Raman Solitons and the Mechanical Analogy Method

Maximo A. Agüero (Corresponding autor)
Universidad Autonoma del Estado de Mexico
Instituto Literario No.100, Toluca, C.P. 50000, Edo.Mex., Mexico
&
Prokhorov General Physics Institute, Russian Academy of Science
119991 Moscow, Vavilov Str. 38. Moscow, Russia
E-mail: maaguerog@uaemex.mx

Alexandr Ya. Karasik
Prokhorov General Physics Institute, Russian Academy of Science
119991 Moscow. Vavilov Str. 38. Moscow, Russia

Received: July 31, 2011 Accepted: September 5, 2011. Published: November 1, 2011
doi:10.5539/apr.v3n2p152 URL: http://dx.doi.org/10.5539/apr.v3n2p152

The research was financed by the Secretaria de Investigacion y Estudios Avanzados, Universidad Autonoma del Estado de Mexico (sponsoring information).

Abstract

A comprehensive resume on the soliton solutions obtained by studying the Raman Effect on nonlinear propagation of optical pulses is presented. Additionally, we show the powerful method for studying the complex nonlinear differential equation that describes the Raman waves, by means of the mechanical analogy method.

Keywords: Raman solitons, Mechanical analogy method, Nonlinear optics

1. Introduction

As is well known, when a monochromatic radiation with determined frequency w_1 insides on optical active media most of it is transmitted without any change but additionally some scattering of the radiation could occur. In the scattered radiation there will be observed not only the frequency w_1 associated to the incident radiation but also pairs of new frequencies like $w_1 \pm w_r$. The scattering without change of frequencies is called Rayleigh scattering and that scattering that occurs with changed frequencies is named Raman scattering or Raman effect. In synthesis it could be said that Raman scattering is the inelastic scattering of light. Thus the incident photon is exchanged for a photon of slightly different energy or frequency. This energy exchange corresponds to a quantum transition within the medium, which is usually rotational or vibrational in nature. In the first stage of the process, a molecule accepts an incoming photon, and is excited to one of the virtual levels. In the second stage, the molecule decays from the virtual level to the second level, with the emission of the outgoing photon.

This process can be subdivided into three separate phenomena a) Stokes scattering when the final frequency is less than the incident photon. b) Anti-stokes scattering when the final photon acquires more energy or frequency and the photon is blue shifted. In contrary the ground states of optical media suffer opposite effects. Stimulated Raman scattering (SRS) of high energy Laser pulse when insides in two-level medium has been intensively studied these by many authors , for example see review (Raymer & Walmsley, 1991) .

Great efforts have been also developed to study the nonlinear processes linked to the interactions of powerful ultra short pulses with active optical media. One of the important processes is the so named stimulated Raman self scattering (SRSS) of femtosecond optical solitons. This effect takes different names in scientific literature, for example it is often called intropulse stimulated Raman scattering (ISRS) or soliton Raman Self Frequency shift (Serkin, et al., 2003).

Various experiments were performed on the coherent pulse propagation in nonlinear media cooperative scattering. As is well known, there is a case when radiation pulse can travel through the resonance medium without absorption. . Under the influence of laser pulse the ensemble of two level atoms transforms to a coherent excited state under the action of first half of the pulse (from pulse) and coherently relax t the ground state under the action of the second half of the field (back of pulse) . Thus the radiation will not be absorbed although the pulse passing the medium. The interactions of pulse with medium are represented only by the exchange of energy to and back the pulse. This effect is named self transparency effect (Allen & Everly, 1978).

It is well known that the SRSS can play a destructive as constructive influence in different applications. The destructive role of this effect can be found in solitons communications lines and femtosecond soliton lasers due to the constriction of the pulse duration by taking the radiation spectrum out of gain line profile. To prevent this negative influence there are several techniques. In relation of the positive effect of SRSS we can mention the frequency tuning of ultrashort pulses that permits the control of parameters of femtosecond laser systems.

One of the crucial moments in nonlinear optics was the inclusion of the nonlinear dependence of the refractive index optical material and particularly of a single-mode glass optical fiber in dependence on the light intensity $n(I) = n_0 + n_2 I$. Here n_0 is the refractive index in the linear approximation and n_2 represents the nonlinear refractive index). This new approach was proposed to achieve effective control over the frequency - time envelope of laser light.

The stimulated Raman scattering (SRS) laser pulses of high energy two-level half medium has been intensively studied in recent years (see e.g. Raymer & Walmsley, 1991). Several experimental results (Drauhl et al., 1983) show peaks of the pumping radiation (Raman peaks) emerging spontaneously in pumping depletion zone, see also (Gakhovich et al., 1993). This effect of nonlinear Raman amplification was used then as a tool to observe the macroscopic fluctuations of the phase Stokes initial vacuum (Englund & Bowden, 1986).

On the other hand, intense works was dedicated to the non-stationary interaction of ultrashort pulses of light with matter. This particularly was done in the process of interaction of two photons in the inelastic scattering of excitation in crystals (Karasik & Chunaev, 2007). This mentioned paper studied the coherence properties of non stationary stimulated Raman radiation in a crystal in the presence of amplification of spontaneous noise and intense, broadband radiation. Broadband Stokes super luminescence appearing in the fluoride crystal undergoes non stationary Raman amplification in the oxide crystal. The theory of the finding results is still under construction but the main experimental aim was successfully obtained.

Some simplifications of the SRS equations have a pair of Lax and therefore theoretical and experimental work were dedicated to finding the proposed Raman solitons supporting the integrability of the equations. In particular, it was thought that the peak pumping radiation observed in (Drauhl et al., 1983) is a soliton. However, it has been shown that the Raman peak is not an observed soliton, but simply is a manifestation of the continuous spectrum (Claude et al. 1995).

In this resume we will try to review the appearance of multipeaks my means of an appropriated review of method of the strong analog to the well studied case of the dynamics of single particle in mechanics. Specifically, it was demonstrated that after separating, the SRS intrapulse cause fundamental solitons continually reduce frequencies through the Raman effect. Therefore, the division of the pulse, along with RSFS eventually leads to the total disintegration of a high order soliton, which will emit a flow of fundamental solitons, one after another.

According to the equations, the solitons expelled earlier have higher amplitudes, shorter duration, and hence, demonstrating strong SFSR. This leads to a sequence fundamental solitons with different carrier frequencies, which constantly increase their temporary separation during spread due to the effect of RSFSR.

We devote the next section to the discussion of the main peculiarities of the stimulated cooperative scattering and solitons. The third section we display with some details the method of mechanical analogy applied to nonlinear optics. Finally some discussion issues are displayed in the final section.

2. Raman effect and its regimes

Let us say some words about the mathematical model and classification of regimen of SRSS. Major details can be found in well devoted books Agrawal (Agrawal, 1995) and Hasegawa (Hasegawa, 1989), and papers (Serkin, et.al. 2003, Karasik & Chunaev, 2007). There are two possible SRSS regimes. The first one is the dispersion non-soliton regime and the second one is called the soliton regime of Raman scattering in optical fibers. This last regime need to be satisfied the condition of negative group velocity dispersion.

The equation for description of propagation of an intense wave packet through a nonlinear Raman active dispersion medium in the quasi classical approximation can be written as

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

$$\mu^2\frac{\delta^2 Q}{\delta\tau^2}+2\mu\delta\frac{\partial Q}{\partial\tau}+Q=|\,\psi\,|^2, \tag{2}$$

With Q being the amplitude of molecular vibrations (Raman contribution) and is described by the second part in the nonlinear wave equations (2). This equation describe the complex envelope of the total electric field ψand is given in terms of dimensionless soliton variables in a conventional way. The parameters are given as $\mu=(\tau_0\Sigma_t)^{-}1,\delta=(T_{2r}\Sigma_r)^{-1},\beta=\frac{GT_r}{(\varphi_{nl}\,2\pi T_2 r)}$. Here Σ_t is the resonance Raman frequency and the time T_{2r} is related to the line width of spontaneous Raman scattering, T_{1r} is the relaxation time of vibrational excitation. The β parameter contains the main information on the nonlinear regime of radiation in SRS and on the medium parameters which can be directly measured. The case $\beta=0$ is the well known system NSE completely integrable. The parameter φ_{nl} represents the strength of the nonlinear phase incursion of the wave induced by the Kerr Effect and G is the total increment of SRSS amplification of the pulse across the length of the medium.

The equations (1, 2) were solved numerically and obtained the regimes of validation of the SRSS effect (Serkin et al., 2003). The first dispersion less regime corresponds typical for organic crystals while the Kerr contribution is vanished. The result of computer experiments shows that: as the center of gravity of the pulse shifts to the Stokes domain, in the pulse there occur no noticeable frequency changes at all (in the neighborhood of the peak of the envelope), as was the case in the non soliton SRSS regime, i.e. the spectrum of a soliton pulse continuously drifts as an entity to the red domain, while the non soliton self-scattering regime is accompanied with breakdown of the spectrum into separate Stokes components. When the study of the same system is made with a more accuracy, i.e. when one considers the generation dynamics of ultra short pulses during SRSS in optical fibers taking into account the high order approximations of the dispersion theory, the equation (1) transforms to the next one

$$i\frac{\partial\psi}{\partial z}=\frac{1}{2}\frac{\delta^2\psi}{\partial\tau^2}+|\,\psi\,|^2\,\psi-\sigma\psi\frac{\partial\,|\,\psi\,|^2}{\partial\tau}+\varepsilon_3\frac{\partial^3\psi}{\partial\tau^3}+\varepsilon_4\frac{\partial^4\psi}{\partial\tau^4} \tag{3}$$

with $\sigma=2\mu\delta$. The central frequency of the pulse during its propagation in the frequency representation falls to different dispersion regions of a medium, determined by the interrelation between ε_i. The detailed description of passing from Eqs. (1,2) to the eq. (3) can be found in the work of (Dianov et al., 1992).

The perturbation theory for solitons describes correctly the Stokes frequency shift and the shift of the center of gravity of a soliton under the action of cubic dispersion (2). Meanwhile this approach cannot describe the process of the soliton self-compression appearing during the shift of its spectrum. Self-compression appears during the shift of its spectrum (Mitschke & Mollenauer 1986, Gordon 1986). Indeed, two additive terms (third and fourth in Eq. (2), acting simultaneously, should cause the self-compression of a colour soliton (i.e., moving in the frequency representation) when its spectrum will fall to regions with a gradually decreasing total dispersion. Computer experiments for solving the equations were performed and it has been found that the soliton saturation appears. When the soliton spectrum approaches the zero-dispersion point, the Stokes wing appears due to four-photon mixing, which prevents the further shift of the spectrum to the Stokes region and, hence, prevents the shortening of the soliton duration. This saturation effect occurs because the continuous Stokes shift of the soliton frequency becomes impossible, and the energy is transferred to the region of the positive group-velocity dispersion, which is forbidden for the soliton (Serkin, V.N. et. 2003b).

3. Mechanical analogy method

The mechanical analogy method is actually an effective method to study the nonlinear behavior of static solutions of nonlinear field differential equation. Now, in general terms we describe the method. Let us have a scalar field $\varphi(x,t)$ whose Lagrangian has the form

$$L = \int dx \left[\frac{1}{2}\left(\partial\varphi / \partial t\right)^2 - \frac{1}{2}(\nabla\varphi)^2 - U(\varphi) \right] \tag{4}$$

With the potential $U(\varphi)$ bounded from below. Instead a finite discrete number of degrees of freedom now we have a continuous range, so the number of degrees of freedom is infinite, i.e. the field value φ at each point x. So, the Lagrangian density can be written as

$$L = T[\varphi] - V[\varphi] \tag{5}$$

with the kinetic energy

$$T[\varphi] = \frac{1}{2}\int dx \left(\frac{\partial\varphi}{\partial t}\right)^2 \tag{6}$$

and the potential energy

$$V[\varphi] = \int dx \left[\frac{1}{2}(\nabla)^2 + U(\varphi) \right] \tag{7}$$

while the Euler - Lagrange equation takes the form

$$\frac{\partial^2\varphi(x,t)}{\partial t^2} = -\frac{\delta V[\varphi]}{\delta\varphi(x,t)} \tag{8}$$

For the $1+1$ dimensional case, the equation of motion (8) for the static field configuration one obtains

$$\varphi'' = -\frac{\partial U(\varphi)}{\partial\varphi} \tag{9}$$

This relationship is a differential equation of second order. Now, if we make the variable x plays the same role of "time" τ, and the field φ plays the "coordinate" role of a particle ξ of unit mass, consequently, the equation (9) represents the Newton's second law of motion for the movement of certain "Particle analog" ξ in a given potential $-U(\xi)$. In other words, what we do is the following mapping: $\varphi \longrightarrow \xi, \quad x \longrightarrow \tau$. Unlike the Newton's equation of classical mechanics, the Eq. (9) has a positive sign in its right hand side. So, the evolution of field configuration problem now is reduced to the study of a single analog "particle" that is much easier for treatment. Similar reduction can be done in the studies of shock or multipeaks pulses in optics related to Raman soliton states as explained below.

The experimental observation of the Raman multipeak states (Podlipensky et al. 2007, Podlipensky et al. 2008) and by the early numerical findings (Allen & Everly 1978), report some features of Raman multipeak states predicted before. The qualitative explanation will be done on the base of the powerful concept of gravity-like potential introduced in Refs. (Allen & Everly 1978, Akhmediev et.al. 1996). This approach will provide the possibility of forming Raman soliton states with more than two peaks in PCFs, thus leading to a complete violation of the soliton splitting law of Eqs. (1-2), and to new ways to manipulate SCG in micro structured fibers by controlling exotic states of light in the fiber.

In the paper of (Truong et al. 2010) was studied the short version of the equation (3) for $\varepsilon_i = 0$.

$$i\psi_z + \frac{1}{2}\psi_{tt} + |\psi|^2\psi - \tau_R(|\psi|^2)_t = 0 \tag{10}$$

In Eq. (10), ψ is the envelope of the electric field, scaled with the soliton power $P_0 = |\beta_2|/(\gamma t_0)$, where β_2 is the second order dispersion coefficient, i.e. the nonlinear coefficient of the fiber, and t_0 is the input pulse duration. The dimensionless propagation length z is scaled with the second order dispersion length $L_{D2} = t_0^2/|\beta_2|$. The temporal variable t is scaled with t_0. The last term in Eq. (10) represents the Raman Effect, and $\tau_R = T_R / t_0$, where T_R about 100-200 fs in silica is the Raman response time. The Eq. (10) is written in the anomalous dispersion regime. This because in the absence of Raman term τ_R, bright solitons are expected to appear.

Next, it is necessary to introduce the Gagnon-Belanger Phase transformation (Gagnon & Belanger 1990, Allen & Everly 1978). For some details on this transformation we recall here the main results obtained in the cited papers. Let us start with the Eq. (10) with delay time τ_R. By using the symmetric transformation method, indeed the one parameter (λ) symmetric group of Eq. (10) one can concludes that this equation keeps its form under the transformation

$$z' = \lambda + z, t' = \frac{g}{2}\lambda^2 + gz\lambda + t \quad 11)$$

$$\psi'(z', t') = \psi(z,t) exp\left[i\left(\frac{g^2}{6}\lambda^3 + \frac{g^2}{2}\lambda^2 z + gt\lambda - a\lambda \right) \right] \quad (12)$$

With a, b and λ are real free parameters. The infinitesimal generator of this point transformation is

$$[\partial_z] + a\,[-i(\psi\,\partial_\psi - \psi^*\,\partial_{\psi^*})] + g[z\,\partial_t + i(\psi\,\partial_\psi - \psi^*\,\partial_{\psi^*})] \quad (13)$$

The brackets contain the symmetry generator of the phase translation $z' = z + z_0$ the constant change of phase $\varphi' = \varphi\, exp(iu_0)$ and the Galilean transformation

$$t' = t + v_0 z, \quad z' = z, \quad \psi' = \psi(z,t) exp\left[i\left(v_0 t + \frac{v_0^2}{2} z \right) \right] \quad (14)$$

with constants z_0, φ_0, v_0. As it is demonstrated, this is also a symmetry transformation of Eq. (10). By using this symmetry it is possible to derive the accelerating like frame transformation that could reduces the Eq.(10) to a friendly ordinary differential equation. This method is known as the symmetry-reduction method of partial differential equation and is based on the characteristics of invariant quantities. The invariants for Eq.(10) are possible to find by using the following variable transformations

$$\xi = t - \frac{g}{2}z^2, \qquad f = \psi(z,t)\ exp\left[i\left(\frac{g^2}{3}z^3 - gzt + az \right) \right] \quad (15)$$

and also the conjugate f^*. Thus, supposing that there are intense accelerating soliton, in this frame we use the Gagnon-Belanger transformation (15) with $\xi = t - gz^2/2$ and $g = 32\tau_R a^2/15$. The resulting nonlinear Schrödinger equation is

$$if_z + (a - g\xi)f + \frac{1}{2}f_{\xi\xi} + |f|^2 f - \tau_R f \delta_\xi |f|^2 = 0 \quad (16)$$

For the first simple case when ignoring all nonlinear terms, the equation (16) would correspond to the stationary Schrödinger equation for a unitary mass particle of energy q subject to a gravitational potential $U(\xi) = g\xi$.

On the other hand, the division of the pulse is a well known process that occurs in the initial moments of the pulse propagation in nonlinear optical fibers. According to the most authoritative theory of the division of the pulse in the femtosecond regime, higher-order solitons are affected by stimulated Raman scattering (SRS) and higher-order terms, the dispersion became unstable and eventually break down into several fundamental solitons (Tai et al., 1988, Kodama & Hasegawa, 1987). This was done meanly because of the results obtained in experiments on Raman multi peaks states (Mitschke & Mollenauer 1986, Gordon 1986). Their approach was based on the so named gravity like potential factor. This is the possibility of forming multipeaks Raman soliton. Indeed by computer experiments they found multiple peaks for the equation. As a rule the central peak is more robust than satellites and is quite stable. In contrast to this, the other peaks are not stable. If the solution supports more peaks they are less robust and the smaller the propagation length required for them to collapse.

We will follow the paper (Conti et al. 2010) by presenting some main results, more detailed explanation could be found in the cited work. First, the equation (16) is transformed via the standard hydrodynamical ansatz $f = \sqrt{\rho}\, exp(i\varphi)$ after which it is easy to find two equations

$$\rho_z + \partial_\xi (\rho v) = 0 \tag{17}$$

$$\varphi_\zeta + \frac{1}{2}\varphi_\xi^2 = -g\xi + a + \rho - \tau_R \partial_\xi \rho + \frac{1}{4\sqrt{\rho}} \frac{\partial}{\partial \xi} \frac{\rho_\xi}{\sqrt{\rho}} \tag{18}$$

Next, it is defined the new variable that is the instantaneous frequency inside the pulse and named as velocity field $v = -\varphi_\xi$. Deriving again the Eq. (18) with respect to ξ it is obtained

$$v_z + v v_\xi = -\partial_\xi (U_{QP} + U) \tag{19}$$

with the potential

$$U_{QP} = \frac{1}{4\sqrt{\rho}} \frac{\partial}{\partial \xi} \frac{\rho_\xi}{\sqrt{\rho}} \tag{20}$$

and

$$U = g\xi - \rho + \tau_R \partial_\xi \rho \tag{21}$$

This potential was also introduced by (Gorbach &. Skryabin, 2007). The equation (19) can be easily transformed to that one that is common in dynamical systems by standard methods

$$\frac{d\xi}{dz} = v \tag{22}$$

$$\frac{dv}{dz} = -\partial_\xi U(\xi) \tag{23}$$

The previous system can be reduced to the form of the motion of a particle with trajectory $\xi(z)$ in the potential U and can be rewritten as a single Newton-like equation

$$\frac{d^2\xi}{dz^2} = -\frac{\partial U}{\partial \xi} \tag{24}$$

Using this mechanical analogy it was possible to find at least numerically several important conclusions. The first one concerned with shocks. These structures in the phase space (ξ, v) can display a vertical slope that is determined by the relation $d\xi / dv = 0$. The geometrical interpretation of shocks could be outlined as following. A shock occurs when we face with multivalued function $v = v(\xi)$ in the plane (ξ, v) for trajectories reaching the same position ξ at the same value z with different velocities. It has been observed that when the Raman parameter τ_R increases the shocks profusely appear. This phenomenon contradicts the perfectly regular oscillations of the soliton breathing when the Raman effect is absent (Agrawal 1995).

4. Some results and discussion

As an example of studying the nonlinear "mechanical" equation numerically, it is possible to provide the results of emergence 3 peak Raman solitons (Fig. 1) for the nonlinear equation (10) which was transformed into a mechanical system analog dynamic equation (Truong et.al. 2010). These solutions were found by solving the boundary value problem (BVP) by means of a shooting method with appropriate boundary conditions, for $\tau_R = 0.1$. It is possible to observe that these solutions have Airy tails on the leading edge of pulses. This because of the tunneling of the solutions in the case of linearized Schrodinger equation. But quite surprisingly these tails are quite small when one uses the physically relevant parameters for example when the slope b of the gravity like potential gets larger the Airy tails will be more pronounced. So we can see that using a simple but powerful mechanical analogy method one is able to obtain at least qualitative valid predictions on dynamics of coherent structures in nonlinear processes.

References

Agrawal G.P. (1995). *Nonlinear Fiber Optics* , San Diego: Academic Press.

Akhmediev, et.al. (1996), Influence of the Raman-effect on solitons in optical fibers, *Optics Comunications* 131, 260-266. http://dx.doi.org/10.1016/0030-4018(96)00283-0

Allen L., Everly G. (1978). *Optical resonance in two level atom*. Courier Dover Publications, 233 p.

Claude C., Ginovart, F., Leon, J. (1995). Nonlinear theory of transient stimulated Raman scattering and its application to long – pulse experiments, *Physical Review A* 52, 767. http://dx.doi.org/10.1103/PhysRevA.52.767

Conti C. et al. (2010). Multiple hydro dynamical shocks induced by Raman effect in photonic crystal fibers, *Physical Review A*, Vol. 82, No. 1. 013838. http://dx.doi.org/10.1103/PhysRevA.82.013838

Dianov E.M., Grudinin A.B., Prokhorov A.M., Serkin V.N. (1992). Non-linear transformation of laser radiation and generation of Raman solitons in optical fibers. In Taylor J.R. (Ed.) *Optical Solitons-Theory and Experiment.* pp. 197 -261 Cambridge: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511524189.008

Drauhl K , Wenzel, R.G., Carlsten, J.L. (1983). Observation of Solitons in Stimulated Raman Scattering. *Physics Review Letters.* 51, 1171. http://dx.doi.org/10.1017/CBO9780511524189.008

Englund, J.C., Bowden, C.M. (1986). Spontaneous Generation of Raman Solitons from Quantum Noise. *Physical Review Letters,* 57, 2661. http://dx.doi.org/10.1103/PhysRevLett.57.2661.

Gakhovich, D.E., Grabchikov, A.S., Orlovich V.A. (1993). Spontaneous solitons in short length geometry of stimulated Raman scattering*Optics Communications,* 102, 485. http://dx.doi.org/10.1016/0030-4018(93)90427-7

Gagnon L. and P. A. Belanger. (1990). Soliton self-frequency shift versus Galilean-like symmetry *Optics. Letters,* 15, 466-468. http://dx.doi.org/10.1364/OL.15.000466

Gorbach A. V., Skryabin D. V. (2007). Light trapping in gravity-like potentials and expansion of supercontinuum spectra in photonic-crystal fibres. *Nature Photonics*. 1, 653-657. http://dx.doi.org/10.1038/nphoton.2007.202

Gorbach, A. V., Skryabin, D. V. (2007). Theory of radiation trapping by the accelerating solitons in optical fibers. *Physical Review A* 76, 053803**.** http://dx.doi.org/10.1038/nphoton.2007.202

Gordon J. P. (1986). Theory of the soliton self-frequency shift, *Optics Letters*, 11, 662-664 http://dx.doi.org/10.1364/OL.11.000662

Hasegawa A. (1989) *Optical Solitons in Fibers*. Berlin: Springer-Verlag. http://dx.doi.org/10.1007/BFb0041283

Karasik A. Ja. and Chunaev, D.S. (2007). Nonstationary Raman amplification of superluminescence in crystals, *JETP Letters , Vol. 85, No. 7, pp. 315-318.* http://dx.doi.org/10.1134/S0021364007070028

Kodama, Y. & Hasegawa, A. (1987). Nonlinear pulse propagation in a monomode dielectric guide. *IEEE Journal* *of Quantum Electronics*, 23, 510-524. http://dx.doi.org/10.1109/JQE.1987.1073392

D.C. MacPherson, R.C. Swanson, J.L. Carlsten, (1989). Spontaneous solitons in stimulated Raman scattering. *Physical Review A,* 40, 6745. http://dx.doi.org/10.1103/PhysRevA.40.6745

Mitschke, F. M. & Mollenauer, L. F. (1986). Discovery of the soliton self-frequency shift. *Optics Letters*, 11, 659-66. http://dx.doi.org/10.1364/OL.11.000659

Podlipensky, A. et al. (2007). Bound soliton pairs in photonic crystal fibers. *Optics Express,* 15, 1653-1662 http://dx.doi.org/10.1364/OE.15.001653

Podlipensky, A. et al. (2008). Anomalous pulse breakup in small-core photonic crystal fibers *J. Opt. Soc. Am. B* 25, 2049-2056. http://dx.doi.org/10.1364/JOSAB.25.002049

Raymer, M.G., Walmsley I.A. (1991). The quantum coherence properties of stimulated Raman scattering. *Prog. in Optics*, 28, 216

Serkin, V.N., et.al. (2003). Stimulated Raman self-scattering of femtosecond pulses. I. Soliton and non-soliton regimes of coherent self-scattering, *Quantum Electronics,* 33(4) 325-330. http://dx.doi.org/10.1070/QE2003v033n04ABEH002413

Serkin, et al. (2003b). Stimulated Raman self-scattering of femtosecond pulses. II. The self-compression of Schrödinger solitons in a spectrally inhomogeneous dispersion medium. *Quantum Electronics,* 33(5) 456-459. http://dx.doi.org/10.1070/QE2003v033n05ABEH002434

Truong X. Tran, et al. (2010). Theory of Raman multipeak states in solid-core photonic crystal fibers. *ARXiv:1005.4920v1 [physics.optics]* 26 May

Tai, K., Hasegawa, A. & Bekki, (1988). N. Fission of optical solitons induced by stimulated Raman effect *Optics Letters.,* 13 392-395. http://dx.doi.org/10.1364/OL.13.000392

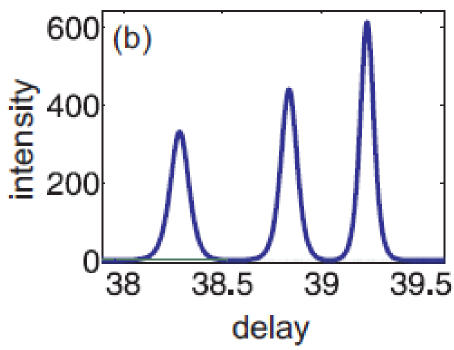

Figure 1. Profile of 3 peak Raman solitons obtained by using the gravital like potential $U(\xi)$