DAC-less and DSP-free PAM-4 Transmitter at 112 Gb/s with Two Parallel GeSi Electro-Absorption Modulators

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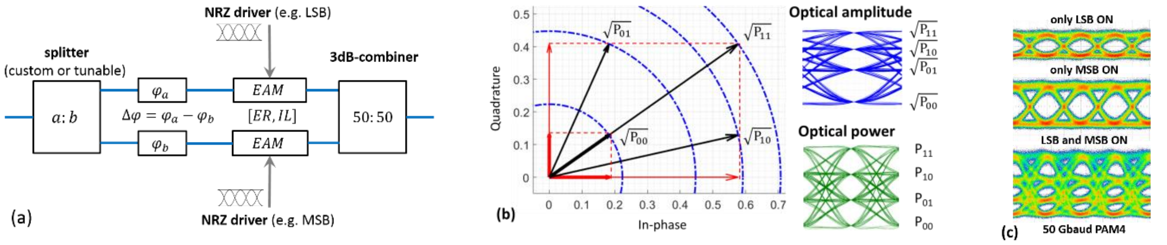
Abstract *We present a novel integrated PAM-4 modulator based on the vector addition of 2 binary driven parallel GeSi electro-absorption modulators. Clear open eyes at 56 GBaud up to 2 km of SSMF without any DSP are demonstrated.*

Introduction

Four-level pulse amplitude modulation (PAM-4) is widely assumed to be the modulation format of choice for next generation 400 Gigabit Ethernet short-reach optical interconnects. A four lane 100 Gb/s (50 GBaud PAM-4) scheme would be particularly interesting as it keeps the lane count low, offering higher spatial efficiency. Currently, most of the optical PAM-4 transmitters at 100 Gb/s and above use an electrical digital-to-analog converter (DAC) to generate the multi-level signal to drive a single intensity modulator. However, to drive the modulator the DAC needs to be able to provide a sufficiently large voltage swing or it has to be followed by a linear output driver. Both options substantially increase the power consumption of the transmitter with respect to a conventional non-return-to-zero (NRZ) driver at the same data rate. Shifting the DAC operation to the optical domain (i.e. using binary driving signals) would reduce the complexity and the power consumption of the transmit side electronics significantly. Recently, some DAC-less solutions have been proposed using a segmented Mach-Zehnder modulator (MZM)[1], two parallel MZMs[2], Si ring modulators[3-4] or by using polarization division multiplexing (PDM) for the least and the most significant bit (LSB and MSB) [5-6]. However, the MZM-based options[1-2] are less suitable for compact, low-power short-reach interconnects as they typically still require transmission line electrodes for contacting the phase shifters of several millimetres long as well as a power-consuming 50Ω termination. Si ring modulators have been used[3-4], but the speed currently is limited to 80 Gb/s even with offline digital signal processing (DSP) at the transmit (TX) and receive (RX) side. Rings have the additional disadvantage that they are very temperature sensitive and require extra control for stable operation. Polarization multiplexing can be used to transport the LSB and MSB over the optical channel by using an electro-absorption modulated laser in InP[5-6]. This allows an independent power addition of the two bits at the receiver, provided it is polarization insensitive. A drawback of this scheme is that it already occupies both polarizations to generate PAM-4, removing the possibility of doubling the data rate by using PDM. Moreover, the demonstrations still rely on discrete external components to perform the polarization rotation and combination needed for the PAM-4 generation,



$$P_{00} = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{b}{IL_b.ER_b}} + \frac{e^{j\Delta\varphi}}{\sqrt{2}}\sqrt{\frac{a}{IL_a.ER_a}}\right|^2, P_{01} = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{b}{IL_b.ER_b}} + \frac{e^{j\Delta\varphi}}{\sqrt{2}}\sqrt{\frac{a}{IL_a}}\right|^2, P_{10} = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{b}{IL_b}} + \frac{e^{j\Delta\varphi}}{\sqrt{2}}\sqrt{\frac{a}{IL_a.ER_a}}\right|^2, P_{11} = \left|\frac{1}{\sqrt{2}}\sqrt{\frac{b}{IL_b}} + \frac{e^{j\Delta\varphi}}{\sqrt{2}}\sqrt{\frac{a}{IL_a}}\right|^2 \quad \text{(d)}$$

Fig. 1: (a) Block diagram of the transmitter proposed in this work; (b) example of an equidistant PAM-4 generation using the first quadrant of the complex plane where the power split ratio a:b was chosen as 0.33:0.66, Δφ=90° and the EAMs have no IL and limited ER (10 dB). In this special case, the optical power eye openings decrease with decreasing ER but they remain equidistant, without changing Δφ. (c) Example of optical eyes for the proposed transmitter at 50 GBd; (d) Equations describing the 4 power levels for the proposed transmitter.

as this is not readily available on an InP integration platform. Implementing a compact, low-power 100 Gb/s silicon-based PAM-4 transmitter would provide a low-cost solution, which could be produced in high volume leveraging the existing CMOS fabrication infrastructure. In this paper, we present a novel single-lane, single-polarization integrated PAM-4 transmitter topology based on the vector addition of 2 binary driven compact parallel GeSi electro-absorption modulators (EAMs), outperforming a multilevel driven single GeSi EAM significantly in terms of eye quality without requiring any DSP. A prototype was fabricated in imec's silicon photonics platform (iSIPP50G) realizing the first 112 Gb/s PAM-4 transmission over 2km of standard single mode fiber with a silicon-based modulator without any DSP, DAC or long transmission line structures and power-consuming terminations.

Principle of Operation

As the transfer function of an EAM is typically non-linear and not even symmetrical (in contrast to MZMs), producing a clean PAM-4 eye from a single EAM can be challenging. A power hungry DAC or clever analog pre-distortion method is often needed to produce equidistant PAM-4 eye levels. If the EAMs have a limited extinction ratio (ER < 10dB), this becomes even more difficult (Fig. 3). In Fig. 1 we present a new type of optical DAC where the EAMs are used as binary driven switches to bypass their non-linear transfer function.

The proposed PAM-4 modulator consists of a splitter (with a power ratio a:b), two identical EAMs and a DC thermal phase shifter. The phase shifter is included to provide an additional degree of freedom to generate equidistant power levels in the PAM-4 signal. The input power splitting ratio is given by $a{:}b$. The EAMs are characterized by a bias and voltage swing dependent extinction ratio ER and insertion loss IL. The DC phase shift between both branches is $\Delta\varphi$. When branch a corresponds to the LSB and b to the MSB, the output power levels are given by (assuming for simplicity no phase difference between the 0 and 1 level is introduced by the EAMs) the equations in Fig. 1d. For a given ER and IL of the EAMs, the power split $a{:}b$ and $\Delta\varphi$ can be optimized to shape the output eye. Equidistant eyes can be obtained, or eyes can be shaped (predistortion) to minimize BER. An example of an equidistant PAM-4 eye is given in Fig.1b, where a:b were chosen 1/3:2/3 and $\Delta\phi = 90°$ for EAMs with 10 dB ER and no insertion loss. Even if the EAMs behave as non-perfect switches (ER < 10 dB, unbalanced IL, non-zero average phase-shift), we can still properly generate PAM-4 by adjusting the phase and power split. In some cases, tuning only the phase or only the power split can be sufficient.

Experiment setup

To verify the operation, a first prototype of this transmitter (Fig. 2b-c) was fabricated with two 50/50 splitters (1x2 multi-mode interferometers), a heater in each arm acting as a DC phase shifter and 2 identical 80 µm long GeSi EAMs as were used in our previous work[7]. As this structure does not have an optimized power splitting between both parallel arms, we mimic this effect by (1) driving one arm with a 6 dB smaller voltage swing and (2) further increasing the bias of this EAM, at the cost of a higher insertion loss w.r.t. an optimized power ratio. Nevertheless, this operation allows us to validate the proposed transmitter topology. When we introduce a DC phase shift close to 90° in one arm, the observed PAM-4 eyes match the predicted eyes quite well, resulting in almost perfectly equidistant eye-levels (Fig. 3c).

The experiment setup is shown in Fig. 2a. A fiber-coupled 12 dBm laser source at 1577nm is coupled to the chip through fiber-to-chip grating couplers (~6dB insertion loss). An in-house developed 4-to-1 multiplexer is used to generate two 2^7-1 long pseudo-random bit sequences (PRBS) at 56 Gb/s from 4 x 28 Gb/s NRZ signals generated by an FPGA. Both PRBS streams are decorrelated by adding a tunable time delay after one of the outputs. Operation with longer PRBS sequences up to 2^{15}-1 was investigated with an arbitrary waveform generator (AWG) up to 50 GBaud. Even though the performance was limited by the bandwidth of the AWG (<30GHz), no eye penalty was

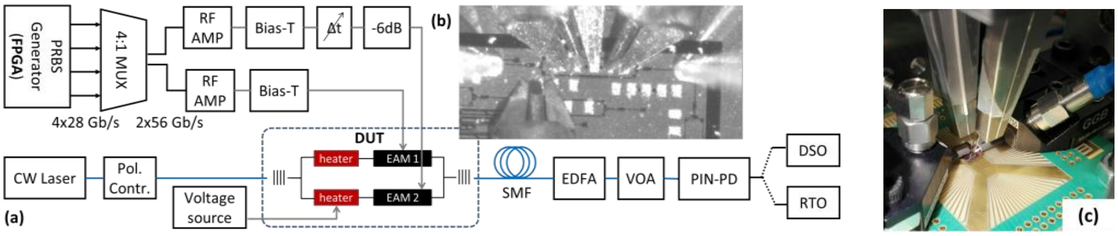


Fig. 2: (a) Experiment setup, (b) micrograph of die during experiments; (c) photo of setup

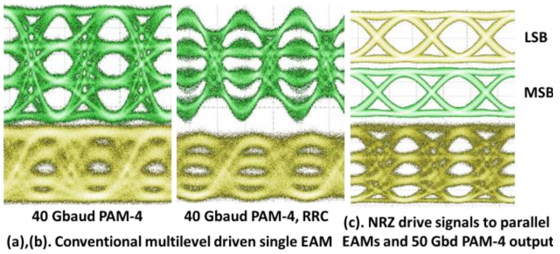


Fig. 3: (a) Electrical (top) and optical (bottom) eye diagrams at 40 Gbaud for a multilevel driven single GeSi EAM. (b) Even with root-raised cosine (RRC) pulse shaping, the eye is degraded w.r.t (c) the proposed TX

observed for longer PRBS sequences. Next, a 50 GHz RF amplifier increases both driving signals up to ~2.2 Vpp and ~1.1 Vpp, respectively. The EAMs are biased at -0.7V and -1.8V through internal bias-Ts in the RF-amplifiers. The modulators had an estimated IL and ER of around 7 dB. As no high-speed linear transimpedance amplifier (TIA) was available, an erbium-doped fiber amplifier (EDFA) is used to compensate the grating coupler losses and to produce a sufficiently large voltage swing at the output of a commercial photodiode (BW = 50 GHz). Replacing the grating couplers by low-loss edge couplers and adding a linear TIA to the link would allow the EDFA to be removed in future implementations. Finally, the RX signals are captured by a 50 GHz sampling oscilloscope (DSO) for eye diagrams and by a 63 GHz 160 GSa/s real-time oscilloscope (RTO) for offline error counting.

Results and Discussion

Due to the lack of a real-time PAM-4 bit-error ratio (BER) analyzer, BER estimation is done offline, by resampling the 160 GSa/s-waveforms and determining the sampling point that minimizes the BER. To guarantee a statistically relevant BER, the waveform length was extended until at least 10 bit errors had occurred. No offline equalization or other DSP was used before the BER counting.

Fig. 4 shows the received eyes at 50 and 56 GBaud after 0,1 and 2 km of standard single mode fiber (SSMF), resulting in a BER of 1.12E-6 (b2b), 4.24E-6 (1km) and 1.4E-4 (2km), all well below the hard decision forward error coding limit (HD-FEC) with 7% overhead of 3.8E-3. For 56 GBaud the electrical driving electronics started to be bandwidth limited. Nevertheless, we obtained a BER of 1.71E-6 (b2b), 5E-5 (1km) and 1.4E-3 (2km), below HD-FEC. An additional benefit of using EAMs as modulators, next to its compact size and high-speed operation, is that the same device can be used as a photodiode. We already demonstrated that these GeSi EAMs are capable of receiving 100 Gb/s NRZ with a responsivity close to 1 A/W[7].

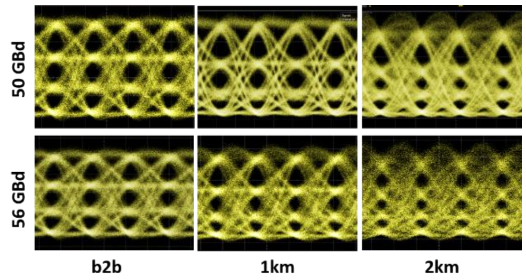


Fig. 4: Eye diagrams for 50 and 56 GBaud PAM-4 over 0, 1 and 2km of SSMF.

Conclusions

We have presented a new type of optical DAC capable of generating PAM-4 by using 2 binary driven parallel germanium EAMs. Using this topology, we demonstrated the first compact integrated 56 GBaud PAM-4 transmitter allowing transmission over 2 km without requiring any DAC, DSP or transmission-line structures in a silicon photonic platform. These results demonstrate the potential of silicon photonics as possible disruptive technology for compact and low-power transceivers for 400 GbE short-reach optical interconnects.

Acknowledgements

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