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Corresponding Author:	xiaoyong chen Madrid, SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	
Corresponding Author's Secondary Institution:	
First Author:	xiaoyong chen
First Author Secondary Information:	
Order of Authors:	xiaoyong chen
	Paloma R. Horche
Order of Authors Secondary Information:	
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A low-cost alternative DQPSK receiver based on a polarization maintaining fiber

Xiaoyong Chen[1,*], Paloma R. Horche[1]

[1]Departamento de Tecnología Fotónica y Bioingeniería, ETSIT, Universidad Politécnica de Madrid, Ciudad Universitaria 28040 Madrid, Spain
*xiaoyong.chen@alumnos.upm.es

Abstract

We propose and demonstrate a low-cost alternative scheme to detect 40 Gbps optical differential quadrature phase shift keying (DQPSK) signals. The scheme is based on a polarization maintaining fiber, in which a phase shift keying (PSK) signal is converted into a polarization shift keying (PolSK) signal. Then, the PolSK signal is converted into two intensity modulation signals by a polarization beam splitter. Compared with the conventional DQPSK receiver based on two delay interferometers, our proposed receiver is simpler since the in- and quadrature-phase demodulation paths share the same hardware. Moreover, the total cost is reduced due to fewer components used in our proposed receiver. Demodulation of 40 Gbps nonreturn to zero (NRZ) DQPSK and return to zero (RZ) DQPSK signals are demonstrated through simulations. Performance of the proposed receiver is analyzed through sensitivity, narrow optical filtering and polarization mode dispersion tolerance. Simulation results show that the proposed receiver performed as well as the conventional receiver.

Keywords: differential quadrature phase shift keying (DQPSK), polarization maintaining fiber (PMF), optical communications, optical receiver

1. Introduction

Differential quadrature phase shift keying (DQPSK) modulation format has been proposed to further increase the chromatic dispersion and polarization mode dispersion (PMD) tolerance of 40 Gbps channels [1-8]. Owing to its reduced optical bandwidth relative to the traditional binary systems, it is proposed as a promising candidate for high-speed long-haul optical transmission systems. In addition, its compatibility with the 50 GHz International Telecommunication Union (ITU) grids could allow mixing 10 Gbps NRZ and 40 Gbps DQPSK channels in a same wavelength division multiplexing (WDM) transmission system. Thus, when a 10 Gbps WDM system is saturated in terms of capacity, one could consider replacing step by step the 10 Gbps channels by the 40 Gbps ones as a function of the capacity needed [4].

The main drawback of DQPSK systems is that it requires more complex transmitter and receiver architectures compared with conventional binary systems. At the transmitter, a DQPSK signal is typically obtained by two embedded Mach-Zehnder modulators, driven by two nonreturn to zero (NRZ) data streams I and Q. At the receiver, direct-detection receiver based on two delay interferometers (DIs) [4] is usually used to detect a DQPSK signal.

Many previous works have reported some methods for detecting DQPSK signals. In [9], a DQPSK receiver based on a single DI and an integrated 4 x 4 star coupler was reported. In [10], a rate-tunable DQPSK receiver based on a tunable birefringent element was presented. In comparison with the conventional DIs DQPSK receiver, the receiver proposed in [10] is simpler and more stable. However, it has a drawback of high-cost due to many active components are used, such as a tunable birefringent component and a polarizer stabilizer. In addition to direct-detection, coherent-detection is also proposed to demodulate DQPSK signals [11]. Coherent receiver has merits of high chromatic dispersion tolerance and polarization mode dispersion tolerance, but at the expense of high cost and complex design due to a local oscillator laser with tight linewidth is required.

In this paper, we present a low-cost alternative scheme for DQPSK demodulation, which is based on a polarization-maintaining fiber (PMF). Compared with the DQPSK receivers mentioned above, our scheme has the following merits: 1). the structure is much simpler since the in-phase (I) and quadrature-phase (Q) paths share the same hardware; 2). It is much easier to implement due to fewer components are used; 3) the total cost is reduced because only low-cost commercial components are used in our scheme. This paper is organized as follows. The operating principle is presented in Section 2, and the simulation setup is presented in Section 3. Section 4 is devoted to the comparative performance analysis of the receiver in back-to-back operation, under narrow optical filtering and in the presence of first-order PMD. Finally, conclusions are drawn in Section 5.

2. Operating principle

The structure of the proposed PMF based DQPSK receiver is shown in Fig. 1. In our scheme, a PMF is used to convert a DQPSK signal into a polarization shift keying (PolSK) signal [12]. Then, the PolSK signal is converted into two intensity modulation (IM) signals by a polarization beam splitter (PBS). Finally, two balanced photodetectors are used to detect the converted IM signals. The role of the linear polarizer is to launch the signal at 45º with respect to the slow (or fast) axis of the PMF.

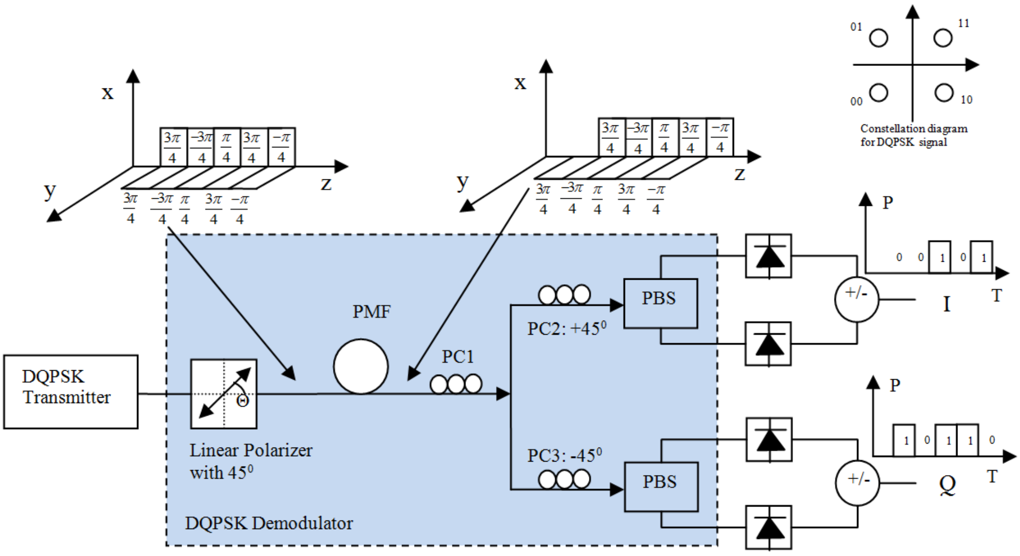


Fig. 1. Principle diagram of the proposed PMF based DQPSK receiver

Taking into account the former considerations, a DQPSK signal can be written as:

$$\vec{\boldsymbol{E}}(t) = (\vec{\boldsymbol{E}}_x + \vec{\boldsymbol{E}}_y)e^{j\omega t} \tag{1}$$

where the signal is decomposed into two orthogonal components, $\vec{\boldsymbol{E}}_x$ and $\vec{\boldsymbol{E}}_y$. Here, we assume that $\vec{\boldsymbol{E}}_x$ is parallel to the fast axis, while $\vec{\boldsymbol{E}}_y$ is parallel to the slow axis of the PMF. These two orthogonally polarized components propagate with different group and phase velocity in the PMF such that they are delayed with respect to each other depending on the PMF length.

The operation of the receiver can be described by Jones matrices [10]. To simplify the calculation, we ignore the attenuation and chromatic dispersion generated in the fiber. The matrices of the PMF and the phase compensation element, polarization controller (PC), are given in (2) and (3), respectively:

$$\begin{bmatrix} e^{j\left(\frac{\omega\cdot\Delta T}{2}+\frac{\theta}{2}\right)} & 0 \\ 0 & e^{-j\left(\frac{\omega\cdot\Delta T}{2}+\frac{\theta}{2}\right)} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} e^{-j\frac{\theta}{2}} & 0 \\ 0 & e^{j\frac{\theta}{2}} \end{bmatrix} \quad (3)$$

where ΔT is the DGD, and θ is the PMF induced phase difference between x and y polarization components. In our proposed scheme, the DGD generated in the PMF is one-symbol period, $\Delta T = T_{symbol}$.

Combining (1) and (2), the signal at the PMF output can be expressed as (4), including a relative group delay and a fiber induced optical phase difference:

$$\vec{E}(t) = \vec{E}_x e^{j\omega\left(t-T+\frac{\Delta T}{2}\right)+\frac{j\theta}{2}} + \vec{E}_y e^{j\omega\left(t-T-\frac{\Delta T}{2}\right)-\frac{j\theta}{2}} \quad (4)$$

where T is the average propagation time. Followed by the PMF is a commercial PC used for compensating PMF induced phase difference θ. Then, the signal is split equally into two parts and shifts of ±45° are introduced using a PC such that the two parts undergo a relative phase shift of 90°. Finally, these two resulting elliptically polarized signals each passes through a PBS for being converted into two IM signals and two balanced photodetectors are used to detect the demodulated signals.

When the DGD is equal to one-symbol period and each signal launched into the PBS is linearly polarized at 45°, the outputs of two balanced photodetectors represent the differentially detected I and Q signals, and can be written as:

$$P_I = \frac{\sqrt{2}}{4}\vec{\boldsymbol{E}}^2[\cos(\Delta\varphi) - \sin(\Delta\varphi)] \quad (5)$$

$$P_Q = \frac{\sqrt{2}}{4}\vec{\boldsymbol{E}}^2[\cos(\Delta\varphi) + \sin(\Delta\varphi)] \quad (6)$$

where $\vec{\boldsymbol{E}}$ is the optical field, and $\Delta\varphi$ is the phase difference between the successive symbols, $\Delta\varphi = \omega \cdot \Delta T$. As a DQPSK signal, the phase difference between the adjacent symbols can be one of the four possible states, {45°, 135°, 225°, 315°}, according to the inset of constellation diagram shown in Fig. 1. These two equations are the same as that derived from a conventional DIs based DQPSK receiver [13].

In order to analyze the performance of the proposed receiver, it is important to calculate the bit error rate (BER) of the received signal. In this work, the BER is calculated by Gaussian algorithm. According to Agrawal [14], the BER can be described as follows:

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{\sqrt{2\pi}Q} \quad (7)$$

where $Q = \frac{I_1 - I_0}{\sigma_0 + \sigma_1}$, I_1 and I_0 represent the average received current for bits of "1" and "0", respectively. Normally, bits of "1" and "0" are decided by making a comparison between the received current I and the threshold current I_D. It calls bit "1" if $I > I_D$ or bit "0" if $I < I_D$. σ_1 and σ_0 are the effective standard deviations of the sampled values, respectively. The BER will be decreased as Q increases and become lower than 10^{-9} for $Q > 6$ or 10^{-12} for $Q > 7$.

3. Simulation setup

According to the principle diagram shown in Fig. 1, we built a simulation setup as shown in Fig. 2, and detail of two types of receivers shown in Fig. 3.

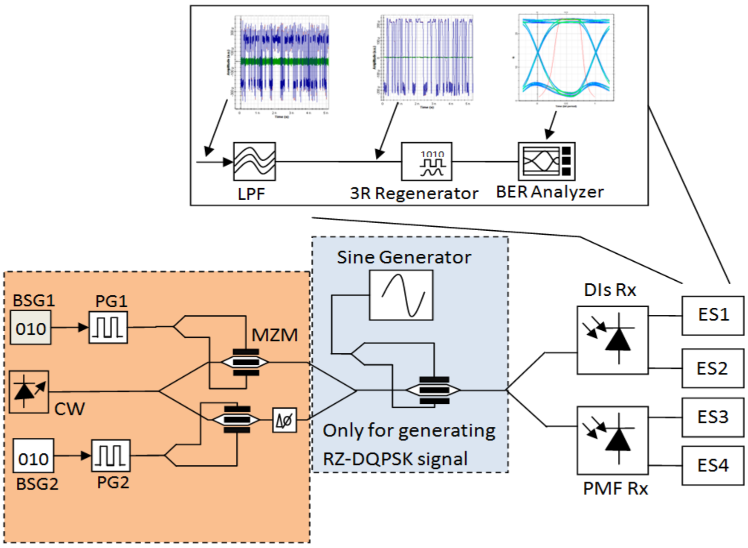


Fig. 2. Simulation system design, including NRZ/RZ-DQPSK signal transmitters, a PMF receiver and a typical DIs receiver

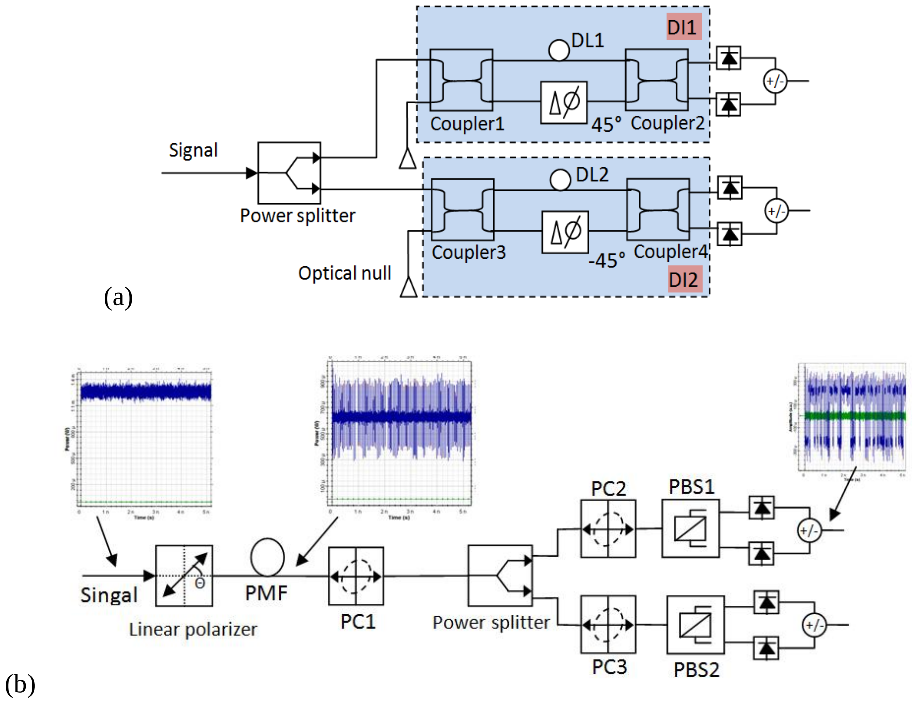


Fig. 3. Details of the two kinds of DQPSK receivers: (a) Typical DIs receiver; (b) The proposed PMF receiver

In the transmitter, an 1552.52 nm (193.1 THz) continuous wave (CW) source was modulated by double-nested LiNbO3 Mach-Zehnder modulators (MZMs), driven by two 20 Gbps NRZ data streams I and Q, which are pseudo random bit sequences (PRBS) of length 2^{15}-1, to generate a 40 Gbps NRZ-DQPSK signal. In order to generate a 40 Gbps RZ-DQPSK, another MZM, driven by 40 Gbps sine signal, is used.

The signal was then launched into an erbium-doped fiber amplifier (EDFA) with a variable optical attenuator (VOA) in front to adjust the received optical signal to noise ratio (OSNR). In the receiver, the noise-loaded signal was first filtered out by a second-order Gaussian filter with a 3-dB bandwidth of 62.5GHz (the EDFA and filter are not shown in the Fig. 3). Then, the filtered-signal was launched into the demodulation section.

The principle of operation of the demodulation process is described in detail in Section 2. One thing needed to mention is that the PMF induced phase difference θ was 45º in the simulation. Therefore, the phase compensator, PC1, was set to be -45º. Finally, two optical signals each reached, through a PC, a balanced photodetector, and the BER analyzers were used to analyze the output electrical signals. We have to point out that the PMF used in the simulation is based on the model of Panda style MP 1550-HP produced by the THORLABS. The attenuation is < 1 dB/km @ 1550nm, and the beat length (the distance that the fast and slow polarization modes have 2π of phase shift) is ≤ 5 mm @ 1550 nm. In the simulation, we set the attenuation to be 0.9 dB/km, and the beat length to be 5 mm, corresponding to DGD = 1033 ps/km.

4. Simulation results

To assess the performance of the proposed DQPSK demodulator and receiver architecture, we performed a set of simulations. In order to analyze the performance of the receiver, the sensitivity in back-to-back operation is obtained. Moreover, the receiver performance is studied under narrow optical filtering and in the presence of polarization mode dispersion. In addition, impairment induced by nonideal behavior of receiver components is also evaluated.

4.1 Back-to-back performance

Sensitivity is the most important parameter for analyzing the performance of a receiver. Usually, the receiver performance is characterized by measuring the BER as a function of the received average optical power. Figure 4 shows the simulated BER in back-to-back operation as a function of the sensitivity, including NRZ-DQPSK and RZ-DQPSK formats.

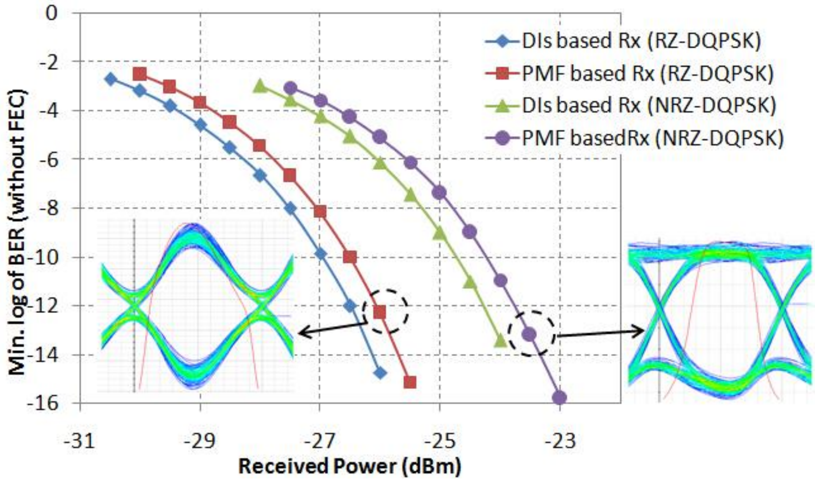
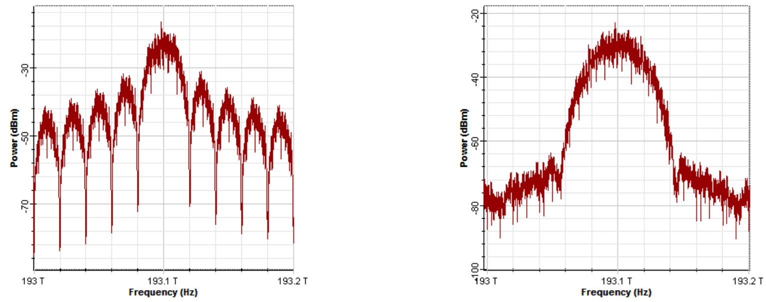


Fig. 4. BER as a function of the received power in 40Gbps DQPSK systems



(a) (b)

Fig. 5. Spectrum of the signals: (a) NRZ-DQPSK signal; (b) RZ-DQPSK signal

The sensitivity of the proposed receiver at a BER of 10^{-12} is -26.1 ± 0.2 and -23.8 ± 0.2 dBm for RZ-DQPSK and NRZ-DQPSK formats, respectively. The insets of eye diagrams in Fig. 4 display large vertical eye opening for both formats. The sensitivity difference in detecting NRZ-DQPSK and RZ-DQPSK signals can be understood by signal spectrum, as shown in Fig. 5. The bandwidth of a RZ-DQPSK signal is much wider than that of a NRZ-DQPSK signal. In other words, the pulse width of a RZ-DQPSK signal is much narrower than that of a NRZ-DQPSK signal in the time domain, which means, with the same received power, the peak power of the pulse of a RZ-DQPSK signal is much higher than that of a NRZ-DQPSK signal. Due to this characteristic, the RZ-DQPSK signal has higher sensitivity and higher PMD tolerance. By contrast, the NRZ-DQPSK signal is more tolerant to the filter bandwidth.

Figure 4 also shows the simulated sensitivity of the DIs receiver based on Pincemin [4]. As can be seen, the sensitivity of the DIs receiver is about 0.4 ± 0.2 dBm higher than that of the proposed receiver, either for NRZ-DQPSK or for RZ-DQPSK formats. That is because the PMF induced effects, such as chromatic dispersion, attenuation and nonlinear effects, can affect the signal quality.

4.2 Performance under narrowband (cascaded) optical filtering

In optical networks, an optical signal may traverse a large number of reconfigurable optical add-drop multiplexers (ROADMs) and optical cross-connect (OXC) nodes, and as a result of this, the signal spectrum is filtered seriously. Also, due to that the 40 Gbps DQPSK signal is compatible with the 50-GHz ITU grid and the 50-GHz based ROADMs [4], we test the receiver performance under narrow optical filtering in this section.

In the simulation, we used the 50-GHz third-order Butterworth filter as the optical filter because most of the optical filters used in optical networks can be modeled as third-order Butterworth filters [15]. The simulation results (Fig. 6) show that either NRZ-DQPSK or RZ-DQPSK signals, the PMF based receiver performs as well as the DIs based receiver. In comparison with the NRZ-DQPSK system, fewer filters are allowed to be cascaded in the RZ-DQPSK system in the same conditions. This is because the bandwidth of the RZ-DQPSK signal is much wider (Fig. 5), resulting in lower tolerance to narrowband optical filtering. With 1-dB eye opening penalty (EOP), only about 12 filters can be cascaded in the RZ-DQPSK system, while this value can be increased to 17 in the NRZ-DQPSK system.

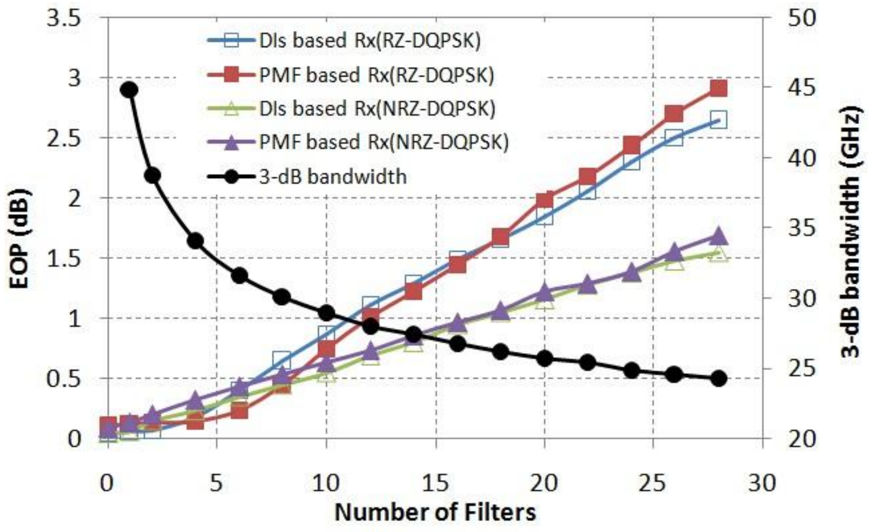


Fig. 6. Eye opening penalty (EOP) as a function of number of filters in a PMF and a typical DI receiver

Note that although the effective bandwidth of 20 filters concatenation (about 26 GHz) is wider than the signal bandwidth (about 20 GHz), much more EOP is induced due to the filter concatenation effect, which is dominated by effective bandwidth and phase linear region [15]. With the number of cascaded filters increase, not only the effective bandwidth decreases, but also the phase linear region decreases.

4.3 Differential group delay (DGD) tolerance

The tolerance to PMD is a key issue for high-speed systems. It is well known that as the baud rate increases, the tolerance to PMD reduces proportionately [16]. In this section, we test the receiver performance under the first-order PMD, which is also called DGD. In the simulation, another PMF was used as the DGD element, and different values of DGD are obtained by changing the PMF length. In order to work with the worst case, a PC was used to launch the signal at 45º with respect to slow (or fast) axis of the PMF.

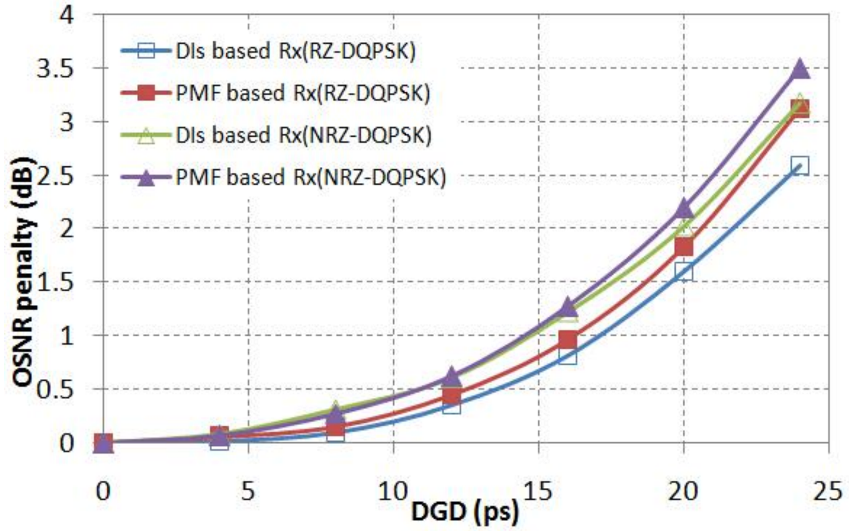


Fig. 7. OSNR penalty as a function of DGD

The simulation results are shown in Fig. 7. With 1-dB OSNR penalty, DGD tolerance is about 15 and 16 ps for the NRZ-DQPSK and RZ-DQPSK signals, respectively. These results are similar to that got from a DIs based receiver. Also, 1-dB OSNR penalty occurs at a DGD between 30 and 40% of the symbol duration; this tolerance is in agreement with the theory [16]. Figure 7 also shows that the RZ-DQPSK signal is more resilient to DGD compared with the NRZ-DQPSK signal. This is due to that the RZ-DQPSK signal has narrower pulse, resulting in higher tolerance to DGD-induced pulse broadening.

4.4 Impairment induced by non-ideal behavior of receiver components

In our proposed receiver, the PMF induced phase shift between two orthogonal components is compensated by a commercial PC. However, in practical conditions, it is very hard to compensate accurately this phase shift. Thus, in this section we test the OSNR penalty induced by phase compensating deviation. Another PC was inserted between the PMF and PC1 for realizing this test, and a set of simulations were carried out varying the phase shift from -8° to 8°. The simulation results are shown in Fig. 8. As can be seen, with 1-dB OSNR penalty, phase shift of 4° is permitted. Moreover, when the phase shift is lower than 2°, OSNR penalty is lower than 0.2 dB.

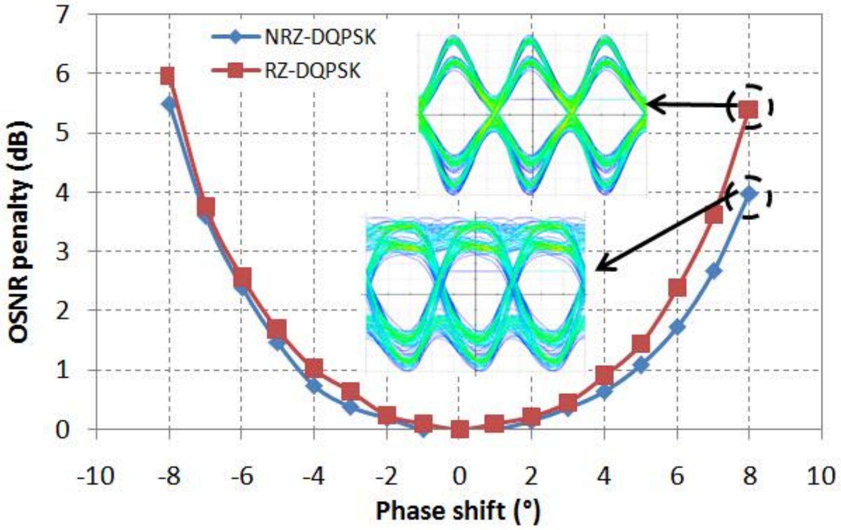


Fig. 8. OSNR penalty as a function of phase shift

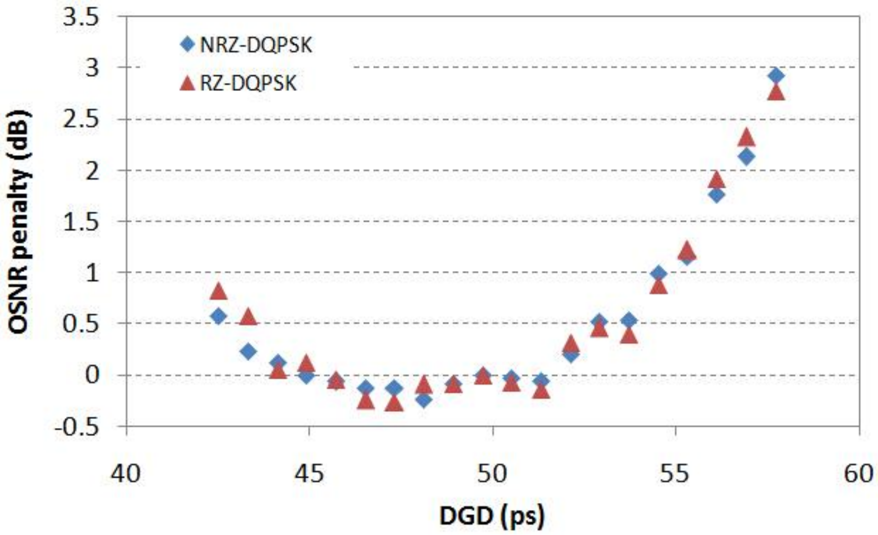


Fig. 9. OSNR penalty induced by non-ideal DGD value

Usually, an ideal delay of 50 ps is required for demodulating a 40 Gbps DQPSK signal. However, in real conditions, it is very difficult to accurately measure the DGD of a PMF, and this parameter will also be affected by the environment. Therefore, in this section, we also study the receiver performance under nonideal DGD value generated by the PMF. This test was realized by changing the PMF length in the simulation, and the simulation results are shown in Fig. 9. With 1-dB OSNR penalty, deviation value from -8 to 5 ps is allowed. The simulation results also show that the proposed receiver is more tolerant to negative than positive deviation value. In addition, we can see that the best performance of the receiver is not corresponding to the ideal delay of 50 ps. This can be understood that the optimal demodulator delay depends on system parameters, such as residual chromatic dispersion and the optical filtering bandwidth of the system.

5. Conclusions

In this paper, we have proposed and demonstrated, via simulation, a low-cost alternative scheme to detect a 40 Gbps DQPSK signal using a commercial PMF. Through analysis of back-to-back sensitivity and the major optical impairments, we show that the proposed receiver performs as well as the conventional DIs based receiver. In a back-to-back operation without FEC technology, the sensitivity is -26.1 ± 0.2 and -23.8 ± 0.2dBm at a BER of 10^{-12} for RZ-DQPSK and NRZ-DQPSK signals, respectively. Receiver performance under narrow optical filtering shows that 17 50-GHz filters can be cascaded with 1-dB OSNR penalty in NRZ-DQPSK system, while this value is reduced to 12 in RZ-DQPSK system. We have also quantified the performance under impairment of PMD. The DGD tolerance is ~15ps with 1-dB OSNR penalty. Finally, we have also discussed the impact of non-ideal behavior of receiver components on the receiver performance.

Compared with the conventional DIs based receiver, our proposed receiver has the following advantages: a). Fewer components are used in the receiver, which not only make the structure simpler but also make it easier to implement; b). the reliability is improved as the in-phase (*I*) and the quadrature-phase (*Q*) paths share the same hardware, leading to reducing the external effects, such as temperature, on two paths. In addition, in comparison with the tunable receiver proposed in [10], our receiver also has its own merit: without active components used, our receiver not only sharply reduces the total cost, but also become easier to manufacture and implement.

The good performance, taken together with the lower complexity receiver structure, may offer a promising alternative for cost-sensitive applications such as 40G Ethernet transport.

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References:

[1] L.N. Binh, M. Firus, T.N.K. Hoan, Wavelength re-generation and re-modulation using optical phase lock loop techniques for 100-Gb/s DQPSK up-stream transmission in DWDM passive optical networks, Photonic Network Communications, 19 (2010) 265-276.

[2] S. Faralli, K.N. Nguyen, J.D. Peters, D.T. Spencer, D.J. Blumenthal, J.E. Bowers, Integrated hybrid Si/InGaAs 50 Gb/s DQPSK receiver, Optics Express, 20 (2012) 19726-19734.

[3] X. Chen, P.R. Horche, A.M. Minguez, A low-cost alternative scheme to detect a 100 Gbps PM-DQPSK signal, Photonic Network Communications, (2014). doi: 10.1007/s11107-014-0441-7

[4] E. Pincemin, J. Karaki, Y. Loussouarn, H. Poignant, C. Betoule, G. Thouenon, R.L. Bidan, Challenges of 40/100 Gbps and higher-rate deployments over long-haul transport networks, Optical Fiber Technology, 17 (2011) 335-362.

[5] A. Consoli, J.M.G. Tijero, I. Esquivias, Time resolved chirp measurements of gain switched semiconductor laser using a polarization based optical differentiator, Optics Express, 19 (2011) 10805-10812.

[6] G. Charlet, P. Tran, H. Mardoyan, M. Lefrancois, T. Fauconnier, F. Jorge, S. Bigo, 151x43 Gbps transmission over 4080 km based on return-to-zero differential quadrature phase-shift keying, ECOC 2005, Glasgow, 2005, pp. 5-6.

[7] J. Zhang, D. Duan, A. Yin, Analysis modulation formats of DQPSK in WDM-PON system, Optik, 123 (2012) 2050-2055.

[8] A.H. Gnauck, P.J. Winzer, C. Dorrer, S. Chandrasekhar, Linear and nonlinear performance of 42.7-Gb/s single-polarization RZ-DQPSK format, IEEE Photonics Technology Letters, 18 (2006) 883-885.

[9] C.R. Doerr, D.M. Gill, A.H. Gnauck, L.L. Buhl, P.J. Winzer, M.A. Cappuzzo, A. Wong-Foy, E.Y. Chen, L.T. Gomez, Simultaneous reception of both quadratures of 40-Gb/s DQPSK using a simple monolithic demodulator, OFC 2005, Anaheim, CA, 2005, pp. PDP12.

[10] L. Christen, Y.K. Lize, S. Nuccio, L. Paraschis, A.E. Willner, Experimental Demodulation of Reduced Complexity 43-Gb/s RZ-DQPSK Rate-Tunable Receiver, IEEE Photonics Technology Letters, 20 (2008) 1166-1168.

[11] M. Seimetz, Phase diversity receivers for homodyne detection of optical DQPSK signals, Journal of Lightwave Technology, (2006) 3384-3391.

[12] E. Ciaramella, G. Contestabile, A. D'Errico, A novel scheme to detect optical DPSK signals, IEEE Photonics Technology Letters, 16 (2004) 2138-2140.

[13] K.-p. Ho, Phase-Modulated Optical Communication Systems, Springer, New York, 2005.

[14] G.P. Agrawal, Fiber-Optic Communication Systems, fourth ed., Wiley, New Jersey, 2010.

[15] X. Chen, P.R. Horche, A.M. Minguez, Optical signal impairment study of cascaded optical filters in 40 Gbps DQPSK and 100 Gbps PM-DQPSK systems, SPIE 2013, San Diego, CA, 2013, pp. 88550C.

[16] P.J. Winzer, R.-J. Essiambre, Advanced optical modulation formats, Proceedings of the IEEE, 94 (2006) 952-985.

Figure 1
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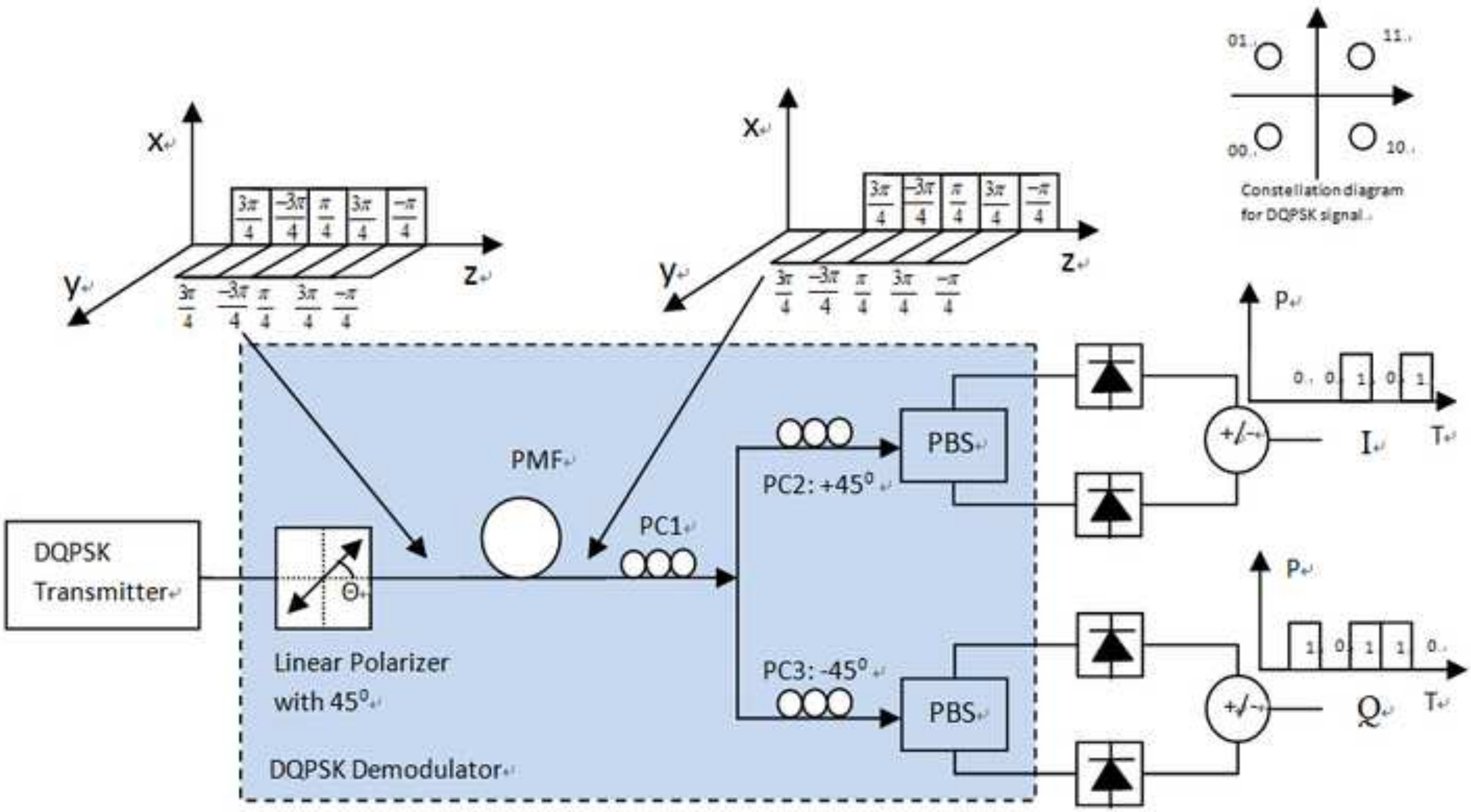

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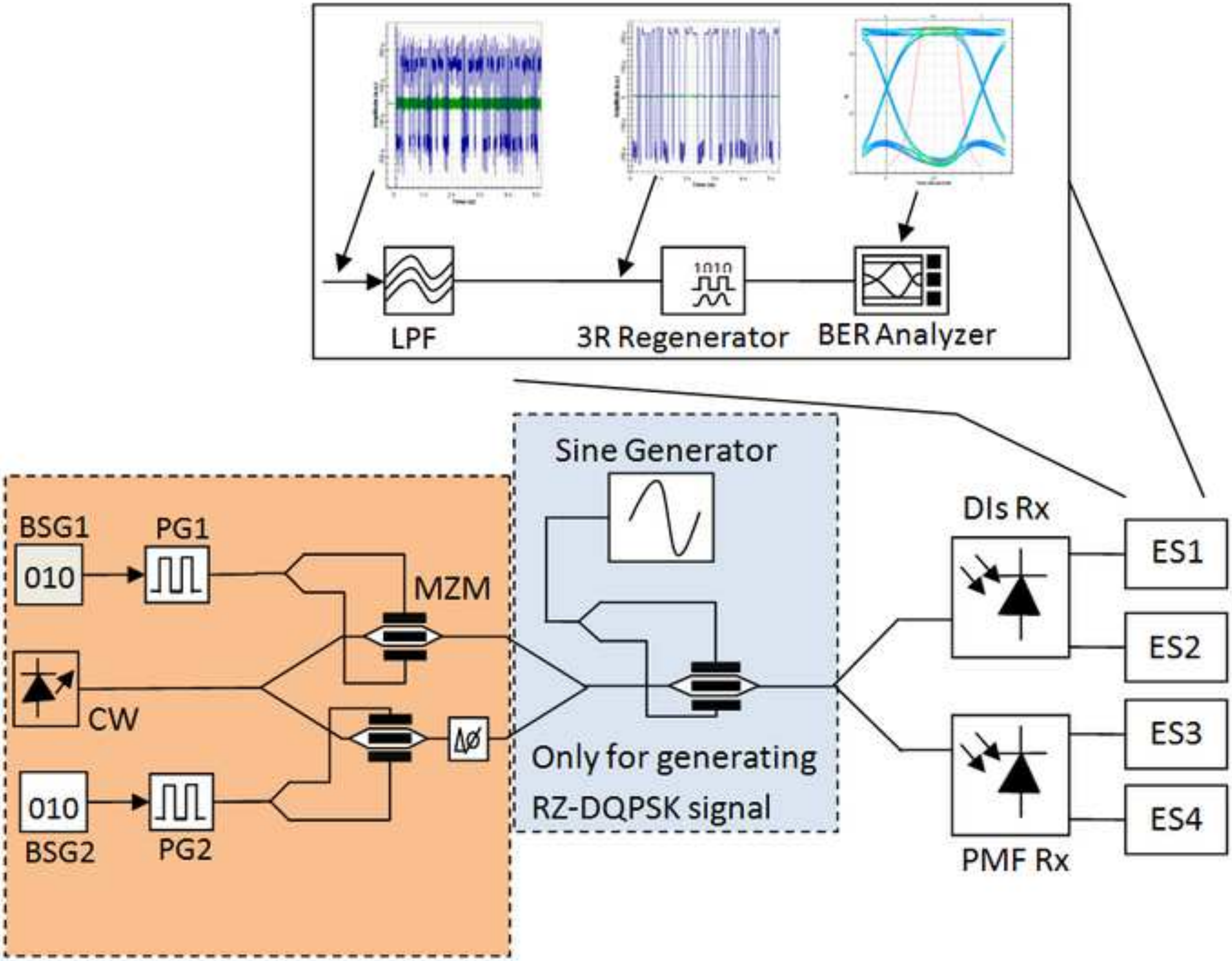

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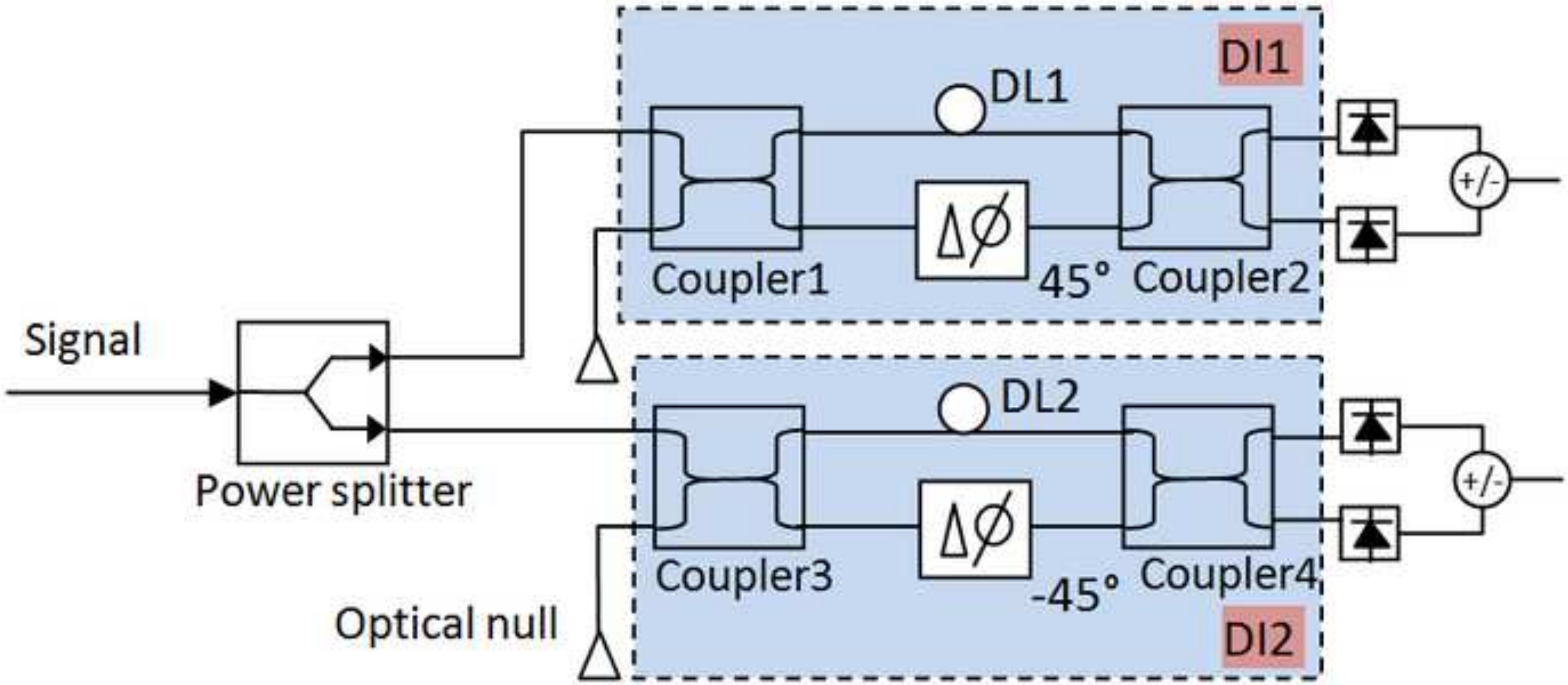

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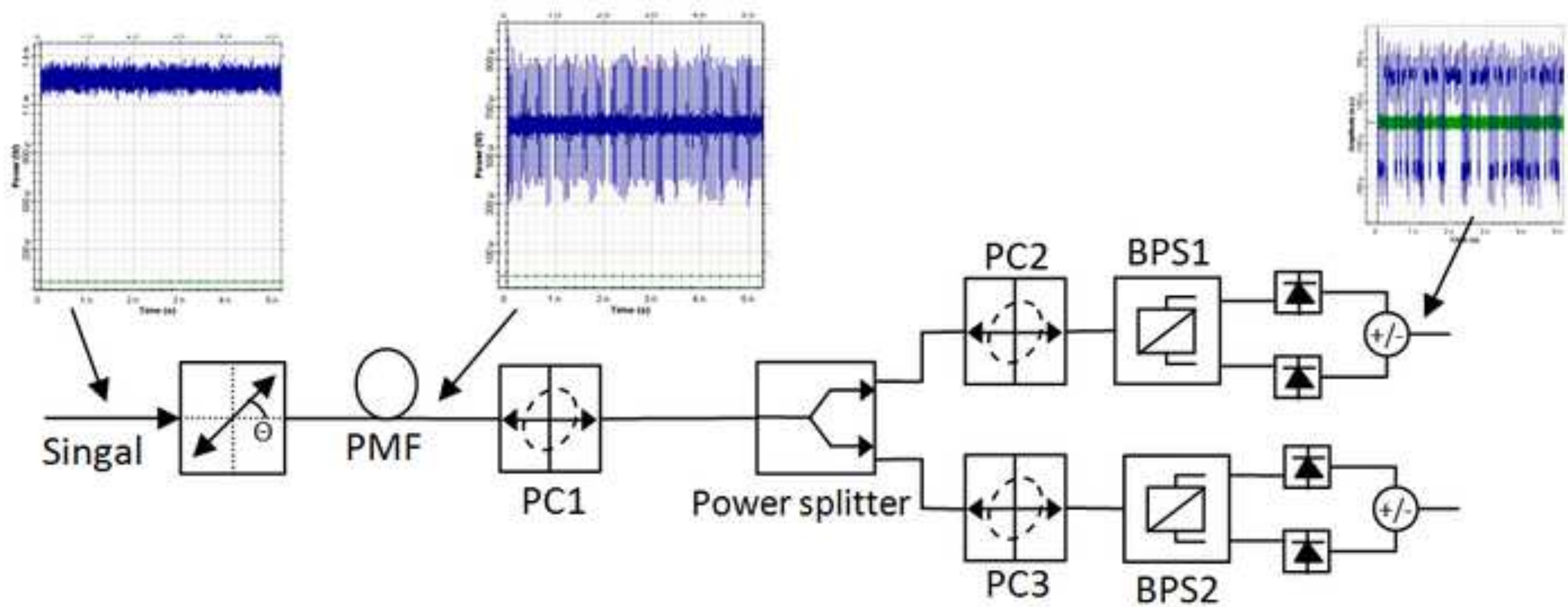

Figure 4

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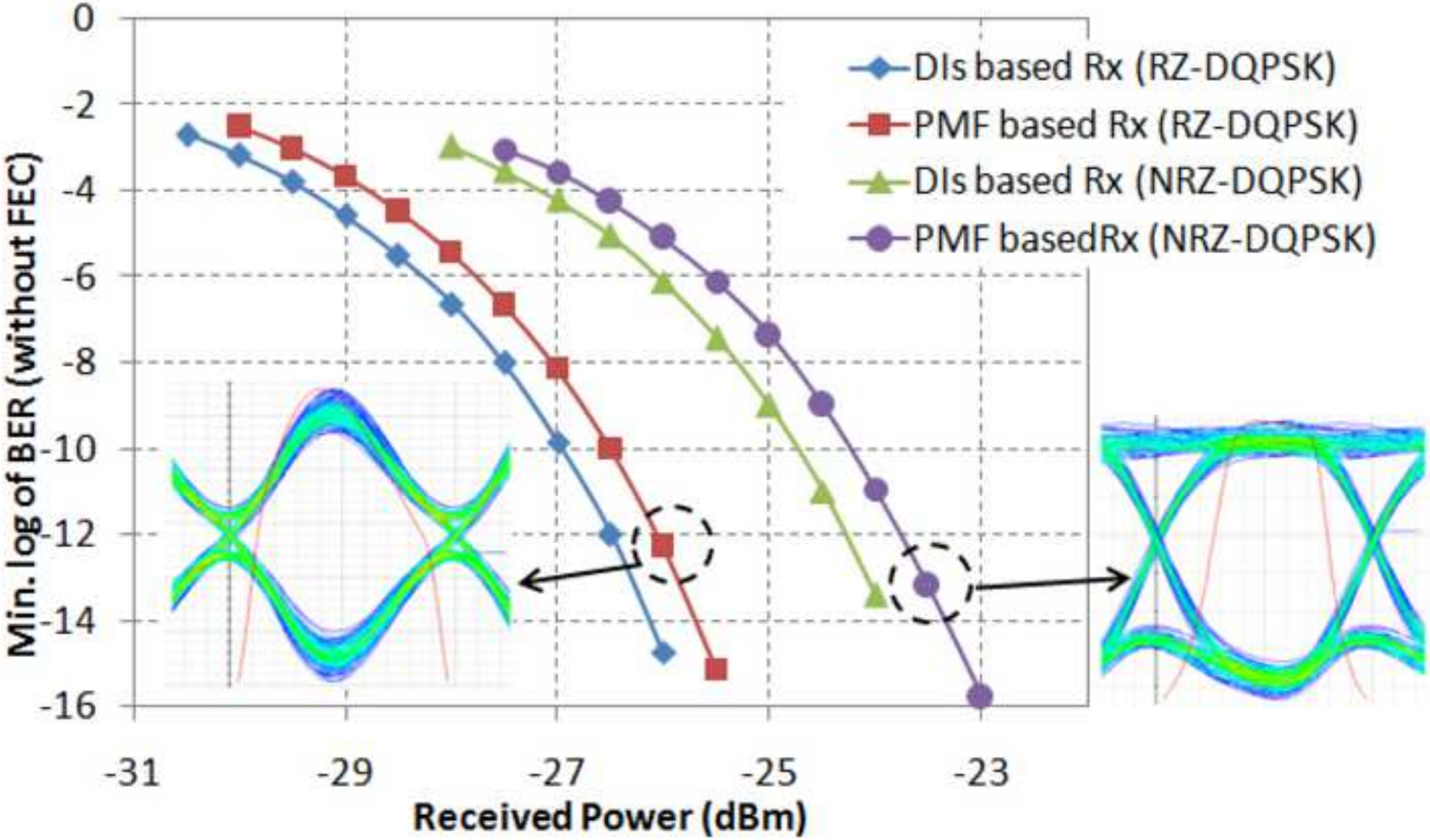

Figure 5(a)
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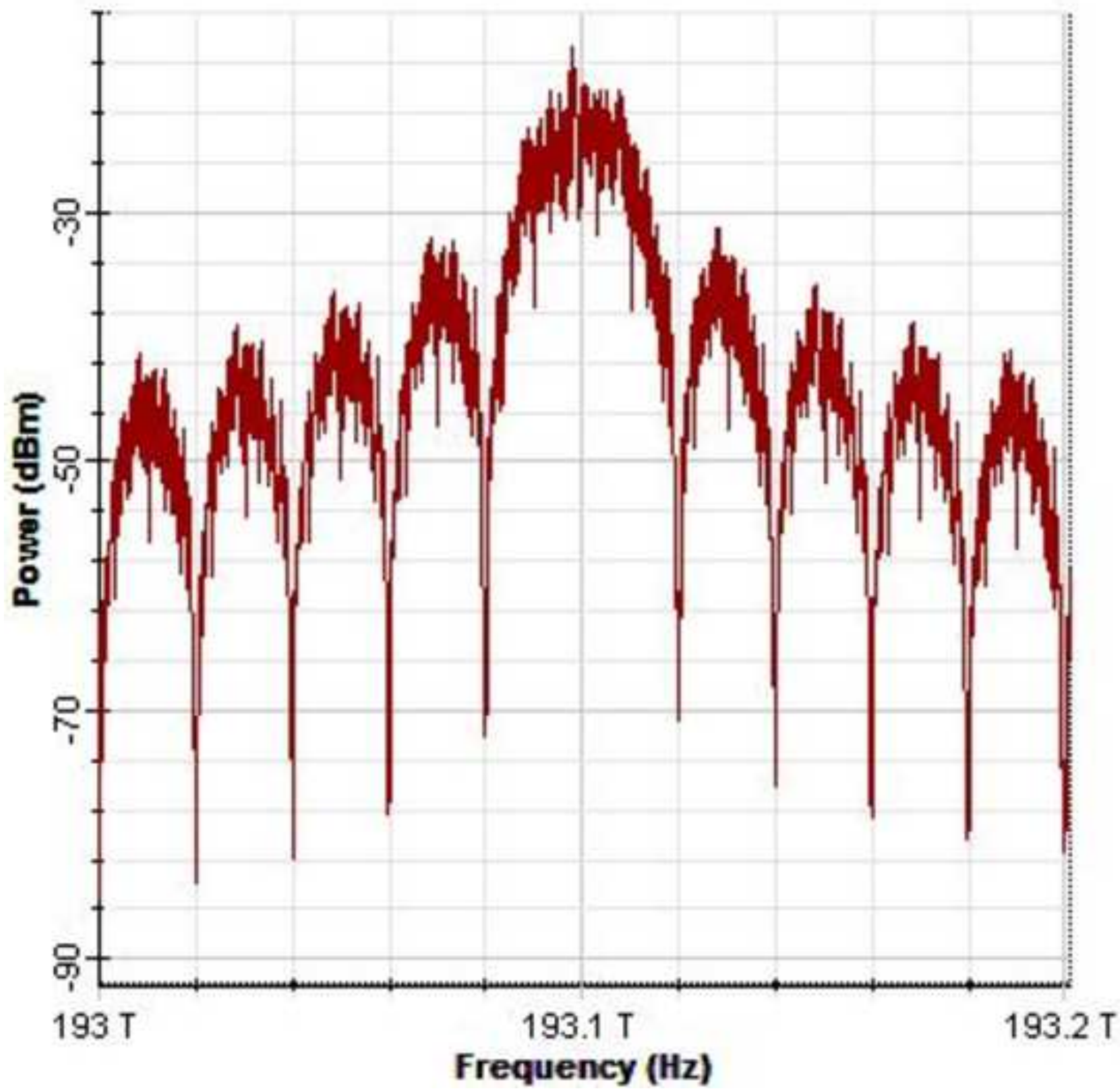

Figure 5(b)
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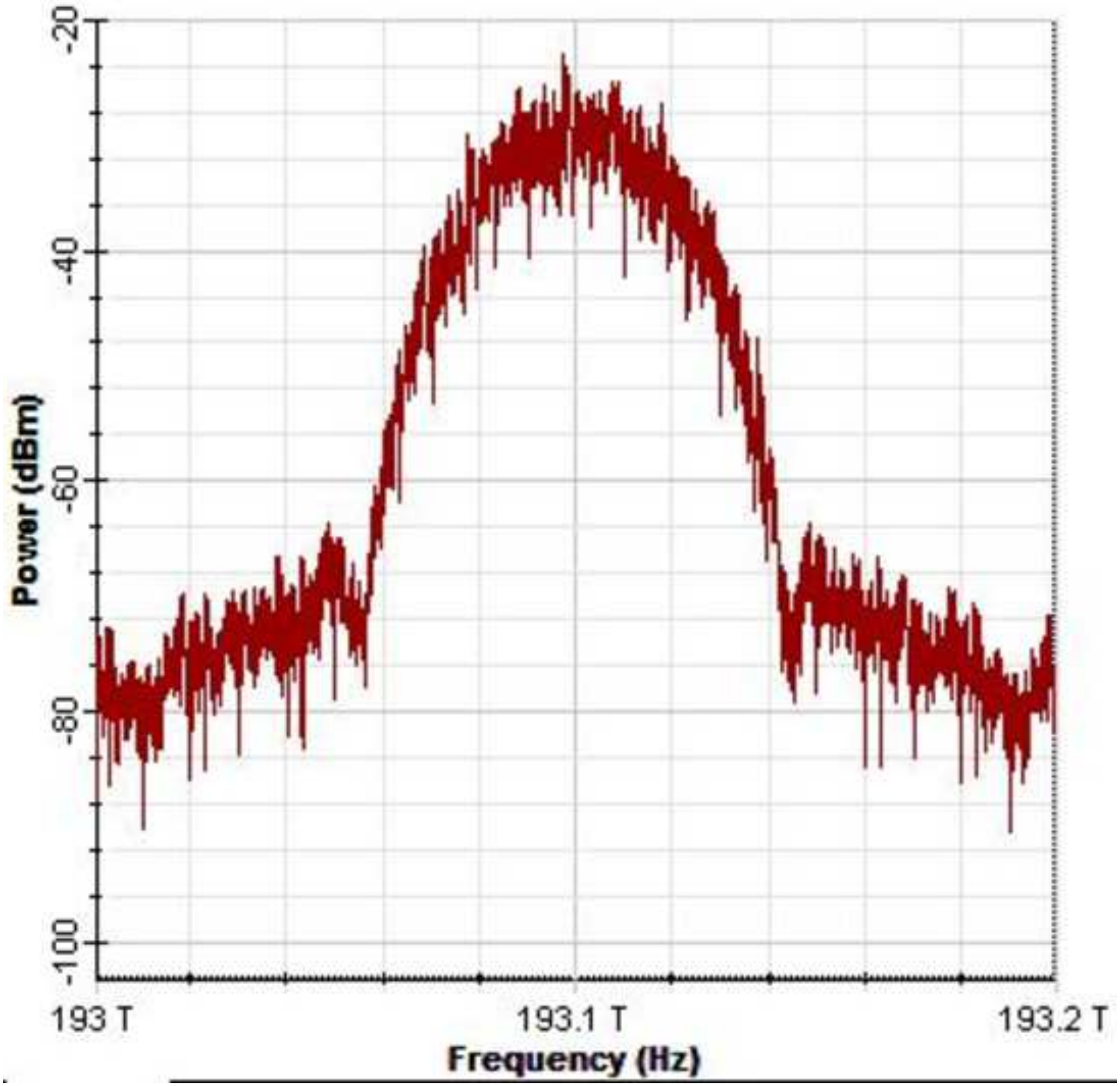

Figure 6
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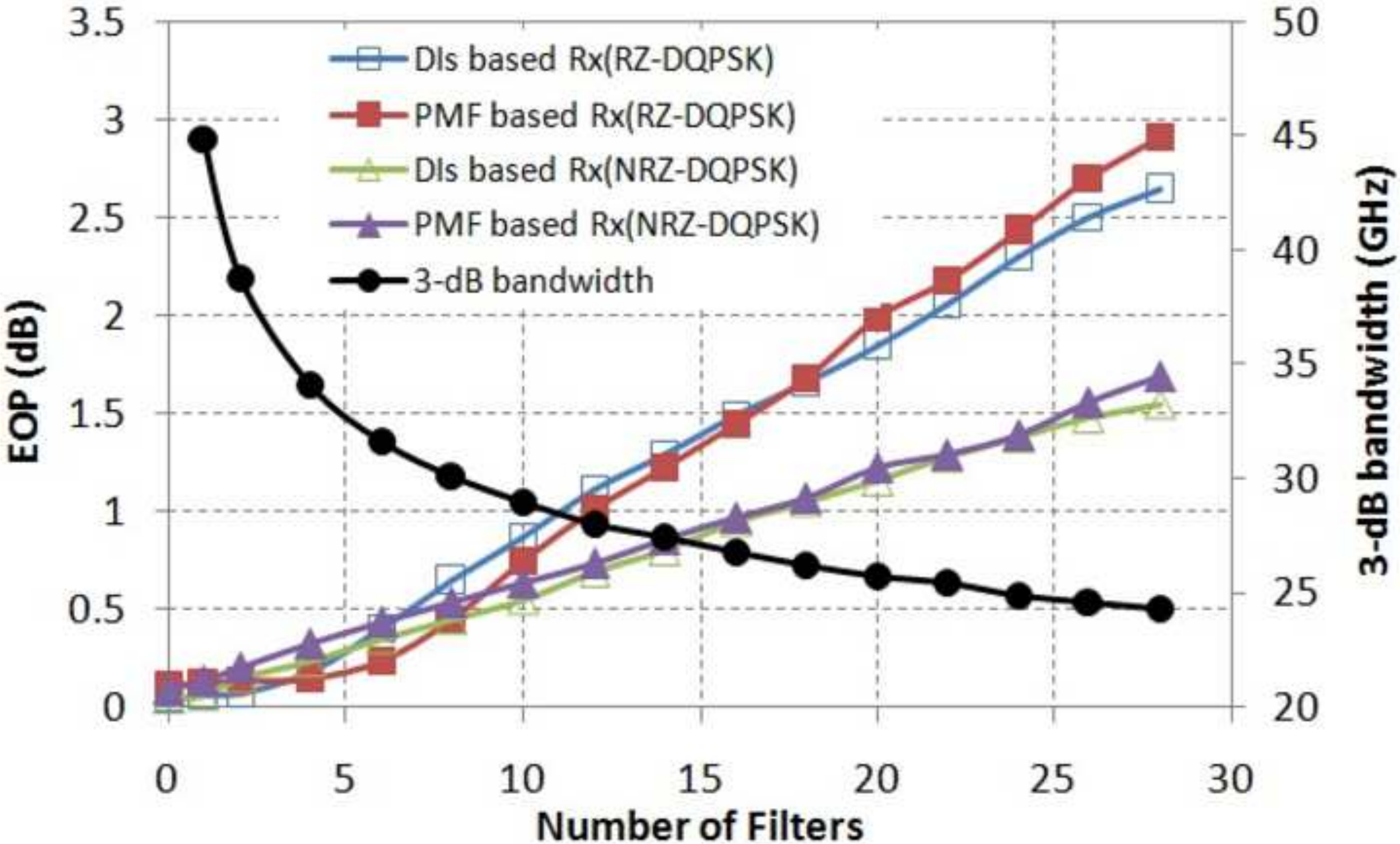

Figure 7
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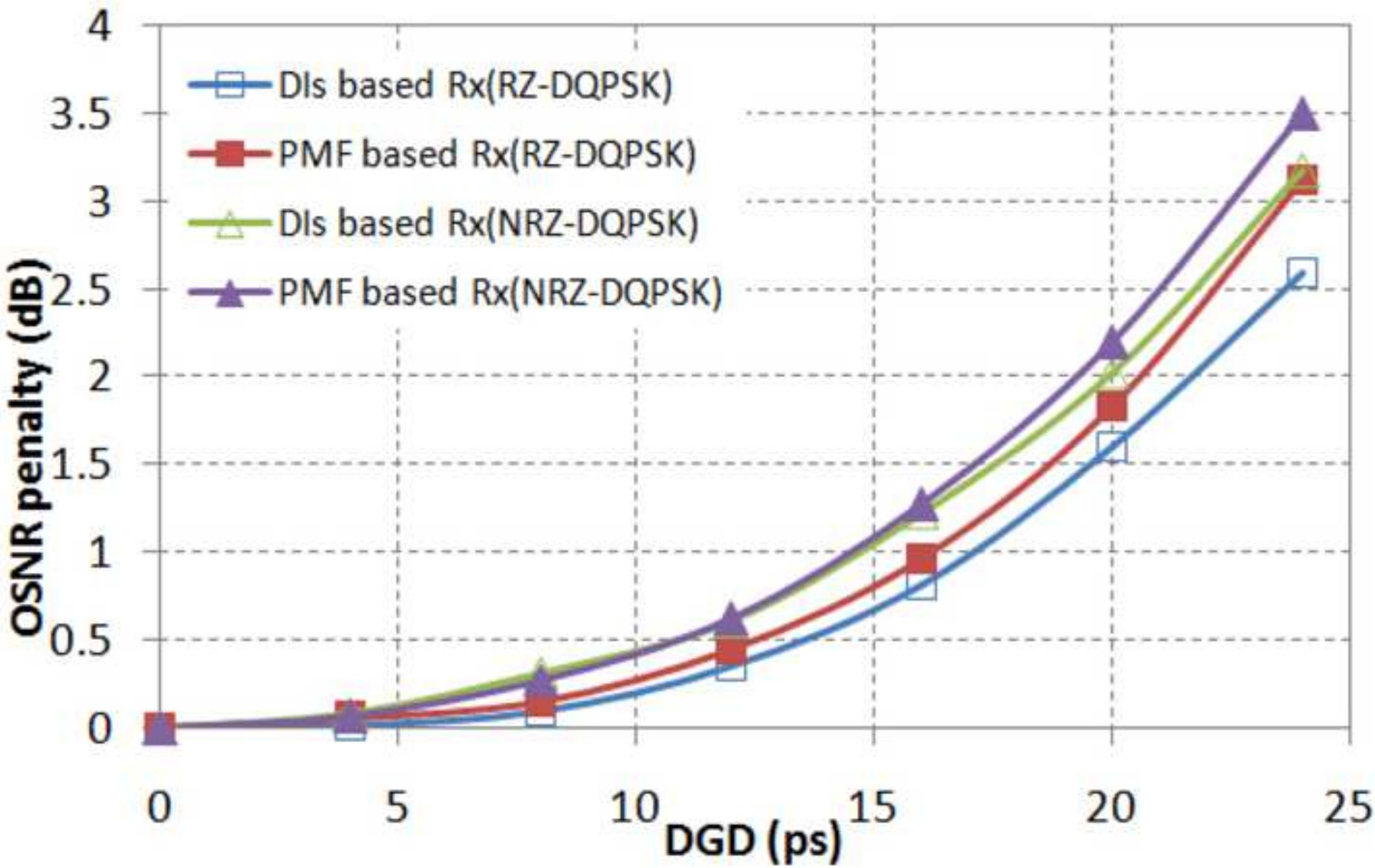

Figure 8
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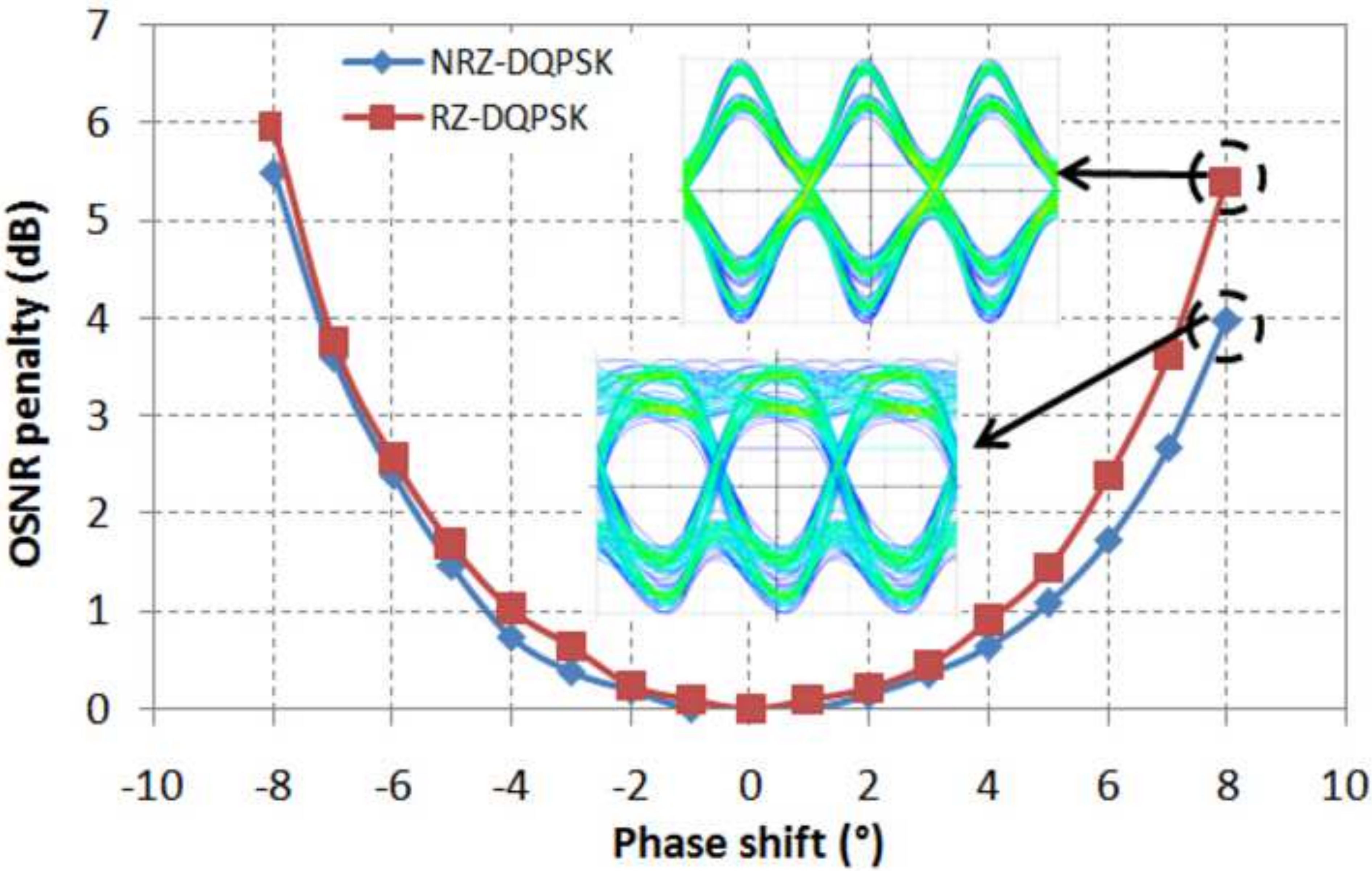

Figure 9
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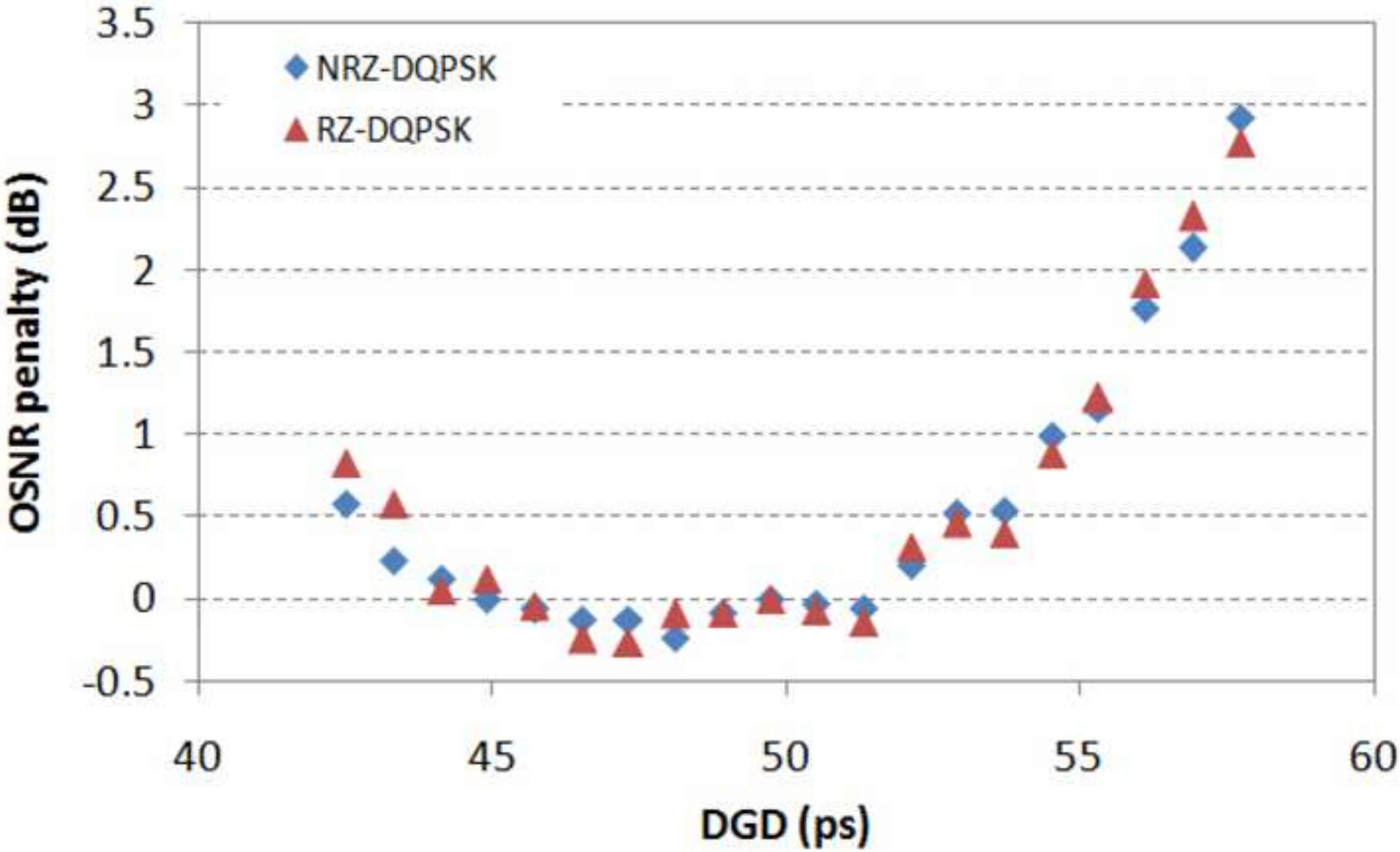

Author Biography (250 words max.)

Xiaoyong Chen received his Bachelor degree from School of Science for Optical Information Science and Technology, Beijing Jiaotong University, China, in 2009. Currently he is developing PhD in the Department of Photonic Technology and Bioengineering - ETSIT School (UPM, Spain). He is interested in optical communications, especially study about receivers of advanced modulation formats.

Paloma R. Horche received her Telecommunication Engineering degree in 1986 and her PhD degree in Communications in 1991, both from the ETSIT-School for Telecommunication Engineering, Universidad Politécnica de Madrid (UPM). Since 1990 she has been a member of the faculty of the ETSIT-UPM, currently as a Professor Titular de Universidad of Optical Communications in the Department of Photonic Technology and Bioengineering. Her main research activities are in the area of Optical Signal Processing with special emphasis on the fields of Optical Communications and Systems. She is a member of OSA.

Xiaoyong Chen
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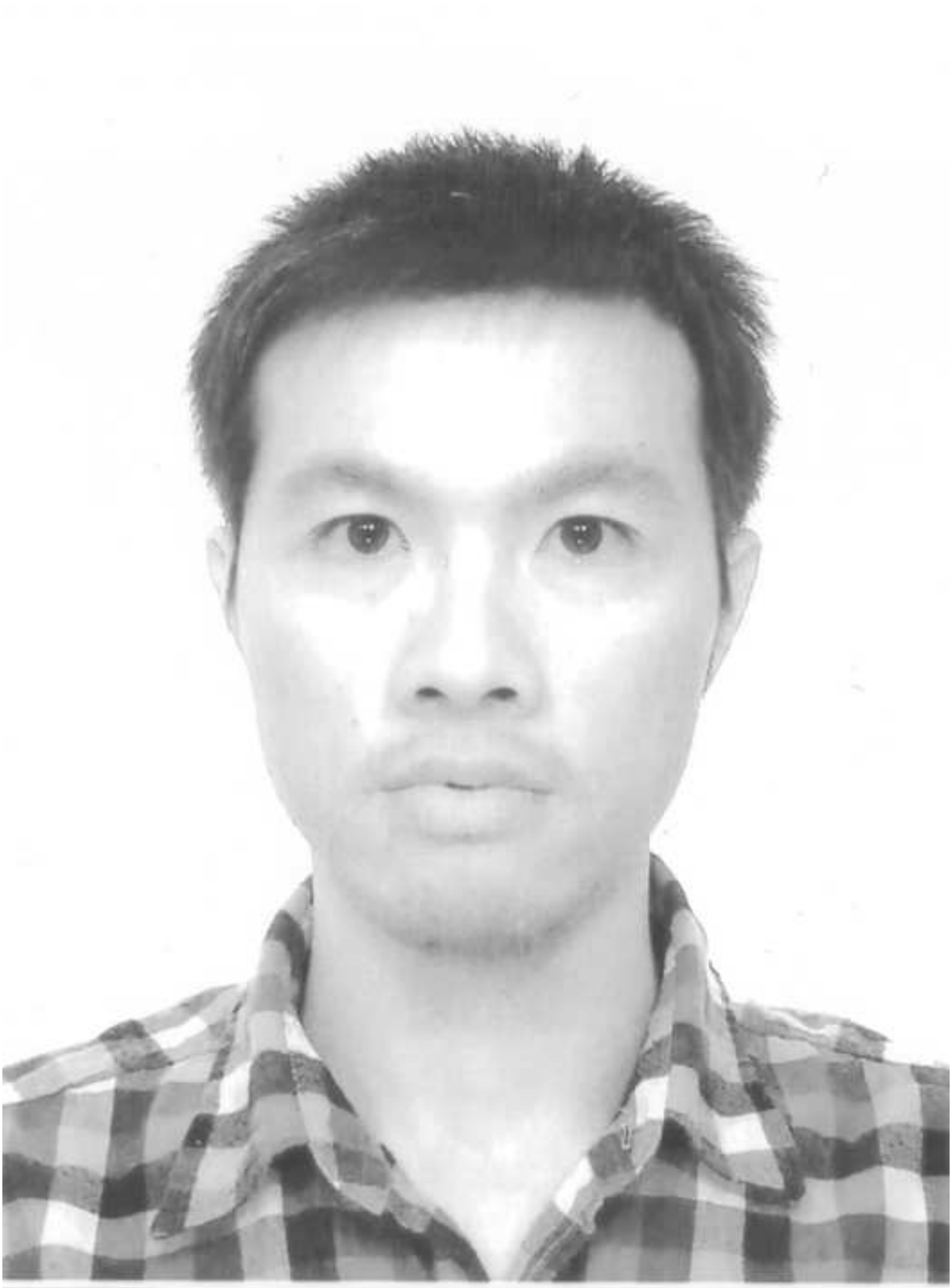

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