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Comparative investigation and suitability of various data formats for 10 Gb/s optical soliton transmission links at different chirps

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Abstract

This paper presents the comparative investigation and suitability of various data formats for optical soliton transmission links at 10 Gb/s for different chirps (−0.7 to 0.7). Here the investigations focused on data formats: NRZ, RZ soliton, RZ raised cosine and RZ super Gaussian. The comparative results and suitability of data formats is based on various performance measures such as *Q*-factor, eye opening, BER and jitter. It has been indicated that RZ super Gaussian yields the highest value of *Q* (34.08 dB), good eye opening and lowest BER.
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Keywords: Soliton; *Q*-factor; BER; Data format; Eye diagram

1. Introduction

With the increased demand for capacity in long-haul lightwave transmission systems, the selection of a suitable optical modulation format is a key issue to ensure optimum system performance. Today's long-haul transmission systems represent the fourth generation utilizing multiple carrier wavelengths, which has led to an explosion of channel capacity. At the same time, deregulation of telecommunication markets and global success of the internet has driven up the demand for higher and higher system capacity.

Conventionally, non-return to zero (NRZ) modulation format has been used in long-haul transmission systems [1,2]. These systems are based on the fact that fiber dispersion and nonlinearities are detrimental effects. NRZ is used advantageously as it provides minimum optical bandwidth and minimum optical peak power per bit interval for given average power. However, with increased bitrates, it has been shown that RZ modulation formats offer certain advantages over NRZ, as they tend to be more robust against distortions [3]. For instance, RZ modulation is more tolerant to non-optimized dispersion maps than NRZ schemes [4]. This can be explained by the fact that optimum balancing between fiber nonlinearities and dispersion is dependent on the pulse shape. A RZ-modulated signal stream consists of a sequence of similar pulse shapes, whereas an NRZ-modulated stream does not.

From system designer's point of view, impairments in optical transmission need to be addressed. Moreover, how these affect the performance of the transmission link has to be investigated and ways to improve it have to be suggested. Therefore, it is important to investigate the robustness of various existing data formats on the

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performance of optical soliton transmission link. Comparison of the modulation formats CRZ, RZ, NRZ in generic undersea system using noise-free simulations has already been done by O. Sinkin et al. [5].

For high-speed optical soliton communication, the data transmission reliability is degraded by the system impairments like GVD and fiber nonlinearities. Pre-chirping has been observed to be one of the very effective techniques for employing 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. Pre-chirping 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 [6], it has been demonstrated that the concept of pre-chirping for constant dispersion fibers allows both width and chirp of the soliton to vary in each fiber section between two amplifiers.

Recently, dependence of timing jitter on data format for ideal dispersion-compensated 10 Gb/s optical communication systems has been reported in [7]. Here the simulations have been carried out for data formats RZ, NRZ, RZ soliton and duobinary and their subcategories with and without dispersion compensation for optical communication systems. The results show that, in general, dispersion compensation improves timing jitter.

In this paper, we have analyzed the performance of different optical data modulation formats in 10 Gb/s optical soliton transmission link taking into account the 'chirp', which is inadvertently present in all optical sources of short wavelength. The different data formats used by us present some notable differences in the context of data-rate/distance trade-offs and other device-related parameters that affect transmission performance. Modulation formats other than the conventional NRZ such as RZ soliton, RZ raised cosine and RZ super Gaussian have been investigated for certain performance measures viz. Q factor, bit error rate (BER), eye opening, jitter, etc. in a 10 Gb/s optical soliton transmission link. Different chirp factors have been included in the scope of this paper. The investigations have been carried out with chirp factor of −0.7, 0, 0.5 and 0.7 at the optical source itself.

2. Performance measures

The right choice of the performance evaluation criteria for the characterization of optical transmission links represent one of the key issues for an effective design of future long-haul optical systems. The evaluation criteria should provide a precise determination and separation of dominant system limitations, making them crucial for the suppression of propagation disturbances and a performance improvement.

Long-haul transmission links experience performance degradations due to ASE-noise from optical amplifiers along the line. In transoceanic systems, a large number of amplifiers are cascaded; each of them adds noise onto the signal stream. Besides changing the pulse energy, ASE-noise affects the pulse position in nonlinear pulse propagation as well. In fact, it turned out that ASE-noise-induced timing jitter is the ultimate limiting effect in single-channel soliton propagation. To maintain a safe pulse separation, the pulse width needs to be reduced and peak powers increased, when the path length/channel bit rate is increased. The most widely used performance measures for performance evaluation are the OSNR, Q-factor, BER and jitter.

2.1. *Q*-factor

Q-factor represents the signal-to-noise ratio at the receiver decision circuit in voltage or current unit. Fig. 1 shows the *Q*-factor definition. This definition considers soliton stability, interactions between pulses, timing jitter effects and other effects. In soliton-based systems using relatively higher signal power, we can use relatively short bit patterns because the stability of soliton pulses and nonlinear interactions between adjacent pulses are dominant compared with the pulse pattern effects and signal-to-noise ratio.

2.2. BER

The BER can be estimated from Eq. (1), and requires $Q>6$ for the BER 10^{-9}. This BER gives the upper limit for the signal because some degradation occurs at the receiver end.

$$\mathrm{BER}=\frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)\approx\frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}}. \tag{1}$$

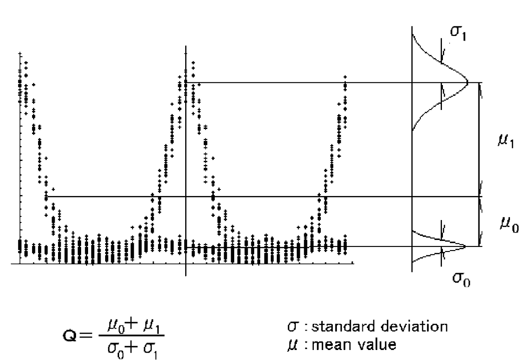

Fig. 1. *Q*-factor definition.

2.3. Eye opening

Considering only samples at the optimum sampling instant, it is the difference between the minimum value of the samples decided as logical "1" and the maximum value of the samples decided as logical "0". The unit of this measurement is equal to the unit of the electrical input signal.

2.4. Jitter

Jitter value is an estimate of the input signal jitter when it has an RZ format. This output data does not mean anything when dealing with NRZ signal. The jitter value is evaluated as the standard deviation of the position of the maximum of the received signal referred to the bit frame.

If the bit duration is T and bits are synchronized to the following time frame:

$t_j = t_0 + jT$,

for each bit, the maximum is found at the instant t_j^{max}:

$t_0 + jT < t_j^{max} < t_0 + (j+1)T$.

Then the jitter is estimated as the standard deviation of the random variable

$\Delta t_j = t_j - t_j^{max}$.

3. System description and results

Fig. 2 shows simulation set-up of 10 Gb/s optical soliton transmission link with different data formats. The simulation has been carried out using a commercial package *OptSim*™. Fig. 2 represents the circulating loop set-up, where each loop consists of 50 km long standard single-mode fiber (SMF) and an optical amplifier (EDFA).

Soliton pulses travel through total 8 loops or a transmission length upto 400 km. SMF offers an attenuation $\alpha = 0.2$ dB/km with dispersion $D = 0.2$ ps/km nm at 1550 nm and fiber PMD = 0.1 PS/$\sqrt{}$km. The fixed

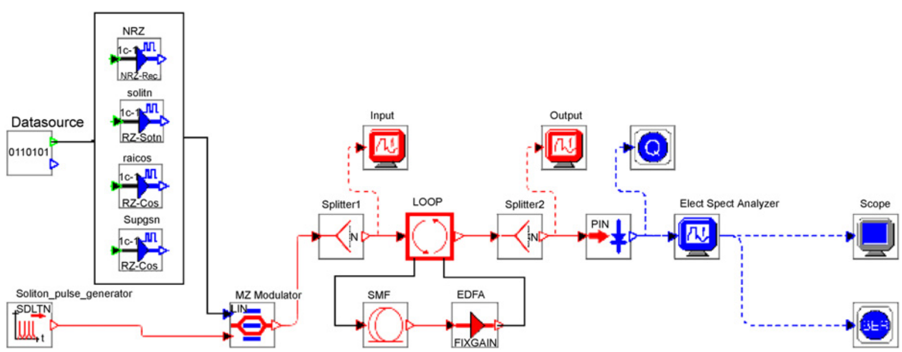

Fig. 2. Layout for 10 Gb/s optical soliton transmission link with different data formats.

Table 1. Comparison of the performance metric indices for 10 Gb/s optical soliton transmission link with different data formats

Parameter	Chirp factor	NRZ	RZ soliton	RZ raised cosine	RZ super Gaussian
Q (dB)	−0.7	22.05646	6.52236	14.58592	25.62515
Eye opening		0.96619e−02	0.96195e−05	0.10489e−04	0.34090e−03
BER		0.94716e−35	0.87632e−02	0.75963e−07	0.99999e−40
Jitter (ns)		0.00354648	0.0470047	0.0212409	0.0252351
Q (dB)	0	29.81784	9.78043	15.81618	34.08796
Eye opening		0.82791e−02	0.45588e−04	0.11694e−04	0.54802e−03
BER		0.99999e−40	0.27637e−03	0.26651e−08	0.99999e−40
Jitter (ns)		0.00151575	0.0126279	0.0185163	0.00739658
Q (dB)	0.5	22.43079	9.68540	13.04974	31.92020
Eye opening		0.86763e−02	0.49471e−04	0.10273e−04	0.43652e−03
BER		0.85358e−37	0.59362e−04	0.55634e−05	0.99999e−40
Jitter (ns)		0.00352908	0.0298223	0.0355234	0.00231935
Q (dB)	0.7	20.40332	8.30696	11.87742	28.81032
Eye opening		0.60846e−02	0.19704e−04	0.90199e−05	0.37993e−03
BER		0.36205e−25	0.65437e−03	0.43931e−04	0.99999e−40
Jitter (ns)		0.00408167	0.038497	0.0372427	0.0106632

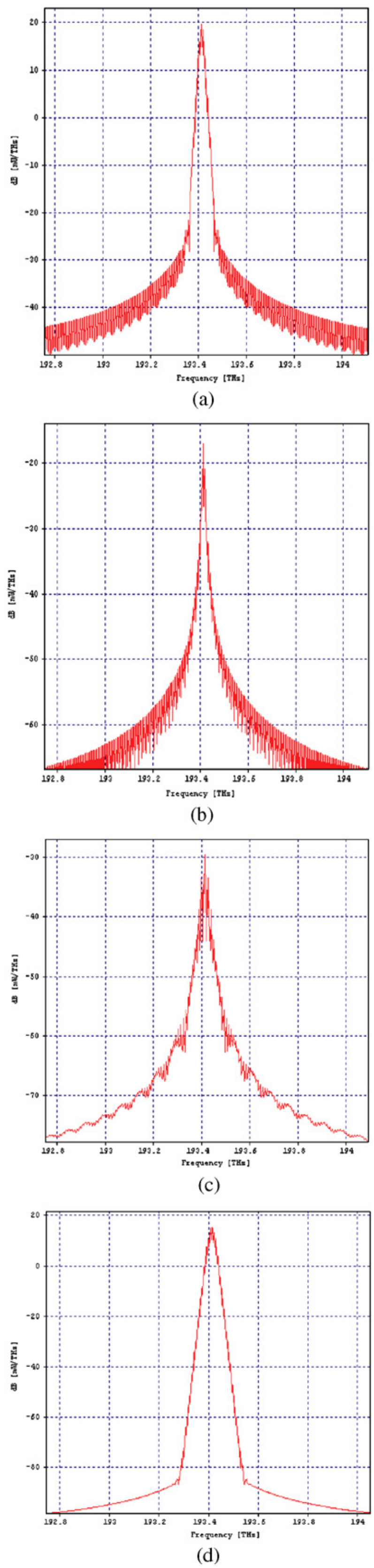

Fig. 3. Optical power spectrum of (a) NRZ, (b) RZ-soliton, (c) RZ-raised cosine and (d) RZ-super Gaussian.

values associated with nonlinear refractive index are $n_2 = 3 \times 10^{-20}\,\mathrm{m^2/W}$, $\omega_0/c = 2\pi/\lambda = 2\pi/1.55 \times 10^{-6}\,\mathrm{m^{-1}}$, $A_{\mathrm{eff}} = 60.805\,\mu\mathrm{m}^2$. The dominant nonlinear fiber parameter considered during simulation is the Kerr nonlinearity coefficient $\gamma = n_2\omega_0/cA_{\mathrm{eff}}$. Data source generates a binary sequence of data stream. Modulation driver generates different types of data formats other than the conventional NRZ such as RZ soliton, RZ raised cosine and RZ super Gaussian. A soliton source is used to generate pulses of "sech" shape with center emission wavelength of 1550 nm, peak power = 25.584 mW and pulse width (FWHM) = 17.627 ps with time between two adjacent pulses equal to 200 ps. The pulses are then modulated using MZ modulator at 10 Gb/s bit rate. Amplitude Dual-Arm Mach Zehnder Modulator is used to modulate optical signal of desired format having the following parameters: offset voltage corresponding to the phase retardation in the absence of any (on both arms) electric field is 0.5 V, extinction ratio = 20 dB and average power reduction due to modulation is 3 dB. Optical splitter of attenuation 0 dB at each output port was used to observe the results before and after ideal dispersion compensation. Electrical scopes with Gaussian filter are used to observe change in performance. PIN diode is used to detect the optical signal, i.e. conversion into electrical signal having characteristics quantum efficiency = 0.7, responsivity (at reference frequency) 0.8751 A/W, 3 dB bandwidth 20 GHz, dark current 0.1 nA; reference wavelength 1550 nm and including quantum noise was

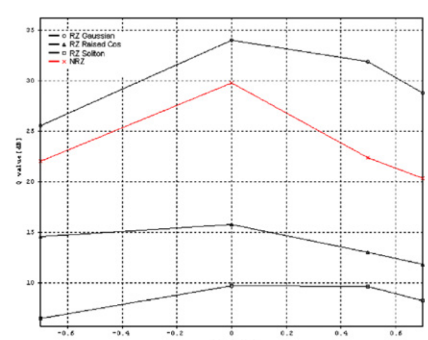

Fig. 4. *Q*-factor plot for different data formats at different chirps.

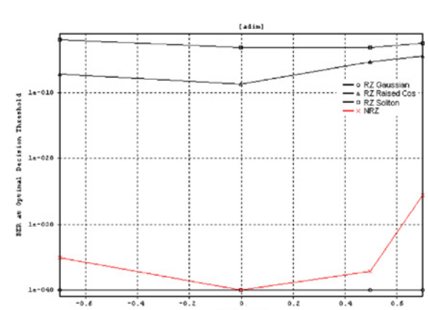

Fig. 5. BER plot for different data formats at different chirps.

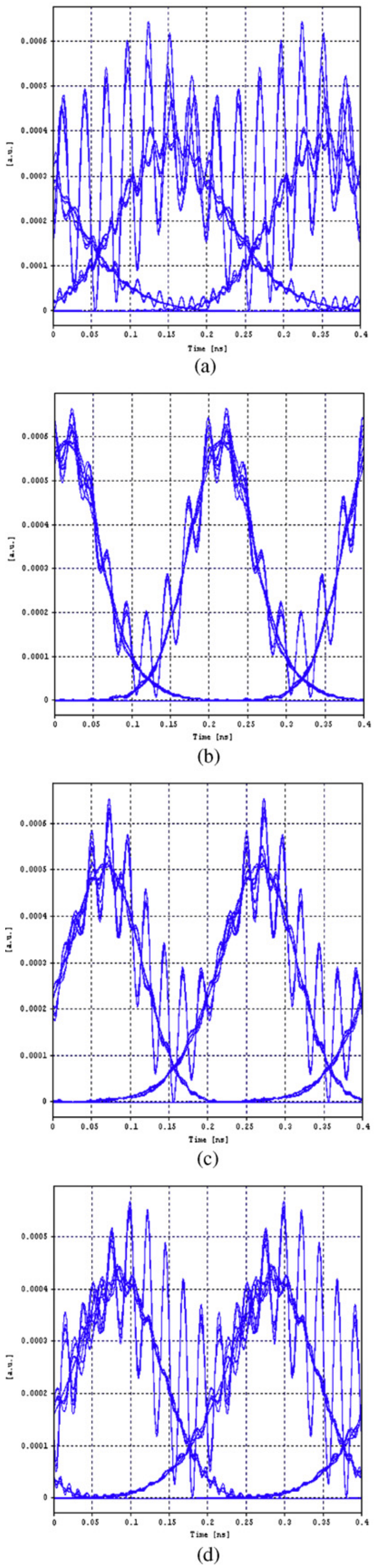

Fig. 6. Eye diagram for RZ super Gaussian at (a) $C = -0.7$, (b) $C = 0$, (c) $C = 0.5$ and (d) $C = 0.7$.

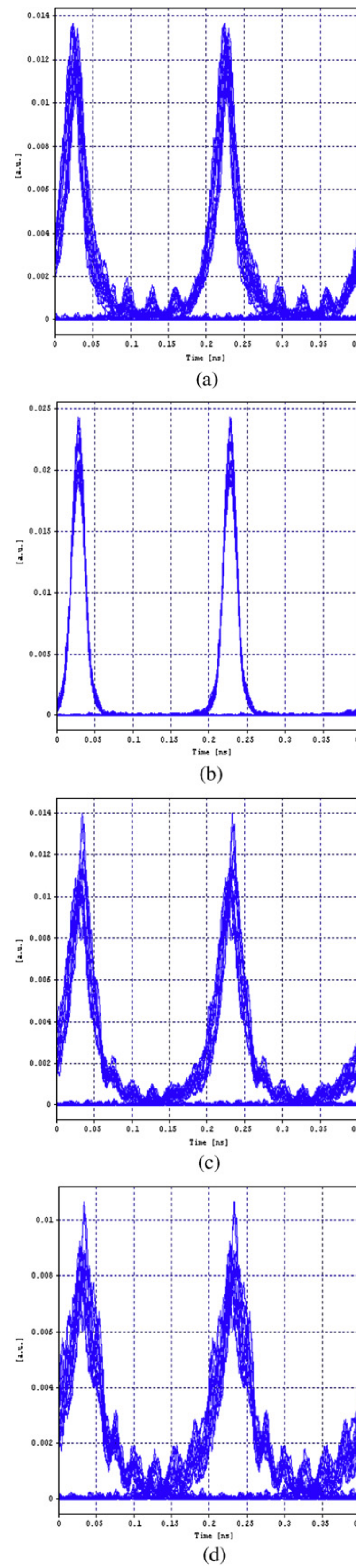

Fig. 7. Eye diagram for NRZ at (a) $C = -0.7$, (b) $C = 0$, (c) $C = 0.5$ and (d) $C = 0.7$.

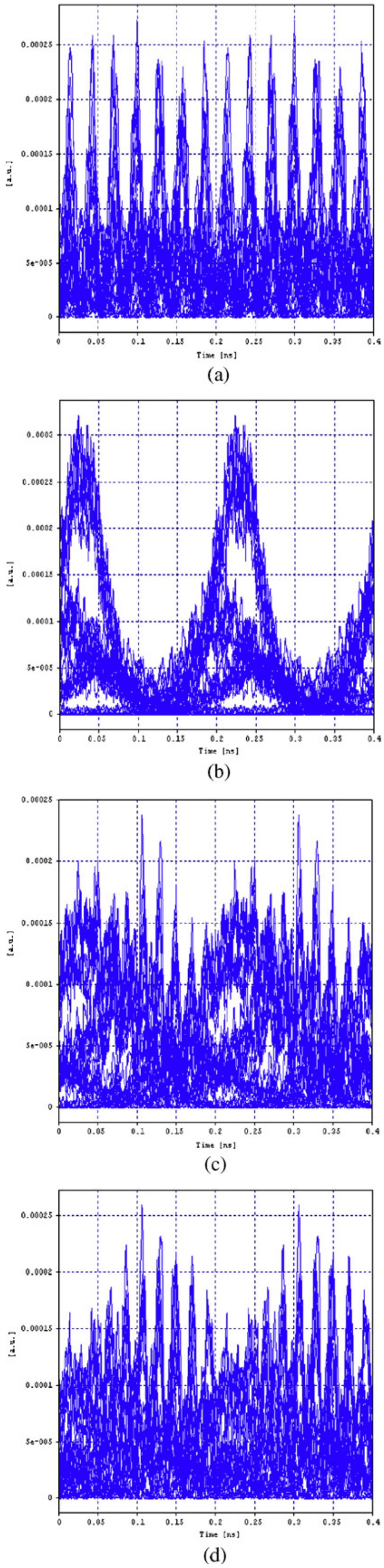

Fig. 8. Eye diagram for RZ soliton at (a) $C = -0.7$, (b) $C = 0$, (c) $C = 0.5$ and (d) $C = 0.7$.

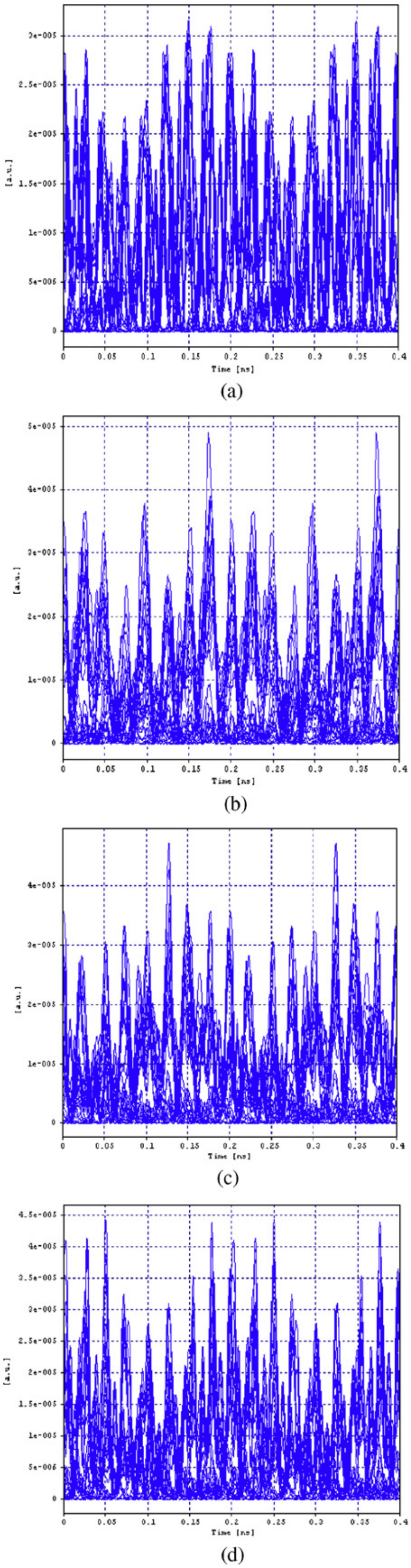

Fig. 9. Eye diagram for RZ raised cosine at (a) $C = -0.7$, (b) $C = 0$, (c) $C = 0.5$ and (d) $C = 0.7$.

included. Q-factor meter, BER tester and eye diagram analyzer and electrical spectrum analyzer are used to observe the output signal and power spectrum.

Table 1 presents a summary of comparative investigation on the performance metric indices viz. Q (dB); eye opening; BER and jitter (ns) for 10 Gb/s optical soliton transmission link with different data formats (NRZ, RZ soliton, RZ raised cosine and RZ super Gaussian at different chirp factors −0.7, 0, 0.5 and 0.7). Fig. 3 indicates the optical power spectrum of different data formats. The optical power spectrum in case of RZ super Gaussian is more compact as compared with other data formats. Figs. 4 and 5 show Q-factor and BER plots, respectively, for various data formats at different chirps.

Our investigations reveal that peak value of Q-factor is highest; 34.08 dB in case of RZ super Gaussian followed by NRZ, RZ raised cosine and RZ soliton with Q penalties 4.27012, 18.27178 and 24.30753 dB, respectively. Similarly, the lowest value of BER of order of 0.99999e−40 is obtained in the case of RZ super Gaussian and NRZ while it is 0.26651e−08 and 0.27637e−03 for RZ raised cosine and RZ soliton, respectively, for ideal source ($C = 0$). Further, it has been observed that the Q penalty is less in the cases of negatively chirped source for NRZ and RZ raised cosine and positively chirped sources for RZ super Gaussian and RZ soliton.

Further it is reported that the jitter value remains low for all the data formats in general and also no considerable impact of chirp on jitter has been recorded. Figs. 6–9 show the eye diagrams at different chirps for different data formats. In a comparative investigation, eye opening in the case of NRZ has been reported to be the best; however, it is also reasonably good for RZ super Gaussian as seen from Fig. 6.

4. Conclusions

In this paper, we have carried out the comparative performance evaluation of data formats in 10 Gb/s optical soliton transmission link. The results have been reported for different data formats, viz. NRZ, RZ soliton, RZ raised cosine and RZ super Gaussian at different chirps (−0.7 to 0.7). In the case of RZ super Gaussian the highest value of Q (34.08 dB), good eye opening, lowest BER and its non-susceptibility at different chirps makes it the best choice among the data formats mentioned. Jitter value remains low for all the data formats in general and also no considerable impact of chirp on jitter has been recorded. In a comparative study, eye opening in case of NRZ has been reported to be the best; however, it is also reasonably good for RZ super Gaussian.

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