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RESEARCH ARTICLE

Simulation and comprehensive assessment of single channel RZ-DPSK optical link by dispersion management with channel bit rate beyond 40 Gbits/s

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Abstract This paper studied the influence of return to zero-differential phase-shift-keying (RZ-DPSK) data format on techniques of pre-, post- and pre/post combination dispersion compensation for faithful transmission of optical signal at 80 and 100 Gbits/s channel bit rate via simulation. The purpose of this study was to find out the dispersion compensation techniques for optimal transmission with the interaction effects of self-phase modulation (SPM) and amplifier spontaneous emission (ASE) for RZ-DPSK encoded optical data. By the simulation method, it was found out that the RZ-DPSK data format can be allowed with a transmission distance of about 700 km of standard single mode fiber (SMF) at 100 Gbits/s, and it can be provided with farther transmission distance of more than 1000 km at 80 Gbits/s with the combination of the pre- and post-compensation technique. To efficiently suppress the effect of ASE and improve optical signal-to-noise ratio (OSNR), the bandwidth frequency of optical receiver filter was found to be at least equal to bit rate.

Keywords return to zero-differential phase-shift-keying (RZ-DPSK), dispersion compensation, self-phase modulation (SPM), amplifier spontaneous emission (ASE), bit rate, optical filter bandwidth

1 Introduction

Laser technology and optical fiber have been helpful to realize the speed of up to 40 Gbits/s data rates. Higher data rate is still needed at the backbone network at per channel to increase the capacity of the network in the metropolis.

By the increasing the bit rate of per-channel to 80, 100 Gbits/s or even more, a dense wavelength division multiplexing (DWDM) system with very high spectral efficiency and large transport capacity can be obtained. However, to maintain the same amplifier spacing as those of existing 10 and 40 Gbits/s systems, high optical input power will be required as utilizing the bit rate larger than 40 Gbits/s. High input optical power is restricted due to the nonlinear effects of the transmission fiber [1,2]. In single-channel transmission system, signal suffers degradation due to the interaction between self-phase modulation (SPM) and group velocity dispersion (GVD) in the presence of high-power. The technique of dispersion compensation is used to combat this impairment from the interaction between SPM and GVD. In wavelength division multiplexing (WDM) systems, each channel can be separately provide by pre-, post- or pre/post combination dispersion compensation (symmetric or hybrid compensation).

There are two devices popular for dispersion compensation. One is dispersion compensation fiber (DCF). DCF is a wide band device with small effective mode area of only about 20 μm^2. It makes DCF be used to enhance nonlinear effects at high input power [1]. The disadvantage of DCF is the need of erbium-doped fiber amplifiers (EDFA) to compensate for insertion loss. DCF is very expensive although it is very good for ultra-long haul transmission. The other device for dispersion compensation is chirped fiber Bragg grating (CFBG). CFBG is a narrow band device and provides a compact low-loss means of compensating fiber dispersion [3]. However, CFBG device is rarely used in ultra-long-haul transmission [4]. When CFBGs are used in long-haul systems, many CFBGs are cascaded and the available bandwidth is narrowed. The dependence of the system performance on the signal

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wavelength is observed and fine adjustments of signal wavelength are required for optimal performance [5]. This implies a strict requirement on the source of CFBG-based system. It is one of the main obstacles that impair the use of CFBGs in an ultra-long-haul system.

In the system of optical communication transmission, modulation format plays a key role in determining the input power for long-haul transmission link [6]. Among several modulation format, return to zero differential phase-shift keying (RZ-DPSK) has great tolerance to nonlinear phase noise as reported in Ref. [7]. And it is useful for ultra-long-haul transmission [8]. Modulation format and channel power are main issues for the optimum design of high bit rate and long-haul lightwave systems [6].

In this study, a simulative analysis was carried out to give a comprehensive assessment of a single channel optical link utilizing 80 or 100 Gbits/s RZ-DPSK signal. The degradation of performance due to SPM-induced impairments in a noisy and noise free system was investigated with parameters of transmitter and receiver minutely chosen for a good output. The evaluation is done with pre-, post- and the combination of the two dispersion compensation management by varying the input power. The following of this paper is divided into three sections. In Section 2, a brief theoretical analysis is given to emphasize the impact of and noise on the quality of the output of an optical signal through an optical link. It also describes the simulation set up and parameters. In Section 3, the results of the performance of the link with or without both nonlinearities and noise are analyzed. In Section 4, it is concluded for this work.

2 Basic theory and simulation set up

In single channel optical transmission, the signal suffers much degradation due to the effects of GVD or SPM. SPM is a nonlinear phase modulation due to intensity modulation and fiber nonlinearity. It broadens the spectrum of an optical pulse, which will result in waveform distortion under the combination effect of chromatic dispersion caused by GVD. A highly dispersive system becomes vulnerable to SPM. If waveform distortion caused by chromatic dispersion can be corrected by dispersion compensation at the end of each span, the distortion caused by SPM cannot be totally eliminated. At high-bit rate, the distortion caused by both SPM and GVD is significant especially when the dispersion length (L_D) is comparable to the nonlinear length (L_NL). These two quantities are described by the following [1]: $L_\mathrm{D} = T^2/|\beta_2|$, $L_\mathrm{NL} = (\gamma P)^{-1}$, where T is the pulse width; $\beta_2 = -\lambda D/2\pi c$, describes the GVD parameter; $\gamma = 2\pi n_2/\lambda A_\mathrm{eff}$, is the expression of the nonlinear constant; and P is the optical input power. n_2 is the nonlinear refractive and A_eff is the effective area. If $L_\mathrm{D} = L_\mathrm{NL}$, the pulse suffers broadening from GVD effects, and the transmission is limited by SPM effects. For $L_\mathrm{D} \approx L_\mathrm{NL}$, dispersion and nonlinearity act together on the propagating signal [1,9].

The Q-factor is a metric to consider for a worse case of $Q > 10$ dB, when evaluating optical network as suggested in Ref. [10]. For the DPSK signal, Q is given as [11]

$$Q = \frac{\pi}{2\sqrt{(\sigma_\mathrm{L}^2 + \sigma_\mathrm{NL}^2)}}, \tag{1}$$

where σ_L^2 and σ_NL^2 are the variance of the amplifier noise and the variance of the nonlinear phase noise Φ_NL, respectively. The expressions of these two quantities are as follows [10,11]:

$$\sigma_\mathrm{L}^2 = \frac{1}{2\mathrm{OSNR}}, \tag{2}$$

$$\sigma_\mathrm{NL}^2 = \frac{(\Phi_\mathrm{NL})^2}{\left(\mathrm{OSNR} + \dfrac{1}{2}\right)^2}\left(\frac{2}{3}\mathrm{OSNR} + \frac{1}{6}\right) \approx \frac{2\,(\Phi_\mathrm{NL})^2}{3\,\mathrm{OSNR}}. \tag{3}$$

The approximation in Eq. (3) was given in Ref. [12]. The Q value in Eq. (1) can be evaluated using Eqs. (2) and (3). The OSNR in Eqs. (2) and (3) is the optical signal-to-noise ratio at the receiver input end and was given as [9,12]

$$\mathrm{OSNR} = \frac{P_\mathrm{in}}{2Nhc\mathrm{NF}(G-1)B_\mathrm{o}}, \tag{4}$$

Φ_NL is the accumulated mean nonlinear phase shift express as [13]

$$\Phi_\mathrm{NL} = NP_\mathrm{in}L_\mathrm{eff}, \tag{5}$$

where P_in represents the average optical power launched in each fiber span, N is the total number of amplified fiber spans, h is the Planck's constant, c is the speed of light, NF is the EDFAs effective noise figure, G is the effective optical amplifier gain of the EDFAs mounted along the fiber link, B_o is the receiver optical bandwidth, L_eff is the effective nonlinear fiber length per span and is given as $L_\mathrm{eff} = (1-\exp(\alpha L))/\alpha$, with L being the fiber length as per span and α is the attenuation coefficient of the fiber.

The schematic diagrams of the simulation with pre-, post- and pre/post dispersion compensation are shown in Figs. 1, 2 and 3, respectively. The simulation is run for a sequence length of 1024 bits with 32 samples per bit in order to ensure results accurate. The DPSK transmitter at the standard frequency 193.1 THz for the three set up is same, and it is composed of a continuous wave laser and two Mach–Zehnder modulators (MZMs). The first MZM is modulated by 80 or 100 Gbits/s pseudorandom bit sequence (PRBS) of $2^{15}-1$ length to obtained non-return-to zero (NRZ) signal. The NRZ optical signal is shaped with a clock signal in the second MZM to generate 33% return-to-zero (RZ) waveform signals. The generated

RZ-DPSK signal is amplified to 0 dBm by the booster amplifier as shown in Figs. 1, 2 and 3. The amplified signal is varied from -5 to $+5$ dBm using a variable optical attenuator (VOA). The transmission link consists of 100 km of SMF and 17 km of DCF with two EDFA amplifiers stages per span at 1550 nm wavelength channel frequency. Depending on the placement of DCF in each span, the dispersion compensation is categorized into the three implementations: dispersion pre-compensation, dispersion post-compensation and dispersion pre/post-compensation. In the pre-compensation scheme shown in Fig. 1, the DCF is placed prior to the transmission fiber (SMF). The signal into the span passes through the DCF fiber with normal dispersion regime ($D < 0$) before getting into the SMF fiber. In the post-compensation scheme, the DCF is placed after the SMF as shown in Fig. 2. Here, the signal into the span travels through the SMF fiber with anomalous dispersion region ($D > 0$), then through the DCF fiber. In the pre/post-compensation schemes, the fiber span is composed of two amplifiers stages to compensate for the loss in the SMF and DCF. The combination of pre/post-compensations illustrated in Fig. 3 is accomplished with two SMF fibers, two DCF fibers and four amplifiers stage per span. Here, half of the dispersion is compensated before SMF, pre-compensation; and the other half compensated after it, post-compensation.

The modulated signal gets into the span through the booster optical amplifier (booster Amp) mounted to pre-amplify the signal before transmission. The inline EDFAs (IL Amp) with noise figure 5 dB supplied gain to compensate for the loss in the different fibers. The gains of the inline amplifiers are fixed to 20 and 8 dB for SMF

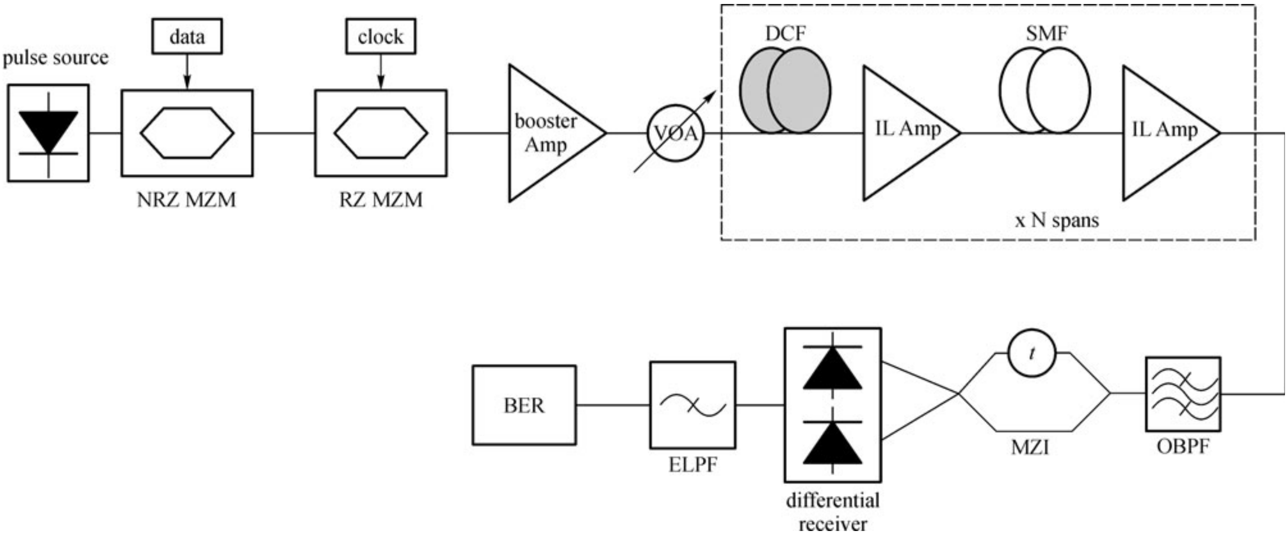


Fig. 1 Pre-compensation dispersion scheme

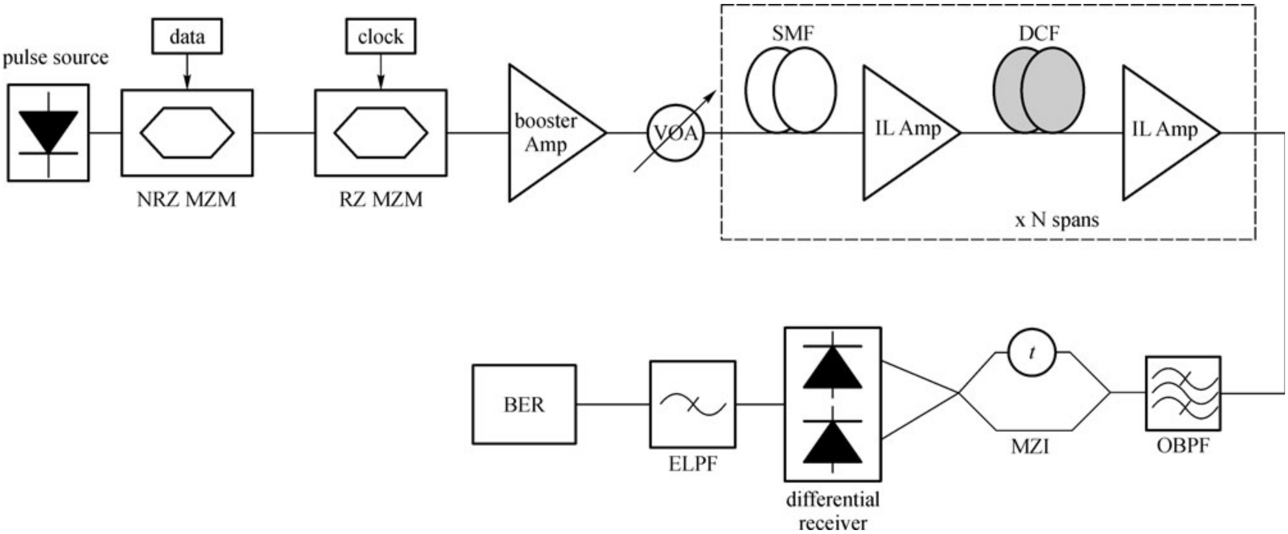


Fig. 2 Post-compensation dispersion compensation scheme

Table 1 Fiber parameters

fiber	$\alpha/(\mathrm{dB\cdot km^{-1}})$	D/(ps/km-nm)	$S/(\mathrm{ps/km\text{-}nm^2})$	$A_{\mathrm{eff}}/\mu\mathrm{m}^2$	$n_2/(10^{-20}\ \mathrm{m^2\cdot W^{-1}})$
SMF	0.2	17	0.058	80	2.6
DCF	0.5	−100	−0.34	21	2.6

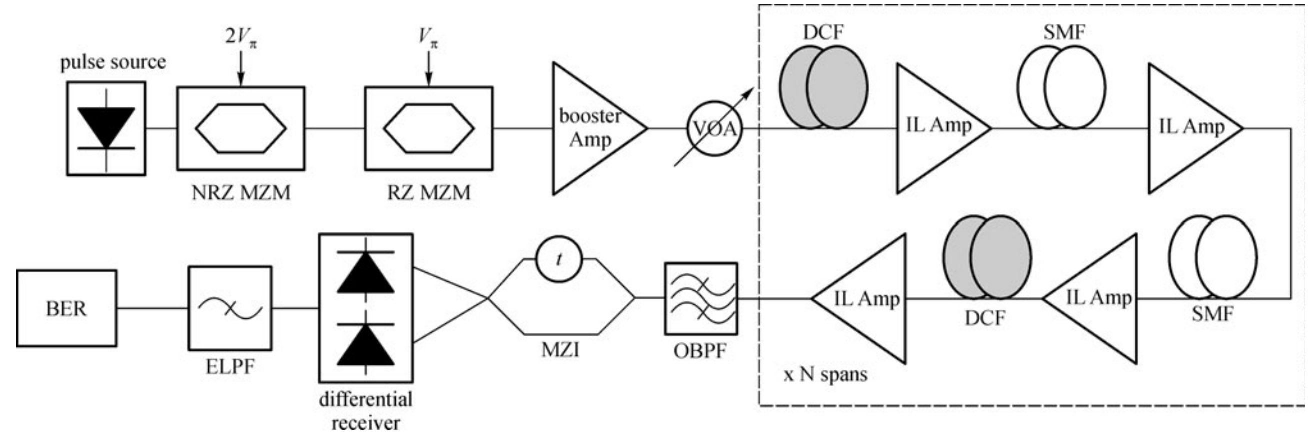


Fig. 3 Pre/post-compensation dispersion compensation scheme

and DCF in the pre- and post-compensation schemes, respectively. In the case of pre/post scheme, these values are set to 10 and 4 dB for SMF and DCF, respectively.

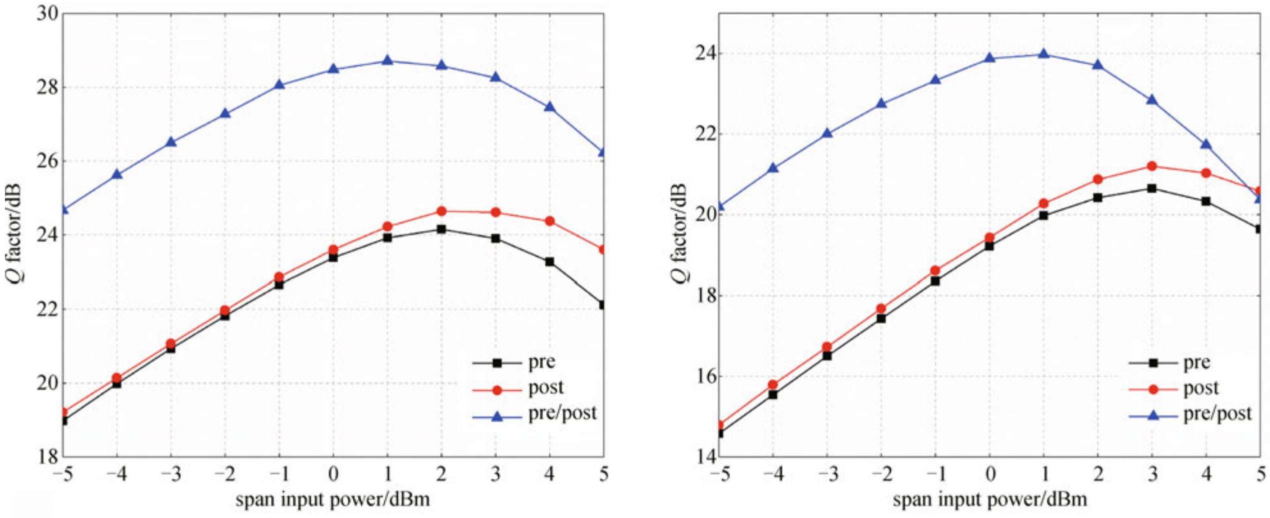
The settings in the amplifier model are allowed the inclusion and exclusion of the noise. The fibers parameters are shown in Table 1. The parameter α is the attenuation coefficient and accounts for the optical signal loss in the fiber. The dispersion D and the dispersion slope S are the chromatic dispersion parameters selected to ensure full compensation. The accumulated dispersion in the 100 km SMF is 1700 ps/nm compensated for by the cumulative dispersion −1700 ps/nm in the 17 km DCF. The effective core area A_{eff} and the nonlinear refractive index n_2 are used to determine the nonlinear coefficient γ according to the relation describes in the first paragraph of this section. The values of the nonlinear coefficient of SMF and DCF calculated at 1550 nm wavelength are $\gamma = 1.3$ and 5.0 $\mathrm{W^{-1}\cdot km^{-1}}$, respectively. The Raman scattering effects were ignored in this simulation. In the receiver, the signal passes through an optical band pass filter with optical bandwidth frequency of at least equals the bit rate. The signal is detected by a one-bit differential optical delay Mach-Zehnder interferometer (MZI), and balanced receiver is adopted with two positive-intrinsic-negative (PIN) detectors. Each PIN photodiode (PD) has responsive of 1 A/W and dark current = 0.1 nA. After detection, the signal is filtered by a 4th-order Bessel low-pass filter (ELPF), with a cut-off frequency equal 0.75 bit rate and a depth of 100 dB. Thereafter, three regenerators are used to regenerate an electrical signal connected directly to the bit error rate (BER) analyzer, which is used as a visualizer to generate graphs and results, such as eye diagram, BER, Q value, eye opening, etc.

3 Results and discussion

3.1 Optimum power of signal input

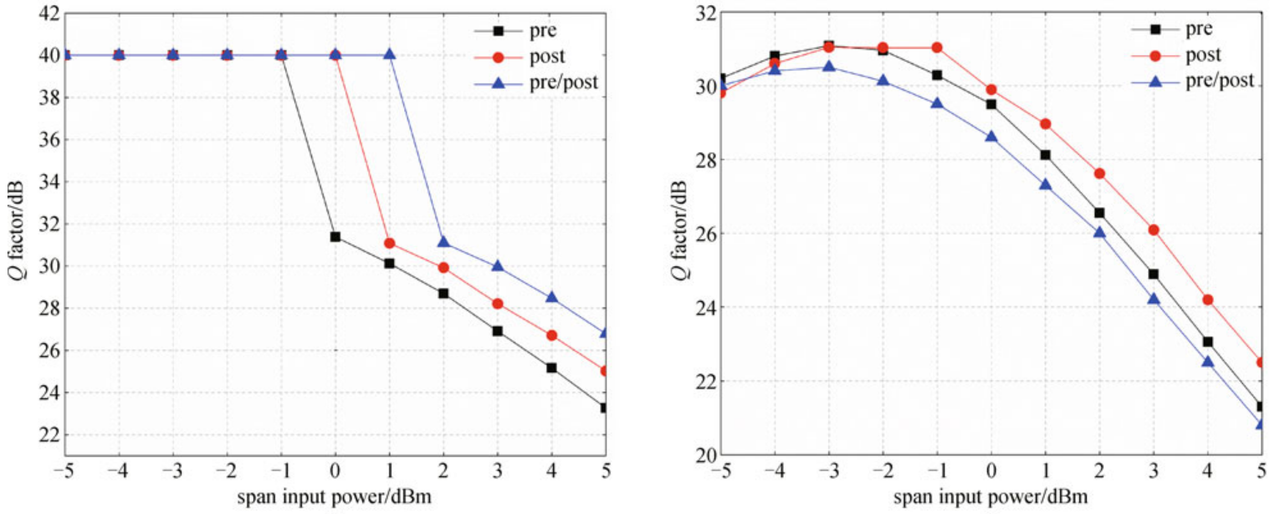
To make an assessment of the RZ-DPSK optical communication link, we first investigate many power levels with a transmission distance of 200 km, which enables us to find the optimum power level. The average power of signal input in each span is varied between −5 to + 5 dBm in step of 1 dBm. A variable optical attenuator placed after the booster amplifier helps to adjust the signal power, which is sent into the transmission link. In Fig. 4, it is shown that the Q factor of the link as the function of power span of signal input for schemes of three dispersion compensation. The optimum power levels range from 1 to 4 dBm with the threshold at 2 and 3 dBm at 80 and 100 Gbits/s for the pre- and post-compensation schemes, respectively. The pre/post-compensation scheme offers the optimum power of input span at 1 dBm irrespective of the rate of channel data under the combined effect of SPM and ASE. The effects of dispersion are assumed to be meaningless since total dispersion and slope compensation are applied. The ASE effects are more severe for input powers below 0 dBm as depicted in Fig. 5, which shows the results for various span of input powers against Q factor in noise free environment. This can be explained by the fact that at these input powers the OSNR is about 18.5 dB, and in the absence of amplifier noise it increases to 37 dB. The measured Q factor increases averagely above 10 dB for these power ranges in the noise free environment particularly for the pre- and post-compensation schemes. For the combination of pre and post scheme, the maximum increment is about 10 dB as shown in Table 2.

Signal at input powers above 0 dBm suffers more degradation due to fiber nonlinearities than that of amplifier noise. Therefore, at span input powers, where SPM effects are degradation factors, the pulse power into the DCF due to their small core area should be controlled to minimize these effects.



(a) (b)

Fig. 4 Q factor (dB) at various span input power with noise and nonlinearities with chromatic dispersion and attenuation fully compensated at channel bit rate (a) 80 Gbits/s; (b) 100 Gbits/s



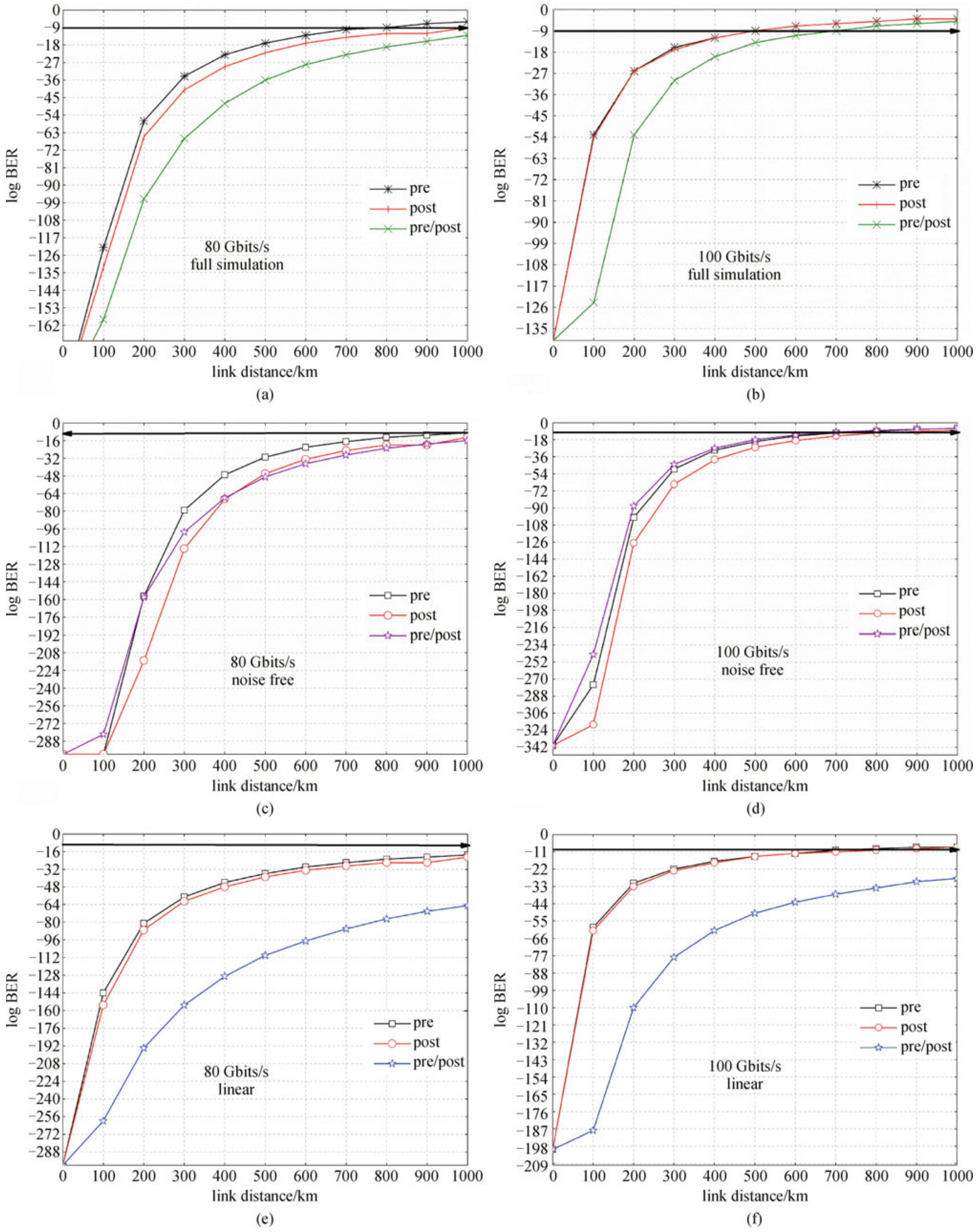
(a) (b)

Fig. 5 Q factor (dB) at various span input power without noise with chromatic dispersion and attenuation fully compensated for each span at channel bit rate (a) 80 Gbits/s; (b) 100 Gbits/s

Table 2 Q factor (dB) variations for the worse case and the threshold input powers to the reach of the ASE limit effects on span input power

	pre^{-5}	post^{-5}	pre/post^{-5}	pre^{0}	post^{0}	pre/post^{0}
80 Gbits/s						
full simulation	19	19.2	24.4	23.4	23.6	28.3
noise free	40	40	40	31.4	40	40
100 Gbits/s						
full simulation	14.6	14.8	20.2	19.20	19.4	23.9
noise free	30.2	29.8	30	29.5	29.9	28.6

Note: −5 and 0 represent here the span input powers of −5 and 0 dBm, respectively



(a) (b) (c) (d) (e) (f)

Fig. 6 Log BER as the function of transmission distance for single channel simulation with both nonlinearities and noise (a, b); without noise (c, d) and without nonlinearities (e, f) at 80 and 100 Gbits/s

To make a comparison between the three schemes, we chose a fixed input span power of 2 dBm for the rest of the simulation to investigate the link distance limit due to ASE and SPM-induced impairments.

3.2 Transmission distance limit

The main aim of this study is to assess the transmission distance attainable with RZ-DPSK modulated signal at speed as high as 100 Gbits/s to achieve a minimum 10^{-9} BER. For a single channel optical transmission, dispersion and attenuation are fully compensated. Thus, noise and fiber nonlinearities are primarily responsible for the degradation of an optical pulse. But, it is difficult to ascertain that total compensation will give the optimal output due to the interaction between GVD and SPM.

High power of input signal can improve OSNR, leading to a longer transmission distance. But high input power may cause signal degradation, due to SPM. Based on its basic definition, SPM depends on the power of pulse and the area of fiber. And since DCF has small core area, the input signal power in the DCF should be managed properly to limit SPM effects for the optimal output.

Running the simulation programs without amplifier noise or disregarding nonlinearities can be used to identify the origin of signal degradations. Figure 6 shows the corresponding BER as the function of the SMF distance using the average input span power of 2 dBm, which is in the optimum launch power range with reference to the result in Section 3.1.

The RZ-DPSK modulation format shows the robustness to noise and higher-order nonlinearities at the limit distances of 800 km for pre-compensation scheme and about 1000 km for both post- and pre/post-compensations at 80 Gbits/s bit rate with a BER of 1×10^{-9} limit. The distance reach 500 km at 100 Gbits/s for both pre- and post-compensation schemes and 700 km for pre/post-compensation at 1×10^{-9} BER limit.

The longer distance for the pre/post-compensation scheme can be achieved due to the interaction between SPM and GVD in this transmission scheme. First, the pulse is compressed because of the interaction between GVD and SPM in normal regime (pre-compensating). In the transmission fiber, SPM and GVD may cooperate with each other in such a way that the SPM-induced chirp is just right to offset the GVD-induced broadening of the pulse [2]. Then, the pulse is compressed again after transmission (post-compensation).

We carried another assessment of the transmission link about the optical filtering bandwidth at the receiver in relation to the optical bandwidth (B_o) to bit rate (R) ratio (B_o/R). Since noise has much larger bandwidth than that of the signal, its impact can be reduced by large bandwidth optical filters. At high power level SPM-induced impairments lead to great deterioration of the performance. SPM-induced chirping broadens the spectrum and adds high frequency components to the side lobes, which may require larger bandwidth to maintain the required peak value of the BER and its equivalent Q factor. Consequently, higher optical bandwidth may be required for the optimum performance at higher launch power level. From the results shown in Fig. 7, it will be recommended to adapt an optical filter with greater bandwidth, which is more than that of the bit rate for optimal performance achievement.

4 Conclusions

In this paper, an assessment of a single channel optical transmission link was presented at channel bit rate of 80 and

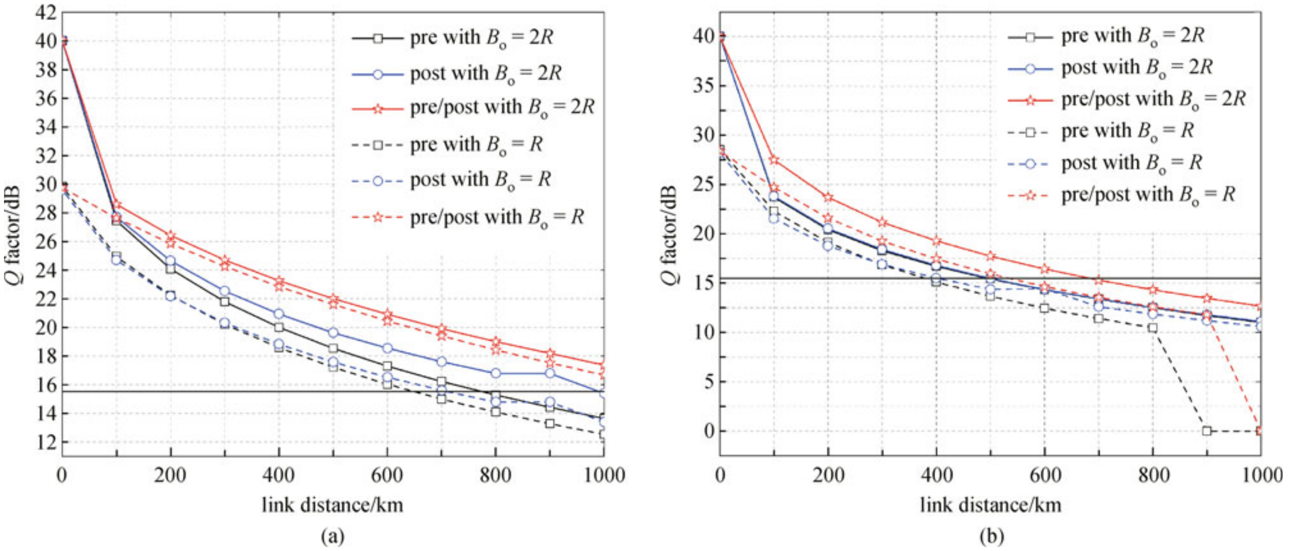


Fig. 7 Q factor vs link distance for optical filter bandwidth (B_o) equal to bit rate and twice the bit rate at 80 (a) and 100 Gbits/s (b)

100 Gbits/s under dispersion management with noise and SPM-induced impairments. Transmission distances of 700 km at 100 Gbits/s and 1000 km at 80 Gbits/s were achieved at 2 dBm span input power, with an optical filtering bandwidth of twice the bit rate. The simulation results in this study show that the performance of the system depends on not only the RZ-DPSK modulation format, but also the optical filtering parameters at the receiver side, and the signal input power into the transmission link mitigate SPM-induced impairments and amplifier noise.

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