Progress In Electromagnetics Research, PIER 54, 95–108, 2005

SOLITON-SOLITON INTERACTION WITH POWER LAW NONLINEARITY

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Abstract—The intra-channel collision of optical solitons, with power law nonlinearity, is studied in this paper with the aid of quasi-particle theory. The perturbation terms that are considered in this paper are of Hamiltonian type. The suppression of soliton-soliton interaction, in presence of these perturbation terms, is achieved. The numerical simulations support the quasi-particle theory.

1. INTRODUCTION

The propagation of pulses through an optical fiber, for a Kerr nonlinear medium [2], in an optical communication system, is governed by the Nonlinear Schrodinger's Equation (NLSE). The dimensionless form of the NLSE, for the power law nonlinearity, is given by

$$i\frac{\partial q}{\partial Z}+\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^{2p}q=0 \tag{1}$$

Here q represents the dimensionless optical field in the fiber core while Z & T are the independent variables. Here, Z represents the distance along the fiber while T is the time. Equation (1) is not integrable by Inverse Scattering transform (IST) unless $p=1$ in which case the Kerr law nonlinearity is recovered.

It is to be noted that various materials exhibit power law nonlinearities, including semiconductors [16, 17]. Here, it is necessary to have $0<p<2$ to prevent wave collapse [18]. In particular, it is necessary to impose the restriction $p\neq 2$ to avoid the self-focusing singularity issue [2, 6, 8, 14, 18].

In the anomalous dispersion regime [2], the particularly relevant solutions to (1) are called solitons, or nontopological solitons. In most cases, the interest is confined to a single pulse described by the 1-soliton solution of the NLSE. However, in this paper, the effects of the perturbation terms in NLSE on two soliton interaction will be studied. It is necessary to launch the solitons close to each other for enhancing the information carrying capacity of the fiber. If two solitons are placed close to each other then it can lead to its mutual interaction thus providing a very serious hinderance to the performance of the soliton transmission system. However, the presence of the perturbation terms of the NLSE can lead to the suppression of the two soliton interaction thus solving our problem.

The perturbed NLSE that is going to be studied in this paper for the soliton-soliton interaction (SSI) is

$$i\frac{\partial q}{\partial Z}+\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^{2p}q=i\epsilon R[q,q^*] \tag{2}$$

where

$$R=\lambda\frac{\partial}{\partial T}\left(|q|^2q\right)+\nu q\frac{\partial}{\partial T}\left(|q|^2\right)-\alpha\frac{\partial q}{\partial T}-\gamma\frac{\partial^3 q}{\partial T^3}-i\sigma\frac{\partial^4 q}{\partial T^4} \tag{3}$$

In fiber optics ϵ is called the relative width of the spectrum, that arises due to quasi-monochromaticity, and is assumed that $0<\epsilon\ll 1$.

In (3), α is the frequency separation between the soliton carrier and the frequency at the peak of EDFA gain. Also, λ is the self-steepening coefficient for short pulses [3, 4, 11, 25] (typically $\leq$ 100 femto seconds), ν is the higher order dispersion coefficient [11, 25] and γ is the coefficient of the third order dispersion [11, 19, 25]. Moreover, σ represents the coefficient of fourth order dispersion.

It is known that the NLSE, as given by (1), does not give correct prediction for pulse widths smaller than 1 picosecond. or example, in solid state solitary lasers, where pulses as short as 10 femtoseconds are generated, the approximation breaks down. Thus, quasi-monochromaticity is no longer valid and higher order dispersion terms come in. If the group velocity dispersion is close to zero, one needs to consider the third order dispersion for performance enhancement along trans-oceanic distances. Also, for short pulse widths where the group velocity dispersion changes within the spectral band-width of the signal can no longer be neglected, the presence of the third order dispersion needs to be taken into account.

The quasi-particle theory (QPT) of SSI has been investigated [2, 3, 7, 8] for Kerr law nonlinearity and it is proved by virtue of it that the interaction can be suppressed due to linear gain and filters. Here, it will be proved that using the QPT, the SSI can be suppressed due to the NLSE given by (1) and also in presence of the perturbation terms in (2).

In (2), if $\epsilon = 0$, (1) is recovered. Although (1) is not integrable by IST, it supports soliton solution of the form

$$q(Z,T) = \frac{\eta}{\cosh^{\frac{1}{p}}[\zeta(T - vZ - T_0)]} e^{(-i\kappa T + i\omega Z + i\sigma_0)} \tag{4}$$

with

$$\kappa = -v \tag{5}$$

and

$$\omega = \frac{\zeta^2}{2p^2} - \frac{\kappa^2}{2} \tag{6}$$

while

$$\zeta = \eta^p \left(\frac{2p^2}{1+p}\right)^{\frac{1}{2}} \tag{7}$$

Here, η is the amplitude (or the inverse width) of the soliton, v is its velocity, κ is the soliton frequency while T_0 and σ_0 are the center of the soliton and the center of the soliton phase respectively.

Also the 2-soliton solution of the NLSE (1) takes the asymptotic form

$$q(Z,T) = \sum_{l=1}^{2} \frac{\eta_l}{\cosh^{\frac{1}{p}}[\zeta_l(T - v_l Z - T_{0_l})]} e^{(-i\kappa_l T + i\omega_l Z + i\sigma_{0_l})} \tag{8}$$

with

$$\kappa_l = -v_l \tag{9}$$

and

$$\omega_l = \frac{\zeta_l^2}{2p^2} - \frac{\kappa_l^2}{2} \tag{10}$$

while

$$\zeta_l = \eta_l^p \left(\frac{2p^2}{1+p}\right)^{\frac{1}{2}} \tag{11}$$

In the study of SSI, the initial pulse waveform is taken to be

$$q(0,T) = \frac{\eta_1}{\cosh^{\frac{1}{p}}\left[\zeta_1\left(T - \frac{T_0}{2}\right)\right]} e^{i\phi_1} + \frac{\eta_2}{\cosh^{\frac{1}{p}}\left[\zeta_2\left(T + \frac{T_0}{2}\right)\right]} e^{i\phi_2} \tag{12}$$

which represents the injection of 2-soliton like pulses into a fiber with amplitudes A_1 and A_2 and the corresponding widths as D_1 and D_2 respectively while the respective phases are ϕ_1 and ϕ_2. Here, T_0 represents the initial center-to-center separation of the solitons. For $T_0 \to \infty$ (8) represents exact soliton solutions, however, for $T_0 \sim O(1)$ it does not represent an exact 2-soliton solution. Corresponding to the input waveform given by (12), in this paper, the case of in-phase injection of solitons with unequal amplitudes will be considered. Thus, (12) simplifies to

$$q(0,T) = \frac{\eta_0}{\cosh^{\frac{1}{p}}\left[\zeta_0\left(T - \frac{T_0}{2}\right)\right]} + \frac{1}{\cosh^{\frac{1}{p}}\left[\zeta\left(T + \frac{T_0}{2}\right)\right]} \tag{13}$$

where, for convenience, the choice $\eta_1 = \eta_0$, $\eta_2 = 1$ and $\phi_1 = \phi_2 = 0$ is made and

$$\zeta_0 = \eta_0^p \left(\frac{2p^2}{1+p}\right)^{\frac{1}{2}} \tag{14}$$

and

$$\zeta = \sqrt{\frac{2p^2}{1+p}} \tag{15}$$

2. QUASI-PARTICLE THEORY

The QPT dates back to 1981 since the appearance of the paper by Karpman and Solov'ev [3]. The mathematical approach to the SSI using the QPT will be presented. Here, the solitons are treated as particles. If two pulses are separated and each of them is close to a soliton they can be written as the linear superposition of two soliton like pulses [2]:

$$q(Z,T) = q_1(Z,T) + q_2(Z,T) \tag{16}$$

with

$$q_l(Z,T) = \frac{A_l}{\cosh^{\frac{1}{p}}[D_l(T-T_l)]} e^{-iB_l(T-T_l)+i\delta_l} \tag{17}$$

where $l = 1, 2$ and A_l, B_l, T_l and δ_l are functions of z. Here, A_l and B_l do not represent the amplitude and the frequency of the full wave form. However, they approach the amplitude and frequency respectively for large separation namely as $\Delta T = T_1 - T_2 \to \infty$, then $A_l \to \eta_l$ and $B_l \to \kappa_l$. Since the waveform is assumed to remain in the form of two pulses, the method is called the quasi-particle approach. The equations for A_l, B_l, T_l and δ_l using the soliton perturbation theory will be first derived. Substituting (16) into (2) yields

$$\begin{aligned} i\frac{\partial q_l}{\partial Z} + \frac{1}{2}\frac{\partial^2 q_l}{\partial T^2} &= i\epsilon R[q_l, q_l^*] - \left[\sum_{r=0}^{p} \binom{p}{r} q_1^{p-r} q_2^r\right] \\ &\quad \cdot \left[\sum_{r=0}^{p} \binom{p}{r} (q_1^*)^{p-r} (q_2^*)^r\right] (q_1 + q_2) \end{aligned} \tag{18}$$

where $l = 1, 2$ and $\bar{l} = 3 - l$ with the definition

$$\binom{n}{r} = \frac{n(n-1)\cdots(n-r+1)}{r(r-1)\cdots 3.2.1} \tag{19}$$

Here, the separation

$$|q|^{2p} q = \left[\sum_{r=0}^{p} \binom{p}{r} q_1^{p-r} q_2^r\right] \left[\sum_{r=0}^{p} \binom{p}{r} (q_1^*)^{p-r} (q_2^*)^r\right] (q_1 + q_2) \tag{20}$$

was used based on the degree of overlapping. By the soliton perturbation theory [2] the evolution equations are

$$\frac{dA_l}{dZ} = F_1^{(l)}(A, \Delta T, \Delta\phi; p) + \epsilon M_l \tag{21}$$

$$\frac{dB_l}{dZ} = F_2^{(l)}(A, \Delta T, \Delta\phi; p) + \epsilon N_l \tag{22}$$

$$\frac{dT_l}{dZ} = -B_l - F_3(A, \Delta T, \Delta\phi; p) + \epsilon Q_l \tag{23}$$

$$\frac{d\delta_l}{dZ} = \frac{B_l^2}{2} + \frac{A_l^{2p}}{p+1} + F_4(A, \Delta T, \Delta\phi; p) + \epsilon P_l \tag{24}$$

where

$$M_l = \frac{1}{2-p}\left(\frac{2p^2}{1+p}\right)^{\frac{p-3}{2p}} \frac{\Gamma\left(\frac{1}{p}+\frac{1}{2}\right)}{\Gamma\left(\frac{1}{p}\right)\Gamma\left(\frac{1}{2}\right)} \int_{-\infty}^{\infty} \Re\left\{\hat{R}[q_l, q_l^*]e^{-i\phi_l}\right\} \frac{1}{\cosh^{\frac{1}{p}}\tau_l} d\tau_l \tag{25}$$

$$N_l = \frac{2}{p}A_l^{p-1}\left(\frac{2p^2}{1+p}\right)^{\frac{p-1}{2p}} \frac{\Gamma\left(\frac{1}{p}+\frac{1}{2}\right)}{\Gamma\left(\frac{1}{p}\right)\Gamma\left(\frac{1}{2}\right)} \int_{-\infty}^{\infty} \Im\left\{\hat{R}[q_l, q_l^*]e^{-i\phi_l}\right\} \frac{\tanh\tau_l}{\cosh^{\frac{1}{p}}\tau_l} d\tau_l \tag{26}$$

$$Q_l = \frac{1}{A_l^{p+1}}\left(\frac{p+1}{2p^2}\right)^{\frac{p+2}{2p}} \frac{\Gamma\left(\frac{1}{p}+\frac{1}{2}\right)}{\Gamma\left(\frac{1}{p}\right)\Gamma\left(\frac{1}{2}\right)} \int_{-\infty}^{\infty} \Re\left\{\hat{R}[q_l, q_l^*]e^{-i\phi_l}\right\} \frac{\tau_l}{\cosh^{\frac{1}{p}}\tau_l} d\tau_l \tag{27}$$

$$P_l = \frac{1}{A_l^{p+1}}\left(\frac{2p^2}{p+1}\right)^{\frac{p+1}{2p}} \frac{\Gamma\left(\frac{1}{p}+\frac{1}{2}\right)}{\Gamma\left(\frac{1}{p}\right)\Gamma\left(\frac{1}{2}\right)} \int_{-\infty}^{\infty} \Im\left\{\hat{R}[q_l, q_l^*]e^{-i\phi_l}\right\} \frac{(1-\tau_l\tanh\tau_l)}{\cosh^{\frac{1}{p}}\tau_l} d\tau_l \tag{28}$$

and $F_1^{(l)}$, $F_2^{(l)}$, F_3 and F_4 that are functions of A, ΔT and $\Delta\phi$ are obtained by virtue of SPT due to integrations of the right side of (18) on using the soliton form given by (19). Also, in (25)–(28), $\Re$ and $\Im$ stands for the real and imaginary parts respectively. In addition, the following notations are used

$$\begin{aligned}\hat{R}[q_l, q_l^*] &= R[q_l, q_l^*] - i\left[\sum_{r=0}^{p}\binom{p}{r} q_1^{p-r}q_2^r\right] \\ &\cdot \left[\sum_{r=0}^{p}\binom{p}{r}(q_1^*)^{p-r}(q_2^*)^r\right](q_1+q_2) + i|q_l|^{2p}q_l \end{aligned}\tag{29}$$

$$\tau = A_l(T - T_l) \tag{30}$$
$$\phi = B_l(T - T_l) - \delta_l \tag{31}$$
$$\Delta\phi = B\Delta T + \Delta\delta \tag{32}$$
$$\Delta T = T_1 - T_2 \tag{33}$$
$$\Delta\delta = \delta_1 - \delta_2 \tag{34}$$
$$A = \frac{1}{2}(A_1 + A_2) \tag{35}$$
$$B = \frac{1}{2}(B_1 + B_2) \tag{36}$$
$$D = \frac{1}{2}(D_1 + D_2) \tag{37}$$
$$\Delta A = A_1 - A_2 \tag{38}$$
$$\Delta B = B_1 - B_2 \tag{39}$$
$$\Delta D = D_1 - D_2 \tag{40}$$

Moreover, it was assumed that

$$|\Delta A| \ll A \tag{41}$$
$$|\Delta B| \ll 1 \tag{42}$$
$$|\Delta D| \ll B \tag{43}$$
$$A\Delta T \gg 1 \tag{44}$$
$$D\Delta T \gg 1 \tag{45}$$
$$|\Delta A|\Delta T \ll 1 \tag{46}$$
$$|\Delta D|\Delta T \ll 1 \tag{47}$$

From (35) to (38), one can now obtain

$$\frac{dA}{dZ} = \epsilon M \tag{48}$$
$$\frac{dB}{dZ} = \epsilon N \tag{49}$$
$$\frac{d(\Delta A)}{dZ} = F_1^{(1)}(A, \Delta T, \Delta\phi; p) - F_1^{(2)}(A, \Delta T, \Delta\phi; p) + \epsilon\Delta M \tag{50}$$
$$\frac{d(\Delta B)}{dZ} = F_2^{(1)}(A, \Delta T, \Delta\phi; p) - F_2^{(2)}(A, \Delta T, \Delta\phi; p) + \epsilon\Delta N \tag{51}$$
$$\frac{d(\Delta T)}{dZ} = -\Delta B + \epsilon\Delta Q \tag{52}$$
$$\frac{d(\Delta\phi)}{dZ} = \frac{A_1^{2p} - A_2^{2p}}{p+1} + \frac{\Delta T}{2}\left(F_2^{(1)} + F_2^{(2)}\right) + \epsilon B\Delta Q + \epsilon\Delta P \tag{53}$$

where

$$M = \frac{1}{2}(M_1 + M_2) \tag{54}$$

$$N = \frac{1}{2}(N_1 + N_2) \tag{55}$$

and ΔM, ΔN, ΔQ and ΔP are the variations of M, N, Q and P which are written as for example

$$\Delta M = \frac{\partial M}{\partial A}\Delta A + \frac{\partial M}{\partial B}\Delta B \tag{56}$$

assuming that they are functions of A and B only, which is, in fact, true for most of the cases of interest, otherwise, the equations for

$$T = \frac{1}{2}(T_1 + T_2) \tag{57}$$

and

$$\phi = \frac{1}{2}(\phi_1 + \phi_2) \tag{58}$$

would have been necessary. In presence of the perturbation terms, as given by, (3), the dynamical system of the soliton parameters, by virtue of soliton perturbation theory, are

$$\frac{dA}{dZ} = 0 \tag{59}$$

$$\frac{dB}{dZ} = 0 \tag{60}$$

$$\begin{aligned} \frac{dT_0}{dZ} &= -B - \frac{\epsilon}{2}A^2(3\lambda + 2\nu)\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{1}{2}+\frac{2}{p}\right)}\frac{\Gamma\left(\frac{2}{p}\right)}{\gamma\left(\frac{1}{p}\right)} \\ &\quad -\epsilon(\alpha + 3\gamma B^2) + \frac{3\epsilon\gamma D^3}{p^2}\left[\frac{\Gamma\left(\frac{p-1}{p}\right)}{\Gamma\left(\frac{1}{p}\right)}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{3}{2}+\frac{2}{p}\right)} + 1\right] \end{aligned} \tag{61}$$

so that by virtue of (50)–(53),

$$\frac{d(\Delta A)}{dZ} = F_1^{(1)}(A, \Delta T, \Delta\phi; p) - F_1^{(2)}(A, \Delta T, \Delta\phi; p) \tag{62}$$

$$\frac{d(\Delta B)}{dZ} = F_2^{(1)}(A, \Delta T, \Delta\phi; p) - F_2^{(2)}(A, \Delta T, \Delta\phi; p) \tag{63}$$

$$\frac{d(\Delta T)}{dZ} = -\Delta B - \frac{\epsilon}{4} A\Delta A(3\lambda + 2\nu)\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{1}{2}+\frac{2}{p}\right)}\frac{\Gamma\left(\frac{2}{p}\right)}{\Gamma\left(\frac{1}{p}\right)}$$
$$-\frac{3\epsilon\gamma}{4p^2}\Delta D[12D^2 + (\Delta D)^2] + \frac{3\epsilon\gamma}{p^2}\Delta D[12D^2 + (\Delta D)^2]$$
$$\cdot\frac{\Gamma\left(\frac{p-1}{p}\right)}{\Gamma\left(\frac{1}{p}\right)}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{3}{2}+\frac{2}{p}\right)} \tag{64}$$

which can be rewritten, by virtue of (53), as

$$\frac{d(\Delta T)}{dZ} = -\Delta B - \frac{\epsilon}{4}(3\lambda + 2\nu)g_1\left\{\frac{d(\Delta\phi)}{dZ}\right\}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{1}{2}+\frac{2}{p}\right)}\frac{\Gamma\left(\frac{2}{p}\right)}{\Gamma\left(\frac{1}{p}\right)}$$
$$-\frac{3\epsilon\gamma}{4p^2}g_2\left\{\frac{d(\Delta\phi)}{dZ}\right\} + \frac{3\epsilon\gamma}{p^2}g_2\left\{\frac{d(\Delta\phi)}{dZ}\right\}\frac{\Gamma\left(\frac{p-1}{p}\right)}{\Gamma\left(\frac{1}{p}\right)}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{3}{2}+\frac{2}{p}\right)} \tag{65}$$

$$\frac{d(\Delta\phi)}{dZ} = \frac{A_1^{2p} - A_2^{2p}}{p+1} \tag{66}$$

For in-phase injection of solitons with unequal amplitudes,

$$A = \frac{1}{2}(A_0 + 1) \tag{67}$$
$$B = 0 \tag{68}$$
$$\Delta A_0 = A_0 - 1 \tag{69}$$
$$\Delta B_0 = 0 \tag{70}$$
$$\Delta T_0 = T_0 \tag{71}$$
$$\Delta\phi_0 = 0 \tag{72}$$
$$\Delta\phi = \Delta\delta \tag{73}$$

so that for $\Delta B = 0$

$$\Delta T = T_0 - \frac{\epsilon}{6}(3\lambda + 2\nu) - \frac{\epsilon}{4}(3\lambda + 2\nu)h_1 \left\{\frac{d(\Delta\phi)}{dZ}\right\} \frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{1}{2}+\frac{2}{p}\right)} \frac{\Gamma\left(\frac{2}{p}\right)}{\Gamma\left(\frac{1}{p}\right)} - \frac{3\epsilon\gamma}{4p^2}h_2 \left\{\frac{d(\Delta\phi)}{dZ}\right\} + \frac{3\epsilon\gamma}{p^2}h_2 \left\{\frac{d(\Delta\phi)}{dZ}\right\} \frac{\Gamma\left(\frac{p-1}{p}\right)}{\Gamma\left(\frac{1}{p}\right)} \frac{\Gamma\left(\frac{1}{2}+\frac{1}{p}\right)}{\Gamma\left(\frac{3}{2}+\frac{2}{p}\right)} \quad (74)$$

where

$$h_j(s) = \int g_j(s)ds \quad (75)$$

for $j = 1, 2$. Thus,

$$\Delta T = T_0 + O(\epsilon) \quad (76)$$

Now, $T_0 \sim O(1)$ so that $\Delta T \nrightarrow 0$ and thus the pulses do not collide during the transmission. This will be observed in the numerical results in the next section.

3. NUMERICAL SIMULATIONS

In this section, the numerical simulations of the quasi-particle theory for the soliton-soliton interaction due to Hamiltonian perturbation with power law nonlinearity will be observed. In all cases, A_0 is taken to be equal to 1.1 and ϵ was set to 0.1 while $T_0 = 7$. The following cases are studied.

1. With the third order dispersion, namely when γ is turned on, equation (74), for $p = 1$, modifies to

$$\Delta T = T_0 - \frac{\epsilon\gamma}{2}\Delta\delta \quad (77)$$

   Again, since $T_0 \sim O(1)$ so that $\Delta T \nrightarrow 0$ during transmission and thus the pulses do not collide during the transmission as seen in Figure 1, where $\gamma = 0.14$.

2. When all the perturbation terms are turned on, equation (74), for $p = 1$, modifies to

$$\Delta T = T_0 - \frac{\epsilon}{6}(3\lambda + 2\nu + 3\gamma)\Delta\delta \quad (78)$$

Once again $T_0 \sim O(1)$ so that $\Delta T \not\to 0$ and thus the pulses do not collide during the transmission. This phenomenon is also observed numerically in Fig. 2, where $\lambda = 0.3$, $\nu = 0.16$, $\gamma = 0.14$ and $\sigma = \alpha = 0.5$.

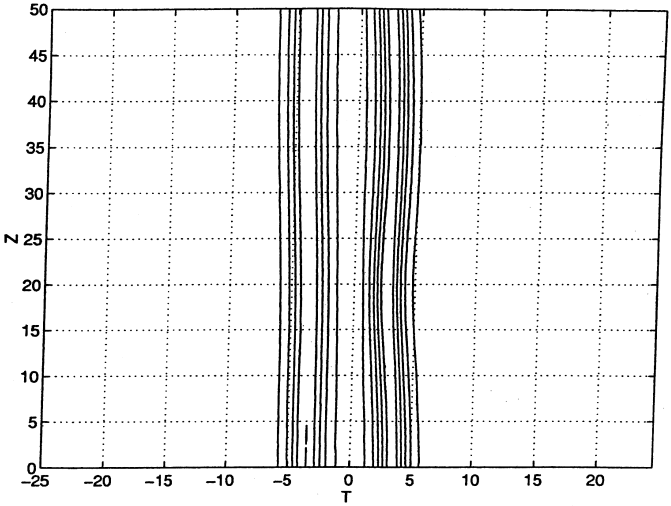

Figure 1. $\gamma = 0.14$.

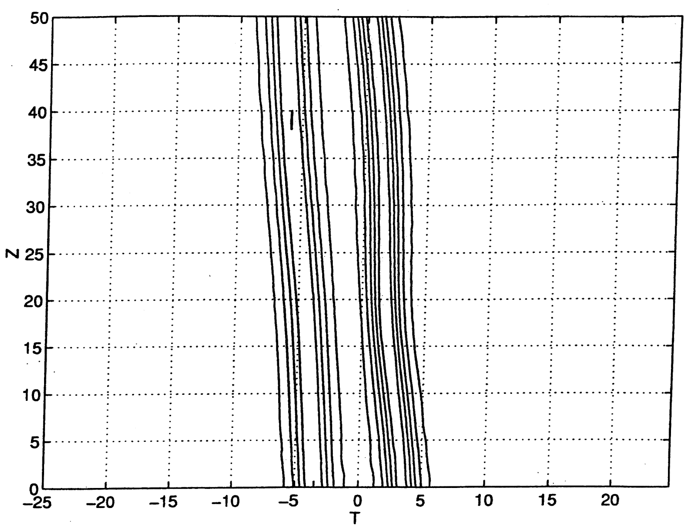

Figure 2. $\lambda = 0.3$, $\nu = 0.16$, $\gamma = 0.14$, $\sigma = 0.5$, $\alpha = 0.5$.

4. CONCLUSIONS

In this paper, the SSI of the NLSE, with power law nonlinearity, in presence of Hamiltonian perturbation terms, was studied. The case with in-phase injection of solitons with unequal amplitudes was considered. It is proved, by the aid of quasi-particle theory, that long distance transmission of solitons due to Hamiltonian perturbations, can be achieved without any kind of interaction of solitons in optical fibers. Thus, this can be of very great advantage in applied soliton community. So, information can be transmitted through optical fibers, without any loss.

In future, one can study the soliton-soliton interaction in optical fibers, due to other laws of nonlinearity namely the parabolic law as well as the dual-power law of nonlinearity. The quasi-particle theory due to these non-Kerr laws are yet to be developed and these results will be reported in future publications. Also, the 3-soliton interactions and higher numbers are to be studied with the aid of quasi-particle theory. The results with these ideas are awaited at this time.

ACKNOWLEDGMENT

The work of the first author is partially supported by the Department of Science and Technology (DST), Government of India, through the R&D grant SP/S2/L-21/99. Therefore S. K. would like to acknowledge this support with thanks.

This research for the second author was fully supported by NSF Grant No: HRD-970668 and the support is thankfully appreciated.

REFERENCES

1. Afanasjev, V. V., "Interpretation of the effect of reduction of soliton interaction by bandwidth-limited amplification," *Optics Letters*, Vol. 18, 790–792, 1993.
2. Biswas, A., "Soliton-soliton interaction in optical fibers," *Journal of Nonlinear Optical Physics and Materials*, Vol. 8, No. 4, 483–495, 1999.
3. Biswas, A., "Quasi-stationary optical solitons with non-Kerr law nonlinearity," *Optical Fiber Technology*, Vol. 9, Issue 4, 224–259, 2003.
4. Chu, P. L. and C. Desem, "Mutual interaction between solitons of unequal amplitudes in optical fibre," *Electronics Letters*, Vol. 21, 1133–1134, 1985.

5. Chu, P. L. and C. Desem, "Effect of third order dispersion of optical fibre on soliton interaction," *Electronics Letters*, Vol. 21, 228–229, 1985.
6. Desem, C. and P. L. Chu, "Soliton interactions in presence of loss and periodic amplification in optical fibers," *Optics Letters*, Vol. 12, 349–351, 1987.
7. Gordon, J. P., "Interaction forces among solitons in optical fibers," *Optics Letters*, Vol. 8, 596–598, 1983.
8. Hasegawa, A. and Y. Kodama, *Solitons in Optical Communications*, Oxford University Press, 1995.
9. Hermansson, B. and D. Yevick, "Numerical investigation of soliton interaction in optical fibers," *Electronics Letters*, Vol. 19, 570–571, 1983.
10. Karpman, V. I. and V. V. Solov'ev, "A perturbational approach to the two-soliton systems," *Physica D*, Vol. 3, 487–502, 1981.
11. Kodama, Y. and K. Nozaki, "Soliton interaction in optical fibers," *Optics Letters*, Vol. 12, No. 12, 1038–1040, 1987.
12. Kodama, Y., M. Romagnoli, and S. Wabnitz, "Soliton stability and interaction in fiber lasers," *Electronics Letters*, Vol. 28, No. 21, 1981–1983, 1992.
13. Kodama, Y. and S. Wabnitz, "Reduction of soliton interaction forces by bandwidth limited amplification," *Electronics Letters*, Vol. 27, No. 21, 1931–1933, 1991.
14. Kodama, Y. and S. Wabnitz, "Physical interpretation of reduction of soliton interaction forces by bandwidth limited amplification," *Electronics Letters*, Vol. 29, No. 2, 226–227, 1993.
15. Kodama, Y. and S. Wabnitz, "Reduction and suppression of soliton interaction by bandpass filters," *Optics Letters*, Vol. 18, No. 16, 1311–1313, 1993.
16. Kodama, Y. and S. Wabnitz, "Analysis of soliton stability and interactions with sliding filters," *Optics Letters*, Vol. 19, No. 3, 162–164, 1994.
17. Nakazawa, M. and H. Kubota, "Physical interpretation of reduction of soliton interaction forces by bandwidth limited amplification," *Electronics Letters*, Vol. 28, 958–960, 1992.
18. Uzunov, I. M., V. D. Stoev, and T. I. Tsoleva, "N-soliton interaction in trains of unequal soliton pulses in optical fibers," *Optics Letters*, Vol. 17, 1417–1419, 1992.
19. Wabnitz, S., "Control of soliton train transmission, storage, and clock recovery by cw light injection," *Journal of the Optical Society of America B*, Vol. 13, No. 12, 2739–2749, 1996.

20. Xu, Z., L. Li, Z. Li, and G. Zhou, "Soliton interaction under the influence of higher-order effects," *Optics Communications*, Vol. 210, Issues 3–6, 375–384, 2002.

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