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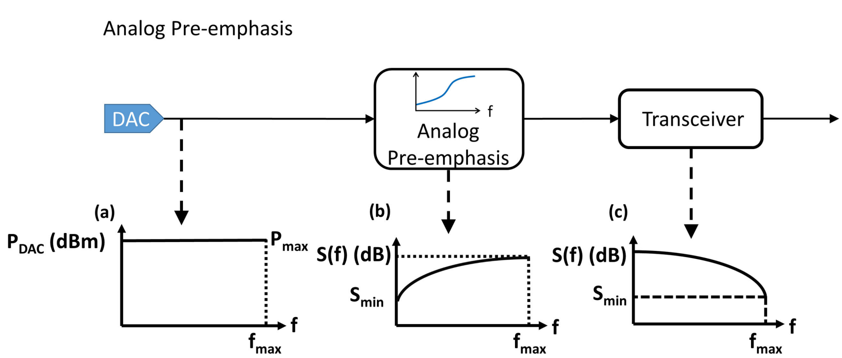

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Impact of Analog and Digital Pre-Emphasis on the Signal-to-Noise Ratio of Bandwidth-Limited Optical Transceivers

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Abstract: The ever-growing machine-to-machine traffic in data centers has stimulated the increase of transceiver data rate from 25 Gb/s/λ to 100 Gb/s/λ and beyond. It is believed that advanced modulation formats and digital-to-analog converters (DACs) will be employed in next generation short-reach transceivers. Digital pre-emphasis techniques are widely employed in DAC-based transceivers to compensate for the high frequency roll-off due to the RF and optoelectronics components in optical transceivers. However, digital pre-emphasis essentially reduces the magnitude of the signal low frequency components for a flat frequency response, which unavoidably increases quantization error, reducing the overall signal-to-noise ratio. This trade-off between SNR and bandwidth conflicts with the high SNR requirement of advanced modulation formats such as the Nyquist-shaped pulse amplitude modulation (PAM). To mitigate the quantization error induced SNR degradation, we show that analog pre-emphasis filters can be used in conjunction with digital pre-emphasis for improved system performance. To understand the impact of the analog pre-emphasis filter on system performance, we analyze the relationship between the flatness of the system frequency response and the SNR degradation due to digital pre-emphasis, and demonstrate 1.1-dB increase of receiver sensitivities, for both 64-Gb/s and 128-Gb/s intensity-modulation direct detection (IM-DD) PAM4 signals, respectively employing a directly modulated laser (DML) and an electroabsorption modulator (EAM).

Index Terms: Optical transmitter, data center interconnection, directly-modulated laser (DML), dxternally-modulated laser (EML), digital signal processing (DSP), pulse amplitude modulation (PAM), digital pre-emphasis, RF equalization.

1. Introduction

Digital-to-Analog converters (DACs) are essential in generating high spectral efficiency modulation formats such as Nyquist-shaped pulse amplitude modulation (PAM), subcarrier modulation (SCM), and orthogonal frequency division multiplexing (OFDM) [1]–[3]. Using a 92-GSa/s CMOS DAC and transmitter-side digital signal processing (DSP), researchers have recently demonstrated 4 × 112-Gb/s transmission of Nyquist-shaped 4-level pulse amplitude modulation (PAM4) over 300 km of standard single-mode fiber (SMF-28) [4]. By interleaving two DACs in the frequency domain, up to 100 GHz discrete multitone (DMT) signals were generated for over 200-Gb/s short-reach data transmission [5], [6]. In these works, digital pre-emphasis played central roles in compensating for the frequency roll-off caused by the sample-and-hold circuit and the bandwidth-limited electronic and optoelectronic components. For a DAC with a given output voltage range, the 'digital emphasis' of the high frequency component essentially attenuates the magnitude of the low frequency components in the digital domain, resulting in fewer quantization levels for the low frequency components. This partial use of the DAC's full quantization range trades off the signal-to-noise ratio (SNR) for a flat frequency response [7]. Consequently, the SNR is subjected to significant degradation in bandwidth-limited transmitters, precluding the use of higher order modulation formats [8] and low-overhead forward error correction (FEC) that are desired in communication systems.

To optimize the performance of DAC-based transceivers, researchers have exploited advanced DSP techniques to compensate for the harmonic distortions due to quantization and RF amplifier nonlinearity. For example, in [9] the Volterra equalizer was shown to mitigate the harmonic distortions in transceivers. G. Khanna *et al.* [10] showed a 2.5 dB reduction in required optical signal-to-noise-ratio (OSNR) using a digital resolution enhancement algorithm. Notwithstanding, the DSP-based methods still suffer from the fundamental trade-off between SNR and bandwidth, and are unable to optimize performance of a DAC [11]. A. Matsushita *et al.* [12] demonstrated optical equalization aided digital pre-emphasis technique and showed 1.7 dB OSNR tolerance improvements for PDM-256QAM signal. However, this method is limited by optical loss and reduced OSNR. High analog bandwidth, high over sampling rate DAC can mitigate the SNR degradation due to the bandwidth-resolution trade-off, but this unavoidably adds cost and power consumption that preclude its use in cost-sensitive applications such as short-reach intra-data center interconnections.

Analog equalizer circuits have been widely used in broadband optical systems to equalize system frequency responses [13]–[19]. Sophisticated active and passive circuit designs, with tuning capabilities, based on variable or transversal filtering techniques [14], [18] were shown to be capable of operation from few to several 10s of Gb/s. Such circuits help improve system performance by equalizing the frequency domain response for an improved eye diagram and therefore reducing error rates, through a process of tuning and optimization. For example, T. Lengyel *et al.* designed an active two-tap electronic pre-emphasis filter for a short-reach optical fiber link and demonstrated 2-dB receiver sensitivity improvement for a 52-Gb/s on-off keying (OOK) signal [17]. However, while the effectiveness of analog pre-emphasis has been known for a long time, the relationship between the signal SNR degradation and the flatness of the frequency response has not been studied. Furthermore, the performance improvement provided by combining analog pre-emphasis with digital pre-emphasis has not been demonstrated.

In this paper, we investigate the impact of analog pre-emphasis on the SNR of DAC-based transceivers with linear digital pre-emphasis. We explore a simple passive analog filter that potentially offers performance enhancement with low complexity and cost, ideal for cost-sensitive short-reach data center interconnections. We study different levels of analog pre-emphasis (which impacts the flatness of the transceiver frequency response), using different analog filter designs. Their impact on system bit error ratio (BER) and SNR was experimentally studied using two types of transceivers: a 16-GHz direct modulation direct detection (DM-DD) transceiver and a 40-GHz electroabsorption modulator (EAM) based intensity-modulated direct-detection (IM-DD) transceiver, with Nyquist-shaped 32-GBd (64 Gb/s per wavelength) and 64-GBd (128 Gb/s per wavelength) four-level pulse amplitude modulation (PAM4) signals, respectively. This paper has two main contributions: first, from our study of the relationship between SNR degradation and the flatness of frequency response, we show that SNR improvement can be obtained by partially compensating for the frequency roll-off in bandwidth-limited transceivers, which allows for the maximum use of the DAC dynamic range over the whole signal bandwidth. Secondly, we experimentally demonstrate the performance of a DAC-based transceiver with both digital and analog pre-emphasis, showing that optimum transmitter design should consider pre-emphasis in both domains.

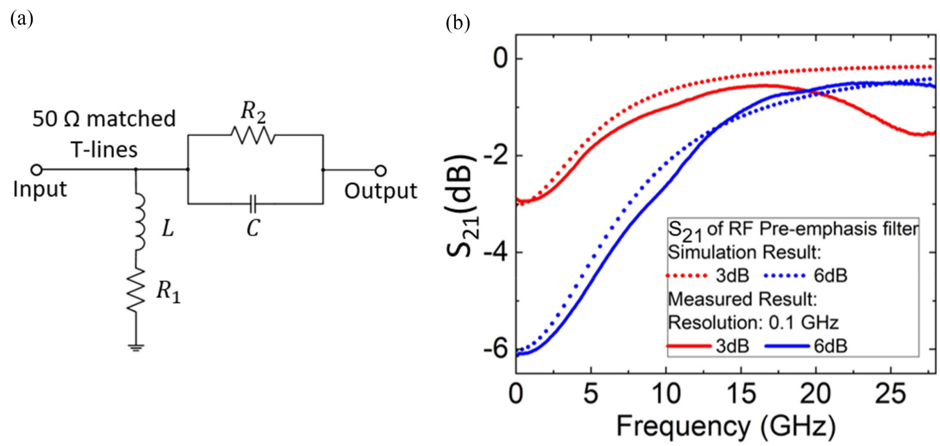

Fig. 1. (a) Circuit diagram of RF pre-emphasis filter (b) Frequency response of the 3-dB and 6-dB RF pre-emphasis filter. Red curve: 3-dB; Blue curve: 6-dB; Dotted line: Simulation result; Solid line: Measured result (with 0.1 GHz).

TABLE 1
Parameters for RF Pre-Emphasis Filter

RF Pre-emphasis Level	3 dB	6 dB
R_1	100 Ω	100 Ω
R_2	10 Ω	50 Ω
C	3 pF	0.5 pF
L	3 nH	2.5 nH

The rest of the paper is organized as follows. Section 2 discusses the circuit design of the analog pre-emphasis filters. In Section 3, we show, analytically, the relationship between signal SNR, transceiver frequency roll-off response and the impacts of analog and digital pre-emphasis. Section 4 shows our experimental investigation using two sets of transceivers. In Section 5, we present results and evaluate the performance improvement of the analog pre-emphasis implementation. Section 6 concludes the paper.

2. Analog Pre-Emphasis Filter Design

Fig. 1(a) shows the schematic diagram of our RF pre-emphasis filter. In this study, we employed a first-order continuous-time passive equalizer circuit, which is a modification of the constant-K LC T-section high-pass filter [20], [21]. Resistors R_1 and R_2 set the pre-emphasis level while the inductance and capacitance values were selected to achieve the desired frequency response zero and slope with 50 Ω microstrip transmission lines connecting the equalization circuit to input and output RF connectors. The values of the components for two circuits designed for 3-dB and 6-dB pre-emphasis levels are summarized in Table 1. In this paper, the pre-emphasis level is defined as the power gain applied to the highest frequency component with respect to the 100-MHz frequency component.

The transfer function of the circuit is given by

$$H(s) = \frac{R_1 + (L + R_1 C)\, s + LCs^2}{R_1 + R_2 + (L + R_1 C)\, s + LCs^2} \quad (1)$$

with the pre-emphasis level set by the ratio $R_1/(R_1 + R_2)$ and zero at $1/(R_2C)$.

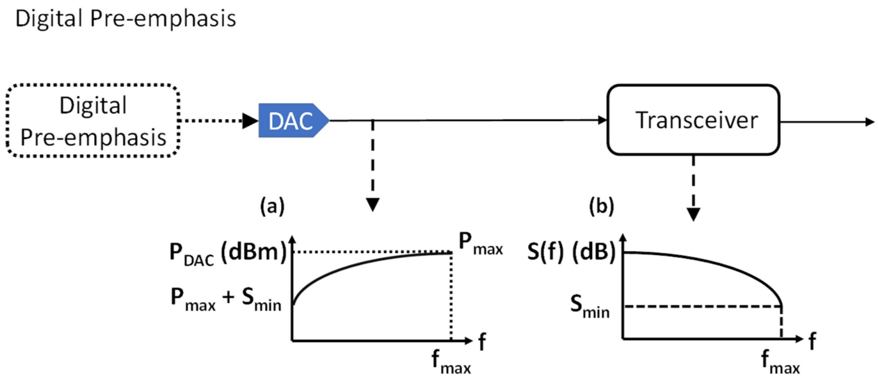

Fig. 2. Signal chain with digital pre-emphasis only (a): Spectrum of digitally emphasized signal; (b): System frequency response.

The required inductance values may be realized using the self-inductance of lengths of copper, and off the shelf surface-mount microwave capacitors and resistors may be adopted in implementing the design.

Fig. 1(b) shows the frequency response (forward gain –S_{21}) of the two circuits. The dotted curves show the simulated S_{21} and the solid curves show the measured S_{21} using a vector network analyzer (Keysight N5227A) with a resolution of 0.1 GHz. The red and blue curves represent the response of the 3-dB and 6-dB RF pre-emphasis filters, respectively. At peak amplitude, the 3-dB and 6-dB filters have insertion losses of 0.6 dB and 0.8 dB, respectively. The measured frequency roll-off of the 3-dB RF pre-emphasis filter (red solid curve) was mainly due to the frequency limitation of the standard SMA connectors used in the circuit. This imperfection was eliminated in our 6-dB RF pre-emphasis circuit by using precision SMA connectors, resulting in a flat high frequency response up to 27 GHz. The slope of the filters' roll-off can be customized by careful choice of the values of the circuit components, to compensate for different system frequency roll-off. It is worth pointing out that our filters are designed to compensate for transceivers with a smooth roll-off. A more sophisticated design will be required if a transceiver has a more complex frequency response with fluctuations or dips in their S_{21} characterization.

In addition to the designs shown in Fig. 1(a), a similar response could be achieved by a constant-resistance bridged-T amplitude equalizer described in [22]. However, the adopted design, being more compact, offers the potential for wider bandwidth performance, with the added advantage of lower insertion loss. In practice, an active equivalent of the continuous time equalizer in Fig. 1(a), implemented on-chip [21], or an adaptive analog pre-emphasis circuit would be more efficient as these would provide both equalization and gain [13]–[19]. However, these implementations require sophisticated RF integrated circuit processes to achieve similar bandwidth performance, which will significantly increase both cost and design complexity [15], [16] and may also increase power consumption due to the multiple taps required for equalization [13], [14].

3. SNR Enhancement Using Analog Pre-Emphasis

We investigate and compare the performance of digital pre-emphasis to analog pre-emphasis by analyzing the signal chain illustrated in Figs. 2 and 3.

In general, SINAD (Signal to Noise and Distortion ratio) is used to characterize DACs. However, in data communications, SNR, which is calculated from received waveforms, is used to show system performance. Also, for broadband signals, the distortions occur in all frequency components and can therefore be approximated as a noise term. For these reasons, we use the term SNR here for the study. Assuming uniformly distributed quantization error and added white noise due to the thermal noise and sampling jitter, the relationship between the effective number of bits (ENOB) and

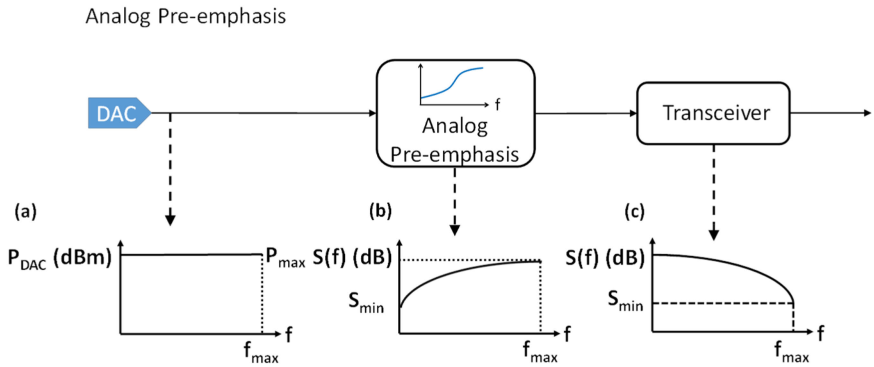

Fig. 3. Signal chain model of analog pre-emphasis (a): Spectrum of emphasized signal; (b): Frequency response of ideal analog pre-emphasis filter; (c): System frequency response.

the average SNR of the signal generated by a DAC is [23]:

$$SNR_{ave} = 6.02M + 1.76 \quad (2)$$

where, M is the ENOB in bits. Without losing generality, we use a smooth frequency roll-off as shown in Fig. 2(b) as example, in which S(f) represents the system frequency response, f_{max} is the highest signal frequency, at which the signal power is attenuated by S_{min} (dB). When the digital pre-emphasis is applied, the spectrum of the emphasized signal has higher power in its high frequency region compared to the low frequency region. Since the DAC has a fixed dynamic range, the peak-to-peak voltage of low frequency components is attenuated in the digital domain to create the emphasized signal. For example, the power of a sinusoidal signal generated from a DAC with peak-to-peak voltage (V_{pp}) is $V_{pp}{}^2/2R_L$, where R_L is the matched load impedance, which is shown as P_{max} in Fig. 2(a). To generate a flat modulated signal spectrum, the low frequency components has to be attenuated by S_{min} (dB) in the digital domain, resulting in less digits and an increased quantization error that degrades the SNR. The SNR at frequency f is:

$$SNR\,(f) = 6.02M + 1.76 + S_{min} - S\,(f) \quad (3)$$

In contrast, as shown in Fig. 3, an analog pre-emphasis filter makes the overall system response become flatter. This effectively eliminates the need for attenuation of the low frequency components digitally. When an ideal analog pre-emphasis is applied, the DAC utilizes its full dynamic range across the whole signal frequency range, as shown in Fig. 3(a). The trade-off, however, is an increased RF power which will be discussed later in this paper.

It should be noted that while we use smooth frequency roll-off to facilitate easy understanding, similar analysis can be applied for frequency response with ripples. It is also worth noting that although the application of analog pre-emphasis allows the DAC to use its full dynamic range across the signal frequency range, it reduces the power of the analog output signals, primarily due to the attenuation of the low frequency components which is required for equalization, hence a slight increase of amplifier gain is needed to drive the transmitters, as we will discuss in Section 4. In practical signal generation, the non-flat phase response of the analog pre-emphasis filter might introduce inter-symbol-interference that degrades the signal performance. However, in a DAC-based system, the phase response of the transceiver can be compensated without reducing the SNR.

4. Experimental Set-Up

Fig. 4 shows the experimental setup. We investigated two transmitters, a directly modulated laser (DML) and an EAM based transmitter. The DML is a low-cost discrete mode laser emitting at

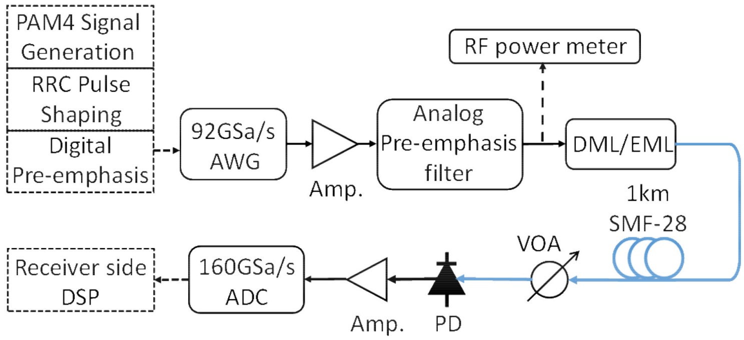

Fig. 4. Experimental set-up for externally-modulated laser (EML) and directly-modulated laser (DML). RRC: root-raise-cosine, DAC: digital-to-analog converter, ADC: analog-to-digital converter, PD: photodiode, VOA: variable optical attenuator, DSP: digital signal processing, SMF−28: standard single-mode fiber.

1549 nm [24]. It has a bandwidth of 16 GHz when biasing at 95 mA with a sharp roll-off between 16–18 GHz [7]. The DML was 50 Ω coupled to a linear RF driver (SHF100BP-ML), outputting 8 dBm driving power. In the EAM experiment, a distributed feedback laser (DFB) laser emitting 12-dBm continuous wave (CW) at 1554 nm was connected to a 40-GHz EAM biased at its linear region (−2 V), resulting in 1.5 dBm optical power after modulation. The EAM was driven by a 28-GHz, 13-dB gain low-noise RF amplifier (ADI: HMC994A) before being passed through our RF pre-emphasis filter. The peak-to-peak driving voltage was optimized to 1.3 V, balancing the trade-off between SNR and modulation nonlinearity. Due to the transmitters' different bandwidths, we modulated 32-GBd (64-Gb/s) PAM4 signals on to the DML and generated 64-GBd (128-Gb/s) optical PAM4 signals using the EAM based transmitter, respectively. The RF pre-emphasis filters described in Section 2 were connected at the transmitter side to investigate their performance in both transmitters. The additional losses due to the RF pre-emphasis filters was compensated by increasing the output power of the AWG. More specifically, for our experiments with back-to-back transmission, the measured output power of the AWG was increased from −1.65 dBm (without RF filter) to 0 dBm, 1.76 dBm and 3.22 dBm when the 3-dB, 6-dB and 9-dB (a cascade of the 3-dB and 6-dB filters) analog pre-emphasis were applied, respectively. While cascading the 3-dB and 6-dB analog pre-emphasis filters provides the same level of pre-emphasis as a single 9-dB filter, the insertion losses from both units are also compounded. However, in our setup, as the 3-dB filter has a measured insertion loss $<$ 0.5 dB at 16 GHz (the upper frequency limit for the DML), the overall insertion loss was comparable to a single 9-dB filter. For our experiments with 1-km transmission, the measured output power of the AWG was increased from −1.71 dBm (without RF filter) to −0.35 dBm, 1.14 dBm and 2.78 dBm when 3-dB, 6-dB and 9-dB analog pre-emphasis were applied, respectively. An RF power meter was used to ensure the same driving power to the DML.

The PAM4 symbols were generated from a pseudo-random binary sequence (PRBS) of length of 2^{16}. A root-raised-cosine (RRC) filter with a roll-off factor of 1% was used to generate Nyquist-shaped PAM4 digital samples. The digital samples were interpolated to 92 GSa/s to generate the RF signals using AWG (33 GHz bandwidth, ENOB of about 5 bits). A linear digital pre-emphasis filter [4] was implemented to compensate for both the amplitude and phase response in the signal chain, including the frequency responses of the DAC, RF cables and amplifier, optical transmitters, and the receiver. The digital pre-emphasis filter fully compensates for the frequency roll-off from DC to the maximum signal bandwidths, i.e., 0-16 GHz for the DML and 0-32 GHz for the EAM. Consequently, the received signals have flat electronic spectra after detection. The impact of the DAC nominal resolution was studied by quantizing the digital samples to a limited number of levels of 2^N, where $N = 5$, 6, and 8 were tested.

At the receiver side, the optical signals were fed into a variable optical attenuator (VOA) for receiver sensitivity measurement. The signals were detected by a 40-GHz photodetector (0.6 A/W

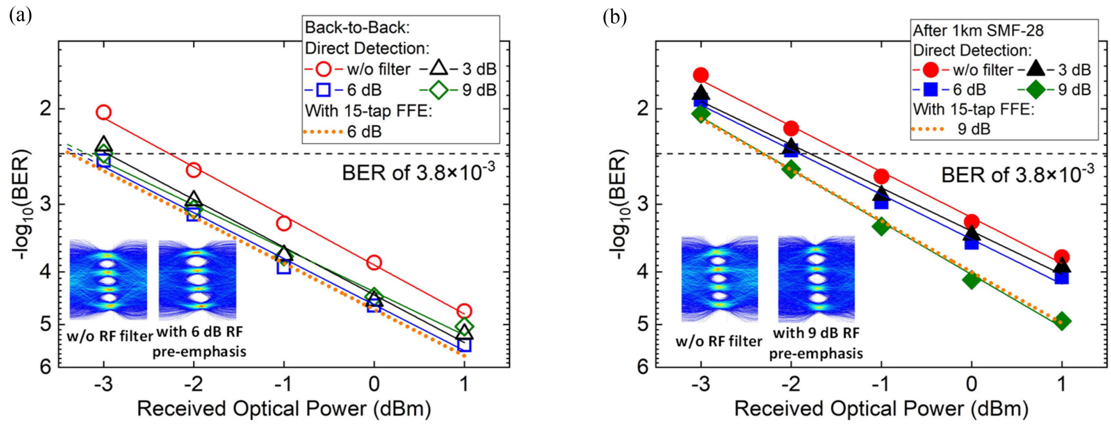

Fig. 5. Receiver sensitivity measurements at (a) Back-to-Back, (b) After 1km SMF-28 transmission. The markers show BER curves using filters with different pre-emphasis levels. Red circle: no analog pre-emphasis; Green diamond: 9 dB; Black triangle: 3 dB; Blue square: 6 dB; Orange dotted line in (a) shows the BER using 6-dB analog pre-emphasis, digital pre-emphasis and 15-tap FFE (b) 9-dB RF pre-emphasis, digital pre-emphasis and 15-tap FFE.

responsivity) and amplified by a 40-GHz RF power amplifier with 17 dB gain. The electrical waveforms were captured by a 63-GHz, 160-GSa/s analog-to-digital converter (ADC). To emulate the threshold detection in a real-time PAM4 receiver, the captured samples were down-sampled to one sample per symbol for threshold detection. Digital equalization using 15-tap an adaptive feedforward equalizer was also implemented to compare the performance with and without receiver-side DSP [25]. The bit error ratio (BER) was calculated from 1.5×10^6 bits. The frequency responses using different analog filters were calculated from the received samples.

A 1-km SMF-28 fibre with 0.5 dB total loss and a dispersion of 16 ps/(nm•km) was used to emulate short-reach data center interconnection. After transmission, the fiber dispersion causes frequency fading in the high frequency region (25–32 GHz). Due to the limited dispersion, this frequency fading acts as a low pass filtering, with no dip in the spectrum. Therefore, we can use digital pre-emphasis to compensate for this effect and obtain flat spectra.

5. Results and Discussion

5.1 DML Based 64-Gb/s Transmission

First, we tested the performance of our analog pre-emphasis filters using the DML based transceiver. The resolution of AWG is set to 8 bits. Fig. 5(a) shows the measured BER of the 32-GBd (64-Gb/s) PAM4 signals at different received powers at back-to-back. The insets in Fig. 5(a) show the eye diagrams with and without the 6-dB analog pre-emphasis filter. The red markers show BER with digital pre-emphasis only. The triangle, square and diamond markers show the BER curves when analog pre-emphasis filters of 3, 6, and 9-dB pre-emphasis levels were implemented. Digital pre-emphasis was implemented in all cases to equalize the residual frequency roll-off and ripples for optimized performance of the Nyquist-shaped PAM4. It should be noted that the high frequency roll-off of the 3-dB pre-emphasis filter will not affect the performance of the DML transmitter, as the signal bandwidth was limited to 16 GHz.

Using digital pre-emphasis only, the required optical power at the HD-FEC threshold of 3.8×10^{-3} BER was −2.2 dBm. After implementing both the analog and digital pre-emphasis, receiver sensitivities were improved to −2.9, −3.3 and −3.0 dBm, with the analog pre-emphasis levels of 3 dB, 6 dB and 9 dB, respectively. The best performance was achieved using the 6-dB analog pre-emphasis filter, which yielded 1.1-dB sensitivity improvement. Adaptive FFE based post-compensation showed similar results regardless of the analog pre-emphasis filter

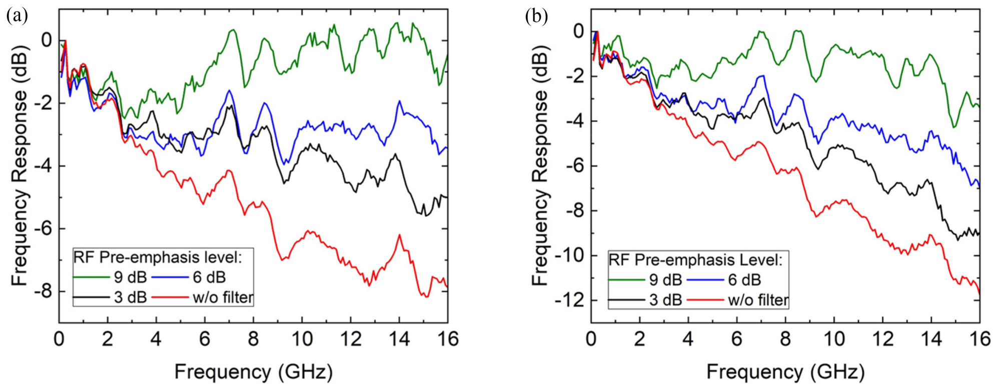

Fig. 6. Measured system response with no pre-emphasis and post-compensation applied at (a) Back-to-Back, (b) After 1 km SMF-28 transmission. The colors show measured frequency responses using filters with different pre-emphasis levels. Red: no analog pre-emphasis; Green: 9 dB; Black 3 dB; Blue: 6 dB.

used. Thus, we plot the BER with both pre and post compensation (including digital and analog pre-emphasis and the adaptive FFE at receiver side) as the orange dotted line in Fig. 5(a), to show the optimized transceiver performance. It may be noted that the BER with FFE is similar to threshold detection with the 6-dB analog pre-emphasis filter (as the blue line in Fig. 5(a)), which implies that post-compensation can be eliminated when optimal analog pre-emphasis filter is used. This is because the inter symbol inference (ISI) caused by frequency roll-off was almost fully compensated by the transmitter-side analog and digital pre-emphasis, the receiver signal is limited by noise rather than distortion. Fig. 5(b) shows the receiver sensitivity after transmission over 1-km SMF-28. The insets in Fig. 5(b) show the eye diagrams with and without the 9-dB RF pre-emphasis filter. After transmission over 1-km SMF28, the high frequency component of the detected signal has a stronger roll-off due to the chromatic dispersion (CD). This CD-induced fading requires an increase to the pre-emphasis level to obtain flat spectra, which consequently reduced the signal SNR, resulting in 1.1 dB power penalty (at a BER of 3.8×10^{-3}) compared to the digital pre-emphasis only results at back-to-back. Using the analog pre-emphasis filters of 3, 6, and 9 dB, the receiver sensitivities were improved to -1.7, -1.9, and -2.2 dBm, respectively. The 9-dB analog pre-emphasis filter yielded the best performance, showing 1.1 dB sensitivity improvement. Similar to the back-to-back case, the benefit of adaptive FFE is negligible when optimal analog pre-emphasis filter is applied (see orange dotted line in Fig. 5(b)).

The performance improvement using different analog pre-emphasis filters may be understood by observing the system frequency response shown in Fig. 6. It is worth noting that digital pre-emphasis and post compensation were not applied when measuring the frequency response. Fig. 6(a) shows the frequency response for the back-to-back scenario. The red curve in Fig. 6(a) shows the frequency response without RF pre-emphasis. It has a 6-dB roll-off from DC to 10 GHz and a relatively flat response up to 15 GHz before falling due to the DML's bandwidth limitation. The black, blue, and the green curves in Fig. 6(a) show the frequency response after connecting our 3-dB, 6-dB, and 9-dB analog pre-emphasis filters, respectively. It may be noted that our analog pre-emphasis filters mainly equalize the frequency roll-off at the low frequency region (DC-10 GHz, see Fig. 1(b)). Compared to the 6-dB filter, the 3-dB filter only partially compensates for the frequency roll-off. Thus, the SNR is lower than the signal generated with the 6-dB filter. The 9-dB pre-emphasis filter, however, over-attenuated the low frequency component and resulted in SNR degradation. Compared to the 9-dB and 3-dB curves, we found that the 6-dB curve has a flatter frequency response. Thus, it resulted in a better receiver sensitivity, as we analyzed in Section 3. Fig. 6(b) illustrates the measured system response after 1-km SMF-28 transmission. Due to the frequency fading caused by fiber dispersion, the system response has a higher frequency roll-off compared to the back-to-back scenario, resulting in about 10 dB roll-off from DC to 16 GHz.

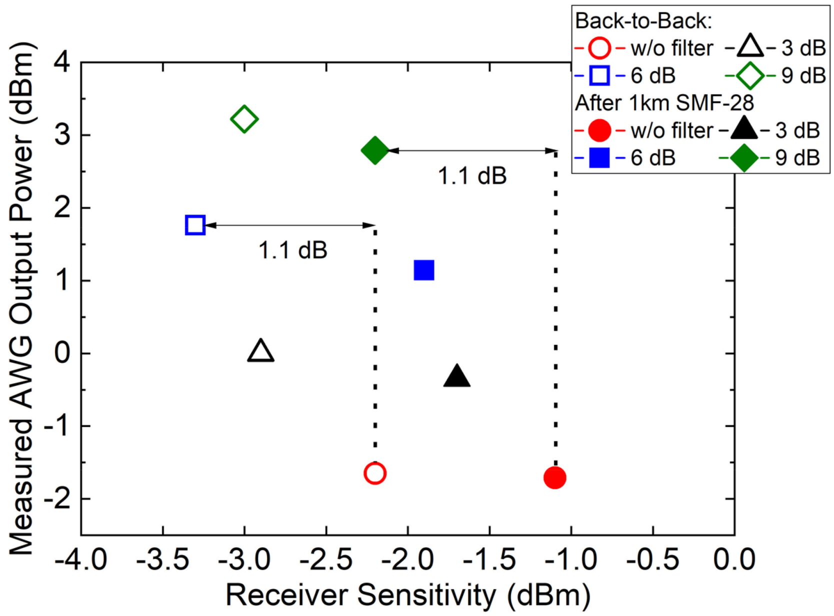

Fig. 7. Relationship between receiver sensitivity (at HD-FEC threshold) and measured AWG output power for different RF pre-emphasis filters. Red circle: no analog pre-emphasis; Green diamond: 9 dB; Black triangle: 3 dB; Blue square: 6 dB.

Compared to the 9-dB filter, the 3-dB and 6-dB filters only partially compensate for the frequency roll-off, leading to degraded BER performance. Although the 6-dB and 9-dB filters showed improved performance for back-to-back and 1-km SMF-28 transmission, respectively, they are not ideal because there were still power fluctuations in the frequency response. The transceiver performance could be further improved by using a higher order analog pre-emphasis filter to fully compensate for the roll-off. Nevertheless, this does not undermine our conclusion that an analog pre-emphasis filter does improve the signal SNR and the receiver sensitivity.

Implementing passive RF pre-emphasis trades the power consumption for higher receiver sensitivity primarily due to the resistive losses required for equalization. Fig. 7 shows the receiver sensitivity (at HD-FEC threshold) and the measured AWG output power (with digital pre-emphasis applied) for different RF pre-emphasis filters. For the back-to-back condition, compared to digital pre-emphasis only, the 6-dB RF pre-emphasis filter helped achieve 1.1-dB sensitivity improvement. However, it requires additional RF power of 3.4 dB. Similarly, after the 1-km transmission, the 9-dB RF pre-emphasis filter helped increase the sensitivity by 1.1 dB at the cost of 4.5-dB increase in the power consumption.

5.2 EML Based 128-Gb/s Transmission

Currently, the data rate of the short-reach intra-data center interconnection is evolving from the 25 Gb/s to 100 Gb/s per lane. Here, we show the performance of analog pre-emphasis for an EAM based 128-Gb/s Nyquist shaped PAM4 transceiver. As was for the DML based experiment, the AWG resolution is set to 8 bits. As we showed in Fig. 1(b), the high-frequency bandwidth of the 3-dB filter is limited to 25 GHz, which is insufficient for the 64-GBd Nyquist shaped PAM4. Therefore, in the EML experiment, only the 6-dB filter is tested to validate performance improvement.

The open markers in Fig. 8(a) show the measured BER for the 128-Gb/s PAM4 signals at back-to-back condition and the closed markers show the BER after 1-km SMF-28 using direct detection. In both cases, digital pre-emphasis fully compensates for the amplitude and phase responses to ensure a flat spectrum for the RRC shaped signals. As shown in Fig. 8(a), for the back-to-back

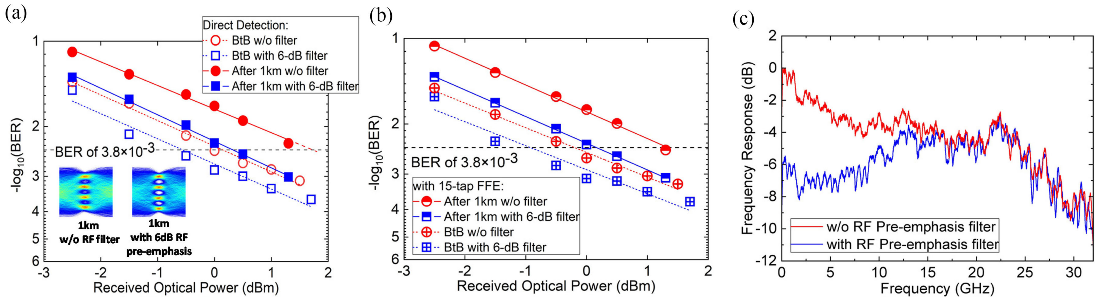

Fig. 8. Receiver sensitivity measurements at (a) Direct detection, (b) with 15-tap FFE, (c) Measured frequency response.

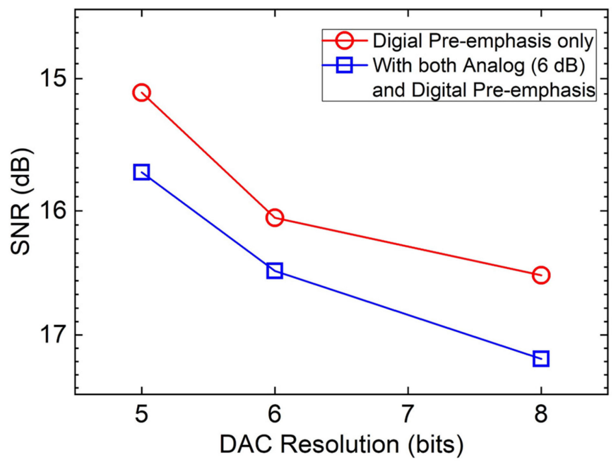

Fig. 9. Performance improvement of using RF pre-emphasis filter using different DAC resolutions.

case, the BER curve with the 6-dB RF pre-emphasis filter (blue markers) showed a sensitivity improvement of ~0.7 dB at the BER of 3.8×10^{-3}. After transmission over the 1-km SMF-28, the lowest BER achieved using digital pre-emphasis only was 5×10^{-3}, limited by the optical power (1.3 dBm) and the significant digital pre-emphasis due to the dispersion induced high-frequency roll-off (about 18-dB attenuation from DC to 32 GHz). The linear relationship between the optical power and the $-\log_{10}$(BER) suggests the signal is noise limited. Thus, we can linearly fit the BER points to obtain the sensitivity at the HD-FEC threshold. Using the 6-dB analog pre-emphasis filter, the BER after transmission was reduced to 9×10^{-4}. Using the 6-dB analog pre-emphasis filter, we obtained a clearer eye diagram (insets in Fig. 6) and about 1.1 dB sensitivity improvement at the BER of 3.8×10^{-3}. Fig. 8(b) shows the relationship between BER and received optical power after applying 15-tap FFE. By comparing Fig. 8(a) and (b), it can be concluded that adding FFE at receiver side only slightly improves the receiver sensitivity by about 0.2 dB.

Fig. 8(c) shows the system frequency response for the back-to-back set-up. The frequency response of the EAM-based transceiver features a roll-off of about 4 dB from DC to 15 GHz, followed by a relatively flat response to 23 GHz and a sharp roll-off from 23 to 32 GHz. Our 6-dB RF pre-emphasis filter partially compensates for the roll-off from DC to 15 GHz, yielding fluctuations of about ± 3 dB across the whole signal frequency range. The spectral roll-off from 23 GHz to 32 GHz is due to the limited bandwidth of RF amplifier and the DAC, and this was equalized by digital pre-emphasis in this experiment.

Finally, we investigate the performance of the RF pre-emphasis filter with different DAC resolutions. The SNRs were measured at back-to-back. Digital pre-compensation was implemented to fully equalize system frequency response (the blue curve in Fig. 8(c)). The amount of digital pre-emphasis equals to the inverse of system response. As shown in Fig. 9, we observed a clear performance improvement using the 6-dB analog pre-emphasis filter and digital pre-emphasis operating at the 8-bit DAC resolution, obtaining an increased SNR values from 16.5 dB to 17.2 dB. When reducing the DAC resolution to 6 and 5 bits, the SNRs were increased from 16.0 dB to 16.5 dB and from 15.1 dB to 15.7 dB, respectively. Due to the imperfection of DAC, the SNR improvement varies for different DAC resolutions. Nevertheless, we can conclude that our analog pre-emphasis technique improves the performance of transceivers using DACs of different resolutions.

6. Conclusion

We exploit analog pre-emphasis to compensate for the frequency roll-off in a bandwidth-limited transceiver. Compared to digital pre-emphasis only, we obtained clear performance improvement by combining analog and digital pre-emphasis techniques. Our experimental results reveal that analog pre-emphasis should be jointly considered with digital pre-emphasis techniques to achieve optimized system performance. The simple RF pre-emphasis circuits adopted have low insertion loss and can be integrated with transceiver modules. With these, we obtained 1.1-dB sensitivity improvement for DML-based 32-GBd (64-Gb/s) PAM4 and 1.1-dB receiver sensitivity improvement for 64-GBd (128-Gb/s) PAM4 signals, respectively, after transmission over 1-km SMF-28. Though our experiments only investigated short-reach IM-DD transceivers, our analysis indicates that analog pre-emphasis can improve the SNR of any DAC-based transceiver with inherent frequency roll-off. Therefore, it is expected that the technique will lead to performance improvement in coherent transceivers.

Reference

[1] N. Kikuchi, R. Hirai, and T. Fukui, “Practical implementation of 100-Gbit/s/lambda optical Short-Reach Transceiver with nyquist PAM4 signaling using electroabsorptive modulated laser (EML),” in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2015, Paper Th3A.2.

[2] M. S. Erkilinc *et al.*, “Spectrally efficient WDM nyquist Pulse-Shaped 16-QAM subcarrier modulation transmission with direct detection,” *J. Lightw. Technol.*, vol. 33, no. 15, pp. 3147–3155, Aug. 2015.

[3] S. Jansen, I. Morita, T. Schenk, and H. Tanaka, “121.9-Gb/s PDM-OFDM transmission with 2-b/s/Hz spectral efficiency over 1000 km of SSMF,” *J. Lightw. Technol.*, vol. 27, no. 3, pp. 177–188, Feb. 2009.

[4] Z. Liu, T. Xu, G. Saavedra, and P. Bayvel, “448–Gb/s PAM4 transmission over 300-km SMF-28 without dispersion compensation fiber,” in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2018, Paper W1J.6.

[5] H. Yamazaki *et al.*, “Digital-Preprocessed Analog-Multiplexed DAC technology for High-Speed optical transmission,” *J. Lightw.Technol.*, vol. 34, no. 7, pp. 1579–1584, 2016

[6] X. Chen, S. Chandrasekhar, P. Pupalaikis, and P. Winzer, “Fast DAC solutions for future high symbol rate systems,” in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2017, Paper Tu2E.3.

[7] Z. Liu *et al.*, “Discrete multitone format for Repeater-Less Direct-Modulation Direct-Detection over 150 km,” *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3223–3229, Jul. 2016.

[8] M. Nakazawa, S. Okamoto, T. Omiya, K. Kasai, and M. Yoshida, “256-QAM (64 Gb/s) coherent optical transmission over 160 km with an optical bandwidth of 5.4 GHz,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 3, pp. 185–188, Feb. 2010.

[9] J. Jignesh *et al.*, “Transmitter-side volterra filtering for increased dispersion tolerance in 56 Gbaud PAM-4 systems,” in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2018, Paper M2C.6.

[10] G. Khanna *et al.*, “Experimental verification of 400G 64QAM using 4 bits DACs enabled by digital resolution enhancer,” in *Proc. Eur. Conf. Exhib. Opt. Commun.*, 2018, Paper We3F.5.

[11] D. Rafique, N. Eiselt, H. Griesser, B. Wohlfeil, M. Eiselt, and J.-P. Elbers, “Digital Pre-Emphasis based system design Trade-offs for 64 gbaud coherent data center interconnects,” in *Proc. Int. Conf. Transparent Opt. Netw.*, 2017, Paper Mo.D3.1.

[12] A. Matsushita *et al.*, “64-GBd PDM-256QAM and 92-GBd PDM-64QAM signal generation using Precise-Digital-Calibration aided by Optical-Equalization,” in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2019, Paper W4B.2.

[13] A. Borjak, P. P. Monteiro, J. J. O’Reilly, and I. Darwazeh, “High-Speed generalized Distributed-Amplifier based Transversal-Filter topology for optical communication systems,” *IEEE Trans. Microw. Theory Techn.*, vol. 45, no. 8, pp. 1453–1547, Aug. 1997.

[14] P. M. R. S. Moreira, I. Z. Darwazeh, and J. J. O’Reilly, “Distributed amplifier signal shaping strategy for multigigabit digital optical transmission,” *Electron. Lett.*, vol. 29, no. 8, pp. 655–657, 1993.

[15] S. Giannakopoulos, Z. S. He, and H. Zirath, “Tunable equalizer for 64 GBPS data communication systems in 130 NM SiGe,” in *Proc. Asia-Pacific Microw. Conf.*, pp. 627–629, 2018.

[16] R. Mettetal, A. Ouslimani, J. Dupuy, and M. Riet, “A 1-tap feed-forward equalizer based on InP DHBT cascode amplifier cells for more than 100-GBd optical communication applications,” in *Proc. Int. Conf. Elect. Eng./Electron., Comput., Telecommun. Inf. Technol.*, pp. 1–4, 2016.
[17] T. Lengyel, K. Szczerba, P. Westbergh, M. Karlsson, A. Larsson, and P. A. Andrekson, “Sensitivity improvements in an 850-nm VCSEL-Based link using a Two-Tap Pre-Emphasis electronic filter,” *J. Lightw. Technol.*, vol. 35, no. 9, pp. 1633–1639, May 2017.
[18] P. Monteiro, A. Borjak, F. da Rocha, J. O’Reilly, and I. Darwazeh, “10-Gb/s pulse-shaping distributed-based transversal filter front-end for optical soliton receivers,” *IEEE Microw. Guided Wave Lett.*, vol. 8, no. 1, pp. 4–6, Jan. 1998.
[19] M. S. Chen, M. C. F. Chang, and C. K. K. Yang, “A low-PDP and low-area repeater using passive CTLE for on-chip interconnects,” in *Proc. IEEE Symp. VLSI Circuits, Dig. Tech. Pap.*, 2015, vol. 2015-August, pp. C244–C245.
[20] T. T. Wong, “*Fundamentals of Distributed Amplification*,” Norwood, MA, USA: Artech House, 1993, pp. 33–35.
[21] P. K. Hanumolu, G. Y. Wei, and U. K. Moon, “Equalizers for high-speed serial links,” *Int. J. High Speed Electron. Syst.*, vol. 15, no. 02, pp. 429–458, 2005.
[22] X. Huang *et al.*, “1.6 Gbit/s phosphorescent white LED based VLC transmission using a cascaded pre-equalization circuit and a differential outputs PIN receiver,” *Opt. Exp.*, vol. 23, no. 17, pp. 22034–22042, 2015.
[23] W. R. Bennett, “Spectra of quantized signals,” *Bell Syst. Tech. J.*, vol. 27, no. 3, pp. 446–472, 1948.
[24] J. O’Carroll, R. Phelan, B. Kelly, D. Byrne, L. P. Barry, and J. O’Gorman, “Wide temperature range $0 < T < 85$ °C narrow linewidth discrete mode laser diodes for coherent communications applications,” *Opt. Exp.*, vol. 19, no. 26, pp. B90–B95, 2011.
[25] H. Bülow, F. Buchali, and A. Klekamp, “Electronic dispersion compensation,” *J. Lightw. Technol.*, vol. 26, no. 1, pp. 158–167, Jan. 2008.