160-Gb/s Nyquist PAM-4 Transmission with GeSi-EAM Using Artificial Neural Network Based Nonlinear Equalization

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Abstract: We experimentally demonstrate optical interconnects of PAM-4 signal with a single lane bit rate of 160Gb/s generated by a compact silicon based GeSi electro-absorption modulator using artificial neural network based nonlinear equalization.

1. Introduction

With the emerging applications such as cloud computing, the Internet of Things, 4K high-definition video and virtual reality technology, the Internet traffic grows rapidly in short-reach data center networks. Recently, the IEEE P802.3bs Task Force has discussed and approved the 400-GE standards to meet the ever-growing bandwidth demands [1]. Optical transceivers with lane rate beyond 100G is a prominent and promising solution to accommodate 400-GE interface of data center interconnects (DCI).

Silicon photonic (SiP) modulator is also a highly attractive platform for the future data center applications due to its small footprint, low power consumption and complementary metal oxide semiconductor (CMOS) compatibility [2]. Several beyond 100Gb/s/λ results with SiP modulator have been recently reported using four-level pulse amplitude modulation (PAM-4). 128Gb/s/λ PAM-4 signal transmitting over 1km standard single mode fiber (SSMF) with a bit error rate (BER) below the 7% hard-decision forward error-correction (HD-FEC) threshold of 3.8×10^{-3} was demonstrated based on a silicon dual-drive traveling-wave Mach-Zehnder modulator (TW-MZM) [3]. However, the TW-MZM, which relies on free-carrier dispersion effect, typically operates with limited bandwidth, mm^2 order's footprint and power consumption of pJ/bit [4]. Alternatively, GeSi electro-absorption modulators (EAM) based on the Franz–Keldysh (FK) effect [5], is a promising candidate for broadband, smaller footprint and lower power consumption modulation. A demonstration of 112 Gb/s/λ PAM-4 signal transmission over 2km SSMF with a BER below the 7% HD-FEC threshold using a GeSi EAM was reported in [6]. In [7], a 112Gb/s PAM-4 signal is synthesized by two on-off keying (OOK) signals of different amplitudes using two parallel EAMs and transmitted over 2km SSMF with a BER below 3.8×10^{-3}.

In this paper, 160Gb/s/λ Nyquist PAM-4 transmission over 2km SSMF was experimentally demonstrated by using a GeSi EAM with a 3-dB bandwidth of ~30GHz using artificial neural network based nonlinear equalization (ANN-NLE). The measured BER after transmission is 8.2×10^{-3} that is well below the 20% HD-FEC threshold of 1.5×10^{-2}. To the best of our knowledge, it is the highest single-wavelength PAM-4 transmission on a single EAM, which indicates the potential DCI application of EAM.

2. Modulator Characteristic and Experimental Setup

Fig. 1(a) shows the structure of the GeSi EAM fabricated through IMEC's silicon photonics ISIPP50G technology, which is 140μm long and 20μm wide with p-i-n junction. The GSG pads are built for radio frenquency (RF) probe to apply the bias voltage and the high-speed driving signals. The fabricated modulator is based on the FK effect, where an applied electric field modifies the optical properties of direct bandgap semiconductors by increasing the absorption of photon with energies near the material bandgap [5]. The light is coupled in and out of the waveguide device by fiber-to-chip grating couplers with an insertion loss of ~5 dB per coupler. Fig. 1(b) shows the measured electro-optic response of the GeSi EAM. As the reverse bias exceeds 1V, the 3-dB bandwidth of the EAM is about 30 GHz. We chose 1.2V as the reverse bias in the following tests.

The operation of the EAM will bring frequency chirp that is due to the phase change caused by intensity modulation. According to the previous work [8], an intensity modulated optical signal $P = P_b(1 + s)$ is assumed, where P_b is the bias optical power and s represents the Nyquist PAM-4 signal. The additional phase modulation of the GeSi EAM can be generally modelled as follows.

$$\frac{d\phi}{dt}=\frac{\alpha}{2P}\frac{dP}{dt}\Rightarrow\phi=\frac{\alpha}{2}\int\frac{1}{P}\frac{dP}{ds}ds\approx\frac{\alpha}{2}\left(s-\frac{s^2}{2}+\frac{s^3}{3}+\cdots\right),\tag{1}$$

where α is the chirp parameter. Therefore, the optical field can be obtained as follows.

$$E=\sqrt{\frac{P}{P_b}}e^{-j\phi}\approx 1+\frac{1-j\alpha}{2}s-\frac{1}{4}s^2+\left(\frac{3}{8}+\frac{j\alpha}{12}\right)s^3+\cdots. \tag{2}$$

Then we use operator $\hat{D}\{\cdot\}$ to represent the fiber chromatic dispersion (CD), The received photocurrent after square law detection of photodiode can be derived as follows.

$$I\propto\left|\hat{D}\{E\}\right|^2\approx 1+\mathrm{Re}\left\{(1-j\alpha)\hat{D}\{s\}\right\}+\frac{1+\alpha^2}{4}\left[\left|\hat{D}\{s\}\right|^2+\mu\,\mathrm{Re}\left\{\hat{D}\{s^2\}e^{j\theta}\right\}\right]+\cdots, \tag{3}$$

where μ and θ are constant parameters. In Eq. (3), the second term is the required signal. The third and the following terms indicate the high-order nonlinear distortion caused by frequency chirp. Here we utilize ANN-NLE [9] to compensate the nonlinear impairment. Fig. 1(c) displays the structure of ANN-NLE with 2 hidden layers consisting of 21 and 11 nodes, where rectified linear unit (ReLU) activation function is applied at both hidden layers. The parameters of the ANN are learned by minimizing the mean square error between the transmitted and the received symbols with the back propagation (BP) algorithm [10].

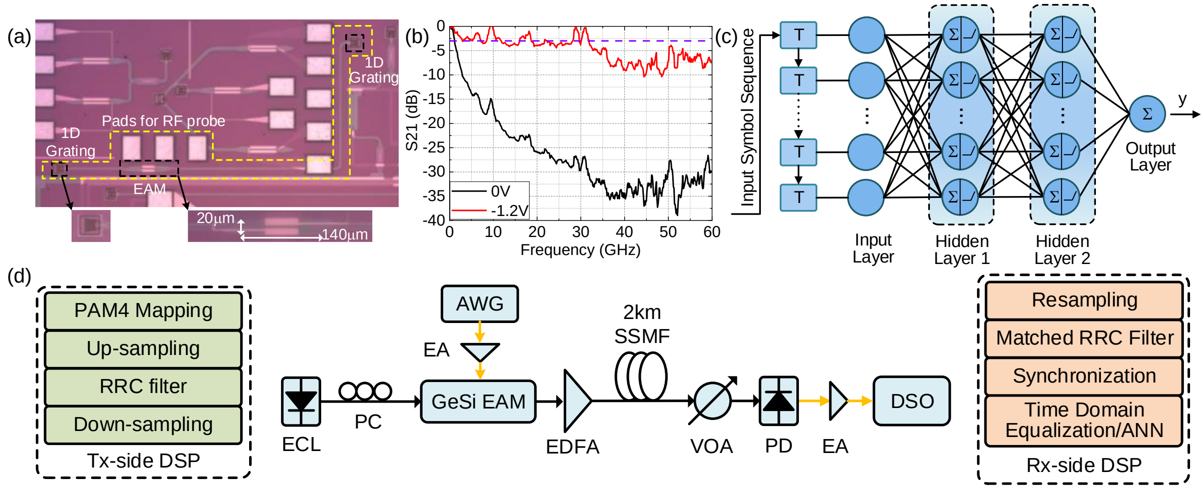

Fig. 1. (a) Micrograph and (b) Electro-optic response of the GeSi EAM. (c) The block diagram of the proposed ANN-NLE with 2 hidden layers. (d) Experimental setup and DSP program. ECL: external cavity lasers; PC: polarization controller; AWG: arbitrary waveform generator; EA: electrical amplifier; EDFA: erbium-doped fiber amplifier; SSMF: standard single-mode fiber; VOA: variable optical attenuator; PD: photodiode; DSO: digital storage oscilloscope. Tx: transmitter; Rx: receiver; RRC: root raised cosine; TDE: time domain equalization; ANN-NLE: artificial neural network based nonlinear equalization.

The experimental setup and digital signal processing (DSP) diagram are depicted in Fig. 1(d). At the transmitter, an external cavity lasers (ECL) with ~100kHz linewidth is employed as the optical source. A polarization controller (PC) is applied to adjust the polarization state of the light coupling to the chip. The baseband Nyquist PAM-4 signal is generated by an arbitrary waveform generator (AWG) (Keysight M8194A) operating at 120GSa/s. After amplified by an electrical amplifier (EA), the electrical waveform from AWG is used to drive the on-chip GeSi EAM through a GSG microwave probe with 40GHz bandwidth. Then the optical signal is launched into the 2km SSMF link after amplified by an erbium-doped optical fiber amplifier (EDFA). At the receiver, a variable optical attenuator (VOA) is employed to control the received power. Then the signal is detected by a single-ended photodiode (PD) and subsequently amplified by an EA both with a bandwidth around 50 GHz. Finanlly, the electrical signal is sampled by a real-time digital storage oscilloscope (DSO) (Keysight DSA-X 96204Q) operating at 160GSa/s to perform off-line DSP.

In the Tx-side DSP, the bit stream is mapped to PAM-4 first. After 15 times up-sampling, the signal is digitally shaped using a root raise cosine (RRC) filter with roll-off factor of 0.01. Then the signal is down-sampled before send to AWG. In the Rx-side DSP, firstly the signal is re-sampled to 4 samples per symbol, matched RRC filtered and synchronized. Time domain equalization (TDE) with the recursive least square (RLS) algorithm is applied as a comparison of ANN-NLE.

3. Experimental Results

Fig. 2(a)-(c) shows the mearsured BER as a function of the received optical power for 128/144/160Gb/s PAM-4 signals at BTB and 2km SSMF transmission scenarios, respectively. In the BTB case, compared with TDE, ANN-NLE can respectively provide 2dB and 2.6dB received power improvement for 128/144Gb/s signals at the BER of

2.0×10^{-2}. For 160Gb/s signal, the BER can be reduced from 1.98×10^{-2} to 9.02×10^{-3} with the help of ANN-NLE. In the 2km SSMF transmission case, it should be noted that the fiber dispersion would cancel the chirp effect induced by the GeSi EAM, leading to a better transmission performance than the BTB case. For 128Gb/s signal, compared with TDE, ANN-NLE can reduce the BER from 1.23×10^{-2} below the 20% HD-FEC threshold (1.5×10^{-2}) to 2.75×10^{-3} that is below the 7% HD-FEC threshold (3.8×10^{-3}). For 144/160Gb/s signals, ANN-NLE can reduce the BER below the 20% HD-FEC threshold. Fig. 2(d) displays the measured optical spectrums of Nyquist PAM-4 signals in BTB scenario with different baud rates at 0.02nm resolution. Fig. 2(e) shows the BERs versus bit rates with TDE and ANN-NLE, respectively, in BTB case and after 2km transmission. Fig. 2 (i)-(vi) depict the eye diagrams of PAM-4 signals with different baud rates after TDE or ANN-NLE at 2km transmission scenarios.

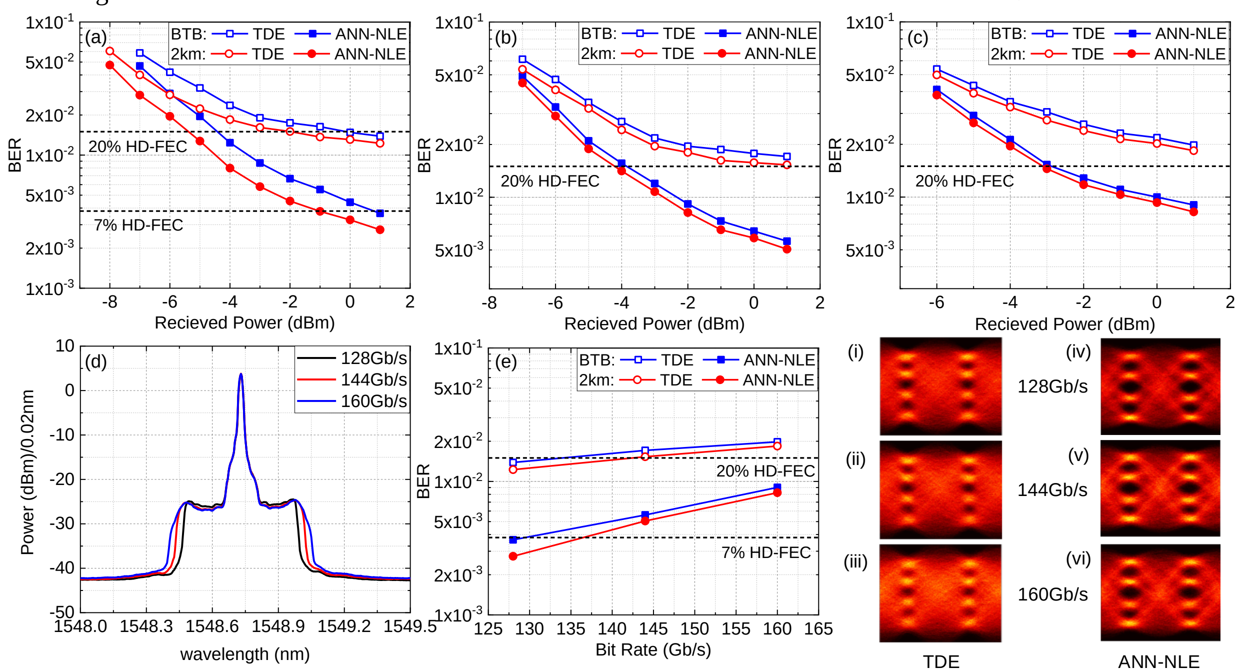

Fig. 2. Measured BER versus received optical power for (a) 128Gb/s (b) 144Gb/s (c) 160Gb/s PAM-4 signals at BTB and 2km SSMF transmission scenarios, respectively. (d) Measured optical spectra of Nyquist PAM-4 signals with different bit rates at BTB. (e) Measured BERs versus bit rate with TDE and ANN, respectively, in BTB case and after 2km SSMF transmission. (i)-(vi) eye diagrams of PAM-4 signals with different baud rates after TDE or ANN at 2km SSMF transmission scenarios.

4. Conclusions

In this paper, we demonstrate high baud rate Nyquist PAM-4 transmission by using an on-chip GeSi EAM with a 3-dB bandwidth of ~30GHz. The experiment results show that ANN-NLE can well inhibit the high-order nonlinear distortion caused by frequency chirp and achieve considerable performance improvement. The measured BER of 160Gb/s/λ PAM-4 signal after 2km SSMF transmission is well below the 20% HD-FEC threshold. Our work shows that high-performance EAM combined with advanced ANN-NLE has great potential to meet next-generation 400-GE requirement for data center applications.

5. Acknowledge

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