Reach and BER improvement of 160 Gb/s Single channel Soliton Transmission using Optical Filtering, Raman Amplification and iPDM

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Abstract ¾ **We report, through numerical simulations, that the proper use of counter-pumping distributed Raman amplification, narrow bandwidth optical filtering, and intrabit polarization-division multiplexing (iPDM) techniques improve the reach and BER of a 160 Gb/s single channel Soliton transmission system. Using these techniques, the maximum 100 km error free transmission is enhanced to 525 km using 25 km as the amplification length and operating near to the zero dispersion wavelength. The filter spacing is optimized to 25 km with a bandwidth of about 3 nm.**

Keywords ¾ **Fiber optics, Optical fiber communication, pulse propagation and solitons, 160 Gb/s, Raman amplification, optical filter, iPDM.**

I. Introduction

Soliton systems have been demonstrated to be useful for single channel high-speed transmission where the pulsewidth is in the order of sub picoseconds [1-6]. At high bit rates, the transmission length (L_T) is reduced severely due to the second order reduction of the dispersion length (L_D) as a function of pulsewidth. For this reason, the operation is limited near to the zero dispersion wavelength of the fiber to reduce the dispersive wave generation. Also, the small value of L_D limits severely the amplifier spacing (L_a) to a few tens of kilometers in loss-managed average soliton [1].

Although the fiber dispersion can be reduced through the carrier selection near the zero dispersion wavelength, the relatively high value of third order dispersion (TOD) is the serious obstacle at high bit rate transmission. TOD produces a shift in the soliton position, distorts the soliton pulses, and generates dispersive waves. Also, the effect of polarization-mode dispersion (PMD) is more pronounced near the zero dispersion wavelengths [2,7]. At high bit rates, the interaction between adjacent soliton pulses is the most limiting factor due to small bit slot (*1/B*; where *B* is the bit rate) in order of sub picoseconds. The interaction would lead to jitter in the arrival time of soliton, increasing the bit error rate (BER) and giving rise to the presence of dispersive waves. In addition, the soliton self frequency shift (SSFS) is more significant, leading to spectrum broadening such that the high frequency components of a pulse can transfer energy to the low-frequency components and slow-down the pulse propagation in the anomalous-GVD regime. The strength of nonlinear interpulse interaction can be reduced by increasing the soliton pulse spacing, corresponding to pulse shortening. But, shorter pulses lead to increased third order dispersion TOD [8] and SSFS [7] effects, hence, more dispersive waves.

As a second method, interpulse interaction can be reduced by using intra-bit polarization diversity modulation (iPDM), where successive bit slots carry orthogonally polarized solitons. The nearly preserved orthogonality of two consecutive bits reduces the interpulse interaction. Reduced interpulse interaction helps to pack the soliton more tightly, reduces the bit-error-rate (BER), and increases the transmission reach [9]. In this case, the polarization mode dispersion can induce a small change in the state of polarization of the entire soliton but the soliton integrity is preserved under a small perturbation. However, the operation near to zero dispersion wavelength (small value of fiber dispersion) can violate the robustness of solitons to the fiber birefringence fluctuations, although the natural tendency of a soliton is to preserve its integrity under perturbations that affect its state of polarization [10].

In lossy transmission, the loss-induced soliton broadening leads to more interpulse interaction, jitter in the arrival time, and higher bit error rates. The loss can be managed periodically, using either lumped or distributed amplification with amplifier spacing (L_a) much smaller than L_D to manage the dispersive waves [1]. But, due to economic reasons, this condition is violated at high bit rates such as 160 Gb/s, where the dispersion length is in order of a few tens of kilometers. This violation produces significant dispersive waves that accumulate over a given number of amplifiers. The destructive effects on solitons can be well controlled using distributed Raman amplification [7], in which the loss is compensated gradually along the transmission path, reducing the power ripple. Also, the power preemphasis of fundamental soliton is reduced considerably, reducing the nonlinearity effects, maintaining the soliton width steadier,

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and reducing the accumulation of dispersive waves. However, the Raman induced spectral shift leads to considerable changes in the evaluation of solitons and modifies the gain spectrum and the dispersion experienced by solitons [11]. The spectral shift can be reduced using band limited amplifiers and optical filters that stabilize the soliton carrier frequency close to the peak of the Raman gain. The distributed scheme is realized through the nonlinear effect of stimulated Raman scattering to transfer the maximum energy at 13 THZ frequency shift of the pump, corresponding to a wavelength shift of ~100 nm for a signal at 1500 nm [1]. Among the three schemes of Raman amplification, the backward pumping is preferred economically to provide high gain where the signal is relatively weak.

The other limiting factor is the Raman amplifier noise that introduces the fluctuation in the pulse energy, converted into fluctuations in the soliton frequency through the Raman effect and generates timing jitter and dispersive waves. The noise is produced by the spontaneous Raman scattering, intrapulse Raman, Rayleigh backscattering, interpulse interactions, and cross-phase modulation (XPM) effects [7,12,13]. The noise can be reduced by band limiting filters to block the wide spectrum amplifier spontaneous emission (ASE). Moreover, optical filters can reduce the interaction between adjacent pulses through rapid soliton phase change between successive solitons. This can average out the soliton interpulse interaction by alternating the nature of the interactions force from attractive to repulsive and vice versa [11]. Also, the optical filters help in reducing the accumulation of dispersive waves through the spectrum shift of solitons, blocking the dispersive waves produced at earlier stages together with ASE. In addition, the jitter is reduced at the end of the fiber link through reducing the accumulation of GVD effect. However, the usage of optical bandpass filters leads to higher insertion losses that must be compensated by increasing the gain of optical amplifiers. More amplification gain generates additional noise, Rayleigh backscattering, intrapulse Raman and more pronounced SSFS at high bit rates. Also, the passband of filters widens at higher bit rates, enhancing the accumulation of non-filtered noise, which deteriorates the SNR and reduces severely the transmission reach.

In this article the previously described techniques are applied to enhance the transmission length or improve the bit error rate for a given L_T. The article is organized as follows. In section II the theoretical model of transmission is presented. Then, in section III the results of transmission simulations of a single solitonic channel at 160 Gb/s is explained, demonstrating the effect of iPDM, spectral fixed-frequency filters, fiber dispersion value, and the comparison of lumped and distributed amplifications. We show the reach enhancement of soliton transmission at 160 Gb/s soliton pulses to 525 km, maintaining the BER at 10^{-9}. Longer transmission length could be obtained using dispersion management techniques with short periods of the dispersion map, in order of tens of meters [14]. Finally, we study the effect of input pulsewidth on reach of the system. At the final section the conclusion is presented.

II. Theoretical model of transmission

The simulated communication system includes a model of transmitter, optical fiber, and the receiver [15]. The transmitter is composed of a generator of a train of chirp-free hyperbolic-secant pulses at 40 GHz. The pulse streams are modulated by a pseudo-random bit sequence in non-return-to-zero (NRZ) format, produced by a pseudo-random binary sequence pattern generator (PRBS) with pattern-length of 10^7 bits. The output of the modulator is a train of return-to-zero (RZ) optical pulses. Using the optical time division multiplexing (OTDM) technique [5,8] the output of four modulators are multiplexed with orthogonal polarizations, generating a train of solitons at 160 Gb/s. The pulses are applied to the link consisting of 25 km dispersion-shifted fiber (DSF) as the Raman amplification path. The characteristics of a typical fiber are shown in table I.

The computational model for the back-propagating Raman amplifier provides the time averaged power evolution of the soliton and the noise, Also, it considers the effect of spontaneous Raman scattering and its temperature dependence, Rayleigh scattering with multiple reflections, and stimulated Raman scattering (SRS) [15]. Also, the response of Raman amplifier is considered as instantaneous. The obtained Raman gain is incorporated into the nonlinear Schrödinger (NLS) equation. The signal power variation along the transmission is obtained by solving the NLS equation, using Split-step Fourier method [1]. The desired transmission length is obtained through multiple signal traveling in the given optical fiber. At the receiver end, the equivalent electrical signal is obtained through modeling a PIN photo detector. An active electrical lowpass filter is used with Bessel format of fifth order and 3dB bandwidth of 0.57 × 160 GHz to limit the noise and finally the output NRZ bit stream is produced by a comparator. The BER is calculated from the eye opening of output bit streams in comparison to the initial NRZ PRBS bit train using the Monte Carlo method.

TABLE I. PARAMETERS USED IN SIMULATION.

Parameter	Symbol (unit)	Value
Dispersion Slope	S (ps/km. nm^2)	0,075
Zero Dispersion wavelength	?$_0$ (nm)	1550
Nonlinear refractive index	n_2 (m^2/W)	2,7×10^{-20}
Fiber core diameter	d (μm)	6,6
Effective area	A_{eff} (μm^2)	50
Amplification length	L_a (km)	25
Fiber loss at signal wavelength	α (dB/km)	0,203
Dispersion coefficient	ß$_2$ (ps^2 /km)	-0,048 / -0,115
Rayleigh loss	Γ (km^{-1})	6.62×10^{-5}

III. Simulation results

Table II shows the simulated systems of single channel soliton transmission at 160 Gb/s. The operation is designed near the zero dispersion wavelengths at two positions with group velocity dispersion of -0,048 and -0.115 ps^2/km, to study the effect of dispersion. Three different pulsewidths are selected as 1.3, 1.5, and 1.7 ps, to study the q_0 factor effect (normalized spacing between neighboring solitons) on the reach and BER of the transmission system. For systems #1, #5 and #12, the loss is managed by Erbium doped fiber amplifiers (EDFA) with 3 dB bandwidth of 30 nm, noise figure of 4.8 dB, and the gain saturation effect is not considered. The power preemphasis of soliton power is about 1.7 in lossy system #1 and #5 that should be enhanced to compensate for the insertion loss of band limited filters (system #12). The loss management of other systems is based on the Raman amplification scheme, considering continuous-wave (CW) pump laser. The Raman on-off gain ($G_{on\text{-}off}$) is 5.077 dB, pump wavelengths are 1452 nm, and 1452.6 nm for signal wavelength of 1550.5 and 1551.2 nm, and the fiber loss at pump wavelength is about 0.247 dB/km. The power preemphasis of solitons is about 1.13 obtained by the iterative 4th order Runge-Kutta method [16]. The effect of iPDM is studied through the comparison of systems #1 with #5, with lumped amplification scheme and systems #3 with #4 or systems #7 with #8 with optical filter at every amplification length or systems #9 with #14 at a channel with less group velocity dispersion. The effect of optical filter is studied through the comparison of systems #5 with #12, with lumped amplification or systems #3 with #7, with distributed amplification. The optimized filter position is found through the comparison of systems #10, #11, and #14.

TABLE II. SYSTEMS CONFIGURATION USED IN SIMULATIONS.

System	β_2 (-ps^2/km)	T_{FWHM} (ps)	Amplification method	iPDM	Filter
1	0,048	1,5	EDFA	-	-
2	0,048	1,5	Raman	-	-
3	0,115	1,5	Raman	-	-
4	0,115	1,5	Raman	Yes	-
5	0,048	1,5	EDFA	Yes	-
6	0,048	1,5	Raman	Yes	-
7	0,115	1,5	Raman	-	L_f=L_a
8	0,115	1,5	Raman	Yes	L_f=L_a
9	0,048	1,5	Raman	-	L_f=L_a
10	0,048	1,5	Raman	Yes	L_f=3L_a
11	0,048	1,5	Raman	Yes	L_f=2L_a
12	0,048	1,5	EDFA	Yes	L_f=L_a
13	0,048	1,7	Raman	Yes	L_f=L_a
14	0,048	1,5	Raman	Yes	L_f=L_a
15	0,048	1,3	Raman	Yes	L_f=L_a

Fig. 1 shows the reach of the systems listed in Table II. As it can be seen the reach is very small (around 100 km) for system #1 due to the large effects of SSFS, TOD and relatively large value of GVD dispersion, giving rise to dispersive waves and interpulse interaction. The transmission reach is improved if we use distributed Raman amplification as shown for system #2. The improvement is explained through reduced variation of signal power in distributed scheme. The transmission length is enhanced a little by using a channel with smaller GVD dispersion as obtained for System #3. The iPDM technique improves the reach considerably due to the reduction of interpulse interaction (system #4). More improvement is due to the smaller GVD at a channel near the zero dispersion, as obtained for the system #6, applying distributed amplification and iPDM techniques. For smaller GVD, the dispersion length is increased, the generation of dispersive waves is reduced, and the input soliton power is diminished, hence, the nonlinear effects are less pronounced. However, the effect of TOD is more pronounced near the zero dispersion wavelength (λ_0). It is verified through the simulation of transmission system #2, assuming zero TOD (β_3= 0). The results show that the reach is improved to 320 km. Moreover, it can be verified that the effect of iPDM technique is more significant in low dispersion channels through the comparison of system #4 with #6 or #8 with #14. The reach is enhanced considerably by optical filtering at every amplification length, which can be verified by comparing system #3 with #7, #4 with #8, or #6 with #14.

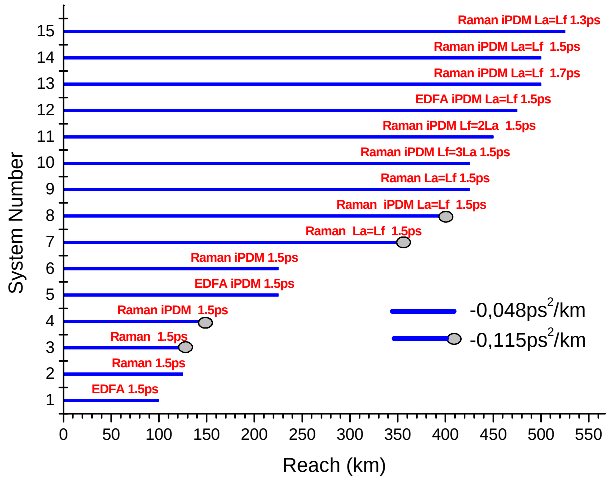

Fig. 1. Simulated transmission reach for several optical soliton systems considering the effect of amplification model, iPDM, optical filtering, GVD dispersion, and pulsewidth.

More simulations on the effect of optical filtering show that the optimum filter bandwidth is about 2.97 nm, as shown in Fig. 2. This bandwidth is approximately equivalent to the spectral bandwidth of 1.5 ps optical pulses, that is necessary to maximize the noise filtering. Although a narrower filter can further reduce the noise, its impact on the solitonic shape degrades the reach of the system.

The effect of filter allocation is verified by looking at systems #10, #11, and #14 with filtering length L_F= 3L_a, L_F= 2L_a, and L_F= L_a, respectively. The best result is obtained for system #14 with filtering repetition every amplification length. We observed the reach degradation of about 10%, if we change the amplification method to lumped one (system #12). Therefore, optical filtering can enhance the reach of system #3 (~130 km) to more than 350 km (~170% enhancement), system #4 (~150 km) to more than 400 km (~166% enhancement), and system #2 (~130 km) to 425 km (~227% enhancement). As it can be seen in Fig. 2, the optimum bandwidth of optical filter applied to systems #9 is narrower than the one used in system #14. The Narrower bandwidth is required to remove the dispersive waves generated through interpulse interaction, the problem that is solved through the iPDM technique.

The effect of pulsewidth on transmission reach is studied using the simulation systems #13, #14, and #15 with 1.7, 1.5, and 1.3 ps, respectively. It is observed that the maximum reach of 525 km is obtained for narrowest pulsewidth due to smaller interpulse interaction. However, further reduction of pulsewidth increases the required input power, leading to more nonlinear effect, and increases the effect of SSFS, TOD, producing more dispersive waves and reducing the transmission length as verified for system #15.

Considering the variation of the dispersion coefficient, the results indicate that the channels of lower dispersion present better performance. This can be verified through the comparison of intrabit polarization multiplexed train of solitons with Raman amplification in system #4 and #6, periodically filtered in distributed amplification scheme in system #7 with #9 and #8 with #14 when the periodic orthogonal polarization technique is additionally used.

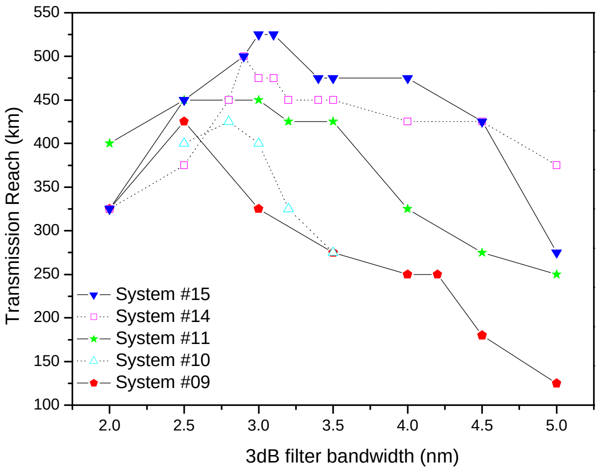

Fig. 2. Reach optimization as a function of Bandwidth of optical filter for several system of 160 Gb/s soliton transmission.

Also, it can be observed that there is not a significant improvement of the system performance by alteration of the model of loss management when periodic filtering or iPDM techniques are implemented. It can be verified through the comparison of system #5 with #6 or #12 with 14. Therefore, the main technique to improve the transmission quality or transmission reach is the periodical optical filtering with band limited to the bandwidth of pulse train.

Moreover, the effect of the cited techniques on the bite error rate is verified. For this purpose, the eye diagram of a 250 km 160 Gb/s soliton transmission is obtained as shown in Fig. 3. Fig. 3-a shows the eye diagram of system #2 as a basic transmission system without applying iPDM and optical filtering. In this case, the eye diagram is closed, equivalent to high rate of errors, because the soliton is unable to sustain itself due to excess timing jitter. Considerable enhancement is obtained by using iPDM technique, bandpass optical filters, and a better technique of loss compensation as illustrated in Fig. 3-b to 3-f. The BER is improved by using the iPDM technique, although the lumped amplification scheme is used (Fig. 3-b). Substitution of lumped amplification method by the distributed one does not change considerably the BER of system #5, which can be verified by comparing Fig. 3-b with -c. Considerable improvement of transmission is obtained using iPDM or optical filter technique individually (comparison of Fig 3-a with -c or -d). The simultaneous use of iPDM technique and optical filtering improves considerably the Eye diagram (comparison of Fig. 3-a with Fig. 3-e or -f). The eye diagram is optimized through the reduction of filtering length (comparison of Fig 3-e ($L_F = 3L_a$) with Fig. 3-f ($L_F = L_a$)).

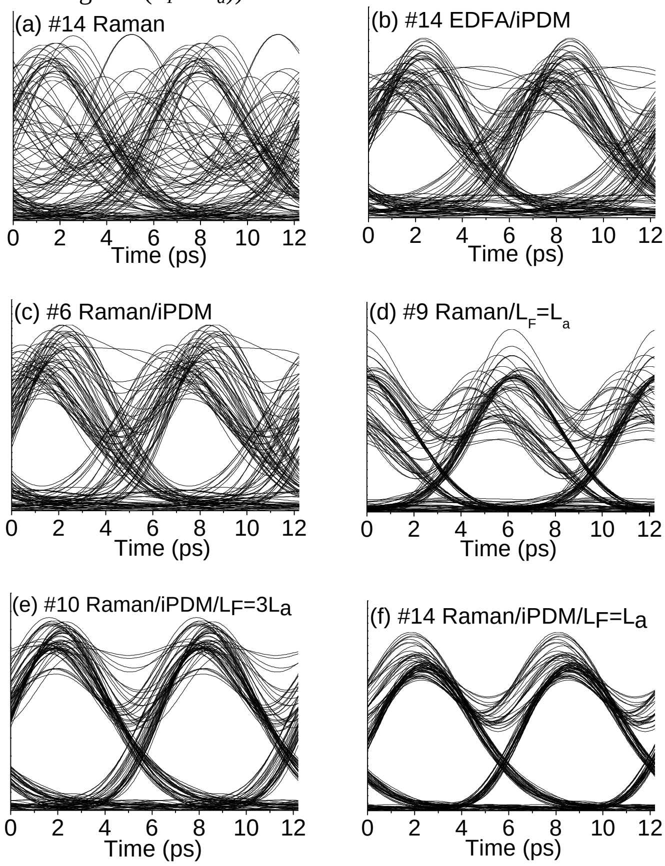

Fig. 3. Eye diagrams of 160 Gb/s signal transmitted at 250 km for different system configurations described in Table II. a) system #2, b) system #5, c) system #6, d)system #9, e) system #10, f) system #14.

IV. CONCLUSIONS

The numerical simulations of the single channel soliton transmission at 160 Gb/s through a lossy fiber with amplification length of 25 km was presented with maximum error free transmission of 100 km. The considerable dispersive wave generation was the reason of operation near to the zero dispersion wavelength. The results demonstrate the enhancement of performance using counter-propagating Raman pump, narrow bandwidth optical filter, and iPDM, enhancing the transmission length to 525 km. These techniques help to reduce the dispersive wave generation along the soliton transmission, decrease the interpulse interaction, and remove the excess noise generation, enhancing the BER for a given transmission length. The filter spacing is optimized at 25 km with bandwidth of 3 nm.

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