Generation and Transmission of SSB-PAM4 Signal with a DSP-free Phase Alignment Scheme

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***Abstract*—A DSP-free phase alignment scheme is proposed and experimentally demonstrated in a 56-Gb/s SSB-PAM4 transmission system. BERs are reduced significantly with the new phase alignment scheme in both the back-to-back case and after 40-km transmission.**

Keywords—modulation, PAM4, single sideband, phase alignment

I. Introduction

With the continuous growth of the bandwidth demands for metro and data center interconnection (DCI) applications, direct detection (DD) systems have received great attention, considering their advantages of low cost and low power consumption. The impairments in DD systems mainly come from limited bandwidth, chromatic dispersion (CD) and nonlinearities. If a DD system is scaled up in data rate, CD induced power fading may have a detrimental influence on the system performance, severely limiting the capacity and the reach of the system [1].

Many efforts have been dedicated to solve the dispersion-related power fading in recent years [2-5]. Among these schemes, digital CD pre-compensation and single-sideband (SSB) modulation are two methods widely employed in current DD systems. In the digital CD pre-compensation method, by multiplying the inverse response of the CD, the original signal can be pre-dispersed in the digital domain, thus avoiding the power fading at the receiver [2]. However, a feedback from the receiver is required to obtain the knowledge of the dispersion response, leading to an increased system complexity. Compared to the digital CD pre-compensation, the SSB modulation is easier to implement and possesses a doubled optical spectrum efficiency. Two methods can be used to generate the SSB signal. In the vestige-sideband (VSB) modulation [3], one sideband of the double-sideband (DSB) signal is removed by an optical filter in the optical domain. Also in the digital domain, Hilbert transform can be adopted to remove the redundant sideband. The Hilbert transform-based SSB (H-SSB) method is a promising solution in metro/DCI scenarios, since it does not need an additional optical band-pass filter (OBPF) with a sharp edge as in the VSB case. In recent years, various high-capacity DD systems have been demonstrated employing SSB modulation and advanced modulation formats, such as discrete multi-tone modulation (DMT), carrier-less amplitude phase modulation (CAP) and pulse amplitude modulation (PAM) [3-5].

However, the direct detection of the SSB signal is different from that of the conventional DSB signal. In DD systems, the desired signal is contained in the carrier-signal beating term (CSBT) after the square-law detection, which means that the relative phase difference between the carrier component and the signal component is important. For the optical intensity-modulated DSB signal, the optical carrier is modulated in one dimension (i.e. amplitude), and the carrier phase is inherently aligned with the signal phase, thus the CSBT is exactly the desired signal. However, in the SSB modulated system, the optical carrier is modulated in two dimensions (i.e. amplitude and phase), and the phase alignment should be performed between the carrier component and the complex signal component, to obtain the desired signal from the CSBT. Such phase alignment can be implemented by using the digital signal proposing (DSP) at the transmitter or at the receiver [6,7], to extract the original signal after the direct detection, which however leads to an increased complexity.

In this paper, a novel DSP-free phase alignment scheme is proposed. By simply biasing one sub-Mach-Zehnder modulator (MZM) of the in-phase/quadrature (IQ) modulator at the quadrature point while the other sub-MZM at the null point respectively, the phase alignment can be performed in the optical domain, without additional DSP operation at the transmitter or at the receiver. Based on the new phase alignment scheme, a 56-Gb/s PAM4-SSB signal is generated and successfully transmitted over a 40-km single mode fiber (SMF) with a bit error ratio (BER) of 7×10^{-3} without dispersion compensation, enabled by signal-signal beating interference (SSBI) cancellation, feedforward equalization (FFE) and nonlinear equalization (NLE).

II. Operation Principle

In a DD system, a carrier co-propagates with the information bearing signal. Before hitting the photodetector (PD), the complex optical field envelope can be expressed as:

$$E(t)=[C+S(t)]e^{j\omega t} \tag{1}$$

where C is the optical carrier, $S(t)$ is the information bearing signal and ω is the optical carrier frequency.

After square-law detection, the detected signal after the PD is:

$$I(t)=|E(t)|^2=|C|^2+2\mathrm{Re}\{C^*\cdot S(t)\}+|S(t)|^2 \tag{2}$$

where $\mathrm{Re}\{\cdot\}$ denotes the real part of the complex signal. The first term is a direct current (DC) component, which can be removed by a DC blocker. The second term contains the desired signal, which is distorted by the third term, i.e. the SSBI.

In H-SSB systems, an IQ modulator can be used to generate the optical SSB signal, driven by the original signal and its Hilbert transform in the in-phase channel and the quadrature channel, respectively. For the conventional method, two sub-modulators of the IQ modulator are both biased above the null points, to provide an optical carrier. Such biases result in a phase rotation of the carrier, leading to a crosstalk from the quadrature channel, which can be removed by an additional phase alignment operation in the DSP. In our proposed method, we bias the upper sub-MZM at the quadrature point, which is driven by the original signal, while the lower sub-MZM is biased at the null point and driven by the Hilbert transform of the original signal. By this means, the phase alignment can be performed in the optical domain, without an additional DSP operation required.

The analytical derivations are detailed subsequently. Expressions of C and $S(t)$ for a DSB signal, a VSB signal, a conventional H-SSB signal and a proposed H-SSB signal are presented respectively as follows.

$$\begin{cases} C=\mathrm{A},\ S(t)=s & \text{, DSB signal} \\ C=\mathrm{A},\ S(t)=s+\mathrm{j}\hat{s} & \text{, VSB signal} \\ C=\mathrm{A}e^{\mathrm{j}\theta},\ S(t)=s+\mathrm{j}\hat{s} & \text{, Conv. H-SSB signal} \\ C=\mathrm{A},\ S(t)=s+\mathrm{j}\hat{s} & \text{, Prop. H-SSB signal} \end{cases} \quad (3)$$

where the original signal is denoted by s, while its Hilbert transform is denoted by $\hat{s}$. A is the amplitude of the carrier. θ is the phase rotation of the carrier in the conventional H-SSB signal, which is equal to $\pi/4$ when the two biases of the IQ modulator are both at the quadrature points. The case of $\theta=\pi/4$ for the conventional H-SSB signal is investigated in following derivations.

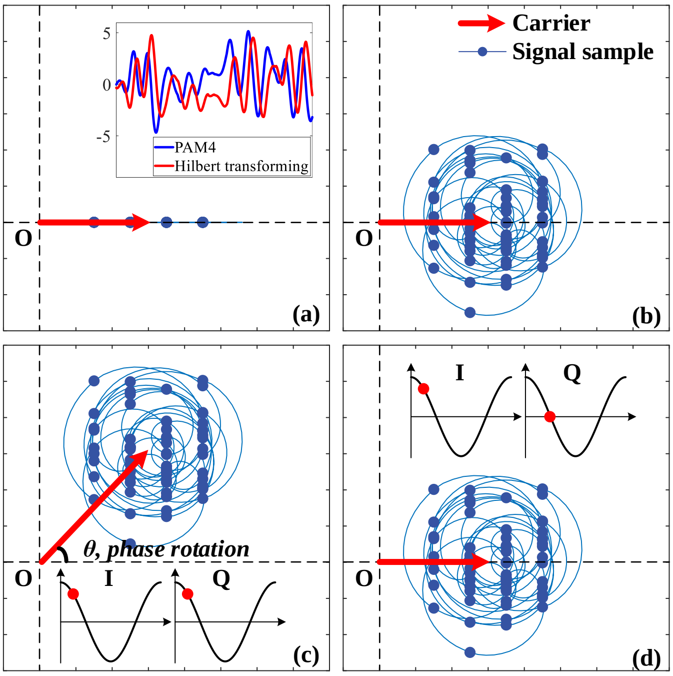

Fig. 1. Time trajectories of (a) a DSB-PAM4 signal, (b) a VSB-PAM4 signal, (c) a conventional H-SSB PAM4 signal, and (d) a proposed H-SSB PAM4 signal, respectively. Inset: baseband PAM4 signal and its Hilbert transform.

Time trajectories of these signals are shown in Fig. 1. The corresponding detected signals after square-law detections can be expressed as follows.

$$I(t)=\begin{cases} \mathrm{A}^2+2\mathrm{A}s+s^2 & \text{, DSB signal} \\ \mathrm{A}^2+2\mathrm{A}s+s^2+\hat{s}^2 & \text{, VSB signal} \\ \mathrm{A}^2+2\mathrm{A}s+2\mathrm{A}\hat{s}+s^2+\hat{s}^2 & \text{, Conv. H-SSB signal} \\ \mathrm{A}^2+2\mathrm{A}s+s^2+\hat{s}^2 & \text{, Prop. H-SSB signal} \end{cases} \quad (4)$$

As shown in (4), there is a crosstalk component, i.e. $2\mathrm{A}\hat{s}$, in the detected conventional H-SSB signal. The Hilbert transformed signal which is amplified by the carrier can result in severe performance degradation, if a phase alignment in the DSP is not used [7]. While for the detected signal in our proposed H-SSB method, no crosstalk is observed from the quadrature channel, and the CSBT, i.e. $2\mathrm{A}s$, is exactly the desired signal.

III. EXPERIMENTAL SETUP

To verify the feasibility of the proposed DSP-free phase alignment scheme, an experiment is performed, as shown in Fig. 2. The original digital signals are generated offline by Matlab, and then converted to electrical analog signals using two channels of an arbitrary waveform generator (AWG) (Keysight M8195A), with a 56-GSa/s sampling rate. After amplified by two electrical amplifiers (EA), the electrical signals are used to drive the two sub-MZMs of a 22-GHz IQ modulator. The two sub-modulators of the IQ modulator are both biased at the quadrature points for the conventional H-SSB generation scheme, while one is biased at the quadrature point and the other is biased at the null point for the proposed H-SSB generation scheme. A continuous wave light from a distributed feedback laser (DFB) at 1550 nm is modulated by the electrical signals in the IQ modulator. After electrical-to-optical (E/O) conversion, the optical signal is boosted by an erbium-doped fiber amplifier (EDFA), and then fed into a single-span 40-km single mode fiber (SMF). At the receiver, the received optical signal is firstly amplified by another EDFA and then filtered by an OBPF with a 1-nm bandwidth. The filtered optical signal is detected by a 40-GHz PD, and the acquired electrical signal is captured by a digital storage oscilloscope (DSO) (LeCroy 36Zi-A) at 80 GSa/s.

Fig. 3(a) shows the DSP flow chart. At the transmitter side, a binary sequence is mapped to PAM4 symbols with Gray coding, then a training sequence and a synchronization sequence are added. After up-sampled by a factor of 2, pulse shaping is performed by a raised cosine filter with a roll-off factor of 0.1. The Hilbert transform is used to generate the quadrature signal, which is sent to the AWG with the in-phase signal. At the

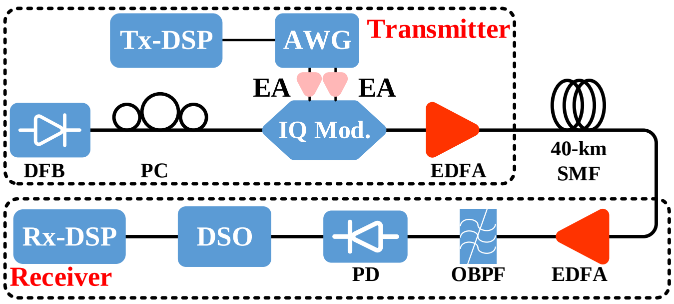

Fig. 2. Experimental setup.

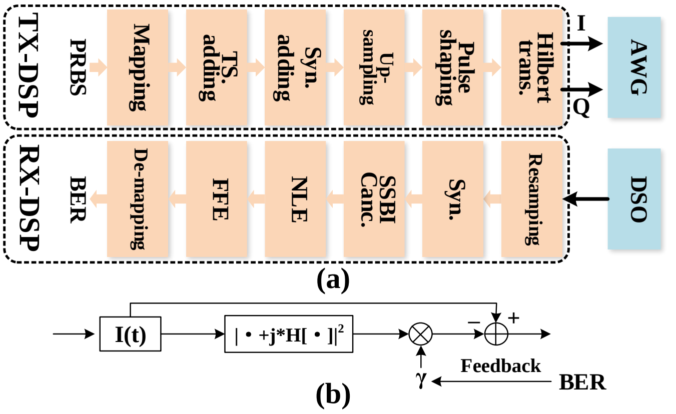

Fig. 3. (a) DSP flow chart. (b) Block diagram of the SSBI cancellation algorithm.

receiver side, resampling is firstly performed to align the sampling rate of the AWG. After synchronization, a SSBI cancellation algorithm is employed [8], with its block diagram illustrated in Fig. 3(b). In the SSBI cancellation algorithm, a feedback from the BER calculation is used to optimize the parameter of γ. Only once iteration is performed in our experiment, to avoid high complexity from multiple iterations. After the SSBI cancellation, NLE algorithm and FFE algorithm are implemented to alleviate the nonlinear and linear distortions. Finally, de-mapping and BER calculation are performed.

IV. Results and Discussion

By carefully adjusting the bias voltages of the IQ modulator, an optical PAM4-SSB signal with accurate phase alignment is generated. Fig. 4(a) shows the optical spectrum of the generated SSB signal after the IQ modulator, with a 1.12-pm spectrum resolution measured by an optical spectrum analyzer (OSA) (APEX 2040C). The compressed optical bandwidth is attributed to the Nyquist pulse shaping, and a single-sideband suppression ratio up to 24 dB can be observed. Before launched into the SMF, the total launch power of the optical SSB signal is optimized to 6.5 dBm, as presented in the Fig. 4(b). The BER curves for optical back-to-back (OBTB) and after 40-km SMF transmission are plotted in Fig. 4(c), respectively. First, for the proposed SSB signal, a BER of 2.3×10^{-4} can be achieved at a –10-dBm received optical power in the OBTB case, owing to the proposed phase alignment scheme. After the fiber transmission, an error floor at 7×10^{-3} is observed above –11-dBm received optical power. At the 20% soft decision-forward error correction (SD-FEC) threshold of 2.4×10^{-2}, a 1.5-dB power penalty is observed after the 40-km fiber transmission. For the conventional SSB signals without phase alignments, the corresponding BER curves are also provided for comparison. It can be seen that their BERs increase significantly in both the OBTB case and the transmission case, which is caused by the amplified Hilbert component, as aforementioned in section II. This amplified Hilbert component cannot be alleviated by the SSBI cancellation algorithm or the NLE algorithm in the time domain, which however can be removed by the phase alignment operation. Compared to the conventional SSB signal without phase alignment, the BER of the proposed SSB signal is reduced by two orders of magnitude, i.e. from 2.4×10^{-2} to 2.3×10^{-4}, in the OBTB case. Fig.4(d) shows the eye diagrams in the different cases investigated in the experiment, measured at a received optical power of –8 dBm.

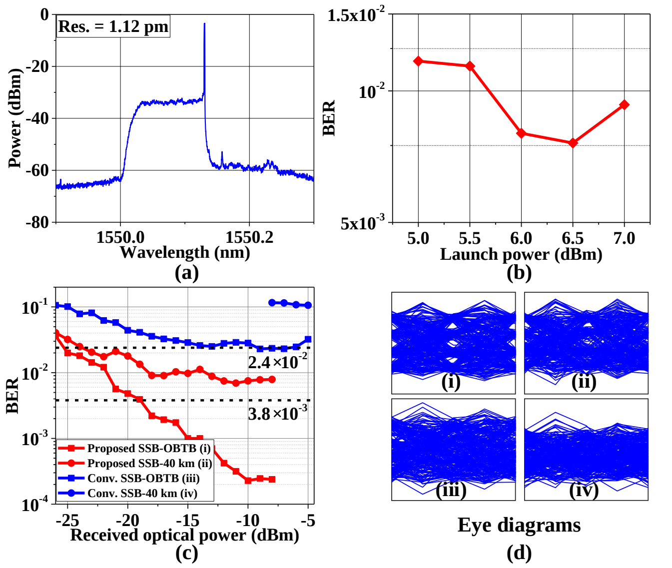

Fig. 4. (a) Optical spectrum of the generated SSB signal. (b) BER versus launch power. (c) BER curves for the OBTB case and after the 40-km SMF transmission. (d) Eye diagrams in the different cases.

V. Conclusion

In this paper, we propose a SSB generation method with a novel DSP-free phase alignment scheme for metro/DCI applications. A 56-Gb/s SSB-PAM4 signal is successfully transmitted over a 40-km SMF without dispersion compensation with a BER of 7×10^{-3}. By using the proposed phase alignment scheme, a BER reduction from 2.4×10^{-2} to 2.3×10^{-4} is achieved in the OBTB case.

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