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Performance evaluation of simple CSRZ-QDPSK transmitter configurations for 20-Gbps PON applications

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Abstract: The performance of 1 and 2 Mach–Zehnder modulator (MZM)-based simple carrier suppressed return to zero differential quadrature phase shift keying (CSRZ-QDPSK) transmitters is analyzed in a 20 Gb/s single-mode fiber optic link. The link's performance under the transmitter schemes is evaluated by analyzing the received constellation, eye diagram, quality factor, and eye opening penalty (EOP) in a passive optical networks (PON) scenario. It is observed that the simple transmitter provides performance closer to the case of the standard 3 MZM CSRZ-QDPSK-based transmitter reported in the literature and implemented in experiments.

Key words: Carrier suppressed return to zero differential quadrature phase shift keying, Mach–Zehnder modulator, dual drive Mach–Zehnder modulator, passive optical networks

1. Introduction

The demand for higher transmission capacity in optical fiber communication links has led researchers toward the development of improved modulation schemes. However, the optimum solution should also result in minimal alteration of the already existing infrastructure. Increased wavelength division multiplexing (WDM) channel data rates and narrower channel spacing are important requirements for future optical networks. Conventional on–off keying (OOK)-based transmission shows drastic performance degradation while operating at higher data rates and hence is restricted to a distance of few tens of kilometers. With data rates moving to tens of Gbps, dispersion in the fiber limits the distance over which the data can be transmitted. Other impairments such as polarization mode dispersion also become significant at high data rates. Further chirp in direct modulation mandates the need for external modulation at higher data rates. Single drive Mach–Zehnder modulators (MZMs) and dual drive Mach–Zehnder modulators (DD-MZMs) are popular candidates for external modulation and have been widely used for digital and analogue applications. A single stage DD-MZM for radio over fiber (RoF) architecture is suggested [1]. An integrated photonic radio frequency phase shifter using a DD-MZM is proposed [2]. The phase of the RF signal is shifted by tuning the amplitude of RF signal and DC bias voltage.

M-ary modulation schemes are spectrally efficient and investigated under different formats. CSRZ-QDPSK is one of the most promising modulation schemes for long haul and high data rate optical communication systems. In addition to the improved spectral efficiency it also provides better dispersion tolerance [3].

A differential quadrature phase shift keying (QDPSK) generation based on a single MZM whose 2 arms

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are driven by using the in-phase and quadrature-phase components is proposed [4]. By adjusting the operating points of the DD-MZM, phase modulation is achieved. The results indicate that at receiver bandwidth of 40 GHz, NRZ QDPSK requires at least 60 GHz modulation bandwidth, which leads to low spectral efficiency.

A single chip QDPSK encoder is proposed that provides increased tolerance to chromatic dispersion [5]. This encoder is hardware that precodes and phase modulates the in-phase and quadrature phase components into the laser carrier and thus needs only a pulse carver to complete the modulation. However, this simple structure results in increased cost of the transmitter.

QDPSK signal generation using a single MZM with 4 level drive voltages is reported in [6]. Generation of such a 4 level drive signal requires separate circuits to convert the input data into a 4 level amplitude phase shift keying (4-ASK) signal and thus increases transmitter complexity. Although 2 level or 3 level drive signals can also be used, it leads to a 3 dB reduction in the optical signal to noise ratio (OSNR).

A mathematical analysis of carrier suppressed return to zero-differential phase shift keying (CSRZ-DPSK) signal generation based on single dual-drive MZM is presented in [7]. The output intensity and phase of the MZM are determined by adjusting the modulation voltages and the bias points of the MZM. Analytical derivation for the differential phase shift keying (DPSK) signal generation is also reported.

The experimental demonstration of a new scheme to generate return to zero/carrier suppressed return to zero-differential phase shift keying (RZ/CSRZ-DPSK) signal that uses a single MZM and simple, commercially available digital integrated circuits is presented [8]. A clock pulse and a high speed XOR gate generate the required pulse stream, which is then modulated using a single DD-MZM. However, the data rate of this study is restricted to 10 Gbps. This approach was extended to CSRZ-DQPSK [9]. However, two DD-MZMs are used here, which can be improved to make it simple and more cost effective.

From the literature available to date, it is observed that the CSRZ-QDPSK transmitter is normally realized using 3 MZMs and schemes employing 2 and 1 MZM are sparse. The single MZM and 2 MZM-based reports available in the literature either provide a costlier implementation or are inefficient. Further detailed link analysis of their performance has not been investigated. Some of them are restricted to RF signal generation, but only the report of [3] provides a complete analysis of 20 Gbps data transmission using a CSRZ-QDPSK modulator utilizing 3 MZMs. There is a huge demand for a low cost, reduced complexity transmitter for high data rate passive optical network (PON) applications. Hence, this paper investigates a CSRZ-QDPSK transmitter with 1 and 2 MZMs that is simple and cost effective. Detailed performance analysis of a 20 Gbps, single channel optical link incorporating the proposed CSRZ-QDPSK transmitter is carried out in the optisystem simulation tool. From the perspective of passive optical networks, no amplifiers or dispersion compensated fiber were used. A comparative study with existing 3 MZM schemes predicts similar performance, illustrating the benefits of the proposed scheme.

2. Three MZM-based CSRZ-QDPSK transmitter

There are several schemes for generating a QDPSK signal, and one common approach using a 3 cascaded MZM is shown in Figure 1 [3]. Normally, a precoder is required in order to avoid recursive decoding in the receiver and error propagation and to reduce hardware complexity. The operation of the precoder is given by the following set of equations:

$$I_i(\overline{Q_{i-1} \oplus I_{i-1}})(\overline{d_i \oplus I_{i-1}}) + (Q_{i-1} \oplus I_{i-1})(\overline{g_i \oplus I_{i-1}}) \quad (1)$$

$$Q_i(\overline{Q_{i-1} \oplus I_{i-1}})(\overline{d_i \oplus I_{i-1}}) + (Q_{i-1} \oplus I_{i-1})(\overline{g_i \oplus I_{i-1}}). \quad (2)$$

The logic operation of the precoder is shown in Table 1 [4].

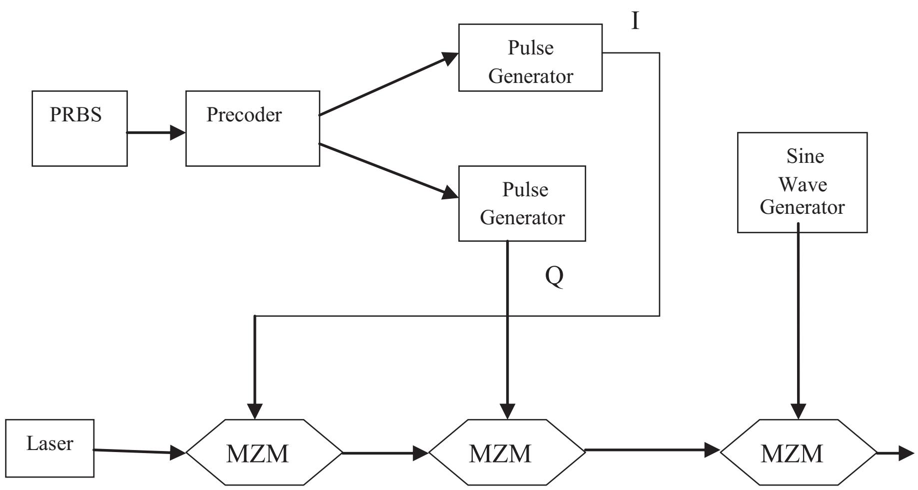

Figure 1. Block diagram of a 3 MZM-based CSRZ-DQPSK transmitter.

Table 1. Phase shift corresponding to various input bit pairs.

Data	Phase Diff $\Delta\theta$	I_k	Q_k
00	180°	$\overline{I_{k-1}}$	$\overline{Q_{k-1}}$
01	90°	Q_{k-1}	I_{k-1}
10	270°	Q_{k-1}	I_{k-1}
11	0°	I_{k-1}	Q_{k-1}

The precoded in-phase data are loaded to the first MZM to generate a phase shift of 0 or π. Similarly the quadrature phase data are given to the second MZM, generating a quadrature phase shift of 0 and $\pi/2$. For the values of I and Q (00, 01, 10, 11) the phase of the modulated signal is 0, $\pi/2$, $3\pi/2$, and π when coupled along the first MZM. The bias voltage and RF signal voltage are adjusted appropriately to get the desired phase response. The third MZM is used as a pulse carver that provides the required CSRZ pulse shaping. This is realized by driving a sinusoidal RF signal with frequency one quarter of the bit rate. The pulse carver is biased at the switching voltage (V_π) with a peak-to-peak amplitude of $+V_\pi$ and $-V_\pi$ for generating the CSRZ signal. This overall system generates the 4 states of the optical carrier required for the DQPSK modulation format.

3. Proposed CSRZ-QDPSK transmitter schemes

3.1. Two MZM-based

From [6], it can be inferred that using one DD-MZM greatly simplifies the design of the DQPSK transmitter.

Hence in the present article it is proposed to replace 2 single MZMs in the 3 MZM scheme by a single DD-MZM. To realize carrier suppression, a single drive modulator is retained. The block diagram of the CSRZ-QDPSK transmitter with 2 MZMs is shown in Figure 2. The optical carrier is suppressed using a single MZM.

The in-phase and quadrature phase data are given as input to two electrodes in the DD-MZM for which the suppressed optical carrier is provided as an input.

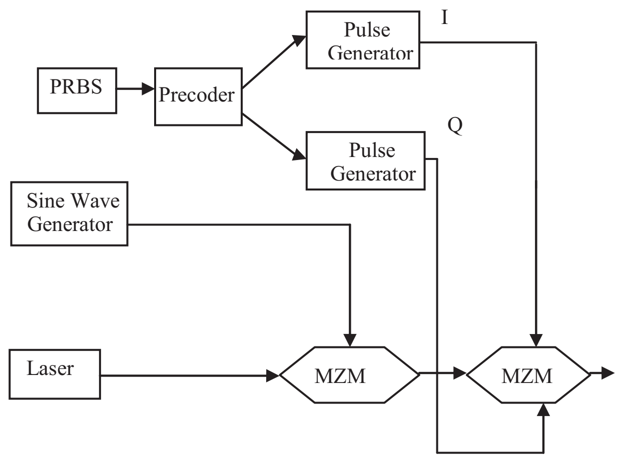

Figure 2. Two MZM-based transmitter.

The precoder is exactly similar to that used in the existing 3 MZM scheme. The output electric field of a DD-MZM is given by [10].

$$E_o(t) = \frac{E_{in}}{2} = \left\{ \left[\exp j\pi \left(\frac{V_1(t)}{V_{\pi RF}} + \frac{V_{B1}}{V_{\pi DC}} \right) \right] + \left[\exp j\pi \left(\frac{V_2(t)}{V_{\pi RF}} + \frac{V_{B2}}{V_{\pi DC}} \right) \right] \right\} e^{jw_c t} \tag{3}$$

where E_{in} is the amplitude of continuous wave light electric field and w_c is the optical carrier frequency. The switching RF voltage and bias voltage are given by $V_{\pi RF}$ and $V_{\pi DC}$, respectively. V_{B1} and V_{B2} are the DC bias voltages applied to the 2 arms. The RF modulating electrical voltages are given by $V_1(t)$ and $V_2(t)$. The phase shift in upper arm and lower arm are given by

$$\varphi_{UPPER} = \exp j\pi \left(\frac{V_1(t)}{V_{\pi RF}} + \frac{V_{B1}}{V_{\pi DC}} \right) \tag{4}$$

$$\varphi_{LOWER} = \exp j\pi \left(\frac{V_2(t)}{V_{\pi RF}} + \frac{V_{B2}}{V_{\pi DC}} \right) \tag{5}$$

When RF phase shifts and DC bias are properly chosen, it is possible to obtain various modulation formats ranging from pure intensity to pure phase modulations. The output field of the DD-MZM should have the upper arm $\varphi_{UPPER} = \pm\, 1$ and lower arm $\varphi_{LOWER} = \pm j$, respectively, for generating the constellation points. The peak-to-peak drive voltages of V_l and V_2 are kept identical and equal to V_π.

3.2. Single DD-MZM-based

By proper choice of the phase shift and the bias voltage of the electrical signal applied to the modulator electrodes, various modulation formats such as optical single side band, optical double side band, and optical carrier suppression can be generated as stated in [11]. Carrier suppression and double side band requires π phase shift between the two modulating signals, but the single side band requires a phase shift of $\pi/2$ and $\pm\pi/2$ phase due to the bias voltage applied to the electrodes. The elimination of sine wave generator gives similar performance to that of the 2 MZMs-based scheme. However, a constant envelope signal is not possible in this scheme. The block diagram for the CSRZ-QDPSK transmitter based on a single DD-MZM is shown in Figure 3.

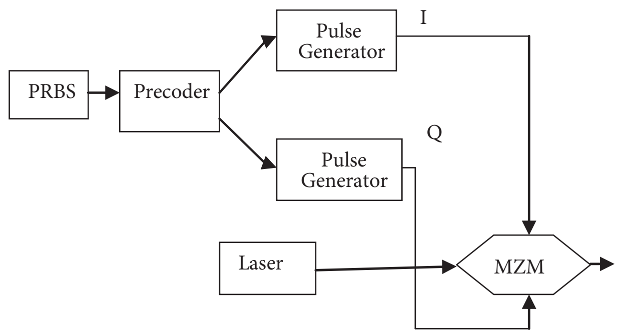

Figure 3. One DD-MZM-based transmitter.

The output electric field can be rewritten in complex form as

$$E_o(t) = \frac{E_o}{2} e^{jw_c t} \left[\sum_{n=-\infty}^{+\infty} j^n J_n(m_1) e^{jn(w_{RF}t+\theta_1)} e^{j\theta_2} + \sum_{n=-\infty}^{+\infty} j^n J_n(m_2) e^{jnw_{RF}t} \right] \tag{6}$$

where $J_n(.)$ represents the first kind Bessel function with order n, and m_1 and m_2 are the modulation indexes given by

$$m_1 = \frac{\pi V_1}{V_\pi}; \quad m_2 = \frac{\pi V_2}{V_\pi} \tag{7}$$

V_1, V_2 are the amplitudes of RF voltages given to the 2 electrodes. The output consists of infinite series of frequency components. Based on the values of phase shift and the bias voltages, the required component can be suppressed.

4. Noncoherent receiver for all schemes

The block diagram of a noncoherent receiver for CSRZ-QDPSK modulation is shown in Figure 4 [12]. The absence of a local oscillator in noncoherent detection makes this technique an attractive one. The receiver uses two sets of Mach–Zehnder delay interferometers (MZDIs) and balanced receivers to detect the in-phase and quadrature components of the received signals. In MZDIs, a delay of symbol duration and phase shift of $+\pi/4$ to $-\pi/4$ is introduced for I and Q components. These additional phase shifts are required to separate the 2 orthogonal phase components. The balanced detector increases the OSNR. The photoresponsivity and dark current of the PIN detectors are fixed as 0.8 A/W and 10 nA, respectively. All noise sources in the photo detector are added in the analysis. This approach follows the scheme reported in [9].

5. Simulation results

The CSRZ-QDPSK transmitter based on the 2 schemes, i.e. single and dual MZM-based schemes, are implemented in the optisystem tool as shown in Figure 5. The parameters for simulation are listed in Table 2.

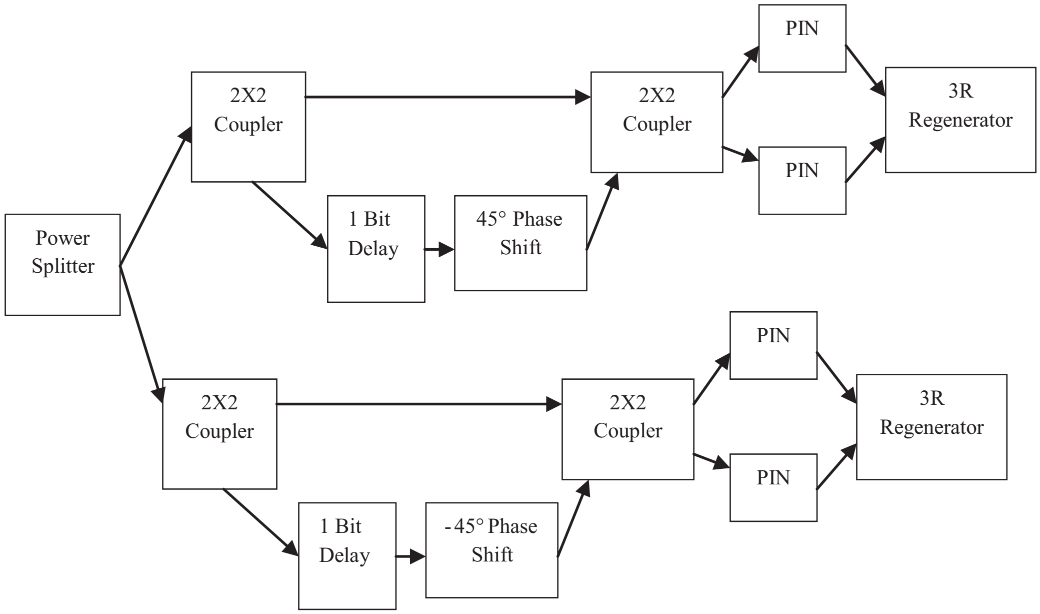

Figure 4. Block diagram noncoherent DQPSK receiver.

Table 2. Simulation parameters.

S. no	Parameters	Values
1	Bit rate	20 Gbps
2	PRBS order	31
3	Optical power from laser	0 dBm
4	Laser linewidth	1 MHz
5	Fiber distance	20 km
6	Fiber attenuation	0.2 dB/km
7	Photodiode responsivity	0.8 A/W
8	Dark current	10 nA
9	LPF cut-off frequency	10 GHz

A laser source with center frequency of 193.1 THz is used to transport the generated QDPSK signal at a power level of 0 dBm. The first MZM is driven by a sinusoidal RF signal that operates at one fourth of the bit rate for the carrier suppression. A pseudo random bit sequence generator provides the 20 Gbps random data. The precoder converts the random input sequence to inphase and quadrature phase components.

Figure 6 shows the spectrum at the transmitter end for 1, 2, and 3 MZM cases. However, there is a power reduction of 3 dB (approximately) in the proposed 2 and 1 MZM transmitter, compared to the conventional 3 MZM case. The schemes using 2 level signals will have an additional 3 dB loss than the conventional one as stated in [6]. The carrier at the center frequency (193.1 THz) is absent for all the schemes justifying the carrier suppression.

Figure 7 shows the envelope of the modulated waveform using 2 MZM and 3 MZM schemes. The power for the proposed 2 MZM structure is reduced to half that of the conventional structure, which is also evident in the spectrum. Figure 8 shows the phase details of the modulated waveform for the proposed CSRZ-QDPSK transmitter. The phase change occurs at the multiples of $0°$, $90°$, $180°$, and $270°$. The generated signal is launched into the single mode fiber of length 20 km, with attenuation of 0.2 dB/km and dispersion of 17

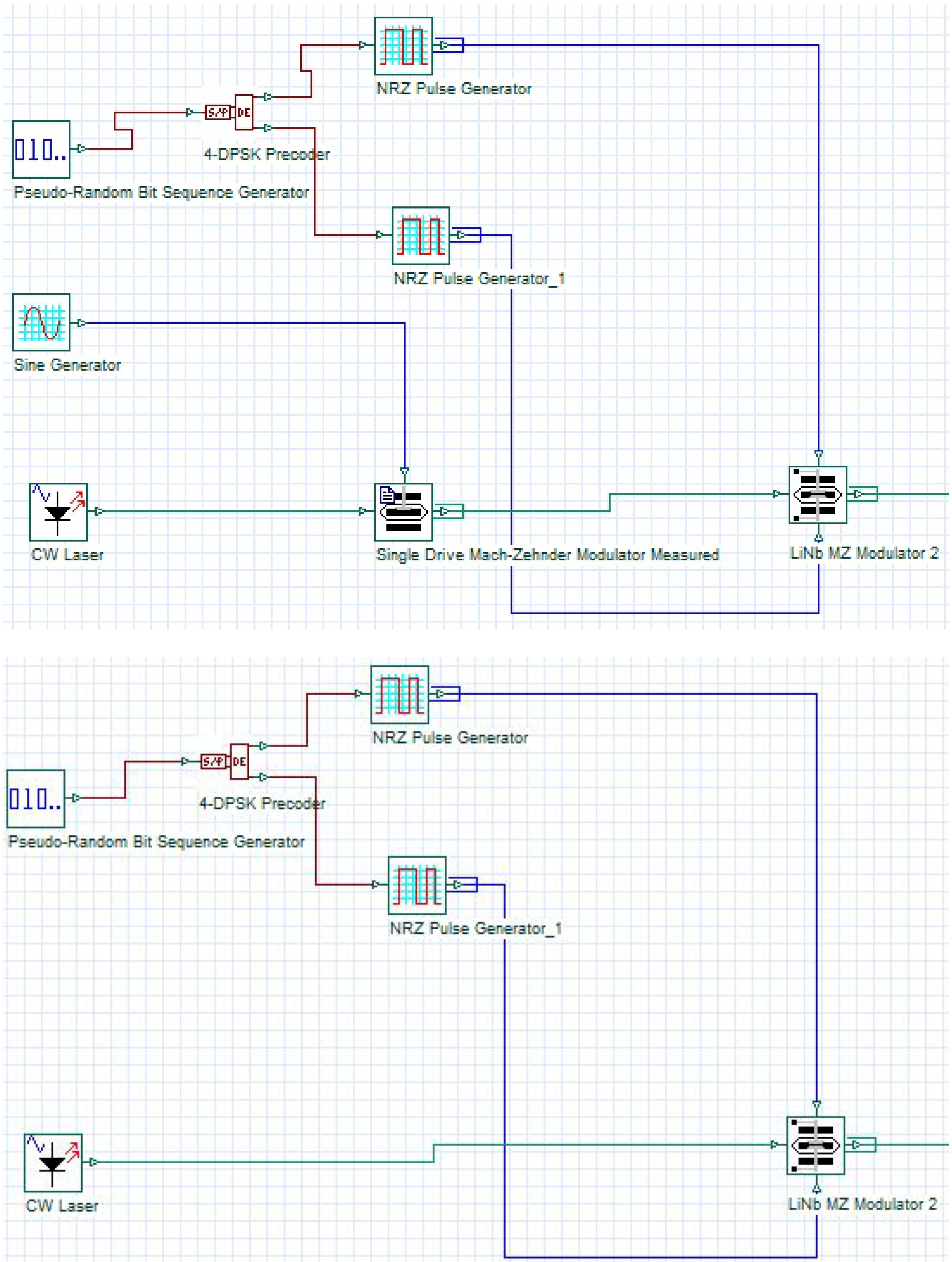

Figure 5. Simulation set-up for the proposed transmitter in optisystem tool: (a) Two MZM; (b) Single DD-MZM.

ps/nm.km. The optical link does not include any amplifier or regenerator to boost the signal power, which suits a passive optical network.

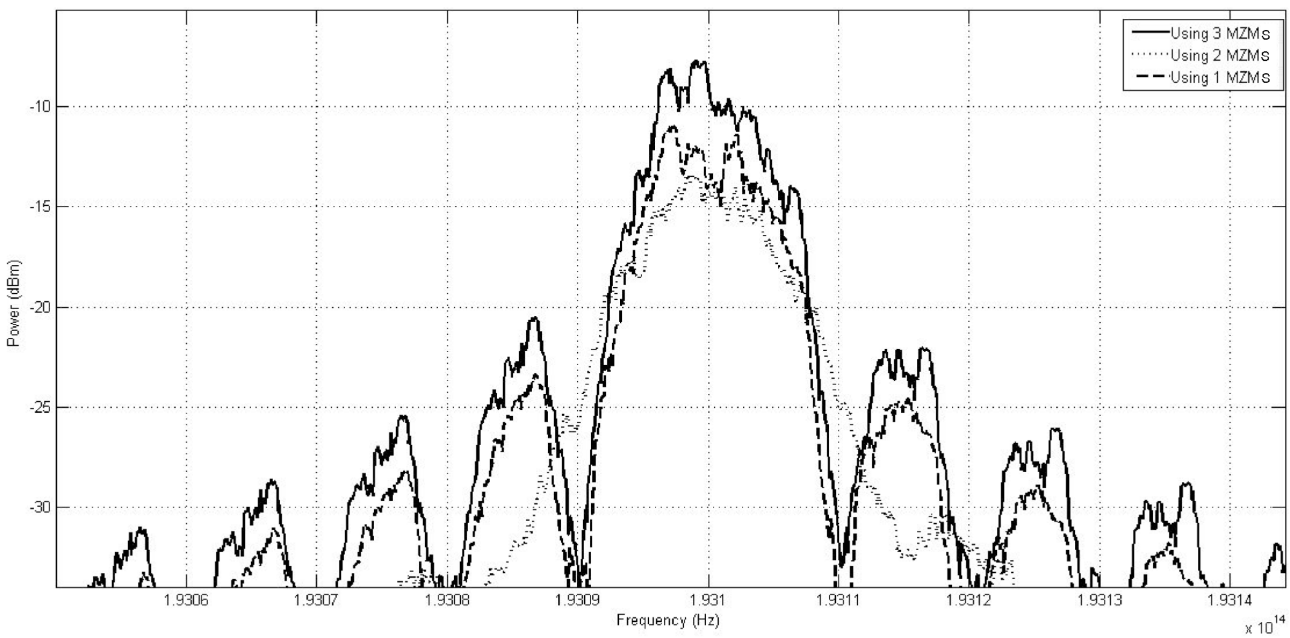

Figure 6. Optical spectrum of DQPSK.

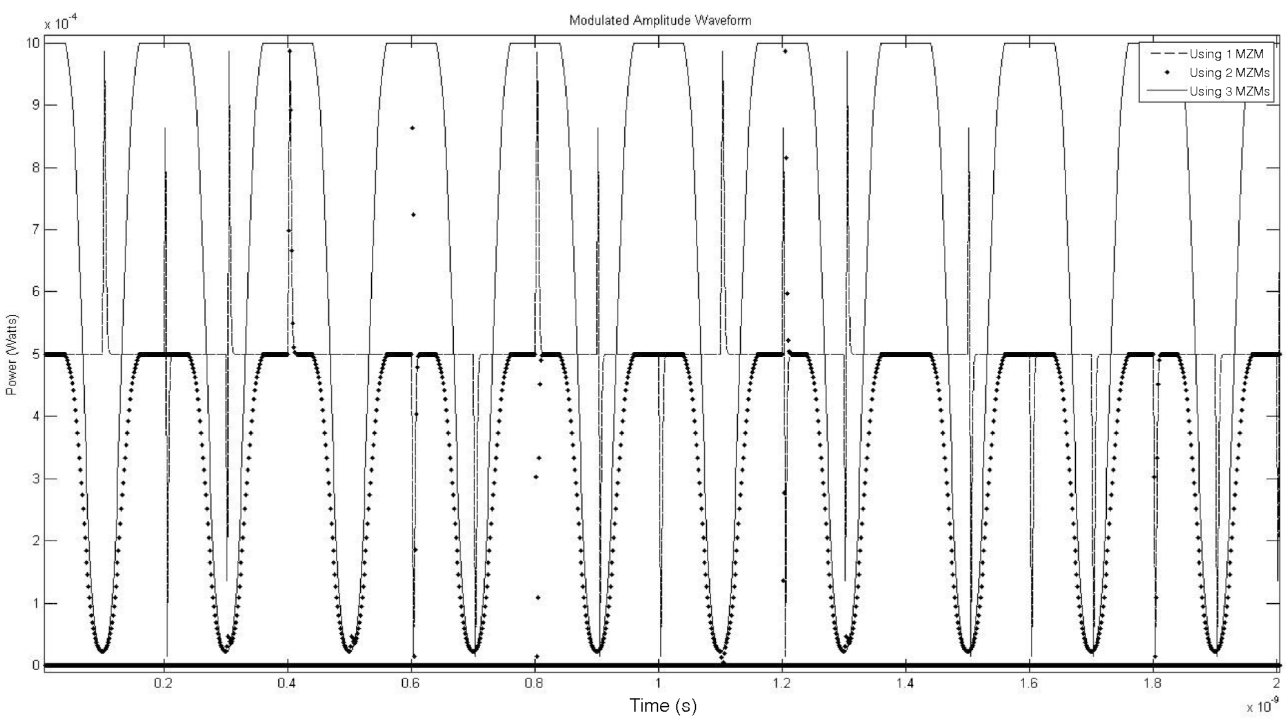

Figure 7. Amplitude of modulated signal waveform.

Figure 9 shows the optisystem implementation of noncoherent structure used for the detection of QDPSK signal. In this scheme, the received signal is split to a pair of MZDIs to perform the detection of the I and Q

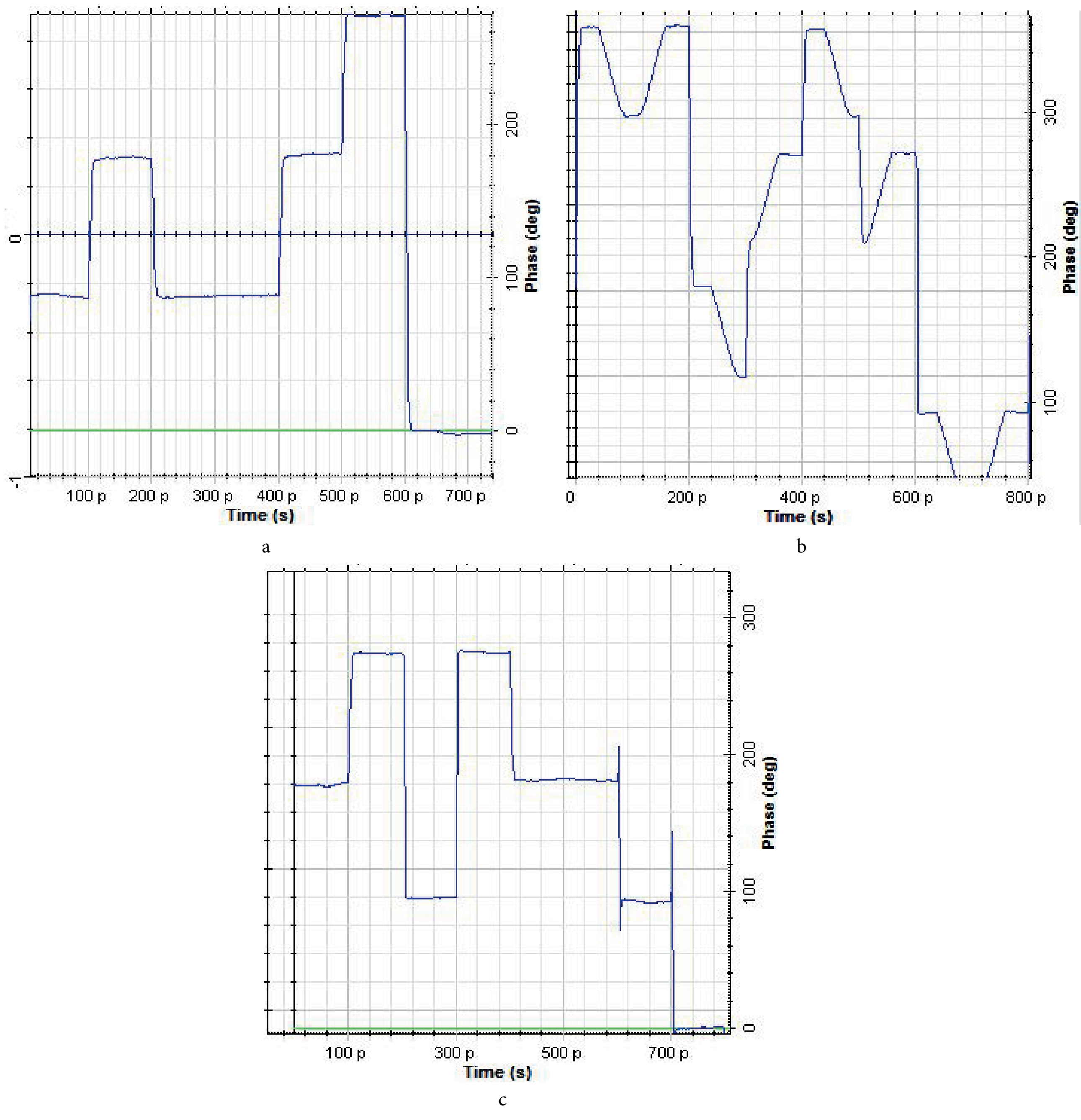

Figure 8. Modulated phase waveforms for (a) 3 MZM transmitter; (b) 2 MZM transmitter; (c) 1 MZM transmitter.

components of the QDPSK signal. The phase information transmitted undergoes a shift of 45° and a delay of one symbol duration in one branch and a phase shift of –45° and a delay of one symbol duration at the other branch. Figure 10 shows the received constellation diagram for all the 3 schemes, at the receiver end of 20 km. As the transmission distance increases the constellation points move towards the center as the amplitude reduces. Constellation rotation is visible for the 3 and 2 MZM cases, but the single MZM case shows better performance out of the 3 schemes. However, smearing of points also occurs in the single MZM case.

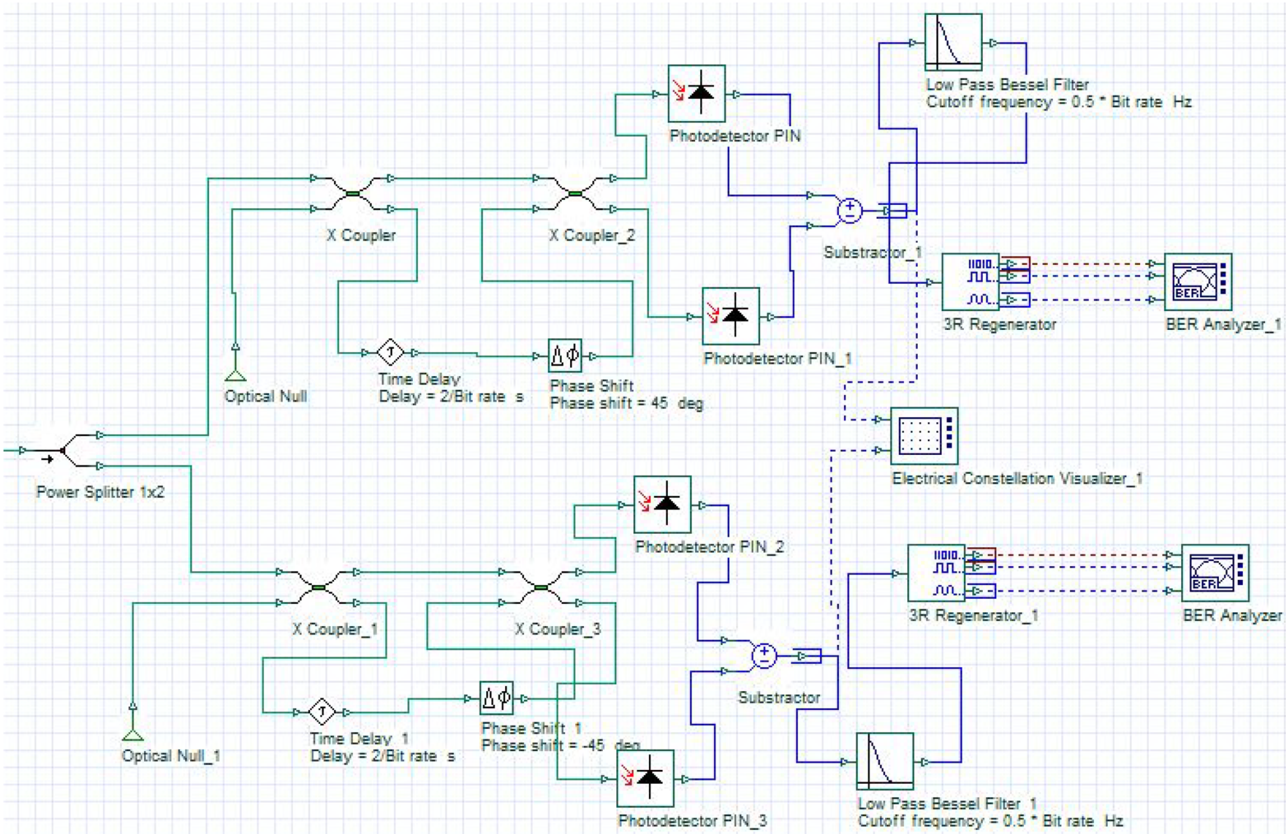

Figure 9. Simulation set-up for noncoherent receiver in optisystem tool.

In order to observe the received data, eye diagram simulation is carried out for all the cases. Figures 11 and 12 show the received eye diagram of the I and Q component for the all three cases of transmitter. It is observed that the eye opening is clear for all the schemes. In this analysis also, the single MZM case shows better performance, which coincides with the findings in the scatter plot. Figure 13 shows the quality factor for various fiber distances for both conventional and proposed transmitters. Up to 25 km, the quality factor is above 5 for the proposed schemes. However, for shorter distances, the 3 MZM scheme shows better Q factor. The standard distance for passive optical networks is 20 km and the quality factor is found to be around 9.8 in the 2 MZM scheme and 7.8 in the 1 MZM scheme, which satisfies the standard requirements.

Figure 14 gives the simulation results on eye opening penalties, which increase with the length of the fiber in all the cases. Figure 15 gives the simulation results of min.log of bit error rate by varying the fiber distance from 10 km to 50 km.

6. Conclusion

In this paper, we report two cost-effective CSRZ-QDPSK transmitter schemes. One uses 1 DD-MZM and a single arm MZM, the other using a single DD-MZM, which can be used for PON applications. The link simulation is carried using the proposed transmitters and compared with the existing 3 MZM scheme. The proposed schemes are found to provide comparable results with the existing 3 MZM scheme. The Q factor at a distance of 20 km is found to be 9.8 and 7.8 for schemes using 2 MZMs and one MZM, respectively. Eye opening penalty at a distance of 20 km is found to be 0.4 and 0.6 dB for schemes using 2 MZMs and 1 MZM, respectively. By this approach, the number of optical components used in the transmitter is reduced for similar performance. Hence, it is inferred that a single DD-MZM can be used for both carrier suppression and signal modulation by appropriate choice of the bias voltages.

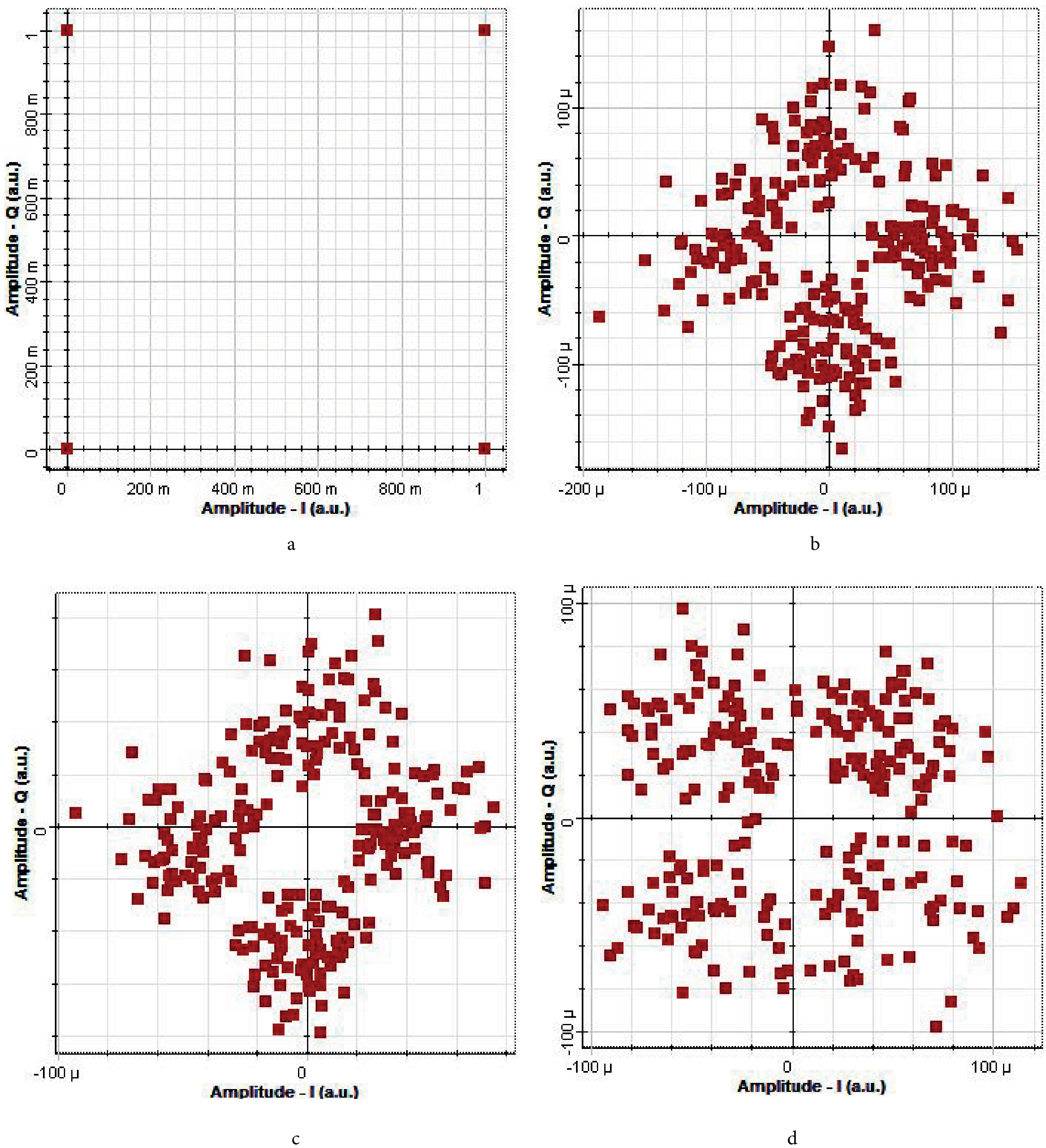

Figure 10. Signal constellation (a) Transmitter side; (b) Received constellation for 3 MZM transmitter; (c) Received constellation for 2 MZM transmitter; (d) Received constellation for 1 MZM transmitter.

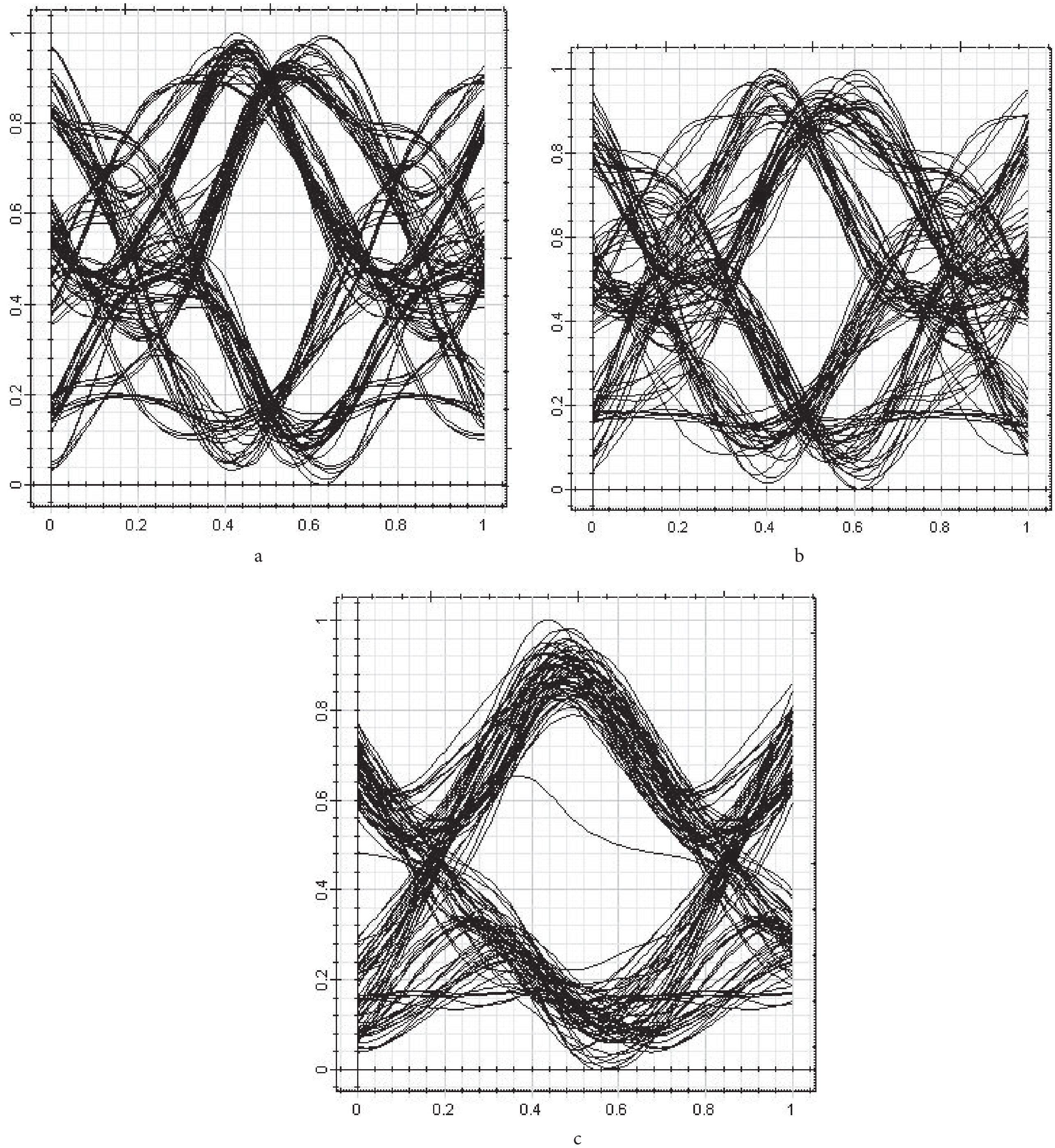

Figure 11. Receiver eye diagram (I component) (a) 3 MZM transmitter; (b) 2 MZM transmitter; (c) 1 MZM transmitter.

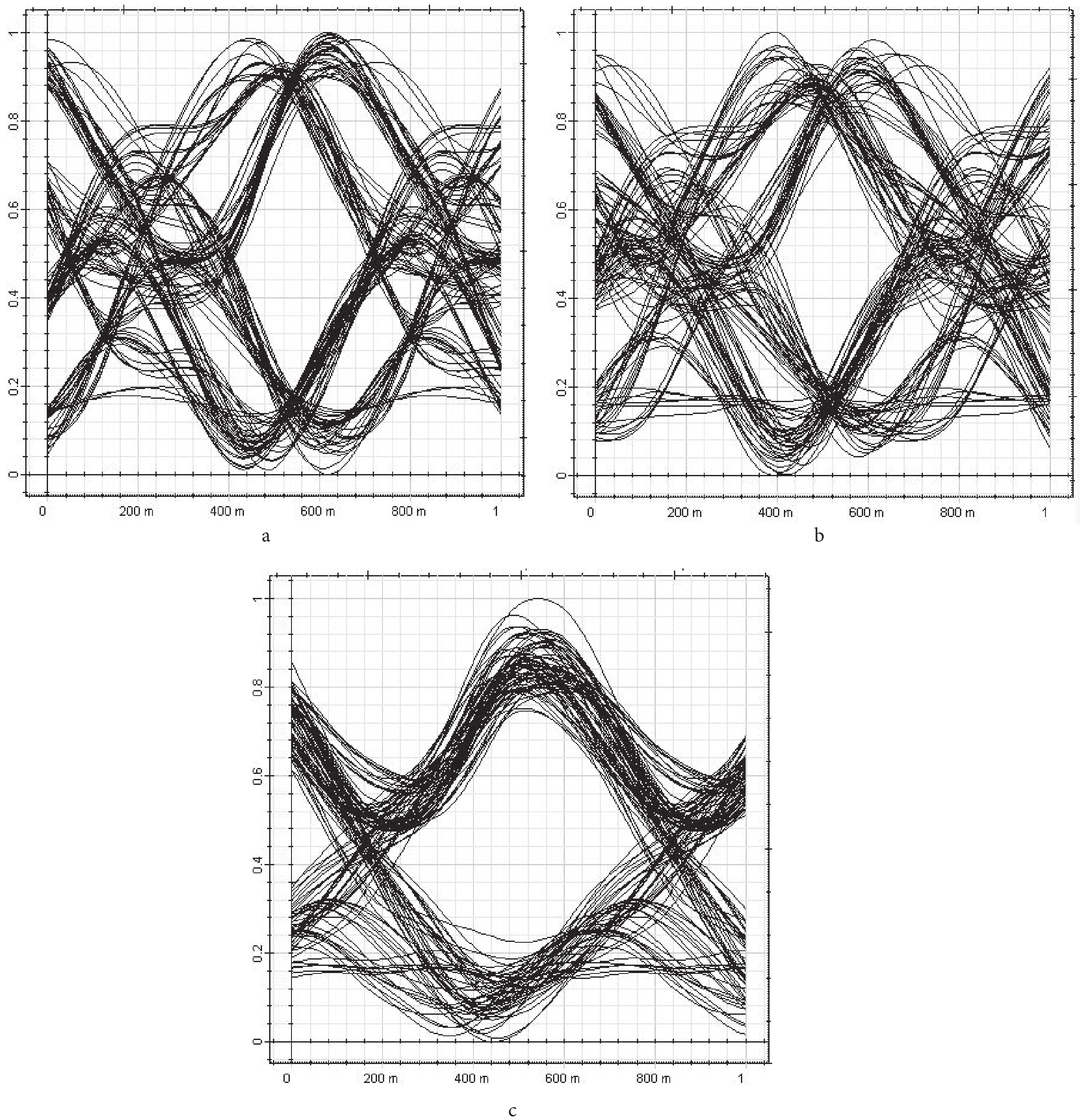

Figure 12. Receiver eye diagram (Q component) (a) 3 MZM transmitter; (b) 2 MZM transmitter; (c) 1 MZM transmitter.

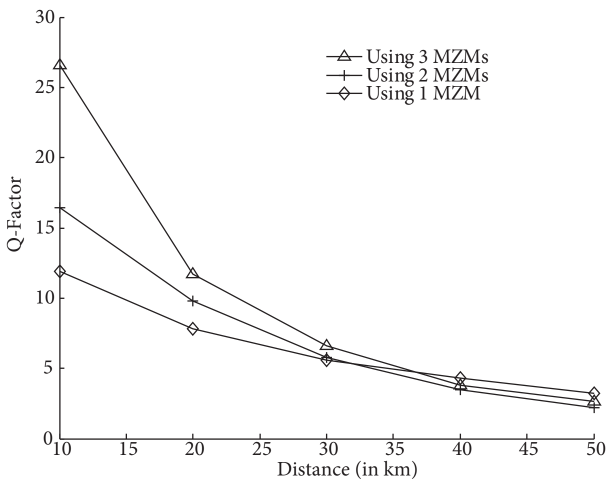

Figure 13. Q factor vs. fiber distance.

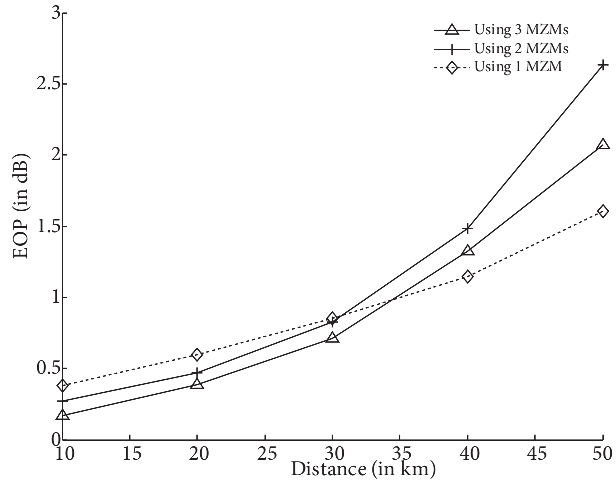

Figure 14. EOP vs. fiber distance.

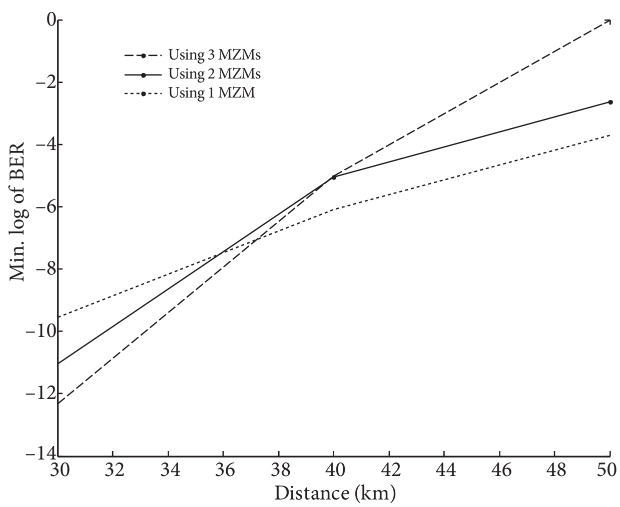

Figure 15. Log BER vs. fiber distance.

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