Heterogeneous Multi-wavelength Optical Injection Locked System-on-chip: a Proposal & Proof-of-concept Experiment

Di Liang[1], Erwen Li[1], Sudharsanan Srinivasan[1], Antoine Descos[1], Zhixin Liu[2], Geza Kurczveil[1], Zhihong Huang[1], and Raymond G. Beausoleil[1]

1 Hewlett Packard Labs, Hewlett Packard Enterprise, Palo Alto, USA

2 Department of Electronic and Electrical Engineering, University of College London, London, UK

di.liang@hpe.com

Abstract: We present proof-of-concept work towards an integrated multi-λ optical injection locked system-on-chip using just one master laser. Tremendous improvement of direct modulation (4→20 Gb/s) and single-mode operation on slave microring laser was achieved.

1. Introduction

Optical injection locking (OIL) is a powerful technique in optical communication and signal processing [1]. It can significantly enhance the modulation bandwidth of directly modulated lasers with reduced the relative intensity noise, and enable phase and frequency locking a slave laser to a master. In a typical OIL configuration, one slave laser requires one master laser with optical isolation in between. Thus, integration of OIL system on a traditional III-V photonic chip is challenging. Our recently developed high-performance comb and microring lasers on a heterogeneous photonic integration platform [2] is promising to enable a compact, efficient and low-cost OIL system-on-chip. When using a microring laser as slave, its traveling-wave structure allows for unidirectional lasing and convenient OIL in a transmission configuration with Optical gain medium we integrate on the silicon photonics wafer is quantum dot (QD) material which shows huge tolerance to optical feedback [3]. Both features encourage to eliminate bulky discrete circulator or isolator. Despite of critical advantages in QD material such as high-temperature gain stability, low threshold current density, large spectral gain bandwidth and low noise, 1310 nm QD lasers normally show direct modulation bandwidth of only a few GHz due to finite intra-band relaxation time and the gain saturation effect. Therefore, OIL can be of great help to boost modulation capability of QD lasers.

Here we propose a novel fully-integrated dense wavelength division multiplexing (DWDM) OIL transmitter for our energy-efficient, low-latency exascale supercomputing and future neuromorphic computing applications. Proof-of-concept OIL on microring lasers through a multi-λ master laser was demonstrated for the first time to our best knowledge. Achieved OIL performance is comparable to use a high-end commercial single-λ master laser.

2. Proposed Structure and Experiment

Fig. 1 shows our proposed fully-integrated DWDM OIL system on our heterogeneous QD-on-silicon integration platform. The architecture includes an on-chip QD comb master laser to generate multiple constantly-spaced wavelengths like a demonstrated 12-ch. comb laser spectrum [4] in Fig. 1. Then an optional silicon ring resonator with a heater above can interleave odd and even numbered comb lines into two streams with effectively doubled channel spacing if channel crosstalk is significant with intrinsic channel spacing. Then 6 comb lines in each stream can lock 6 QD microring lasers successively to create a 12-λ OIL system-on-chip, e.g., 12-λ DWDM transmitter when directly modulating the slave microring lasers. The free spectral range (FSR) of the ring lasers must be carefully designed so that each comb line from the master laser is resonant with only one microring laser. This configuration provides multiple benefits: 1) *seamless on-chip integration* of only *one* master laser to lock *many* slave lasers on the same silicon chip with little optical loss in between; Single master laser configuration will result in *tremendous energy saving, footprint reduction, design and control simplification, etc.* 2) huge *bandwidth scalability* through OIL-induced large modulation bandwidth enhancement and DWDM architecture; 3) each of microring slave laser can *selectively amplify* the

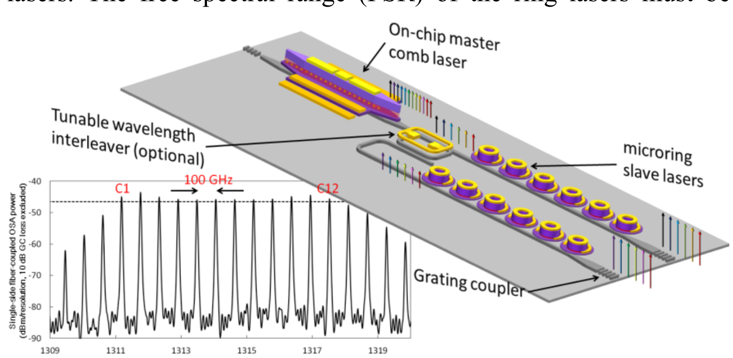

Fig.1. Schematic of a proposed fully heterogeneously integrated OIL DWDM system-on-chip. Inset: measured spectrum of a heterogeneous QD comb laser demonstrated recently [4].

individual locked comb line in an energy efficient manner. Compared with using conventional semiconductor optical amplifier to boost the entire comb spectrum, this approach *doesn't boost noise floor* outside wavelengths of interest and resonance effect assists *large amplification to weak input*; 4) separate bias on each slave lasers can provide different optical gain to *equalize final output power of comb lines, or boost weak ones to useful level*.

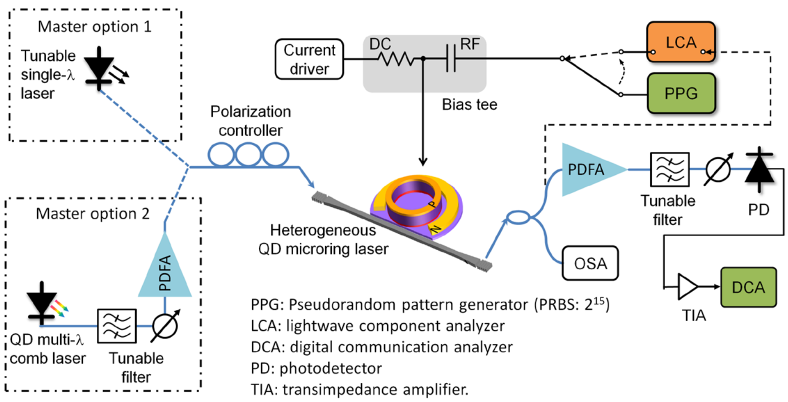

Fig. 2. Schematic of OIL experiment setup using two master laser options.

Fig. 2 shows the schematic of our proof-of-concept OIL experiment. Our recently demonstrated heterogeneous InAs/GaAs QD microring lasers (50 µm in diameter) served as slave lasers [2]. The first master laser option was to use a high-end tunable single-λ laser from Santec as most conventional OIL experiment would use. The second option was to use a standalone InAs/GaAs QD comb laser with a fixed channel spacing of 50 GHz (~0.3 nm) and little tunability. A tunable optical filter was used to select one or several comb lines and then amplified in a Praseodymium-Doped Fiber Amplifier (PDFA) to reach 11 dBm power level, comparable to the Santec laser output. Upon launching into the input grating coupler (GC), about 5% power is cross coupled between bus waveguide and microring laser from simulation. Considering 11 dB insertion loss measured for each GC, we estimated about -13 dBm master laser power to be coupled into the slave laser. The slave laser's output along with the transmitted injected light was fiber coupled from the output GC for spectral, noise, small- and large-signal characterizations.

3. Measurement Results and Analysis

Stable OIL can be first observed from spectra in Fig. 3. Free-running slave microring lasers in this work tend to operate in multiple strong spectral modes because of small FSR in laser resonator and large spectral gain bandwidth of the QD material. Multiple mode operation is detrimental as it can be a source of crosstalk to other channels when multiple lasers are cascaded to form a WDM transmitter. Furthermore, the unwanted modes deplete the injected electrical carriers, reducing direct modulation bandwidth and signal quality. After OIL, single-mode operation with 43 dB side-mode suppression ratio (SMSR) was achieved, using both master setups. The locked mode also had a power increase ~5 dB upon consolidating all energy into one wavelength. When optical filter bandwidth was maximized to 900 pm to let five comb lines (5λ) inject into the bus waveguide, the slave laser could be locked with only one comb line (C3 in Fig. 3(d) inset) and still maintain a SMSR of 40 dB. Since the slave laser's FSR (3 nm) happens to be ten times larger than the channel spacing of the comb laser (~0.3 nm), full comb injection could cause chaos where every 10th comb line tries to lock a different slave laser mode simultaneously. Hence, only five comb lines were filtered out in this proof-of-concept work. Noted that Figs. 3(b-d) were taken when 15 Gb/s RF signal was applied to the slave laser. Compared with four adjacent lines in Fig. 3(d) inset, the C3 line is slightly broadened. This indicates no optical coupling from adjacent comb lines into the slave laser as they are not resonant with the slave laser cavity, which is critical to our proposed OIL system in Fig. 1. Good SMSR remained after reducing Santec laser output from 11 to -3 dBm, indicating a minimum of -27 dBm injection power into the laser to achieve OIL. Increasing the coupling coefficient in slave lasers would largely reduce the output power requirement for

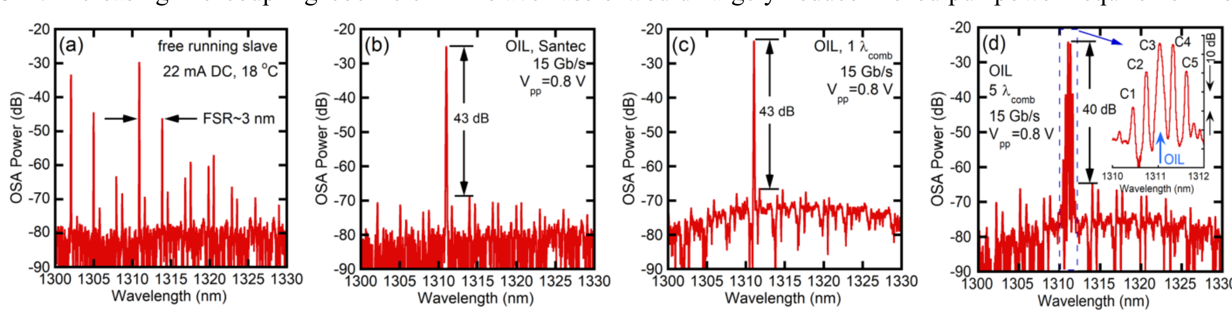

Fig. 3. Spectra of the same slave microring laser with (a) free-running state, and locked by (b) Santec master laser, (c) single-comb line (1λ) and (d) one wavelength (C3) out of five-comb lines (5λ). (inset: zoom-in spectra of filtered 5 comb lines with C3 line locking the slave).

master laser. Stable OIL was further confirmed by measuring the frequency noise of the Santec laser alone and total transmitted signal when the slave laser was locked by the Santec laser. While noise from the slave laser and a single comb laser line was not measured due to signal strength slightly below testing instrument limit, the noise from the slave laser is expected to be reduced significantly as is seen by the coincident frequency noise curves in Fig. 4(a). Compared to typical free-running diode laser with Lorentzian linewidth around a few MHz, stable OIL resulted in a linewidth of ~3 KHz which equals to the value of the standalone Santec laser.

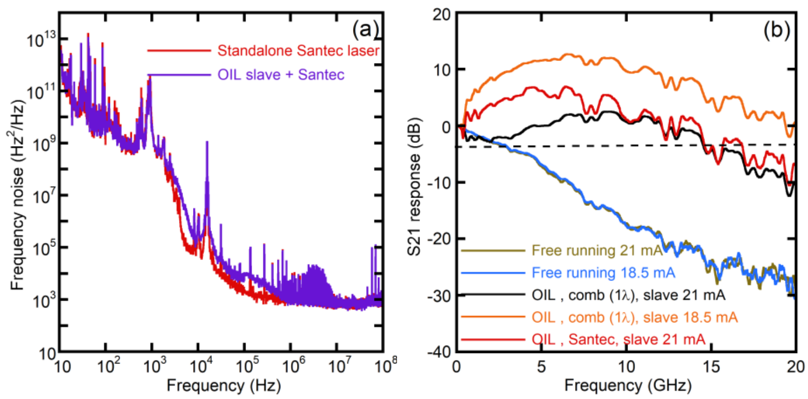

Fig. 4. (a) Frequency noise measurement on standalone Santec laser and microring laser locked by Santec laser, (b) frequency response of slave laser in free-running state, locked by Santec laser, and locked by comb (1λ) laser.

The results of small signal measurement are shown in Fig. 4(b). Slave laser was biased at 21 mA (10× threshold) in free-running state, or while being locked by either Santec laser or single-comb line (1λ). A maximal 3 dB bandwidth extension from 2.8 GHz (free-running) to 15 GHz was observed. Over 20 GHz bandwidth was measured when reducing the slave laser bias to 18.5 mA and locking a different slave laser mode likely due to reduced self Joule heating. Over 10 dB frequency response peaking was seen at 7 GHz. Excessive S21 response peaking or damping observed in certain OIL conditions should be avoided for a good high-speed signal-to-noise ratio (SNR).

Measured slave laser eye diagrams in free-running state (Fig. 5(a)), and locked states under injection from the Santec master laser (Figs. 5(b, c)) or filtered comb laser (Figs. 5(d, e)) exhibit tremendous enhancement from OIL in data transmission speed with better SNR. Open eye diagrams with SNR around 3.8 dB at 20 Gb/s on-off key modulation were measured with Santec master setup. **Record 25 Gb/s** transmission for O-band QD lasers was achieved (Fig. 5(c)) if Santec laser power was slightly over 13 dBm. Filtered single-comb line (1λ) resulted in favorable eye diagram at 20 Gb/s too, even showing better SNR than the case from Santec laser. Eye diagram quality was degraded a little bit when five-comb lines (5λ) were injected though only one comb line was locked. It is because the gain provided by the PDFA to the channel under test (CUT) is less when five comb lines were being boosted simultaneously instead of the CUT by itself. Fig. 5(f) is the eye diagram from an adjacent comb line, i.e., C4 in Fig. 3(d) inset. The flat line response again confirms that no optical crosstalk exists between the neighboring comb lines and the CUT.

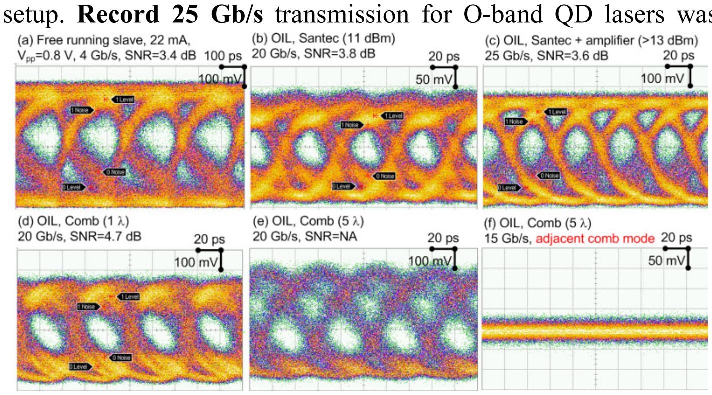

Fig. 5. Measured eye diagrams for the same slave microring laser with (a) free-running state at 4 Gb/s; and injection locked by a Santec master laser at (b) 20 Gb/s and (c) 25 Gb/s; and locked by the comb master laser with (d) single-comb line and (e) five-comb line injection at 20 Gb/s, and (f) response from an adjacent unlocked comb mode at 15 Gb/s.

To summarize, we proposed a novel heterogeneously integrated DWDM OIL system-on-chip based on successful proof-of-concept OIL experiment to lock a QD microring slave laser by a QD comb laser with the same lasing gain medium for the first time. Significant improvement on single-mode operation and direct modulation in slave laser is confirmed by comparing locking results between using a commercial Santec single-λ master laser and a QD comb master laser. Fully-integrated version in the on-going fabrication is expected to be demonstrated by the conference.

[1] E. K. Lau, et al., "Strong optical injection-locked semiconductor lasers demonstrating 100-GHz resonance frequencies and 80-GHz intrinsic bandwidths," OE **16**, 6609-6618, (2008).

[2] C. Zhang, et al., "Hybrid quantum-dot microring laser on silicon," Optica **6,** 1145-1151, (2019).

[3] H. Huang, et al., "Analysis of the optical feedback dynamics in InAs/GaAs quantum dot lasers directly grown on silicon," JOSA B **35**, 2780-2787, (2018).

[4] G. Kurczveil, et al., "On-chip Hybrid Silicon Quantum Dot Comb Laser With 14 Error-Free Channels," in *ISLC* Santa Fe, NM, USA, 2018.