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Reduction in timing jitter by chirp selection for externally modulated return to zero optical soliton pulse at 10 Gb/s

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Abstract

We investigate the chirp selection of externally modulated RZ soliton pulse at 10 Gb/s for fiber optical communication systems for the reduction in timing jitter. We have chosen single arm Mach–Zehnder amplitude modulator with $\sin^2$ electrical shaped input–output (P–V) characteristic and its chirp range has been varied in the range of −5 to 5. The timing jitter, Q factor and bit error rate (BER) generated for the chirp range has been studied for various fiber lengths and post compensation has been demonstrated to reduce the timing jitter. The number of fixed output amplifiers after every 60 km span is varied from 2 to 10 and corresponding accumulated ASE noise has been studied to manage timing jitter and BER in permissible range, i.e. 5 ps and 10^{-9}, respectively. It is observed that when two fiber spans are taken then the compensating fiber length for the system is less than 20 km for each case of the chirp considered. For 10 fiber spans, the compensating fiber length increases in the range 60–90 km depending upon the value of chirp taken. Finally it is shown that the chirp value of external modulator should be set to either 0 or −1 for externally modulated RZ soliton pulse in 10 Gb/s optical communication system which makes the system more insensitive to the timing jitter and the selection of dispersion compensating fiber length.

Keywords: Chirp; Dispersion compensation length; Timing jitter; Bit error rate; Q value

1. Introduction

Focus on optical communications development is tremendous since it offers combination of wide bandwidth and low losses unmatched by any other transmission medium but there are some inherent limitations due to dispersion and fiber nonlinearities resulting in timing jitter. The timing jitter is also caused by the chirp factor of laser diodes and modulators. The current modulation induces changes in the refractive index, which lead to changes in the frequency of the light. This frequency variation is commonly referred to as frequency chirp. Interaction of the frequency chirping with chromatic dispersion in the optical fiber distorts the transmitted signal and results in dispersion penalty. In modern metropolitan area networks, the length of the optical fiber may be on the order of a few hundred kilometers, which means that dispersion-induced problems remain an important issue. The most common way to look upon external modulators is to consider them chirp-free. However, at multigigabit speed on dispersive fibers the

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residual chirp from the modulator should not be neglected. The main interest in chirp has, so far, been shown for lasers. In comparison, a much smaller interest has been shown for the chirp properties of external optical modulators [1–5].

Chromatic dispersion associated with large frequency chirping of transmitters is one of the limiting factors of high speed and long haul telecommunication systems. Different modulators have been studied in the literature to assess timing jitter for different values of chirp to optimize the performance of fiber optical communication system. The external Mach–Zehnder (MZ) modulators, which can provide a low or adjustable chirp parameter, are a key component of high capacity optical telecommunications systems [1]. Knowledge of the chirp parameter of MZ modulators is thus essential to understand the propagation of short pulses in fibres. If the RF electric fields applied to the optical channels of the MZ structure are symmetric, a zero-chirp modulation can be obtained for the case of X-cut $LiNbO_3$ modulators. However, many commercial modulators, such as Z-cut $LiNbO_3$ ones, exhibit an asymmetric structure in order to reduce the half-wave voltage. The electric fields of such devices are not equal in both arms of the MZ interferometer, which causes a residual chirp. The chirp may also appear when the optical branches are unbalanced, i.e. when the extinction ratio is finite [2].

2. Theory

Mathematically, assuming an adjustable DC bias imposes a phase shift $\Delta\varphi_{DC}$ between the two optical branches of the MZ structure. A high frequency sinusoidal voltage $V(t) = V_0 \cos(\Omega t)$ is applied to the transmission lines (where V_0 is the amplitude of the applied voltage, and Ω is the modulation frequency). The output optical field whose spectral density is measured with a scanning Fabry Perot can be written [3] as

$$E(t) = E_0 \exp(\mathrm{i}\omega_0 t) \times [\exp(\mathrm{j}A_1 \times \cos(\Omega t)) + \gamma \times \exp(\mathrm{j}A_2 \times \cos(\Omega t)) + \mathrm{j}\Delta\varphi_{DC}]$$

where ω_0 and E_0 are, respectively, the frequency and amplitude of the optical wave, and the scaling factor γ ($0 \leqslant \gamma \leqslant 1$) accounts for a finite extinction ratio. A_1 and A_2 denote the magnitude of the optical phase induced in each optical path. The chirp parameter of an external modulator is defined as [4]

$$\alpha = \frac{\dfrac{\mathrm{d}\varphi}{\mathrm{d}t}}{\dfrac{1}{2I(t)} \times \dfrac{\mathrm{d}I}{\mathrm{d}t}}$$

where $\varphi(t)$ and $I(t)$ are the instantaneous phase and intensity of the output optical wave, respectively. The most common way to look upon external modulators is to consider them chirp-free. However, at multigigabit speed on dispersive fibers the residual chirp from the modulator should not be neglected. Particularly, chirp selection of external modulators demands attention in addition to earlier work done on the laser chirp [5–9]. For external modulators performed in $LiNbO_3$, the MZ modulator is preferably used. This modulator has the possibility of being designed for perfectly chirp-free operation [6]. However, a completely chirp-free device is not always desirable. It has been shown [8,9] that the power penalty could be reduced with a modulator having a slight chirp compared to a perfectly chirp-free device.

3. Literature review

The influence of modulator chirp in assessing the performance implications of the group delay ripple (GDR) [10–18] of dispersion compensating fiber Bragg grating is observed using four modulators—an electroabsorption modulator (EAM), a monolithically integrated distributed feedback (DFB) laser and electroabsorption modulator (ILM), a multiple quantum-well MZ modulator (MQW-MZM), and a $LiNbO_3$ MZ modulator (LN-MZM) with distinct chirp properties and measured reflection spectra for two dispersion compensating gratings (DCGs) [11]. The parameter α considered is in the range of -5 to 7 [11] in case of different modulators to show their performance. Subsequently receiver sensitivity has been investigated for the chirp in the range -1 to 1.

It is also shown that an increase of composite-second-order (CSO) distortion by increasing fiber length can occur in analog transmission systems using optically linearized MZ modulators and that degradation is due to generation of chirp in the modulator [19]. A novel modulator design where chirp is greatly reduced while preserving excellent linearity was proposed. For an 80-channel, an optimized low-chirp modulator was predicted to extend the CSO-limited range of the system over standard single-mode fiber from approximately 50 km to greater than 300 km.

Theoretical investigation also showed the interplay between the residual and applied chirp of optical duobinary modulated signals in order to improve transmission performance. The residual chirp accompanying from the finite extinction ratio and the applied chirp adjusted by the applied voltage ratio (the chirp parameter) between two electrodes of $LiNbO_3$ modulators are used in 10-Gb/s optical duobinary transmitters to find the best performance [20]. The results suggested that nearly zero chirp during the mark (‘1’) period and large peak chirp at the middle of the space (‘0’) provided the best transmission performance. This zero chirp around marks and high peak chirp at the middle of each space can be controlled by the applied voltage ratio between two electrodes of modulator and the filter bandwidth, respectively.

Kim et al. [21] presented a large signal dynamic model of electroabsorption modulator integrated (EAMI) DFB lasers using the time-dependent transfer matrix method. With this model better predictions are provided regarding the laser and modulator chirp, to accurately estimate the effect of bias voltage, facet reflectance, grating phase, the length of the waveguide region, and isolation resistance. The calculated large-signal chirp using this model has similar characteristics to the measured large-signal chirp for 10-Gb/s EAMI-DFB lasers. This model can be used as an accurate and powerful tool to analyze the large-signal chirp and pulse shape of the output signal.

Another view implies that with the advent of optical amplifiers, fiber losses are no longer a major limiting factor for optical communication systems [22,23]. Indeed, modern light wave systems are often limited by dispersive and nonlinear effects rather than losses. As a result, dispersion-induced degradation of the transmitted signal accumulates over multiple amplifiers. For this reason, several dispersion-management schemes have been developed which are classified as precompensation, postcompensation, optical filters, fiber Bragg gratings, more recently optical conjugation and polarization mode dispersion compensation techniques [24–32].

None of the above papers considered the wide range of the chirp except Cartledge et al. [11] who too did not study the chirp selection of the modulator with dispersion compensation. Also none of the above papers laid stress on timing jitter which is one of the most important factor in optimizing the performance of optical communication systems. In this paper, the work reported in [11,19,24] has been further extended for chirp selection of externally modulated RZ soliton at 10 Gb/s for fiber optical communication system with repeated amplification after every 60 km and with dispersion compensation.

4. System description

The block diagram of optical communication system considered is given in Fig. 1. The data source is pseudo random having bit rate 10 Gb/s with 31 samples per bit using polynomial of 7 degree. The RZ soliton driver converts logical inputs to electrical outputs −2.5 V low level and 2.5 V high level with 30 ps full wave at half maximum (FWHM) pulse width. The number of poles in low pass filter has been kept to 5 and uses the –3 dB cutoff frequency 8 GHz.

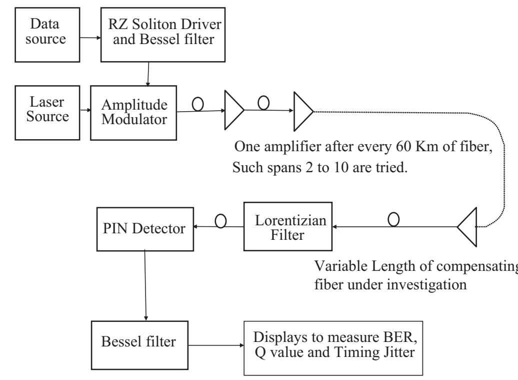

Fig. 1. Externally modulated RZ soliton 10 Gb/s optical communication system simulation model under investigation.

The modulator is a single arm MZ amplitude modulator with $\sin^2$ electrical shaped input–output (*P*–*V*) characteristic. The typical transfer function is taken for a MZ external modulator based on the electro-optic effects in the $LiNbO_3$ devices. The level of extinction ratio (corresponding to the ratio between the maximum and minimum values of the input–output transmission characteristics) is kept ideal and the chirp factor α is varied in discrete values −5, −3, −1, 0, 1, 3, 5. The input voltage is equal to maximum transmissivity offset voltage and the power of the optical signal is attenuated by the excess loss only so that the modulator attains the state of maximum transmission.

The fiber of length 60 km [5–6] is taken in the presence of fiber nonlinearity, fiber PMD, fiber birefringence but without Raman crosstalk. The reference wavelength is 1550 nm at which loss is 0.25 db/km having −2 ps/nm km dispersion and 20 km dispersion correlation length. The fiber nonlinearity coefficient is 1.8, the core effective area is $67.56\times10^{-12}\,m^2$ and fiber PMD is $0.1\,ps/km^{0.5}$.

The in-line EDFA optical amplifier has a fixed output power of 3 dB after every 60 km depending upon the case under investigation. After amplification, optical signal is passed through dispersion compensating fiber of variable length from 10 to 100 km in step change of 5 km with reference wavelength 1550 nm, loss 0.25 dB, dispersion 16 ps/nm km, effective core area $67.56\times10^{-12}\,m^2$ and $0.1\,ps/km^{0.5}$ fiber PMD.

At receiver, optical signal is preamplified with fixed output type amplifier 3 dB m output power and is then passed through three-stage Lorentzian filter of centre wavelength 1550 nm. The detection is done with the use of PIN photodiode at 1550 nm wavelength of 0.7 quantum efficiency and 0.875 A/W responsivity and 0.1 nA dark current. Electrical filter of low pass Bessel type with five poles and −3 dB bandwidth gives the electrical signal which is subsequently measured for BER, Q value, average eye opening and timing jitter.

5. Observation and results

The simulation setup model shown in Fig. 1 is considered for two fiber spans spans to start with chirp values −5, −3, −1, 0, 1, 3 and 5. The corresponding results in the form of graphs is shown in Figs. 2–5 for average eye opening, timing jitter, BER and Q value, respectively, for different dispersion compensating fiber lengths. These graphs indicate that BER is under permissible limit if length is taken 10 to 20 km irrespective of the chirp value. Also, it is observed that the chirp value of −1 and 0 gives wide range of dispersion compensating fiber length selection from 10 to 50 km where BER $< 10^{-9}$ and timing jitter is found to be below 5 ps.

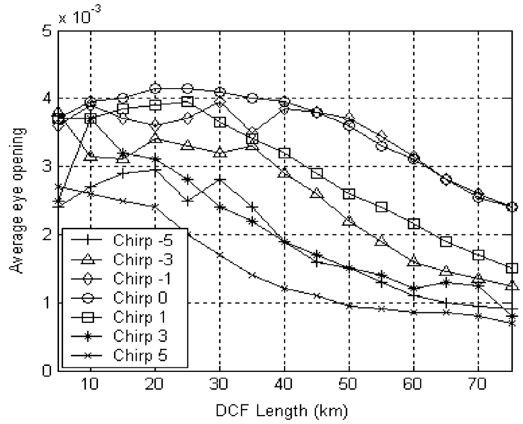

Fig. 2. Average eye opening versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of two fiber spans.

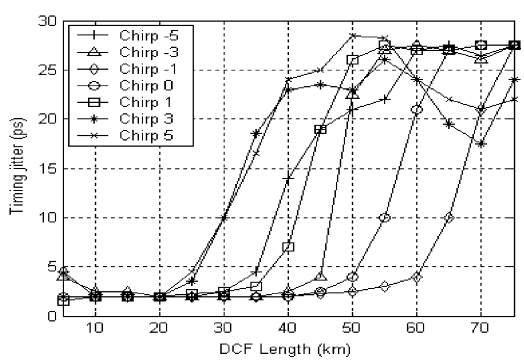

Fig. 3. Timing jitter versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of two fiber spans.

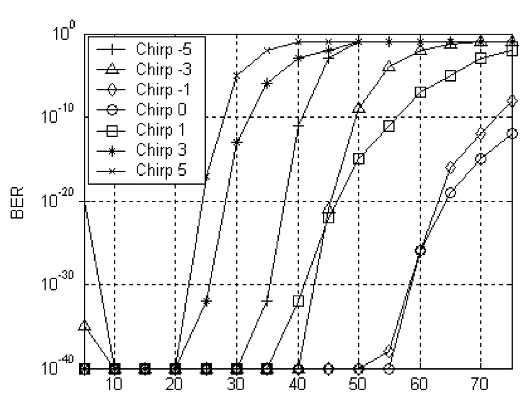

Fig. 4. BER versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of two fiber spans.

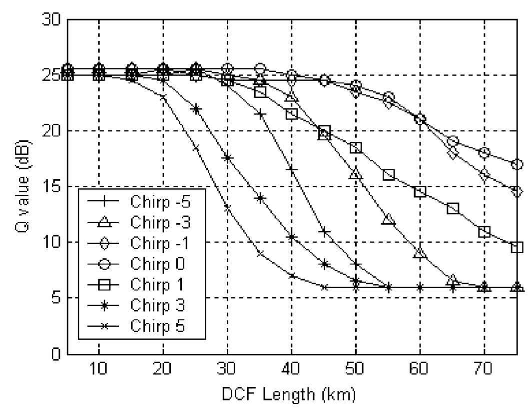

Fig. 5. Q value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of two fiber spans.

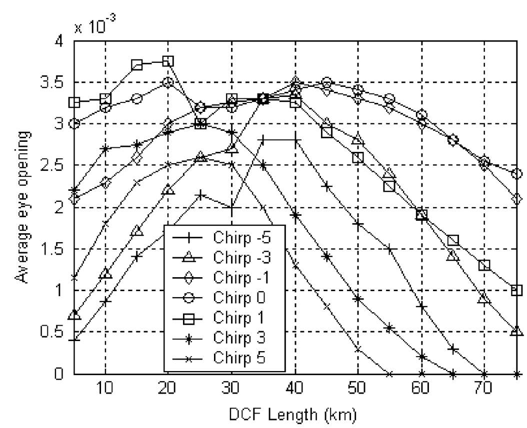

Fig. 6. Average eye opening versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of four fiber spans.

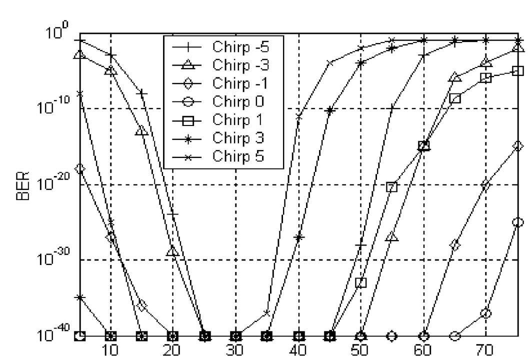

Fig. 7. BER value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of four fiber spans.

Simulation model is now set for four fiber spans and corresponding results have been plotted in Figs. 6–9 indicating eye opening, BER, timing jitter and Q value, respectively, against length of compensating fiber. In each figure, the corresponding chirp value of −5, −3, −1, 0, 1, 3 and 5 have been superimposed for comparison. Here it is evident that compensating fiber length required in each chirp value is shifted to higher length side. In Fig. 7, length required for minimum BER $< 10^{-9}$ is in the range 20–40 km for all chirp cases in place of the range 10–20 km required in Fig. 4, i.e. the length has been increased.

Figs. 6–9 also make evident that chirp selection should be either 0 or −1 to make compensating fiber length

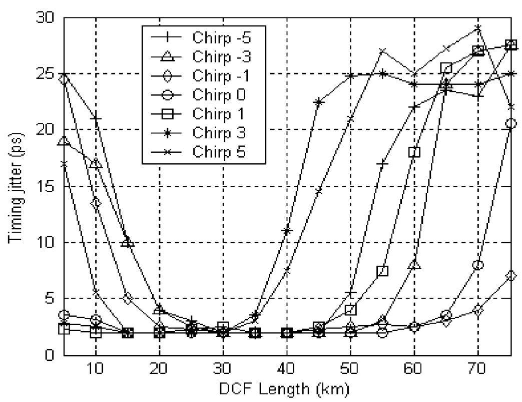

Fig. 8. Timing jitter versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of four fiber spans.

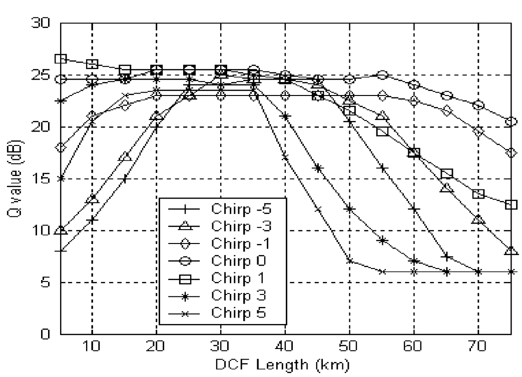

Fig. 9. Q value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of four fiber spans.

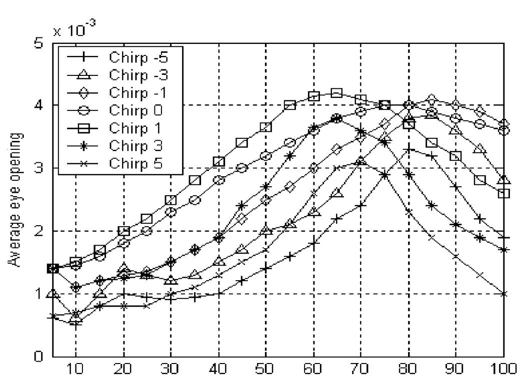

Fig. 10. Average eye opening value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of 10 fiber spans.

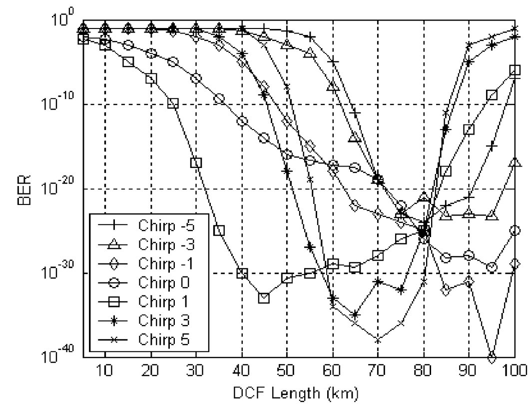

Fig. 11. BER versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of 10 fiber spans.

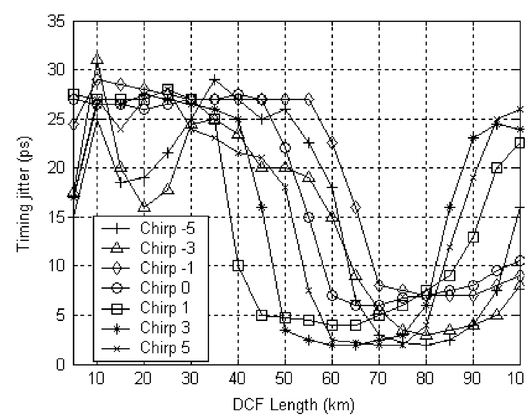

Fig. 12. Timing jitter value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of 10 fiber spans.

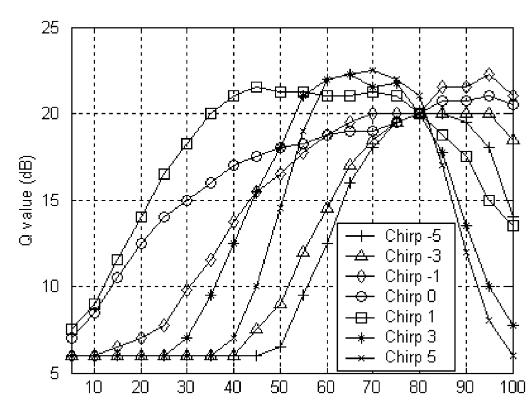

Fig. 13. Q value versus length for various chirp values −5, −3, −1, 0, 1, 3, 5 in case of 10 fiber spans.

insensitive, i.e. wide range of fiber length for dispersion compensation. The idea is extended to see the effect on further extension of fiber spans up to 10. For six fiber spans, it is observed that results again, emphasize selection of chirp −1 or 0 with dispersion compensating fiber in the range of 10–70 km for best performance. But, in general,

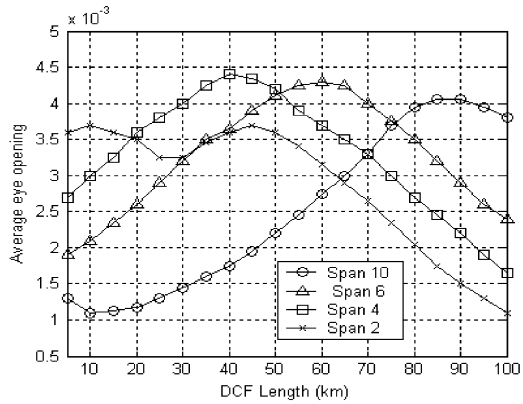

Fig. 14. Average eye opening versus fiber length for fiber spans 2, 4, 6 and 10 by keeping chirp −1 in each case.

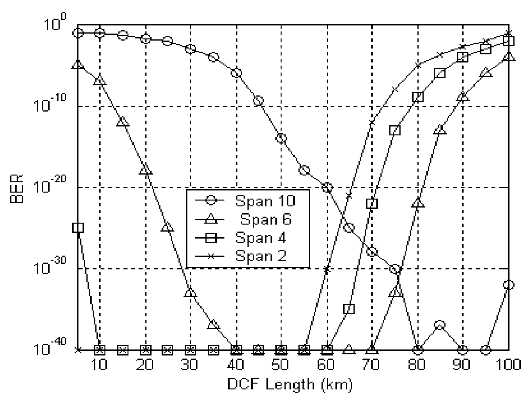

Fig. 15. BER against fiber length for fiber spans 2, 4, 6 and 10 by keeping chirp −1 in each case.

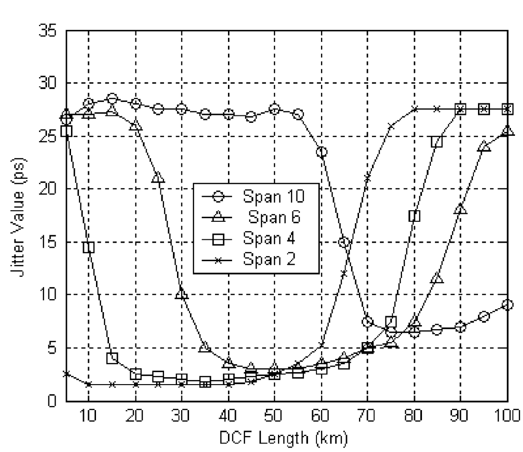

Fig. 16. Jitter value against fiber length for fiber spans 2, 4, 6 and 10 by keeping chirp −1 in each case.

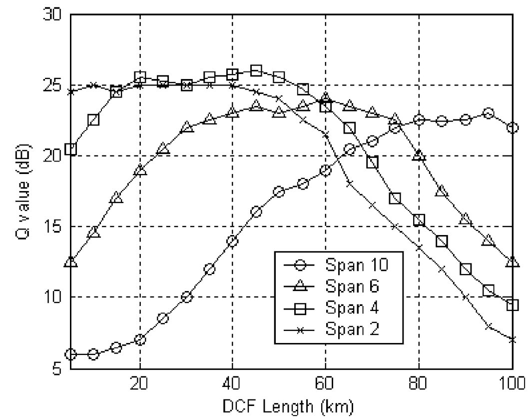

Fig. 17. Q value against fiber length for fiber spans 2, 4, 6 and 10 by keeping chirp −1 in each case.

dispersion compensating fiber length required is 40–50 km for any chirp value giving optimum result.

Lastly, the 10 fiber spans are considered and its corresponding results are shown in Figs. 10–13 indicating similar trend. From Fig. 12, chirp values −1 and 0 show that timing jitter is exceeding 5 ps, therefore higher values of chirp like 5 and 3 should be considered. Also from figures, it is evident that dispersion compensating length required is in the range from 70 to 80 km. This can be justified on the basis of amplified spontaneous emission noise (ASE) which is causing eye closure penalty. In order to see the effect of drift we consider same simulation set up and give chirp of −1 for different fiber spans and corresponding results have been shown in Figs. 14–17. The Fig. 14 clearly shows that the region of maximum average eye opening is shifting toward the higher values of dispersion compensating fiber length. The peak of average eye opening is at 40 km length of compensating fiber, in case of 2 and 4 fiber while it shifts to the length 80–90 km for 10 fiber spans. On parallel lines, Fig. 15 indicates that region of BER minimum has been shifted to compensating fiber length 80–90 km for the case of 10 fiber spans.

6. Conclusion

The results showed that for repeatedly amplified, externally modulated 10 Gb/s RZ soliton optical communication system, chirp selection plays major role in deciding the system performance. The choice of chirp in single arm Mach–Zehnder amplitude modulator with $\sin^2$ electrical shaped input–output (*P*–*V*) characteristic indicates that chirp selection should be either −1 or 0 in comparison to other chirp values in the range −5 to 5 considered in order to have better performance in terms of the permissible values of eye opening, BER, timing jitter and Q value. For two fiber spans of 60 km each and same number of amplifiers to compensate fiber loss, the required compensating fiber length for the system is less than 20 km for the cases of all chirp values −5, −3, −1, 0, 1, 3, 5. Instead, with 10 fiber spans, the compensating fiber length increases from 60 to 90 km depending upon the value of chirp selection. Also chirp value 0 or −1 of external modulator in RZ soliton pulse in 10 Gb/s optical communication system showed that the system becomes more insensitive to the timing jitter and the selection of dispersion compensating fiber length.

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