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Femtosecond soliton spectral tunneling effect: Self-compressing colored solitons and supercontinuum generation

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ABSTRACT

The discovery of stimulated Raman self-scattering (SRSS) effect of femtosecond optical solitons is acknowledged to be among the most notable achievements of nonlinear fiber optics. This effect is also often called intrapulse stimulated Raman scattering (ISRS), or soliton self-frequency shift (SSFS), thereby emphasizing the unusual regime of stimulated Raman scattering, when the spectrum of a high-power ultrashort laser pulse proves to be so broad that it covers the band of Raman resonances of the medium. The soliton-like wave packets with continuously shifted spectrum traveling not only in the ordinary space and time, but also in the spectral space, are known as colored femtosecond solitons. Colored solitons play an important role in the soliton supercontinuum generation. The most interesting features of colored optical solitons are connected with the possibility of their tunneling in the spectral domain through a potential barrier-like spectral inhomogeneity of group velocity dispersion (GVD), including the forbidden band of positive GVD[1]. This effect is known as soliton spectral tunneling effect (SST). In this Report, we consider the influence of the soliton binding energy on dynamics of the SST effect assuming that the amplitude and duration of the tunneling soliton vary in time when the soliton spectrum approaches a forbidden GVD barrier. We show that soliton self-compressing effect has dramatic impact on the SST through forbidden spectral region of positive GVD.

1. **Introducción**

The discovery of stimulated Raman self-scattering (SRSS) of femtosecond optical solitons[2] is acknowledged to be among the most notable achievements of nonlinear fiber optics[3-8]. This effect is also often called intrapulse stimulated Raman scattering (ISRS)[3-8], or soliton self-frequency shift[9], thereby emphasizing the unusual regime of stimulated Raman scattering, when the spectrum of a high-power ultrashort laser pulse proves to be so broad that it covers the band of Raman resonances of the medium. In this case, the Stokes spectral component of the field shifted by the frequency of molecular vibrations is contained within the pump pulse itself. The amplification of low-frequency Stokes components in the field of high-frequency anti-Stokes spectral components of the same soliton pulse results in a continuous red shift of its spectrum, For example, the red shift of the carrier frequency in a passive single-mode optical fiber is inversely proportional to the fourth power of the pulse duration and it is described by expression[3] $df/dz = 0.082/\tau_0^4$, where τ_0 is in picoseconds and df/dz is in THz/km. If $\tau_0 = 0.1$ ps, the "red" frequency shift reaches 820 THz/km. These extraordinary soliton-like wave packets traveling not only in the ordinary space and time, but also in the spectral space, are known as colored solitons[10]. Colored solitons play an important role in the soliton supercontinuum generation[8].

The most intriguing enigma of colored optical solitons is connected with the possibility of their tunneling in the spectral domain through a potential barrier-like spectral inhomogeneity of group velocity dispersion (GVD), including the forbidden band of positive GVD[1,11-14].

In order to experimentally observe the SST effect, a fiber with a narrow normal GVD region surrounded by two regions of anomalous GVD is required. Recently, Dudley and coauthors[12] presented a numerical study of soliton spectral tunneling in an index-guiding photonic crystal fiber with a sub-wavelength central air core defect. Specifically, for a fiber design where two regions of anomalous dispersion bracket a 90 nm wide region of normal dispersion, simulations show tunneling from 1300 to 1475 nm across the forbidden normal dispersion regime, with near unity efficiency. Poletti, Horak, and Richardson[14] designed a number of index-guiding holey fibers with relatively simple structure which possess suitable dispersive properties for the observation of soliton spectral tunneling. Their numerical simulations predict that tunneling across a normal dispersion region of 150 nm width when pumped in the near infrared is in principle possible using just a few meters of these fibers.

Nonlinear dynamic of the NLSE SOLITONS IN time-dependent traps

In this section, we consider the influence of the soliton binding energy on dynamics of the SST effect when the amplitude and duration of the tunneling soliton vary in time when the soliton spectrum approaches a forbidden GVD barrier.

We consider the SRSS effect within the framework of the NLSE

$$i\frac{\partial q(z,\tau)}{\partial z} = \frac{1}{2}\frac{\partial^2 q(z,\tau)}{\partial \tau^2} + (1-\beta)\left|q(z,\tau)\right|^2 q(z,\tau) + \beta Q(z,\tau)q(z,\tau) \tag{1}$$

for the complex amplitude of the laser pulse envelope $q(z,\tau)$ coupled with the so-called oscillator model of stimulated Raman scattering effect[10,11,15-18]

$$\mu^2 \frac{\partial^2 Q(z,\tau)}{\partial \tau^2} + 2\gamma\mu \frac{1}{2} \frac{\partial Q(z,\tau)}{\partial \tau} + Q(z,\tau) = |q(z,\tau)|^2. \qquad (2)$$

In Eqs.(1,2), $Q(z,\tau)$ represents the real amplitude of the wave of molecular vibrations, the "running" time $\tau = (t-z/\upsilon_0)/\tau_0$ is normalized to the initial pulse duration τ_0 ; υ_0 is the group velocity; the distance z is expressed in terms of the dispersion length. Eq. (2) describes a wave of molecular vibrations and contains two dimensionless parameters μ and γ which are related to the initial duration τ_0 of the pump pulse, the molecular vibrational frequency $\Omega_R=2\pi/T_R$, and the Raman line width $T_{2R}=1/(\pi c\Delta\nu_R)$ by the following expressions: $\mu=(\tau_0\Omega_R)^{-1}$ and $\gamma=(T_{2R}\Omega_R)^{-1}$. Here $T_R=2\pi/\Omega_R$ is the period of resonance molecular vibrations and T_{2R} is their dephasing time. The relative contribution of molecular response to the total medium nonlinearity (relative to the purely electronic nonlinear Kerr mechanism n_2) is described by the parameter $\beta = g_R\gamma/(kn_2)$, where g_R is the Raman gain at the centre of the gain line. When the parameter $\beta=0$, the system of equations (1,2) can be transformed to a conventional nonlinear Schrödinger equation for canonical solitons. In cases of practical importance, the Raman contribution to the nonlinear susceptibility acts as a small perturbation $\sigma = 2\beta\gamma\mu = \tau_R/\tau_0 \ll 1$, that is why

$$Q(z,\tau) = |q(z,\tau)|^2 - 2\gamma\mu \frac{\partial}{\partial \tau} |q(z,\tau)|^2 \qquad (3)$$

Eq.(3) leads to the well known model of the SRSS effect

$$i\frac{\partial q(z,\tau)}{\partial z} = \frac{1}{2}\frac{\partial^2 q(z,\tau)}{\partial \tau^2} + |q(z,\tau)|^2 q(z,\tau) - \sigma q(z,\tau)\frac{\partial}{\partial \tau}|q(z,\tau)|^2$$

describing a soliton

$$q_{sol}(z,\tau) = \kappa_0 \,\mathrm{sech}[\kappa_0(\tau + \omega_{sol} z)]\exp[i\theta(z,\tau)] \qquad (5)$$

with a monotonic shift of the central frequency ("color") ω_{sol} of a single-soliton pulse to the low frequency ("red") part of the spectrum.

Here

$$\theta(z,\tau) = \omega_{sol}\tau - \frac{1}{2}\left(\kappa_0{}^2 - \omega_{sol}{}^2\right)z \qquad (6)$$

$$\omega_{sol}(z) = \omega_{sol}(z=0) - \frac{8}{15}\kappa_0{}^4\sigma z \qquad (7)$$

and $\sigma = 2\gamma\mu\beta = \tau_R/\tau_0$, where the characteristic Raman response time τ_R is introduced. For silica glass $\tau_R \approx 6$ fs[3-8]. The corresponding spectral intensity

$$\left|q_{sol}(\omega,\tau)\right|^2 = \frac{1}{4}\mathrm{sec}h^2\left[\frac{\pi}{2}\frac{\varpi-\omega_{sol}(z)}{\kappa_0}\right] \quad (8)$$

represents the main feature of colored solitons that they travel not only in the ordinary coordinate space and time (see Eqs.(5,6)), but also in the spectral space (see Eqs.(7,8).

Let us consider Eq.(1) as the soliton "scattering" on the potential $U_{ext}(z,\tau) = \beta Q(z,\tau)$. It should be emphasized that this scattering potential is not only a function of coordinate, but it also depends on time, and what is more, this scattering potential depends on amplitude and duration of the scattering soliton itself. This fact directly follows from the solution given by:

$$U_{ext}(z,\tau) = \beta\int_0^\infty H(t)\left|q(z,\tau-t)\right|^2 dt, \quad (9)$$

where the causal Green function *H(t)* is represented by

$$H(t) = -\frac{\mu}{\sqrt{1-\gamma^2}}\exp\left(\frac{\gamma}{\mu}t\right)\sin\left(\frac{\sqrt{1-\gamma^2}}{\mu}\right).$$

(10)

Notice that recently, some unexpected analogies of colored optical solitons with other areas of physics have been established. In particular, it was shown that the Raman self-scattering effect can be described by the NLSE model with a linear external potential [19]. Really, assuming that a soliton amplitude does not vary significantly during its self scattering $\left|q_{sol}(z,\tau)\right|^2 = \kappa_0^{\,2}\,\mathrm{sech}^2[\kappa_0(\tau+\omega_{sol}z)]$, we can estimate the last term in Eq.(4) as

$$\sigma\frac{\partial\left|q_{sol}(z,\tau)\right|^2}{\partial\tau} \approx -2\sigma\kappa_0^{\,4}\,\tau \quad (11)$$

and relate Eq.(4) with the following NLSE model:

$$i\frac{\partial q(z,\tau)}{\partial z} = \frac{1}{2}\frac{\partial^2 q(z,\tau)}{\partial\tau^2} + \left|q(z,\tau)\right|^2 q(z,\tau) + 2\sigma\kappa_0^{\,4}\,\tau q(z,\tau) \quad (12)$$

The NLSE model Eq.(12) with a linear external potential $U_{ext}(z,t) = 2\sigma\kappa_0^{\,2}\,\tau$ is known as the Chen and Liu model in a linearly inhomogeneous plasma [20]. That is why, the colored optical solitons and Alfven solitons in a linearly inhomogeneous plasma are closely related to each other[19,20]. Eq.(12) represents one of the so-called exactly integrable models by means of the inverse scattering transform method (IST). This fact explains the remarkable stability of colored Raman solitons in the limit $\sigma \ll 1$, which is guaranteed by the property of the exact integrability of the NLSE with a linear external potential[20].

The properties of colored solitons have engaged our attention primarily because of our interest in the role of the soliton binding energy $\langle E_{bind}\rangle = -\kappa_0^{\,2}/3$ in their dynamics. According to Eq.(8), the soliton self-frequency shift increases as the second power of the soliton binding energy

$$\omega_{sol}(z) = \omega_{sol}(0) - \frac{72}{15}\sigma\langle E_{bind}\rangle^2 z. \quad (13)$$

This fact provides the answer to the question what needs to be done to achieve the best possible SRSS effect. Just as the increasing the soliton form-factor $\kappa_{\square}$ during amplification results in a growth of the soliton binding energy, thus also the enhancement of nonlinearity along the propagation distance results in the same effect[21,22].

Let us show that amplification of a soliton considered in the framework of the following model

$$i\frac{\partial q(z,\tau)}{\partial z}=\frac{1}{2}\frac{\partial^2 q(z,\tau)}{\partial \tau^2}+(1-\beta)\left|q(z,\tau)\right|^2 q(z,\tau)+\beta Q(z,\tau)q(z,\tau)+i\frac{\alpha(z)}{2}q(z,\tau) \qquad (14)$$

after the simple transformation

$$q(\xi,\eta)=\tilde{q}(\xi,\eta)\exp\frac{1}{2}\int_0^{\eta}\alpha(\tau)d\tau, \qquad (15)$$

is mathematically equivalent both to a growing nonlinearity

$$i\frac{\partial \tilde{q}(z,\tau)}{\partial z}=\frac{1}{2}\frac{\partial^2 \tilde{q}(z,\tau)}{\partial \tau^2}+(1-\beta)\exp\left[\int_0^{z}\alpha(z)dz\right]\left|\tilde{q}(z,\tau)\right|^2 \tilde{q}(z,\tau)+\beta Q(z,\tau)\tilde{q}(z,\tau) \qquad (16)$$

and an exponentially increasing external force in the oscillator model

$$\mu^2\frac{\partial^2 Q(z,\tau)}{\partial \tau^2}+2\gamma\mu\frac{1}{2}\frac{\partial Q(z,\tau)}{\partial \tau}+Q(z,\tau)=\exp\left[\int_0^{z}\alpha(z)dz\right]\left|q(z,\tau)\right|^2 \qquad (17)$$

of the Raman soliton self-scattering effect.

Varying nonlinearity provides soliton self-compression during SRSS and because of this, leads to the enhancement of the soliton self-frequency shift

$$\omega_{sol}(z)=\omega_{sol}(0)-\frac{2{\kappa_0}^4\sigma}{15\alpha_0}\left[\exp(4\alpha_0 z)-1\right] \qquad (18)$$

$$\kappa(z)=\kappa_0\exp(\alpha_0 z) \qquad (19)$$

where $\alpha(z)=\alpha_0$ is the gain coefficient.

In Fig.1 we illustrate the most important modifications of the SRSS effect calculated in the framework of the model given by equation system Eqs.(16,17). Two features of the solutions obtained by direct integration of Eqs.(16,17) are noteworthy: (1) First of all, the increase in binding energy results in the soliton self-compression. This fact significantly changes the spectral properties of colored solitons; (2) The dependence of the soliton self-frequency shift on the propagation distance is not linear function now, but it is defined by the exponentially increasing function.

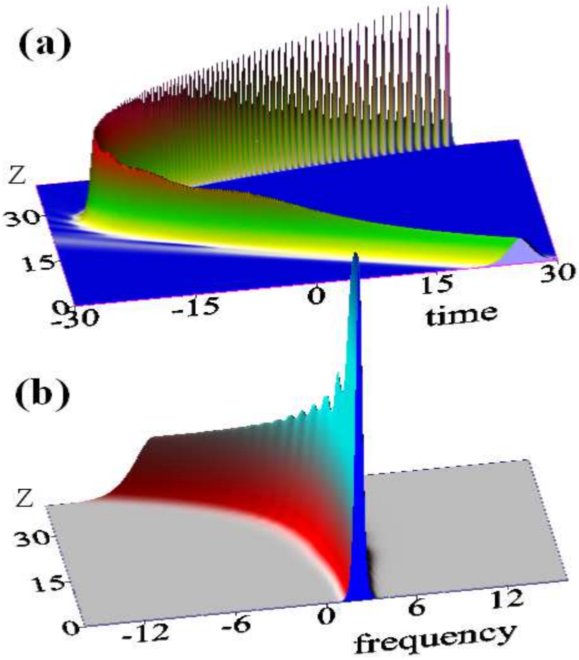

Fig.1. Soliton self-compression and Raman self-scattering effect calculated in the framework of the model Eqs.(30,31) with exponentially increasing soliton binding energy: (a) temporal behavior of self-compressing colored soliton and (b) soliton self-frequency shift after choosing the following parameters: μ = 0.5; γ = 0.3; β = 0.18; υ_0 = 2.25; κ = 0.5; α_0 = 0.05.

Our computer experiments show that the increase in binding energy results in significant changes of the properties of the SST effect. Let us consider the situation when the soliton central frequency is placed far from the localized GVD barrier. The frequency dependence of the GVD barrier can be written conveniently as

$$\frac{\partial^2 \kappa}{\partial \omega^2} = -\frac{\partial^2 \kappa}{\partial \omega^2}(\omega = \omega_{sol})\left[1 - f_2(\omega)\right] \tag{20}$$

where $\frac{\partial^2 \kappa}{\partial \omega^2}(\omega = \omega_{sol})$ represents the GVD parameter at the central soliton frequency and the function $f_2(\omega)$ describes a spectral inhomogeneity

$$f_2(\omega) = h_{bar} \exp\left[-\left(\frac{\omega - \Omega_{bar}}{\Delta\Omega_{bar}}\right)^n\right], \tag{21}$$

where the parameter h_{bar} is the height of a spectral barrier with the spectral width $\Delta\Omega_{bar}$, which is centered at the frequency Ω_{bar}. The variable n = 2, 4, ... makes it possible to alter the slope of the spectral GVD inhomogeneity.

We have computed different tunneling scenarios of self-compressing colored solitons of different amplitudes and velocities, with a variety of the barrier's slope n. In what follows, we define that the main features of the SST effect remain the same. Our numerical simulations reveal a dramatic difference in all possible soliton spectrum tunneling scenarios when the soliton binding energy is being increased. The most important representative results of such computer simulations appear in Fig. 2.

This figure can be considered as summarizing all possible scenarios of nonlinear SST effect. Figure 2(a) shows that during the soliton tunneling through forbidden (positive) barrier in GVD, the colored soliton remains "pure" soliton. Figure 2(b) shows that the increasing of the height of a spectral barrier leads to the full suppression of the SST effect, and figure 2(c) illustrates the enhanced soliton spectral tunneling effect. From our computer simulations, it is clear that the main features of the soliton spectral tunneling effect depend strongly on the soliton binding energy. It should be emphasized that the soliton binding energy has a dramatic impact on the SST effect as shown in Fig.2c. That is why the enhanced soliton spectral tunneling effect of self-compressing solitons could be of fundamental interest in the field of the soliton supercontinuum generation[8].

Conclusion

In this paper, we have shown that increasing the soliton binding energy due to the soliton self-compression enables the test of a long-standing theoretical result, which predicts that an optical soliton can tunnel between two regions of anomalous dispersion across a forbidden region of normal dispersion (enhanced soliton spectral tunneling effect). We would like to conclude by saying that the concept of tunneling is of primary importance in nature and soliton tunneling effect can be one of fundamental attention in nonlinear science.

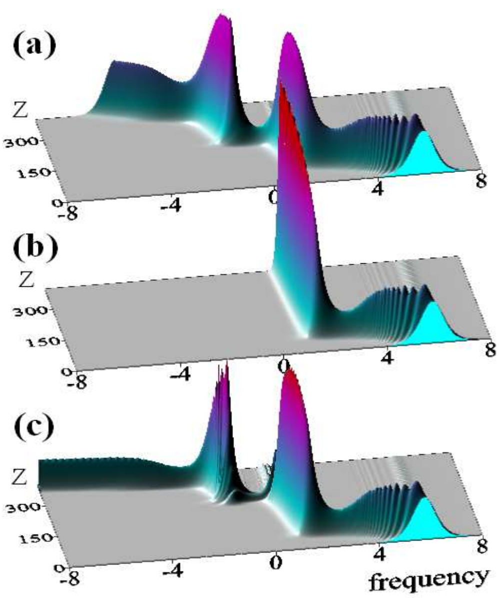

Fig.2. The influence of the soliton binding energy on the soliton spectral tunneling effect. (a) Soliton spectral tunneling through the Gaussian GVD barrier centered at the frequency Ω_{bar} = 0 with the height h_{bar} = 2.5 and the width $\Delta\Omega_{bar}$ = 3. The soliton is initialized far from the localized barrier and is initially placed at the frequency

$\omega_0 =$6 and its behavior is calculated for the case $\alpha_0 = 0$. (b) Total suppression of the SST effect under the GVD barrier height $h_{bar} = 5.0$ calculated for the case $\alpha_0 = 0$. (c) Significantly enhanced soliton spectral tunneling effect of self-compressing colored soliton calculated for the case $h_{bar} = 5.0$ and $\alpha_0 = 0.0015$.

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