Demonstration of 100 Gb/s PAM-4 Signal Transmission in Optical Interconnect with 3-bit DAC Enabled with CRD-NS Technique

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***Abstract*—In this paper, we experimentally demonstrated a 2-km 100 Gb/s optical interconnection with pulse-shaped pre-equalized four-level pulse amplitude modulation (PAM-4) signal generated by a 3-bit digital-to-analog converter (DAC) with the aid of channel response-dependent noise shaping (CRD-NS) technique.**

Keywords—Digital-to-analog converter, four-level pulse amplitude modulation, optical interconnection

I. INTRODUCTION

Optical interconnection is being extensively researched to cope with the dramatically increased IP traffic induced by the emergence of high bandwidth services. For the short-reach optical interconnection, the intensity modulation and direct detection (IM/DD) system is considered as one of the most promising solutions due to its low cost, power consumption, and footprint [1-3]. At present, practical solutions based on IM/DD systems for adaptation to future optical interconnection requirements are being extensively researched by considering both system cost and capacity [1-4]. The pulse-shaped pre-equalized pulse amplitude modulation (PAM) signal with simple and low power consumption characteristics is preferable for IM/DD system to improve optical interconnection capacity [2-4].

Pulse shaping and pre-equalization techniques at the transmitter guarantee the performance of the transmitted PAM signal, while the implementation of those DSPs always results in a large peak-to-average power ratio (PAPR), which indicates that the necessity of the high-resolution digital-to-analog converter (DAC) [5]. The utilization of DAC with high resolution significantly increases the system cost, which is unfriendly to the cost-sensitive optical interconnection. Recently, many studies concentrate on promoting the utilization of low-resolution DAC with quantization noise suppression techniques, such as noise shaping (NS), and digital resolution enhancer (DRE) [5-9]. In both IM/DD and coherent systems, comparisons between NS and DRE have been studied in Ref. [6], which shows that the noise-shaping capability of the NS technique is similar to the DRE technique and the required computational complexity and processing delay decreases significantly. Thus, for low-cost optical interconnection, it is preferable to adopt the NS technique. To further improve the noise-shaping capability of the NS technique, channel response-dependent noise shaping (CRD-NS) is investigated for pre-equalized discrete multi-tone (DMT) signal to mainly overcome the residual quantization noise unevenly distributed issue [7]. The experiment results indicate that for the DMT signal generated by a 3-bit DAC, the CRD-NS technique shows a better noise-shaping capability with traditional NS technique. Different from the DMT signal, the PAM signal is insensitive to unevenly distributed quantization noise. Therefore, the effectiveness of CRD-NS for the high-speed PAM signal with the low-resolution DAC needs to be further studied and explored to reduce the cost of optical interconnection.

In this paper, the transmission of 100 Gb/s pulse-shaped pre-equalized PAM-4 signal using 3-bit DAC is studied with the CRD-NS technique. The experiment results show that about 0.5 dB receiver sensitivity improvement can be observed for 100 Gb/s PAM-4 signal generated by 3-bit DAC when the CRD-NS technique is applied to replace the traditional NS technique at the hard-decision forward error correction (HD-FEC) threshold, without additional computational complexity. Compared to the high computational complexity DRE technique, in which channel response is also considered for quantization noise suppression, about 1 dB receiver sensitivity improvement is observed when the CRD-NS technique is utilized. Thus, among traditional NS, CRD-NS and DRE techniques, considering both computational complexity and noise shaping capability, CRD-NS is regarded as the promising technique to assist the high-speed PAM-4 signal generation with a 3-bit DAC in optical interconnection.

II. THE PRINCIPLE OF CRD-NS TECHNIQUE

The architecture of CRD-NS is shown in Fig. 1, and we can get the output $Y(e^{j\omega})$:

$$Y(e^{jw}) = X(e^{jw}) + (1 + G(e^{jw}))H(e^{jw})E(e^{jw}) \tag{1}$$

where $X(e^{jw})$, $Y(e^{jw})$, $E(e^{jw})$ and $G(e^{jw})$ respectively represent the transmitted signal, received signal, quantization noise, and the channel response of the feedback linear filter. $H(e^{jw})$ represent the channel response of the transmission link. To minimize the difference between the transmitted signal $X(e^{jw})$ and the received signal $Y(e^{jw})$, we can get the following equation:

$$\min_G \sum_{i=1}^{p+q} \left|(1 + G(e^{jw_i}))H(e^{jw_i})E(e^{jw_i})\right|^2 \tag{2}$$

where w_{p+q} is π . since the quantization noise can be modeled as white noise, Eq. (2) can be given by:

$$\min_G \sum_{i=1}^{p+q} \left|(1 + G(e^{jw_i}))H(e^{jw_i})\right|^2 \tag{3}$$

Define the vector $\boldsymbol{K}$ as:

$$\boldsymbol{K}=\begin{bmatrix}1\\1\\\vdots\\1\end{bmatrix}+\begin{bmatrix}e^{-jw_1} & e^{-j2w_1} & \cdots & e^{-jKw_1}\\ e^{-jw_2} & e^{-j2w_2} & \cdots & e^{-jKw_2}\\ \vdots & \vdots & \ddots & \vdots\\ e^{-jw_{p+q}} & e^{-j2w_{p+q}} & \cdots & e^{-jKw_{p+q}}\end{bmatrix}\begin{bmatrix}g_1\\g_2\\\vdots\\g_K\end{bmatrix} \tag{4}$$

suppose $\boldsymbol{A}=\begin{bmatrix}e^{-jw_1} & e^{-j2w_1} & \cdots & e^{-jKw_1}\\ e^{-jw_2} & e^{-j2w_2} & \cdots & e^{-jKw_2}\\ \vdots & \vdots & \ddots & \vdots\\ e^{-jw_{p+q}} & e^{-j2w_{p+q}} & \cdots & e^{-jKw_{p+q}}\end{bmatrix}, \boldsymbol{g}=\begin{bmatrix}g_1\\g_2\\\vdots\\g_K\end{bmatrix}$.

Then Eq. (3) can be expressed as:

$$\min_{g}\|\boldsymbol{HK}\|_2^2=\min_{g}\|\boldsymbol{H}(1+\boldsymbol{Ag})\|_2^2 \tag{5}$$

To further reduce the quantization noise in signal bandwidth, a weighting matrix $\boldsymbol{W}=diag(W_1,W_2,\cdots,W_p,W_{P+1,}\cdots W_{p+q})$ is introduced to Eq. (5), where the W_1~W_p and W_{p+1}~W_{p+q} respectively represent the weighting for the signal bands and the unused bands. In the pre-equalized system, the system noise other than quantization and clipping noise can be modeled as white noise, thus the value of weighting W_1~W_p and W_{p+1}~W_{p+q} are constant [7]. For simplicity, we utilize W_s and W_I to represent the values of W_1~W_p and W_{p+1}~W_{p+q}, respectively. The bandwidth using W_1~W_p to weight is B_s. By introducing the weighting matrix, Eq. (5) can be expressed as:

$$\min_{g}\|\boldsymbol{WH}(1+\boldsymbol{Ag})\|_2^2 \tag{6}$$

At last, the feedback filter coefficient $\boldsymbol{g}$ can be obtained according to Eq. (6) [7, 8].

Different from the traditional NS with the principle of minimizing the signal difference before and after quantization, the approach of the CRD-NS technique is realized by minimizing the difference between the transmitted and received signal. Therefore, the residual quantization noise elimination during channel transmission is considered for obtaining the coefficients of the feedback linear filter in the CRD-NS technique. Thus, for the high-speed PAM signal, compared to the traditional NS technique, a better noise-shaping capability can be obtained in the CRD-NS technique.

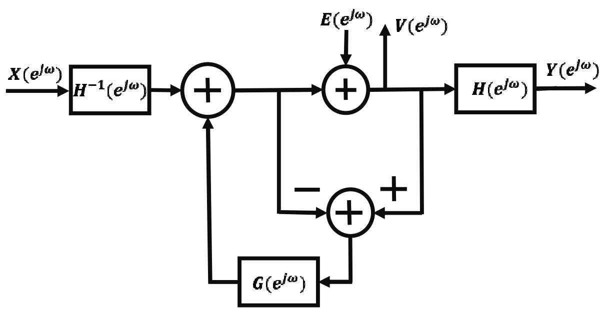

Fig. 1 The architecture of the CRD-NS technique.

III. Experiment Setups

The experimental setups and offline DSPs of 100 Gb/s PAM-4 signal are given in Fig. 2. The PAM-4 signal is generated by the pseudo-random binary sequence (PRBS). A 19-taps linear finite impulse response (FIR) filter is utilized for pre-equalization to reduce the influence of bandwidth limitation. After pre-equalization, a root-raised cosine (RRC) filter with a roll-off factor of 1/16 is used for pulse shaping to improve the spectral efficiency and signal-to-noise ratio (SNR) at the receiver. Then, a 3-bit quantizer combined with NS/CRD-NS/DRE techniques are used to quantize the signal and redistribute quantization noise. For 100 Gb/s PAM-4 signal, the value of W_s is set as 16 and the W_I is set as 1. The taps length of feedback filter $\boldsymbol{g}$ for both CRD-NS and traditional NS techniques are set as 5, which indicates that no additional computational complexity is required for the CRD-NS technique. Both of them are optimized for the traditional NS and CRD-NS based on the corresponding PAM-4 signal generated by a 3-bit DAC with an 80 Gsa/s sampling rate. For the DRE technique, parameters are kept consistent with Refs. [6, 7, 9]. After quantization, the analog signal is generated by an 8-bit DAC with an 80 Gsa/s sampling rate. The generated analog signal is amplified by an electrical amplifier (EA) with fixed 23 dB gains. The electric-to-optical conversion is realized by a 30 GHz Mach-Zehnder modulator (MZM) based on a quadrature point. The generated optical signal is injected into a 2-km single-mode fiber (SMF). At the receiver, the optical-to-electric conversion is realized by a photodiode (PD) and the output electric signal is detected by an 80 Gsa/s oscilloscope (OSC). For the receiver DSP, a matching filter implemented by a RRC filter with the same roll-off factor at the transmitter is applied, then synchronization and post-equalization implemented by a 19-taps feed-forward equalizer (FFE) are utilized for data recovery.

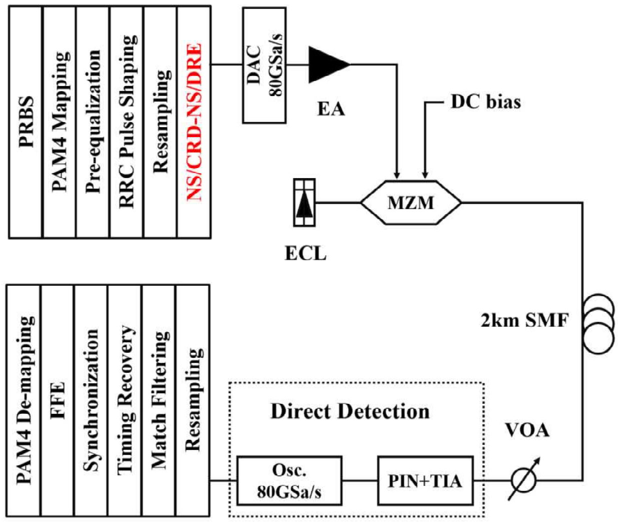

Fig. 2 The experimental setups and offline DSPs of 100 Gb/s PAM-4 signal.

IV. Experimental Results

The experimental results of 100 Gb/s PAM-4 signals with various schemes are shown in Figs. 3(a)-3(c), where the results of optical back-to-back (OBTB) and 2-km SMF transmission are respectively given in Figs. 3(a) and 3(b). The bit error ratio (BER) performance of pulse-shaped pre-equalized PAM-4 signal generated by 3-bit DAC is terrible as shown in Fig. 3(a), and obvious BER performance improvement can be observed as the traditional NS, CRD-NS, and DRE techniques are utilized. Compared to the PAM-4 signal with the traditional NS technique, about 0.5 dB receiver optical power (ROP) improvement can be found at the HD-FEC threshold when the CRD-NS technique is used. Fig. 3(c) shows the complementary cumulative distribution function (CCDF) curves of signals with various schemes. The PAPR of the signal with the DRE technique is larger than the signal with CRD-NS and traditional NS technique, which indicated that signals with the CRD-NS and traditional NS

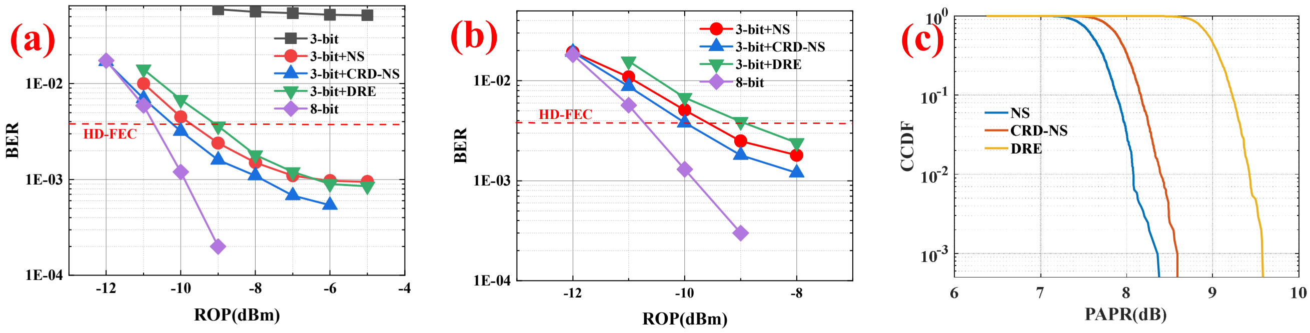

Fig. 3 BER versus ROP of PAM-4 signal over (a) OBTB and (b) 2-km SMF transmission. (c) The CCDF curve of PAM-4 signal.

techniques suffer from fewer nonlinear distortions. In addition, larger effective SNR will be obtained under the peak power constraint system for the CRD-NS and traditional NS techniques [10]. The BER performance of signals with CRD-NS and traditional NS techniques outperforms the signal with the DRE technique. About 1 dB receiver sensitivity improvement can be observed when the CRD-NS technique is utilized to replace the DRE technique. The improvement can still be observed when the signal is over 2-km SMF transmission as shown in Fig. 3(b). However, there still exists about 0.8 dB ROP penalty compared to the signal generated by an 8-bit DAC at the HD-FEC threshold.

V. Conclusion

The transmission of 100 Gb/s pulse-shaped pre-equalized PAM-4 signal over 2-km SMF using 3-bit DAC is experimentally demonstrated with the assistance of CRD-NS technique in this paper. For the 100 Gb/s pulse-shaped pre-equalized PAM-4 signal, the CRD-NS technique outperforms traditional NS and DRE techniques by considering the required computational complexity and noise-shaping capability. Thus, the CRD-NS technique is regarded as the promising technique to assist the high-speed PAM-4 signal generation with a 3-bit DAC in optical interconnection.

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