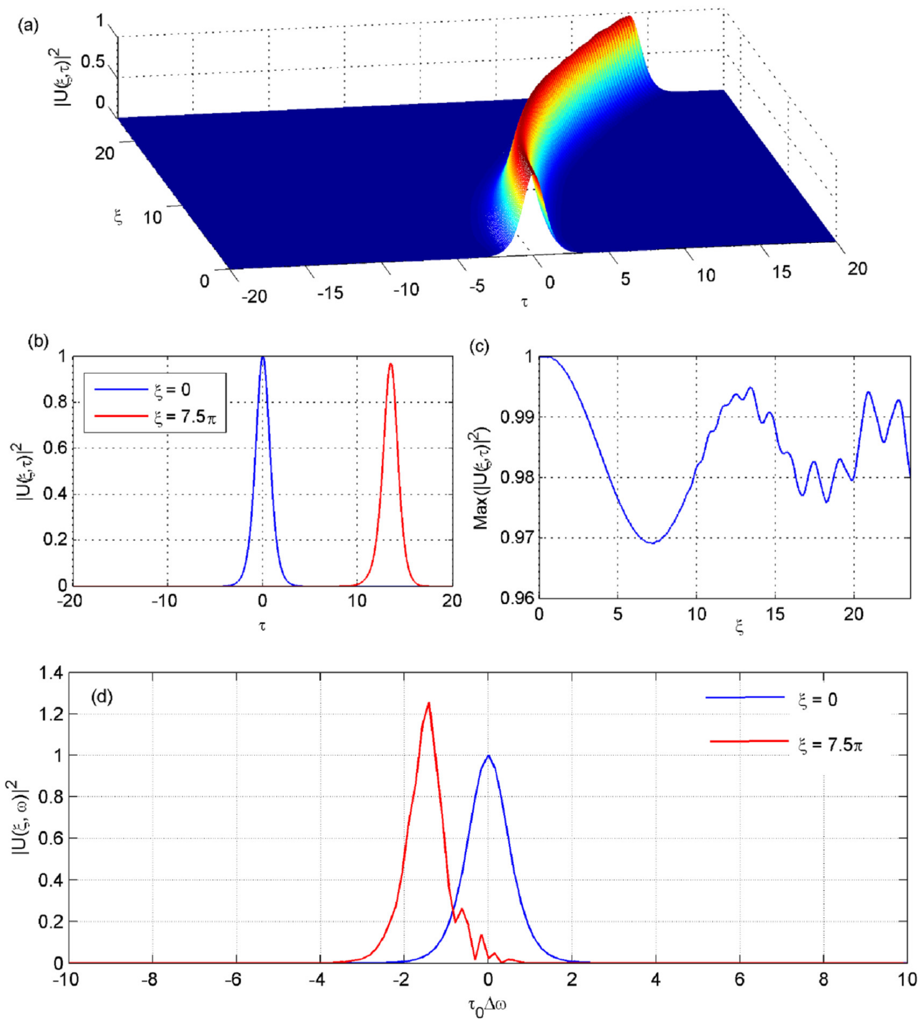


***Figure 2.*** *Effects of Raman scattering on fundamental soliton.*

The nonlinear phenomena due to Raman scattering has made change both the pulse intensity and spectrum. The frequency of the pulse is shifted to low frequency domain (Figure 2d) and the intensity of the low frequency was being increased. This phenomenon is called the phenomenon of soliton self - frequency shift. Thus for low - intensity pulses (N = 1, fundamental soliton) the effect of scattering Raman on pulse width is negligible (Figure 2b) and the change of the pulse peak intensity is not significant (Figure 2c). So, in this case, the propagating pulse is still considered as soliton.

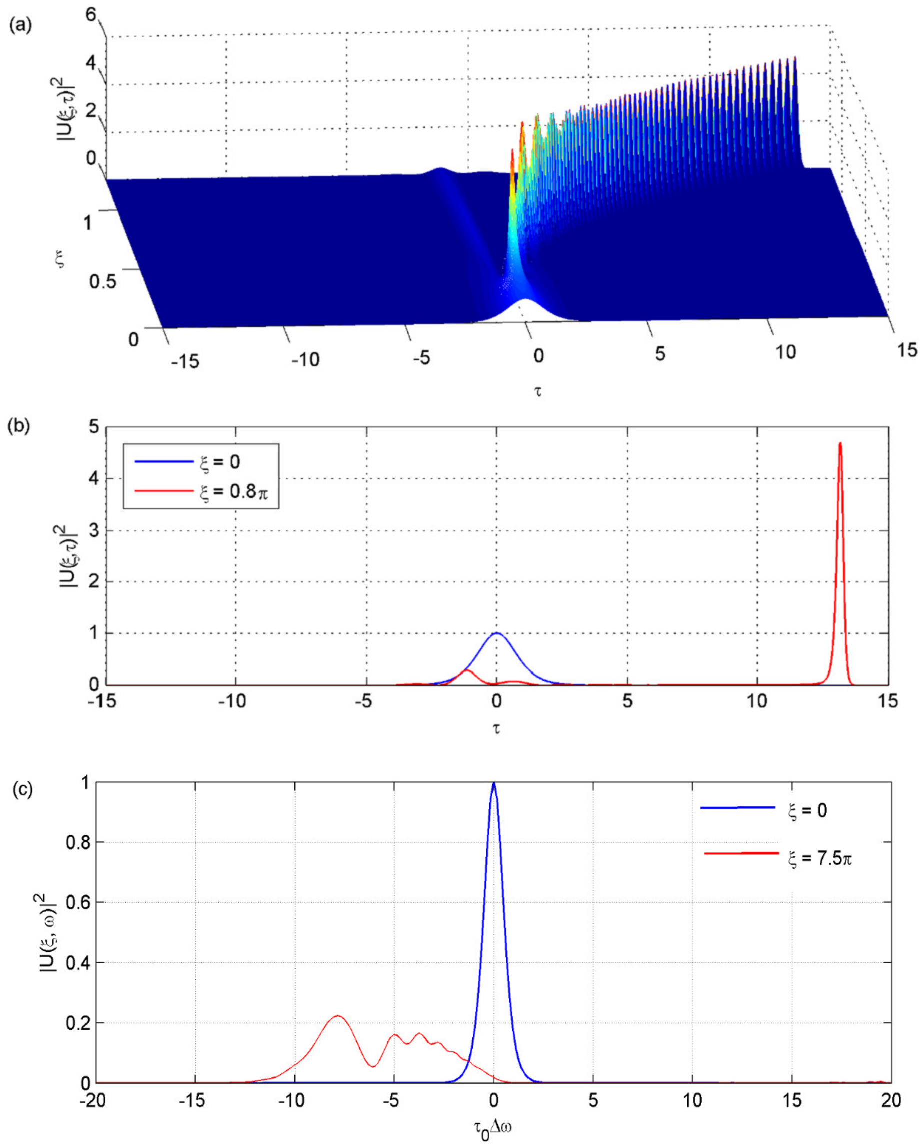


***Figure 3.*** *Effects of Raman scattering on third order soliton.*

Effects of Raman scattering on soliton propagation in optical fiber will be totally different when we consider for pulses of high intensity. Figure 3 shows propagation of the ultrashort pulse with the initial hyperbolic secant shape with the power parameter $N = 3$ over the distance $\xi = 0.8\pi$. From this figure we see that, when the intensity of the pulse increase, in addition to the shift of the frequency of the pulses to the lower region also pulse splitting process has appeared (Figure 3c). During the propagation over a short distance, the pulse already splits to two parts: the main strong peak moves rapidly to the later time and the much lower peak. During the further propagation the main peak is strongly compressed and its width is much smaller than the input pulse.

## 4. CONCLUSION

In this paper, the influence of Raman scattering and higher-order dispersion effects on the propagation of optical pulses in a highly nonlinear fiber is investigated. It is shown that third order dispersion can lead to a pulse-breakup above a certain pulse power. The splitting is followed by an expansion of the spectrum towards longer wavelengths. The influences of higher - order effects such as Raman scattering on soliton are also investigated, and it is found that Raman scattering can significantly enhance pulse compression under certain conditions.

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## TÓM TẮT

ẢNH HƯỞNG CỦA TÁN XẠ RAMAN VÀ TÁN SẮC BẬC BA
LÊN SỰ LAN TRUYỀN SOLITON TRONG SỢI QUANG

*Trong nghiên cứu này chúng tôi xem xét phương trình Schrödinger phi tuyến tổng quát mô tả quá trình lan truyền sóng phi tuyến trong sợi quang với các hiệu ứng bậc cao như là tán sắc bậc ba, tự biến điệu pha và tán xạ Raman. Sử dụng phương pháp số, ảnh hưởng của các số hạng tán sắc bậc ba và tán xạ Raman lên sự lan truyền của xung cực ngắn đã được nghiên cứu chi tiết.*

**Từ khóa:** Tán xạ Raman; Tán sắc bậc ba; Soliton.

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