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C band 112 Gb/s PAM4 signal transmission over 320 km with a quasi-linear double-side electro-absorption modulated laser (DS-EML)

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A B S T R A C T

The growing traffic demand in data center interconnections (DCIs) requires high-speed and low-cost transceivers that can flexibly adapt to different transmission distances up to 80 km or further. In this paper, based on the double-side electro-absorption modulated laser (DS-EML), we propose a transmitter with a fixed 90-degree phase rotation on one side of the DS-EML that can realize quasi-linear complex modulation. We verify the application of the quasi-linear DS-EML for a 112 Gb/s CD pre-compensation 4-level pulse amplitude modulation (PAM4) signal transmission over 320 km by simulation. Compared with the $LiNbO_3$ in-phase quadrature (IQ) modulator and the dual-drive Mach-Zehnder modulator (DDMZM), our proposed transmitter has several obvious advantages, such as low cost, small footprint, ease of integration and reduced power consumption.

1. Introduction

A recent CISCO report predicts that 99% of global internet traffic will be data center related [1]. Optical fiber transmission system with high bandwidth, low loss, and low latency is a feasible solution for data center interconnections (DCIs) [2]. Considering system cost, power consumption, footprint, latency, advanced intensity modulation format, such as pulse-amplitude modulation (PAM) [3–5], carrier-less amplitude and phase (CAP) [6–8] and discrete multi-tone (DMT) modulation [9–11] combined with direct detection (DD) is the best choice for DCIs.

Short Range (SR) from 2 m to 300 m usually uses 850 nm vertical-cavity surface-emitting laser (VCSEL) array transmitting in multimode fiber (MMF). Long Range (LR) from 300 m to 20 km and Extended Range (ER) from 20 km to 40 km can use a directly modulated laser (DML) or a electro-absorption modulated laser (EML) transmitting at the O band (1310 nm), which ignores CD impairments. While the transmission distance is extended up to 80 km or further for the ZR applications, at the O band, we must face the problem of large power loss and the lack of a mature high-performance amplifier makes it difficult for a single line transmission with 100 Gb/s to further achieve this distance. At the C band, CD (~17 ps/nm/km) induces serious frequency-selective power fading for low-cost intensity modulation with direct detection (IM-DD) optical transmission systems. After 80 km standard single-mode fiber (SSMF) C band transmission, the available bandwidth of the power fading channel is less than 7 GHz, as shown in Fig. 1.

In recent years, researchers have tried to use the digital signal processing (DSP) technology in the electrical domain to improve the dispersion tolerance of the systems under the low-cost DD technology, achieving breakthroughs in target rates and distances. In order to meet the requirements of low-cost and low-power consumption of DCIs, single-sideband (SSB) modulation [12–14] and CD pre-compensation [15–17] have been developed to improve the dispersion robustness in DD system. The SSB modulation can obtain a linear mapping result by suppressing one of the sidebands of the conventional double-sideband signal and extracting the beat term between the signal and the carrier at the receiver. In this way, the CD induced power fading can be avoided. Although the SSB signal after DD can obtain the linear mapping term of the channel, it will also generate nonlinear SSBI. To cope with this problem, Kramers-Kronig receiver and iterative SSBI estimation cancellation methods have been proposed [18,19]. But these methods either need high sample rate or complex computation. Alternatively, a pre-distortion DSP technology based on the CD pre-compensation at the transmitter side has been developed to improve the dispersion robustness in DD system. Firstly, use the obtained prior knowledge of link dispersion to pre-distort the signal by transmitter side DSP, then use in-phase quadrature (IQ) modulator or dual-drive Mach-Zehnder

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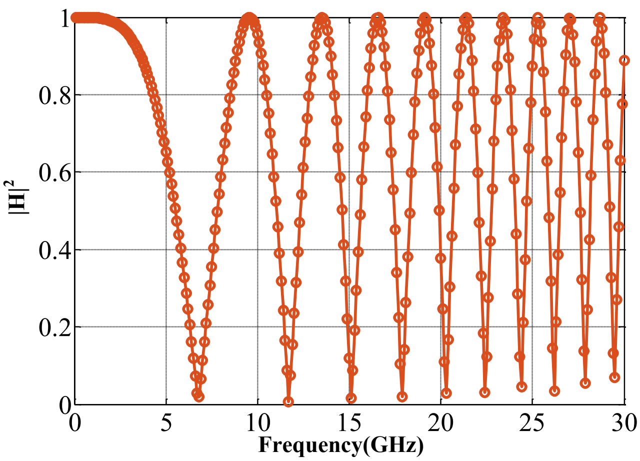

Fig. 1. CD induces serious frequency-selective power fading for IM-DD systems after 80 km transmission.

modulator (DDMZM) to make the digital signal that has been dispersion pre-compensated linearly mapped to the optical electric field, which cancels the actual dispersion damage of the link during the transmission. Thus, the signal at receiver is not affected by the dispersion. By using SSB or CD pre-compensation methods, IQ or DDMZM modulators have been proven to be key components for implementation. However, these modulators are large in size and not easy to integrate, resulting in high cost of optical transmitters and difficult of miniaturization packaging. Compared to IQ and DDMZM modulators, EML has the features of low price, small size, and easy integration. The traditional EML is a single-ended output device that can only achieve the intensity modulation of one real signal while the signals processed by SSB or CD pre-compensation are complex signals. The real and imaginary parts of the complex signal need to be modulated separately, and when they are modulated, the injected light corresponding to the two parts needs to be homologous to ensure that the frequency and phase of the optical carrier are aligned.

Taking the EML a step further, the double side EML (DS-EML) has been proposed to improve optical system performance [20,21]. It comprises a distributed feedback (DFB) laser with electro-absorption modulators (EAMs) located on both sides of the laser. The emission wavelength of the DFB laser is at the C band. It provides two independent optical modulated signals at the same wavelength. We have proposed quasi-linear DS-EML in [22]. In this paper, we provide a more detailed analysis on the principle of how to build complex signals from DS-EML for CD pre-compensation PAM4 signal. And by using the quasi-linear DS-EML, the performance of a 112 Gb/s CD pre-compensation PAM4 signal transmission over 320 km is studied. For comparison, The $LiNbO_3$ IQ modulator and the DDMZM are also studied.

2. Principle of DS-EML modulator

Schematics of our method showing how to build complex signals from DS-EML are sketched in Fig. 2 for the CD pre-compensation PAM4 signal, although we emphasize that the approach can be readily adapted to work for arbitrary IQ modulation. The quasi-linear DS-EML contains two independent intensity modulators and a fixed 90-degree phase rotation on one side. At the transmitter side, the original PAM4 signal $E_{PAM4}(t)$ after CD pre-compensation can be expressed as

$$E_{cdc}(t) = E_{PAM4}(t) \otimes h_{cd}^{-1}(t) \tag{1}$$

where $h_{cd}^{-1}(t)$ is the inverse of CD in optical fiber.

The complex signal can be separated into the real part $I_{cdc}(t) = Re\{E_{cdc}(t)\}$ and the imaginary part $Q_{cdc}(t) = Im\{E_{cdc}(t)\}$. Then $I_{cdc}(t)$ and $Q_{cdc}(t)$ are modulated on to the DS-EML respectively. With a fixed 90-degree phase rotation, the output of the modulator can be expressed as,

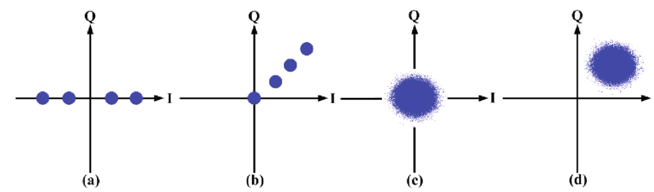

Fig. 2. Operational principle of the proposed transmitter, (a) constellation diagram of the original PAM4 signal (without DC), (b) constellation diagram of the generated PAM4 signal using the proposed transmitter, (c) constellation diagram of the CD pre-compensation PAM4 signal (without DC), (d) constellation diagram of the CD pre-compensation PAM4 signal using the proposed transmitter.

$$E_{out}(t) = \sqrt{I_{cdc}(t) + A} + j\sqrt{Q_{cdc}(t) + A} \tag{2}$$

where A is the DC bias.

We can now use the Taylor series expansion on the square-root term. The detected signal becomes,

$$E_{out}(t) = \sqrt{A} + \frac{I_{cdc}(t)}{2\sqrt{A}} - \frac{I_{cdc}^2(t)}{8A^{\frac{3}{2}}} + \cdots + j\cdot\left(\sqrt{A} + \frac{Q_{cdc}(t)}{2\sqrt{A}} - \frac{Q_{cdc}^2(t)}{8A^{\frac{3}{2}}} + \cdots\right) \tag{3}$$

The high order terms can be suppressed by A, the Eq. (3) can be simplified as,

$$E_{out}(t) \approx (1+j)\sqrt{A} + \frac{1}{2\sqrt{A}}(I_{cdc}(t) + j\cdot Q_{cdc}(t)) \tag{4}$$

From Eq. (4), it is observed that the electrical CD pre-compensation PAM4 signal is quasi-linearly converted to the optical domain. Thus, a CD free signal can be obtained after single-end PD detection. Since DS-EML is essentially intensity modulation, the constellation of the synthesized signal lies in the first quadrant of the complex plane and its optical spectrum contains a carrier component, which must be large enough to suppress the nonlinear component and to maintain quasi-linear modulation.

3. Simulation results and discussion

The simulation setup and the corresponding DSP procedures for a single-lane 112 Gb/s CD pre-compensation PAM4 signal transmission system with the quasi-linear DS-EML modulator are depicted in Fig. 3.

Firstly, the PAM4 signal is generated by 2ˆ16 pseudo-random binary sequence (PRBS). Up-sampling and CD pre-compensation are applied to generate complex signal, which increases the peak-to-average power ratio (PAPR), so that signal clipping is necessary. Then the dispersion pre-compensated signal is added to arbitrary waveform generator (AWG) for digital-to-analog (D/A) conversion. Then, two linear electrical amplifiers are used to boost the real and imaginary parts of the electrical signals. The amplified electrical signals are loaded onto the DS-EML with 90-degree phase rotation. The output optical signal is launched into SSMF, which has the chromatic dispersion coefficient of 17 ps/nm/km. At the receiver side, an optical bandpass filter is used to filter the out-of-band ASE noise. This progress is simulated based on VPI Transmission Maker. Finally, use the DSP technology in the digital domain consisting of normalization, re-sample, LMS-Based equalization, DDFTN, PAM4 decision and BER counting to further analyze the performance of the system.

Simulation results of the electrical spectrum for a 112 Gb/s CD pre-compensation PAM4 signal is depicted in Fig. 4. The electrical spectrum for a 112 Gb/s PAM4 signal after 80 km transmission with CD pre-compensation is shown as Fig. 4(c). For comparison, the electrical

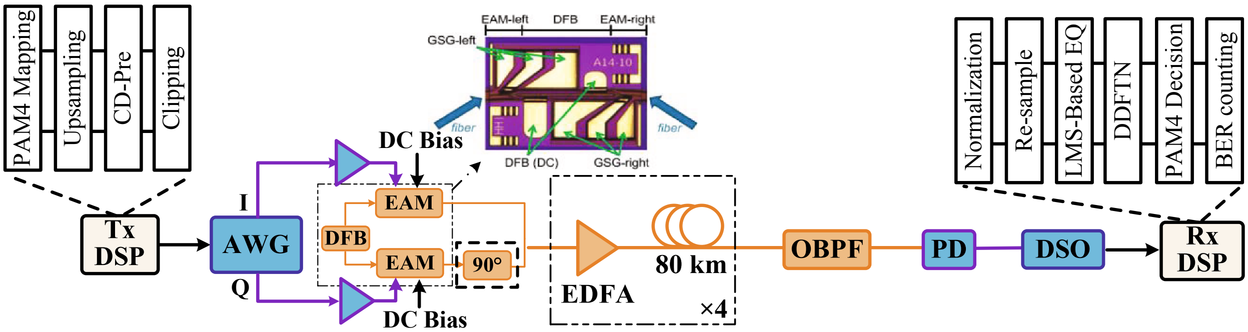

Fig. 3. Simulation setup and corresponding DSP procedures for a 112 Gb/s PAM4 signal transmission using DS-EML quasi-linear modulator.

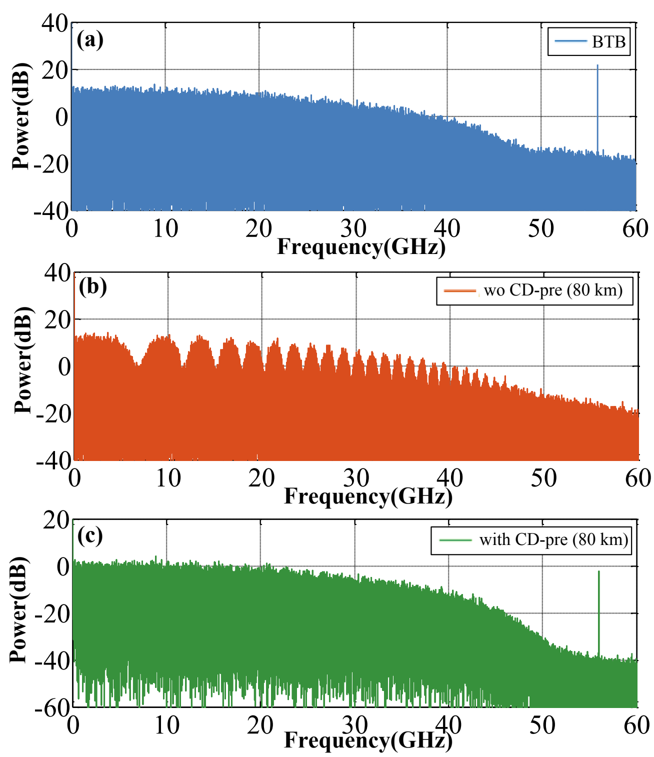

Fig. 4. Electrical spectrum for a 112 Gb/s CD pre-compensation PAM4 signal after PD detection, (a) back to back (BTB) transmission, (b) after 80 km transmission without CD pre-compensation, (c) after 80 km transmission with CD pre-compensation.

spectrum for a 112 Gb/s PAM4 signal after 80 km transmission without CD pre-compensation is depicted in Fig. 4(b). Without CD pre-compensation, multiple dips are observed due to CD-induced power fading and the available bandwidth is less than 7 GHz, which limits the data rate and transmitting distance. These problems are solved by the implement of pre-distortion DSP technology based on the proposed quasi-linear DS-EML. No such fading is observed in Fig. 4(c) and it is nearly the same shape as Fig. 4(a), which depicts the 112 Gb/s PAM4 signal for BTB transmission. In other word, our proposed transmitter based on DS-EML can realize the full field of the optical signal generation. It should be noted that with high carrier to signal power ratio (CSPR), the signal component is smaller and hence it is obvious that the power is slightly smaller for CD pre-compensation transmission based on DS-EML than the BTB case, which impact will be discussed in detail in Fig. 5.

In order to further analyze the system performance based on the proposed quasi-linear DS-EML (ER 10 dB), we investigate the

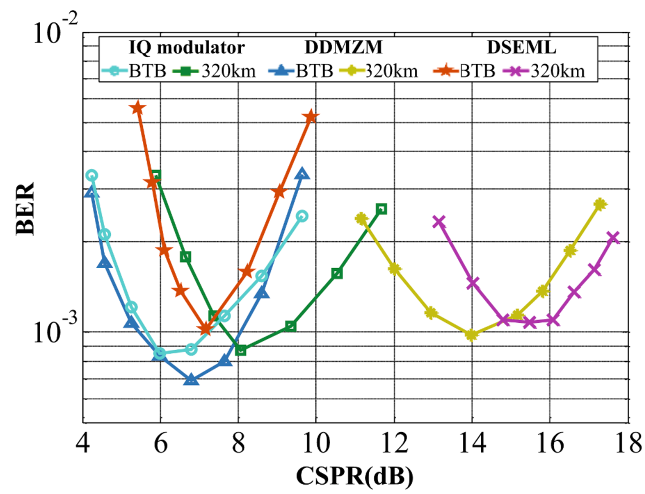

Fig. 5. Simulation results for BER vs. CSPR for a 112 Gb/s CD pre-compensation PAM4 signal with IQ modulator, DDMZM, DS-EML.

transmission performance based on the commercial IQ modulator (for example, FTM7962, ER 25 dB) and the DDMZM (for example, FTM7937, ER 20 dB) for comparation. Before the signal transmitting through fiber channel, the effect of CSPR on the system performance of PAM4 signal with three different modulations need to be analyzed. Fig. 5 shows the BER as a function of the CSPR for the BTB scenario and 320 km transmission based on three modulators. For these three modulators, different OSNRs are used to measure CSPR. For IQ modulator, the required OSNRs are 27 dB and 31 dB for BTB scenario and 320 km transmission, respectively. For DDMZM, the OSNRs are 28 dB at the BTB scenario and 36 dB for 320 km transmission. As for DS-EML, the OSNRs are fixed to be 28.5 dB and 36 dB respectively. The optimal CSPRs of BTB are about 6 dB, 6.8 dB and 7.2 dB, for IQ, DDMZM, DSEML, respectively. In the case of 320 km transmission, the optimal CSPRs are about 8 dB, 14 dB and 15.6 dB for IQ, DDMZM, DS-EML respectively. The differences between BTB and 320 km transmission are 2 dB for IQ modulator, 7.2 dB for DDMZM and 8.4 dB for DS-EML. Obviously, the optimal CSPR increases significantly when DS-EML is used in the experiment. Because the signal lies in the first quadrant of the complex plane and low extinction ratio (ER = 10 dB for DSEML), large CSPR is required to achieve quasi-linear modulation for DS-EML. For a large CSPR, the high-order nonlinear terms can be suppressed so that we can get the quasi-linear modulated signal, which shows in the principle part.

Further, we investigate how tolerance in terms of RCD for three modulators. Fig. 6 shows the BER as a function of the RCD for IQ modulator, DDMZM and DS-EML at optimal CSPRs and fixed OSNRs (OSNR = 31 dB for IQ modulator and OSNR = 36 dB for DDMZM and DS-EML). The positive RCD means that the CD pre-compensation is not sufficient while the negative RCD has the opposite meaning. When the

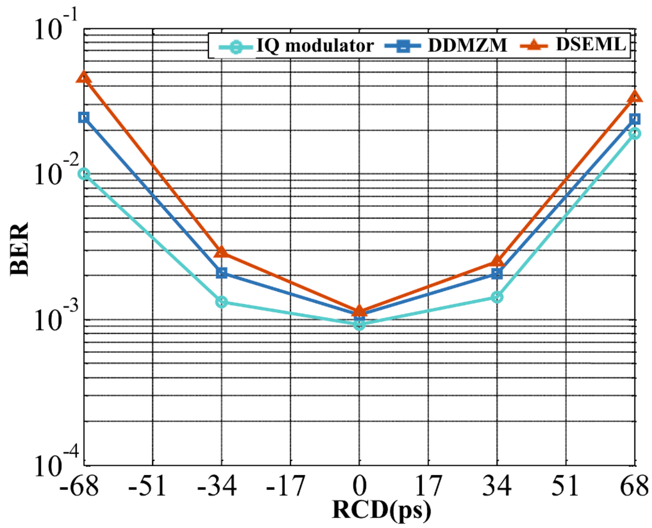

Fig. 6. Simulation results for BER vs. residuals chromatic dispersion (RCD) for a 112 Gb/s CD pre-compensation PAM4 signal with IQ modulator, DDMZM, DS-EML.

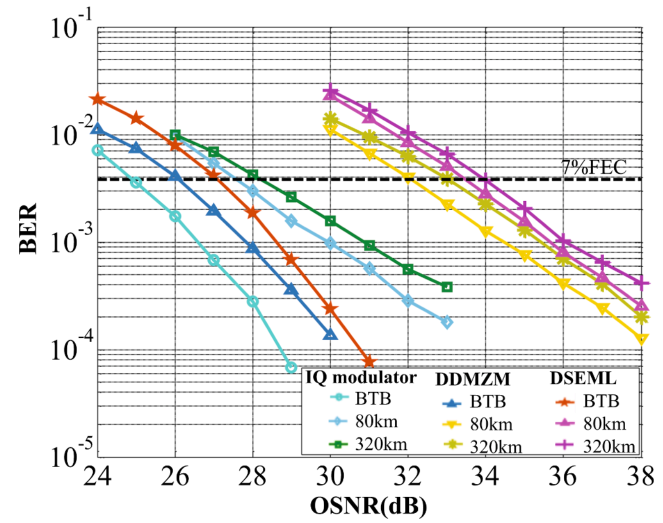

Fig. 7. Simulation results for BER vs. OSNR for a 112 Gb/s CD pre-compensation PAM4 signal at optimal CSPRs with IQ modulator, DDMZM, DS-EML.

RCD is zero, in other words when the CD pre-compensation is optimal, we can see that the three modulators approach the same BER of 1E-3. As the absolute value of RCD increases from 0 to 68 ps, the BER performance decreases accordingly.

Fig. 7 shows the BER as a function of the OSNR at the optimal CSPRs for the scenario of BTB, 80 km and 320 km transmission based on three different modulators. For different modulators, we fix the launch power at 0 dBm. The required OSNR at the BER of 3.8E-3 of 7% FEC is used as reference, which is 25 dB for IQ modulator while the penalties are ~ 2.6 dB for 80 km transmission and ~ 3.2 dB for 320 km transmission. For DDMZM, the required OSNR is 26 dB at the BTB scenario, while the OSNR penalties are ~ 6 dB and ~ 7 dB, for 80 km and 320 km transmission, respectively. As for DS-EML, the required OSNR is 27 dB at the BTB scenario, while the OSNR penalties are ~ 6.5 dB and ~ 7 dB, for 80 km and 320 km transmission, respectively. Because the CD pre-compensation will increase the PAPR of the signal. The higher PAPR will inevitably increase in quantization noise and low power efficiency, therefore the system performance can be influenced. Results show that for DS-EML, as the transmission distance increases from 80 km to 320 km, the required OSNR is relatively stable with only 0.5 dB increased. In this regard, our transmitter provides the capability to compensate CD with intensity modulation that outperforms other modulators. And it shows that our transmitter has about 1 dB OSNR penalty with respect to DDMZM after propagation through 320 km of SSMF, showing that our transmitter is only slightly inferior to DDMZM. Considering the other advantages such as low cost, reduced power consumption and ease of integration, we can draw the conclusion that DS-EML is potentially a good device for high speed and short reach applications, where power consumption and cost are the primary concern.

4. Conclusion

In this paper, a new full field of the optical transmitter is proposed based on DS-EML. With a fixed 90-degree phase rotation on one side of the DS-EML, it can realize quasi-linear modulation. We verify the application of the quasi-linear DS-EML CD pre-compensation PAM4 signal transmission by simulation. Results show that the 112 Gb/s CD pre-compensation PAM4 signal for 320 km transmission needs 34 dB OSNR at BER of 3.8E-3. Compared with IQ modulator and DDMZM, our proposed transmitter has several obvious advantages, such as low cost, small footprint, ease of integration and reduced power consumption, which indicates that the DS-EML is potentially a cost-effective device for future high-speed short reach applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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