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# Impact of optical modulation formats on SPM-limited fiber transmission in 10 and 40 Gb/s optimum dispersion-managed lightwave systems

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## Abstract

In this paper, 10 and 40 Gb/s optical systems have been investigated for nonreturn-to-zero (NRZ), return-to-zero (RZ), carrier-suppressed return-to-zero (CSRZ) and RZ-differential phase-shift-keying (RZ-DPSK) data formats. For the range of the optical signal power from −5 to 15 dBm, a maximum self-phase modulation (SPM)-limited transmission distance $L_{SPM}$ is determined with eye-opening penalty (EOP) $>1$ dB .The observations are based on the modeling and numerical simulation of optimum dispersion-managed transmission link. Transmission over distances of the order of several hundreds of kilometers has been shown with and without amplified spontaneous emission (ASE) noise of the in-line erbium-doped fiber amplifiers (EDFAs).


***Keywords:*** ASE; NRZ; RZ; CSRZ; RZ-DPSK

## 1. Introduction

Increasing the per-channel bit rate from 10 Gb/s up to 40 Gb/s is seen today as a way to achieve a very high spectral efficiency without the need to resort to expensive dense wavelength-division multiplexing (DWDM) filter technology. To upgrade the existing optical terrestrial networks, it is desirable that 40 Gb/s systems should have the same amplifier spacing as existing 10 Gb/s systems. For this reason, 40-Gb/s systems require higher fiber input power in order to attain the same signal-to-noise ratio (SNR) as 10-Gb/s systems. However, fiber input power is restricted due to the nonlinear optical effects in the transmission fiber [1,2]. In the case of single-channel transmission, the interaction between self-phase modulation (SPM) and group velocity dispersion (GVD) causes severe waveform distortion in high-power transmission. Fortunately, there are several techniques that can be used to overcome this nonlinear impairment. Dispersion management, which uses distributed in-line dispersion compensation using dispersion compensated fibers (DCFs) and fiber Bragg grating (FBG) instead of lumped compensation at the receiver or the transmitter, is quite effective in suppressing the SPM–GVD interaction [2].

Modulation format plays a significant role in defining the allowable fiber input power in long-haul transmission link. Conventionally, the nonreturn-to-zero (NRZ)

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modulation format has been used in long-haul transmission systems [3–5]. NRZ is used advantageously as it provides minimum optical bandwidth and minimum optical peak power per bit interval for a given average power, thus enabling higher spectral efficiency in the linear regime. However, with increased bit rates it has been shown that return-to-zero (RZ) modulation formats offer certain advantages over NRZ [3], as they tend to be more robust against waveform distortion induced by the SPM–GVD interaction. 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. The dispersion tolerance of a signal stream can be derived from the superposition of the dispersion tolerance of the individual pulse shapes. Because of this advantage, RZ transmission experiments using single mode fiber (SMF) have been demonstrated at 40-Gb/s (per channel) line rates over distances of 1000 km and above in both terrestrial and transoceanic systems [4–6]. Furthermore, the carrier-suppressed RZ (CS-RZ) format is also being preferred these days because of its high tolerance to the mixed effect of SPM and GVD and the narrower pedestal shape of the optical spectrum than the conventional RZ format [5–8,20]. Akihide Sano et al. [6] reported that the transmission performance of the CS-RZ format improves with moderate phase modulation because the phase of neighboring pulses differs by $\pi$ and the interaction between them is suppressed. It is stronger against linear crosstalk and XPM-induced timing jitter because of its compact spectral width and wide pulse width. This allows a higher input power than the conventional RZ format. Direct-detection differential phase-shift-keying (DPSK) modulation has also attracted a great deal of attention in recent years [7–11,20]. This is attributed to the two main advantages of this modulation format: improved receiver sensitivity and enhanced immunity to the effects of fiber nonlinearities. Takeshi Hoshida et al. [9] showed theoretically and experimentally that the CS-RZ format is less attractive in highly spectral-efficient systems having 75-GHz spacing or less and that the IM-DPSK format has approximately 3 dB higher optical noise tolerance and superior nonlinear tolerance is the optimum modulation format and thus one of the key enabling technologies for spectrally efficient ultralong-haul 40 Gb/s DWDM transmission systems. Kim Takashi Mizuochi et al. [14] observed that when fiber loss is periodically compensated by optical amplifiers, the interaction of fiber Kerr effect and amplifier noises due to amplified spontaneous emission (ASE) induces nonlinear phase noise, often called the Gordon–Mollenauer effect or, more precisely, SPM-induced nonlinear phase noise. Added directly to the signal phase, nonlinear phase noise degrades DPSK signals [14–15,17–19]. An experimental study based on a precise comparison with RZ-OOK has also addressed the advantages of RZ-DPSK for ultralong-haul transmission [14]. Experimental evidence of the Gordon–Mollenauer effect, appearing as a change in the probability density function, has been reported in a 600-km system [15]. Cheng Yong et al. [21] carried out the performance comparison of DCF-based and chirped FBG-based dispersive 40 Gb/s transmission systems.

At high bit rates, modulation format and channel power for modern long-haul fiber-optic transmission systems still remain the critical issue in debate for optimum system design. The subject of this work is to enhance the SPM-limited transmission distance using various data formats in 10 and 40 Gb/s optical communication systems based on numerical simulations and modeling. For a single-channel optimum dispersion-managed lightwave system, the SPM-limited transmission distance for NRZ, RZ, CSRZ and RZ-DPSK formats by varying the input powers has been analyzed taking into account the effect of nonlinear phase noise due to ASE in the erbium-doped fiber amplifiers (EDFAs). This paper is divided into five sections. In Section 2, the theoretical analysis has been illustrated for SPM-limited transmission distance for the variation in the average input power. Section 3 describes the system configuration and the numerical model used to investigate the SPM-limited system performance. Section 4 reports the results of the transmission performance for various data formats without and with ASE noise of EDFAs, and finally in Section 5 conclusions are made.

## 2. Theory

In a single-channel optical communication system, for lower channel powers, the maximum transmission length is determined by the accumulated amplifier noise in the system, and for higher channel powers, the system behavior is limited through the nonlinear effects in the fiber such as SPM [13]. SPM is a parasitic phase modulation caused by signal optical power modulation and fiber nonlinearity, which broadens the signal optical spectrum. In intensity modulated-direct detection systems, this parasitic phase modulation and spectral broadening are converted to an unwanted intensity modulation through chromatic dispersion of the transmission fiber, thus causing waveform distortion. High chromatic dispersion makes a system particularly vulnerable to SPM. Although dispersion compensation at the end of each fiber span can correct for the waveform distortion caused by linear chromatic dispersion, it cannot completely compensate for the distortion caused by SPM as SPM-induced phase shift is created along the fiber in a continuous way and the SPM created at each location requires a different value of optical dispersion compensation. This problem becomes more significant at high data rates and when the dispersion length is comparable to the nonlinear length. As given in Ref. [1,2], the dispersion length $L_D$ and the nonlinear length $L_{NL}$ are defined as

$$L_D = T_0^2/|\beta_2| \text{ and } L_{NL} = (\gamma P)^{-1}$$

where the signaling period $T_0 = T_{FWHM}/1.665$ for Gaussian pulses and $\beta_2 = -\lambda^2 D/2\pi c$. At $\lambda = 1.55\,\mu m$, for the standard SMF (SSMF) with dispersion $D = 17$ ps/(nm km), typical value of $\beta_2 = -20\,ps^2/km$. For bit rate $B = 10$ Gb/s, the slot duration $T_B = 100$ ps, $T_{FWHM} = 50$ ps, $T_0 = 30$ ps; thus $L_D = 115$ km. Whereas for bit rate $B = 40$ Gb/s, the slot duration $T_B = 25$ ps, $T_{FWHM} = 12.5$ ps, $T_0 = 7.5$ ps; thus $L_D = 2.812$ km. For nonlinear coefficient $\gamma = 1.31\,W^{-1}\,km^{-1}$ and optical input power $P = 0.1$ mW, $L_{NL} \approx 76$ km. Since $L_D \ll L_{NL}$ at 40 Gb/s, the nonlinear SPM effect dominates as compared to 10 Gb/s and the waveform distortion caused by SPM at 40 Gb/s is expected to be significant, even with optimum dispersion compensation.

The SPM effect is significant at high input powers and high bit rates. As a criterion for the determination of the SPM effect, at each input optical signal power level a maximum SPM-limited transmission distance $L_{SPM}$ is determined, which is defined as the distance at which the eye-opening penalty (EOP) reaches 1 dB [13], where

$$\text{EOP[dB]} = 10\log_{10}\left(\frac{\text{Eye opening back to back}}{\text{Eye opening after transmission}}\right)$$

Thus,

$$L_{SPM} = N_{max}\,L \tag{1}$$

where $N_{max}$ is the maximum number of spans and $L$ is the length of SSMF in each span. In practical optical systems, another major limitation to the transmission distance is the accumulated ASE noise generated by inline EDFAs through the degradation of receiver SNR. So, EOP is not sufficient to fully characterize the signal quality, we also require a worst-case $Q$-factor $>10$ dB over this fiber length. Neglecting signal waveform distortion and considering the action of signal-spontaneous beat noise alone in the receiver, the SNR-limited receiver $Q$-value is directly proportional to the square-root of optical signal power [12,13] and is given as

$$Q = \sqrt{\frac{\lambda P_{in}}{2Nhc\,NF_{eff}(G_{eff}-1)B_e}} \tag{2}$$

where $P_{in}$ is the average optical power launched into each fiber span, $h$ is the Planck's constant, $c$ is the speed of light, $\lambda$ is the signal wavelength, $B_e$ is the receiver bandwidth and $N$ is the total number of amplified fiber spans. In this noise calculation, each DCF module, which consists of a DCF sandwiched between two in-line EDFAs, is considered as an equivalent optical amplifier with the effective noise figure $NF_{eff} = 4.4$ dB and the effective optical gain $G_{eff} = 20$ dB, which compensates for the loss of the 100 km transmission fiber. Thus using Eq. (2) and setting $Q > 10$ dB SNR-limited transmission distance $N$ can be calculated.

However, it is well-known that DPSK modulation might be vulnerable to the Gordon–Mollenauer effect [14,15,17] where ASE optical intensity noise can be converted into phase noise through fiber nonlinearity, which degrades DPSK signals [7–9,17]. When nonlinear phase noise is considered, as per Ref. [10] the SNR-limited receiver $Q$ value can be evaluated by

$$Q = \frac{\pi}{2\sqrt{2(\sigma_L^2 + \sigma_{NL}^2)}} \tag{3}$$

where $\sigma_L^2$ and $\sigma_{NL}^2$ are the variance of linear optical amplifier noise and variance of nonlinear phase noise, respectively, and they are considered as independent Gaussian noises. The expressions of $\sigma_L^2$ and $\sigma_{NL}^2$ are [10] as follows:

$$\sigma_L^2 = 1/(2\,\text{OSNR}) \tag{4}$$

$$\sigma_{NL}^2 = \frac{2\langle\phi_{NL}\rangle^2}{(\text{OSNR}+0.5)^2}\left(\frac{2}{3}\text{OSNR} + \frac{1}{6}\right) \approx \frac{2\langle\phi_{NL}\rangle^2}{3\text{OSNR}} \tag{5}$$

The approximation in Eq. (5) was given in Ref. [17]. Using both (4) and (5), the $Q$ value in (3) can be evaluated. OSNR in Eqs. (4) and (5) is the optical SNR defined over a matched optical filter with bandwidth $B_e$ and can be expressed [12,13] as

$$\text{OSNR} = \frac{P_{in}}{2\,Nhc\,NF_{eff}(G_{eff}-1)B_e} \tag{5'}$$

and $\langle\phi_{NL}\rangle$ in Eq. (5′) is the accumulated mean nonlinear phase shift and can be expressed [10] as

$$\langle\phi_{NL}\rangle = N\gamma P_{in} L_{eff} \tag{6}$$

where $L_{eff}$ is the effective nonlinear fiber length and is given as $L_{eff} = (1-\exp(-\alpha L))/\alpha$, with $\alpha$ being the attenuation coefficient of the fiber.

Because the $L_{SPM}$ does not rely on a particular span length, Eq. (1) can also be applied to systems in which the length of the fiber spans varies, provided that the individual span lengths are sufficiently larger than the effective length $L_{eff}$ [1].

## 3. System description and numerical model

The schematic of the optical communication system simulation setup is shown in Fig. 1. In all, 10 and 40 Gb/s optical systems are evaluated using the same system setup with central frequency = 193.1 THz. At the transmitter, a binary logical data stream is converted into different modulated optical signals using NRZ, RZ, CSRZ and RZ-DPSK modulators. A $2^6-1$ PRBS data pattern is used to drive the modulator with Samples/bit = 128. An externally modulated CW laser source having line width = 10 MHz with variable input power is used. An EDFA post-amplifier with gain = 20 dB and NF = 4 dB is used in the transmitter to boost the optical signal to the desired power level for transmission through $N$ amplified fiber spans. Each fiber span, except for the last one, consists of 100 km of SSMF and a DCF module of 21.25 km. In the inline span, the DCF is sandwiched between two inline EDFAs, each having NF = 4 dB and gain 20 dB. This link design ensures minimal loss between amplifiers and thus reduces the influence of the dispersion compensator on the OSNR. For the last span ($N$th span), the length of DCF is varied in each simulation to maintain the signal EOP below 1 dB so as to minimize the overall system penalty. The characteristics of both SSMF and DCF are summarized in Table 1. The nonlinear effects due to DCF are made negligible by setting the output power of the first EDFA less than −20 dBm. The launch power into the SSMFs is assumed to be the same for all fiber spans. Because of the symmetrical structure, the system setup is also suited for bidirectional transmission. Dispersion map for the system described is shown in Fig. 1(b). All fiber spans are fully post-compensated by the inline DCFs and the last fiber span of variable length compensates for the residual dispersion in the channel.

In the receiver, the signal is preamplified and is detected by a PIN photodiode (PD) for direct detection of NRZ, RZ and CS-RZ optical signals, while a one-bit differential optical delay Mach–Zehnder interferometer (MZI) and balanced receiver are adopted in the RZ-DPSK optical receiver. MZI is used to correlate each bit with its neighbor and make the phase-to-intensity conversion. PIN PD has responsivity $[A/W] = 1$ and dark current = 10 nA. It is then passed through the low-pass Bessel filter with 3 dB cut-off frequency = 0.65 × bit rate, order of the filter = 4, depth = 100 dB. Thereafter, 3R regenerator is used to regenerate an electrical signal that can be connected directly to the BER analyzer, which is used as a visualizer to generate graphs and results such as eye diagram, BER, $Q$ value, eye opening, etc. To isolate the effect of SPM on signal distortions, ASE noise was turned off during the calculations of Figs. 2–5. However, in Figs. 6 and 7 ASE noise effect of the in-line EDFAs has also been considered. To investigate the impact of SPM and ASE noise on system performance, we performed extensive numerical simulations using the split-step-Fourier method.

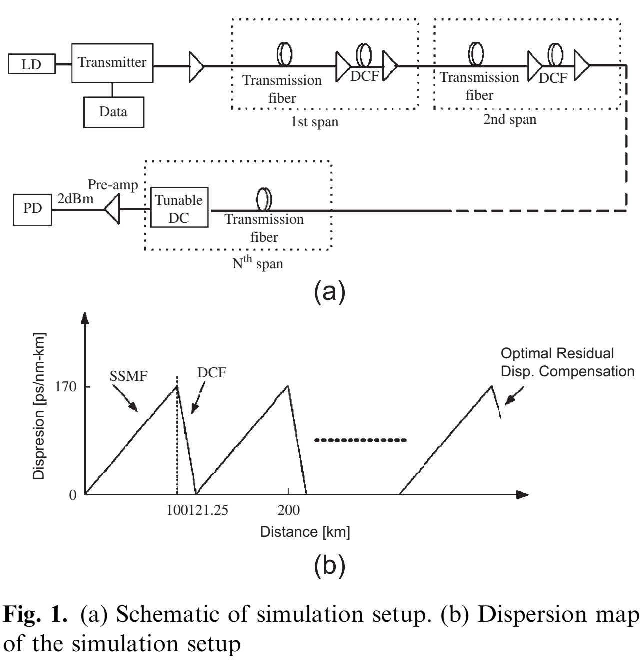


**Fig. 1.** (a) Schematic of simulation setup. (b) Dispersion map of the simulation setup

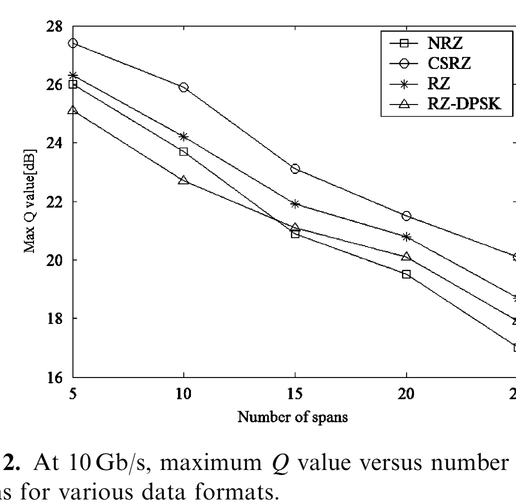


**Fig. 2.** At 10 Gb/s, maximum $Q$ value versus number of fiber spans for various data formats.

**Table 1.** Fiber parameters

| Fiber | Attenuation, α (dB/km) | Dispersion at 1550 nm, $D$ (ps/km nm) | Dispersion slope at 1550 nm, $S$ (ps/km nm$^2$) | Effective core area, $A_{eff}$ (μm$^2$) | Nonlinear refractive index, $n_2$ ($10^{-20}$ m$^2$/w) |
|---|---|---|---|---|---|
| SSMF | 0.2 | 17 | 0.075 | 70 | 2.6 |
| DCF | 0.5 | −85 | −0.3 | 22 | 2.6 |

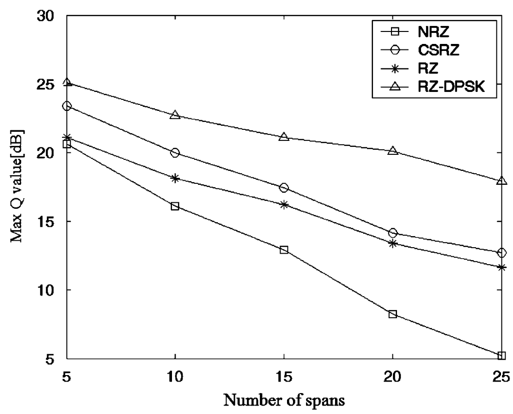


**Fig. 3.** At 40 Gb/s, maximum $Q$ value versus number of fiber spans for various data formats.

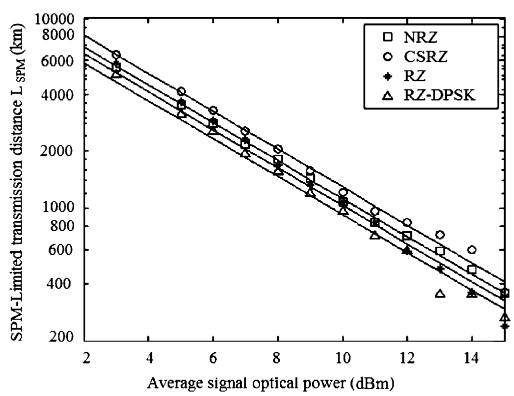


**Fig. 4.** At 10 Gb/s, SPM-limited transmission distance versus launched optical power for various data formats.

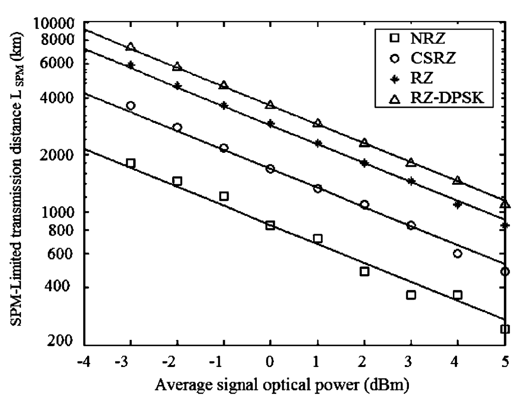


**Fig. 5.** At 40 Gb/s, SPM-limited transmission distance versus launched optical power for various data formats.

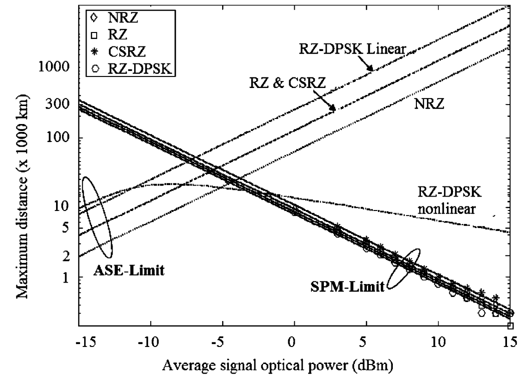


**Fig. 6.** At 10 Gb/s, SPM-limited transmission distance versus launched optical power for various data formats showing SPM limit and ASE limit.

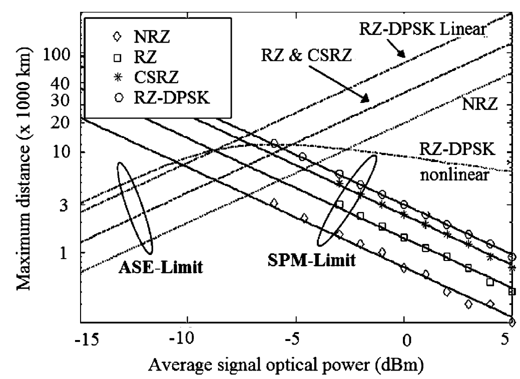


**Fig. 7.** At 40 Gb/s, SPM-limited transmission distance versus launched optical power for various data formats showing SPM limit and ASE limit.

## 4. Results and discussion

Fig. 2 shows the results of numerical simulations for various data formats. Maximum $Q$ value as a function of number of fiber spans has been obtained for the 10 Gb/s system with Pin = 6 dBm. It can be seen in the figure that with the increase in the number of fiber spans the $Q$ value decreases. Since only a single channel has been considered in the system, no nonlinear crosstalk is involved, and the signal degradation is mainly attributed to the SPM nonlinearity at such low power [1]. The CSRZ data format gives the best performance followed by the RZ and RZ-DPSK, whereas NRZ performs better than RZ-DPSK if the number of spans is less than 15. Also the CSRZ format shows almost 3 dB $Q$ value improvement as compared to the NRZ format. This is attributed to the improved tolerance of CS-RZ to SPM as also reported in Ref. [5–9]. It can also be concluded that at 10 Gb/s, RZ-DPSK is less robust to nonlinear effects in long-haul transmission systems. For the 40 Gb/s system, Fig. 3 shows the comparison of various data formats for maximum $Q$ value as a function of the number of fiber spans. Fig. 3 shows the same trend for $Q$ value as shown in the 10 Gb/s system; however, significant reduction in $Q$ value at the 40 Gb/s data rate is observed as compared to 10 Gb/s for all the formats. For 15 fiber spans, $Q$ value reduces from 23.2 dB at 10 Gb/s to 17.8 dB at 40 Gb/s for the CSRZ format.

Since at higher data rates fiber nonlinearity increases, SPM-induced signal degradation also increases [20]. At higher data rates, the RZ-DPSK data format outperforms the CSRZ, RZ and NRZ. It is known that the NRZ, RZ and CSRZ are intensity modulation-based optical systems and SPM originates from the signal intensity modulation. Intuitively, optical phase modulation-based RZ-DPSK lightwave systems significantly reduce the effect of SPM because the optical power is not modulated, which attributes to the increased $Q$ value as compared to the other data formats [10,11,19].

Fig. 4 shows the calculated maximum SPM-limited transmission distance versus the average signal optical power at the input of each transmission fiber span in the 10 Gb/s system. A remarkable feature of this plot is that for all modulation formats, transmission distance $L_{SPM}$ in the logarithm scale is inversely proportional to the average signal optical power $P_{in}$ in dBm. As given in Refs. [13,16], such linear relationship can be expressed as

$$P_{SPM} = L_{SPM}\, P_{in} \tag{7}$$

where $P_{SPM}$ is a figure of merit and is constant depending on the modulation format. Scattered points in Fig. 4 represent the numerically simulated maximum SPM-limited transmission distance for NRZ, RZ, CS-RZ and RZ-DPSK modulation formats and solid lines are the curve fittings using Eq. (7) with slope $-1$. Excellent agreement exists between the simulated data and the fitting curve. In each fiber span at the beginning of the SSMF, a certain amount of SPM-induced chirp is generated, which is then converted into pulse distortions by fiber dispersion. For low signal powers, these waveform distortions are small, and thus, the SPM-induced chirp is insignificant. However, an increase in span count and launch power results in the generation of a nonlinear frequency chirp and its conversion into intensity fluctuations by the fiber dispersion degrades the system performance. Thus the SPM-limited maximum transmission distance $L_{SPM}$ for various modulation formats decreases for varying values of channel powers .It can be seen that reducing the channel power by 3 dBm almost doubles the transmission distance. This shows good agreement with the results reported in Ref. [13] and [16]. The values of $P_{SPM}$ for different formats have been given in Table 2. At 10 Gb/s there is no obvious difference between various modulation formats, and their $P_{SPM}$ values differ by less than 20% as shown in Table 2. This indicates that at low data rate dispersion-managed optical systems, SPM-induced limitation is relatively insensitive to the signal modulation formats. This is attributed to the fact that at low data rate, the dispersion length is longer than the nonlinear length of the fiber. The transmission performance of RZ-DPSK systems at 10 Gb/s is considered to be primarily degraded by the Gordon–Mollenauer effect [10,14].

**Table 2.** $P_{SPM} = P_{in} L_{SPM}$ product for different modulation formats in (mW km)

| Format | 10 Gb/s | 40 Gb/s |
|---|---|---|
| NRZ | 11,222 | 855 |
| RZ | 10,294 | 1683 |
| CS-RZ | 12,926 | 2864 |
| RZ-DPSK | 9254 | 3636 |

Similarly, Fig. 5 shows the maximum SPM-limited transmission distance versus the average signal optical power at the input of each transmission fiber span at the 40 Gb/s system. Not surprisingly, the same linear relationship for all modulation formats holds at 40 Gb/s though the SPM degrading effect is much larger than at 10 Gb/s. Also, using Eq. (7), we can get similar curve fittings in the 40 Gb/s system. Scattered points in Fig. 5 represent numerically simulated maximum $L_{SPM}$. At 40 Gb/s, the system tolerance to SPM-induced nonlinear distortion is strongly affected by signal modulation formats as is evident from Fig. 5. For instance, the $P_{SPM}$ value for RZ-DPSK is approximately 400% larger than the $P_{SPM}$ value for NRZ as is emphasized by the results shown in Table 2. At this data rate, the dispersion length is very less than the effective nonlinear length of the fiber; so, the signal modulation format plays an increasingly important role in determining the resistance against nonlinear degradation such as SPM. For the RZ-DPSK format, since the optical pulses spread quickly and overlap with adjacent pulses before they reach the effective length of the fiber, the effect of the noise will decrease and it gives the best performance. Also the balanced detection of RZ-DPSK is responsible for its enhanced performance. The results show that RZ-DSPK tolerates 1–5 dBm more power than the other data formats. These results are in good agreement with the studies in the papers [16,18,20].

Using Eq. (2), the SNR-limited transmission distance (at which $Q$ is reduced to 10) for average optical signal power has been calculated for various data formats and is shown in Fig. 6 (for 10 Gb/s) and Fig. 7 (for 40 Gb/s). Also, for the RZ-DPSK data format the SNR-limited transmission distance by using Eqs. (3)–(6) was calculated and denoted as dashed lines 'RZ-DPSK nonlinear' as shown in Figs. 6 and 7. It is quite evident that nonlinear phase noise reduces the noise-limited transmission distance at high power levels. We also find that the benefit of the balanced receiver is diminished as nonlinear phase noise becomes dominant over linear noise. In a single-channel 10 Gb/s system, as shown in Fig. 6, the RZ-DPSK modulation format gives the best performance for linear ASE noise but loses its advantage over other modulation formats when nonlinear phase noise is considered, which is consistent with the results in Ref. [16]. However, at 40 Gb/s as shown in Fig. 7, SPM-induced nonlinear waveform distortion is the dominant effect and RZ-DPSK remains the best choice for the modulation format even after considering the effect of nonlinear phase noise.

## 5. Conclusions

Here, investigations of 10 and 40 Gb/s systems having optimum post-dispersion compensation using in-line DCF have been carried out for maximum transmission distance with and without ASE noise. The impact of NRZ, RZ, CSRZ and RZ-DPSK data formats on the transmission with the variation input powers has been shown. Figure of merit $P_{\max}$ is calculated for the various data formats. It is reported that at 10 Gb/s, RZ-DPSK gives the least value of $P_{\max}$ due to the Gordon–Mollenauer effect whereas at 40 Gb/s it gives the highest value of $P_{\max}$, which is 400% larger than the $P_{\mathrm{SPM}}$ value for NRZ. At 10 Gb/s, the CSRZ format gives the best performance and SPM-induced limitation is relatively insensitive to the signal modulation formats. However, at 40 Gb/s, the system tolerance to SPM-induced nonlinear distortion is strongly affected by signal modulation formats and RZ-DSPK can tolerate about 1–5 dBm more power than the other data formats. Also, the reduction in the channel power by 3 dBm almost doubles the transmission distance. It is also shown that nonlinear phase noise reduces the noise-limited transmission distance at high power levels but still RZ-DPSK remains the best choice for data formats at 40 Gb/s.

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