Net 113-Gbps PAM-4 Transmission Using Membrane DML-on-Si with 0.34 pJ/bit at 50 °C

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Abstract *A membrane-III-V-on-Si laser with a ~47.5-GHz bandwidth is demonstrated by achieving stable photon-photon resonance. Direct modulation of 60-GBaud PAM-4 under KP4-FEC (net 113.42 Gbps) over 2-km SSMF with 0.17 pJ/bit at 25 °C and 0.34 pJ/bit at 50 °C have been achieved.*

Introduction

The unprecedented rise of video content in recent years has resulted in surging traffics in datacenters and short-reach links that require transceivers capable of supporting net rates in excess of 100 Gbps/λ[1]. In addition, the stringent requirements on cost and power consumption in these applications have placed directly-modulated lasers (DMLs) as a leading candidate solution[2]. However, for similar power and cost considerations, semi-cool and un-cool operations are highly desirable.

Recently, one key solution for extending the 3-dB bandwidth of DMLs without requiring extra power consumption (i.e., bias current) was the introduction of photon-photon resonance (PPR) effects[3] that alleviate the limitations of the carrier-photon dynamics. Based on such PPR enhancements, InP lasers with >67-GHz bandwidths have been demonstrated[4],[5], with a record DML bandwidth of ~108 GHz achieved by a membrane-III-V-on-SiC laser[5]. Based on these DMLs, net rates of >300 Gbps (gross rates of >400 Gbps) have been achieved[6],[7]. Also, III-V-on-Si lasers with up to 34 GHz have been reported[8]. However, all of the above were performed at room temperatures, while the bias currents and operating powers were several times larger than short-cavity lasers such as VCSELs.

In this work, we rely on our membrane-III-V-on-Si laser technology which can achieve high intrinsic bandwidths at low bias currents due to a high optical confinement factor, while utilizing large Si wafers for cost reduction[9]. By introducing a stable PPR design on a distributed reflector (DR) laser, we expand the 3-dB bandwidth to ~47.5 GHz compared to our previous works on membrane-III-V-on-Si laser. These results denote a ~2x bandwidth improvement for similar bias currents[10]. Further, we demonstrate 60-GBaud PAM-4 (net rate of ~113 Gbps) after 2-km of standard single-mode fiber (SSMF) with 0.17 pJ/bit at 25 °C and 0.34 pJ/bit at 50 °C. Compared to InP DMLs with a similar performance[11], these results denote a higher operating temperature as well as ~3.9x bias current reduction at room temperatures.

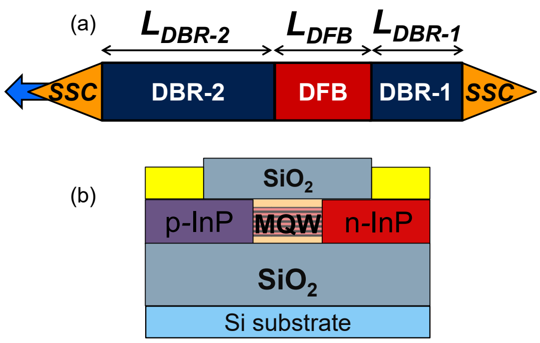


Fig. 1: Laser structure (a) longitudinal (b) cross-section.

Membrane DML-on-Si with PPR

The intrinsic bandwidth of DMLs is determined by carrier-photon dynamics as expressed by the relaxation oscillation frequency (f_R). However, f_R is proportional to the square-root of the bias current (I_b) above threshold, i.e., $f_R \propto \sqrt{I_b - I_{th}}$, where I_{th} denotes the threshold current[5]. This relationship signifies a fundamental tradeoff between intrinsic bandwidth and power consumption, since the latter increases with I_b. One way to bypass this tradeoff and expand the 3-dB bandwidth while keeping the power consumption and bias current low, is to introduce photon-photon dynamics, i.e., PPR, via an appropriate cavity design[3].

Recently, two popular PPR-enabling DML designs have emerged; one relying on a passive feedback waveguide[4],[5] and another relying on a distributed Bragg reflector (DBR) mirror[3],[11]. In this work we focus on the latter by integrating a PPR-enabling DBR mirror to our traditional membrane-III-V-on-Si distributed reflector (DR) laser[9],[10].

The laser structure is depicted in Fig. 1. Similar to our previous DR design[9],[10], we

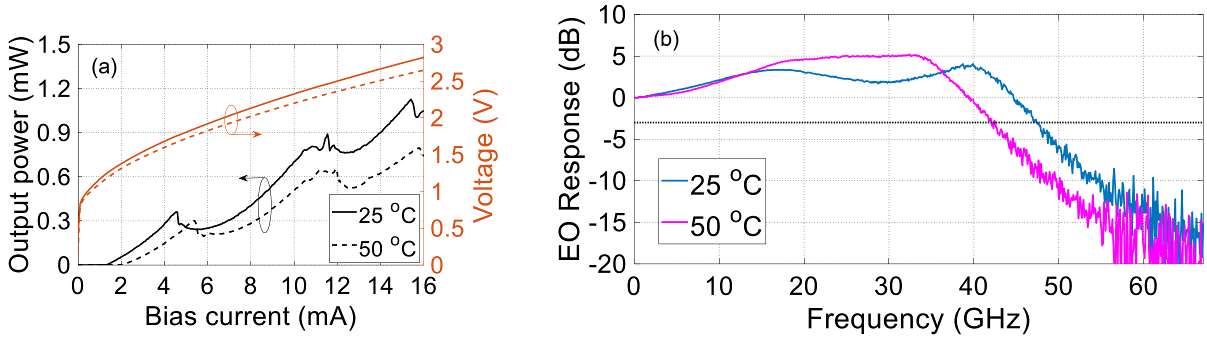


Fig. 2: Laser characteristics: (a) L-I-V and (b) EO response at 25 °C (I_b = 9.1 mA) and 50 °C (I_b = 15.1 mA).

achieve single mode operation by filtering one of the two main longitudinal modes of a non-shifted distributed feedback (DFB) transmittance via a detuned DBR mirror ("DBR-1" in Fig. 1(a)). In addition, a second DBR mirror ("DBR-2" in Fig. 1(a)) is introduced for the PPR generation, by ensuring that the dominant DFB mode coincides with the longer-wavelength slope of the reflectivity spectrum of DBR-2. This longitudinal configuration also enhances the f_R due to the detuned loading effect[11]. For minimizing external reflections and ensuring low-loss coupling to high-numerical aperture (HNA) fibers, two SiO_x spot-size converters (SSCs) are integrated on both sides of the laser[10].

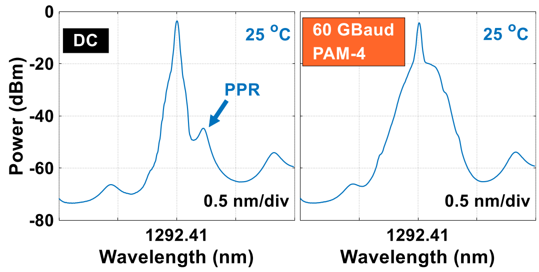
In this work, the grating coupling coefficient was $\kappa = 400\ \mathrm{cm}^{-1}$ for all sections, and the lengths of the DFB, DBR-1, and DBR-2 sections were $L_{DFB} = 100\ \mu\mathrm{m}$, $L_{DBR-1} = 80\ \mu\mathrm{m}$, and $L_{DBR-2} = 200\ \mu\mathrm{m}$, respectively.

The cross-section schematic of our laser is shown in Fig. 1(b). The fabrication procedure was based on our established membrane-III-V-on-Si processes described, e.g., in [10]. 6-period InGaAlAs multiple-quantum wells (MQWs) were used in the fabricated device and the total III-V thickness was ~300 nm. This membrane structure results in a high optical confinement factor, which ensures a high f_R at low bias currents[10]. Surface grating was employed on the III-V layer[9],[10] and InP wire waveguides were employed for the DBR sections.

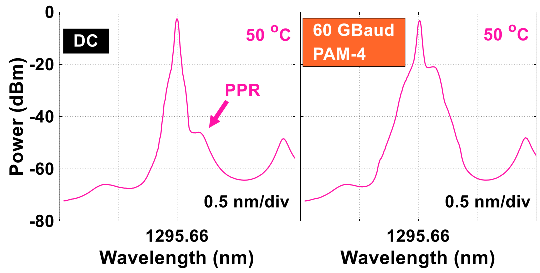
The fiber-coupled L-I-V characteristics of the device are shown in Fig. 2(a) for stage-controlled temperatures of 25 °C and 50 °C. In both cases we could observe three bias current regions with super-linear L-I curves, a common feature of DBR-based lasers enacting detuned loading and PPR effects[11]. This behavior can be explained by an increase in mirror losses when the bias current increases, since the lasing mode follows the DBR-2 reflectivity slope due to a thermal wavelength shift. In-between the super-linear regions mode-hopping was observed, which resulted from the lasing mode to follow additional side-lobes of DBR-2's reflectivity spectrum. A stable side-mode placed 30~40 GHz apart from the lasing mode was observed between $2\ \mathrm{mA} \leq I_b \leq 15\ \mathrm{mA}$ at both 25 °C and 50 °C (see, e.g., Fig. 3), except for the unstable mode-hopping regions. This translated to PPR-enhancements in the electro-optic (EO) response, as shown in Fig. 2(b). In particular, the 3-dB bandwidth at 25 °C (with $I_b = 9.1\ \mathrm{mA}$) and at 50 °C (with $I_b = 15.1\ \mathrm{mA}$) were ~47.5 GHz and ~42.5 GHz, respectively. These results denote a ~2x bandwidth improvement at room temperatures compared to our previous works for similar bias currents[10]. Also, at these bias currents and temperatures the lasing wavelength was 1292.41 nm and 1295.66 nm, respectively, as shown in Fig 3. The side-mode suppression ratio remained > 40 dB in all measurements.

Experimental evaluation: 60-GBaud PAM-4

In order to evaluate our DML for short-reach



(a) At 25 °C and I_b = 9.1 mA.



(b) At 50 °C and I_b = 15.1 mA.

Fig. 3: Optical spectra at DC (left) and with 60-GBaud PAM-4 (right).

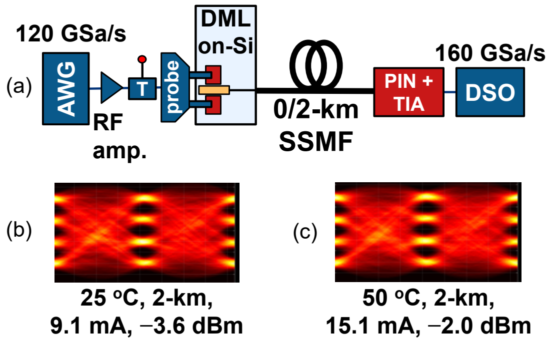


Fig. 4: (a) Experimental setup and equalized eye diagrams after 2-km SSMF at (b) 25 °C and (c) 50 °C.

applications, we performed bit-error rate (BER) measurements of 60-GBaud 4-levels pulse-amplitude modulation (PAM-4) signals over 2-km of SSMF. The experimental setup used is shown in Fig. 4(a). An arbitrary waveform generator (AWG) was used to generate the PAM-4 signal at 75 mV_{p-p} with a sampling rate of 120 GSa/s, shaped by a root-raised cosine (RRC) filter with a roll-off factor of 0.22. The RF signal was then amplified by a 22-dB-gain RF amplifier. The output of the DML was butt-coupled to an HNA fiber, spliced together with a SSMF pigtail. After the 2-km transmission, the optical signal was detected by a commercial ~32-GHz *p*-i-*n* photodetector (PIN), integrated with a trans-

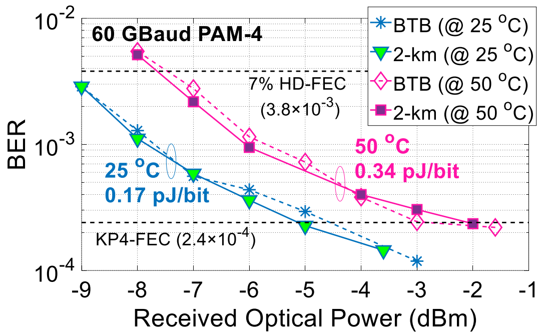


Fig. 5: BER vs. ROP results.

impedance amplifier (TIA). Note that, no optical amplifier was used in our measurements. The signals were then stored by a digital sampling oscilloscope (DSO) at 160 GSa/s and processed offline by a similar 0.22 roll-off matched RRC filter and a low-complexity nonlinear equalizer[12] with 71 linear taps and 51 nonlinear taps, taking account only 10 second-order self-beating terms. The equalized eye diagrams after 2-km SSMF transmission at 25 °C and 50 °C, are shown in Fig. 4(b) and Fig. 4(c), respectively.

The BER versus received optical power (ROP) results at back-to-back (BTB), i.e. 0-km, and after 2-km transmissions at 25 °C and 50 °C are summarized in Fig. 5. The measurements were performed by using a variable optical attenuator prior to the PIN+TIA (not shown in Fig. 4(a)). In all cases, the 400G Ethernet's standard KP4 forward error correction (FEC) threshold[13] was reached, denoting a net rate of ~113.42 Gbps (gross rate: 120 Gbps, FEC overhead: 5.8%). Based on these net rates, the energy/bit can be estimated as 0.17 pJ/bit (= 9.1 mA × 2.15 V / 113.42 Gbps) for the 25 °C case, and 0.34 pJ/bit (= 15.1 mA × 2.56 V / 113.42 Gbps) for the 50 °C case. In comparison to InP DMLs with a similar bandwidth and PAM-4 performance[11], these results denote a higher temperature operation as well as ~3.9x bias current reduction at room temperatures. Also, as a reference, the 7% overhead hard-decision FEC (HD-FEC) threshold[14] is depicted in Fig. 5, which can be achieved with an excess power margin of ~6 dB.

Conclusions

By introducing a DBR-based PPR-design on our membrane-III-V-on-Si DR laser, we have demonstrated a DML with up to ~47.5-GHz bandwidth with a stable PPR-enabling side-mode over a bias current range of up to 15 mA. Based on it, we have achieved direct modulation of 60-GBaud PAM-4 under KP4-FEC (net 113.42 Gbps) over 2-km SSMF with 0.17 pJ/bit at 25 °C and 0.34 pJ/bit at 50 °C.

References

[1] Ethernet Alliance, "2020 Ethernet Roadmap", https://ethernetalliance.org/technology/2020-roadmap/, accessed 24-Aug-2020.

[2] S. Matsuo and T. Kakitsuka, "Low-operating-energy directly modulated lasers for short-distance optical interconnects", *Adv. Opt. Photonics*, vol. 10, no. 3, pp. 567-643, 2018.

[3] G. Morthier *et al.*, "Extended Modulation Bandwidth of DBR and External Cavity Lasers by Utilizing a Cavity Resonance for Equalization", *IEEE J. Quantum Electron.*, vol. 36, no. 12, pp. 1468-1475, 2000.

[4] Y. Matsui *et al.*, "Isolator-free > 67-GHz bandwidth DFB+R laser with suppressed chirp", in *Proc. OFC'20*, San Diego, CA, USA, paper Th4A.1.

[5] S. Yamaoka *et al.*, "239.3-Gbit/s Net Rate PAM-4 Transmission Using Directly Modulated Membrane Lasers on High-Thermal-Conductivity SiC", in *Proc. ECOC'19*, Dublin, Ireland, paper PD.2.1.

[6] Di Che *et al.*, "400-Gb/s direct modulation using a DFB+R laser", *Opt. Lett.*, vol. 45, no. 12, pp. 3337-3339, 2020.

[7] N.-P. Diamantopoulos *et al.*, "Net 321.24-Gb/s IMDD Transmission Based on a >100-GHz Bandwidth Directly-Modulated Laser", in *Proc. OFC'20*, San Diego, CA, USA, paper Th4C.1.

[8] A. Abbasi *et al.*, "Direct and Electroabsorption Modulation of a III–V-on-Silicon DFB Laser at 56 Gb/s", *IEEE J. Sel. Topics Quantum Electron.*, vol. 23, no. 6, p. 1501307, 2017.

[9] T. Fujii *et al.*, “Multiwavelength membrane laser array using selective area growth on directly bonded InP on SiO_2/Si”, *Optica*, vol. 7, no. 7, pp. 838-846, 2020.

[10] H. Nishi *et al.*, “Membrane distributed-reflector laser integrated with SiOx-based spot-size converter on Si substrate”, *Opt. Express*, vol. 24, no. 16, pp. 18346-18352, 2016.

[11] Y. Matsui *et al.*, “55 GHz bandwidth Distributed Reflector Laser”, *J. Lightw. Technol.*, vol. 35, no. 3, pp. 397-403, 2017.

[12] N.-P. Diamantopoulos *et al.*, “On the Complexity Reduction of the Second-Order Volterra Nonlinear Equalizer for IM/DD Systems”, *J. Lightw. Technol.*, vol. 37, no. 4, pp. 1214-1224, 2019.

[13] IEEE Standard 802.3bs: “IEEE Standard for Ethernet - Amendment 10: Media Access Control Parameters, Physical Layers, and Management, Parameters for 200 Gb/s and 400 Gb/s Operation”, 2017.

[14] ITU-T Recommendation G.975.1: “Forward error correction for high bit-rate DWDM submarine systems”, 2004.