Simulation and Evaluation of Soliton Signal Effects In Fiber Optics

Ahmed Chyad Kadhim
Department of Laser and Optoelectronics Engineering, University of Technology, Baghdad, Iraq.

Abstract
A soliton is a solitary wave whose amplitude, shape, and velocity are conserved after a collision with another soliton. Solitons, in general, manifest themselves in a large variety of wave/particle systems in nature: practically in any system that possesses both dispersion (in time or space) and nonlinearity. Solitons have been identified in optics, plasmas, fluids, condensed matter, particle physics, and astrophysics. Yet over the past decade, the forefront of soliton research has shifted to neuroscience. The Soliton model in optical fiber is a recently developed model that attempts to explain how signals are propagated within optical fiber without dispersion. In this research, it proposes that the signals travel along the Single Mode Optical Fiber in the form of certain kinds of sound (or density) pulses known as solitons. The three pulses are generated by the Korteweg-deVries equation with Matlab Program. The results of simulation represent the behaviors of the soliton signal in Fiber Optics. Computer simulation results demonstrated that the soliton signal can be successfully used to reduce the dispersion and attenuation effects and travel for a far distance along an optical fiber compared to Gaussian Signal.

Keywords: Soliton Systems, Fiber Optics, Optical Solitons.

حساب ومحاكاة تأثيرات الموجة الانفرادية في الألياف البصرية

احمد جياد كاظم
قسم هندسة الليزر والالكترونيات البصرية، الجامعة التكنولوجية، بغداد، العراق.

خلاصة:
تتسم الموجة الانفرادية الـSoliton بان صفاتها من اتساع وشكل وسرعة تكون محفوظة من التغير بعد تصادمها مع موجة منفردة اخرى. تظهر الموجات الانفرادية، على العموم ، في الطبيعة على شكل تَشْكِيلة كبيرة مِن لأنظمة الموجيةِ / الجسيمية. اما من الناحية العملية فانها تظهر في اي نظام يمتلك خاصيتي التشتت (الزماني والمكاني) و اللاخطّيةِ. لقد وجد ان الموجات الانفرادية يمكن ان تنشأ في البصريات، البلازما، الموائع، المواد المتكثفة، فيزياء الجسيمية والفيزياء الفلكية. مع كل ذلك فلقد تغيرت طليعة البحث في الموجة الانفرادية باتجاه عِلْمِ الأعصاب. ان النموذج الانفرادي للموجة في الالياف البصرية هو حاليا في طور التطور والذي يحاول ان يوضح كيفية مرور الاشارة داخل الكابل الضوئي بدون تشتت. في هذا البحث يقترح ان الاشارات تنتقل خلال كابل ضوئي احادي النمط على شكل انواع معينه من النبضات الصوتية والمعروفة بالموجات الانفرادية. تم توليد ثلاث نبضات باستخدام معادلة Korteweg–deVries وبرنامج Matlab. حيث مثلت نتائج المحاكاة تصرف الموجة الانفرادية في الالياف البصرية. لقد اظهرت نتائج المحاكاة الحاسوبية ان الموجات الانفرادية يمكنها ان تستخدم بنجاح لتقليل تاثيرات التشتت والتوهين ويمكنها ان تنتقل لمسافاة بعيدة خلال الكابل الضوئي مقارنة باشارة غاوس.

Email: A.Ch.Kadhim@gmail.com

1. Introduction

Nonlinear waves have long been an interest to scientists in a variety of disciplines. A multitude of applications have been employed, ranging from fluid dynamics and plasma physics to even neuroscience and biology. Waves are omnipresent, from tsunamis in the ocean, to gamma waves and sonic booms. The methods and results of computational wave modeling may be adapted to fit the specifics of another field [1].

Nonlinearity permeates our physical world. The evidence for nonlinear behaviors is present in so many aspects of physics, chemistry, biology, economics, etc., that it is not possible to mention them all in here. Among the most striking and aesthetically appealing manifestations of nonlinearity is the propagation of solitons or, more generally, solitary waves, spatial solitons can exist in a broad branch of nonlinear materials, such as cubic Kerr, saturable, thermal, reorientation, photorefractive, and quadratic media, and periodic systems. Furthermore, the existence of solitons varies in topologies and dimensions [2].

Computer-aided modeling and simulation software programs are essential tools to predict how an optical communication component, link, or network will function and perform. These programs are able to integrate component, link, and network functions, thereby making the design process more efficient, less expensive, and faster. The tools typically are based on graphical interfaces that include a library of icons containing the operational characteristics of devices such as optical fibers, couplers, light sources, optical amplifiers, and optical filters, plus the measurement characteristics of instruments such as optical spectrum analyzers, power meters, and bit error rate testers. To check the capacity of the network or the behavior of passive and active optical devices, network designers invoke different optical power levels, transmission distances, data rates, and possible performance impairments in the simulation programs [3].

In this paper, Soliton theory are described and a simulation has been carried out throughout the analysis of the theories of Korteweg-deVries (KdV) equation using Matlab Program to describe the effects of soliton signal through single mode optical fiber.

2. Soliton Systems

In recent years, pressure pulses of very short (picoseconds) time duration have found wide application as a diagnostic tool in the semiconductor industry and in fundamental condensed matter research. Besides their outstanding present technical applications of the solitary pulses difficulties or even (sometimes) impossibility of analytic solutions to describe their propagation (due to the nonlinear character of implied media), as well as about the remarkable efficiency of the computer simulations of otherwise inaccessible scientific problems [4]. Fractals – signals that display scale-invariant or self-similar behavior are ubiquitous in nature and result from a wide variety of physical processes, including diffusion, erosion, turbulence and criticality. The traditional view that the healthy state of an organism is represented by homeostatic, regular, steady-state behavior has been challenged by the observation that many physiological signals are, in fact, non-linear, inhomogeneous and fractal [5].

Both the effects of non-linearity and dispersion produce a self-sustaining and localized density pulse with a moving segment of the nerve membrane in the gel state. This pulse is called a soliton. The solitary wave maintains its shape while it travels at a constant speed less than the sound velocity in the lipid membrane. Solitons can propagate over long distances without loss of energy. The pulse is also called as adiabatic pulse, because no energy is lost to the environment during propagation [6].

In the 1970's it was realized that several of these nonlinear PDEs yield entire families of exact solutions, and not just isolated solitons. These families contain solutions with arbitrary numbers of solitons of varying speeds and application in the studies of nanometer-sized structures, the propagation of these short acoustic pulses over millimeter distances at low temperatures has revealed a new field of picoseconds acoustics, amplitudes, and undergoing mutual collisions. The three most studied systems have been:

• The Korteweg-deVries equation,

$$u_t + 6uu_x + u_{xxx} = 0 \quad (1)$$

This is a generic equation for 'long waves' in a dispersive, energy-conserving medium, to lowest order in the nonlinearity.

• The Sine-Gordon equation,

$\phi_{tt} - \phi_{xx} + \sin(\phi) = 0$ …………………(2)

The name is a play on the Klein-Gordon equation, $\phi_{tt} - \phi_{xx} + \phi = 0$. Note that the Sine-Gordon equation is periodic under $\phi \longrightarrow \phi + 2\pi$

• The nonlinear Schrcodinger equation,

$i\psi_t \pm \psi_{xx} 2|\psi|^2 \psi = 0$ …………..…(3)

Here, ψ is a complex scalar filed depending on the sign of the second term [7].

A Soliton solution of KdV equation is:

$u(x,t) = u(x - Vt)$. Then with $\xi \equiv x - Vt$, We have $\partial_x = \partial_\xi$ and $\partial_t = -V\partial\xi$ when acting on $u(x,t) = u(\xi)$. Thus we have

$-Vu' + 6uu' + u''' = 0$ …………………(4)

Integrating once, yield

$-Vu + 3u^2 + u'' = A$ …………………..(5)

Where A is a constant., integrating once more, obtaining

$-\frac{1}{2}Vu^2 + u^3 + \frac{1}{2}(u')^2 = Au + B$ ……(6)

Where now both *A* and *B* are constants. Assume that u and all its derivatives vanish in the limit $\xi \longrightarrow \pm\infty$ which entails *A*=*B*=*0*. Thus

$$\frac{du}{d\xi} = \pm u\sqrt{V - 2u}$$

With the substitution

$u = \frac{1}{2}V \operatorname{sech}^2(\theta)$ ………………………..(7)

We find $d\theta = \pm\frac{1}{2}\sqrt{V}d\xi$, hence the solution is

$u(x,t) = \frac{1}{2}V \operatorname{sech}^2(\frac{\sqrt{V}}{2}(x - Vt - \xi_o))$ ….(8)

Where x is a distance, V velocity, t time and ξ is a position. Note that the maximum amplitude of the soliton is $u_{max} = \frac{1}{2}V$, which is proportional to its velocity V. The KdV equation imposes no limitations on V other than $V \geq 0$ [7].

3. The Fiber Optic Transmission

In an fiber-optic transmission, an optical signal, serves as the information carrying vehicle. Both analog and digital information are supported. In operation, the light is launched or fed into the fiber. The fiber itself is composed of two layers, the cladding and the core. Due to their different physical properties, light can travel down the fiber by a process called total internal reflection. In essence, the light travels through the fiber via a series of reflections that take place where the cladding and core meet, the cladding-core interface. When the light reaches the end of the line, it is picked up by a light-sensitive receiver, and after a series of steps, the original signal is reproduced. To sum up, a video camera's output or other such signal is converted into an optical signal in an FO system. It is subsequently transmitted down the line and converted back following its Reception [8]. Calculating the performance in optical fiber communications systems in which nonlinearity plays a significant role in transmission is difficult. The difficulty is further enlarged by the complex way in which different modulation formats — such as the return-to-zero, chirped-return-to-zero, and differential phase- shift-keying — interact with modern-day receivers. The details of the optical filtering, electrical filtering, and internal nonlinearity can significantly impact the performance in even a standard receiver with hard-decision decoding. The use of forward error correction and signal processing further complicates the calculation of the performance [9].

3.1. Attenuation Units

Signal attenuation (or fiber loss)is define as the ratio of the optical output power Pout from a fiber of length L to the optical power Pin .This power ratio is a function of wavelength,as is shown by the general attenuation curve in Figure -1 .The symbol α is commonly used to express attenuation in decibel per Kilometer [10].

$\alpha = \frac{10}{L} \log\left(\frac{Pi}{Po}\right)$ dB/Km…………………(9)

Where Pi = optical input power, Po = optical output power and L= length of fiber. An ideal fiber would have no loss so Pout =Pin. This corresponds to a 0-dB attenuation, which is practice impossible. An actual low-loss fiber may have a 3-dB /Km average loss. This means that the optical signal power would decrease by 50 percent over a 1-Km length and would decrease by 75 percent (a 6-dB loose) over 2-Km length, since loss contributions expressed in decibel are additive [10].

3.2. Dispersion Calculation:

The total dispersion in single-mode fibers consists mainly of material and waveguide dispersions. The dispersion *D* is represented by:[7]

$D(\lambda) = \frac{1}{L}\frac{d\tau}{d\lambda}$………………………………(10)

Which is expressed in $ps/(nm.km)$. The total broadening σ of an optical pulse over a length of fiber L is given by:

$\sigma = D(\lambda) L\sigma_{\lambda}$……………………………..(11)

Where σ_{λ} is the wavelength spread of the source. To measure the dispersion, one examines the pulse delay over a wide wavelength range. At the zero-dispersion point the pulse delay will go through a minimum. To calculate the dispersion point the pulse delay will go through a minimum. To calculate the dispersion by:[10]

$D(\lambda) = \frac{\lambda S_0}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right] ps/(nm.km)$……..(12)

for $1200 \leq \lambda \leq 1600$ nm

Where S_o Zero Dispersion Slope: $\leq 0.092\, ps/(nm^2.km)$, λ_0 Zero Dispersion Wavelength 1302nm $\leq$ 1322 nm and λ Operating Wavelength [10].

4. Evaluation of Optical Soliton in Fiber Optics

The fundamental of optical soliton equation is derived from the nonlinear Schrödinger equation:

$\frac{\partial A}{\partial z} = \frac{\alpha}{2}A + \frac{j}{2}\beta_2\frac{\partial^2 A}{\partial t^2} - j\gamma|A|^2A$……………(13)

For the partial differential equation above the first and second term represent the linear effects and the third term represent nonlinear effects. The linear effects involve loss (first term) and group velocity dispersion β_2 (second term) but the nonlinear effects is defined by self phase modulation which depend on (γ nonlinearity coefficient) parameter.

γ coefficient can be calculated from the relation below:

$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$…………………………………(14)

where n_2, A_{eff} are refractive index and affective area respectively.

After applying split step method to solve the nonlinear Schrödinger equation we get the solution below. This solution is defined as soliton signal.

$u(z,t) = \sqrt{\frac{|\beta_2|}{\gamma T_0^2}}\, sech\left(\frac{t}{T_0}\right) exp\left(j\frac{\beta_2 z}{2T_0^2}\right)$……..(15)

This solution represent the optical soliton signal as a function of time and distance. All solutions are parameterized by pulse width T_0, also the solutions can be parameterized in terms of energy as follow: $E = \int |u(z,t)|^2 dt = \frac{2|\beta_2|}{\gamma T_0}$, where the pulse width and peak power are related by: $\sqrt{\frac{\gamma T_0^2 P_0}{|\beta_2|}} = 1$

In optical soliton, the phase of soliton is not stationary which unlike the amplitude. Thus phase evaluation is often described in terms of the " soliton period", where soliton period ($z_0 = \sqrt{\frac{\pi T_0^2}{2|\beta_2|}}$) is another way to parameterized a soliton.

The spectrum of optical soliton can be obtained using inverse scattering method.

$|u(z,\omega)|^2 = \sqrt{\frac{|\beta_2|}{4\gamma}}\, sech\left(\frac{\pi\omega T_0}{2}\right) exp\left(j\frac{\beta_2 z}{2T_0^2}\right)$….(16)

From the equation above can calculate the Full width Half maximum (FWHM) of a pulse, which is defined as the full width of the pulse at this half maximum power level. These parameters can be determined from the equations (17), (18) and (19).

$P_0 = \sqrt{\frac{|\beta_2|}{\gamma T_0^2}}$……………………………..(17)

$T_{FWHM} = 2T_0 acosh(\sqrt{2})$………………..(18)

$\Delta\omega_{FWHM} = \frac{4}{\pi T_0} acosh(\sqrt{2})$……………….(19)

For the solution of the nonlinear Schrödinger the power is given by the square of the Soliton function. Thus T_{FWHM} of the fundamental soliton pulse in normalized time is found from the relationship $sech^2(\tau) = \frac{1}{2}$ with $\tau = \frac{T_s}{2T_0}$ where T_0 is the basic normalized time unit. This yields:

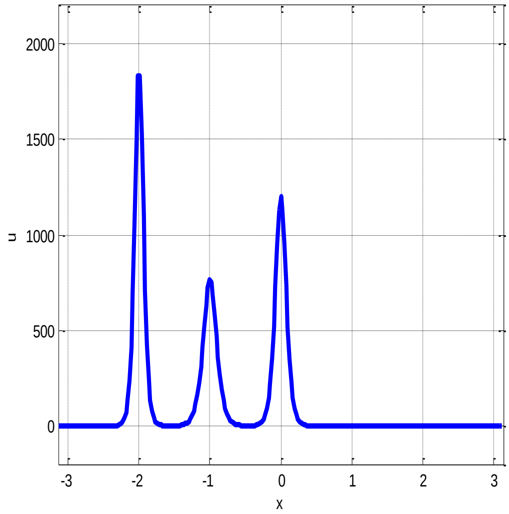
$$T_0 = \frac{T_s}{2acosh(\sqrt{2})} = \frac{T_s}{1.7627} = 0.567T_s \quad (20)$$

5. Results and Discussion

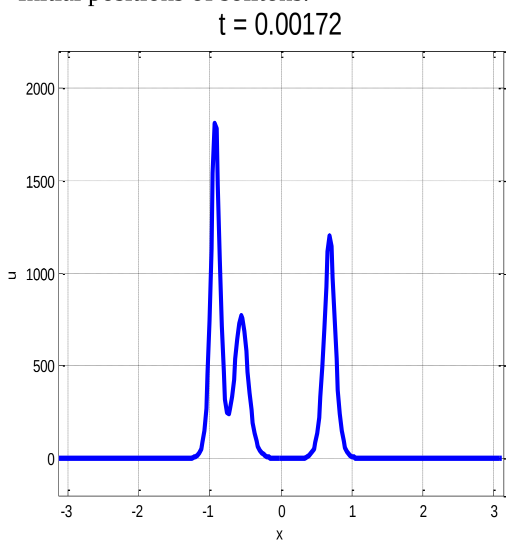
The mathematical description of the dynamic systems is not a simple task for which basic principles suffice. Not all complex systems can be modeled using basic laws to determine their dynamic behavior. An interesting alternative to solve such problems would be an experimental systems identification model. In other words, a model based on an input output system must be founded, which establishes a mathematical relation between input and output data. The assessment of a nonlinear system requires analysis of the dynamic system behavior under a prescribed set of events known as contingencies. Conventionally this is done by simulating the system nonlinear equations. Since the stability limits cannot be determined from a single simulation. More than one simulation is required. The large size of the system adds to the complexity thus three pulses of KdV equation is described as in equation (21).

$$u = A\operatorname{sech}(0.5(A(x+2)))^2 + B\operatorname{sech}(0.5(B(x+1)))^2 + C\operatorname{sech}(0.5(C(x+0)))^2 \qquad ...(21)$$

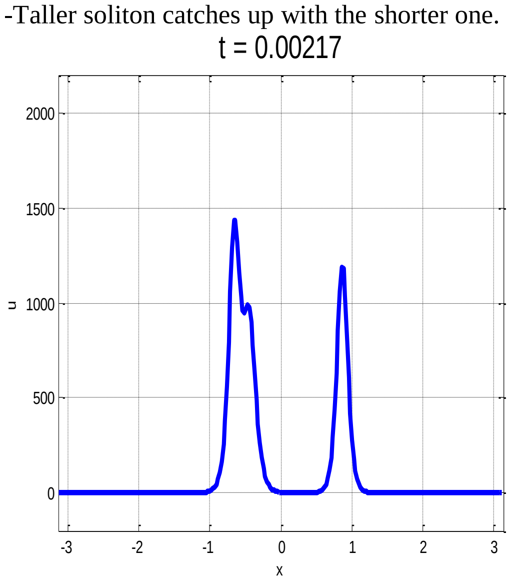
This paper presents a novel method of simulation during and post-fault behaviors of the soliton system for a three soliton pulses, observing its dynamics during a few seconds. This is done by simulating the system nonlinear equations which called Korteweg-deVries (KdV) equation using Matlab. Simulation results on different intervals are carried out. Simulation of three pulses which are generated using equation (21) is shown below, where the amplitudes of these pulses are (20, 12, 14) with initial positions (-2, -1, 0) respectively. Due to this amplitude-dependent speed, as shown in Figure -4(a), a taller soliton originally placed behind a shorter one catches up with the shorter one and moves ahead of it after a collision as shown in Figure -4(b, c and d) . Also the behavior of a taller soliton with the other medium soliton is in the same manner as shown in Figure -5(a, b, c and d). Another important set of properties is observed in this collision process. During the collision as shown in Figure -4(c and d) and Figure -5(b and c), the three solitons do not linearly superpose (nonlinear collision), and as a result experience a significant amount of amplitude modulation. After the collision as shown in Figure -5(d) the three solitons return to their original shapes, however, they have acquired a permanent time (phase) shift due to the nonlinear collision shown by the difference in and in Figure -5(d) (with no time shift, and would be equal, since the time elapse before and after the collision is the same).



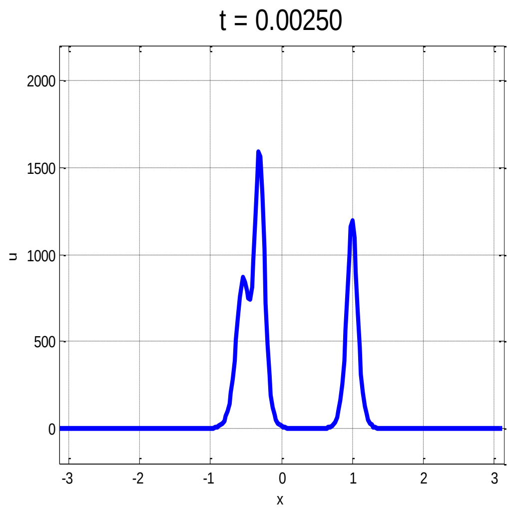
a - Initial positions of solitons.



b -Taller soliton catches up with the shorter one.

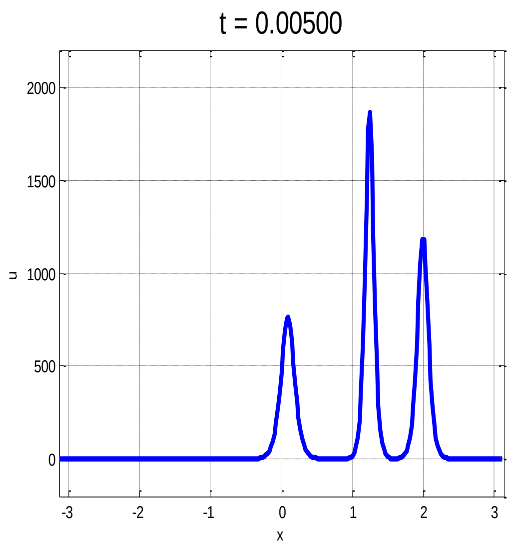


c - collision between taller soliton and shorter soliton

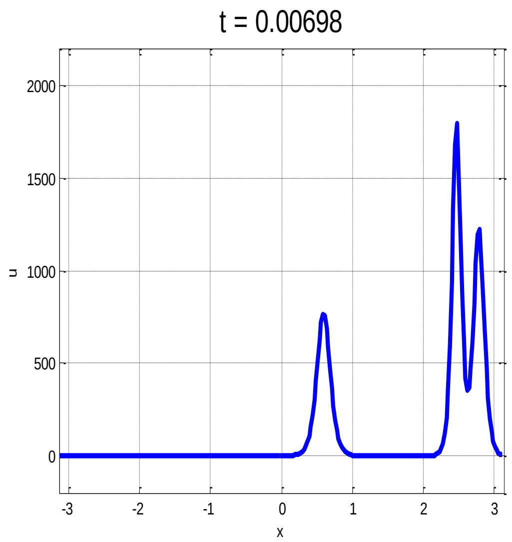


d - After First collision.

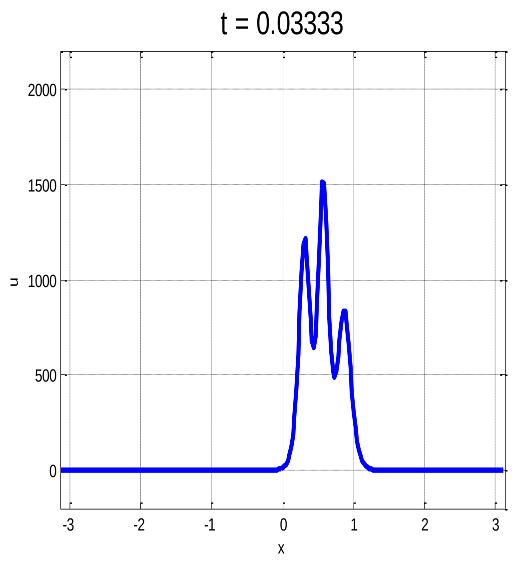
Figure 4. a- Initial positions of solitons. b- Taller soliton catches up with the shorter one.c- The collision between taller soliton and shorter soliton. d- After collision.



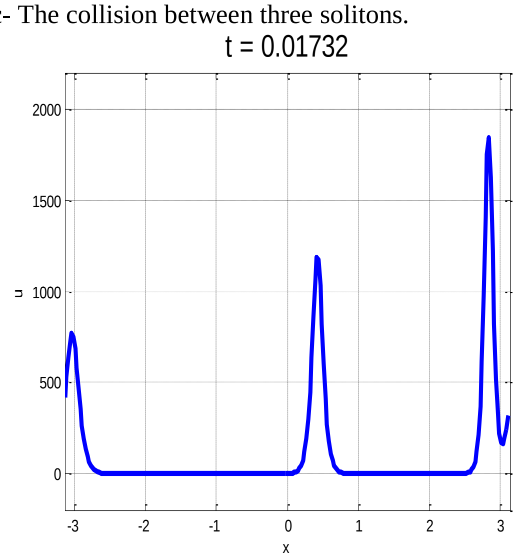
a -After the first collision.



b - Taller Soliton catches up with the medium one.



c- The collision between three solitons.



d- After the second collision

Figure 5- a- After the first collision. b- Taller Soliton catches up with the medium one. c- The collision between three solitons. d- After the second collision.

6. Conclusions

In this paper, it's found that soliton has some properties, such as: amplitude-dependent speed, amplitude modulation during the nonlinear collision phase modulation after the nonlinear collision. The inherent difficulties that arise in estimating the parameters of soliton signals make detecting solitons a difficult task. When the waveform shape varies significantly as a function of the unknown parameter, multiple hypotheses are used with one for each value of the parameter sampled over a prespecified range. This is often the approach used for detection of a signal of unknown frequency or unknown spatial direction. The results display interesting features of nonlinear dynamical systems. Many insights were gained into the behavior of solitons, as well as into an application of nonlinear waves in fiber optics.

7. Reference

1. Srihari Y. Sritharan, **2009**.” Solitons, Shockwaves and Spikes: Computational Simulation of Nonlinear Waves on Lattice”, *Applied Mathematical Sciences*, Vol. 3, No. 59, pp 2933 – 2966.
2. ZhiyongXu, **2007.** ”*All-optical* Soliton Control in Photonic Lattices” ,Phd Thesis, The Institute of Photonic Sciences,
3. Gerd Keiser, **1991**. Optical Fiber Communications. Second Edition.
4. Dan-AlexandruIordache, VioricaIordache and Andrei Petrescu,**2007.**”Study of some Numerical Simulations of the Soliton Pulses Propagation”, SISOM 2007 and Homagial Session of the Commission of Acoustics, Bucharest 29-31 May,
5. John Scucklinga, AlleMeije Wink, Frederic A. Bernard, Anna Barnes, Edward Bullmore, **2008.** “Endogenous multifractal brain dynamics are modulated by age, cholinergic blockade and cognitive performance”, *Journal of Neuroscience Methods*, pp:292–300, Elsevier,
6. Appali R., Petersen S., and van U. Rienen, **2010.** “A comparison of Hodgkin-Huxley and soliton neural theories”, Adv. Radio Sci., 8, pp:75–79,
7. Andersen, S.S.L., Jackson, A.D., Heimburg, T. 2009. "Towards a thermodynamic theory of nerve pulse propagation". *Progr. Neurobiol*. 88 (2), pp:104–113.
8. Crisp J., **2001**. Introduction to Fiber Optics. John Crisp.
9. John M. Senior, M. YousifJamro,**2009**. Optical Fiber Communications Principles and Practice. Pearson Education Limited.
10. Thyagarajan, K. and Ghatak, Ajoy K. **2007**. Fiber Optic Essentials. Wiley-Interscience. Pp:34, ISBN 978-0-470-09742-7