Optical Injection-locked High-speed Heterogeneous Quantum-dot Microring Lasers

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Abstract

We demonstrate >6× modulation bandwidth extension of a heterogeneous quantum-dot microring laser using optical injection locking, obtaining 18 Gb/s on-off-keying modulation with clear open eyes. Single-mode lasing of all 11 longitudinal modes were achieved with >44 dB side-mode suppression and minimal 5 dB power increase.

1 Introduction

Silicon (Si) photonics is becoming a popular integrated photonics solution with increasing share in the transceiver market, particularly for 200 and 400 Gb/s applications and beyond. Heterogeneous III/V-on-Si integration is by far the only platform that is capable of including all key building blocks on the same chip and fabricated in a 300 mm production line [1]. In addition to conventional InP-based quantum well (QW) structure, GaAs-based quantum dot (QD) material has gained significant interests to be a better optical gain medium due to its intrinsic superior properties including high optical gain stability in elevated temperature, large gain spectral range, low threshold current density and low relative intensity noise [2-5]. Their large tolerance to defects and external feedback is also heavily favoured for high reliability and isolator-free low-cost packaging scheme [6, 7]. We recently have developed several key QD optoelectronic components on the heterogeneous platform, including robust comb lasers [8, 9], low-threshold microring lasers [10-12], and low-dark current photodetectors [13].

Directly modulated microring laser array on silicon, in particular, is attractive for its compactness, low power consumption, and natural wavelength division multiplexing (WDM) architecture [14]. They are ideal to provide an energy-efficient and low latency interconnect solution in our high-performance computing systems to handle medium bandwidth traffic (e.g., less than 200 Gb/s per fiber) between computing nodes within a few tens of meters. However, the finite intra-band relaxation time and the gain saturation effect in QDs significantly limit their direct modulation bandwidth, showing only 5-10 GHz bandwidth for 1310 nm InAs/GaAs QD lasers in general.

In this work, we utilized optical injection locking (OIL) to significantly enhance the modulation bandwidth of QD microring lasers. A tremendous modulation bandwidth extension up to 19 GHz was obtained by injection locking a QD microring laser with 3-GHz intrinsic bandwidth. Using a tunable master laser, we obtained stable OIL of 11 longitudinal modes without any complex laser control. The locked mode was able to operate at a single wavelength with increased optical power and high side-mode suppression ratio (SMSR) of about 44-56 dB. The microring structure allows for easy optical injection locking (OIL) in a transmission configuration, eliminating the need for circulator or isolator in conventional OIL setup for potential low-cost and integrated solution. Data modulated up to 18-Gb/s OOK was demonstrated with bit error rate (BER) of less than 10^{-10}.

2. Experiment

QD microring lasers in this experiment were fabricated on our heterogeneous integration platform. A 3D schematic diagram in Fig. 1 shows the finished device structure. Detailed fabrication process can be found in [10, 11]. Fig. 1 shows the schematic of our experimental setup. The device chip was placed on a copper stage with temperature stabled at 18 ^{o}C. The measured devices have low threshold of 2-3 mA and output power about 0.7 mW in the bus waveguide under 25 mA continuous-wave (cw) bias current. An O-band tunable laser with 13 dBm maximal power served as the master laser. The master laser output went through a polarization controller before launching into one of the grating couplers in the bus waveguide via a cleaved standard single mode fiber (SMF-28). OIL of different modes was achieved by tuning the wavelength of the master laser to the individual slave laser modes. The grating coupler loss was measured to be 11 dB, which was due to the fabrication imperfection. About 5% power cross-coupling coefficient between Si bus waveguide and heterogeneous microring laser is obtained from simulation. Thus, we estimate -about - 10.5 dBm (90 μW) master laser power coupled into the slave

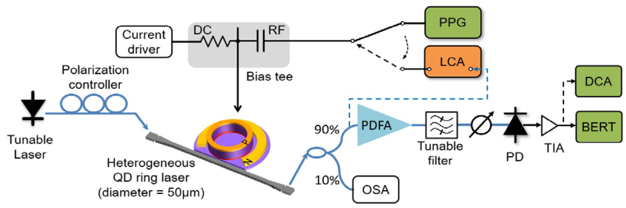

Fig. 1. Schematic of optical injection locking experiment

laser cavity. Although the master laser does have an integrated isolator, it is not strictly required as OIL will result in unidirectional lasing in the ring laser conveniently. As a result, little optical power will be coupled from the ring laser to the master laser.

The slave laser's output along with transmitted injected light is collected by another SMF-28. In the data modulation experiment, RF signal with pseudorandom bit sequence (PRBS) of different length (2^7, 2^{11} and 2^{31}) was generated from a output from a pseudorandom pattern generator (PPG). Then collected light was split into two branches by a 10:90 splitter. The 10% port was connected to an Optical Spectrum Analyzer (OSA) and the 90% port went through a Praseodymium-Doped Fiber Amplifier (PDFA) before passing through a tunable filter. The filtered optical signal was subsequently detected by a 20-GHz bandwidth photodiode followed by a transimpedance amplifier (TIA) for eye diagram characterization in a digital communication analyzer (DCA) or a BER tester (BERT). The frequency response characterization was carried out by a Lightwave Component Analyzer (LCA), as shown in Fig.1.

3 Measurement results

3.1 Spectral measurement

Inhomogeneous broadening effect in self-assembled QD structure effectively broadens the optical gain bandwidth. It can enable widely tunable single-wavelength lasers [3] and large comb width to fit more wavelength channels [15]. But it also can easily support multiple longitudinal mode lasing in lasers without a fine wavelength selection mechanism, such as microring lasers whose lasing mode space is only determined by laser cavity free spectral range (FSR). In this work, device diameter is 50 μm, corresponding to an FSR of ~3 nm, which is too small compared to >40 nm full-width at half maximum in photoluminescence spectrum. Single primary lasing mode with over 40 dB SMSR can be observed in some bias condition when net gain at that moment perfectly aligns with certain mode which depletes most of the electrical carriers to suppress other modes. But commonly, the output of a QD microring laser with small FSR can have multiple longitudinal modes with similar spectral intensity. An example optical spectrum is shown in Fig.2 (black curve, free-running), a QD microring laser biased at 28 mA outputs more than 11 modes with the power of the modes varying from -73 to -22 dBm. Among 11 modes we selected, (above the -76 dBm noise floor at 0.02 nm resolution), five of them have optical signal to noise ratio of >25 dB but the SMSR for the strongest mode M5 at 1311.03 nm was only 4 dB.

The optical injection locking forces the microring laser to lase uni-directionally along the injection direction at the selected modes, resulted in single-mode operation with a simultaneous power increase (all optical power concentrates at the same mode). Transmitted master laser light with microring laser off results in a -19 dBm peak in OSA. OIL boosted the original strongest lasing mode M5 from -22 to -17 dBm, a 5 dB increase. For weak modes at the edge of the lasing spectrum, e.g. M1-2 and M9-11, OIL-induced power increase can be significant, up to 45 dB for M11. In the meantime, the side modes are largely suppressed, leading to a minimal SMSR of 44 dB as shown in Fig.2. For the main lasing modes (M3-8), the SMSR was higher than 50 dB, with the highest SMSR obtained at M6 (56 dB). In this sense, OIL acts as a high gain optical amplifier plus optical filter, as previously discussed in [16]. We noted there was another set of longitudinal modes 0.7 nm apart from the adjacent modes. We believe they are the higher order transverse modes due to multi-mode heterogeneous microring waveguide design with 5 μm wide III/V ring mesa on top 1.5 μm wide Si ring waveguide. They cannot be effectively suppressed when injection locking is not positioned to their grid. Due to the high grating coupler loss, the master laser's output power was kept at 13 dBm for stable injection locking, but stable locking was still attainable at 3.5 dBm optical injection. A further reduction of injection power can be achieved with feedback control [17].

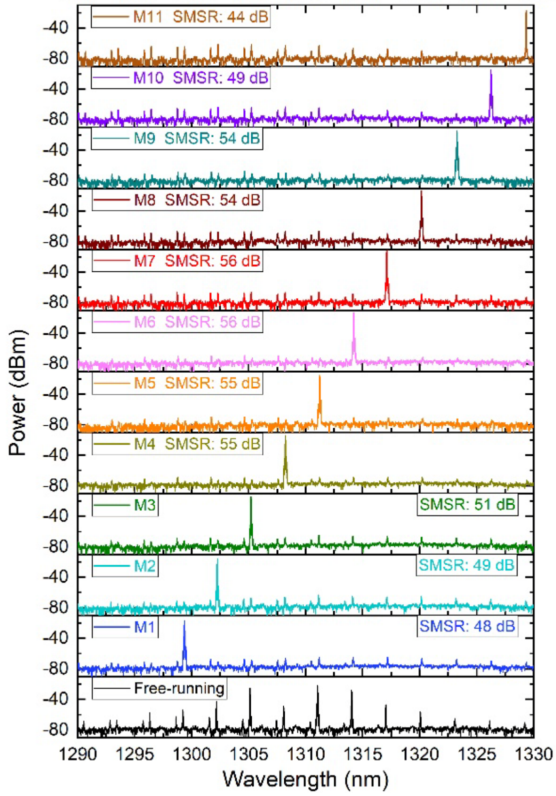

Fig. 2. Laser spectra with no optical injection and under injection showing locking to each of 11 modes.

3.2 Frequency response characterization

Previous research has demonstrated more than 10-fold increase of modulation bandwidth when a slave laser is subjected to high injection power [18]. Fig. 3 shows the measured modulation frequency response with and without OIL to M5 under different bias current. Without OIL, the modulation bandwidth was from 2.6 GHz to 4 GHz, when the bias current increased from 5 mA to 25 mA. Further increase of the bias current to 30 mA led to a reduced bandwidth primarily due to the device self-heating effect. The photon-photon interaction resulted in a resonance peak at around 5-7 GHz and was accompanied with a smooth frequency roll-off that extend the 3-dB modulation bandwidth by more than 3 folds. A 15 GHz bandwidth was observed when biasing at 25 mA.

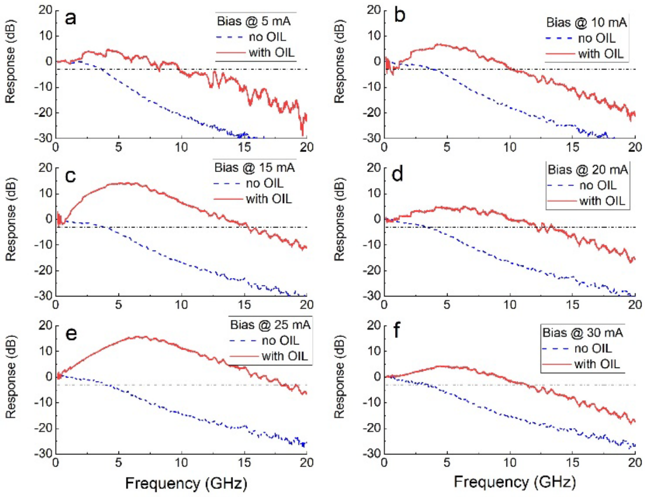

Fig. 3. Direct modulation response with and without OIL at 5, 10, 15, 20, 25, 30 mA dc bias current.

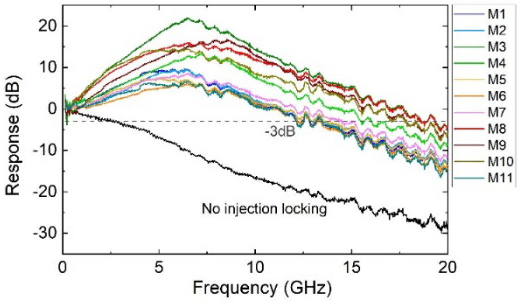

Fig. 4. Direct modulation response with and without OIL for 11 longitudinal modes at 28 mA dc bias current.

Fig. 4 shows the dynamic modulation responses at a fixed dc bias current of 28 mA when each of the 11 modes in Fig. 2 is injection locked respectively. The free-running microring laser only has a bandwidth of 3 GHz. Under OIL to M5, the slave laser's bandwidth was extended to 12-19 GHz in all locked modes. It is also interesting to note that different response peaking in a range of 6 to 22 dB is measured while peak frequency appears around 7 GHz for most of modes, except M4 and M9. Those difference is likely associated with frequency detuning between injection mode and each lasing mode, which is outside the scope of this paper.

3.3 Data modulation

Fig. 5 compares the eye diagrams with and without OIL when biased the slave laser at 28 mA. PRBS length of 2^{11} was used in all the characterisations. Fig. 5(a) shows the eye diagram of the free-running laser operating at 8.5 Gb/s NRZ-OOK modulation (M5) without OIL. Limited by the intrinsic bandwidth, the eye diagram has a long rising and trailing edge, resulted in more than 75% eye closure. Further increased the data rate resulted in a closed eye diagram. After OIL, a significantly improved eye diagram was obtained with only 18% eye closure at 12 Gb/s. We were able to further increase the data rate to about 18 Gb/s (56% eye closure) without any analogue or digital equalization (Fig.5(d)).

Finally, the BER characterization was carried out using the same slave laser operating at 12 Gb/s which is the maximal bandwidth in our BERT. At the BER of 10^{-10}, the receiver sensitivity for PRBS lengths of 2^7 and 2^{11} were -2.8 dBm and -0.2 dBm, respectively. Further increase the PRBS length to 2^{31} led to a decrease of BER to about 2×10^{-6} at -1 dBm. The power penalties using different PRBS lengths were mainly due to the pattern dependent effect and the low frequency noise of the injection locked slave laser. We believe the strong low frequency noise was due to the dithering of the master laser, which changes the frequency detuning of the OIL by up to a few hundred MHz, resulting in a low frequency modulation of the slave laser. Replacing the master laser with a better laser should result in better performance.

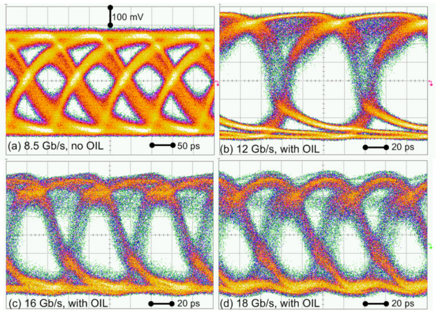

Fig. 5. Eye diagrams at 28 mA bias current (a) without OIL at 8.5 Gb/s and with OIL at (b) 12, (c) 16 and (d) 18 Gb/s.

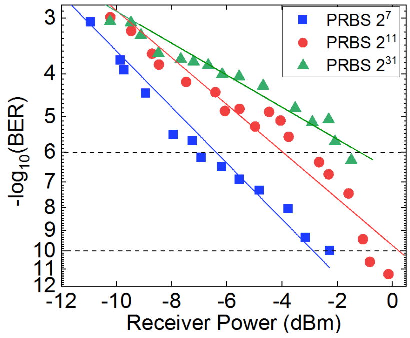

Fig. 6 Measured BER as a function of receiver power at 12 Gb/s under OIL for different PRBS length.

4 Conclusion

We report OIL to heterogeneously integrated QD microring lasers on Si to extend its limited direct modulation bandwidth by more than a factor of six. The transmission configuration allows the stable locking of 11 longitudinal modes with higher than 44 dB SMSR. The enhanced bandwidth enabled up to 18-GBd modulation with improved eye openings and BER of less than 10^{-10}. OIL provides an effective solution to overcome inherent low modulation bandwidth in QD lasers. Our heterogeneous platform allows convenient integration of master and slave lasers, and promising possibility to apply this technique to our wavelength division multiplexing transceiver system with minimal penalty in chip size and power consumption.

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