Linear-Drive Amplifier-Less 112 Gbit/s PAM4 Operation of a Silicon-Organic Hybrid (SOH) Mach-Zehnder Modulator at 265 mV_{pp}

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Abstract: We demonstrate an optically packaged silicon-organic hybrid (SOH) Mach-Zehnder modulator operating at PAM4 data rates of up to 112 Gbit/s. The device is directly driven by a CMOS SerDes chip without additional optical or RF amplifiers.

1. Introduction

Boosting the performance of future hyper-scale data-centers and artificial-intelligence clusters will require a new generation of optical transceivers that offer greatly improved scalability in terms of data rate, integration density, and cost [1]. A promising concept in this context is linear-drive (LD) optical transmission using technically simple intensity modulation and direct detection (IMDD) schemes, which eliminates digital signal processing (DSP) in the optical transceiver and instead relies on the serializer/deserializer (SerDes) blocks of the electrical payload integrated circuit (IC). Eliminating local DSP does not only reduce the complexity and cost of the optical transceiver, but also leads to lower power dissipation and paves a path to higher integration density. On a technical level, the performance of the LD transceivers strongly depends on the underlying electro-optic modulator, which must combine compact footprint and amenability to cost-efficient mass production with the ability to operate with standard DSP schemes as offered by SerDes blocks of widely used CMOS ICs. In addition, low drive-voltage swings of 1 V_{pp} or less are desirable to ideally alleviate the need for additional RF drive amplifiers, thereby further reducing the power dissipation. However, while optical transmission with sub-1 V_{pp} drive voltage swings has previously been demonstrated using different modulator concepts [2–10], these experiments so far either relied on rather bulky devices with lengths of the order of 10 mm [6], offered only limited IMDD data rates of up to 25 Gbit/s using simple on-off-keying (OOK) [2,10], were performed with rather complex offline DSP schemes and/or relied on electrical arbitrary-waveform generators (AWG) for synthesizing the drive signal [3–9], or required fiber amplifiers to boost the optical power levels [2–8,10]. Amplifier-less linear-drive optical transmission at technically relevant data rates hence still remains to be shown.

In this paper we demonstrate amplifier-less linear-drive PAM4 transmission using a CMOS SerDes to directly drive an optically packaged Mach-Zehnder modulator (MZM). The MZM relies on the silicon-organic hybrid (SOH) integration concept and is connected to input and output fibers using 3D-printed photonic wire bonds (PWB). The device is operated directly by the output signal of an industry-standard 56 GBd PAM4 CMOS SerDes without additional RF amplifiers, leading to a peak-to-peak drive voltage swing of only 265 mV_{pp} at the MZM input. The link does not contain any optical amplifiers and relies on a standard photodiode (PD) with a transimpedance amplifier (TIA) at the receiver. We demonstrate 112 Gbit/s PAM4 transmission with bit-error ratios (BER) below the KP4 limit at sub-1 mW optical receive powers. To the best of our knowledge, our experiments represent the first demonstration of amplifier-less linear-drive PAM4 transmission relying on a standard CMOS SerDes to directly drive an MZM. Moreover, we demonstrate the first MZM-based transmission link relying on a sub-1 V_{pp} drive-voltage swing without the need for additional optical amplification. We believe that our work marks an important step towards radically simplified linear-drive optical transceivers that require neither internal DSP nor dedicated driver electronics that can instead rely on sub-500 mV_{pp} input signals provided by standard CMOS circuits.

2. Linear-drive concept and SOH Mach-Zehnder modulator

The concept of linear-drive optical transmission with and without RF amplifier is illustrated in Fig. 1(a). The link connects two electrical payload ICs, acting as a data source and sink. The optical transmitter (Opt. Tx) is radically simplified and contains neither DSP nor amplifier chips to operate the internal MZM. In our proof-of-concept experiment, we use a bit error ratio tester (BERT, ML4039E, MultiLane Inc., Houmal Technology Park, Lebanon) containing an industry-standard CMOS SerDes chip with four transceiver channels, each of which can be operated at PAM4 symbol rates of up to 56 GBd. Since our MZM requires only a single-ended drive signal, we include a balancing unit (balun) to combine the differential outputs of the SerDes. The electrical signal at the output of the balun features a peak-to-peak voltage swing $U_{d,pp}$ of 265 mV. In the subsequent experiments, this signal is either used 'as is' to directly drive the MZM or boosted by an RF amplifier (RF Amp) prior to being fed to the MZM. The MZM is terminated with a 50 Ω load. The MZM fed by a laser source providing a carrier at 1550 nm. In our experiment, the laser was connected to the MZM by a single-mode fiber (SMF) including a polarization controller (PC, not shown). The modulated output

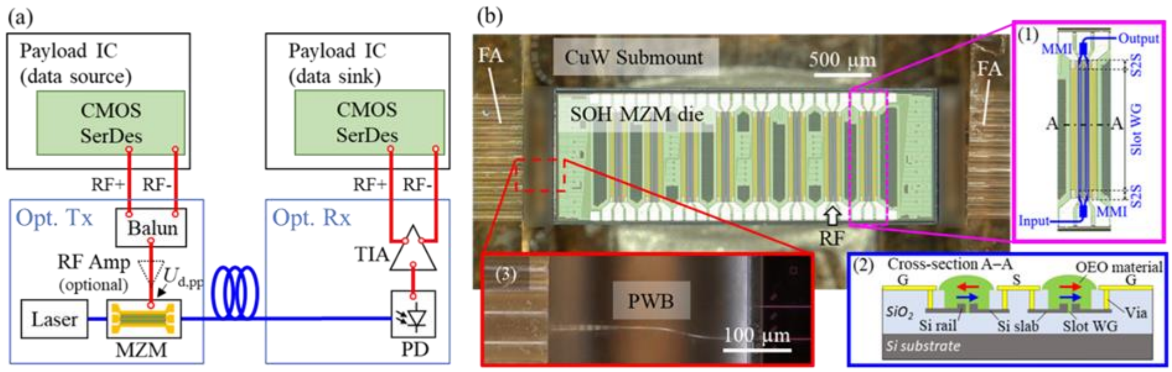

Fig. 1: (a) Schematic of a linear-drive transmission link with optional RF amplifier (RF Amp). Two electrical payload IC act as data source and sink, containing only a CMOS serializer/deserializer (SerDes) chip. Since our MZM requires a single-ended drive signal, we use a balun to combine the differential output of the SerDes. The resulting signal is fed to the MZM with an optional RF Amp. Laser light (1550 nm) is fed to the MZM. The laser, MZM, balun and the optional RF Amp. form the optical transmitter engine (Opt. Tx). The modulated output signal is sent through a single-mode fiber and received by an optical receiver (Opt. Rx) module containing a high-speed photodiode (PD) and transimpedance amplifier (TIA) with differential output which is then directly fed to the input of the SerDes. (b) Top-view of the optically packaged SOH MZM die containing eight devices. Inset (1) shows a more detailed layout of a single SOH MZM, where the optical path is indicated by blue lines. Light is coupled to the modulator and equally split in a multi-mode interference (MMI) coupler and then coupled to a slot waveguide (WG) by a strip to slot converter (S2S). After passing through the 1 mm long slot WG, the light enters another S2S converter before being recombined in a second MMI coupler. The RF signal is fed in from the bottom and propagates along the device on a coplanar waveguide (CPW) in ground-signal-ground (GSG) configuration. The cross-section A-A is shown in Inset (2). The optical signal is guided by the slot WG. The rails of this WG are connected to the GSG transmission line via doped silicon slabs [13] and metal vias. For optical packaging, the SOH MZM die is glued on a CuW submount together with two lidless V-groove fiber arrays (FA). Fiber-chip connections are established using photonic wire bonds (PWB) that can compensate for alignment inaccuracies of the FA and the MZM die, see Inset (3).

signal is sent through a SMF and received by an opto-electronic receiver module (Opt. Rx, MultiLane Inc.), which contains a high-speed PD as well as a TIA supplying a differential output signal, which is then directly fed to the SerDes CMOS chip acting as a data sink.

Clearly, the scheme illustrated in Fig. 1(a) imposes stringent requirements on the underlying MZM, e.g., with respect to modulation efficiency, in particular when the additional RF Amp in the optical Tx is omitted, leaving a $U_{d,pp}$ of 265 mV_{pp} to operate the device. To fulfill these requirements, we rely on the concept of SOH integration, which combines the intrinsic scalability advantages of the silicon photonic integration platform with ultra-high Pockels coefficients of up to 390 pm/V [4], obtained through theory-guided molecular design of organic compounds, and with phase-shifter losses below 1 dB [11]. SOH MZM relying on thermally stable materials have previously been demonstrated to exhibit $U_\pi L$-products down to 0.45 Vmm while permitting PAM4 transmission at symbol rates of up to 140 GBd [3] when using advanced offline DSP along with a broadband electrical AWG. In our experiments, we use optically packaged SOH MZM dies carrying an array of eight devices each and electrically probe the respective device of interest, see Fig. 1(b) for a top view of assembly. A more detailed layout of a single SOH MZM is provided in Inset 1 of Fig. 1(b), where the optical path is indicated by blue lines. Light is coupled to the modulator and equally split in a multi-mode interference (MMI) coupler. In each path, a strip to slot (S2S) converter couples the light from a strip to a slot waveguide (WG). After passing through the 1 mm long slot WG, the light enters another S2S converter before being recombined in a second MMI coupler. The SOH MZM has imbalanced arm lengths (not shown), allowing to set the operating point by tuning the wavelength of the carrier. The RF signal is fed in from the bottom and propagates along the device on a coplanar waveguide in ground-signal-ground (GSG) configuration. Inset 2 depicts a cross section through the device along the line A-A of Inset 1. The optical signal is guided by an optical slot waveguide (slot width approx. 140 nm, WG height approx. 220 nm), which maximizes the overlap of the optical field with organic electro-optic (OEO) material that acts as a top cladding [12]. The rails of the slot waveguide are connected to the GSG transmission line via doped silicon slabs [13] and metal vias. The OEO material is locally dispensed into the slot WG and poled at an elevated temperature. More details on SOH MZM can be found in [4,12]. The π-voltage U_π of the 1 mm long device was measured to be 1 V, leaving potential for further improvement. For optical packaging, the SOH MZM die is glued on a CuW submount together with two lidless V-groove fiber arrays (FA). Fiber-chip connections are established using PWB [14,15] that can compensate for alignment inaccuracies of the FA and the MZM die, see Inset 3. The PWB were written using an industry-grade multi-photon lithography system (Sonata 1000, Vanguard Automation GmbH, Germany) and photoresist (VanCore B, refractive index $n = 1.53$ at $\lambda = 1.55$ µm). For the current implementation, we obtained PWB insertion losses of 2-4 dB, leaving room for further improvement.

3. Linear-drive transmission with and without RF drive amplifier

We use the setup illustrated in Fig. 1(a) to prove the viability of our SOH MZM for linear-drive transmission. In a first experiment, we omitted the RF drive amplifier and simply relied on the drive signals supplied by the CMOS SerDes of our BERT. For PAM4 symbol rates of 24, 48, 54 and 56 GBd, we measure peak-to-peak drive voltage swings $U_{d,pp}$ of 299 mV, 253 mV, 252 mV and 265 mV, respectively. These signals are fed to the optically packaged MZM using an RF probe, and the received optical power is swept by adjusting the power of the laser, while measuring the bit-error ratio (BER). In all transmission experiments, we use gray-coded PAM4 with a pseudo-random bit sequence (PRBS) of length 2^{11}-1. For the Tx predistortion, we stick to the factory settings of the BERT with three filter taps provided. Two equalizers, a multipath-interference canceller and a reflection canceller, are used at the Rx. All used DSP is provided by the SerDes. The BER as a function of received optical power is depicted in Fig. 2 (a), where the KP4 forward error correction limit of 2.4×10^{-4} is indicated by a black dashed line. To benchmark our results, we compare our findings to the requirements of the IEEE 802.3bs 400GBASE-DR4 standard for short-reach (500 m) ethernet transceivers transmitting overall data rates of 400 Gbit/s over four optical lanes. According to this standard, each optical lane should operate at a symbol rate of 53 GBd PAM4 with a BER below the KP4 limit, for optical input powers between -5.9 dBm and 4.2 dBm. As shown in Fig. 2(a), our amplifier-less linear-drive link operates below the KP4 limit for a symbol rate of 54 GBd for optical powers above -1.3 dBm, such that the requirements of the 400GBASE-DR4 standard are not yet fulfilled but should be within reach. Note, that this standard is defined for the O-band, whereas our current device is still operating in the C-band, but we expect similar performance for SOH O-band devices. In a second experiment we explore the impact of higher drive voltages on the BER. To this end, we add an 11 dB RF amplifier (RF Amp in Fig. 1(a)) at the input of the MZM and sweep the PAM4 drive-voltage swing $U_{\mathrm{d,pp}}$ at the MZM input for two symbol rates of 48 Gbd and 56 GBd at a fixed received optical power of 0.6 dBm. The BER vs. $U_{\mathrm{d,pp}}$ normalized to the MZM π-voltage of $U_\pi = 1$ V is shown in Fig. 2(b). We find the optimum $U_{\mathrm{d,pp}}$ to be approximately 45% of U_π, resulting in a BER of 6×10^{-6} for the 56 Gbd experiment. For higher values of $U_{\mathrm{d,pp}}$, the MZM is operated outside of the linear regime, which leads to compression of the outermost PAM4-levels in the optical signal and hence decreases the signal quality. The BER levels found for the optimum drive voltage are far below the KP4 FEC threshold. Note that the current 1 mm-long MZM features a rather high π-voltage of $U_\pi \approx 1$ V, whereas optimized devices can reach values of $U_\pi \approx 450$ mV for the same device length. For such a device, the drive-voltage swing of 265 $\mathrm{mV_{pp}}$ provided by the CMOS SerDes without RF drive amplifier would already correspond to more than 50 % of the MZM π-voltage, thereby greatly improving the transmission performance and possibly fulfilling the 400GBASE-DR4 requirements.

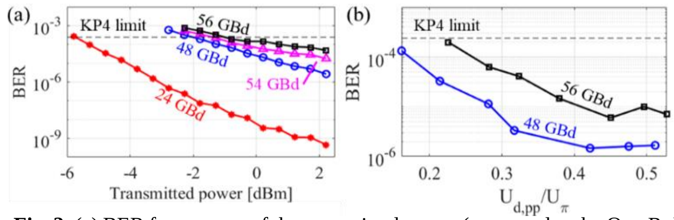

Fig. 2: (a) BER for a sweep of the transmitted power (measured at the Opt. Rx) recorded for different PAM4 symbol rates without an RF amp. (b) BER at a fixed PAM4 symbol rate of 56 GBd and 48 GBd and for a transmitted optical power of 0.6 dBm for a sweep of the modulator drive voltage $U_{\mathrm{d,pp}}$ using an RF amp. $U_{\mathrm{d,pp}}$ is normalized to U_π. The KP4 BER limit is shown by the black dashed line in both graphs.

4. Summary and outlook

We have demonstrated amplifier-less linear-drive PAM4 transmission at peak-to-peak voltage swings of 265 mVpp and data rates of up to 112 Gbit/s utilizing an optically packaged SOH MZM. The drive signal is provided by an industry-standard CMOS SerDes chip, and the scheme neither includes any additional RF driver circuits nor optical amplifiers. We analyze the power-dependent BER performance and find 400GBASE-DR4 standard to be within reach, given that the current implementation was a first proof of concept with room for further improvement. We believe that our work marks an important step towards radically simplified linear-drive optical transceivers that can simply rely on sub-500 mVpp CMOS-level input signals without any additional amplification.

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