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Real-Time Eye Diagram Monitoring for Optical Signals Based on Optical Sampling

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Featured Application: The proposed real-time eye diagram monitoring method has potential applications in modern optical communications and cloud computations.

Abstract: A real-time eye diagram monitoring method for optical signals is proposed and experimentally demonstrated based on optical sampling. In the system, the optical signals under test are directly sampled by an optical sampling pulse train with a narrow pulse width and a high repetition frequency. The sampling pulse train is achieved in a Mach-Zehnder modulator (MZM), gated on-off by an electrical pulse. The sampled optical signals are then broadened and detected by a photodetector (PD). A low-speed electrical analog-to-digital converter (ADC) will then quantify the detected electrical signals. Combining with an algorithm based on the infinitesimal calculus, the quantified data is then used to achieve the eye diagram, according to which more time-domain parameters, such as period, time jitter, *Q* value, and bit error rate (BER) for the optical signals under test, are obtained. Thanks to the high repetition rate of the optical sampling pulse train, the eye diagram and the time-domain parameters of the optical signals are observed in real time. Experimental results show that a real time of about 350-μs eye diagram monitoring for a 2.5-Gb/s optical signal with a dynamic range from −10 to −22 dBm is achieved. In addition, time jitters are measured to range from 4.3 to 49.8 ps. *Q* values are estimated to range from 20.4 to 4.3, corresponding to BERs ranging from 2.3×10^{-92} to 8.5×10^{-6}. The results are also verified by a commercial real-time oscilloscope.

Keywords: microwave photonics; signal processing; eye diagram; optical sampling

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1. Introduction

An eye diagram, which consists of samples of the temporal intensity of a digital signal, is regarded as one of the most effective optical signal quality characterization methods [1,2]. Thanks to the ability to reflect the effects of various sources of impairments on digital optical signal qualities, eye diagram monitoring has been widely used in areas of modern optical techniques [3,4], such as optical communications, ultrafast optics, and cloud computations. In particular, real-time eye diagram monitoring techniques have grown in importance with full-time optical information transmission services. Traditionally, an eye diagram is achieved through photodetection and electrical signal processing. One example is converting the optical signal into an electrical signal via a wide-band photodetector (PD) and processing the electrical signal with a high-speed sample-and-hold circuit [5]. However, the rapidly increasing optical digital signal data rate presents a significant challenge to the bandwidth of the conventional photodetection and electrical signal processing technique. Additionally, achieving real-time eye diagram monitoring at a low operating cost is essential, ensuring optimum resource utilization and guaranteeing dynamic management of optical networks.

The problem of the bandwidth limitation of the conventional photodetection and electrical signal processing technique can be solved by using the photonic signal processing

technique, such as optical sampling, which has the advantages of broad bandwidth, low loss, and immunity to electromagnetic interference [6,7]. In general, conventional optical sampling techniques can be divided into two categories: linear optical sampling [8–10] and nonlinear optical sampling [11–18]. For the linear-optical-sampling-based eye diagram monitoring systems, the gating function is achieved by a short optical pulse. The optical sampling is implemented using a linear optical process in a low-speed PD, where the optical pulse and the optical signal under test are coherently homodyne mixed [8]. The linear-optical-sampling-based eye diagram measurement system can analyze the optical signal under test with a remarkable minimum peak power of about 60 μW. However, the coherent homodyne mixing process puts forward a high requirement for the wavelength controlling the optical pulse and the optical signal under test. For the nonlinear-sampling-based eye diagram monitoring systems, the gating function is achieved by the same short optical pulse used in a linear sampling system. Still, the optical sampling is performed through a second- or third-order nonlinear effect. In general, second-order effect-based sampling can be implemented in nonlinear crystals [14,15]. The third-order effect-based sampling can be achieved in a semiconductor optical amplifier (SOA) [16], a dispersion-shifted optical fiber [17], or a highly nonlinear fiber (HNLF) [18]. Though the nonlinear optical sampling-based eye diagram monitoring systems can measure the eye diagram of a high-speed optical signal, the sensitivity of the system is limited to an mW level due to the low efficiency of the nonlinear effects. In addition, the low repeat frequency limits the eye diagram update time. An eye diagram monitoring method with the advantages of high sensitivity, large dynamic range, and fast update speed is urgently needed.

In this paper, a real-time eye diagram monitoring method for optical signals is proposed and experimentally demonstrated based on a gated on-off optical sampling in a Lithium niobate modulator. The gating function is achieved by an optical pulse train, which is generated by gating on-off modulation of a Lithium niobate Mach-Zehnder modulator (MZM) with a narrow pulse width and a high repetition frequency. The sampling for the optical signal under test is then implemented on the MZM, where the optical signal under test is injected. The sampled optical pulse is then broadened, photodetected, and quantified by a low-speed electrical analog-to-digital converter (ADC) with a high dynamic range. Thanks to the broad bandwidth of the MZM and the high dynamic range of the ADC, the eye diagram of a 2.5-Gb/s optical signal with a dynamic range of about 12 dB is measured. In addition, due to the high optical sampling pulse repetition rate, real-time monitoring is implemented with an eye diagram measurement time of about 350-μs. According to the measured eye diagram, more time-domain parameters such as period, time jitter, Q value, and bit error rate (BER) for the optical signals under test are obtained.

2. Theory of Optical Sampling and Eye Diagram Recovery

Figure 1 shows the schematic diagram of the proposed eye diagram monitoring method for an optical signal. As can be seen, the eye diagram monitoring system can be divided into three parts: optical signal input module (Part 1), sampling and quantizing module (Part 2), and eye diagram recovery and time-domain parameter extraction module (Part 3). In the optical signal input module, the optical signal under test, which is coupled output from an optical transmission link or source, is injected into a polarization controller (PC), where the polarization of the optical signal under test is adjusted to be consistent with that of the MZM in Part 2. In the sampling and quantizing module, the signal from part 1 is injected into an MZM, which is intensity modulated by a gating on-off sampling pulse from an electrical pulse generator (EPG). The modulation pulse has a repetition rate of $1/T_S$ and a pulse width of $T_P = 1/(NT_S)$, where T_S is the period of the sampling pulse, and N is a positive integer. Then, the optical signal under test is optically sampled by the pulse with a repetition rate of $1/T_S$ and a pulse width of T_P. It should be noted that the repetition rate and the pulse width can be tuned by tuning the EPG. Then, a sampled signal is generated from the MZM, and the sampled signal is transmitted into a pulse broadening module, in which the pulse is broadened to match the sample rate of a low-speed electrical

ADC. The broadened sampling pulse is quantified at the same rate as the sampling pulse in the ADC. In addition, a clock generator is used to synchronize the ADC and the EPG, ensuring the quantization rate of the ADC matches the sampling rate of the sampling pulse train. Note that the ADC quantizing efficiency can be increased due to the excellent match between the hold time of the sample-and-hold circuit in the ADC and the pulse width of the broadened sampling pulse.

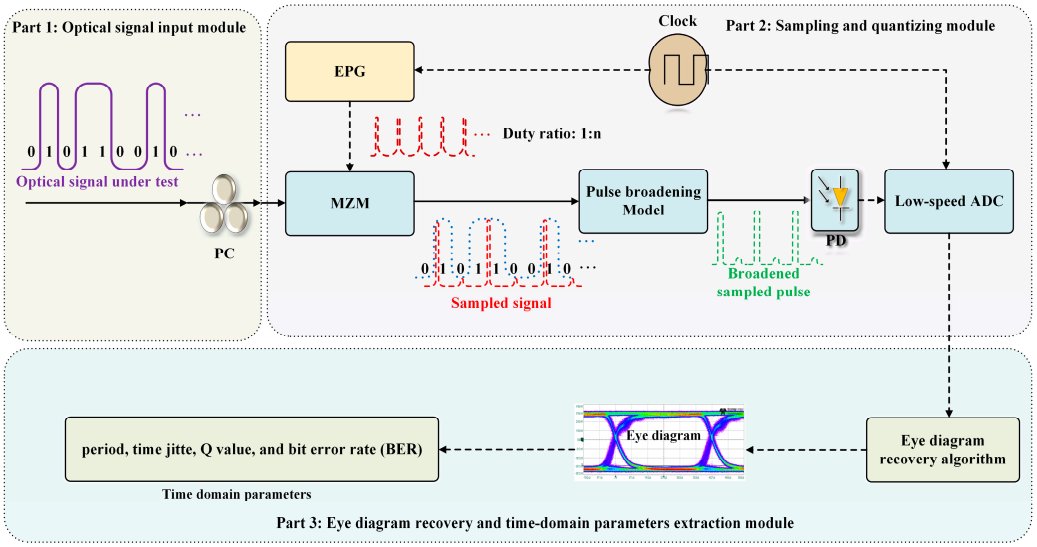


Figure 1. Schematic diagram of the proposed eye diagram monitoring method for an optical signal. PC: polarization controller; EPG: electrical pulse generator; MZM: Mach-Zehnder modulator; PD: photodetector; ADC: analog-to-digital converter; BER: bit error rate.

In the eye diagram recovery and time-domain parameters extraction module, the quantified data from the low-speed ADC is used to recover the eye diagram. Figure 2 shows the principle of random equivalent sampling to recover the eye diagram using the ADC data. The optical pulse is sampled with a repetition rate of $1/T_S$ and a pulse width of $T_P = 1/(NT_S)$. Then, the sampling rate of the ADC is chosen to be $f_S = 1/T_S$. The random equivalent sampling is achieved when the sampling rate $f_S \neq (1/T_S) \times n$, where $n = 1/2, 1, 2, 3 \cdots \cdots$. Assuming the period of the optical signal under test is T_X and moving the sampled and quantified data within $2T_X$ with the specific time relations between the periods of the optical signal under test and the sampling pulse, the eye diagram is obtained with an equivalent sampling rate of $f_{ES} = M/T_S$, where $M = T_X/(T_S - T_X)$. For example, when the period of the optical signal is $T_X = 400$ ps (2.5-Gb/s rate) and the period of the sampling pulse is $T_X = 420$ ps (2.38-GS/s sampling rate), an equivalent sampling rate of $f_{ES} = 50$ GS/s can be achieved.

Generally, the frequency or the period T_X of the optical signal under test can be achieved using a fast Fourier transform (FFT). However, a huge amount of data and computation are necessary to realize the FFT. Here, an algorithm based on the infinitesimal calculus is proposed to directly obtain the period T_X of the optical signal under test and recover the eye diagram. According to the eye diagram in Figure 3, the eye area can be calculated based on the concept of infinitesimal calculus.

$$S = sum(w_i \times h_i), i = 1, 2, 3, \cdots, m, \quad (1)$$

where the eye area is divided into m rectangles, and w_i and h_i are the width and height of the i-th rectangle, respectively.

Figure 4 shows the eye diagram recovery algorithm, and the eye diagram recovery can be realized by the six steps shown below.

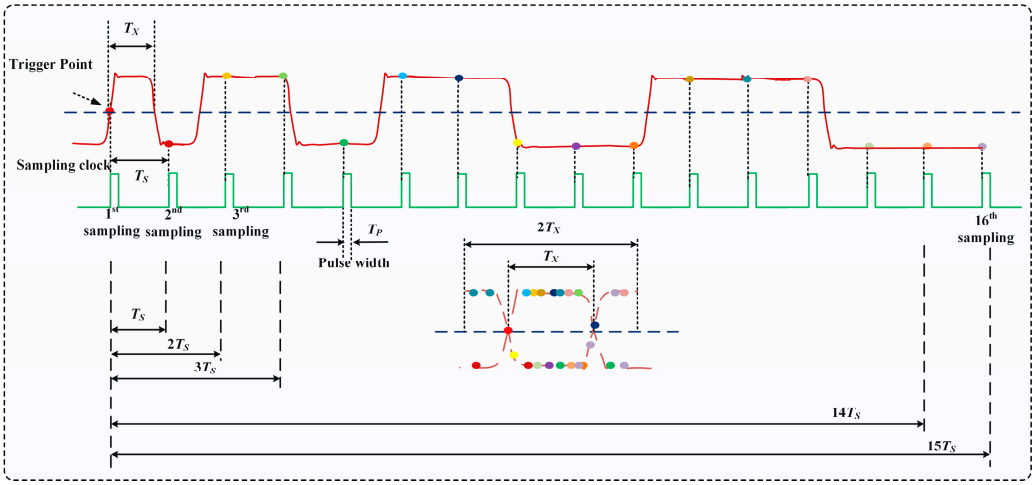


Figure 2. Principle of random equivalent sampling to recover the eye diagram. T_X: the period of the optical signal under test; T_S: the period of the sampling pulse; T_P: pulse width of the sampling pulse.

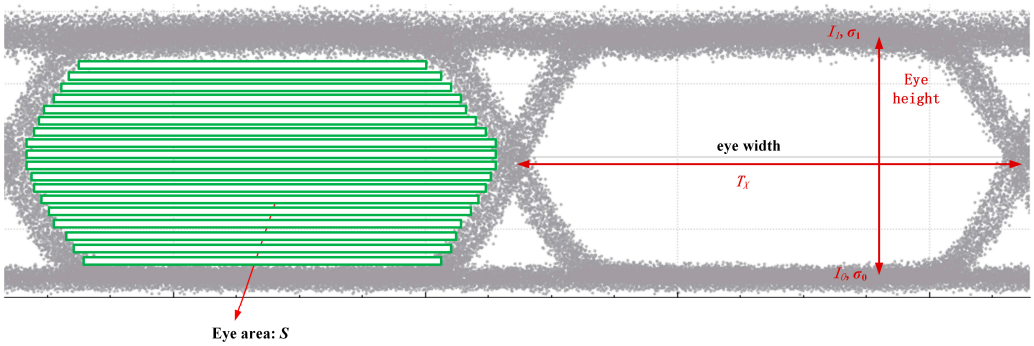


Figure 3. Eye diagram.

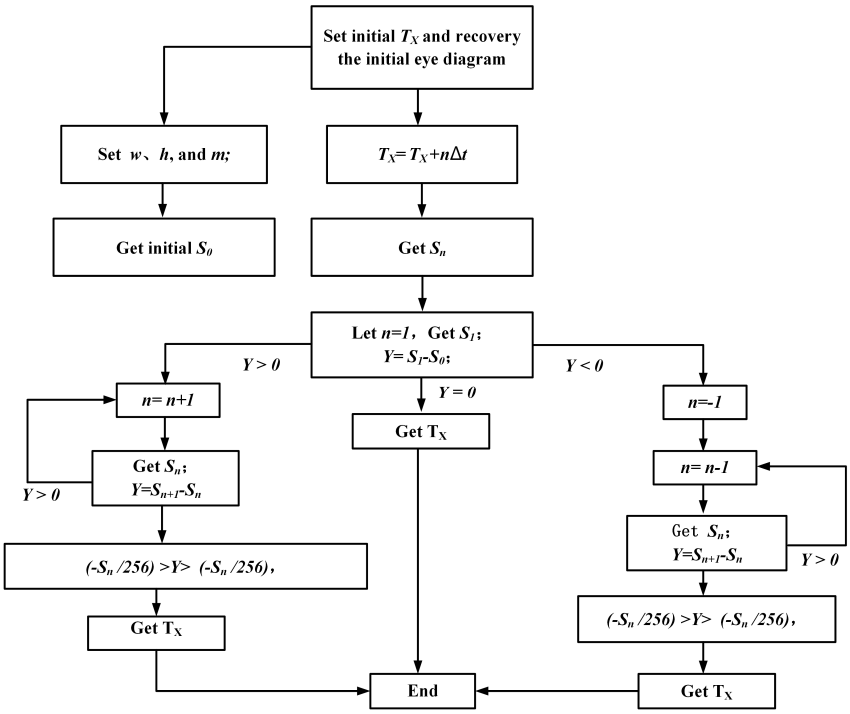


Figure 4. Eye diagram recovery algorithm.

Step 1: Set the expected period T_X of the optical signal under test and recover the eye diagram according to the random equivalent sampling described in Figure 2.

Step 2: Set the quantity m of the rectangle and the width and height of the i-th rectangle to be w_i and h_i, and obtain the initial eye area S according to Equation (1). S_0 indicates the eye area of the initially obtained eye diagram.

Step 3: Increase T_X by $n\Delta t$, repeat step 2, and obtain S_n. It should be noted that Δt is the time resolution for recovering the period of the eye diagram.

Step 4: Let $n = 1$, obtain S_1 using step 2, and calculate $Y = S_1 - S_0$. If $Y > 0$, turn to step 5. If $Y < 0$, turn to step 6. If $Y = 0$, obtain the eye diagram and period T_X.

Step 5: Repeat $n = n + 1$, obtain S_n using step 2 and calculate $Y = S_{n+1} - S_n$. When $S_n/256 > Y > -S_n/256$ (256 corresponds to 8-bit effective bits), obtain the eye diagram and period T_X.

Step 6: Let $n = -1$, Repeat $n = n - 1$, obtain S_n using step 2, and calculate $Y = S_{n-1} - S_n$. Obtain the eye diagram and period T_X when $S_n/256 > Y > -S_n/256$.

According to the recovered eye diagram, more time-domain parameters such as period, time jitter, Q value, and bit error rate (BER) for the optical signals under test are obtained. The eye width is the period T_X of the optical signal under test. The time jitter can be extracted from the jitter histogram. The Q value, which is used to describe the signal quality, can be given by [19]

$$Q = (I_1 - I_0)/(\sigma_1 + \sigma_0), \tag{2}$$

where I_1 and I_0 are the mean values of the eyelid and eye ground marked in Figure 3, respectively. σ_1 and σ_0 are the noise standard deviations of the eyelid and eye ground marked in Figure 3, respectively.

The BER can be calculated based on the Q value as [19]

$$\text{BER} = 1/2\text{erfc}(Q/2^{1/2}) \approx \exp(-Q^2/2)/[(2\pi)^{1/2}Q]), \tag{3}$$

3. Results and Discussion

A proof-of-concept experiment was performed based on the setup shown in Figure 1. The MZM (CETC-40) has a 3-dB bandwidth of about 40 GHz. The PD (Kang Guan KG-PD-10G) has a 3-dB bandwidth of around 10 GHz and a photoresponsivity of 0.8 A/W. The ADC has a sampling rate of 1.5 Gsps, a 10-bit quantization resolution, and a bandwidth of 4 GHz. A pulse having a 1.5-GHz repetition rate and a duty ratio of 1:8 is generated from an EPG (Anritsu MU183021A). When a continuous lightwave with an optical power of 0 dBm is injected into the MZM, the sampling pulse after photodetection is measured in Figures 5a and 5b by a real-time oscilloscope (Teledyne Lecroy SDA 820Zi-B). The broadened sampling pulse is measured using the same method in Figure 5b. To observe the pulse width and the period of the optical pulses, the measured signals in Figures 5a and 5b are re-plotted in Figures 5c and 5d, respectively, with the recording time ranging from 0 to 4 ns. It is seen that the sampling pulse width is broadened from 83.5 to 227 ps, which matches the trace-and-hold capability of the ADC. The period of the optical pulse stays the same at 666.7 ps, corresponding to the sampling rate of 1.5 GHz.

By synchronizing the EPG and the ADC with a 1.5-GHz clock, the ADC trace-and-hold window is located at the flat top of the broadened sampled pulse. Then, the broadened sampled pulse is quantized with high quantizing efficiency by the ADC with a 1.5-GHz repetition rate. Considering the 1.5-GHz sampling frequency and the ~500,000 recording points for the eye diagram recovery, the recording time for the eye diagram is about 350 μs, which means real-time eye diagram monitoring can be implemented.

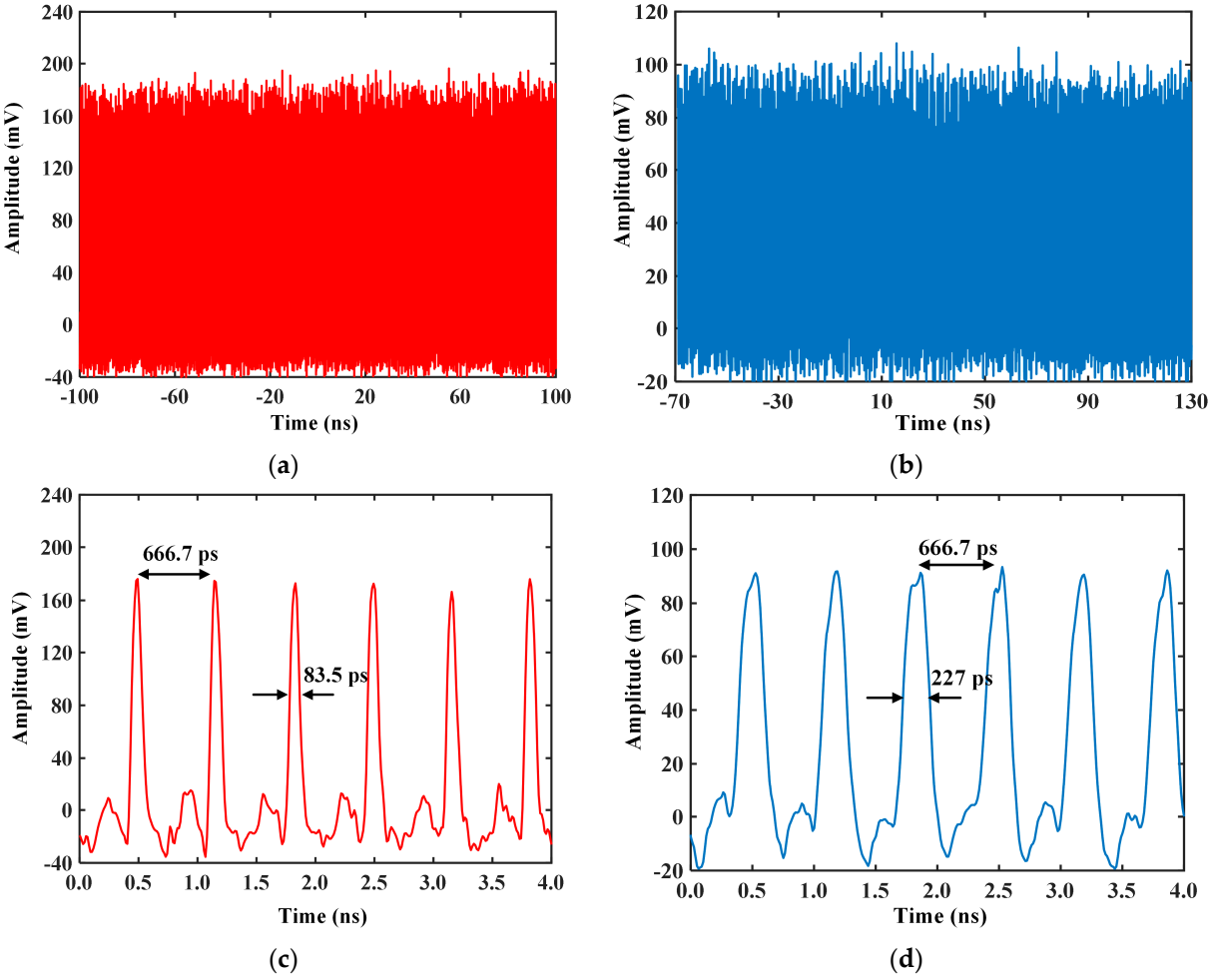


Figure 5. The measured optical pulse train by a real-time oscilloscope. (**a**) The measured pulse train after the MZM with a recording time of 200 ns; (**b**) The measured broadened pulse train before the PD with a recording time of 200 ns; (**c**) The measured pulse train after the MZM with the recording time range from 0 to 4 ns; (**d**) The measured broadened pulse train before the PD with the recording time range from 0 to 4 ns.

Figure 6 shows the measured eye diagrams and time-domain parameters, such as period, time jitter, *Q* value, and BER, of the optical signal generated from a commercial optical transmitter (HUAWEI-2.5GHz-40km). When the optical signals under test have different powers of −8, −14, and −20 dBm, the eye diagrams and the corresponding time-domain parameters are measured in Figures 6a, 6b and 6c, respectively. It is seen that the periods of the optical signals with different powers are measured the same as 401.8 ps, corresponding to the same rate of about 2.488 GHz. The time jitter histograms are also extracted according to the measured eye diagrams. As can be seen, the root means square (RMS) jitters are measured to be 8.4, 9.1, and 30.5 ps when the optical signals have different powers of −8, −14, and −20 dBm. Furthermore, the Q values and the BER are also obtained according to the measured eye diagrams and Equations (2) and (3). When the optical signals have different powers of −8, −14, and −20 dBm, the *Q* values are measured to be 19.1, 12.8, and 4.1, corresponding to different BERs of 1.3×10^{-81}, 1.4×10^{-37}, and 2.4×10^{-5}, respectively. In addition, the measured results by the proposed eye diagram monitoring systems are verified by the measured eye diagram in Figure 6d from a commercial real-time oscilloscope. It is seen that the period of the optical signal is measured to be 401.8 ps, the same as that measured by the proposed eye diagram monitoring system.

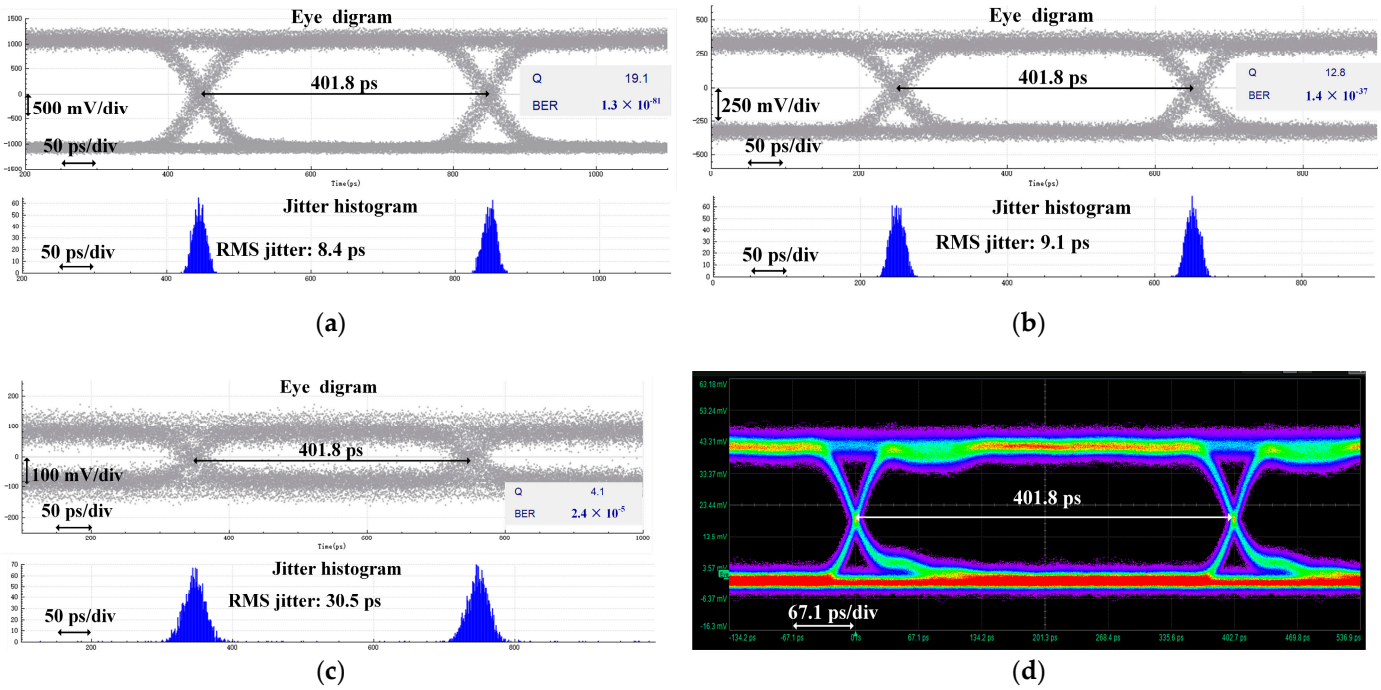


Figure 6. The measured eye diagrams and time jitter histograms when the optical signals under test from an optical transmitter (HUAWEI-2.5 GHz–40 km) have different powers of (**a**) −8 dBm, (**b**) −14 dBm, and (c) −20 dBm. (**d**) The measured eye diagram by the commercial real-time oscilloscope.

To further verify the measurement capacity of the proposed eye diagram monitoring system, the eye diagrams and time-domain parameters of the optical signal generated from a commercial optical transmitter (HUAWEI-2.5 GHz–80 km) are measured in Figure 7. The eye diagrams and the corresponding time-domain parameters are measured in Figures 6a, 6b and 6c when the optical signals under test have different powers of −10, −17, and −22 dBm, respectively. It is seen that the periods of the optical signals with different powers are measured the same as 401.8 ps. The RMS jitters are estimated to be 4.3, 6.4, and 49.8 ps when the optical signals have different powers of −10, −17, and −22 dBm. When the optical signals have different powers of −10, −17, and −22 dBm, the Q values are measured to be 20.4, 11.5, and 4.3, corresponding to different BERs of 2.3×10^{-92}, 6.5×10^{-31}, and 8.5×10^{-6}, respectively. In addition, the measured results of the proposed eye diagram monitoring systems are verified by the measured eye diagram in Figure 6d from a commercial real-time oscilloscope.

The performance comparison of the proposed eye diagram monitoring method with the state-of-the-art works is given in Table 1, where the key figures of merit for eye diagram monitoring methods are listed. Among these works, the nonlinear-optical-sampling-based eye diagram monitoring systems can measure the eye diagram of a high-speed optical signal. Still, the linear-optical-sampling-based eye diagram measurement system has a higher sensitivity than the nonlinear-optical-sampling-based eye diagram measurement system. The low sampling rate limits the eye diagram update time of these previous works. In addition, these previous works did not obtain time-domain parameters such as period, time jitter, Q value, and bit error rate (BER) for the optical signals under test. Thanks to the use of broadband MZM, the high-dynamic ADC, and the highly repetition-rate optical sampling pulse in this work, the proposed eye diagram monitoring method has the advantages of higher sensitivity and faster eye diagram update time. In addition, time-domain parameters such as period, time jitter, Q value, and bit error rate (BER) for the optical signals under test are also obtained according to the achieved eye diagram in this work.

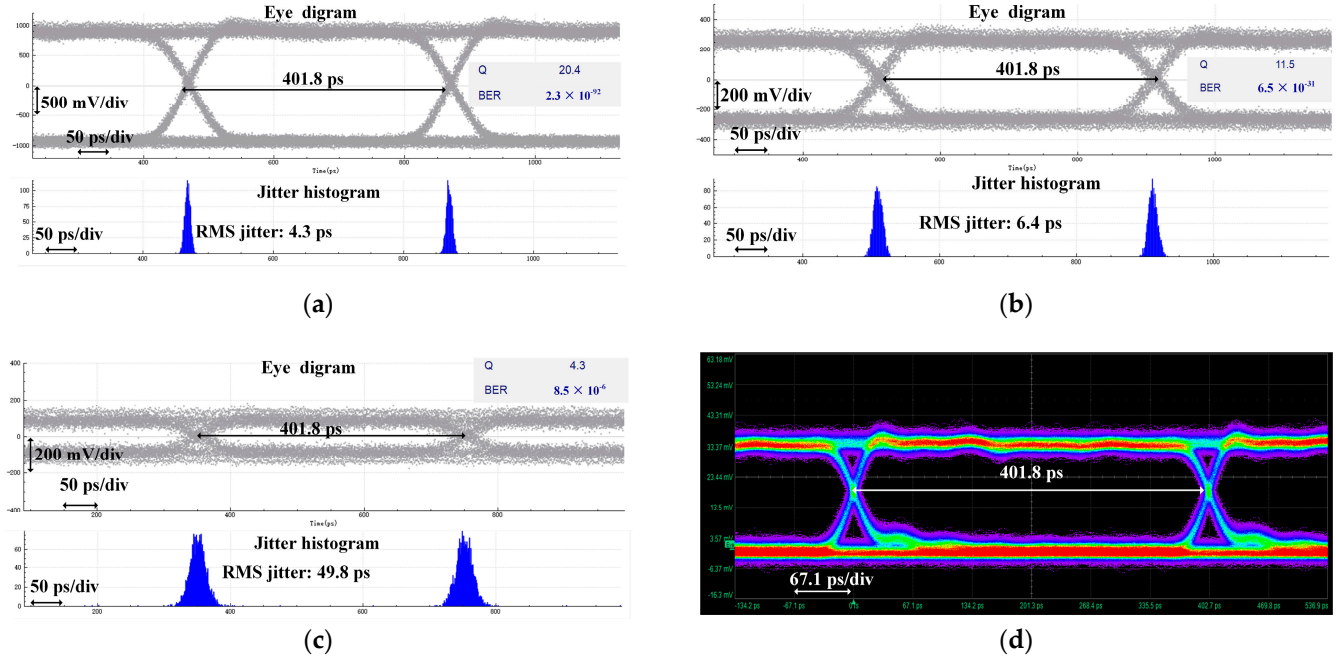


Figure 7. The measured eye diagrams and time jitter histograms when the optical signals under test from an optical transmitter (HUAWEI-2.5 GHz–80 km) have different powers of (**a**) −10 dBm, (**b**) −17 dBm, and (**c**) −22 dBm. (**d**) The measured eye diagram by the commercial real-time oscilloscope.

Table 1. Performance comparison of various eye diagram monitoring methods.

Eye Diagram Methods	Reference	Sampling Rate	Sensitivity	*Q* Value	Time Jitter
Gated on-off optical sampling	This work	1.5 GHz	−22 dBm	4.3 to 20.4	4.3 to 49.8 ps
Linear optical sampling	[8]	10 MHz	−20 dBm	n/a	n/a
	[9]	10 MHz	−12.2 dBm	n/a	n/a
	[10] (Simulation)	n/a	16 dBm	5 to 20	n/a
Nonlinear optical sampling	[11]	100 MHz	>1 dBm	n/a	n/a
	[12]	497 MHz	−1 dBm	n/a	n/a
	[13]	100 MHz	10 dBm	n/a	n/a
	[14]	100 MHz	>1 dBm	n/a	0.16 ps
	[15]	100 MHz	24 dBm	n/a	n/a
	[16]	200 MHz	12 dBm	n/a	n/a
	[17]	4 kHz	5 dBm	n/a	n/a
	[18]	100 MHz	12 dBm	6 to 13	n/a

4. Conclusions

In summary, a real-time eye diagram monitoring method for optical signals was proposed and experimentally demonstrated based on gated on-off optical sampling. In the system, the optical signals under test were directly sampled by an optical sampling pulse train, achieved in an electrical pulse-modulated MZM. The sampled optical signals were then broadened and detected by a PD. A low-speed electrical ADC then quantified the detected electrical signals. The quantified data was then used to achieve the eye diagram based on the concept of infinitesimal calculus. According to the measured eye diagram, more time-domain parameters such as period, time jitter, *Q* value, and bit error rate (BER) were obtained for the optical signals under test. Compared to previous studies on eye diagram monitoring, the proposed eye diagram monitoring method has the advantages of higher sensitivity, a larger dynamic range, and faster eye diagram update time due to the broadband MZM, the high-dynamic ADC, and the highly repetition-rate optical sampling pulse. An experimental demonstration was implemented. A real-time of about 350-μs eye

diagram monitoring and a dynamic range of about 12 dB was achieved for a 2.5-Gb/s optical signal. The results were also verified by a commercial real-time oscilloscope. The successful demonstration of the eye diagram monitoring method based on optical sampling provides a simple and real-time way to realize the eye diagram monitoring and time-domain parameters extraction of an optical signal, which is of fundamental importance for optical communications and cloud computations.

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