4×56-GBaud PAM-4 SDM Transmission Over 5.9-km 125-µm-Cladding MCF Using III-V-on-Si DMLs

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Abstract: We demonstrate 4×56-GBaud PAM-4 signals over 125-µm-cladding, 4-core fiber by simultaneous, direct modulation of four 1.3-µm membrane III-V-on-silicon lasers, each requiring <25-mWatts (@12 mA). A reach extension of ~15x is achieved compared to previous works.

1. Introduction

As the data traffic of optical data center interconnects (DCI) and Ethernet links continues to grow, the demand to reduce the systems' cost and power consumption while maintaining a small transceiver size and cabling complexity has increased. For the transceiver components, silicon (Si) photonics and the membrane III-V-on-Si technology [1] can considerably reduce the fabrication and assembly costs by utilizing large Si wafers. In addition, directly-modulated lasers (DMLs), 4-level pulse-amplitude modulation (PAM-4), and direct detection (DD) provide higher energy efficiency and lower footprints than alternatives, such as coherent detection. Furthermore, optical parallelism, i.e., wavelength- and space-division multiplexing (WDM, SDM), can significantly reduce cabling complexity.

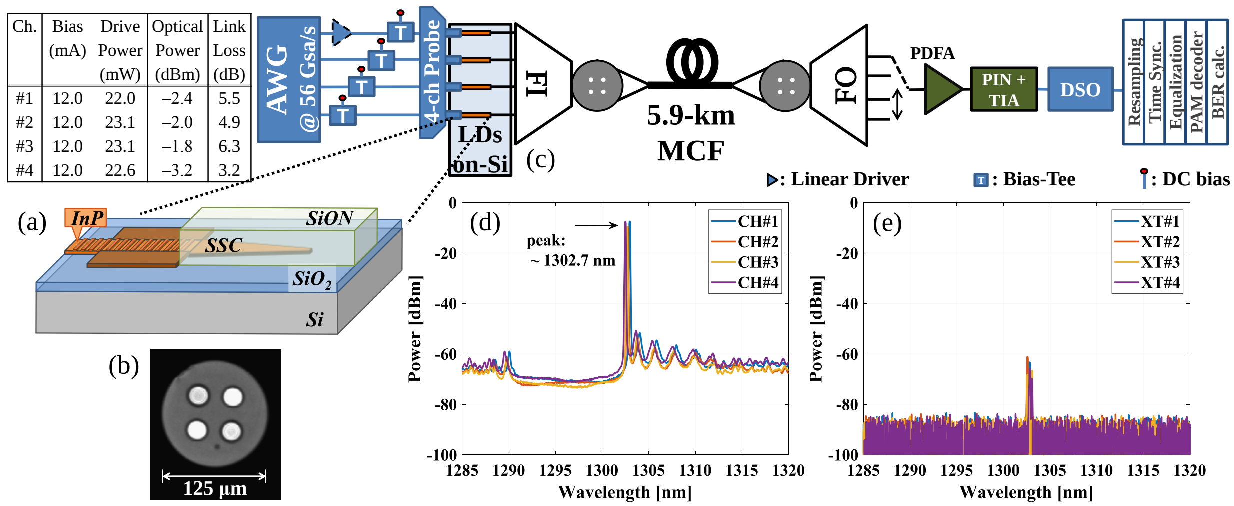
Many promising multi-channel DML-based transmitters for WDM/SDM have been demonstrated based on vertical-cavity surface-emitting lasers (VCSELs) due to their attractive low operating power and cost [2-5]. However, VCSEL design poses challenges regarding to single-mode operation at the 1.3-µm band, fine wavelength tunability, and device spacing for electrical crosstalk (XT). As an alternative, we have demonstrated single-mode DML-arrays-on-Si [6] for both WDM [7] and SDM [8] systems, with VCSEL-level power consumptions, and the ability to support >100-Gb/s at 1.3-µm [9]. Moreover, previous works on SDM for short-reach and DCI applications were based on a single modulator or transmitter [10-14], which doesn't take into account the impact of electrical XT arising from neighboring channels in a compact transceiver [15]. Considering the above, we recently demonstrated discrete multi-tone (DMT) transmission of pre forward-error correction (FEC) 4×100-Gb/s over 425-m multicore fiber (MCF) based on a four-channel DML-array-on-Si, by simultaneously driving and modulating all lasers [16].

In this study, we expand our previous work [16] and demonstrate 4×56-Gbaud SDM-PAM-4 transmission over uncoupled 5.9-km four-core MCF [17], with net rates of 364-Gb/s for hard-decision FEC (HD-FEC) [18] and up to 422-Gb/s for ideal soft-decision FEC (SD-FEC), by simultaneously directly-modulating four lasers from an 1.3-µm membrane III-V-on-Si laser array. A total of only 90.8 mW for driving all lasers (12 mA/laser) was required, which is ~6.6x less compared to conventional 1.3-µm DMLs [19]. Compared to [16], these results extend the reach by ~15x, increase the net rate, reduce the power consumption, and simplify the transceiver complexity.

2. DMLs-on-Si and 125-µm-Cladding MCF for SDM-based DCI

The structure of our 1.3-µm membrane III-V-on-Si lasers is depicted in Fig. 1(a), which consists of a distributed feedback (DFB) laser, a rear distributed Bragg reflector (DBR), and a spot-size converter (SSC). The four lasers used here were part of a laser array with 250-µm pitch for reduced electrical XT [6], and they all designed to have the same lasing wavelength and static/dynamic characteristics. The 80-µm long active region of the devices were based on a membrane InP buried hetero-structure (BH) and InGaAlAs multi-quantum wells that were epitaxially grown on an InP/SiO2/Si substrate. Such BH structure on SiO2 provides high carrier and optical confinement. That enables the lasers to be operated at a low bias (and threshold) current, and, hence, reduces their power consumption. We used a uniform DFB grating instead of a phase-shifted DFB grating in order to suppress the spatial-hole burning effect, which degrades the modulation characteristics. To support single-mode operation, one sideband of the uniform DFB was selected by the detuned DBR. Finally, a SiON spot-size converter (SSC) was also integrated at the lasing facet to enable low-loss and low-reflection coupling to high-numerical aperture (HNA) fibers.

The cross section of our 4-core MCF is shown in Fig. 1(b). The fiber was designed to have a 125-µm cladding diameter for compatibility with conventional SSMF cabling and connector technologies [15], as well as increased



Ch.	Bias (mA)	Drive Power (mW)	Optical Power (dBm)	Link Loss (dB)
#1	12.0	22.0	–2.4	5.5
#2	12.0	23.1	–2.0	4.9
#3	12.0	23.1	–1.8	6.3
#4	12.0	22.6	–3.2	3.2

Fig. 1: (a) Membrane DML-on-Si structure, (b) Cross-section of 125-µm cladding four-core MCF, (c) Experimental setup and parameters, (d) Lasing spectra, and (e) optical XT after fan-in.

mechanical reliability. The MCF had a homogeneous core structure with a trench-assisted profile and a core pitch of 40-µm, which resulted in sufficiently low XT of less than –24 dB/100km at all wavelength bands. The fan-in/out (FI/FO) devices were based on double-layer planar lightwave circuit (PLC) technology [20] and had a matching core pitch of 40-µm. The insertion loss of the FI/FO was ~1 dB at 1550 nm for each device.

3. Experimental demonstration

The experimental setup and the channel parameters are shown in Fig. 1(c). Four Gray-encoded 56-GBaud PAM-4 signals were generated at 56-GSa/s by a ~25-GHz bandwidth arbitrary waveform generator (AWG) without pre-equalization or pulse shaping. The PAM-4 signals were generated using different seeds for a random Mersenne twister bit generator. The lasers were driven at a stage-controlled room temperature of 25°C. All lasers were operated and modulated simultaneously using a 40-GHz four-channel probe with 250-µm pitch. For the channel under test (CUT), a linear driver with 22 dB was used to provide a modulation bias of ~0.9 $V_{p\text{-}p}$ from a 0.075-$V_{p\text{-}p}$ AWG output, for improved modulation linearity. Similarly, the remaining channels were modulated at 0.9 $V_{p\text{-}p}$ directly by the AWG. This configuration ensured that any existing electrical XT was included in the measurements. The lasers were butt-coupled to an array of four HNA fibers with 250-µm pitch, fusion-spliced to four standard single mode fiber (SSMF) pigtails. The output optical powers from the fiber array were –2 to –3 dBm at 12 mA, and all lasers were single-mode with lasing at ~1.302.7 µm as shown in Fig. 1(d). The 5.9-km MCF fiber was spliced to the pair of PLC-type FI/FO with a matching core pitch of 40-µm. At 1.3-µm the total link loss including the FI/FO was 3.2~6.3 dB depending on the channel, and the optical XT was below –60 dBm for all channels (Fig. 1(e)). At the receiver, the received optical power (ROP) was controlled by a Pr-doped fiber amplifier (PDFA) and a variable optical attenuator (VOA), and the signals were detected by a commercial 30-GHz p-i-n photodiode (PIN) integrated with a trans-impedance amplifier (TIA). The signals were finally stored at 160 GSa/s by a real-time digital storage oscilloscope (DSO) and were processed offline. At the receiver's digital signal processing (DSP), the signals were first down-sampled to 56 GSa/s and time synchronization was performed. The signals were then equalized by a decision-directed T/2 least-mean squares nonlinear equalizer (NLE) based on a third-order polynomial filter with linear and nonlinear memories of 61- and 21-input taps, respectively; which included overall only five cross-beating Volterra terms [21]. The down-sampling to 1 samples/symbol was performed inside the NLE. Following the NLE, a 90-tap decision-feedback equalizer was used. Finally, the bit-error rate (BER) was estimated by error counting.

The BER results after single-channel back-to-back (BTB) and simultaneous-four-channel 5.9-km MCF transmissions are shown in Fig. 2(a). Similar BERs were achieved for all channels after the 5.9-km link, with an optimum $ROP_{opt} \approx 1$ dBm and BERs below a 23.1% HD-FEC threshold [18]. Also the aggregate normalized generalized mutual information (NGMI) [22] after 5.9-km transmission at ROP_{opt} was 0.9425, which corresponds to a net rate of up to ~422 Gb/s with ideal binary SD-FEC. Note that the power consumption of SD-FEC could be justified considering that our DMLs with DD are much more energy efficient than e.g., coherent detection. In the BTB case the BERs were below the 7% overhead HD-FEC threshold [23]. Fig. 2(b) summarizes the BER at ROP = 0 dBm for single- and multi-channel operation at BTB and MCF transmissions. It can be seen that the optical XT

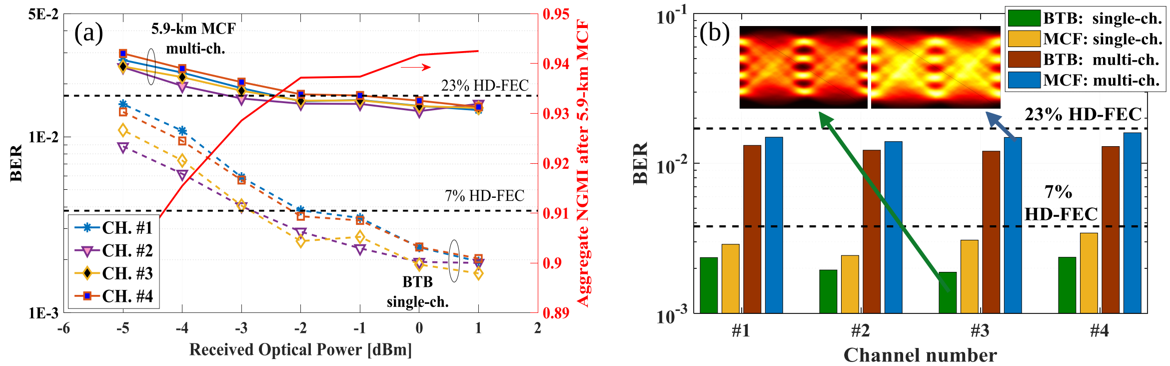


Fig. 2: (a) BER vs. ROP results, (b) dependency of BER on channel operation at ROP = 0 dBm; inset: equalized eye diagrams for channel #3 after single-channel BTB (left) and multi-channel 5.9-km MCF (right) transmissions.

has only a minor impact on the performance, owing to the low-XT MCF and FI/FO. In contrast, the BER degradation for the multi-channel operation compared to the single-channel case for both BTB and MCF cases, suggests a dependency on the electrical XT that needs to be considered carefully. In our setup we further confirmed that the main source of the electrical XT was the multi-channel probe rather than the laser array chip itself. Hence, we believe that careful packaging and assembly will improve the electrical XT and BERs further. In addition, increasing the output power of the DMLs is also important to avoid using the PDFA. This could be achieved by increasing the lasers' active region and by improving their injection efficiency.

4. Conclusions

We have demonstrated net 364-Gb/s (HD-FEC) and up to 422-Gb/s (ideal SD-FEC) 4-channel SDM-PAM-4 transmission over 5.9-km four-core fiber, by using a membrane III-V-on-silicon DML array and simultaneously operating four lasers with less than 25-mWatt/laser. Compared to previous works, these results extend the reach by ~15x and increase the net data rate, while simplifying the transceiver complexity.

5. References

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