Demonstration of a $17 \times 25$ Gb/s Heterogeneous III-V/Si DWDM Transmitter Based on (De-)Interleaved Quantum Dot Optical Frequency Combs

Stanley Cheung, Member, IEEE, Yuan Yuan, Member, IEEE, Yiwei Peng, Geza Kurczveil, Member, IEEE, Sudharsanan Srinivasan, Member, IEEE, Yingtao Hu, Antoine Descos, Di Liang, Senior Member, IEEE, and Raymond G. Beausoleil, Senior Member, IEEE

Abstract—We discuss the design and demonstration of a space and dense wavelength division multiplexed heterogeneous III-V/Si transmitter based on a single multi-wavelength quantum dot laser source and ultra-power-efficient metal-oxide-semiconductor capacitor (MOSCAP) (de-)interleaver. This paper begins by introducing a transceiver architecture capable of $> 1$ Tb/s transmission with $< 1.5$ pJ/bit power consumption, followed by a detailed discussion of the heterogeneous laser source and (de-)interleaver. The O-band quantum dot laser, based on a compound cavity design, has a FSR $\sim 64$ GHz with a $1\sigma$ variation of $\sim 1.08$ GHz and a measured relative intensity noise (RIN) of $\sim -144$ dB/Hz for the largest comb peak. The single-ring-assisted asymmetric Mach-Zehnder interferometer (1-RAMZI) MOSCAP (de-)interleaver exhibit cross-talk (XT) levels down to $-27$ dB for tuning powers of 10.0 nW. Finally, to the best of our knowledge, we have demonstrated for the first time, a simultaneous wavelength and space division multiplexed transmitter fabricated on a heterogeneous III-V-on-silicon platform. Experiments show (de-)interleaved 17 optical comb lines, each modulated at 25 Gb/s non-return-to-zero (NRZ) for an aggregate bandwidth of 425 Gb/s.

Index Terms—Hybrid integrated circuits, integrated optics, photonic integrated circuits, quantum dot lasers, silicon photonics, wavelength division multiplexing.

I. INTRODUCTION

THERE continues to be an increased demand for high bandwidth density optical interconnects for growing mega data centers, long-haul telecommunications, and peta/exa-scale high-performance computing. A study by Cisco suggests 66% of the global population will have internet access by 2023 and the number of devices connected to IP networks will be $3 \times$ the total population [1]. In addition, machine-to-machine (M2M) connections will grow by 50% with the arrival of edge computing, machine learning, artificial intelligence, etc. [1]–[3].

Manuscript received 4 March 2022; revised 10 June 2022 and 2 August 2022; accepted 3 August 2022. Date of publication 8 August 2022; date of current version 3 October 2022. This work was supported by the Advanced Research Projects Agency-Energy (ARPA-E) under Grant DE-AR0001039. (Corresponding author: Stanley Cheung.)

The authors are with the Hewlett Packard Enterprise, Milpitas, CA 95035 USA (e-mail: stanley.cheung@hpe.com; yuan.yuan@hpe.com; yiwei.peng@hpe.com; geza.kurczveil@hpe.com; sudharsanan@ee.itmm.ac.in; yingtao.hu@hpe.com; antoine.descos@hpe.com; di.liang@ieee.org; ray.beausoleil@hpe.com). Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2022.3196914.

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On-chip wavelength (de-)interleavers solve this problem by spatially dividing even and odd numbered OFC frequencies onto separate waveguides [16], [27], [28]. For our architecture, each waveguide will have a half number (10) of the total MRR count (20), but with the channel spacing doubled. By cascading more low-loss (de-)interleavers in series, more spatial channels and wider channel spacing is possible, allowing to use a comb source with tens or hundreds of comb lines but with smaller channel spacing [8]. For demonstration purpose, the channel spacing is chosen to be 65 GHz due to moderate power penalty for 10 Gb/s transmission in DWDM applications [29]. It has also been shown that optimal energy-cost [fJ/bit] lies in low data rate per channel where serializer-deserializer (SERDES) power consumption is lower [30], [31]. In this paper, we demonstrate preliminary link performance based on discrete components (QD OFC + (de-)interleaver) and then modulating each (de-)interleaved comb line. The QD OFC [6], [9]–[14] and MOSCAP (de-)interleaver [15], [16] are constructed on the same platform and can be seamlessly integrated in the future along with energy efficient MOSCAP MRRs [8], [17]–[19]. The paper will first discuss individual component design and performance of the heterogeneous OFC laser source and MOSCAP (de-)interleaver followed by an experimental demonstration linking these two together.

II. INDIVIDUAL COMPONENTS

A. QD Optical Frequency Comb (OFC) Source

On this platform, heterogeneous QD comb lasers are used because homogeneous broadening and low partition noise of QDs offer a broad gain profile and quiet wavelength stream, thus a large number of comb lines can be realized. In addition, QD-based lasers work very efficiently at the elevated temperatures of a typical HPC system [14]. The comb laser used here is based on a coupled cavity defined by L1 (2.6 mm) and L2 (650 μm) as illustrated in Fig. 2(a) and has a center comb wavelength of ~1324 nm. L1 includes a 1.2 mm long SOA section, passive silicon waveguides, and two MMI based loop mirrors designed for a reflectivity of 50%. A 180 μm long saturable absorber (SA) is centered within the SOA region. The external cavity (L2) is defined between the GC and the MMI loop mirror. The FSR of the comb laser is defined by Δλ = (FSR1 × FSR2) / (FSR1 – FSR2) where the subscripts denote cavities L1 and L2. L2 was designed such that FSR2 = 4-FSR1 of cavity L1. This allows us to use a relatively long cavity (thus increasing laser output power when compared to a shorter cavity) while maintaining a relatively large comb channel spacing. A less ideal comb operation whose lasing spectra from the right-sided GC (Fig. 2(b)) was chosen to study the impact of stronger and weaker comb lines to transmitter signal integrity. The measured mean channel spacing of Δλ is 63.93 GHz under a current bias of I_bias = 270 mA and SA bias of V_bias = −5.6 V. The laser testing stage temperature is set to T = 24.6 °C. Fig. 2(c) shows the measured comb channel separation and associated power levels of each comb after measuring through a circulator and 1% directional coupler tap. The shaded green areas indicate the 17 comb lines that will be fed into the (de-)interleaver in the experimental part of Section III.

12 of the 17 combs exhibit relative 3 dB power variation. If we take into account measured grating coupler (GC) loss of ~10 dB, circulator loss of 1dB and a 1% power tap (20 dB) for optical spectrum analyzer (OSA) measurements, the OFC is capable of a 17-wavelength stream (34 channels in total), where 12 out of the 17 combs should have ~7 dBm/line within the output waveguide. We can further improve channel power by minimizing optical waveguide loss, improving loop mirror reflectivity (currently ~50% by design), and integrating SOAs. Recently, we have developed integrated straight Sections III–V/Si QD SOAs capable of 18, 15, and 12 dB small signal gain at 1300 nm for operating temperature of T = 20, 50, and 80 °C. No optical power penalty was observed for a modulated signal or comb laser [24]. The comb line with the largest power (1322.02 nm) had a measured RIN of ~144 dB/Hz. The adjacent combs at 1321.65 and 1322.39 nm had a measured RIN of ~135.1 and ~138.9 dB/Hz respectively. We have also demonstrated error free operation of the comb lines with a FEC-free bit-error-rate (BER) of 10⁻¹² for 5 measured comb lines [14].

The temperature sensitivity of the comb laser was measured to be ~0.1 nm/°C and can lead to a spectral shift of 2.5 nm for temperature ranges from T = 25 to 50 °C. However, we have shown MOSCAP micro-ring devices that can tune up to 2.0 nm at a bias of 6 V with nW power consumption [19].

B. Heterogeneous Platform for Ultra-Energy-Efficient MOSCAP Phase Tuners

Current state-of-the-art silicon photonic MZIs and (de-)interleavers use either power inefficient thermal or current injection phase shifters to compensate for either waveguide phase
errors, power splitting errors, or temperature drift [32], [33].

In this work, we employ the use of a III-V/Si metal-oxide-semiconductor capacitor (MOSCAP) structure to efficiently tune the phase errors in the (de-)interleaver structure such that channel XT is reduced. These ultra-power-efficient MOSCAP phase tuners are based on a GaAs/dielectric/Si heterogeneous structure as shown in Fig. 3(a) and (b). There have been many demonstrations of energy-efficient InGaAsP/InP/Al$_2$O$_3$ MOSCAP phase tuners in the form of MZI structures [34]–[40], however, we believe we are the first to implement GaAs/Al$_2$O$_3$ and GaAs/HfO$_2$ based MOSCAPs for (de-)interleaver structures at 1310 nm. In addition, we have demonstrated these MOSCAP phase shifters in lasers [12], [41], [42] and MRRs [17], [18] individually, thus enabling the possibility of a complete heterogeneously integrated transceiver system based on ultra-low power consumption. The single mode condition for this heterogeneous structure is defined by a width, height, and etch depth of 500, 300, and 170 nm respectively. The wafer-bonded III-V consists of a 190 nm-thick n-GaAs doped at 3×10$^{18}$ cm$^{-3}$, Fig. 4(a) and (b) illustrates the calculated transverse electric (TE) effective index change ($\Delta n_{\text{TEoff}}$) and associated free carrier absorption (FCA) optical losses for both n-GaAs/Al$_2$O$_3$/p-Si and n-GaAs/HfO$_2$/p-Si structures vs. forward bias for various dielectric thicknesses. A 5 nm-thick Al$_2$O$_3$ with a refractive index of $n_{\text{Al}_2\text{O}_3} = 1.75$, will yield calculated optical confinement factors of $\Gamma_{\text{AL}_2\text{O}_3} = 1.154\%$ and $\Gamma_{\text{III-V}} = 28.27\%$ with an overall effective index of $n_{\text{eff}} = 3.1144$. A 5 nm-thick HfO$_2$ with a refractive index of $n_{\text{HfO}_2} = 1.88$ has optical confinements of $\Gamma_{\text{HfO}_2} = 1.159\%$ and $\Gamma_{\text{III-V}} = 28.33\%$ with an overall effective index of $n_{\text{eff}} = 3.1154$. In forward bias, the MOSCAP structure operates in carrier accumulation mode for efficient phase change. Experimentally, we explored 2 different MOSCAP gate oxide designs with varying degrees of Si doping and a dielectric selection of Al$_2$O$_3$ and/or HfO$_2$. These design are shown in Table I.

The bulk HfO$_2$ dielectric has a higher dielectric constant ($k \sim 25$) compared to Al$_2$O$_3$ ($k \sim 9$), therefore an HfO$_2$-based capacitor should have $\sim 3\times$ the capacitance for the same unit area. However, the measured thickness of HfO$_2$ in Design 2 is 10 nm with an additional 3 nm of Al$_2$O$_3$ which indicates the capacitance is only $\sim 1.7\times$ or less compared to Design 1.

Initial phase tuning measurements were performed on a 350 $\mu$m-long p-Si/Al$_2$O$_3$(6 nm)/n-GaAs MOSCAP MZI structure and spectral responses indicated $\sim 1.69$ nm of tuning at a 2 V bias while maintaining an extinction ratio of $\sim 24$ dB. The measured FSR = 17.9 nm and the calculated $V_L = 0.370$ V-cm which is 4× smaller than typical values seen in PN junction-based phase tuners. The observed leakage current appears to be smaller than the current meter limit of sub-nA, indicating negligible power consumption. The MOSCAP MZI is capable of achieving RC constant-limited 4 Gb/s eye diagrams and an $f_{\text{3dB}} \sim 1.5$ GHz. We also measured a MZI with HfO$_2$ (10 nm)/Al$_2$O$_3$ (3 nm) dielectric as shown in Fig. 4(b). The measured FSR = 19.0 nm with 2.26 nm of tuning at a 2V bias while maintaining an extinction ratio of $\sim 30$ dB. The $V_L$ was slightly lower ($V_L = 0.294$ V-cm) than the Al$_2$O$_3$ counterpart even with double the dielectric thickness. Fig. 4 shows a comparison of calculated and experimentally determined refractive index change for both dielectrics. For the case of Al$_2$O$_3$, the measurements point to either an effective thickness of 15 nm or lower $n_{\text{Al}_2\text{O}_3} > 1.75$. Similarly, for HfO$_2$, measurements indicate either larger effective thickness of the HfO$_2$/Al$_2$O$_3$ stack or the respective refractive indices.

TE waveguide losses using the cut-back method were measured for pre-bonded 0.5 and 0.8 $\mu$m wide waveguides and exhibited optical losses of $\sim 9.2$ and 9.8 dB/cm, respectively, at 1310 nm. After III-V removal, TE waveguide losses were measured to be $\sim 21.1$ and 42.2 dB/cm for the 0.8 and 0.5 $\mu$m wide waveguides respectively. TE waveguide losses with the wafer-bonded III-V regions were underestimated due to the absence of these particular test structures. Root causes of high waveguide losses are still under investigation.

Table I: Fabricated Platform Variations

| Design name | Si dop. (cm$^3$) | GaAs dop. (cm$^3$) | Dielectric gate type | $V_L$ (V-cm) |
|-------------|-----------------|-------------------|---------------------|-------------|
| Design 1    | 4e16            | 3e18              | Al$_2$O$_3$ (6 nm)  | 0.370       |
| Design 2    | 5e17            | 3e18              | HfO$_2$/Al$_2$O$_3$ (10/3 nm) | 0.294       |

C. MOSCAP (de-)Interleaver

MOSCAP phase tuners provide power efficient phase error correction for the heterogeneous (de-)interleavers needed to...
Fig. 5. 65 GHz MOSCAP (de-)interleaver (a) device schematic with design values, (b) calculated transmission response with and without phase tuning, (c) measured response without phase tuning, and (d) measured response with phase tuning.

The through and cross port transmission are respectively defined as:

\[
\Phi_{\text{1-ring RAMZI}} = \begin{bmatrix}
c_0(\lambda) & -j s_0(\lambda) \\
-j s_1(\lambda) & c_1(\lambda)
\end{bmatrix}
\times\frac{A_R(z)/A(z)}{e^{j2\pi n_g(\lambda)L_{\text{ring}}/\lambda}}
\times\begin{bmatrix}
c_0(\lambda) \\
-j s_0(\lambda)
\end{bmatrix}
\times\begin{bmatrix}
c_0(\lambda) & -j s_0(\lambda) \\
-j s_1(\lambda) & c_1(\lambda)
\end{bmatrix},
\]

where \( c_{0,1} \) is the power coupling coefficient for each coupler and \( \kappa_r \) is the ring coupling coefficient. The FSR is defined by the ring circumference such that the FSR = \( c/\kappa_r L_{\text{ring}} \). Therefore, a channel spacing of 65 GHz for the 1-ring AMZI requires \( L_{\text{ring}} = 1200 \mu m \) for a calculated group index of \( n_g = 3.78 \). The ideal ring resonator coupling for a 1-RAMZI occurs when \( \kappa_r = 0.89 \), and \( c_{0,1} = 0.50 \). The spectral characteristics of the MOSCAP (de-)interleavers are measured by coupling a Thorlabs superluminescent diode with 40 nm of bandwidth (1290–1330 nm) and a launch power of \( \sim 12 \text{ dBm} \). These devices are fabricated on a 100 mm SOI wafer and is vacuum mounted onto a sample stage of a semi-automatic probe station for measurements at room temperature. Fig. 5(a) and (b) illustrates the device schematic of the 1-RAMZI and calculated transmission spectrum for the bar and cross state. The solid lines in Fig. 5(b) represent the condition for perfect phase matching whereas the dashed lines indicate the case for a \( \pi \) phase offset for the ring resonator. The measured bar and cross channels for the 1-RAMZI before phase tuning show at XT \( \sim -7.3 \text{ dB} \) and \( -10.7 \text{ dB} \). By applying a \(-2 \text{ V} \) bias on the delay length (\( V_{\text{delay}} \)), the XT of the bar channel was improved from \(-7.3 \text{ dB} \) to \(-16.4 \text{ dB} \) while the cross channel XT improved from \(-10.7 \text{ dB} \) to \(-26.6 \text{ dB} \). For a bias of \( V_{\text{delay}} = -2 \text{ V} \), approximately 5.0 nA was drawn resulting in a tuning power consumption of 10.0 nW [16]. In addition to \( \sim 5 \text{ dB} \) lower than the reported best XT for a 1-RAMZI design, there is a 2.5 million reduction in power consumption [33]. In parallel, a similar 1-RAMZI based on p-doped silicon heaters was measured within the same die. These p-doped (1e20 cm\(^{-3}\)) heaters have a width = 2 \( \mu m \) and are placed adjacent to the ring and delay waveguides at an offset of 2 \( \mu m \). Initial phase error correction experiments show a power consumption of 27.59 mW for similar XT levels compared to the MOSCAP devices. It should be noted that optical IL will have the effect of reducing passband flatness, therefore, waveguide scattering should be kept to a minimum. Simulations indicate \( \sim 14\% \) reduction of the 0.5 dB bandwidth for every 10 dB/cm loss incurred in the device. The measured spectral responses shown in Fig. 5(c) and (d) obviously indicate passband shapes that are far from theoretically calculated flat-top response shown in Fig. 5(b).

This indicates a combination of waveguide loss and errors in power coupling coefficients. It was determined that coupling coefficients of \( c_0 = 0.46 \), \( c_1 = 0.43 \), \( \kappa_r = 0.88 \), and a waveguide loss \( \sim 40 \text{ dB/cm} \) resulted in a similar spectrum as shown in Fig. 5(d). None flat-top response is mainly attributed to waveguide loss, whereas increased channel XT indicates non-ideal power coupling coefficients. Experimentally, it is difficult to determine how much the coupling coefficients are off from ideal, however, 3D-FDTD simulations indicate a +/- 20 nm etch depth variation from the nominal etch (170 nm), will produce a +/- 10% change in the coupling coefficient. We plan to fabricate an improved design which consists of robust 50% MMI power couplers for \( c_0 \) and \( c_1 \) as well as tunable MOSCAP directional couplers for \( \kappa_r \). Initial MMI designs show \( \sim +/- 1\% \) variation from a nominal coupling coefficient of 50%, whereas a typical directional coupler show \( \sim +/- 10\% \) variation. Another loss mechanism to consider are the III-V/Si interface transitions. The (de-)interleavers employ an angled III-V interface of 45° with respect to the silicon waveguide. Numerical three-dimensional finite-difference-time-domain (3D-FDTD) simulations indicate a theoretical insertion loss of 0.36 dB/facet with a reflection < -60 dB. Experimentally determined III-V/Si interface losses were evaluated by cutback loss structures which indicate a loss of 1.08, 0.69, and 0.29 dB/facet for interface angles of 0°, 45°, and...
72 °C. We believe these transition losses can be further lowered since Ohno, et al., have demonstrated promising transition losses of ~ 0.055 dB [37].

D. MOSCAP Micro-Ring Modulator

In this section, we discuss a heterogeneous III-V/Si MOSCAP micro-ring modulator capable of transmitting 25 Gb/s OOK data at temperatures up to 80 °C. The modulators are fabricated using the exact same process as that of the QD comb laser and (de-)interleaver. Fig. 6(a) shows a perspective schematic of the modulator as well as the cross-section and a TEM image of the Al₂O₃ dielectric bonding interface. This particular ring has a radius = 10 μm with a 0 ° coupling angle. Fig. 6(b) shows the measured normalized transmission spectra for various bias voltages from 0 to 7 V, indicating a phase tuning efficiency of ~ 1.1 V-cm. As bias voltage increases, the resonance blue shifts with a reduction in quality factor (Q-factor) due to plasma dispersion and increased loss from free carrier absorption (FCA). This also indicates the resonator is initially under-coupled. We have extracted the roundtrip loss, power coupling coefficient, and Q factor as a function of wavelength using the methods identified in [48], and are 13 cm⁻¹, 0.0494, and 8250 respectively.

Next, we measured the small signal response (S_{21}) for several ring diameters of 10, 20, and 30 μm as shown in Fig. 6(c). The S_{21} curves are highly dependent on detuning between the laser wavelength relative to the micro-ring resonance. In this case, the detuning is such that optical modulation amplitude decreases proportionally due to increased contact area. Next, we evaluated large signal performance. Fig. 6(d) shows the measured eye diagrams at 25 Gb/s with a PRBS15 pattern and a peak-to-peak swing of V_{pp} = 4 V for three temperatures of 20, 50, and 80 °C. The extinction ratio (ER) is ~ 5.7 dB at all temperatures. The change in resonance wavelength with stage temperature, without any self-heating effect from two-photon absorption (TPA)-induced free-carrier absorption (FCA) is ~ 73.6 pm/°C. As mentioned in Section II A., the comb laser has a temperature shift of ~ 100.0 pm/°C, thus indicating ~ 0.66 nm drift from a comb line relative to a ring resonance for a temperature increase of 25 to 50 °C. Our previous work on HfO₂ based MOSCAP micro-ring [19] has a tuning range of ~ 2.0 nm and should be able to accommodate temperature drift offset.

III. DWDM TRANSEIVER EXPERIMENT

In this section, we discuss the experimental demonstration of the heterogeneous III-V/Si transmitter based on (de-)interleaved frequency combs without the MOSCAP MRR [17], [19]. However, these MRRs have been independently demonstrated on the same platform but in different chips and will be fully integrated in future versions. The experimental setup is illustrated in Fig. 7. The OFC QD laser is mounted on a temperature controlled stainless steel and biased with the conditions mentioned in Section II A. This operation condition enables the generation of comb lines where 12 out of the 17 combs exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation. The total power consumption of the OFC QD laser is 1309.08 mW, however, if we consider symmetric dual outputs, only half (654.54 mW) should be considered. The comb lines exhibit a 3 dB power variation.
Fig. 8. Measured (a) 1-RAMZI spectrum with ER $\sim 15$–25 dB, and 17 (de-)interleaved OFC comb lines, and (b) extinction ratio (ER) between (de-)interleaved comb lines in the bar and cross ports.

Fig. 9. Measured eye diagrams at 25 Gb/s NRZ based on (de-)interleaved OFC laser source. SNR in order from left to right: 8.53, 6.61, 8.61, 5.76, 6.76, 6.37, 7.47, 7.31, 4.83, 6.94, 8.31, 7.19, 5.42, 7.24, 7.30, 5.92, 5.33 dB.

(de-)interleaved channels are $\sim 14.3$ and 16.0 dB respectively. The non-uniformity of the (de-)interleaved combs is due to both OFC comb source non-uniformity as well as imperfect comb alignment with the peak passband of the (de-)interleaver ($\Delta \lambda_{\text{comb}} = 63.93$ GHz, $\Delta \lambda_{\text{(de-)interleaver}} = 65.78$ GHz). Comb laser alignment with the (de-)interleaver was optimal at 1322.02 nm and sequential (de-)interleaved combs become misaligned for longer wavelengths. As a result, the (de-)interleaved comb near 1326 nm will see an extra 3 dB loss. We expect any misalignments to be remedied in the future with MOSCAP tuning and improved waveguide losses which have a significant effect on passband flatness as discussed in Section II C. Since the comb laser is based on a coupled cavity design, channel spacing can also be tuned via MOSCAP phase shifters or thermal tuners.

Next, the signal goes through SOA1 and SOA2 designed for a center wavelength of 1310 and 1350 nm respectively. The first tunable filter prevents gain saturation into SOA2 and the second tunable filter selects the desired de-interleaved comb line with bandpass of 80 pm. The selected comb line is fed into a 65 GHz LiNbO$_3$ modulator and then into a 40 GHz photodetector with a 0.7 A/W responsivity. Eye diagrams are then monitored on a 60 GHz DCA and we were able to (de-)interleave 8 and 9 comb lines onto the bar and cross waveguide respectively for a total of 17 combs lines. Each line was modulated at 25 Gb/s PRBS9 NRZ OOK for a total of 425 Gb/s as shown in Fig. 9. 25 Gb/s was chosen due to project goals, however, higher data rates are indeed possible. All 17 comb lines show open eye diagrams without equalization which correspond to signal-to-noise ratios (SNRs) from $\sim 5.3$ to $\sim 8.6$ dB. The eye noise should mainly come from the amplified spontaneous emission (ASE) noise generated by multiple optical amplifiers. ASE noise is proportional to optical power, therefore, the “1” level exhibits more noise than the “0” level and is usually more significant for larger eye diagrams. This can be alleviated by eliminating the GC coupling loss after integrating them together. The eye amplitude variance at different wavelengths is mainly due to the optical power and RIN differences per comb line as well as the wavelength offset between the (de-)interleaver and OFC laser. It should be noted that the OFC source center wavelength is $\sim 1324$ nm, whereas the PDFA gain profile
TABLE II

| Channel # | Comb λ (nm) | Δλ (nm) | ER after (De-) Interleaver (dB) | Eye SNR (dB) |
|-----------|-------------|---------|-------------------------------|-------------|
| 1         | 1320.93     | 0.37    | 15.90                         | 8.53        |
| 2         | 1321.3      | 0.37    | 10.17                         | 6.61        |
| 3         | 1321.65     | 0.35    | 14.55                         | 8.61        |
| 4         | 1322.02     | 0.37    | 12.32                         | 5.76        |
| 5         | 1322.39     | 0.37    | 20.24                         | 6.76        |
| 6         | 1322.75     | 0.36    | 10.57                         | 6.37        |
| 7         | 1323.13     | 0.38    | 19.20                         | 7.47        |
| 8         | 1323.47     | 0.34    | 15.89                         | 7.31        |
| 9         | 1323.84     | 0.37    | 19.13                         | 4.83        |
| 10        | 1324.21     | 0.37    | 14.91                         | 6.94        |
| 11        | 1324.56     | 0.35    | 19.50                         | 8.31        |
| 12        | 1324.94     | 0.38    | 17.47                         | 7.19        |
| 13        | 1325.35     | 0.36    | 17.35                         | 5.42        |
| 14        | 1325.65     | 0.35    | 17.21                         | 7.24        |
| 15        | 1326.04     | 0.39    | 11.91                         | 7.30        |
| 16        | 1326.39     | 0.35    | 15.61                         | 5.92        |
| 17        | 1326.76     | 0.37    | 6.385                         | 5.33        |

decreases significantly at these longer wavelengths. We believe more combs could have been measured if we were not limited by the PDFA bandwidth. In the future, either the OFC laser will be centered at 1310 nm, or the (de-)interleaver will use broadband couplers to accommodate improved XT performance in excess of 50 nm bandwidth. Table II itemizes measured performance numbers of the (de-)interleaved comb lines. Eye signals with the largest SNR are typically associated with high ER and associated comb powers.

Inter-channel XT with multiple modulated signals can be of a concern. The inter-channel XT can be determined by $10 \log_{10}(\frac{V_{xt}}{V_{sig}})$ where $V_{xt}$ and $V_{sig}$ is the mean and sigma of level 1 respectively [49]–[51]. We have simulated the case where two lasers spaced 121.0 GHz apart are each modulated at 25 Gb/s. For the two laser case, the XT = $-16.06$ dB, whereas for only 1 laser, the XT = $-16.70$ dB.

IV. TRANSMITTER ARCHITECTURE SPECIFICATIONS

In this section, we discuss details of the transceiver link budget and projected energy efficiency. Table III lists the optical losses of each device and the power consumption in the proposed DWDM link operating at $T = 50^\circ$C. All loss numbers are based on past in-house fabrication and can be improved in an established foundry. We assume a worse case comb laser power/line to be $\sim -12.2$ dBm with a power consumption of $\sim 500$ mW. The booster SOAs that follow the comb laser have an experimentally determined gain of 15 dB with $\sim 300$ mW power consumption. Two (de-)interleavers are employed to spatially separate the front and back comb laser signal into 4 spatial channels that consists of 10 MRR each. This results in an aggregate of 40 MRR operating at 25 Gb/s for a total of 1 Tb/s. Each MRR on a particular spatial channel is designed to have 128 GHz separation. The power consumption of each MRR was determined to be $\sim 0.58$ mW and will be $\sim 23.2$ mW with all 40 MRR being operated. The power consumption of the (de-)interleavers are negligible (nWs) and assumed to be $\sim 0$ mWs. The total calculated loss per channel is $\sim 14$ dBm which becomes the required APD sensitivity. Assuming a reasonable OSNR at 40 dB, a bit-error-rate (BER) of $< 1e^{-9}$ should be attainable according on our past calculations on in-house designed APDs [52]. Assuming the same OSNR, if the comb laser power/line can be $\sim -7$ dB as demonstrated in Section II A., there is reason to believe a BER $< 1e^{-12}$ is achievable. In terms of total power consumption, this architecture will consume $\sim 862.3$ mW, which yields a 0.86 pJ/bit energy-cost number if we assume aggregate 1.0 Tb/s from 40 MRRs operating at 25 Gb/s.

V. CONCLUSION

This work, for the first time, demonstrates a simultaneous wavelength and space division multiplexed transmitter fabricated on a heterogeneous III-V-on-silicon platform. The QD OFC source yields 12 out of 17 comb lines within a 3 dB power variation for a single facet output along with a FSR $\sim 63.9$ GHz. Assuming symmetric dual outputs, the total power consumption of the OFC QD laser is estimated to be $\sim 654.54$ mW. The MOSCAP based 1-RAMZI (de-)interleaver has improved XT levels down from $-11$ dB to $-26$ dB for tuning powers of only 10.0 nW. With both building blocks, we have demonstrated wavelength (de-)interleaving of a QD OFC source with a total of 17 comb lines each modulated at 25 Gb/s NRZ for an aggregate bandwidth of 425 Gb/s. Future demonstrations will include full integration of a 40 channel QD OFC laser source, MOSCAP (de-)interleavers, and 40 MRR modulators capable of > 1 Tb/s transmission.

REFERENCES

[1] “Cisco annual internet report (2018–2023),” 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf

[2] Q. Cheng, M. Bahadori, M. Glick, S. Rumley, and K. Bergman, “Recent advances in optical technologies for data centers: A review,” Optica, vol. 5, no. 11, pp. 1354–1370, Nov. 2018.

[3] S. J. B. Yoo, “Prospects and challenges of photonic switching in data centers and computing systems,” J. Lightw. Technol., vol. 40, no. 8, pp. 2214–2243, Apr. 2022, doi: 10.1109/JLT.2021.3136570.
[4] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomen, “Recalibrating global data center energy-use estimates,” Science, vol. 367, no. 6481, pp. 984–986, Feb. 2020.

[5] N. Jones, “The information factories- data centres are chewing up vast amounts of energy,” vol. 561, 2018.

[6] D. Liang et al., “Integrated green DWDM photonics for next-gen high-performance computing,” in Proc. Opt. Fiber Commun. Conf., 2020, pp. 1–3.

[7] D. Liang et al., “An energy-efficient DWDM heterogeneous silicon photonics integration platform,” IEEE J. Sel. Topics Quantum Electron., vol. 28, no. 6, pp. 18–19, Nov./Dec. 2021.

[8] S. Srinivasan, D. Liang, G. Kurczveil, B. Tossoun, A. Descos, and R. Beausoleil, “8.52 Gb/s DWDM transmitter demonstration on a heterogeneous silicon photonic platform,” in Integrated Photonics Research, Silicon and Nanophotonics, Washington, DC, USA: Optical Publishing Group, 2021, pp. Tu3A–Tu3A.

[9] G. Kurczveil, A. Descos, D. Liang, M. Fiorentino, and R. Beausoleil, “Hybrid silicon quantum dot comb laser with record wide comb bandwidth,” in Frontiers in Optics. Washington, DC, USA: Optical Publishing Group, 2020, pp. FTu6E–FTu6E.

[10] G. Kurczveil, C. Zhang, A. Descos, D. Liang, M. Fiorentino, and R. Beausoleil, “On-Chip hybrid silicon quantum dot comb laser with 14 error-free channels,” in Proc. IEEE Int. Semicond. Laser Conf., 2018, pp. 1–2.

[11] G. Kurczveil, M. A. Seyed, D. Liang, M. Fiorentino, and R. G. Beausoleil, “Error-free operation in a hybrid-silicon quantum dot comb laser,” IEEE Photon. Technol. Lett., vol. 30, no. 1, pp. 71–74, Jan. 2018.

[12] D. Liang et al., “Heterogeneous silicon light sources for datacom applications,” Opt. Fiber Technol., vol. 44, pp. 43–52, Aug. 2018.

[13] S. Srinivasan, B. Tossoun, G. Kurczveil, Z. Huang, D. Liang, and R. Beausoleil, “160Gb/s optical link using Quantum-Dot comb laser source and SiGe APD,” in Proc. IEEE Photon. Conf., 2020, pp. 1–2.

[14] G. Kurczveil, X. Xiao, A. Descos, S. Srinivasan, D. Liang, and R. Beausoleil, “High-temperature error-free operation in a heterogeneous silicon quantum dot comb laser,” in Proc. Opt. Fiber Commun. Conf., Exhib., 2021, pp. 1–3.

[15] S. Cheung et al., “Ultra-power efficient heterogeneous III-Ⅴ/Ⅲ-ⅤⅡⅧ Si-de-interleavers for DWDM optical links,” in Proc. IEEE 17th Int. Conf. Group IV Photon., 2021, pp. 1–2.

[16] S. Cheung et al., “Ultra-power-efficient heterogeneous III–Ⅴ/Ⅲ–ⅤⅡⅧ MOSCAP (de)-interleavers for DWDM optical links,” Photon. Res., vol. 10, no. 2, pp. A22–A34, Feb. 2022.

[17] S. Srinivasan, D. Liang, and R. G. Beausoleil, “High temperature performance of heterogeneous MOSCAP microring modulators,” in Proc. Opt. Fiber Commun. Conf., Exhib., 2021, pp. 1–3.

[18] S. Srinivasan, D. Liang, and R. G. Beausoleil, “Heterogeneous SISCAP microring modulator for high-speed optical communication,” in Proc. Eur. Conf. Opt. Commun. Conf., 2020, pp. 1–3, doi: 10.1117/12.2558305.

[19] X. Huang et al., “Heterogeneous MOS microring resonators,” in Proc. IEEE Photon. Conf., 2017, pp. 121–122, doi: 10.1109/IPC.2017.8116031.

[20] B. Tossoun, G. Kurczveil, S. Srinivasan, A. Descos, D. Liang, and R. G. Beausoleil, “32 Gbps heterogeneously integrated quantum dot waveguide avalanche photodiodes on silicon,” Opt. Lett., vol. 46, no. 16, pp. 3821–3824, Aug. 2021, doi: 10.1364/OL.433654.

[21] Y. Yuan et al., “High responsivity Si-Ge waveguide avalanche photodiodes enhanced by loop reflector,” IEEE J. Sel. Topics Quantum Electron., vol. 28, no. 2, Apr. 2022, Art. no. 3800508, doi: 10.1109/JSTQE.2021.3087416.

[22] Y. Yuan et al., “64 Gbps PAM4 Si-Ge waveguide avalanche photodiodes with excellent temperature stability,” J. Lightw. Technol., vol. 38, no. 17, pp. 4857–4866, Sept. 2020, doi: 10.1109/JLT.2020.2996561.

[23] Y. Peng et al., “Optical signal analysis of Si microring resonator photodiode,” Electronics, vol. 11, no. 2, 2022, Art. no. 183.

[24] A. Descos, G. Kurczveil, D. Liang, and R. Beausoleil, “Heterogeneous O-band InAs/GaAs quantum-dot optical amplifier on silicon,” in Asia Commun. Photon. Conf., 2021, pp. 1–3.

[25] Y. London et al., “Energy efficiency analysis of comb source carrier-injection ring-based silicon photonic link,” IEEE J. Sel. Topics Quantum Electron., vol. 26, no. 2, Mar./Apr. 2020, Art. no. 3300113, doi: 10.1109/JSTQE.2019.2934121.
Stanley Cheung (Member, IEEE) received the B.S. degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA, the M.S. degree in electrical engineering from Columbia University, New York, NY, USA, and the Ph.D. degree in electrical engineering from the University of California, Davis, CA, USA. He is currently a Senior Research Scientist with Hewlett-Packard Laboratories, Milpitas, CA, USA, and is engaged in large-scale integrated photonics. His research interests include heterogeneous III–V/Si lasers/SOAs, neuromorphic/brain inspired computing, programmable photonics, non-volatile photonics, mode-locked semiconductor lasers, widely tunable lasers, and silicon photonics integrated circuits. He is a Member of the Optica Society.

Yuan Yuan received the B.S. degree in electrical engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2016 and the Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, VA, USA, in 2019. He is currently a Research Scientist with Hewlett-Packard Laboratories, Milpitas, CA, USA. His research interests include avalanche photodiodes, single photon counting, and III–V and silicon photonics. He is a Member of the Optica Society.

Yiwei Peng received the B.S. degree in electrical engineering from the Southeast University, Nanjing, China, and the Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, VA, USA, in 2021. He is currently a Postdoctoral with Large Scale Integrated Photonics Group, Hewlett-Packard Laboratories, Milpitas, CA, USA. His research interests include high-speed photodetectors, avalanche photodiodes, analog photonic links, and silicon photonics integrated circuits.

Geza Kurczveil (Member, IEEE) received the Ph.D. degree in electrical and computer engineering from the University of California, Santa Barbara, CA, USA, in 2012. He is currently a Research Scientist with Large-Scale Integrated Photonics Lab, Hewlett Packard Enterprise) Santa Barbara, CA, USA, where he is working on optical buffers. He has authored or coauthored more than 50 journal and conference papers. His current research interests include comb lasers, silicon photonic integrated circuits, and nano photonics.

Sudharsanan Srinivasan (Member, IEEE) received the bachelor’s degree in engineering physics from the Indian Institute of Technology Madras, Chennai, India, and the master’s and Ph.D. degrees from the University of California, Santa Barbara, CA, USA. He is currently a Research Scientist with Hewlett Packard Enterprise, Spring, TX, USA. He has authored or coauthored more than 30 journal papers and two book chapters. His research interests include integrated diode lasers, modulators and photodetectors, electronic photonic co-integration, heterogeneous material integration, and nanofabrication technology.

Yingtao Hu received the B.S. degree in material science from Central South University, Changsha, China, in 2007 and the Ph.D. degree in physical electronics from the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China, in 2012. From 2012 to 2015, he was a Postdoctoral Researcher with Interuniversity Microelectronics Centre and the University of Ghent, Ghent, Belgium, where he worked on graphene modulators on silicon. He is currently a Research Scientist with Hewlett Packard Labs, Palo Alto, CA, USA. His research focuses on hybrid III-V-on-Si photonic devices and integration.

Antoine Descos received the Graduation degree majored in microtechnology from French Engineer School, Ecole Centrale de Lyon, Ecully, France, in 2010, the master’s degree in micro-technology from University Claude Bernard Lyon 1, Villeurbanne, France, in 2010, and the Ph.D. degree in physics from Ecole Centrale de Lyon, Ecully, France, in 2014. He is currently a Research Engineer with Large Scale Integrated Photonics, Systems Research Laboratory, Hewlett Packard Labs, Palo Alto, CA, USA. He is also working with the CEA-LETI, Grenoble, France. He has authored or coauthored 40 papers and conference proceedings. His research focuses on the hybrid III–V on silicon lasers technology. He has designed, fabricated, and characterized different laser kind mainly for telecommunication purpose.

Di Liang (Senior Member, IEEE) received the B.S. degree in optical engineering from Zhejiang University, Hangzhou, China, and the M.S. and Ph.D. degrees in electrical engineering from the University of Notre Dame, Notre Dame, IN, USA. He is currently a Distinguished Technologist with Hewlett Packard Labs, Palo Alto, CA, USA. He has authored or coauthored one book, seven book chapters, and more than 250 journal and conference papers. His research interests include silicon and III–V photonics, diode lasers, high-speed optical monitors and photodiodes, heterogeneous integration techniques and micro/nanophotonics fabrication. He is a Fellow of Optica Society.

Raymond G. Beausoleil (Senior Member, IEEE) received the B.S. degree in physics from Caltech, Pasadena, CA, USA, in 1980 and the Ph.D. degree in physics from Stanford University, Stanford, CA, USA, in 1986. He is currently a Senior Fellow and the Senior Vice-President with Hewlett Packard Enterprise, San Jose, CA, USA, where he is the Director of Large-Scale Integrated Photonics Lab, Hewlett Packard Labs. He has contributed to more than 600 papers and conference proceedings (including many invited papers and plenary/keynote addresses) and five book chapters. He has more than 150 patents issued, and more than four dozen pending. His research interests include high-power all-solid-state laser and nonlinear optical systems, and numerical algorithms for computer firmware (leading to the navigation algorithms for the optical mouse). At Hewlett Packard Labs, he performs basic and applied research in microscale and nanoscale classical and quantum optics for information processing technologies. He is currently an Adjunct Professor of applied physics with Stanford University. He is a Fellow of the American Physical Society and the Optica. He was the recipient of the 2016 APS Distinguished Lectureship on the Applications of Physics.