Reflection sensitivity of InAs/GaAs epitaxial quantum dot lasers under direct modulation

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This paper reports on the reflection sensitivity under direct modulation operation of a 1.3 μm InAs/GaAs quantum dot laser that is epitaxially grown on silicon. The quantum dot laser exhibits a high tolerance to back reflections with low error transmission at 6 Gbps. This study paves the way for developing directly modulated isolator-free photonic integrated circuits based on quantum dot lasers.

Introduction: Silicon photonic technology is promising for overcoming the limited bandwidth and high energy consumption of data communication links that use copper interconnects. This technology offers novel capabilities for high-speed optical communication, short-reach optical interconnections, and applications for optical links between chips [1,2]. Quantum dot (QD) lasers are regarded as the first option for on-chip light sources for silicon photonic integrated circuits (PIC), owing to their high tolerance to threading dislocations that arise during the epitaxial growth of III–V materials on Si [3–5]. In addition to low defect sensitivity, the low lasing thresholds, high thermal stability, low-noise properties, and high optical nonlinearities offered by QD laser pave the way for developing high-performance classical and quantum PICs [6,7].

The chip-scale back-reflection is a great challenge for developing high-performance PICs since it results in severe instabilities from the laser source [8]. Given that developing an on-chip optical isolator that has low loss and sufficient isolation remains a challenge, it is important to develop feedback-insensitive sources [9]. In this context, QD lasers exhibit a strong potential to be applied to isolator-free PICs owing to their high tolerance for chip-scale back-reflections [10]. Our previous work already demonstrated that an externally-modulated QD laser can achieve error-free operation at any feedback condition [11, 12]. In order to develop a more compact optical transceiver by taking advantage of the QD laser, a further investigation on the reflection sensitivity under direct modulation is necessary. Indeed, although directly modulated lasers are more energy-efficient and have higher linearity in short-range microwave photonic links, the addition of a single tone modulation can make them more sensitive to external feedback [13]. To this end, a directly modulated QD laser on native substrate exhibiting a high degree of resistance to back-reflection was recently reported by keeping a low bit-error rate (BER) with a feedback strength at −9 dB [14]. In this study, we go a step further by investigating the feedback sensitivity of a directly modulated QD laser on Si. The remarkable reflection resistance that is comparable with the QD lasers on native substrate observed from the device studied paves the way for developing low-cost and large-scale isolator-free silicon PIC applications because of the high integration and simplified process flow [6].

QD device: The QD laser was grown on a GaP/Si template as shown in Figure 1a. The active region contains five periods of QD layers, each separated by a 37.5 nm GaAs spacer that includes 10 nm of p-type material and the density of QDs is about 5.9 × 10^{10} cm^{-2}. The Fabry–Perot cavity of the laser is 1.35 mm long, with 4 μm wide ridge deeply etched (through the active region), and two top contacts for electrical injection. The cavity facets are symmetric with a power reflectivity of

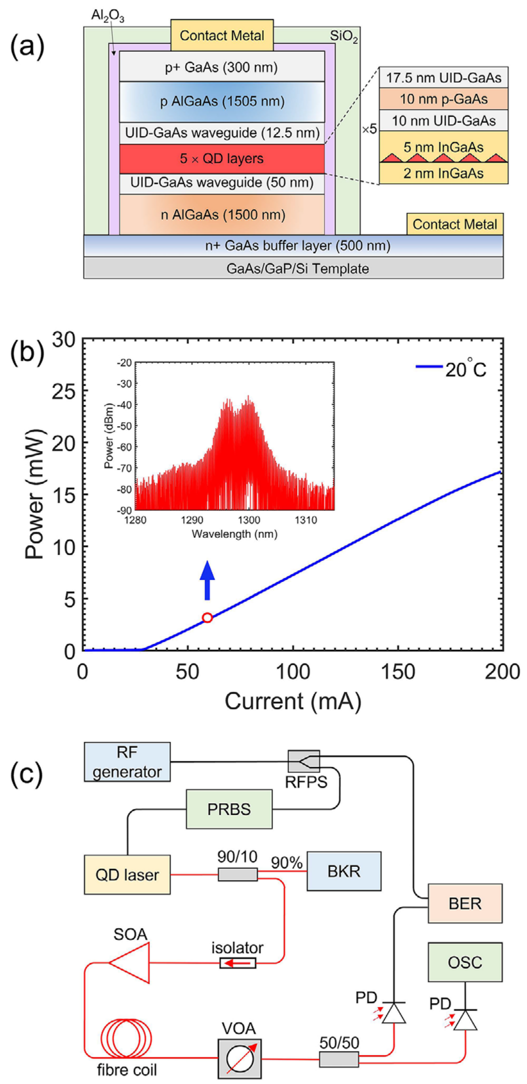

Fig. 1 *(a) Schematic of quantum dots (QD) laser device structure. (b) Power-current characteristics at 20°C. The inset is the spectrum of the QD laser at 60 mA. (c) Schematic of the experimental setup. The black lines show the electrical circuit and the red lines show the light path*

approximately 32%. More detailed device fabrication process information and laser structure are available elsewhere [6,10]. Figure 1b shows the light current characteristics at 20°C where the threshold current (I_{th}) is 30 mA. The inset displays the optical spectrum measured at 60 mA (2 × I_{th}) that corresponds to the operation condition. The QD lasers on Si are known for their near-zero linewidth enhancement factor (LEF). For the device studied, the LEF is below unity in the operating condition [12]. A straightforward consequence of the low LEF is a better immunity against optical feedback, thanks to a weaker interaction between the intra-cavity and reflected light fields [8].

Experimental set-up: To investigate the modulation properties of the QD laser with or without optical feedback, the experimental setup is shown in Figure 1c. The QD laser is directly modulated by the digital generator with a pseudo-random binary sequence and a bit sequence length of 2^7-1 and the applied modulation format is on-off keying. The QD laser was not optimized for high-speed modulation without specific RF packaging, so we did not use a longer sequence length. At the same time, the clock signal is fed into the error detector as a reference signal. Afterward, the emission from the QD laser is coupled into an anti-reflection coated lens-end fibre and it is divided into two paths, the feedback path, and the output path. On the feedback path, 90% coupled power is sent to the back-reflector (BKR) that consists of a mirror and a variable optical attenuator (VOA). The latter is used to change the feedback strength, which is defined as the ratio of returned power to the free-space output power. In this configuration, the achievable feedback

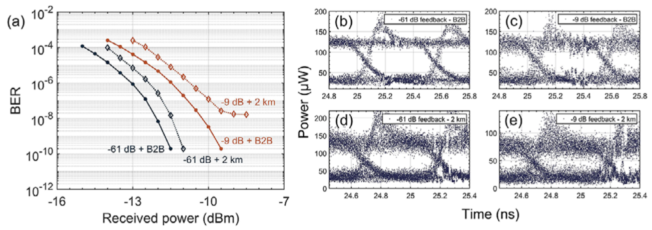

Fig. 2 *(a) Bit-error rate (BER) plots at 2 Gbps for back-to-back (B2B) and after transmission (2 km) with and without feedback for the quantum dots (QD) laser at 20°C. The pump current is $2 \times I_{th}$. The eye diagrams (b) without feedback and (c) with feedback when back-to-back. The eye diagrams (d) without feedback and (e) with feedback after 2 km transmission*

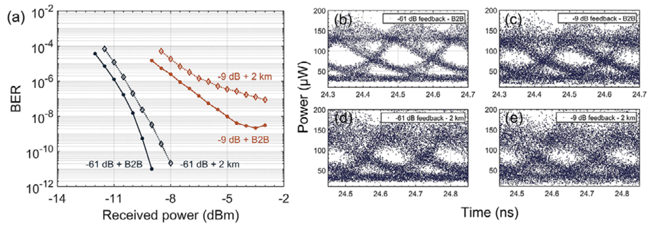

Fig. 3 *(a) Bit-error rate (BER) plots at 6 Gbps for back-to-back (B2B) and after transmission (2 km) with and without feedback for the quantum dots (QD) laser at 20°C. The pump current is $2 \times I_{th}$. The eye diagrams (b) without feedback and (c) with feedback when back-to-back. The eye diagrams (d) without feedback and (e) with feedback after 2 km transmission*

strength ranges from −61 to −9 dB. The other 10% of the coupled power is isolated and then amplified by a semiconductor optical amplifier. The signal is transmitted over a 2 km single-mode fibre coil. In the end, a VOA is used to tune the received power of the error detector in order to analyse the BER performance. A high-speed oscilloscope (OSC) is used to capture the eye diagram. Photodetector converts the optical signal into an electrical signal before entering the BER tester or OSC.

High-speed characteristics: The high-speed response of the QD laser is carried out at twice the threshold current and room temperature. The BERs of the QD laser at 2 Gbps with and without feedback after back-to-back (B2B) and 2 km fibre transmission are plotted in Figure 2a. For the calculation of the feedback strength, we use the feedback strength of BKR (the maximum feedback strength of BKR is −2.2 dB) and include the setup loss (2.7 dB) and the coupling loss (4.1 dB) then get the feedback strength (the maximum feedback strength is −9 dB) [15,16]. When the feedback strength is −61 dB, which is effectively similar to the free-running operation, the minimum BER of the device studied approaches 10^{-10} in the B2B operation and after 2 km transmission. However, a 0.7 dB power penalty is observed after 2 km transmission at the BER level of 10^{-9}, which is attributed to the chromatic dispersion in the fibre. The eye diagrams are thus measured in the condition of high received power. In both B2B and transmission operations, the eye diagram is wide and has clear contours as shown in Figure 2b,d. By increasing the feedback strength to −9 dB, a minimum BER approaching 10^{-10} is still ensured in the B2B operation. Despite the 2 dB power penalty that is induced by the optical feedback at the BER level of 10^{-8}, the eye diagram remains open as shown in Figure 2c. Nevertheless, the BER performance is degraded after 2 km transmission leading to a penalty floor with −9 dB optical feedback. We define the minimum measured BER level as residual BER (RBER). In the transmission operation, the RBER level is 10^{-8}. As shown in Figure 2e, the eye diagram is still open, but the contours are a little blurred. To investigate how the BER QD laser behaves under the same optical feedback conditions but operates at a higher modulation rate, Figure 3a depicts the BER plot with a modulation rate at 6 Gbps. Under a weak feedback strength at −61 dB, the increase of modulation rate from 2 to 6 Gbps keeps an error-free operation in both B2B and transmission configurations, and a BER level below 10^{-10} is always obtained. However, a 2 dB power penalty at the BER level of 10^{-8} results from the increase in modulation rate. It is worth stressing that the degradation due to optical feedback is amplified when the modulation rate is higher. By increasing the feedback strength to −9 dB, the RBER level in the B2B operation is above 10^{-9}, where the received power is −3 dBm. After 2 km transmission, the BER level is further increased to 10^{-7}. Despite the degradation of BER performance, the QD laser still exhibits a reasonable transmission under optical feedback. With a 6 Gbps modulation rate applied, the eye diagrams are open but narrowed and the contours remain clear with or without feedback in B2B operation. It can be noticed that when BER is less than 10^{-8}, there are open and clear eyes. With −9 dB feedback, the BER increases and is greater than 10^{-8} after 2 km transmission, so the eye becomes blurred. In fact, there is a weak overshoot above each eye which may be caused by the high modulation voltage (2 V) used in the study [17]. The IEEE 802.3ah standard indicates that the reflection tolerance of an optical interconnect should be higher than −26 dB [18]. Hence, there will not be such a large feedback (−9 dB) in short-distance data transmission, so the actual BER will perform better at a 6 Gbps modulation rate and will be less than 10^{-8}. Furthermore, the silicon-based quantum dot laser still meets the KP4 forward error correction-certified BER of 2×10^{-4} at 6 Gbps rates and strong feedback [19].

It was found that increasing the received power does not reduce the BER when strong feedback is present. In the future, we may have to continue to optimize laser performance by utilizing on-chip integrated light sources with customized design and packaging. In the latter, the speed of the data transfer can be further improved by considering an improved drive signal transmission.

Conclusion: We have performed for the first-time direct modulation experiments using silicon-based epitaxial quantum dot lasers under different optical feedback conditions. At room temperature, we can implement modulation rates of 6 Gbps for QD lasers and withstand strong feedback. The experimental results provide an encouraging argument for the high-density integration of silicon-based epitaxial quantum dot lasers for silicon photonics applications.

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