2-channel 112-Gbps NRZ Short-Reach Transmission Based on 60-GHz-Bandwidth Directly-Modulated Membrane Laser Array on Si

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Abstract *Directly-modulated membrane lasers on SiO_2/Si with ~60-GHz bandwidths are fabricated using an optimized longitudinal design for photon-photon resonance. A fabricated two-channel array exhibits 2×112 Gbps NRZ modulation over 2-km transmissions, consuming <0.3 pJ/bit operating energy.*

Introduction

Increasing demands for higher throughputs in cloud-related applications have pushed recent data centre and high-performance computing standardizations to rely on data rates of 200- and 400-Gbps, with near-future targets beyond 1 Tbps using >100 Gbps-per-lane[1]. Meanwhile, power consumption has increasingly become a serious issue in these systems due to operational costs and environmental considerations.

In regards to the transmitter, the most power-efficient solution relies on energy-efficient directly-modulated lasers (DMLs)[2]. Even though an inherent trade-off between bandwidth and power consumption exists in conventional DMLs[3], recent longitudinal designs have managed to overcome this limitation by introducing the photon-photon resonance (PPR) effect[3-5]. Based on it, DMLs capable of supporting more than 400 Gbps have been demonstrated by using advanced digital signal processing (DSP) and modulation methods[6,7].

Recently, we have demonstrated the PPR effect in our high-optical-confinement low-power-consumption membrane-III-V-on-Si DMLs by adding a distributed Bragg reflector (DBR) to our previous distributed reflector (DR) membrane laser structure (Figs. 1(a) and 1(b))[2,3,8]. This allowed us to extend the DML bandwidth from ~20 GHz to ~47.5 GHz while keeping the same power consumption, and to demonstrate 120-Gbps PAM-4 using low-complexity nonlinear equalization[3,9]. Relying, however, on a high-order modulation format like PAM-4 increases the overall system power consumption due to the requirements for linear drivers/amplifiers and/or nonlinear DSP[9]. For a more energy-efficient system, therefore, simple non-return-to-zero (NRZ) modulation with a high symbol rate using high-bandwidth DMLs is preferable. Moreover, even though we have also demonstrated >100-Gbps NRZ with our >100-GHz-bandwidth membrane DMLs on SiC substrate previously[4], achieving wider 3-dB bandwidths and data rates on DMLs fabricated on Si substrates is of high scientific and industrial interest.

In this work we optimize our PPR design and demonstrate membrane DMLs-on-Si with 3-dB bandwidths of ~60 GHz (i.e., ~26.3 % increase compared to [3]). This allowed us to achieve 200 Gbps transmission over 2 km of standard

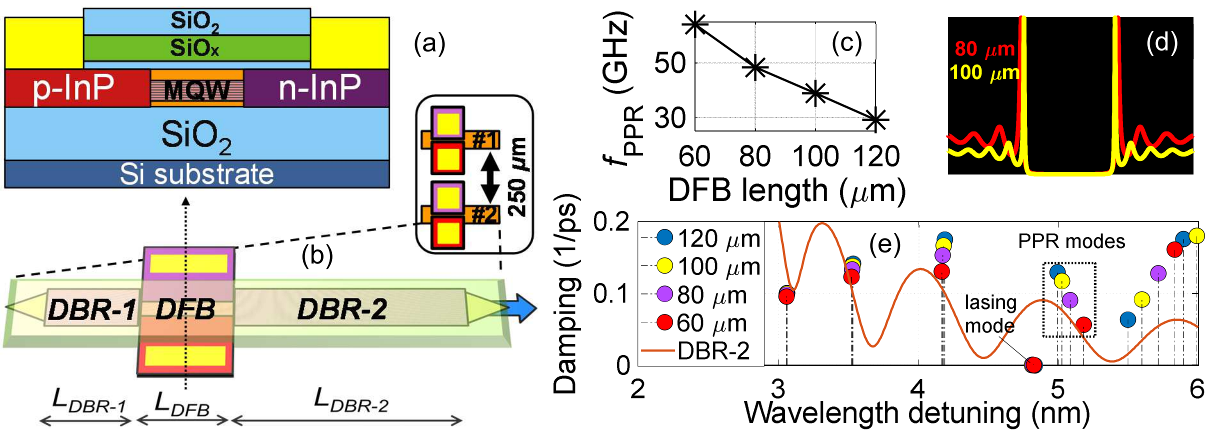

Fig. 1: (a) Cross section of membrane DFB. (b) Longitudinal structure. (c) f_{PPR} vs. DFB length. (d) DFB transmittance for lengths of 80 μm (red) and 100 μm (yellow). (e) Modal analysis for different DFB length. Here the x-axis defines the wavelength detuning in respect to the Bragg wavelength of DBR-2, with L_{DBR-2} = 200 μm.

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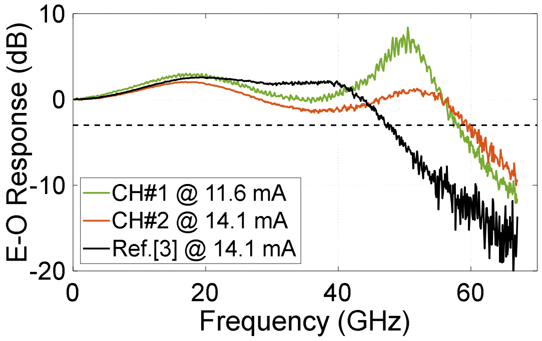

Fig. 2: E-O response.

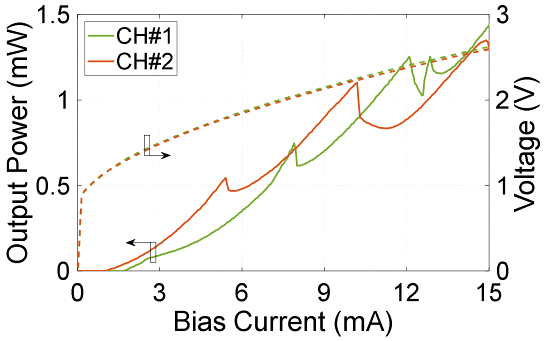

Fig. 3: L-I-V.

single-mode fibre (SSMF) by using 2 × 112-Gbps NRZ signals, generated by a two-channel O-band DML array with <0.3 pJ/bit operating energy.

PPR Optimization

Our membrane laser on SiO_2/Si structure (Fig. 1(a)) is based on a buried heterostructure with an InP lateral p-n junction, with a total III-V thickness of less than 350 nm[2,10]. This structure ensures both high optical and carrier confinement. For operation in the O-band we use a 600-nm wide multiple-quantum well (MQW) core based on InGaAlAs compounds. Edge coupling to high-numerical aperture fibres is performed via a 3 × 3 μm² SiO_x core, by integrating a spot-size converter based on an InP taper. Single-mode operation is ensured by utilizing a distributed-feedback (DFB) section with uniform grating and a detuned 1.5-μm wide InP DBR section (DBR-1), which filters out one of the two main longitudinal DFB modes (Fig. 1(b)). This structure reduces the impact of hole-burning effects compared to λ/4-shifted DFB lasers. For enabling the PPR effect, a second InP DBR section (DBR-2) is also integrated, which is designed to have a Bragg wavelength similar to that of the DFB section. In our previous design[3], the lengths of the DFB, DBR-1, and DBR-2 sections were 100, 80, and 200 μm, respectively. The coupling coefficients were ~525 cm^{-1} for the DFB section and ~400 cm^{-1} for the DBR sections, based on surface gratings on InP.

Our previous design could achieve a relaxation oscillation frequency (f_R) of more than 15 GHz and a PPR frequency (f_{PPR}) of ~40 GHz, resulting in a total E-O response with 47.5 GHz bandwidth (Fig. 2). One key aspect of maximizing the E-O response bandwidth in PPR lasers is to optimize the f_{PPR}-f_R separation. A very large f_{PPR}-f_R separation results in a dip in the E-O response and, hence, either on a 3-dB bandwidth determined only by f_R or on a "bumpy" (i.e. non-flat) response which is undesirable for single-carrier modulations like NRZ and PAM. On the other hand, a small f_{PPR}-f_R separation, even though it ensures response flatness, could hinder the full potential of the PPR effect on enhancing the 3-dB bandwidth.

In this work, by increasing f_{PPR}, we have optimized the f_{PPR}-f_R separation compared to [3] and designed it to be ~30 GHz. Since f_{PPR} is given by the wavelength separation between the main longitudinal lasing mode and the nearest side-mode[3], this can be achieved by decreasing the κL coefficient of the DFB section, which will increase the separation between modes and side-lobes as shown by the DFB transmittances in Fig. 1(d). The designed f_{PPR} values for different DFB lengths are shown in Fig. 1(c). As it can be seen by Fig. 1(c) and the modal analysis for our laser structure in Fig. 1(e), $\Delta f_{PPR} \approx 10$ GHz (i.e., $f_{PPR} \approx 50$ GHz) can be achieved by keeping the same coupling coefficient and reducing the DFB length by 20 μm, from 100 μm to 80 μm. Also, as it can be seen from the E-O response of the fabricated devices shown in Fig. 2, the DMLs' 3-dB bandwidth could be extended to ~60 GHz from the previous ~47.5 GHz[3] for the same bias current (see CH#2). A small deviation in the Bragg wavelength of CH#1 due to fabrication resulted in a lower bias current for a similar ~60 GHz bandwidth. Note that, a further reduction of the DFB length would have increased the dip between f_R and f_{PPR}, which would hinder the flatness and 3-dB bandwidth of the E-O response.

The L-I-V curves for both CH#1 and CH#2 are shown in Fig.3. Typical super-linear behavior of DBR-based PPR with mode-hoppings[3] can be observed for both devices. The fibre-coupled output power of both devices were between

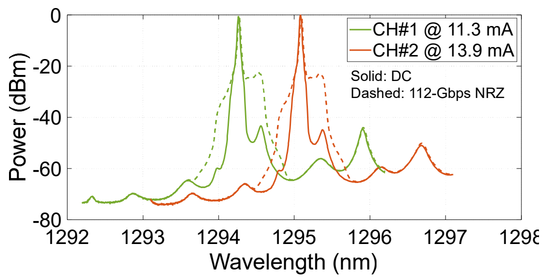

Fig. 4: Optical spectra.

0 to 1 dBm, with lasing wavelengths around 1294.3 nm for CH#1 and 1295.1 nm for CH#2 (solid lines in Fig. 4). The laser pitch between the two lasers was 250 *μ*m to avoid crosstalk.

Experimental evaluation: 2-ch. 112-Gbps NRZ

The 112-Gbps NRZ signals were generated by an arbitrary waveform generator (AWG) with 60 GHz analogue bandwidth (Keysight M8194A) at 120 $mV_{p\text{-}p}$ for CH#1 and at 140 $mV_{p\text{-}p}$ for CH#2 and by using a root-raised cosine filter with 10% roll-off. The signals were subsequently amplified by a 22-dB-gain RF driver. An RF probe was used to drive the DML array, which was stage-temperature-controlled at 25 °C. An 11-tap pre-emphasis filter was used at the AWG in order to mitigate RF impairments (e.g. due to RF probe, RF cables, etc.). CH#1 was driven at a bias current and voltage of 11.3 mA and 2.347 V and CH#2 was driven at 13.9 mA and 2.517 V. Therefore, the resulting operating energies were ~26.5 mW for CH#1 and ~35.0 mW for CH#2. The optical spectra at these conditions with and without the 112-Gbps NRZ signals are shown in Fig. 4. As it can be seen, the resulting modulated spectra are clearly enhanced by the PPR effect.

The signals were measured either in an optical back-to-back (BTB) setup or after 2-km transmission over SSMF, without using any optical amplifiers. For photo-detection, an in-house uni-travelling-carrier photodetector was used with responsivity of ~0.23 A/W and a 3-dB bandwidth of >67 GHz. A commercial 18-dB-gain RF amplifier was placed after the UTC-PD for signal amplification due to the lack of a trans-impedance amplifier. Finally the bit-error rates (BERs) were evaluated by using a real-time oscilloscope at 160 GSa/s and a 5-tap offline decision-feedback equalizer.

The BER results versus received optical power (ROP) and the obtained eye diagrams are shown in Fig. 5 and Fig. 6, respectively. For all 112-Gbps NRZ transmissions, the standardized 200/400GbE KP4 forward-error correction (KP4-FEC)[11] threshold has been reached. Taking into consideration the operating energies discussed above, the 112-Gbps NRZ signals have been achieved with 0.24 pJ/bit for CH#1 and 0.31 pJ/bit for CH#2. By taking into consideration 5.8% overhead for KP4-FEC[11] (net rate of 211.72 Gbps), the energy-per-bit cost for the 200 Gbps DML array is (0.24 + 0.31) mW / 211.72 Gbps ≈ 0.29 pJ/bit.

As a comparison, the BER at BTB for CH#2 and the resulting eye-diagram for 100 GBaud PAM-4 (i.e., 200 Gbps) are shown in Fig. 5. Here nonlinear equalization similar to the one used in [3] was applied and the bias current was 14.1 mA.

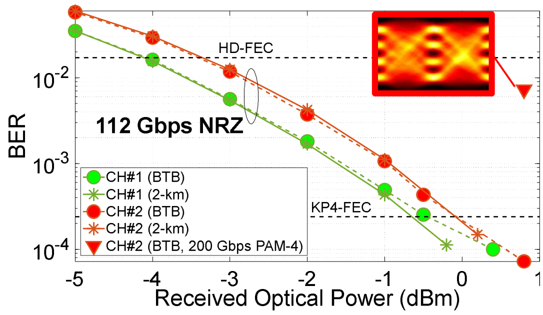

Fig. 5: BER vs. ROP.
Inset: Eye diagram for CH#2 at 200 Gbps PAM-4.

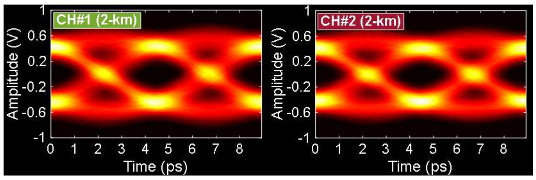

Fig.6: 112 Gbps NRZ eye diagrams for CH#1 (left) and CH#2 (right) after 2-km SSMF transmissions. ROPs are − 0.2 dBm and + 0.2 dBm, respectively.

In that case, the achieved BER was ~7.3E-3 which is higher than the KP4-FEC threshold, but can be reached with higher-overhead hard-decision FEC (HD-FEC)[12] at the expense of higher power consumption and latency.

Conclusions

We have demonstrated a 2-channel DML-array with ~60-GHz 3-dB bandwidth based energy-efficient membrane-III-V-on-Si lasers exhibiting the PPR effect. Based on it, a 200-Gbps short-reach transmitter has been demonstrated using 112-Gbps NRZ signals with a DML operating energy-per-bit of 0.29 pJ/bit.

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