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INTERACTION OF HIGHER ORDER SOLITONS

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In this work, the interaction of higher order solitons is investigated by solving the nonlinear Schrödinger equation which models the propagation of solitons in the optical fiber for the propagation of two soliton pulse. The loss of the optical fiber is also taken into account in the Schrödinger equation. The Schrödinger equation is solved by using split-step Fourier transform technique. It is specifically investigated the interaction of the second order solitons which compensates the broadening effect of the optical fiber loss and compresses to the one fourth of the initial pulsewidth at the half period. It is found that the loss of the optical fiber increases the interaction of solitons.

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1. Introduction

It is known that the bit rate of optical fiber communication systems is greatly reduced due to the fact that the waveguide and material dispersion of the optical fiber broaden the pulses propagating through the optical fiber. It was proposed by Hasegawa and Tappert [1] and shown experimentally by Mollenauer et al [2] that the dispersion of pulses in the optical fiber can be compensated by using the small nonlinearity of refractive index of the optical fiber. If this compensation is exact, the fundamental soliton which preserves its shape during the course of propagation through the optical fiber arises. If the nonlinearity of fiber is made a certain amount bigger than the dispersion, the higher order solitons which are initially compressed and broadened back to the initial shape within a certain period result. Due to the shape preserving property of the fundamental soliton, it was considered as a candidate carrier for a long distance and a high bit rate optical communication systems. It was later understood that the pulses are broadened directly due to the loss of the optical fiber [3,4]. Numerical solution of loss included Schrödinger equation showed that the pulsewidth is doubled for every 3 dB loss of the optical fiber [3,4]. Furthermore, the numerical simulation of two fundamental soliton propagating through the optical fiber revealed that the bit rate and the distance was severely limited due to mutual interaction of these pulses after propagating a certain distance in the optical fiber [5,6]. Generally, the interaction of first order solitons is considered in the papers. It was suggested that the higher order solitons, specifically the second order soliton, can be used to compensate the broadening of pulses due to the optical loss by tailoring the initial compression of the second order soliton [7]. But, one needs to look at the mutual interaction of two second order soliton propagating in the optical fiber. The mutual interaction of optical solitons can also be investigated by using the mathematical techniques which solves nonlinear Schrödinger equation and coupled nonlinear Schrödinger equations analytically [8,9,10,11]. In this work, the interaction of two second order soliton and the effect of the optical fiber loss to this interaction are investigated by solving the perturbed nonlinear Schrödinger equation numerically using split step Fourier transform method.

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2. Theory

The perturbed nonlinear Schrödinger equation which models the propagation of the optical pulses through the optical fiber under the effects of the negative group velocity dispersion of the optical fiber, the loss of the optical fiber and the nonlinear variation of the optical fiber refractive index with the intensity is given by [3,7]

$$i\frac{\partial q}{\partial \zeta} + \frac{1}{2}\frac{\partial^2 q}{\partial s^2} + \mid q \mid^2 q = -i\Gamma q \tag{1}$$

where is alized slowly varying entance, s is the normalized time and ¡ is the loss of the optical fiber. The real values of the variables given in Equation (1), can be calculated by using the following transformations. These transformations are:

$$s = \frac{1}{t_c}(t - \beta_o' z) \tag{2}$$

$$\zeta = \frac{\mid \beta_o'' \mid z}{t_c^2} \tag{3}$$

$$q = t_c \left(\frac{n_2 w_o}{4c \mid \beta_o'' \mid} \right)^{1/2} \Phi \tag{4}$$

In the above equations, Φ is the slowly varying envelope function, w_o is radian frequency, $\beta_0^{''}$ is the total dispersion at the radian frequency, $\beta_0^{'}$ is the inverse of the group velocity at the radian frequency, c is the speed of light, t is the time, z is the distance, n_2 is the coefficient of the nonlinear variation of the refractive index with the intensity and t_c is the arbitrary time scale. The time scale t_c in this transformation allows a pulse of standard duration in the dimensionless variable s to correspond to a pulse of any desired duration in time t. The loss of optical fiber γ is transformed by the following transformation.

$$\Gamma = \frac{\gamma t_c^2}{\mid \beta_o'' \mid} \tag{5}$$

In the absence of loss and the third order dispersion, Equation (1) can be solved analytically for soliton solutions by using the inverse scattering theory for the initial condition of

$$q(\zeta = 0, s) = N sech(s) \tag{6}$$

where N which represents the order of the soliton is an integer [12]. $N = 1$ is the fundamental soliton preserving its shape during the propagation through the optical fiber if the loss and the third order dispersion are neglected. The fundamental soliton solution ($N = 1$) of the Equation (1) is given by [12]

$$q_1 = e^{-i\zeta/2} sech(s) \tag{7}$$

$N = 2$ is the second order soliton which compresses one fourth of its initial width at the half period and resumes its initial shape at the full period. The period of oscillation in normalized units is $\pi/2$ corresponding to actual distance given by the following equation

$$z_o = 0.322\frac{\pi^2 c\tau^2}{D\lambda^2} \tag{8}$$

where z_o is the soliton period, τ is the FWHM, λ is the wavelength and D is the dispersion. Equation (8) is found from Equation (3) by setting $\zeta=\pi/2$ and using $t/t_c = 2cosh^{-1}\sqrt{2}$. We will consider 1.3 μm communication system with a pulse width of 4 psec. At this wavelength, dispersion of 8 μm diameter single mode fiber is 3.2 psec/nm/km. Then, soliton period with these parameters will be 2.8 km.

Although Equation (1) can be solved analytically for the integer values of N, these soliton solutions can not be used in practice because of soliton solutions of Equation (1) are very complex and lengthy for higher order solitons. Therefore, Equation (1) is solved numerically to investigate the interaction of higher order solitons and the effect of the optical fiber loss to the soliton interaction. Equation (1) is numerically solved for the second order solitons by using the beam propagating or split step Fourier transform method by neglecting the third order dispersion. The initial condition representing the pulses in the fiber is taken as

$$q(\zeta = 0, s) = 2sech(s - s_o) + 2sech(s - s_o)e^{i\Theta} \tag{9}$$

where $2s_o$ is the separation of pulses, Θ is the relative phase difference and $N = 2$ is considered. When the split step Fourier transform method is applied to the Equation (1), the necessary equation to propagate the pulse of $q(\zeta = 0, s)$ for a small distance step size of δ is found as [3]

$$q(\zeta + \delta, s) = F^{-1}\left\{e^{(-i\frac{\delta\Delta w^2}{4})}F\left\{e^{[i|q(\zeta+\delta/2)|^2-\Gamma]\delta}F^{-1}\left\{e^{(-i\frac{\delta\Delta w^2}{4})}F[q(\zeta, s)]\right\}\right\}\right\} \tag{10}$$

where F is the Fourier transform and Δw is the normalized frequency step size. Δw =32 and Δs = 0.03125 are taken in the simulation of the interaction of higher order solitons. The normalized distance step size δ is arbitrarily chosen depending on the order of the soliton, the length of the optical fiber and to provide a total accuracy of 10^{-5}. The distance between the soliton pulses is chosen as a variable. The interaction of the higher order solitons is investigated by solving the Equation (10) iteratively together with the initial condition given in Equation (9).

3. Results and conclusions

For the computer simulation of propagation of two second order soliton through the optical fiber, a single mode optical fiber which has a core diameter of 8 μm, the total dispersion of 3.2 psec/nm/km at the wavelength of 1.3 μm, the optical fiber loss of 0.5 dB/km, the core refractive index of 1.46 and the coefficient of the nonlinear variation of the optical fiber refractive index with the intensity of 1.22×10^{-22} m^2/V^2 is chosen. For these values of the parameters and the initial pulsewidth of 4 psec, the value of ¡ which represents the optical fiber loss is calculated as 0.11. The value of the peak power which is necessary to obtain the first order soliton is calculated as 457 mW. The peak power for higher order soliton is directly proportional to the square of the soliton order N.

It is first necessary to investigate the propagation of the single second order soliton through the optical fiber with and without the optical fiber loss in order to understand the interaction of the two second order soliton. Fig. 1 represents the propagation of the second order soliton through a

69 km optical fiber under the effect of loss and without loss. As it can be seen from Fig. 1a, the second order soliton first compresses to the one fourth of the initial pulsewidth at the half period and then returns to the initial pulse shape at the full period if the loss of the optical fiber is neglected. When the propagation of the second order soliton under the effect of the loss which is shown in Fig. 1b is investigated, the second order soliton compresses less at the half period and it can not return to the initial pulse shape at the full period. Since the optical fiber loss reduces the peak power of the soliton, soliton increases its pulsewidth against to this power loss in order to keep its shape during the propagation. Soliton period which is proportional to the pulsewidth changes due to the change in pulsewidth of soliton. Hence, the loss of the optical fiber causes an increase in pulsewidth and the period of the second order soliton. Since the order of the soliton is two, the compression effect of the nonlinear variation of the refractive index with the intensity is much more effective than the dispersion of the optical fiber. Therefore, the pulsewidth of the soliton at the half period is always less than the initial pulsewidth.

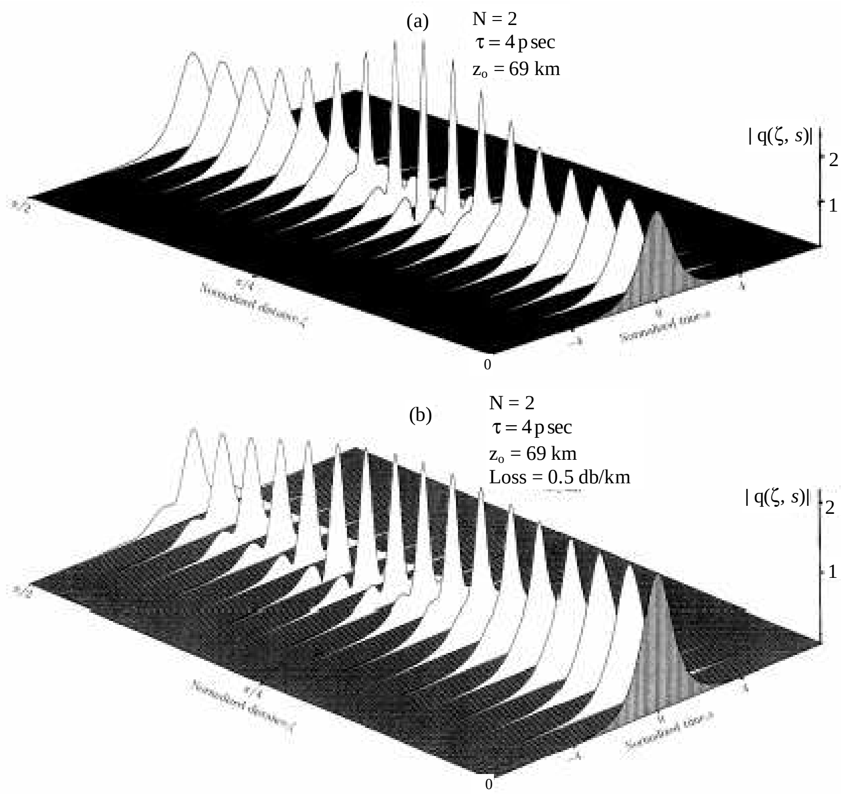

Fig. 1. Propagation of the single second order soliton. (a) without the loss, (b) with the loss.

Fig. 2 represents the propagation of the two second order soliton through a 28 km lossless optical fiber. The time between the pulses is taken as 12 psec in Fig. 2a and 6 psec in Fig. 2b. Since the time between the pulses is much longer in Fig. 2a, there is no interaction between the solitons and they propagate same as in Fig. 1a. Fig. 2a also shows that the propagation of the two second order soliton through the lossless optical fiber is also periodic. When the time between the pulses is reduced to 6 psec as shown in Fig. 2b, the interaction between the solitons starts. Fig. 2b shows that the solitons first compress and then they pass through each other and resume their initial pulse shapes. In addition, the interaction of the solitons changes the period. Fig. 2 shows that the solitons can interact to each other even in the lossless optical fiber and this interaction depends on the time difference between the solitons. In order to understand the reason of the interaction of solitons, the properties of solitons are first be understood. Soliton has particle properties as electron and neutron. As in this particles, solitons can collide with each other and they can separate after these collisions by keeping its initial shapes. Therefore, these pulses are called soliton [1].

Pulses collide to each other due to fact that electric fields of soliton pulses attract each other. Attraction of electric field depends on the time between the pulses and relative phase difference of pulses [13].

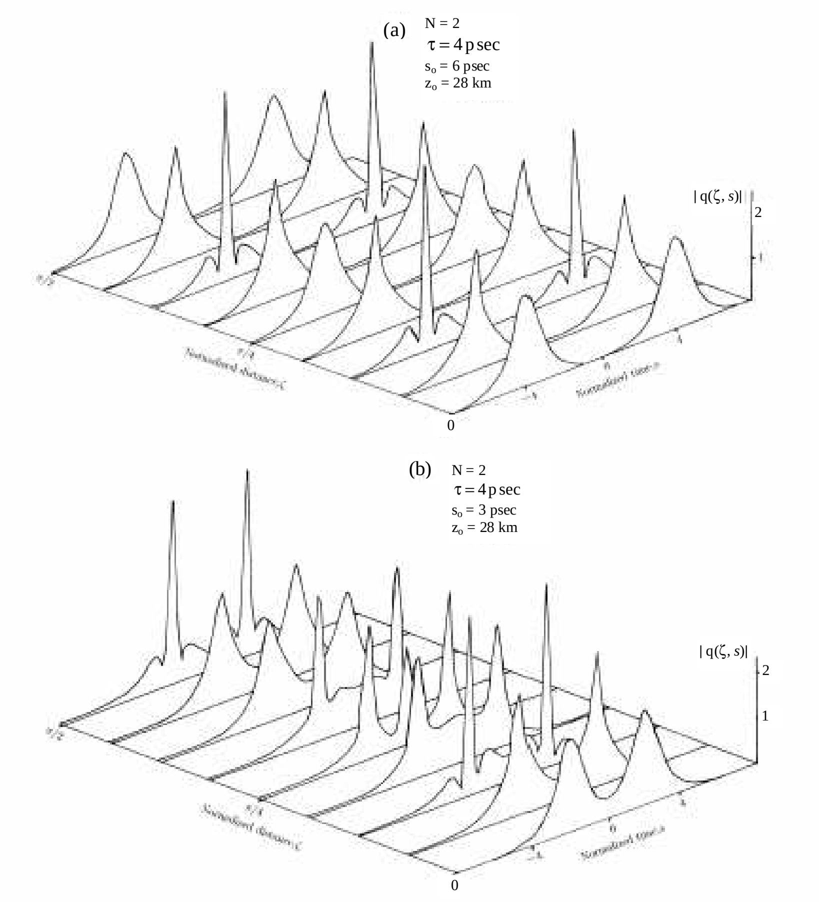

Fig. 2. Propagation of the two second order soliton through lossless optical fiber. (a) Pulse separation 12 psec, (b) Pulse separation 6 psec.

Fig. 3 show the propagation of the two second order soliton through of 28 km optical fiber which has a loss of 0.5 dB/km ($\Gamma = 0.11$). The time between the pulses is taken as 12 psec and 6 psec in Fig. 3 as in Fig. 2. In Fig. 3a and Fig. 3b, soliton completely lose its properties due to the fact that soliton interact with each other and the loss of the optical fiber increases this interaction. Although the time difference between the pulses is longer in Fig. 3a, solitons interact and disappears under the effect of the optical fiber loss unlike Fig. 2a. Fig. 3b shows this much more clearly. The reason why the optical fiber loss increases the interaction can explained as follows. As it was explained before, the loss of the optical fiber decreases the peak power of the pulses and this results in an increase in the pulsewidth. The decrease in the peak power decreases the attraction of electric field of solitons and leads to decrease in the interaction of solitons. But, increase in the pulsewidth decreases the time between solitons and this in turn increases the interaction of solitons. Increase in the interaction due to pulsewidth increase is much more effective than the decrease in the interaction due to the decrease of electric field. Therefore, soliton disappears and loses its properties after the propagation through the optical fiber under the effect of loss.

Interesting correlation between the longitudinal and transversal instabilities have been found recently [14] and these can be useful for design and rizing of the communication systems based on optical fibers.

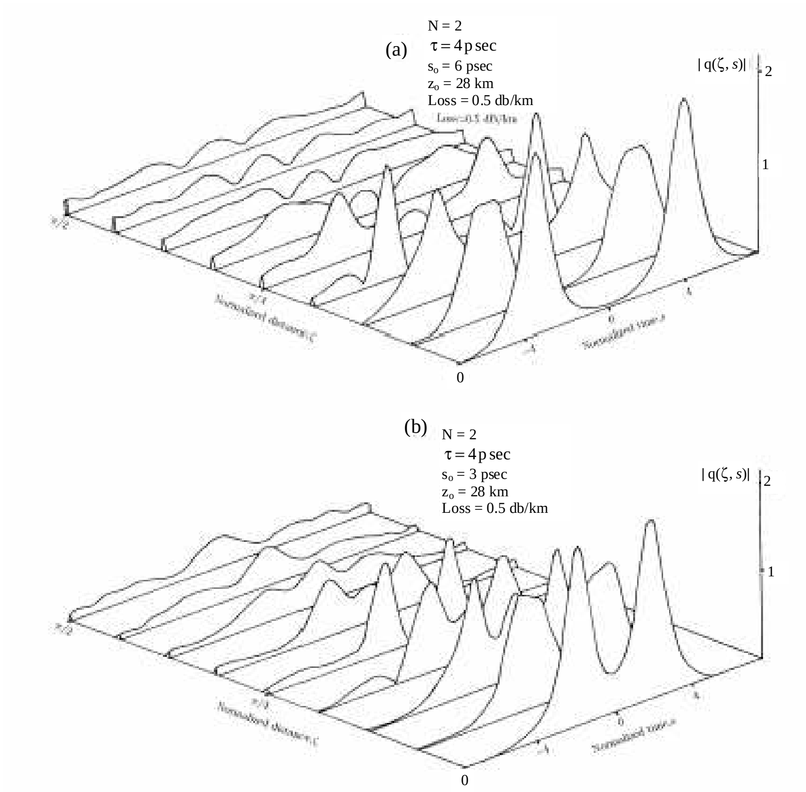

Fig. 3. Propagation of the two second order soliton under the effect of the optical fiber loss. (a) Pulse separation 12 psec, (b) Pulse separation 6 psec.

The results obtained from the computer simulations of the two second order soliton propagation through the optical fiber shows that solitons interact with each other depending on the time between the pulses if the loss of the optical fiber is neglected. It is also found that the loss of the optical fiber increases this interaction. It is observed that the interaction of the solitons can lead to lose the properties of the solitons and hence, this can prevent the use of solitons in high bit rate optical fiber communication systems.

References

[1] A. Hasegawa, F. Tappert, I. Anomalous dispersion, Appl. Phys. Lett. **23**, 142 1(981).
[2] L. F. Mollenauer, R. H. Stolen, J. P. Gordon, Appl. Phys. Lett. **45**, 1095 (1980).
[3] M. S. Ozyazici, Ph.D thesis, University of London, 1988.
[4] A. Hasegawa, Y. Kodama, Proc. IEEE **69**, 1145 (1981).
[5] K. J. Blow, N. J. Doran, Elec. Lett. **19**, 429 (1983).
[6] B. Hermansson, D. Yevick, Elec. Lett. **19**, 570 (1983).
[7] M. S. Ozyazici, M. Sayin, J. Optoelectron. Adv. Mater. **5**, 447 (2003).
[8] M. Gedalin, T. C. Scott, Y. B. Band, Phys. Rev. Lett. **78**, 448 (1997).
[9] K. Porsezian, J of Nonlinear Math. Phys. **5**, 126 (1998).
[10] M. N. Vinoj, V. C. Kuriakose, J of Physics **57**, 987 (2001).
[11] K. Nakkeeran, J. of Modern Optics **48**, 1863 (2001).
[12] J. Satsuma, N. Yajima, Suppl. Prog. Theor. Phys. **55**, 284 (1974).
[13] J. P. Gordon, Optics Letters **8**, 596 (1983).
[14] V. I. Vlad, V. Babin, J. Optoelectron. Adv. Mater, **4**(3), 581 (2002).