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Significance of prechirping on long-haul path-averaged soliton impulse in re-circulating loop at 10 and 20 Gb/s with TOD

Manoj Kumar[a,1], Ajay K. Sharma[b,*], T.S. Kamal[c]

[a] DAV Institute of Engineering and Technology, Jalandhar 144008, Punjab, India
[b] National Institute of Technology (Deemed University), Jalandhar 144011, Punjab, India
[c] Sant Longowal Institute of Engineering and Technology, Longowal 148106, Punjab, India

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Abstract

In this paper, we have investigated the performance of first- and second-order path-averaged soliton long-haul transmission link including the impact of third-order dispersion (TOD) at varied chirp. Here, the varied chirp is considered keeping in view the inadvertent frequency chirp imposed on all practical sources of short optical pulses. The propagation of strongly chirped pulses in loss-managed long-haul path-averaged soliton transmission network has been shown. The investigations reveal that in first-order ($N=1$) path-averaged soliton transmission link at 10 and 20 Gb/s, SPM effect on the rising and falling edges of a pulse results in spectral broadening for all values of induced chirp. On the contrary, spectral narrowing of the pulses is observed in second-order negatively chirped path-averaged soliton pulses. The effect of the nonlinearity changes from narrowing to broadening of pulses if the sign of the initial chirp is changed to positive. The results ascertain that the system is capable of transmitting a pulse up to the distance of 24,500 km at bit rates of 10 and 20 Gb/s. Investigations have been carried out by varying the chirp factor in the range −1 to 1 and −1 to 0.4] for 10 and 20 Gb/s, respectively, to demonstrate the robustness of the long-haul soliton link. The observations establish that the pulse width (full-width at half-maximum (FWHM)) remains within the optimal range even at the transmission distance of 24,500 km without and at discrete values of the chirp factor.

Keywords: Path-averaged soliton; Long-haul transmission; Prechirping; TOD

1. Introduction

Optical soliton transmission is one of the most attractive techniques for future optical communication systems because of its potential of long-haul and/or high bit-rate communication. Rapid progress in lightwave communications is stimulated by increasing demand for telecommunication services. In the recent years, impressive results have been achieved in ultra-long high-bit-rate optical communications using both the linear transmission concept [1] and the soliton-based optical signal transmission [2]. The term “linear concept” is used here for the methods that overcome the detrimental effects of nonlinearity and dispersion without balancing them as in the soliton approach.

Typical designs of soliton long-haul lightwave communication systems involve continual balance along its

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[*] Corresponding author.
E-mail addresses: mk_daviet@rediffmail.com (M. Kumar), sharmaajayk@rediffmail.com (A.K. Sharma).
[1] Tel.: +91 181 220 0126; fax: +91 181 220 7650.

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path between the dispersive and nonlinear Schrodinger equation allowing for uniform cancelation of signal attenuation using periodically installed in-line erbium-doped fiber optical amplifiers [3,4]. The important feature of such systems is that the amplifier spacing is considerably shorter than the characteristic dispersion and nonlinear lengths and, therefore, both dispersion and nonlinearity can be treated as perturbations on the scale of one amplification period. In the leading order, only fiber loss and periodic amplification are significant factors affecting the pulse evolution between two consecutive amplifiers. These factors cause the power oscillations, while the form of the pulse approximately remains unchanged. On larger scales, nonlinearity and dispersion come into play and the pulse propagation in such communication systems is described by the well-established path-average (guiding-center) soliton theory. In every soliton transmission system, the pulse parameters suffer an initial rapid transient and then a smooth monotonic trend with a ripple superimposed. The physical mechanisms that govern the transient and the ripple show that these behaviors are due to an incorrect choice of the starting parameters of the soliton. The understanding of such mechanisms suggests a way to increase both the quality of the transmission and the amplifier spacing and leads to a generalization of the concept of path-average soliton [5–8]. The path-averaged soliton regime (PASR [9–13]) allows large amplifier gains and provides good stability. It has been shown that solitons can maintain their shape in periodically amplified fiber links if amplifier spacing L_A is kept smaller than fiber dispersion length L_D.

For high-speed optical soliton communication, data transmission reliability can be degraded by some or all of the system impairments, resulting in a quality of service that is lower than that demanded by the system's specifications. Prechirping is one of the important techniques used to employ pre-compensation. Pre-compensation schemes are based on the idea of modifying the characteristics of the input pulses at the transmitter before being launched into the optical fiber so that the dispersion negates the applied pre-compensation and an undistorted signal results at the receiver. Prechirping is the process of appropriately phase modulating the light carrier in order to compensate for the pulse width broadening that would otherwise result from the chromatic dispersion of the optical fiber. In the 1550 nm band, conventional optical fibers suffer from anomalous dispersion, that is, longer wavelengths have a lower group velocity than shorter wavelengths. In this case, the spreading of the bit into adjacent slots can be delayed by making the light in the leading edge of the pulse of longer-than-average wavelength and that in the trailing edge of the bit to be of shorter-than-average wavelength. As a result, the pulse initially becomes narrower as it travels along the fiber, which means that the allowable transmission length for a system with prechirp is greater than that of a system with an ideal external modulator. However, further transmission causes the pulses to broaden again and intersymbol interference results. Therefore, it is very important to study the impact of chirp on the optical soliton transmission systems. In [14], it has been presented that the concept of prechirping for constant dispersion fibers allows both width and chirp of the soliton to vary in each fiber section between two amplifiers.

A soliton is fully described by four parameters of the time domain: peak amplitude, phase, chirp and temporal width. Once all the contributions that concur to the pulse evolution and distortion have been individualized, the evolution of the parameters, and hence of the soliton, along the amplified line can be predicted. In this work, we have studied the impact of chirp parameter because it is well known that it plays an important part in the evolution of all other pulse parameters along the fiber.

In this paper, the investigations have been carried out without and with varied chirp at the optical source itself, although no separate technique for prechirping has been used. Pulse width (FWHM) and pulse evolution for first- and second-order ($N = 1$ and 2) single soliton pulses for path-averaged transmission links at 10 and 20 Gb/s for 24,500 km at a chirp factor in the range -1 to 1 and -1 to 0.4, respectively, have been presented. The optimum value of chirp for loss-managed long haul have been obtained keeping in view the inadvertent frequency chirp imposed on all practical sources of short optical pulses. The observations establish that the pulse width (FWHM) remains within the optimum range even at the transmission distance of 24,500 km.

After the introduction in Section 1, Section 2 presents the system description. The results are discussed in Section 3 and the final concluding remarks are given in Section 4.

2. System description

Here, the system demonstrates the robustness of the PASR in fiber link with loss and periodical amplification up to 24,500 km including third-order dispersion (TOD). The PASR for a single soliton pulse passing through a chain of amplifiers forming loss-managed soliton link with 10 and 20 Gb/s optical signal was created. Here, the amplifier gain is considered as $G = \exp(\alpha L_A)$, and then the enhancement factor for loss-managed soliton can be derived as

$$f_{LM} = \left[\frac{1}{L_A}\int_0^{L_A} \exp(-\alpha z)\,dz\right]^{-1} = \frac{\alpha L_A}{1-\exp(-\alpha L_A)} = \frac{G \ln G}{G-1}. \tag{1}$$

In the system that we realized for carrying out simulations for loss-managed, long-haul optical soliton transmission link of 24,500 km comprised 70 amplifiers inserted after every 350-km span of a dispersion-shifted fiber (DSF). At the transmitter an optical pulse source is a mode-locked laser generating a single pulse of "sech" shape with $u(t) = \operatorname{sech}(t/T_0)$, $T_{\mathrm{FWHM}} = 2T_0 \ln(1+\sqrt{2})$ (full-width at half–maximum (FWHM)) and specified power and width. The NRZ format was used here since it requires less bandwidth both for transmitter as well as for receiver. The linear chirp was included via a chirp factor C and the results were obtained by varying it from -1 to 1 and -1 to 0.4 for first- and second-order ($N = 1$ and 2) single soliton pulse evolution at a bit rate $B = 10$ and 20 Gb/s, respectively. The expression for the field amplitude of a chirped pulse $u_{\mathrm{chirp}}(t)$ is given by

$$u_{\mathrm{chirp}}(t) = u(t)\exp\left(-j\frac{C}{2T_0^2}T^2\right) \tag{2}$$

and the expression for the additional spectral width due to pulse chirp is given by

$$\Delta\lambda = 2\left[\left(\frac{1}{\lambda_0} - \frac{C}{4\pi c T_0}\right)^{-1} - \lambda_0\right]. \tag{3}$$

The re-circulating loop was constructed by using a 350-km long DSF and an EDFA. A spectrum analyzer is connected at the end of a re-circulating loop to observe the output power spectrum. The output from loop was inserted into a property map analyzer that produced maps of dispersion and power along a fiber soliton transmission link.

In our system setup, we have considered that the fiber loss $\alpha = 0.2$ dB/km and amplifier spacing L_{A} is 350 km. Hence, gain $G = 70$ dB and enhancement factor $f_{\mathrm{LM}} = 16.12$. Second- and third-order fiber dispersion parameters are $\beta_2 = -0.2178\,\mathrm{ps}^2/\mathrm{km}$ and $\beta_3 = 0.0745\,\mathrm{ps}^3/\mathrm{km}$ and nonlinear coefficient $\gamma = 1.75\,\mathrm{e}^{-31}/\mathrm{m/W}$, and input pulse width $T_0 = 14.18$ ps and $\lambda = 1550$ nm will provide second- and TOD lengths as [15]

$$L_{\mathrm{D}_{\beta_2}} = \frac{T_0^2}{|\beta_2|} \approx 923\,\mathrm{km},\quad L_{\mathrm{D}_{\beta_3}} = \frac{T_0^3}{|\beta_3|} \approx 38{,}297\,\mathrm{km} \tag{4}$$

and soliton peak power $P_0 = 6.197$ mW. The launched peak power will be $(f_{\mathrm{LM}} \times P_0)$, and thus soliton evolution in lossy fibers with periodic lumped amplification is identical to that in lossless fibers with launch power P_0 providing $L_{\mathrm{A}} < L_{\mathrm{D}}$. The dominant nonlinear fiber parameters considered during simulation are the Kerr nonlinearity coefficient:

$$\gamma = \frac{n_2\omega_0}{cA_{\mathrm{eff}}}. \tag{5}$$

For the fixed values of nonlinear refractive index

$$n_2 = 2.6 \times 10^{-20}\,\mathrm{m}^2/\mathrm{W},$$
$$\omega_0/c = 2\pi/\lambda = 2\pi/1.55 \times 10^{-6}\,\mathrm{m}^{-1},\ A_{\mathrm{eff}} = 60.31\,\mu\mathrm{m}^2. \tag{6}$$

3. Results and discussion

The investigations have been carried out at bit rate $B = 10$ and 20 Gb/s for the first- and second-order path-averaged soliton pulse without and with varied chirp factor C ranging from -1 to 1 and -1 to 0.4, respectively, for the transmission distance of 24,500 km. The measurements recorded for pulse width (FWHM) range in the path-averaged soliton regime measured along the propagation distance of 24,500 km at 10 and 20 Gb/s for $N = 1$ and 2 have been recorded in Table 1.

It is important to investigate the performance of optical soliton transmission at varied chirp factors because the initial chirp can be detrimental to soliton propagation simply because it disturbs the exact balance between the GVD and SPM [16]. Chirp has generally been avoided in NRZ systems because it increases the optical bandwidth and hence the effects of GVD. However, recently, phase modulation prior to launch, which is similar to chirp, has been used as a countermeasure against the deleterious effects of fiber nonlinearity [17].

3.1. Case 1: 10 Gb/s soliton transmission link

The system was modeled for the transmission rate at 10 Gb/s capable of transmitting up to the distance of 24,500 km with and without initial chirp at pulse width (FWHM); $T_{\mathrm{FWHM}} = 25$ ps. Fig. 1(a)–(g) indicates the pulse width (FWHM) for first-order ($N = 1$) path-averaged soliton transmission link at 10 Gb/s for 24,500 km at chirp factor of $C = -1$, -0.7, -0.5, 0, 0.5, 0.7 and 1 respectively. It has been observed that the soliton pulse remains intact maintaining its pulse width (FWHM), which stays within the range 25–27 ps without initial chirp, i.e. chirp factor $C = 0$. It has been shown in Fig. 1 that there is initial pulse compression due to fiber nonlinearity on the pulse propagation for fundamental soliton ($N = 1$) at zero and positive values of chirp, while there is no initial pulse compression at negative values of chirp. At negative values of chirp, viz. $C = -1$, -0.7 and -0.5 the pulse width (FWHM) falls within the range 25–88, 25–52 and 25–41 ps, respectively [see Fig. 1(a)–(c)]. At positive values of chirp, viz. $C = 0.5$, 0.7 and 1.0, the pulse width (FWHM) falls within the range 25–53, 25–78 and 25–170 ps, respectively [see Fig. 1(e)–(g)]. SPM effect on the rising and falling edges of a pulse results in spectral broadening for all values of induced chirp except at $C = 0$, which has

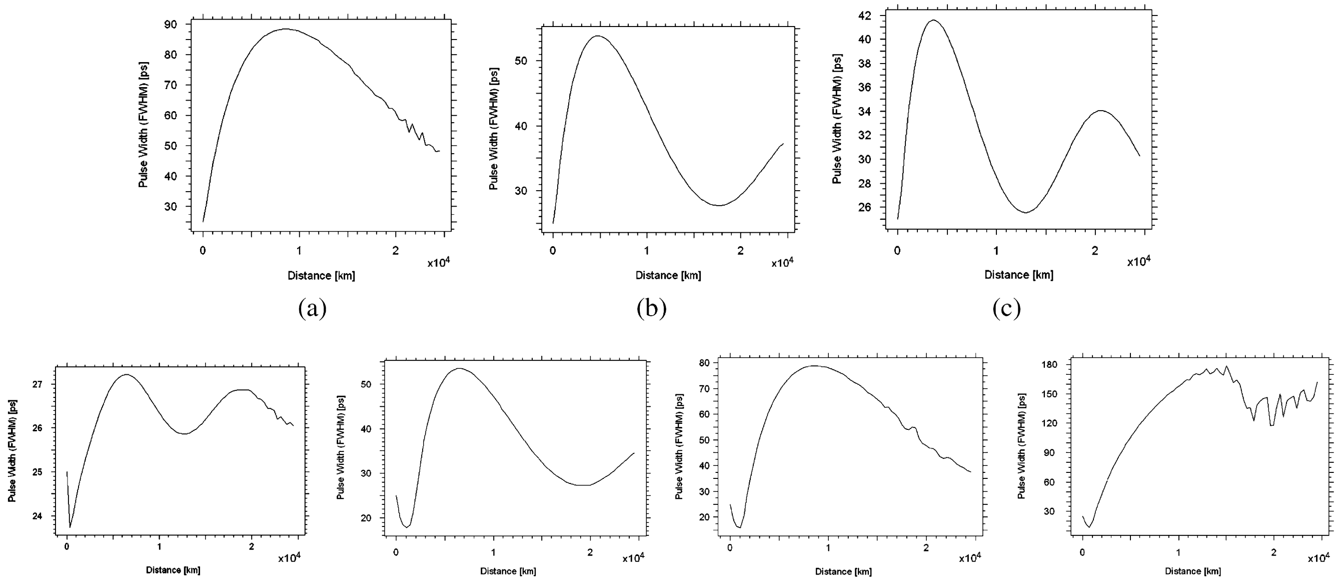
Table 1. Pulse width (FWHM) range in the path-averaged soliton regime at 10 and 20 Gb/s for $N = 1$ and 2

Chirp factor	FWHM range (ps)	(24,500 km)	FWHM range (ps) measured along the propagation distance of 24,500 km				
Bit rate $B = 10$ Gb/s							
$N = 1$; $T_{\mathrm{FWHM}} = 25$ ps							
$C = -1$	25–88	Distance (km)	0–10,000	10–20,000	20–24,500	–	–
		FWHM (ps)	25–88	88–55	55–45	–	–
$C = -0.7$	25–52	Distance (km)	0–5000	5–10,000	10–15,000	15–20,000	20–24,500
		FWHM (ps)	25–54	54–40	40–29	29–27	27–37
$C = -0.5$	25–41	Distance (km)	0–4000	4–13,000	13–20,000	20–24,500	–
		FWHM (ps)	25–41	41–25	25–34	34–30	–
$C = 0$	25–27	Distance (km)	0–6000	6–24,500	–	–	–
		FWHM (ps)	25–27	27–26	–	–	–
$C = 0.5$	25–53	Distance (km)	0–7000	7–20,000	20–24,500	–	–
		FWHM (ps)	25–53	52–27	27–33	–	–
$C = 0.7$	25–78	Distance (km)	0–8000	8–20,000	20–24,500	–	–
		FWHM (ps)	25–78	78–47	47–35	–	–
$C = 1$	25–170	Distance (km)	0–16,000	16–24,500	–	–	–
		FWHM (ps)	25–170	70–120	–	–	–
$N = 2$; $T_{\mathrm{FWHM}} = 25$ ps							
$C = -1$	25–13	Distance (km)	0–20,000	2–24,500	–	–	–
		FWHM (ps)	25–16–22	20–12–24	–	–	–
$C = -0.7$	25–11	Distance (km)	0–18,000	18–24,500	–	–	–
		FWHM (ps)	25–17	17–22–11	–	–	–
$C = -0.5$	25–11	Distance (km)	0–15,000	15–24,500	–	–	–
		FWHM (ps)	25–27–14	14–11–25–18	–	–	–
$C = 0$	25–70	Distance (km)	0–3000	Pulse broadens and then splits into multiple pulses moving outward			
		FWHM (ps)	25–70				
$C = 0.5$	25–27	Distance (km)	Pulse splits into multiple narrow pulses and forms a large number of pig tails				
		FWHM (ps)					
Bit rate $B = 20$ Gb/s							
$N = 1$; $T_{\mathrm{FWHM}} = 12.5$ ps							
$C = -1$	12.5–32.5	Distance (km)	0–2000	2–5000	5–24,500	–	–
		FWHM (ps)	12.5–32.5	32.5–18	18–23–15–24	–	–
$C = -0.4$	12.5–22	Distance (km)	0–15,000	15–20,000	20–24,500	–	–
		FWHM (ps)	12.5–21.5	21.5–15	14–21	–	–
$C = 0$	12.5–23	Distance (km)	0–2000	2–24,500	–	–	–
		FWHM (ps)	12.5–21.5	21.5–18	–	–	–
$C = 0.2$	12.5–32	Distance (km)	0–3000	3–7000	7–24,500	–	–
		FWHM (ps)	12.5–32	32–18	18–24	–	–
$C = 0.3$	12.5–48	Distance (km)	0–4000	4–10,500	10.5–24,500	–	–
		FWHM (ps)	12.5–48	48–12		–	–
$C = 0.4$	12.5–80	Distance (km)	0–5000	5–8000	8–24,500	–	–
		FWHM (ps)	12.5–80	80–12.5	12.5–40	–	–

also been reported in [18]. In case of a fundamental soliton ($N = 1$), the optimum value of pulse width (FWHM) is obtained at zero chirp.

Fig. 2 demonstrates first-order ($N = 1$) path-averaged single soliton pulse evolution over 70 amplifier spans in a re-circulated loop setup – each span consisting of 350-km fiber and amplifier. The results have been obtained over a transmission link of 24,500 km at a bit rate of 10 Gb/s at a varied chirp factor of $C = -1$, -0.7, -0.5, 0, 0.5, 0.7 and 1. It has been observed that the best results for first-order ($N = 1$) path-averaged single soliton pulse evolution are obtained for chirp factor $C = 0$ and the acceptable values of chirp factor range from -0.7 to 0.5 during which soliton pulse remains stable. As the chirp factor increases from 0.5 to 0.7, a part of the energy is shed as dispersive wave during the process of soliton transmission because all the input energy is not contained within the soliton pulse.

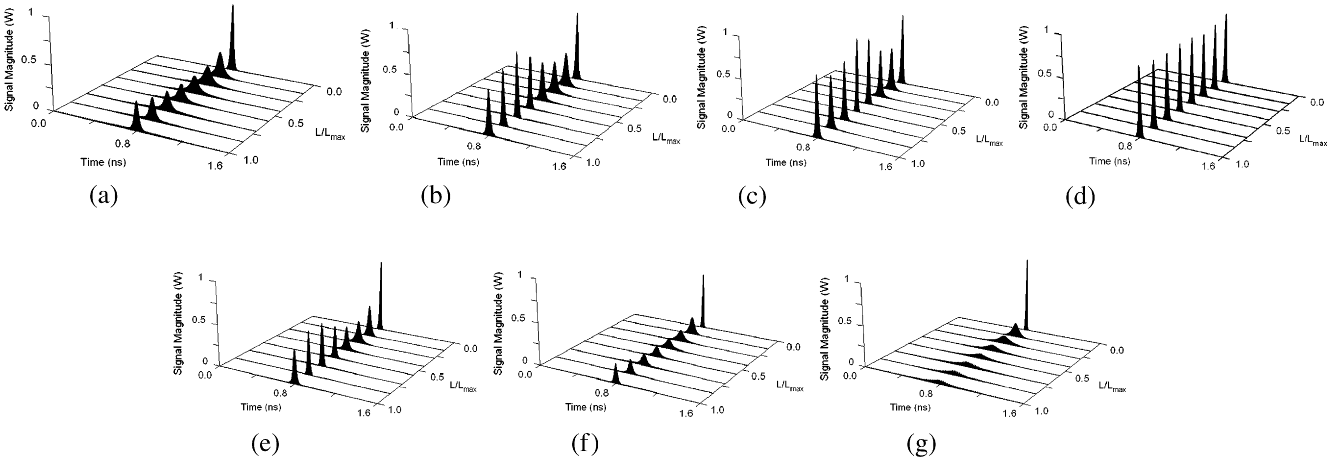
Fig. 3(a)–(e) indicates the pulse width (FWHM) for second-order ($N = 2$) path-averaged soliton transmission



(a) (b) (c)

(d) (e) (f) (g)

Fig. 1. Pulse width (FWHM) for path-averaged soliton ($N = 1$) transmission link at 10 Gb/s for 24,500 km at (a) $C = -1$, (b) $C = -0.7$, (c) $C = -0.5$, (d) $C = 0$, (e) $C = 0.5$, (f) $C = 0.7$ and (g) $C = 1$.



(a) (b) (c) (d)

(e) (f) (g)

Fig. 2. Evolution of first-order ($N = 1$) path-averaged single soliton pulse over a transmission link of 24,500 km at bit rate 10 Gb/s at varied chirp factor(s) (a) $C = -1$, (b) $C = -0.7$, (c) $C = -0.5$, (d) $C = 0$, (e) $C = 0.5$, (f) $C = 0.7$ and (g) $C = 1$.

link at 10 Gb/s for 24,500 km at a chirp factor of $C = -1$, -0.7, -0.5, 0 and 0.5, respectively. It is observed from Fig. 3 that there is initial pulse compression due to fiber nonlinearity at all values of chirp ($C = 0$, <0, >0) as the effect of SPM is more predominant in case of higher order solitons with $N = 2$ and above. At negative values of chirp, viz. $C = -1$, -0.7 and -0.5, the pulse width (FWHM) falls within the range 25–11 ps [see Fig. 3(a)–(c)]. Our investigations reveal that on the contrary for $N = 2$, the SPM results in spectral narrowing of the optical spectrum for negatively chirped pulses.

The negative chirp imposed on second-order path-averaged soliton pulse evolution results in keeping the pulse width (FWHM) remarkably controlled and narrow which makes it suitable for transmission over long haul at a bit rate of 10 Gb/s. In Fig. 3(d) and (e), we show that the effect of the nonlinearity changes from narrowing to broadening of pulses if the sign of the initial chirp is changed to positive. At chirp factor $C \geqslant 0$, the pulse width (FWHM) does not fall in the optimum range unlike in the case of negatively chirped soliton pulses.

Fig. 4 demonstrates second-order ($N = 2$) path-averaged single soliton pulse evolution. The results have been obtained over a transmission link of 24,500 km at a bit rate of 10 Gb/s at a varied chirp factor of $C = -1$, -0.7, -0.5, 0 and 0.5. It has been observed that the best

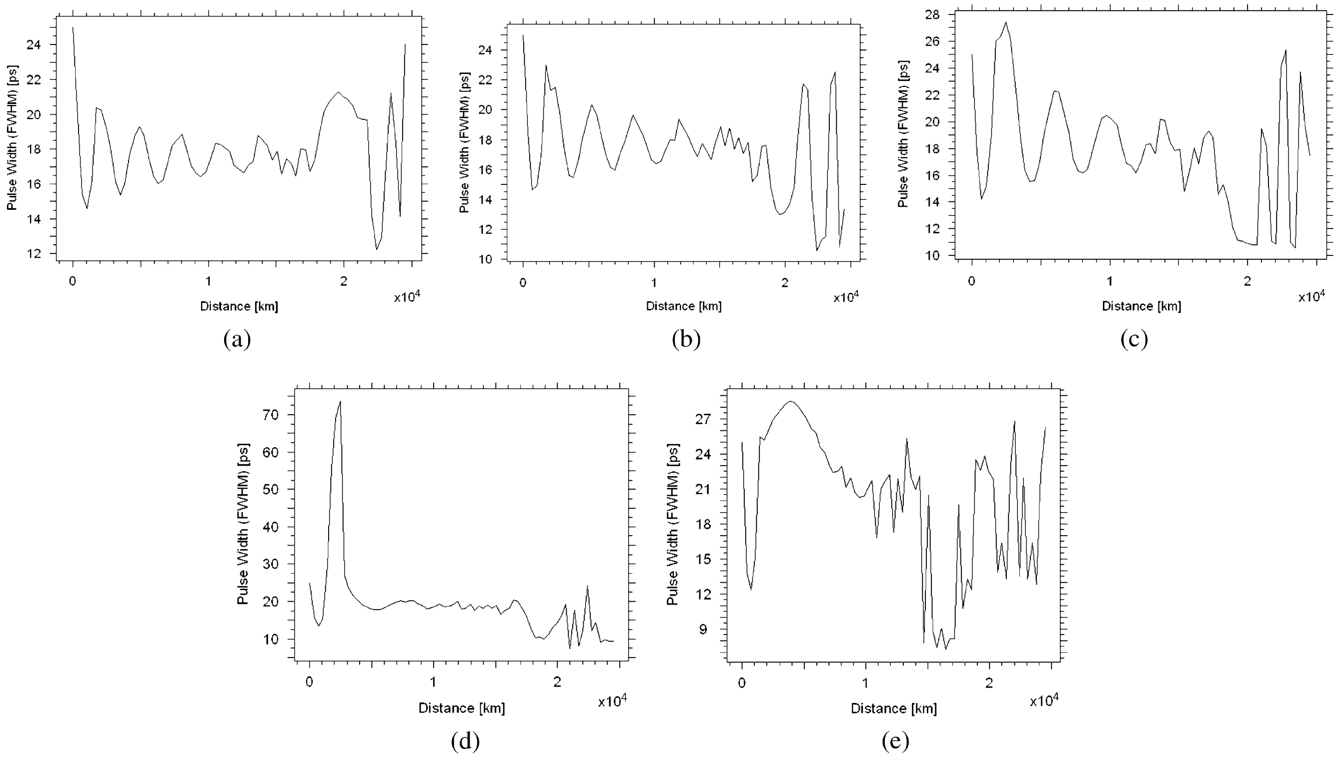


Fig. 3. Pulse width (FWHM) for path-averaged soliton ($N = 2$) transmission link at 10 Gb/s for 24,500 km at (a) $C = -1$, (b) $C = -0.7$, (c) $C = -0.5$, (d) $C = 0$ and (e) $C = 0.5$.

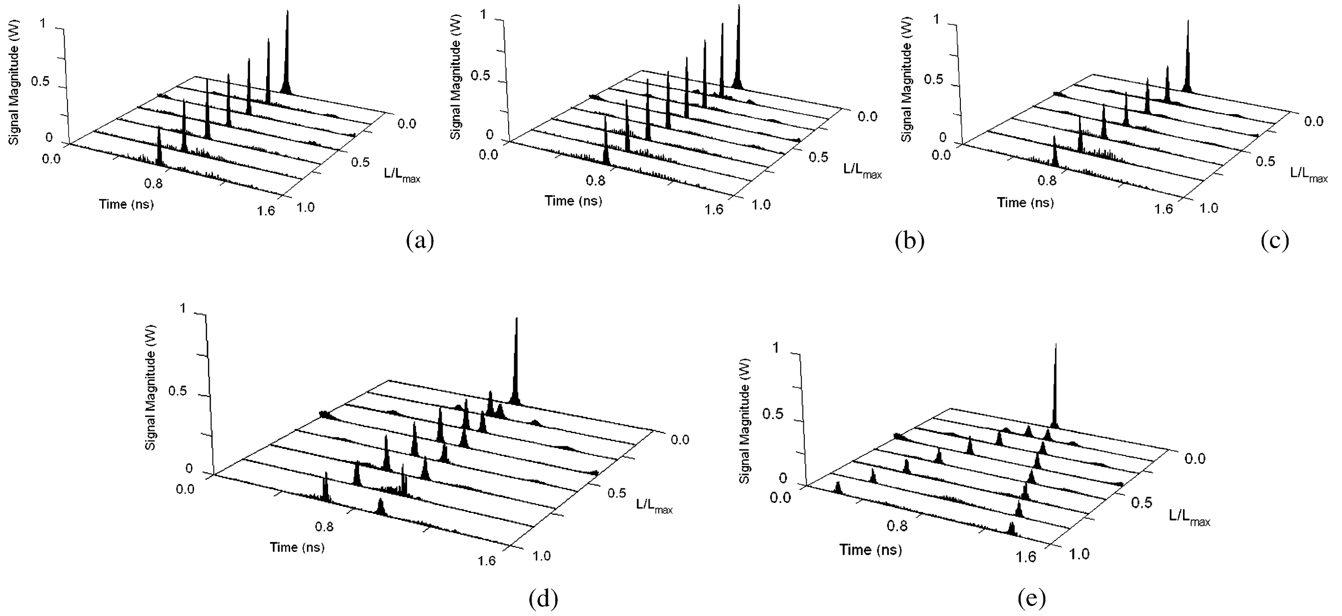


Fig. 4. Evolution of second-order ($N = 2$) path-averaged single soliton pulse over a transmission link of 24,500 km at bit rate 10 Gb/s at varied chirp factor(s) (a) $C = -1$, (b) $C = -0.7$, (c) $C = -0.5$, (d) $C = 0$ and (e) $C = 0.5$.

results for second-order ($N = 2$) path-averaged single soliton pulse evolution are obtained for negative chirp i.e. $C<0$ as observed from Fig. 4(a) and (b). For chirp factor $C \geqslant 0$, the pulse broadens and splits into multiple pulses moving outward.

3.2. Case 2: 20 Gb/s soliton transmission link

In this case, system was modeled for the transmission rate of 20 Gb/s capable of transmitting up to the distance of 24,500 km with and without initial chirp at pulse width (FWHM); $T_{\mathrm{FWHM}} = 12.5\,\mathrm{ps}$. Fig. 5(a)–(f) indicates the pulse width (FWHM) for first-order ($N = 1$) path-averaged soliton transmission link at 20 Gb/s for 24,500 km at a chirp factor of $C = -1$, -0.4, 0, 0.2, 0.3 and 0.4, respectively. Our investigations reveal that as the data transmission rate has been enhanced to 20 Gb/s there is no initial pulse compression at all values of induced chirp.

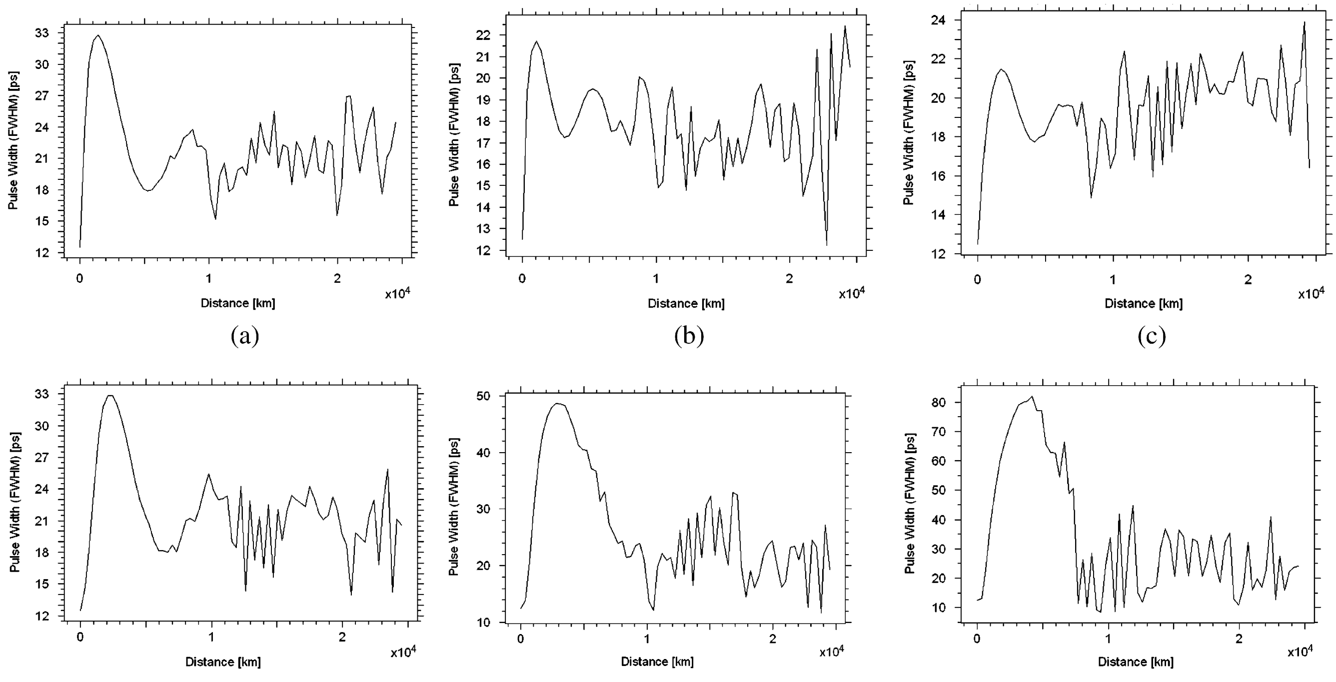
It is observed that negative chirp imposed on first-order path-averaged soliton pulse evolution at a bit rate of 20 Gb/s results in keeping the pulse width (FWHM) remarkably controlled and restrained, which makes it suitable for transmission over long haul. The optimum value of the chirp factor ranges from -0.4 to 0 for first-order ($N = 1$) path-averaged soliton transmission at 20 Gb/s over a long distance of 24,500 km. The resulting optimum range of pulse width (FWHM) is 12.5–23 ps as observed from Fig. 5(b) and (c). The positive chirp results in the broadening of the pulses as the pulse width (FWHM) increases beyond the optimum values as observed from Fig. 5(d)–(f).

Fig. 6 demonstrates first-order ($N = 1$) path-averaged single soliton pulse evolution. The results have been obtained over a transmission link of 24,500 km at a bit rate of 20 Gb/s at a varied chirp factor of $C = -1$, -0.4, 0, 0.2, 0.3 and 0.4. It has been observed that the best results for first-order ($N = 1$) path-averaged single soliton pulse evolution are obtained for negative chirp i.e. $C \leqslant 0$ as observed from Fig. 6(a)–(c). For chirp factor $C > 0.2$, as observed from Fig. 6(e)–(f), the pulse broadens, peak amplitude diminishes and large number of pig tails are formed breaking it into multiple pulses.

Further, the results have been reported at bit rate $B = 10$ and 20 Gb/s to map signal cumulative dispersion and power vs. fiber length, respectively, for the transmission distance of 24,500 km (see Fig. 7). The dispersion accumulates to $-5500\,\mathrm{ps}^2$ but SPM prevents pulse broadening due to high dispersion. Moreover, Fig. 7(b) depicts that the fiber loss is managed by the EDFAs over 70 spans for each fiber length of 350 km and it is maintained within the range of -10 to -78 dBm.

4. Concluding remarks

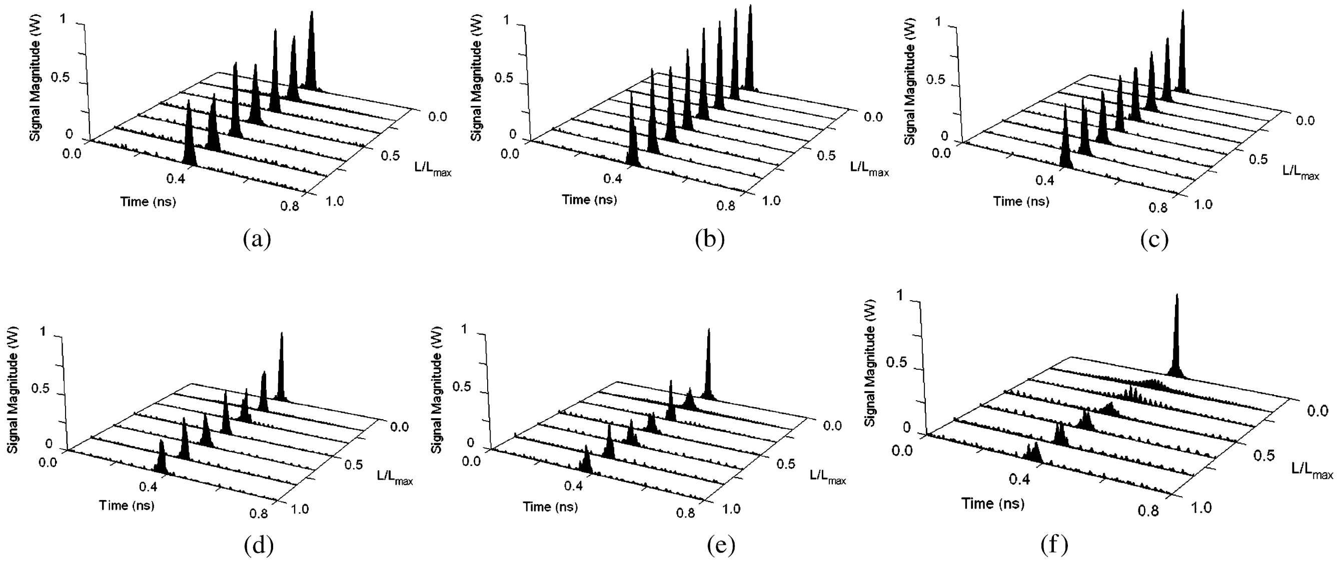
In this paper, we have demonstrated the propagation of first- and second-order path-averaged soliton pulse in a long-haul transmission link of 24,500 km at a bit rate of 10 and 20 Gb/s including the impact of third-order dispersion (TOD) without and with varied chirp. Here, the performance of loss-managed optical soliton transmission at various chirp factors has been investigated, keeping in view that many practical sources of short optical pulses have a frequency chirp imposed on them. Pulse width (FWHM) and pulse evolution for first- and second-order ($N = 1$ and 2) single soliton pulses for path-averaged transmission links at 10 and 20 Gb/s for 24,500 km at a chirp factor in the range -1



(a) (b) (c)

(d) (e) (f)

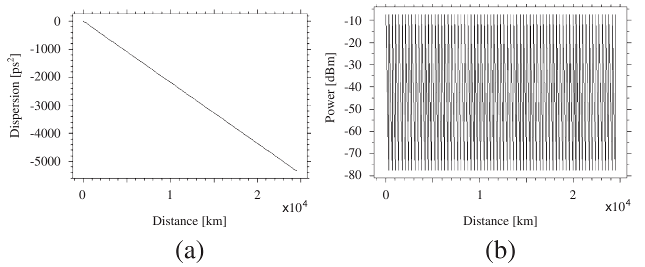
Fig. 5. Path-averaged soliton ($N = 1$) transmission link at 20 Gb/s (a) $C = -1$, (b) $C = -0.4$, (c) $C = 0$, (d) $C = 0.2$, (e) $C = 0.3$ and (f) $C = 0.4$.



(a) (b) (c)

(d) (e) (f)

Fig. 6. Evolution of first-order ($N = 1$) path-averaged single soliton pulse over a transmission link of 24,500 km at bit rate 20 Gb/s at varied chirp factor(s) (a) $C = -1$, (b) $C = -0.4$, (c) $C = 0$, (d) $C = 0.2$, (e) $C = 0.3$ and (f) $C = 0.4$.



(a) (b)

Fig. 7. (a) Cumulative signal dispersion; (b) optical power vs. fiber length.

to 1 and −1 to 0.4, respectively, have been presented in 70 recalculating loops with 350-km dispersive fiber and EDFAs.

It is investigated that there is initial pulse compression due to fiber nonlinearity on the pulse propagation for fundamental soliton ($N = 1$) at zero and positive values of chirp at a bit rate of 10 Gb/s, while there is no initial pulse compression at negative values of chirp. SPM effect on the rising and falling edges of a pulse results in spectral broadening for all values of induced chirp. In the case of a fundamental soliton ($N = 1$), the optimum value of pulse width (FWHM) is obtained at zero chirp and the acceptable values of chirp factor range from −0.7 to 0.5 during which the soliton pulse remains stable.

For second-order ($N = 2$) path-averaged soliton transmission link at 10 Gb/s, there is initial pulse compression due to fiber nonlinearity at all values of chirp($C = 0$, <0, >0) as the effect of SPM is more predominant in the case of higher-order solitons with $N = 2$ and above. Our investigations reveal that at negative values of chirp, viz. $C = -1$, −0.7 and −0.5 the pulse width (FWHM) falls within the range of 25–11 ps. On the contrary, for $N = 2$, the SPM results in spectral narrowing of the optical spectrum for negatively chirped pulses. The negative chirp imposed on second-order path-averaged soliton pulse evolution results in keeping the pulse width (FWHM) remarkably controlled and narrow, which makes it suitable for transmission over long haul at a bit rate of 10 Gb/s. We show that the effect of the nonlinearity changes from narrowing to broadening of pulses if the sign of the initial chirp is changed to positive. At chirp factor $C \geqslant 0$, the pulse width (FWHM) does not fall in optimum range unlike in the case of negatively chirped soliton pulses. The best results for second-order ($N = 2$) path-averaged single soliton pulse evolution are obtained for negative chirp, i.e. $C < 0$. For chirp factor $C \geqslant 0$, the pulse broadens and splits into multiple pulses moving outward.

Our investigations reveal that as the data transmission rate has been enhanced to 20 Gb/s there is no initial pulse compression at all values of induced chirp. It is observed that negative chirp imposed on first-order path-averaged soliton pulse evolution at a bit rate of 20 Gb/s results in keeping the pulse width (FWHM) remarkably controlled and restrained, which makes it suitable for transmission over long haul. The optimum range of chirp factor ranges from −0.4 to 0 for first-order ($N = 1$) path-averaged soliton transmission at 20 Gb/s over a long distance of 24,500 km. The positive chirp results in the broadening of the pulses as the pulse width (FWHM) increases beyond the optimum values. It has been observed that the best results for first-order ($N = 1$) path-averaged single soliton pulse evolution are obtained for negative chirp, i.e. $C \leqslant 0$. For chirp factor $C > 0$, the pulse broadens, peak amplitude diminishes and large number of pig tails are formed breaking it into multiple pulses.

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