Domination of intra-pulse Raman scattering over third order dispersion on avoiding in-phase soliton interaction

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We have successfully demonstrated the influence of higher order nonlinear effect (HONE) on soliton interaction. The basic feature higher order nonlinear effects are to shift the soliton pulses temporally such that this shifting helps in avoiding the interaction of in-phase soliton pulses. Here we have concentrated on Third order dispersion (TOD) and intra-pulse Raman scattering (IRS) as these effects are dominant in shifting the pulses comparative to other effects. The phase and temporal shifting characteristics of the soliton is analyzed using the Perturbation theory and Method of Moments theory analytically. Similarly, the Split-Step Fourier transform (SSFT) is used to analyze the effect numerically and we have good approximation between the analytical and numerical studies. Further, finally the influence of these effects on soliton interaction is noted in a single channel telecommunication model and the outputs are characterized by Time domain analyzer (TDA) view and Q-value measurements.

1. Introduction

Solitons are self-trapped, self-localized wave packets that are robust towards dispersive medium due to the perfect balance between dispersion and nonlinearity [1]. The soliton is of great interest for their particle like interaction phenomenon, as they can exert the force on each other and can result in soliton fission [2], fusion [3], annihilation [4], spiraling [5] and breakup into multiple fragments [6] etc. The behavior of soliton mimics the massive particle and is relative to the phase and initial spacing between them, where in-phase solitons interact while out-of-phase solitons repel each other [7]. This particle nature of soliton has more influence in the broad spectrum of applications like supercontinuum generation [8], data transmission [9], ultra-speed optical switching [10], all-optical signal processing and logic gates [11] etc. However, the key principle of soliton interaction can be controlled with respect to various applications.

In fiber optics, solitons with perfect cancellation between the chirps induced by dispersion (GVD) and self-phase modulation (SPM) skilled it to travel at long distance without any dispersion compensation [12]. With such stability, the solitons communication is expected to form major echelon in modern optical transmission technique. But, unfortunately, soliton interaction builds the barrier in preventing high bit rate transmission, where the collision between two soliton pulses results in bit error [13].

Various efforts were made on controlling the soliton interaction with respect to the application. Since from the soliton interaction studied experimentally by Aitchison in 1991 [14], various attempts were made to restrain soliton from colliding or interacting.

Researchers tried with transmitting soliton pulses with unequal amplitude [15], large initial relative spacing, different phase [16], imparting partial incoherence [17], low power [18] and higher order nonlinear effects (HONE) like Third Order Dispersion (TOD), Intra-pulse Raman Scattering (IRS) and Self-Steepening (SS) Effects etc [19] to lead the issue. Also, apart from modeling or transforming pulse characteristics, even attempts were made with fitting fiber with the proper parameter of interest (mainly dispersion and nonlinear coefficient) such that the interaction is avoided [20,21].

The soliton pulses are highly pronounced to HONE when the initially transmitted pulsewidth is lesser or equal to 5ps [22]. As already discussed, this is of high concern in dealing with increasing single channel bitrate, especially in 160Gbps system, where the pulse width becomes shorter with the increase in bitrate [23]. Essiambre *et al* detail out the transition of domination on timing jitter from frequency fluctuation to amplitude fluctuation depending upon the pulse width, where for T_o=20ps and 1ps, the jitter is dominated by frequency fluctuation (familiar concept of Gordon Haus jitter) and amplitude fluctuation (Raman induced shift) respectively. Such that Essiambre et al concludes the domination of IRS over negligible TOD on the combined influence of them on soliton of width T_o=3ps [22,23]. Also, later, this shifting due to IRS becomes of more concern on considering single channel

160Gbps telecommunication system, while other effects like TOD and SS only contribute low was proved [24].

When continuous search for various aids in suppressing interaction was in progress, it was quite fascinating when the researchers suggested that HONE can also be a powerful candidate in the same track. When it was the time where workers are more concern about HONE induced shift and dynamics being a problem statement to soliton stability, the complete inverse action of HONE as an added advantage admired scientific workers. It was the first time, Chu et al in 1985 [25] started with TOD helping in avoiding interaction following Hermansson et al in 1983 [26] who first pictured the phase effects on interaction. At this stage, it was an introduction of such nonlinear parameter (TOD) to influence soliton interaction, so there was no clear picture on high bitrate system.

As, it is well known as TOD has its influence only near ZD wavelength, Uzunov *et. al* [27] proposed the analytical model of the interaction of two solitons with ZD wavelength by 1995 and He concludes that the separation between solitons can be stabilized by phase modulation process and due to which, stability of the amplitude and phase position was unchanged throughout the trains of series pulses. In addition to that, the series of solitons pulse interaction pulse energy is conserved for N number of order of solitons pulse such that, Gerdjikov *et. al* [28] developed the NLS model for N order of slotion interaction with unchanging amplitude and phase point. Later, In 1997 [29], the independent condition was exposed using system level non-integral for Schrodinger equation to make the independency of amplitude and width.

Following the same track, Dowluru Ravi et al [30] gives the picture of TOD induced shifts resulting in interaction with other pulses in sequence although collision between the so-called two pulses was avoided. On considering TOD, its meritorious feature was utilized when launching soliton near the ZD wavelength of SMF or DSF. But in reality, the introduction of IRS in suppressing ultra short soliton is a breakthrough in interaction dynamics.

As, the talk is mainly dealt around 160 Gbps system (with pulsewidth less than 2ps), this implementation of IRS (which comes into action when pulsewidth is <5ps) in shifting soliton pulses is mostly welcome. This influence of IRS on interaction was noted using *'Perturbation theory'* analytically by Hause et al in 2009 [31]. Hause et al have given a clear idea on the analytical and numerical model (using SSFT) where the IRS induced frequency shift (known as Raman induced frequency shift, RIFS) helps in soliton shift thereby reducing interaction. Further, Panoiu et al [32] showed the combined effect of TOD and IRS on dual frequency soliton leading to the separation between two solitons at interaction point (I_p) using *'Split-Step Fourier Transform'* numerically and reported the domination of IRS over TOD in shifting. Recently Govindaraji et al [33] have pointed out the combined effect of TOD and Self-Steepening (SS) on two soliton switching in directional coupler, where switching becomes inefficient due to the active participation of TOD and SS in deviating out the soliton pairs.

In our work, we consider the effect of TOD and IRS on soliton interaction. We first analyze the shift caused by TOD and IRS on soliton analytically using *'Method of Moments'* (MOM) and numerically using SSFT. Secondly, the phase characteristics of soliton are analyzed analytically using *Perturbation theory approach* and numerically using SSFT. Thirdly, the combined equations of PT and MOM are used to show the avoidance of soliton interaction and similarly using SSFT. Finally, the influence is realized in a single channel telecommunication system to justify the assumption and calculated values.

2. Shifting of soliton pulses

The higher order Schrodinger equation considered to study these effects is as follows [34],

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} = i\gamma\left(|A|^2 A + \frac{i}{\omega_o}\frac{\partial}{\partial T}|A|^2 A - T_R\frac{\partial|A|^2}{\partial T}\right) \quad (1)$$

where, A represents the envelope of traveling pulse while α, γ, β_2, β_3, ω_o and T_R denotes the fiber loss, nonlinear co-efficient, dispersion, TOD parameter, steepening parameter and intra-pulse Raman shift time respectively. Eqn.(1) is studied by SSFT to realize the temporal shift of the soliton in the fiber. In SSFT, eqn.(1) can be written as,

$$\frac{\partial A}{\partial z} = (\widetilde{D} + \widetilde{N})\boldsymbol{A} \quad (2)$$

where, $\widetilde{\boldsymbol{D}}$ is the differential operator that denominates the dispersion and lossed within the linear medium and $\widetilde{\boldsymbol{N}}$ is the nonlinear parameter that governs the nonlinearities experienced by the pulse during propagation inside the fiber.

$$\widetilde{D} = -i\frac{\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2} \quad (3)$$

$$\widetilde{N} = i\gamma\left(|A|^2 + \frac{i}{\omega_o}\frac{\partial}{\partial T}|A|^2 A - T_R\frac{\partial|A|^2}{\partial T}\right) \quad (4)$$

Normally, the dispersion and nonlinearities act together on pulse during propagation, but SSFT employs an approximate solution where the dispersion and nonlinearity are considered independently for a small distance from z to z+h. The pulse propagation from z to z+h is carried out in two steps, ih first step nonlinearity acts alone and $\widetilde{\boldsymbol{D}} = \boldsymbol{0}$ and in next step dispersion acts alone while $\widetilde{\boldsymbol{N}} = \boldsymbol{0}$. Mathematically, we can express as, and the Split-Step procedure happens to take place by considering the propagation of pulse from small segment, z to z+h as,

$$A(z+h,t) \approx$$
$$\exp\left(\frac{h}{2}\widetilde{D}\right) exp\left(\int_z^{z+h} \widetilde{N}(z')\,dz'\right) \exp\left(\frac{h}{2}\widetilde{D}\right)A(z,T) \quad (5)$$

It must be noted from eqn.(5), that the nonlinearity is included in the center rather than the boundary, so this equ. is named as symmetric Split-step method.

Similarly, the Moments equation can be derived from equation (1) where it is considered when dealing with the short pulses with $T_o < 5ps$. It becomes more significant to consider TOD even when launching pulse far away from ZD point of the fiber in such case of short pulses. The equation can take new form by using normalized amplitude U as [32],

$$A(z,\tau) = \sqrt{P_o}\exp(-\alpha z/2)\,U(z,\tau) \quad (6)$$

$$\frac{\partial U}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 U}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 U}{\partial T^3} =$$
$$i\gamma P_o e^{-\alpha z}\left(|U|^2 U + \frac{i}{\omega_o}\frac{\partial}{\partial T}(|U|^2 U) - T_R U\frac{\partial^2 |U|^2}{\partial T}\right) \quad (7)$$
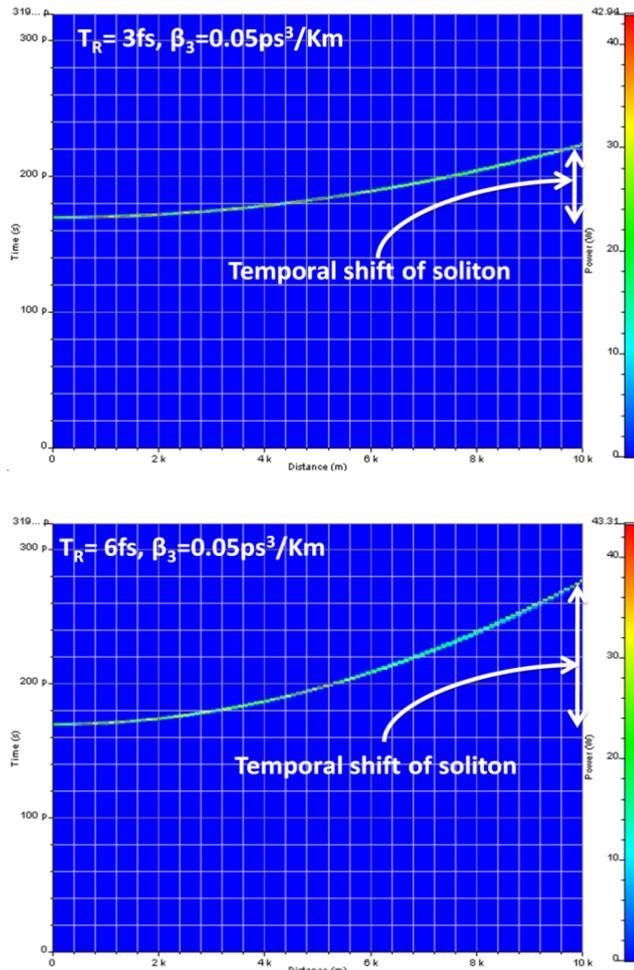

Fig. 1. Shift of pulse under combined influence of TOD and IRS (HONE) with (a) $\beta_3=0.05\ ps^3/km$ and $T_R=3fs$ (b) $\beta_3=0.05\ ps^3/km$ and $T_R=6fs$ for 10km using SSFT

Although the parameters changes continuously, the Moment method may be applied if the higher order effects

are weak enough so that the pulse shape remains unaffected. Now the Equation (7) is written as,

$$U(z,t) = a_p sech\left(\frac{T-q_p}{T_p}\right)exp\left[i\Omega_p(T-q_p) - iC_p\frac{(T-q_p)^2}{2T_p^2} + i\phi_p\right] \quad (8)$$

where a_p, T_p, C_p, and φ_p are the amplitude, time, chirp and phase of the pulse. Normally, the Moment method treats the optical pulse as particle for which the energy E_p, RMS width σ_p and chirp C_p are related to U(z,t) as [35],

$$E_p = \int_{-\infty}^{\infty}|U|^2 dT \quad (9)$$

$$\sigma_p^2 = \frac{1}{E_p}\int_{-\infty}^{\infty}T^2|U|^2 dT \quad (10)$$

$$C_p = \frac{i}{E_p}\int_{-\infty}^{\infty}T\left(U^*\frac{\partial U}{\partial T} - U\frac{\partial U^*}{\partial x}\right)dT \quad (11)$$

By differentiating above using the above Equations (9), (10), and (11), and after some algebraic process with relations such as $E_o = \sqrt{\pi}T_o$ and $T_p = \sqrt{2}\sigma_p$ we can form four sets of equations as [36],

$$\frac{dT_p}{dz} = (\beta_2 + \beta_3\Omega_p)\frac{C_p}{T_p} \quad (12)$$

$$\frac{dC_p}{dz} = \left(\frac{4}{\pi^2} + C_p^2\right)\frac{\beta_2}{T_p^2} + \frac{4\gamma P_o}{\pi^2}\frac{T_o}{T_p} + \frac{6\Omega_p^2}{\pi^2}(2\beta_2 + \beta_3\Omega_p) + \beta_3\left(\frac{4}{\pi^2} + 3C_p^2\right)\frac{\Omega_p}{2T_p^2} + \frac{48\gamma P_o}{\pi^2}\frac{T_o}{T_p} \quad (13)$$

$$\frac{dq_p}{dz} = \beta_2\Omega_p + \frac{\beta_3}{2}\Omega_p^2 + \frac{\beta_3}{6T_p^2}\left(1 + \frac{\pi^2}{4}C_p^2\right) + \frac{\gamma P_o}{\omega_o}\frac{T_o}{T_p} \quad (14)$$

$$\frac{d\Omega_p}{dz} = -\frac{8T_R\gamma P_o}{15}\frac{T_o}{T_p^3} + \frac{2\gamma P_o}{3\omega_o}\frac{T_o C_p}{T_p^3} \quad (15)$$

It can be also seen from Equations (8) and (12)-(15) that, the characteristics of the pulse is noted by six parameters such as a_p, T_p, C_p, φ_p, q_p and Ω_p which may change along the distance z in fiber. While the parameters q_p and Ω_p (from Equations (14) and (15) respectively) represents the temporal shift of pulse and frequency shift of the spectrum respectively which is of great importance. Now, considering the telecommunication design, the relation between T_o and T_{FWHM} is given as $T_{FWHM} = 2\ln(1+\sqrt{2})T_o \approx 1.763\,T_o$. The Dispersion Length is, $L_D = T_o^2/|\beta_2| = 0.1570Km$, where the dispersion parameter $\beta_2 = -20\,ps^2/Km$ and initial pulse width, To~1ps. Nonlinear coefficient is $\gamma = n_2\omega_o/cA_{eff} = 1.418\,W^{-1}Km^{-1}$ in which n_2, ω_o, c, and A_{eff} are the nonlinear index (2.8×10^{-20}), frequency, speed of light and effective area ($80\mu m^2$) respectively. The Power can be calculated by introducing a parameter, $N^2 \geq L_D/L_{NL} =$

$\gamma P_o T_o^2/|\beta_2|$, from which for N=1, we have $P_o = 1/\gamma L_D = 4.4866 W$.
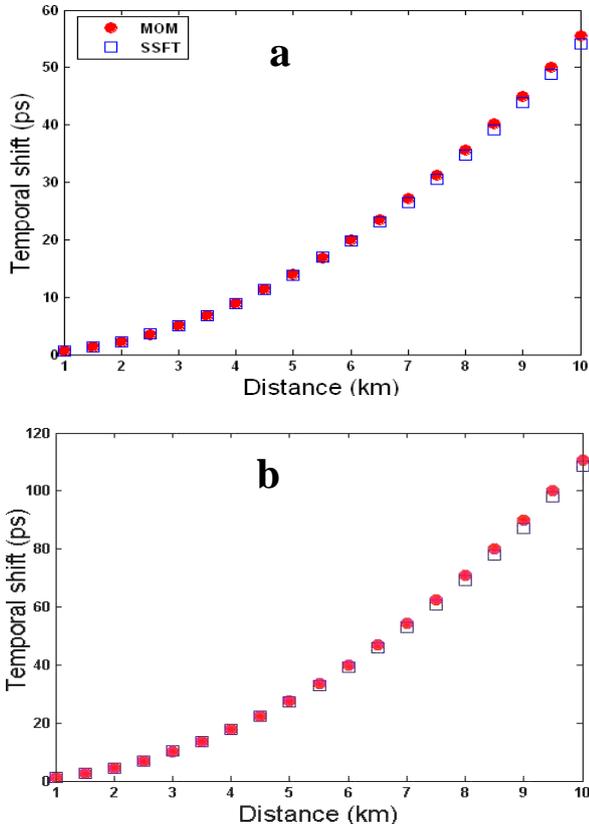

Fig. 2. MOM and SSFT method in calculation of temporal shift with HONE $\beta_3=0.05 ps^3/km$ and T_R as (a) 5fs and (b) 6fs for 10km distance

By using the design parameters, the Fig. 1 shows the temporal shift of soliton under the influence of TOD and IRS strictly respecting equation (1) without considering the steepening parameter. It could be noted that soliton shifts higher for the higher value of Raman shift time or IRS parameter T_R. Also eqn. (14) can be solved for unchirped ($C_p=0$) input pulse without changing the shape ($T_p=T_o$) and differentiating. The good approximation of MOM and SSFT can be justified from Fig. 2 which gives the soliton shift for 10 km.

It could be seen that the shift due to IRS is not linear like TOD as the IRS depends on the square of distance inversely. From this section, the calculation of temporal shift by MOM analytically is seen as a substitute for numerical SSFT.

3. Interaction of soliton pulses

Now the phase characteristics of solitons are noted using the Perturbation theory approach. Normally, unlike the Gaussian pulses, in-phase soliton attracts each other and out-of phase soliton repel each other. The interaction

of the soliton pulses are determined the phase (ψ) and initial relative spacing (q_o) of soliton. In this regard, we can consider two eqns. As,

$$\frac{d^2 q}{d\xi^2} = -4e^{-2q}\cos(2\psi) \tag{16}$$

$$\frac{d^2 \psi}{d\xi^2} = -4e^{-2q}\sin(2\psi) \tag{17}$$

Equations (16) and (17) are solved mathematically and solution can be considered for the two solitons with same amplitude and frequency as we consider in our study, then,

$$q(\xi) = q_o + \frac{1}{2}\ln[\cosh^2(2\xi e^{-q_o}\sin\psi_o) + \cos^2(2\xi e^{-q_o}\cos\psi_o) - 1] \tag{18}$$

In the eqn.(18), q_o and ψ_o represent the initial spacing and phase respectively. It is seen that for a certain value of ψ_o, the q becomes zero which is known as the collision. Also, in our simulation we consider the effect of in-phase soliton, so substituting $\psi = 0$ in eqn.(18), then as,

$$q(\xi) = q_o + \ln|\cos(2\xi e^{-q_o})| \tag{19}$$

For the in-phase soliton, q(ξ) becomes zero at the time of collision,

$$-q_o = \ln|\cos(2\xi e^{-q_o})| \tag{20}$$

Now, to removing ln function we multiply both sides by exponential term and get as,

$$\xi = \frac{1}{2}e^{q_o}(\cos)^{-1}(e^{-q_o}) \approx \frac{\pi}{4} \exp(q_o) \tag{21}$$

Due to the periodic nature of eqn.(21), the soliton interact periodically and return to their initial condition at the end of one cycle of collision length. We know, $\xi = z/L_D$, so Equation (21) becomes,

$$L_{coll} = \frac{\pi}{2}L_D \exp(q_o) \equiv z_o\exp(q_o) \tag{22}$$

In Eqn.(22) we assume z as L_{colll} as, we consider one collision period to study the interaction. And the z_o is the soliton period which can be related as follows,

$$z_o = \frac{\pi}{2}L_D = \frac{\pi}{2}\frac{T_o^2}{|\beta_2|} \approx \frac{T_{FWHM}^2}{2|\beta_2|} \tag{23}$$

The collision length (L_{coll}) is noted from eqn. (8) by considering the design parameter as, $L_{coll} = \frac{\pi}{2}L_D \exp(q_o) \equiv z_o \exp(q_o) = 4.2160$ because, $\xi = L_{coll}/L_D = 48.43/24.2160$. Such that the interaction point, $I_p=24.2$ km is fixed with the used parameters. The Fig. 3 and 4 shows the interaction point at 24.2 km within one collision period of 48.4 km using PT and SSFT method respectively for initially separated soliton of $q_o=5.28$. From this figures it can be seen that the analytical modeling of soliton phase characteristics suing PT is perfectly matching the SSFT numerically.
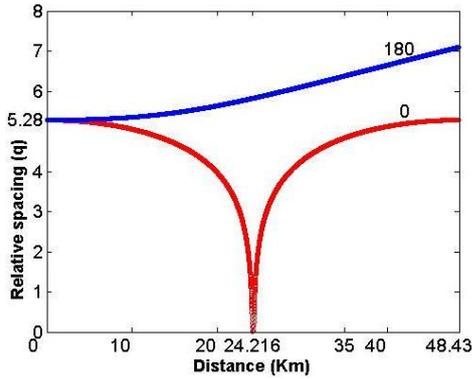
Fig. 3. The interaction and repulsion of in-phase and out0of phase soliton using PT approach using eqn. (18) for the considered design parameters
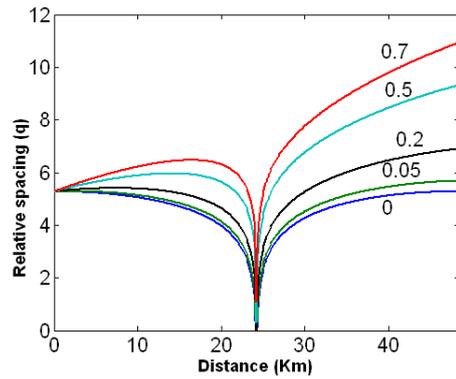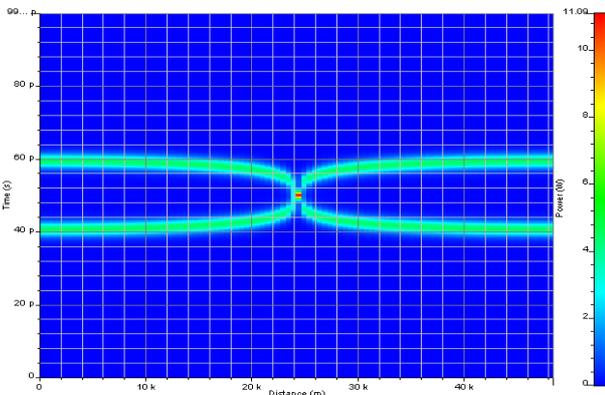

Fig. 4. The interaction of in-phase pulses at 24.2km using SSFT method

4. Influence of TOD and IRS on interaction of soliton pulses

Now, the combined influence of HONE (TOD & IRS) of soliton interaction is numerically studied using SSFT and analytically by combining the PT and MOM theory, (P-MOM)T. The Fig. 5 shows the influence of TOD on soliton interaction without considering IRS analytically.

As, discussed before even on increasing the β_3 values to impractical values of $0.7ps^3/km$, we cannot see the separation of soliton pulses at I_p. Following that Fig. 6 gives the influence under IRS only for 30 km length.

From Fig. 6, the domination of IRS on avoiding soliton interaction is noted. As the Raman parameter increases the separation between soliton pulses at I_p increases. The Fig. 7 gives the clear picture on separation of soliton pulses at 24.2 km using SSFT method.

Now the SSFT and P-MOM theories demonstrated numerically and analytically respectively have stated the approximation of proposed analytical model.
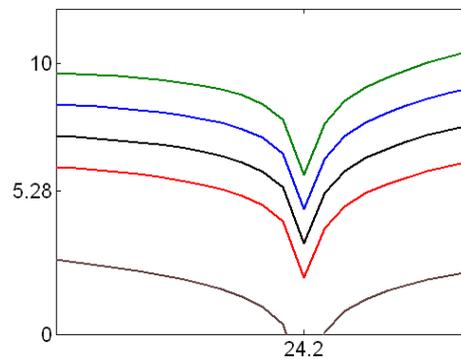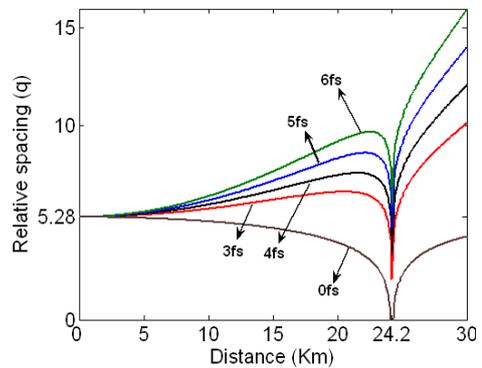

Fig. 5. (a) Analytical analysis of various TOD values on interaction (b shows the zoom)

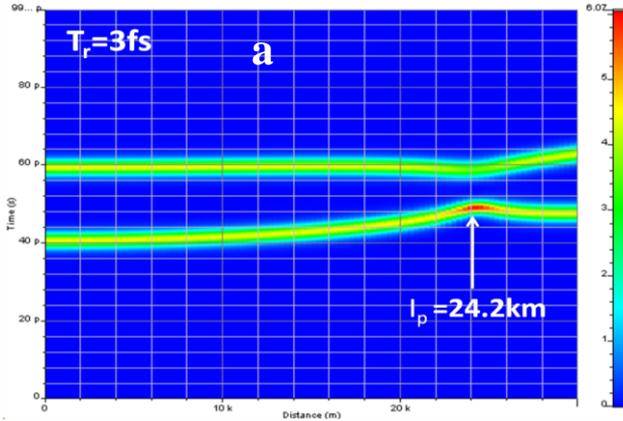*Fig. 6. (a) Analytical analysis of various IRS values on interaction (b shows the zoom)*

Fig. 7. (a) Numerical analysis on influence of IRS (T_R=3fs) values on soliton interaction using SSFT

5. Realization in 160Gbps single channel telecommunication system

The Random binary bits are generated by Psuedo-Random Binary Sequence (PRBS) generated and coded to pulse by Line coder. Here, the Return-to-zero (RZ) format is used for coding, where the soliton pulse is allotted half the bit slot (0.5bit). Here RZ coder is used as in our analytical calculation only half of the bit slot is allotted for the bit placed. It must be also noted that RZ has more average power than Non-Return to zero (NRZ) which is the characteristics of high power soliton pulse. The mode locked laser is used as the source that produces the hyperbolic-secant profile pulse, the so called solitons which are coded with respect to the voltage provided by the line coder to the parallel plates of Mach-Zehnder modulator. The fiber used is the Conventional Single Mode Fiber (C-SMF). At the receiver end, the PIN photo detector is used to convert the optical pulses to electrical pulses. The pulses are then filtered by a 4th order low pass Bessel filter to remove unwanted frequencies and regenerated by 3R regenerator (3R- re-shape, re-time or re-position and re-amplify). The Bit Error Rate (BER) tester and Time domain analyzer are used to characterize the received pulses. The skeletal model of simulation set-up is shown in Fig. 8 and the design values are same as used for theoretical calculations.

The tracing of soliton under the combined influence by SSFT in Fig. 7a clearly provides the knowledge on the temporal shift of pulses along with avoidance of interaction. Similarly, the TDA view in Fig. 9(a) gives the separation of soliton at I_p=24.2km under the combined influence of TOD with β_3=0.1ps³/km and IRS with T_R=3fs. The shift increases in the order of T_R values as 3,4,5 and 6fs. The black thick plot depicts the characteristics of two soliton pulse at I_p without any effect. The pulse perfectly overlapped resulting in the hike of power and there appears a single pulse thus proving the perfect location of interaction point in our analytical studies. Fig. 9(b) gives the influence at the end of once collision period. It can be clearly seen as the distance increases the separation between the pulse increases and also the shift of the pulse

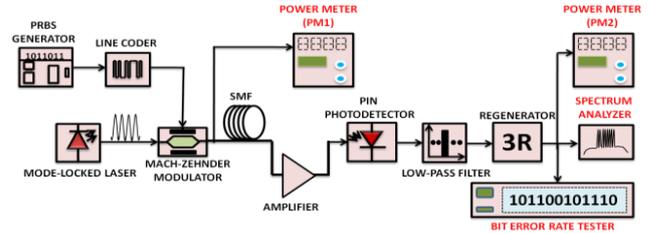increase as demonstrated by the analytical and numerical studies.

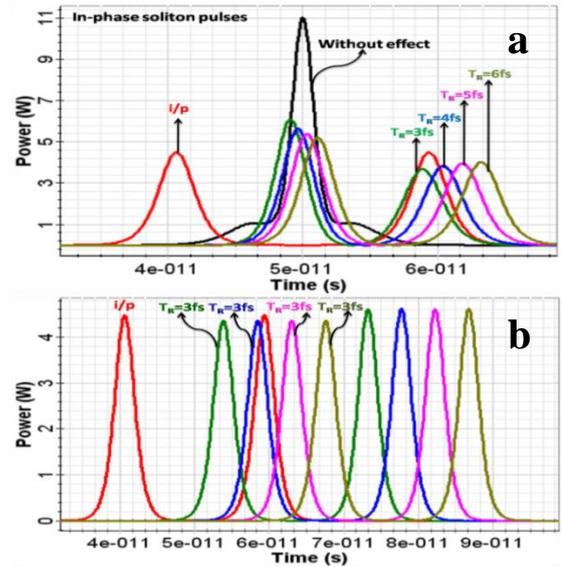Fig. 8. 160 Gbps telecommunication set-up

Fig. 9. TDA view of soliton pulses for different T_R implemented in 160 Gbps telecommunication set-up at (a) I_p=24.2km and (b) end of one collision length, 48.4km

The Fig. 9 gives the performance analysis of 160 Gbps system with bit sequences transmitted for L_{coll}=48.4 km. At 0fs, the TOD only is insufficient to separate the pulses so the Q perfectly drops to zero at I_p. It could be seen for T_R=4 and 5fs, the system yields Q of 72.88 and 83.87 respectively at I_p=24.2 km. For 6fs, it could be noted that, the pulse starts to deviate more than the bits lot even before reaching the interaction point and even drops to Q=0 within one collision period itself.

Now the strength of TOD under the combined influence is noted in Fig. 10. Although the strength of TOD is very small to cause the shift of soliton pulse separately, it can convenience the IRS during the combined shift. This can be understood by coming back to the eqn.14, in which the second term can be noted as $(\beta_3/2)\Omega_p^2$, which shows the coupling of Raman frequency and TOD. So, for the high value of T_R, TOD can actively participate in shifts. On considering Fig. 11, we have simulated the 160Gbps system using the negative and positive TOD fibers. Fig. 4.13 shows the combined influence of β_3=±0.1ps³/km and T_R=4fs in which the system implemented with positive TOD has yielded the Q

of 72.88 while negative TOD fiber yielded 48.73. Moreover, when the system is fitted with positive and negative TOD fiber which has $T_R=6fs$, the positive TOD fiber yielded Q of 28.61 while the negative TOD yielded Q of 66.86 which shows the strength of TOD.
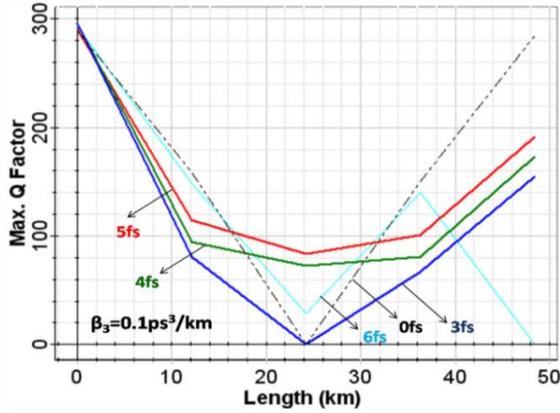

Fig. 10. Performance analysis of the system for a distance of once collision period under the combined influence of TOD ($0.01ps^3/km$) and IRS (3fs) on in-phase soliton sequence in 160Gbps system
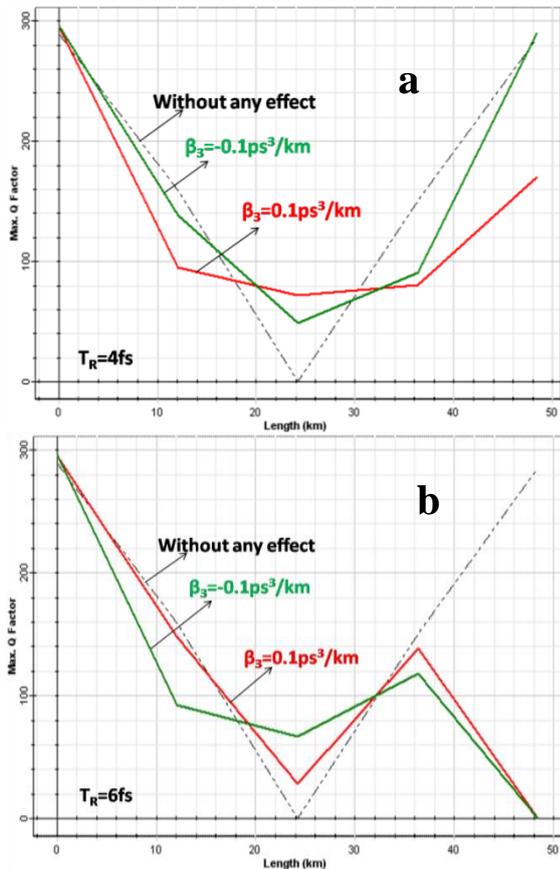

Fig. 11. Performance analysis of the system for a distance of one collision period under the combined influence of positive and negative TOD ($0.01ps^3/km$) with (a) $T_R=3fs$ and (b) $T_R=6fs$ on in-phase soliton sequence in 160Gbps system

Fig. 8 can be used to observe the signal power dependence. The graph shows output gain values for drastically ranged signal power values. The signal power of 1mW is observed to the most optimal value owing to the constant gain throughout the wavelength range. When the signal power is increased or decreased the output gain is found to have instability with maxima and minima. For a 900% increase in signal power from 10 mW to 100 mW the output gain increases by just 46% approximately. Thus altering the output gain using the signal power is not an energy efficient solution.

6. Conclusion

By the analytical and Numerical calculations, it was justified that the IRS is dominant over TOD in shifting the soliton pulses thereby avoiding the interaction at 24.2 km. The telecommunication system also supports the selection of design values were we find the interaction perfectly at 24.2 km and the pulses by TDA view. Similarly, the dropping of Q to zero at interaction point depicting the overlapping of pulses proves the bit error in the system. Further under the influence of TOD and IRS we find the fair Q which demonstrates the pulses remains non-overlapped.

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