Characteristic Study on Conventional and Soliton Based Transmission System

Bhupeshwaran Mani, S. Radha, A. Jawahar, A. Sivasubramanian

***Abstract*—**Here, we study the characteristic feature of conventional (ON-OFF keying) and soliton based transmission system. We consider 20Gbps transmission system implemented with Conventional Single Mode Fiber (C-SMF) to examine the role of Gaussian pulse which is the characteristic of conventional propagation and Hyperbolic-secant pulse which is the characteristic of soliton propagation in it. We note the influence of these pulses with respect to different dispersion lengths and soliton period in conventional and soliton system respectively and evaluate the system performance in terms of Quality factor. From the analysis, we could prove that the soliton pulse has the consistent performance even for long distance without dispersion compensation than the conventional system as it is robust to dispersion. For the length of transmission of 200Km, soliton system yielded Q of 33.958 while the conventional system totally exhausted with Q=0.

***Keywords*—**Soliton, dispersion length, Soliton period, Return-to-zero (RZ), Q-factor.

I. Introduction

SOLITONS resembles the characteristics of massive particles which are self-localized due to the balance between physical phenomenon diffraction and self-focusing or self-lensing effect [1]. The word soliton was first coined by Zabusky and Kruskal in dealing with the wave motion of the one dimensional lattice vibrations called as Korteg de Vries equation [2]. In 1971, Zakharov and Shabat shown analytically that the solitons can be generated in the nonlinear dispersive medium [3]. Following, Hasegawa and Tappert et al. demonstrated the soliton via Nonlinear Schrödinger equation in optical fibers for telecommunication applications [4]. This theoretical model was proved experimentally by Mollenauer et al. with laser centered 1.55µm in 1980's [5].

Soliton pulse propagation happens in fiber due to the compensation of negative chirping by Group Velocity Dispersion (GVD) and positive chirping by the nonlinearity Self-Phase Modulation (SPM). Due, to this possibility of long transmission without dispersion, it was highly expected to form new trend in optical communication [6]. It was a great hurdle for the deployment of optical soliton practically in telecommunication was due to the impossibility of usage of EDFA which performs in third optical transmission window. Moreover, the availability of laser at that spectrum with high power was in demand to operate solitons All the way problem came to an end with the introduction of laser at 1.55µm [7], [8]. So many workers have demonstrated the soliton transmission with EDFA other than Raman compensation which could be seen in [9]-[13].

After the breakthrough with implementation of EDFA, different types of line coding technique were realized using soliton transmission. There always existed a debate between the usages of soliton modulation technique or non soliton format like Non-Return to zero (NRZ), Returen-to-zero (RZ), chirped RZ etc. is preferable for high data rate communication. Earlier experiments were tried with NRZ coding technique which is evident from various works reported by [14]-[17]. Masatoshi Suzuki et al. demonstrated the long range transmission of 10 Gbps to 12,200 Km using Alternating Amplitude soliton which is nothing but Alternate Mark Inversion (AMI) coding, where alternate 1's are reversed in amplitude [18]. It is to be noted, the transmission was with Dispersion Shifted Fibers (DSF) without any special type of in-line control. R.-M. Mu and C. R. Menyuk et al. [19] implemented chirped RZ to minimize the timing jitter and inter-pulse interaction in Wavelength Division Multiplexed soliton system with normal Conventional Single Mode Fiber (C-SMF) of length 160 Km.

The line coding technique forms a major role in reducing the interaction and also timing jitter [20]. Apart from taming jitter which could be reduced by increasing the ration of bit period to jitter variance [21], soliton has peculiar fashion of interaction with adjacent pulses in a sequence [1], [22]. As stated already, the massive particle nature of soliton makes it to attract or repel each other with respect to the phase of the pulses. In conventional system, when we consider the Gaussian approximation for the pulses, we could note the pulse broadening results in Inter-symbol Interference (ISI) resulting in Bit error, while in case of solitons the adjacent particles bends towards or repel apart for in-phase and out-of phase pulses respectively [23]-[26]. As in-phase solitons collide at the interaction point with respect to the initial spacing and phase of soliton, Masatoshi Suzuki et al. demonstrates with AMI as noted before [18].

It must be also noted that, the characteristic study by Nakazawa et al. stress that the soliton forms the major role in optical networks in 21st century [25]. But, a proper analysis between the soliton and conventional pulse must be studied to realize various parameter of interest along the length of the fiber. Although high bit rate is possible in conventional WDM

Bhupeshwaran Mani is currently pursuing his PhD degree under Anna University and he is with Dept. of Electronics and Communication Eng., SSN College of Engineering, Anna University, Kalavakkam-603 110, India (phone: 8056085952; e-mail: bhupeshwaranm@ssn.edu.in).

Dr. S. Radha is Professor and Head, Dept. of Electronics and Communication Engg., SSN College of Engineering, Kalavakkam-603 110.

Dr. Jawahar is Professor in Dept. of Electronics and Communication Engineering, SSN College of Engineering, Kalavakkam-603 110.

Dr. A. Sivasubramanian is Professor in School of Electronics Engineering, VIT University, Chennai-600 127, India.

International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:9, No:6, 2015

system, like as noted in [27], where 32 channels of 20 Gbps data totally comprising of 640Gbps was studied, it is still a unbreakable theme to increase a single channel bitrate. Moreover, increasing number of channels results in less spacing between them in third optical window and lead to high influence of inter-channel impairments or nonlinearities like Four Wave Mixing (FWM), Stimulated Raman Scattering (SRS) etc.

So, now the purpose of soliton transmission can be realized where a single channel can be utilized for ultra-high bitrate. Nakazawa et al. [28] and Leonardo D. Coelho et al. [29] depict the idea of 160 Gbps transmission in a single channel using soliton pulse in Dispersion Shifted Fiber (DSF) and Non-Zero Dispersion Shifted Fibers (NZ-DSF) for S and C bands respectively. Very recently, Jing Huang et al. clear the doubt of enhanced performance by increasing the bitrate of the system by comparing the system of WDM and system with Time Division Multiplexing (TDM) [30]. They noted that for system deployed with NZ-DSF, the 160 Gbps (4x40 Gbps) WDM system can help in transmission only up to 1000Km qualitatively, while the system with single channel using TDM could helped better transmission up to 2000 Km. So, the clear idea of increasing bitrate of single channel is realized and it is of great importance to study the features of soliton and conventional in single channel specifications.

In our proposed work, we intend to note these pulse characteristics in conventional and soliton system to give the clear picture of dispersion, chirping etc. with respect to distance. We study the system implemented with C-SMF in 20 Gbps and trace the pulse for various dispersion lengths in case of conventional system and soliton period in case of soliton system.

II. Pulse Propagation in fiber

The pulse propagating in an optical fiber is governed by Non-Linear Schrödinger's wave equation as [31],

$$\frac{\partial A(z,t)}{\partial z} = \frac{-\alpha}{2}A(z,t) + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A(z,t)}{\partial t^3} - i\gamma|A(z,t)|^2 A(z,t) \quad (1)$$

where, in the right hand side of the equation,first term corresponds to attenuation, second term corresponds to first order GVD which is characterized by Dispersion parameter $D = -\frac{2\pi c}{\lambda^2}\beta_2$, third term corresponds to second order GVD which is characterized by Dispersion Slope as $S = \frac{dD}{d\lambda} = \left(\frac{2\pi c}{\lambda^2}\right)^2\beta_3 - \frac{2}{\lambda}D$ and fourth term refers to non-linearity. From eqn.1, the effect of GVD is considered as,

$$i\frac{\partial A(z,t)}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} \quad (2)$$

The above equation is considered to analyze the effect of Dispersion only and neglecting the effect of SPM, higher order dispersion and attenuation. Since the length of transmission is limited to bitrate of the system, the dispersion length is noted as,

$$L_D = \frac{T_o^2}{|\beta_2|} \quad (3)$$

To support soliton transmission, the combined effect of SPM and GVD is needed in anomalous regime, so now (1) becomes as,

$$i\frac{\partial A(z,t)}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - i\gamma|A(z,t)|^2 A(z,t) \quad (4)$$

To characterize SPM, the important term used is non-linear length (L_{NL}) which is given as,

$$L_{NL} = \gamma P_o \quad (5)$$

where, γ is the non-linear co-efficient with n_2 is the non-linear index, ω_o is the frequency, A_{eff} is the effective area and c is the speed of light.

$$\gamma = \frac{n_2\omega_o}{cA_{eff}} \quad (6)$$

The normalizes form of (1) is written by considering the dimensionless variables, $U = A/\sqrt{P_o}$, $\xi = z/L_D$ and $\tau = T/T_o$ as,

$$i\frac{\partial U}{\partial \xi} = sgn(\beta_2)\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2|U|^2 U \quad (7)$$

where, a new parameter N is defined as the soliton order defining parameter as,

$$N^2 = \frac{\gamma T_o^2 P_o}{|\beta_2|} \quad (8)$$

The parameter N can be eliminated by defining, $u = NU = \sqrt{\gamma L_D A}$, where (7) takes the standard form of NLS eqn. As,

$$i\frac{\partial u}{\partial \xi} = \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} - |u|^2 u = 0 \quad (9)$$

Now, the most general solution can be written as,

$$u(\xi,\tau) = -2\sum_{j=1}^{N}\lambda_j^*\psi_{2j}^* \quad (10)$$

where, ψ_{2j}^* is obtained by solving the equations as,

$$\psi_{1j} + \sum_{k=1}^{N}\frac{\lambda_j\lambda_k^*}{\zeta_j-\zeta_k^*}\psi_{2k}^* = 0 \quad (11)$$

$$\psi_{2j}^* - \sum_{k=1}^{N}\frac{\lambda_j\lambda_k^*}{\zeta_j-\zeta_k^*}\psi_{1k} = \lambda_j^* \quad (12)$$

and λ_j is givem as,

$$\lambda_j = \sqrt{c_j}\exp(i\zeta_1\tau + i\zeta_j^2\xi) \quad (13)$$

The most fundamental soliton propagation is given as the following by substituting by N=1,

$$u(\xi,\tau) = \eta\,\mathrm{sech}[\eta(\tau-\tau_s+\delta\xi)]\exp[\frac{i(\eta^2-\delta^2)\xi}{2} - i\delta\tau + i\phi_s] \quad (14)$$

While the soliton period is found to be as, by relating $\xi = z/L_D$ and $\xi_0 = \pi/2$,

$$z_o = \frac{\pi}{2} L_D \tag{15}$$

Equation (15) gives the picture of period for which the soliton maintains its perfect characteristics.

III. Simulation Parameter and Set-up

In this section, the simulation parameters and design flows are discussed. The system is operated with the bitrate of 20Gbps, where the bitslot can be noted as inverse of bitrate. But the Full Width Half Maximum (FWHM) of the pulse is related to the initial pulse width as follows,

$$T_{FWHM} = 2\ln\left(1+\sqrt{2}\right)T_o \approx 1.763\ T_o \tag{16}$$

From (16) the initial pulse width is calculated from the full width half maximum time.

In order to launch soliton the Dispersion length (L_D) and Nonlinear length (L_{NL}) must be equal. The Dispersion length and Nonlinear length can be given as $L_D = T_O^2/|\beta_2|$ and $L_{NL} = 1/\gamma P_o$ respectively, where β_2 is the dispersion parameter, γ is the nonlinear coefficient, $\gamma = n_2\omega_o/cA_{eff}$ in which n_2, ω_o, c, and A_{eff} represents to non-linear refractive index, frequency, speed of the light and effective area of fiber respectively.

The power required to launch soliton can be calculated from (17), where for fundamental soliton N=1,

$$N^2 \geq \frac{L_D}{L_{NL}} = \frac{\gamma P_o T_o^2}{|\beta_2|} \tag{17}$$

It is to be noted, that the soliton pulse experience their originality with constant phase and intensity for a period called Soliton period (z_o) which is given in (3)

$$z_o = \frac{\pi}{2} L_D = \frac{\pi}{2}\frac{T_o^2}{|\beta_2|} \approx \frac{T_{FWHM}^2}{|\beta_2|} \tag{18}$$

TABLE I
Physical Parameters Used for Fiber in 20Gbps System

Parameters	Values	Units
Reference wavelength (λ)	1550	nm
Dispersion Coefficient(β_2)	-20	ps^2/Km
Dispersion Slope	0.085	$ps/nm^2/Km$
Attenuation (α)	0	dB/Km
Effective Area (A_{eff})	80	μm^2
Non-linear index (n_2)	2.8×10^{-20}	m^2/W
Mode field diameter	9.2-10	μm

TABLE II
Physical Parameters Used for Fiber in 20Gbps System

Parameters	Hyperblic secant	Gaussian	Units
T_{FWHM}	25	25	ps
T_o	14.18	15.15	ps
Power (P)	70.10	1	mW
Non-linear Coefficient (γ)	1.418		$W^{-}Km^{-1}$
Dispersion length (L_D)	10.05	11.27	Km
Non-linear length (L_{NL})	10.05	-	Km
Soliton period (z_o)	15.79	-	Km

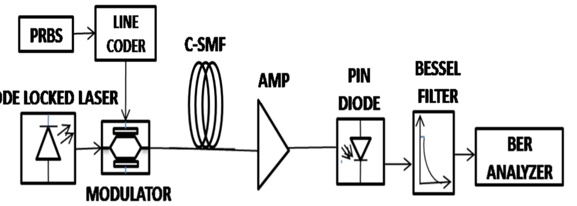

Fig. 1 Skeletal view of basic telecommunication model

Equations (16)-(18) are used to calculate the values to be implemented in 20 Gbps system and shown in Table II and the model is shown in Fig. 1. The Psuedo Random Binary Sequence (PRBS) is generated by Random bit Generator and is coded by Return-to-Zero (RZ) line coder which controls the voltages on the plates of Mach-Zehnder modulator which in turn modulate the light from the laser (mode-locked for soliton and CW laser for conventional) that has the hyperbolic-secant profile. The amplifier is Erbium-doped Fiber amplifier, which is only to compensate the losses by the SMF and set to such that it does not introduces any nonlinearity due to Amplified Spontaneous emission, because our effort is to note the characteristics of soliton ideally in fiber without any other effects by devices. At the receiver side, the PIN photo detector (Responsivity=1A/W, Dark current=10 nA) is used to detect the optical pulses to electrical pulses. The low pass Bessel filter of fourth order is used to cut off frequencies and finally bit patters are analyzed.

IV. Results and Discussions

In this section, first the characteristics of single pulse propagating insider the fiber is noted for conventional and soliton system. Secondly, the system is analyzed for sequence transmission for 10 Km and 200 Km without dispersion compensation.

A. Characteristics of Single Conventional and Soliton Pulse

The pulse propagating insider the fiber is strictly governed by (7) for soliton and (4) for the conventional system. The higher order effects like Raman Scattering, Self-steepening and third order dispersion of soliton is not considered and for conventional only second order dispersion and nonlinearity is considered. Fig. 2 shows the pulse characteristics before and after fiber approximated with a Gaussian pulse. Fig. 2 (a) is an evidence of unchirped input Gaussian pulse. The horizontal line across the pulse shows the frequency chirping, where it is perfectly zero for unchirped pulse. The Gaussian pulse, which travels along the length of the fiber gets broadened due to dispersion in anomalous dispersion (D>0 or β_2<0). For Gaussian pulse, the dispersion length is calculated as L_D=11.27 Km for initial pulse width of T_o=15.10ps. The fiber received after this length gets broadened while the pulse width remains same within this limit. After one L_D, we could see the pulse has broadened and the frequency chirping increases from the leading edge to the trailing edge. Moreover, in anomalous regime, the blue frequency lies in the leading edge of the pulse and red frequencies lay in the trailing edge of the pulse, so these blue frequencies travels faster than the red frequency leading to broadening. Fig. 2 (b) demonstrates that the blue frequency in leading edge is depicting increase in frequency chirping and reduced chirping along the leading edge denoting the red frequencies [31].

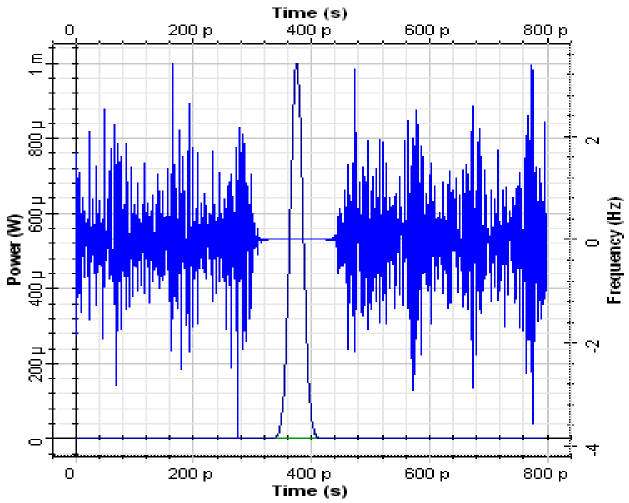

Fig. 2 (a) Characteristic analysis of Gaussian pulse approximating in Conventional system before fiber

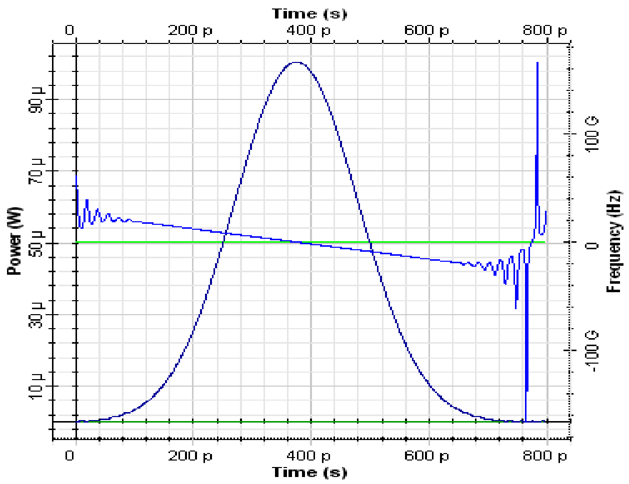

Fig. 2 (b) Characteristic analysis of Gaussian pulse approximating in Conventional system after fiber for one dispersion length

Now, considering the soliton pulse which is nothing but the hyperbolic-secant pulse is noted initially with zero chirp (Fig. 3 (a)). Even after one soliton period of z_o=15.79Km, the input pulse width of T_o=14.18ps remains without broadening. This characteristic feature is possible with balance between the dispersion and nonlinearity. It is to be noted that, the Gaussian pulse in the same system was propagated with an input power of P_o=1mW. But, here in case of soliton pulse, an input power of P_o=70.10 mW which helps in balancing with dispersion. The idea could be clearly noted that, where this input power produced red chirping in the leading edge of pulse and blue chirping in the trailing edge of the pulse. So, in anomalous regime, this introduction of chirping inversely to the present chirping helps in cancelling of negative chirp by GVD and positive chirp by SPM. This is evident from Fig. 3 (b) where the chirping is constant across the pulse due to cancelling of chirps.

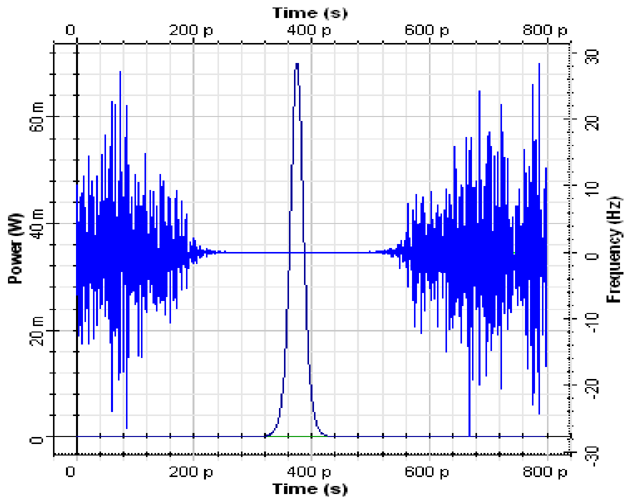

Fig. 3 (a) Analysis of hyperbolic-secant pulse approximating soliton system before fiber

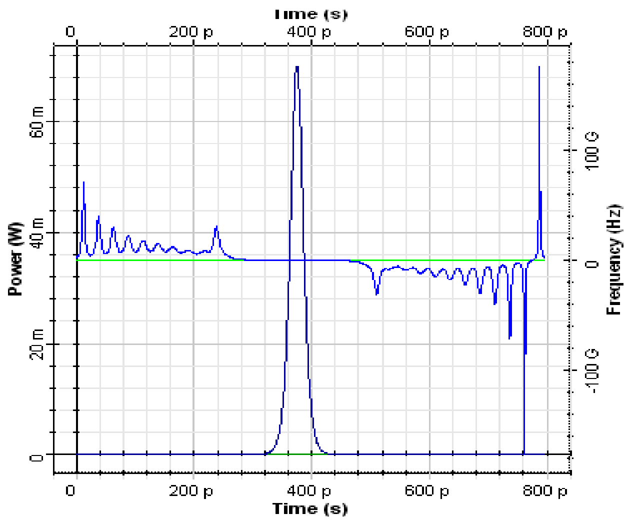

Fig. 3 (b) Analysis of hyperbolic-secant pulse approximating soliton system after fiber for one soliton period

International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:9, No:6, 2015

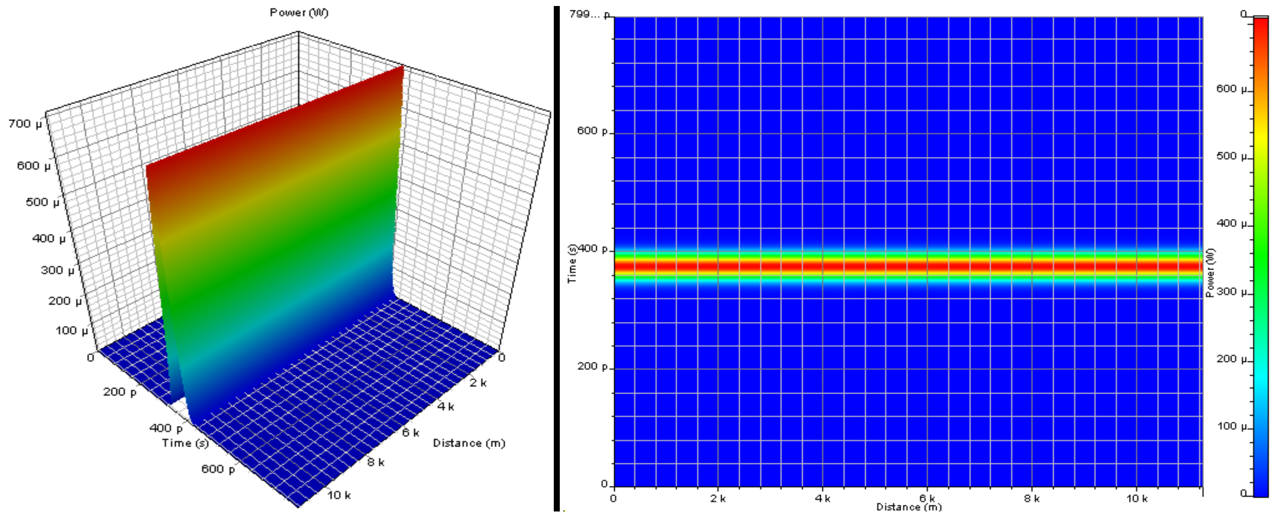

Fig. 4 (a) 3D view of Gaussian pulse received at the end of one dispersion length, L_D=11.27Km

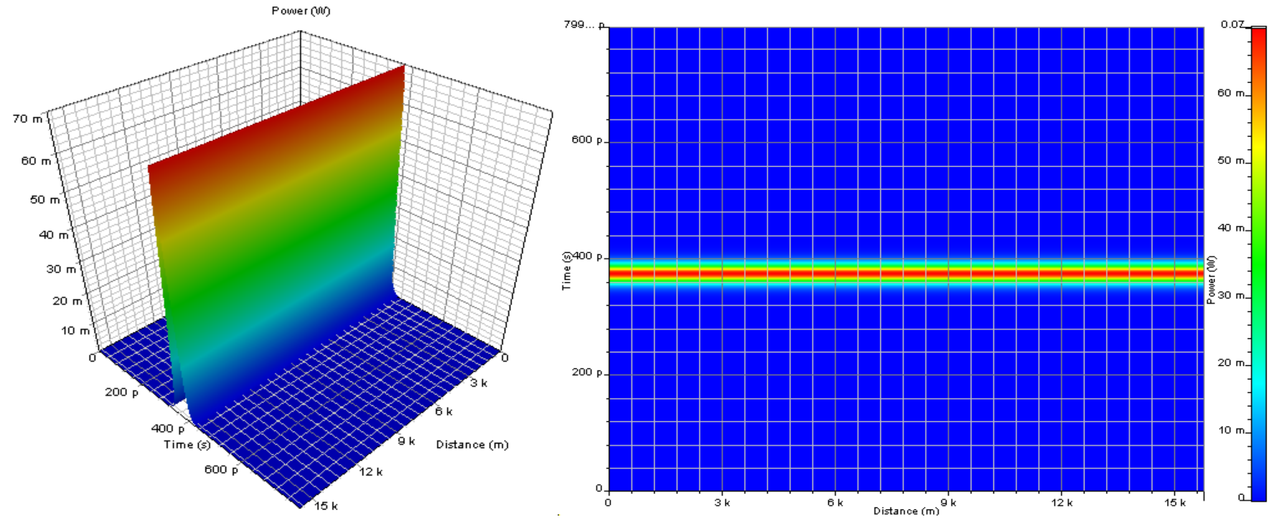

Fig. 4 (b) 3D view of soliton pulse at the end of one soliton period, z_o=15.79 Km

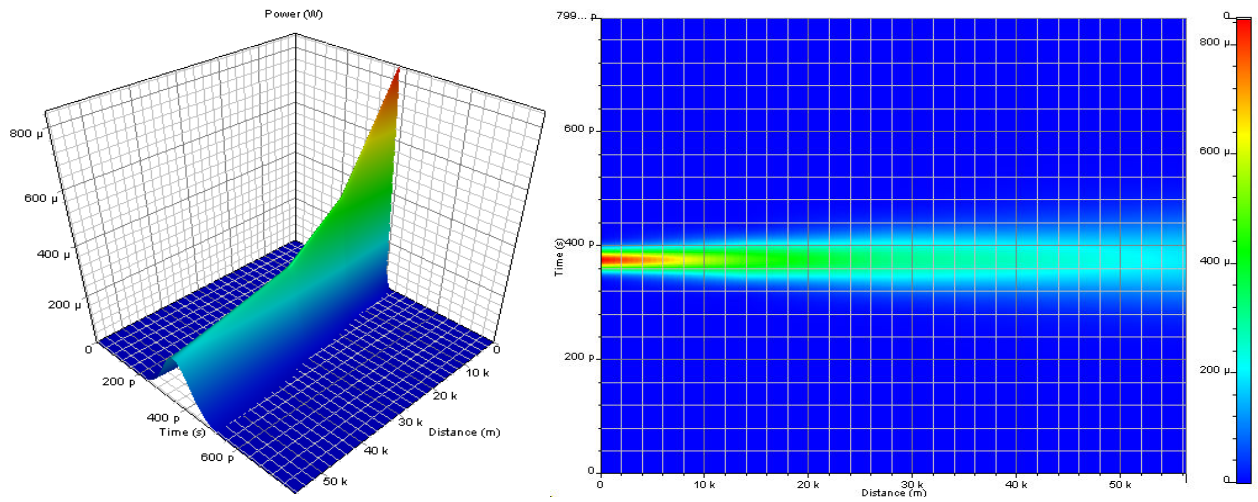

Fig. 5 (a) 3D view of Gaussian pulse received at the end of five dispersion length, 5L_D=56.35Km

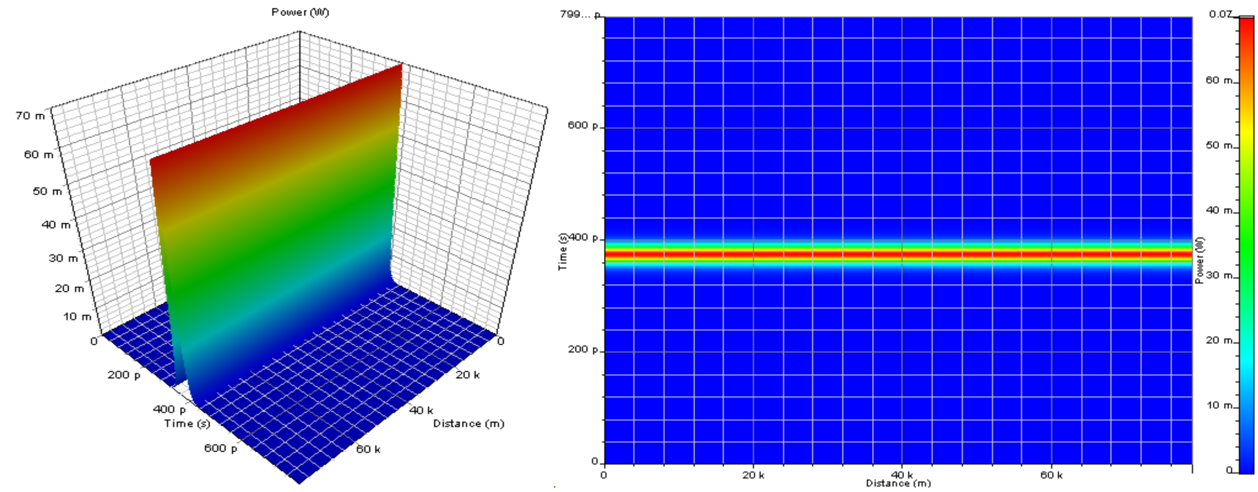

Fig. 5 (b) 3D view of soliton pulse at the end of five soliton period, $5z_o$=78.95 Km

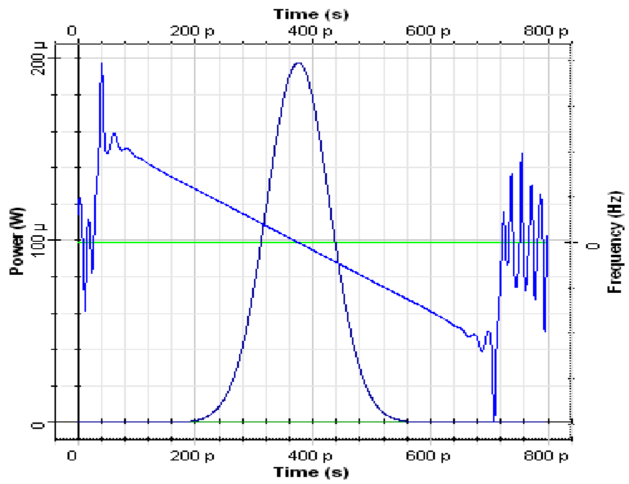

Fig. 6 (a) Time domain analyzer view of Gaussian pulse received at the end of $5L_D$=56.35 Km

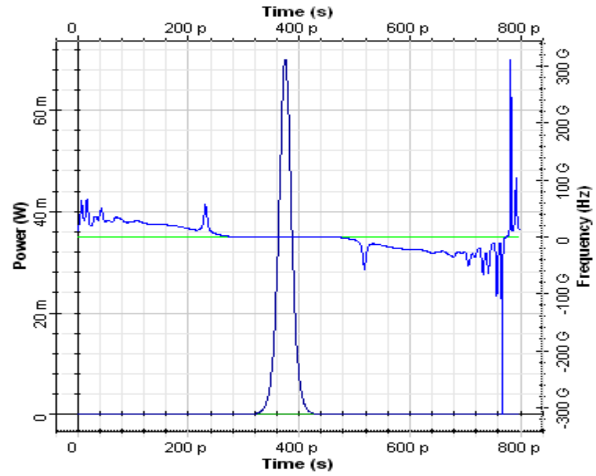

Fig. 6 (b) Time domain analyzer view of Hyperbolic secant pulse received at the end of $5z_o$=78.95

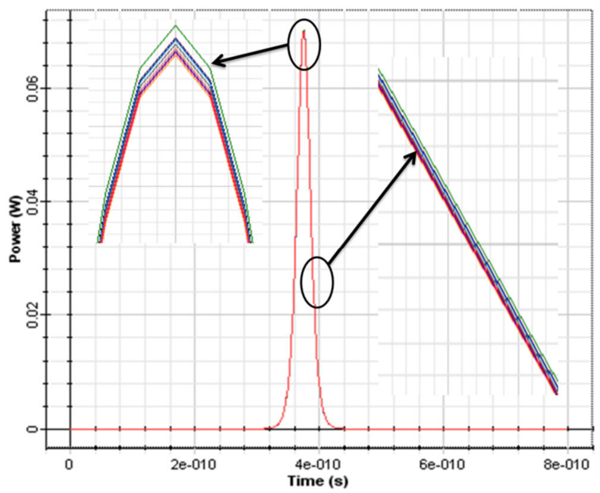

Fig. 7 (a) Time domain analyzer view of pulse received for different sweeps of soliton period (z_o, $2z_o$, $3z_o$, $4z_o$ and $5z_o$)

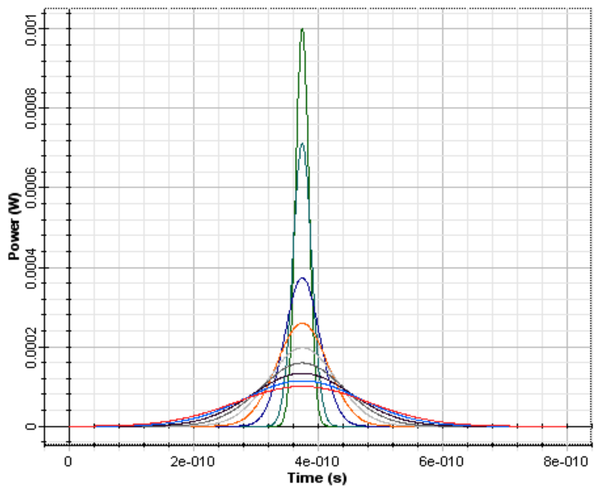

Fig. 7 (b) Pulse received for the different sweeps of dispersion length (L_D, $2L_D$, $3L_D$, $4L_D$ and $5L_D$)

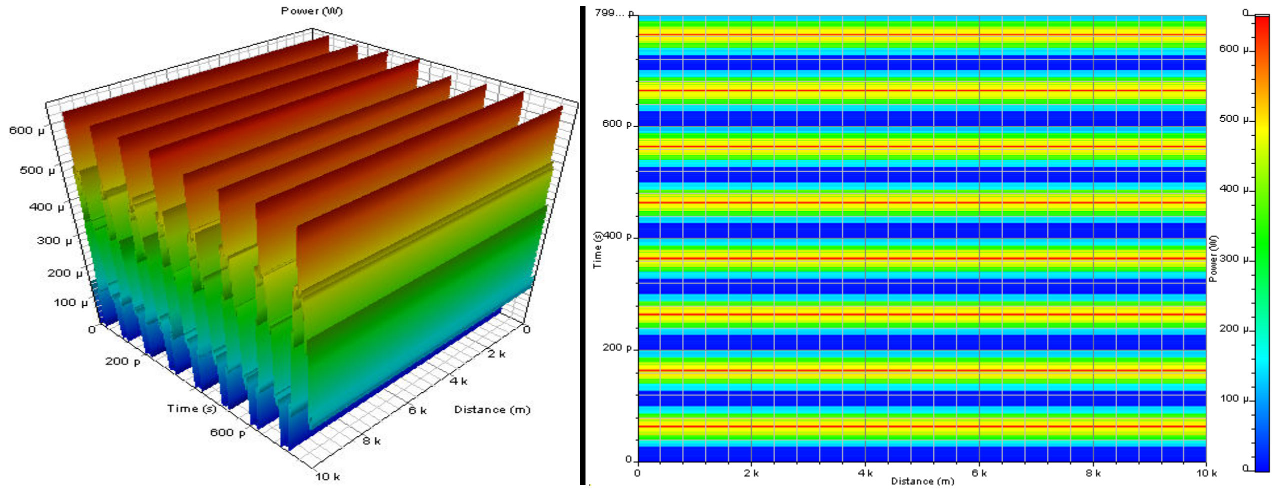

Fig. 8 (a) The pulse sequence received at the end of 10 Km fiber length implemented in Soliton system

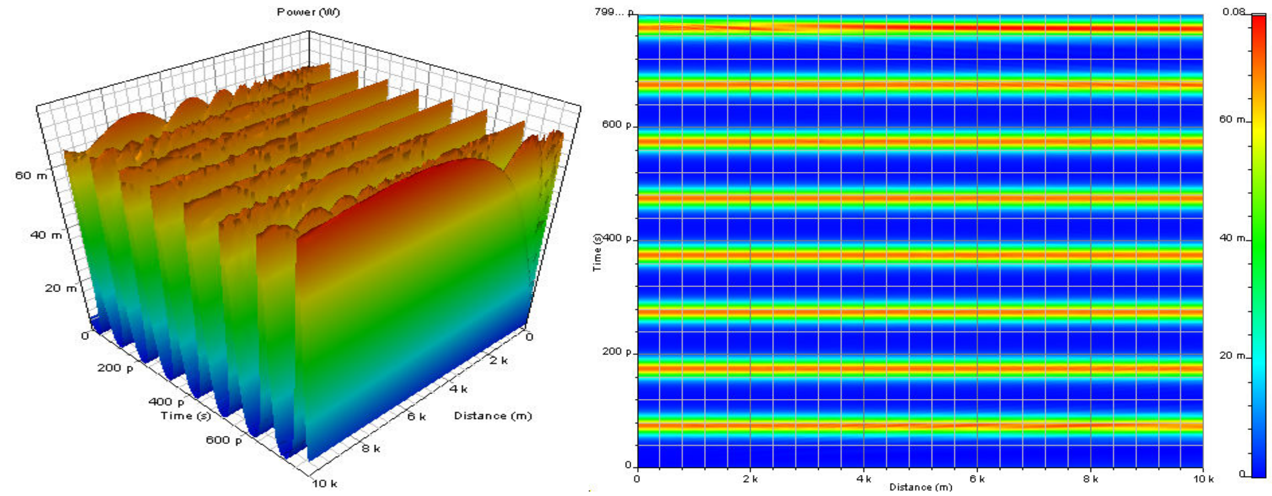

Fig. 8 (b) The pulse sequence received at the end of 10 Km fiber length implemented in Conventional system

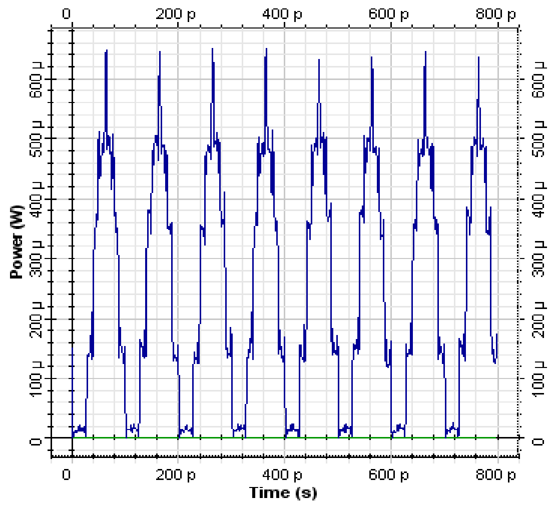

Fig. 9 (a) Time domain analyzer view of bit patterns in conventional transmission system

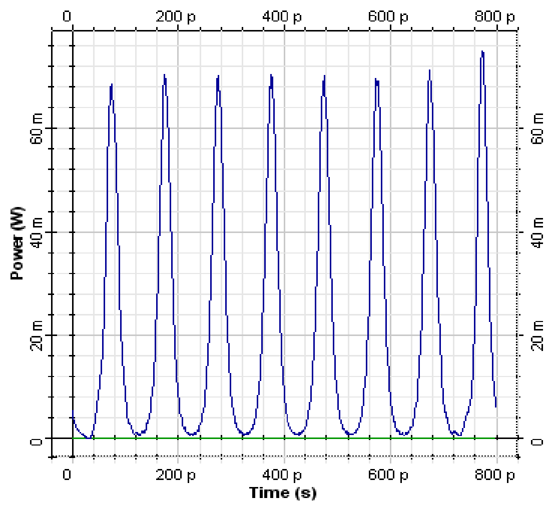

Fig. 9 (b) Time domain analyzer view of bit patterns in soliton transmission system

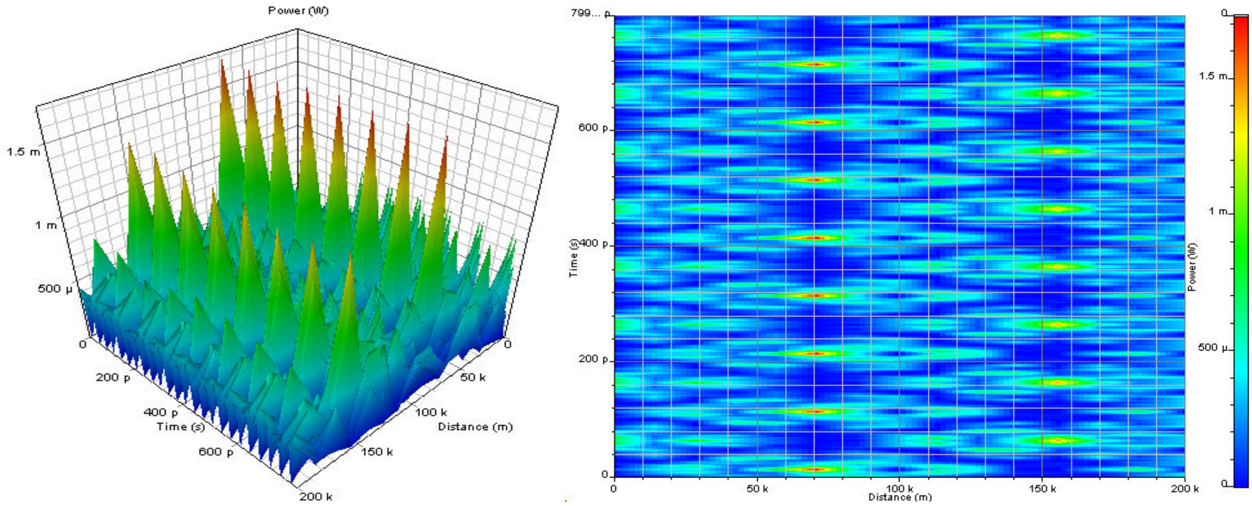

Fig. 10 (a) The pulse sequence received at the end of 200 Km fiber length implemented in soliton transmission system

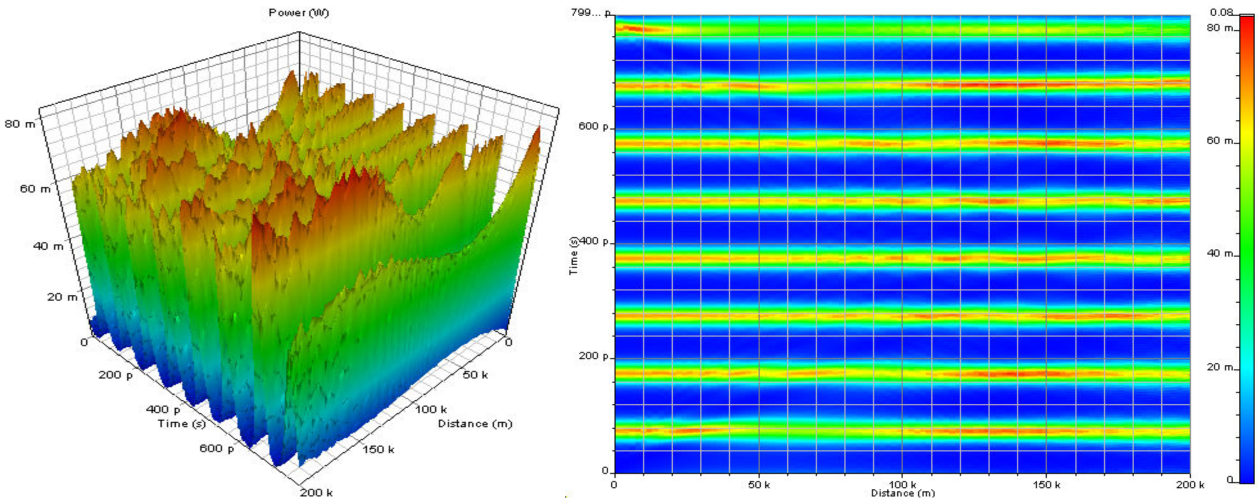

Fig. 10 (b) The pulse sequence received at the end of 200 Km fiber length implemented in Conventional transmission system

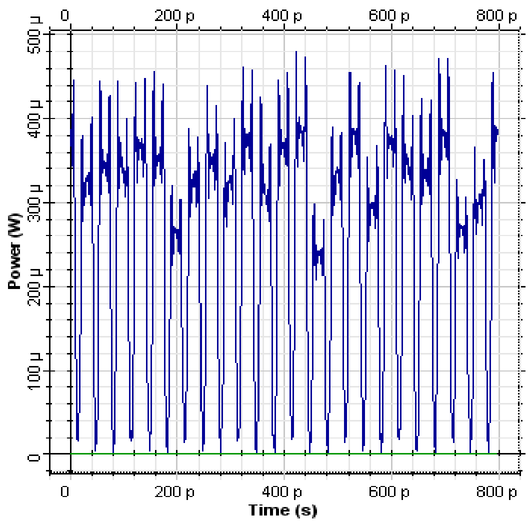

Fig. 11 (a) Time domain analyzer view of pulse sequence received at the end of 200 Km fiber length implemented in conventional system

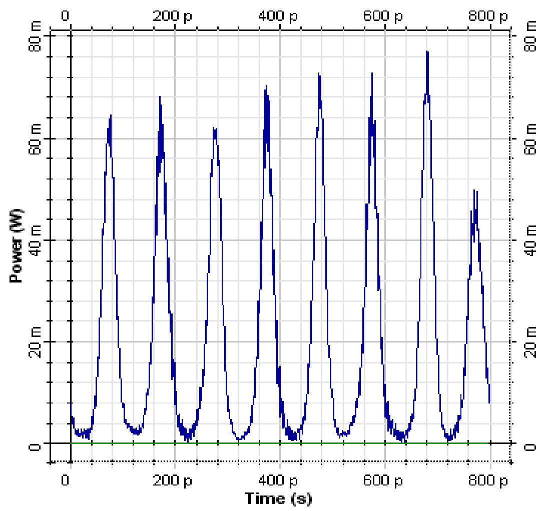

Fig. 11 (b) Time domain analyzer view of pulse sequence received at the end of 200 Km fiber length implemented in soliton system

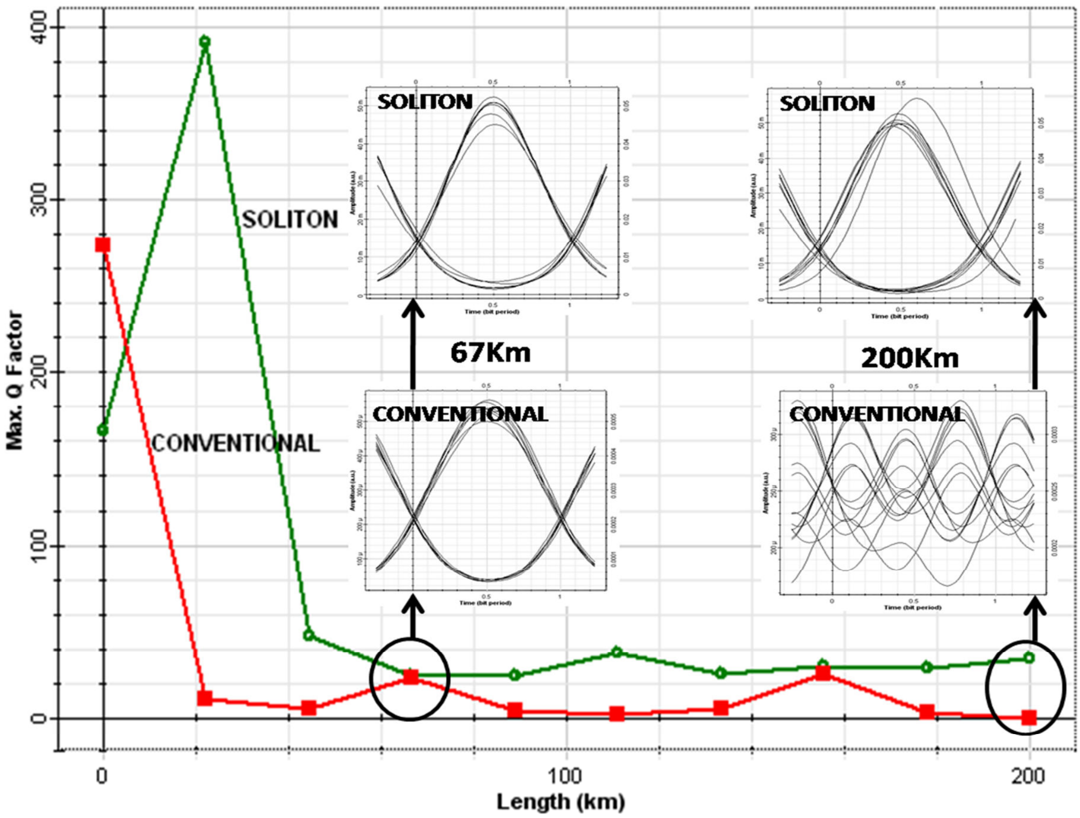

Fig. 12 Performance analysis of Conventional and soliton transmission system

Figs. 4 (a) and (b) show the 3D view of the Gaussian pulse and hyperbolic secant pulse respectively. For this small length, we could not find a very large broadening of the pulse. But, Fig. 5 shows the clear differentiation of Gaussian and hyperbolic secant pulse for five dispersion lengths and soliton period respectively. Fig. 5 (a) clearly pictures the broadening of pulse for increased lengths which also resulted in decrease of power. But, the soliton pulse in Fig. 5 (b) is very stable for 5 soliton period demonstrating its stability towards dispersion. It is needed to estimate the chirping characteristics, where Fig. 6 (a) shows the large variation of chirps in leading and trailing edge as compared to that of Fig. 2 (b). As the length increases, the blue frequencies in the leading edge and red in trailing edge increases resulting in heavy broadening. We have also trailed out the characteristics of soliton and Gaussian pulse for various lengths and we could find from Fig. 6 (a), where for any soliton period the pulse received without large broadening and very small broadening exists between them. While Fig. 6 (b) gives the picture on broadening increases with increased distance for the Gaussian pulse.

The comparative study on pulse broadening can be noted from Figs. 7 (a) and (b) gives the clear visualization of soliton and conventional pulses in a system. Even for five soliton period, the soliton pulse is very highly robust and large scale magnification shows very small broadening.

B. Pulse Characteristics in Sequence and Realization in Optical Telecommunication System

Now, the characteristics of pulse in conventional and soliton system are studied. The bit sequence of length 16 bits with 64 samples per bit, totally contributing 1024 samples is noted in the system. The length of the fiber considered is 10Km and 200 Km. The conventional system is ON-OFF keyed, indirectly modulated laser of continuous nature, while soliton uses mode locked laser.

Figs. 8 and 10 show the sequence of 10101… fashion comprising 16 bits per sequence propagating for 10Km and 200Km fiber length. Figs. 8 (a) and (b) shows the soliton sequence with good reception of pulses at this small length of 10 Km. Moreover the time domain analyzer view of bit patterns evidently prove the non-disintegration of pulses with small length (see Fig. 9). The sequence is noted with alternate 1's and 0's to also realize the adjacent bit interference. We also found the Q factor for the soliton transmission system and conventional system as 282.70 and 148.7 respectively. Even for this small length, soliton proves its much enhanced nature in terms of Q.

But for long transmission of 200 Km without any dispersion compensation, we could find that the soliton pulse seems to be very good in sequence (Fig. 10 (b)) but the pulse broadening has disintegrated the conventional system due to Inter-symbol Interference. The temporal view of the pulse sequence in Figs. 11 (a) and (b) corresponding to conventional and soliton system once again confirms the ISI strategy. The soliton system performed with very good Q of 33.96 and BER of 3.99×10^{-253} while the conventional system totally exhausted and Q falls to zero. Even at 50 Km, the conventional system has dropped its performance where it yielded Q=5.65 (BER=7.28×10^{-9}) while soliton system shown Q=41.16 (BER=0).

V. Conclusion

The simulation studies prove the characteristics of soliton and conventional comparatives. The soliton system can easily persuade any other telecommunication model with its stability. It can be noted from Fig. 12, at small lengths conventional system started with high Q value than soliton system. But, the real fact is the stability with respect to distance. Conventional system started with such high Q must have at least ended up with small Q but unfortunately exhausted and drained to Q=0. But soliton system has continuously supported the system for even longer length. So, soliton can form good range of telecommunication with even very high bit rate per channel with proper dispersion compensation.

Acknowledgment

The author Bhupeshwaran Mani would like to thank Dr.Senthil Mani Rajan, Assistant Professor, University College of Engineering, Ramanthapuram Campus, Anna University for the technical discussions and Dr.Chitra, Professor, School of Electronics Engineering, VIT University, Chennai for the support.

References

[1] Stegeman, G.I., Segev, M.: Optical spatial solitons and their interactions: universality and diversity. Science 286, 1518–1523 (1999).
[2] N.J. Zabusky and M.D. Kruskal, Interaction of solitons in a collisionless plasma and recurrence of initial state, Phy. Rev Lett., 15 (6), 1965, 240-243.
[3] Masataka Nakazawa, Soliton transmission in Telecommunication Networks, IEEE Communication Magazine, 1994
[4] A. Hasegawa and F. Tappert. Transmission of stationary nonlinear optical pulse in dispersive dielectric fibers I. Anomalous dispersion, Applied Phy. Lett. 23 (3), 1976, 142-144.
[5] Mollenauer, L.F., Smith, K.: Demonstration of soliton transmission over more than 4000 km in fiber with loss periodically compensated by Raman Gain. Opt. Lett. 13, 1988, 675–677.
[6] Haus, H.A., Wong, W.S.: Solitons in optical communication. Rev. Mod. Phys. 68(2), 1996, 423–444.
[7] M. Nakazawa, Kimura, and K. Suzuki, Efficient Er^{3+} doped optical fiber amplifier pumped by a 1.48µm in InGaAsP laser diode, App. Phy Rev Lett., 13, 1988, 675-677
[8] Li, T., The impact of optical amplifiers on long-distance lightwave telecommunications, Proc. IEEE 81, 1568–1579.
[9] Desurvire, E., J. R. Simpson, and P. C. Pecker, 1987, ‘‘High gain erbium-doped traveling-wave fiber amplifier,’’ Opt. Lett.12, 1987, 888–890.
[10] Mears, R. J., L. Reekie, I. M. Jauncey, and D. N. Payne, Low-noise erbium-doped fibre amplifier operating at 1.54 µm, Electron. Lett. 23, 1987, 1026–1028.
[11] Chernikov, S. V., D. J. Richardson, R. I. Laming, E. M. Dianov, and D. N. Payne, 1992, ‘‘70 Gbit/s fibre based source of fundamental solitons at 1550 nm,’’ Electron. Lett. 28, 1989, 1210–1212.
[12] Desurvire, E., J. W. Sulhoff, J. L. Zyskind, and J. R. Simpson, 1990, ‘‘Spectral dependence of gain saturation and effect of inhomogeneous broadening in erbium-doped aluminosilicate fiber amplifiers,’’ in *Optical Amplifiers and their Applications*, 1990 Technical Digest Series, Vol. 13 (Optical Society of America, Washington, D.C.), 1989, p. PdP9.
[13] Tachibana, M., R. I. Laming, P. R. Morkel, and D. N. Payne, 1991, Erbium-doped fiber amplifier with flattened gain spectrum, IEEE Photonics Technol. Lett. 3, 1991, 118–120.
[14] Runge, P. K., ‘Undersea lightwave systems, AT&T Tech. J. 71, 1992, 5–13.
[15] Bergano, N. S., and C. R. Davidson, Circulating loop transmission experiments for the study of long-haul transmission systems using erbium-doped fiber amplifiers, J. Lightwave Technol. 13, 1995, 879–888.
[16] Forghieri, F., R. W. Tkach, and A. R. Chraplyvy, WDM systems with unequally spaced channels, J. Lightwave Technol.13, 1995, 889–897
[17] Hansen, P. B., 2.488 Gbit/s unrepeatered transmission over 423 km employing remotely pumped post- and preamplifiers, Electron. Lett. 31, 1995, 466–467.
[18] Masatoshi Suzuki, Noboru Edagawa, Hidenori Taga, Hideaki Tanaka, Shu Yamamoto, and Shigeyuki Akiba, 10 Gb/s, Over 12200 km Soliton Data Transmission with Alternating-Amplitude Solitons, IEEE Photonic Tech. Lett. 6 (6), 1994, 757-759.
[19] R.-M. Mu and C. R. Menyuk, Convergence of the Chirped Return-to-Zero and Dispersion Managed Soliton Modulation Formats in WDM Systems, Journal of Lightwave Tech. 20 (4), 608,617, 2002.
[20] O. V. Sinkin, J. Zweck, and C. R. Menyuk, Comparative study of pulse interactions in optical fiber transmission systems with different modulation formats, Optics Express 9 (7), 2001, 339-352.
[21] P. Shum & H. Ghafouri-Shiraz, Effects of gordon-haus jitter on soliton transmission, Fiber and Integrated Optics, 16(3), 1997, 303-319.
[22] Segev, M., Stegeman, G.: Self trapping of optical beams, spatial solitons. Phys. Today. 51, 1998, 42–48.
[23] Aitchison, J.S., Weiner, A.M., Silberberg, Y., Leaird, D.E., Oliver, M.K., Jackel, J.L., Smith, P.W.E.: Experimental observation of spatial soliton interactions. Opt. Lett. 16(1), 1991, 15–17.
[24] Konar, S., Biswas, A.: Intra-channel collision of Kerr law optical solitons. Progr. Electromagn. Res. PIER 53, 2005, 55–67.
[25] Nakazawa, M., Kubota, H., Suzuki, K., Yamada, E., Sahara, A.: Recent progress in soliton transmission technology. Chaos 10, 2000, 486–514.
[26] Bhupeshwaran Mani · K. Chitra · A. Sivasubramanian, Realization of soliton interaction in 100 Gbps, uncompensated single channel telecommunication system implemented with various telecom fibers, J. of optical and Quantum Electronics, Published September 25, (2014).
[27] H. S. Chung, S. K. Shin, D. W. Lee, D. W. Kim and Y.C Chung, 640 Gbit/s (32x20Gbit/s) WDM transmission with 0.4 (bit/s)/Hz spectral efficiency using short-period dispersion-managed fibre, Elect. Lett 37 (10), 618-620, 2001.
[28] M. Nakazawa, E. Yoshida, E. Yamada, K. Suzuki, T. Kitoh and M. Kawachi, “I 6OGbitk soliton data transmission over 200km”, Elect. Lett., 31(7),1995. 565-566.
[29] Leonard D. Coelho, Camelo J. A. Bastos-Filho and Joaquim F. Martins-Filho, 160 Gbit/s Soliton Transmission in the S and C Bands, Proceedings of SBMO/IEEE MTT-S IMOC 2003, 245-249
[30] Jing Huang, Jianquan Yao, Performance comparison between 160 Gb/s WDM and TDM systems, Optik 123 , 2012 2254– 2259.
[31] Agrawal, G.P.: Nonlinear Fiber Optics, 4th edn. Academic Press, USA (2008)