High reflection tolerance quantum dots LC-DFB laser for hybrid-silicon photonic integrated circuit

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ABSTRACT

Quantum dot distributed feedback lasers with high optical reflection tolerance are of great significance as the isolator-free light sources for hybrid-silicon photonic integrated circuit. In this work, we experimentally investigate the optical feedback tolerance of our O-band quantum dot lateral coupled distributed feedback lasers, using a fiber-based back reflector. The optical spectra show that the quantum dot distributed feedback laser can maintain stable output power and wavelength under external optical feedback up to -6 dB. Moreover, a high side-mode suppression ratio over 50 dB is also maintained without spectral width broadening, which is significantly different from the broadening observed in the quantum well counterpart. As the optical feedback strength increases to -6 dB, the relative intensity noise of the quantum dot distributed feedback laser remains around -135 dBc/Hz, while the relative intensity noise of commercial quantum well distributed feedback laser increases by 10 dB over the 0 - 20 GHz range. These results indicate the high optical feedback tolerance of our O-band quantum dot lateral coupled distributed feedback lasers laser, making it a promising isolator-free light source solution for the hybrid-silicon photonic integrated circuit.

Keywords: quantum dot, distributed feedback laser, optical feedback, relative intensity noise

1. INTRODUCTION

With the development of big data models, there is an increasing demand for data transmission volume and speed, and optical interconnects are a promising solution. Silicon photonic integration, whose fabrication technology is compatible with that of metal–oxide–semiconductor (CMOS), has the potential for low-cost and large-scale production, promoting the implementation of optical interconnections[1]. Distributed feedback (DFB) lasers exhibit high stability, narrow linewidth, single longitude mode and high output power, making them promising light source for high-speed data transmission. DFB laser arrays with different output wavelengths can also achieve DWDM, further enhancing data capacity.

However, the light reflection introduced at the device coupling interface or within the fiber loop may degrade laser performance[2,3], causing issues such as spectral broadening, mode-hopping, side-mode suppression ratio (SMSR) decline, relative intensity noise (RIN) increase, and even coherence collapse, which damage system performance and stability. Besides, introducing optical isolators would increase costs and optical losses. Consequently, a light source with high external optical feedback (OFB) tolerance is needed. Quantum dots (QDs) have a gain structure with three-dimensional carrier localization, making QD lasers less sensitive to defects. Additionally, they also exhibit higher lasing efficiency, higher temperature stability, and nearly zero linewidth enhancement factor, making them more resistant to OFB[4].

In this work, we report an O-band GaAs-based QD lateral coupled (LC)-DFB laser with OFB tolerance at least -6 dB. Under an OFB strength of -6 dB, the laser maintains its single longitudinal mode wavelength, output power, an SMSR as high as 50 dB, and a stable RIN level of -135 dBc/Hz, comparable to its OFB-free operating state. This performance is compared and analyzed against a commercial QW counterpart with the same output power, demonstrating the broad application prospects of our QD laser as an isolator-free light source in hybrid-silicon photonic integrated circuits.

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2. METHODOLOGY

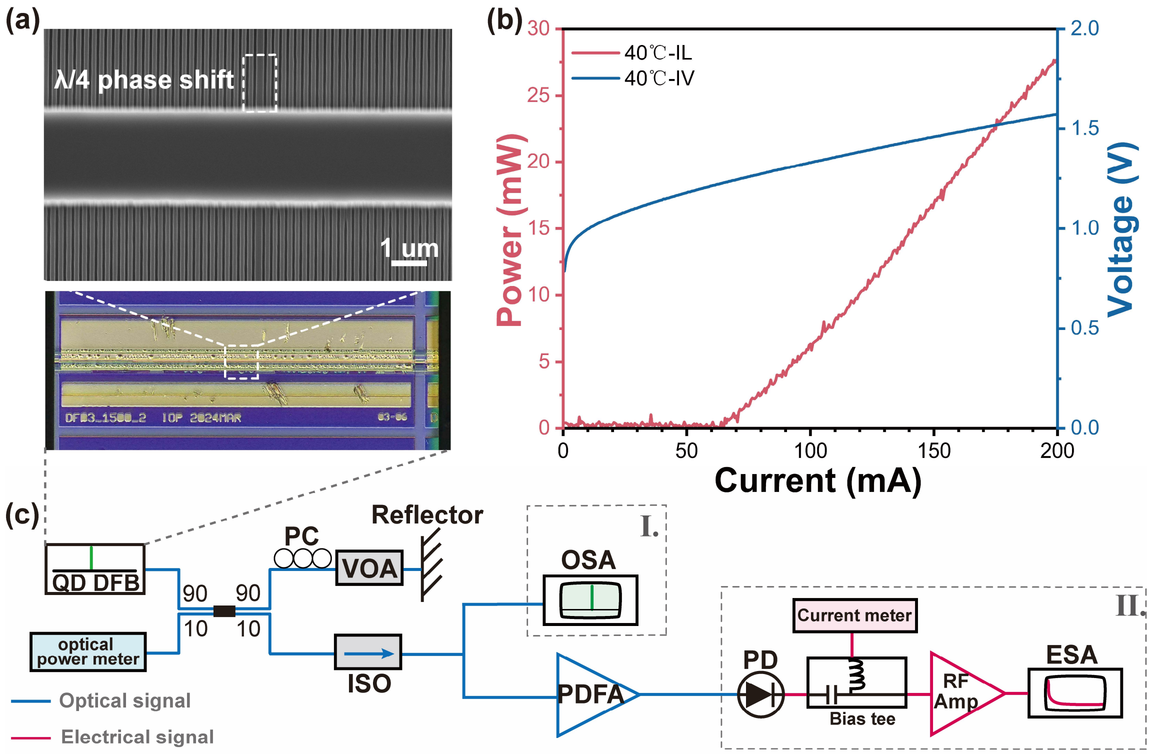

Figure 1. (a) SEM image of the etched Si gratings with a λ/4 phase shift in the middle. The bottom shows the micrograph of the DFB laser used in the experiment. (b) The 40 °C continuous-wave light-current-voltage (L-I-V) characteristics of GaAs-based QD DFB laser. (c) Experimental arrangement for the optical spectral (I) and RIN (II) measurements of the QD DFB laser under different OFB strengths. VOA, variable optical attenuator; ISO, optical PM isolator; PDFA, praseodymium-doped fiber amplifier; PC, polarization controller; RF Amp: electrical amplifier; PD, photodetector; OSA, optical spectrum analyzer; ESA, electrical spectrum analyzer.

In this work, the QD DFB laser structure is grown via molecular beam epitaxy (MBE) of InAs/GaAs QDs on an n-type GaAs (100) substrate. The gain structure features an optimized 7-layer QD gain layer and detailed structure and growth procedures can be found in our previous work[5]. The micrograph of the DFB laser is shown at the bottom of Fig. 1(a), with the top SEM image showing the λ/4 phase shift placed in the middle of the gratings. The total cavity length is 1500 µm, with the anti-reflection (AR) coated front facet and the as-cleaved rear facet.

The QD DFB laser under test is placed on a copper base with a thermistor and thermoelectric cooler (TEC) packaged together. The front facet of the laser is coupled with a lensed fiber for further characterization. The experimental setup is shown in Fig. 1(c). The QD DFB laser is driven in continuous-wave (CW) mode by a current source (Keithley 2401). A fiber coupler splits the optical power, with 90% directed into a back reflector (BKR) for optical feedback and 10% into the output path, which has an optical isolator (ISO) to prevent unintentional OFB from the characterization side. A variable optical attenuator (VOA) on the BKR path is used to continuously adjust the OFB strength, while a polarization controller (PC) maximizes the effects of OFB. The OFB strength is defined as the percentage of the optical power reflected back to the laser facet from its total output power. In this work, the OFB strength can be tuned from -40 dB to -6 dB.

As shown in Section I of Fig. 1(c), the optical spectrum is measured by an optical spectrum analyzer (OSA) (Yokogawa AQ6370D). Section II of Fig. 1(c) shows the RIN measurement setup. An O-band praseodymium-doped fiber amplifier (PDFA) (Thorlabs PDFA100) is used to compensate the relatively lower output power from 10% coupler port. The photodetector (Optilab PD-40M) converts optical signals into electrical signals, which are analyzed by an electrical spectrum analyzer (ESA) (Keysight N9030B).

3. RESULTS AND DISCUSSIONS

Figure 1(b) shows the continuous-wave light-current-voltage (L-I-V) characteristics of the QD DFB laser at 40 ℃ and in an OFB-free condition. The threshold current (I_{th}) is 64 mA, indicating relatively high internal losses brought by the current device structure and process procedure. The external efficiency η is calculated to be 22.1%, through $\eta = \frac{q\lambda}{hc}\frac{\Delta P}{\Delta I}$, with q the electron charge, λ the laser lasing wavelength, h the Planck constant and c the speed of light[2].

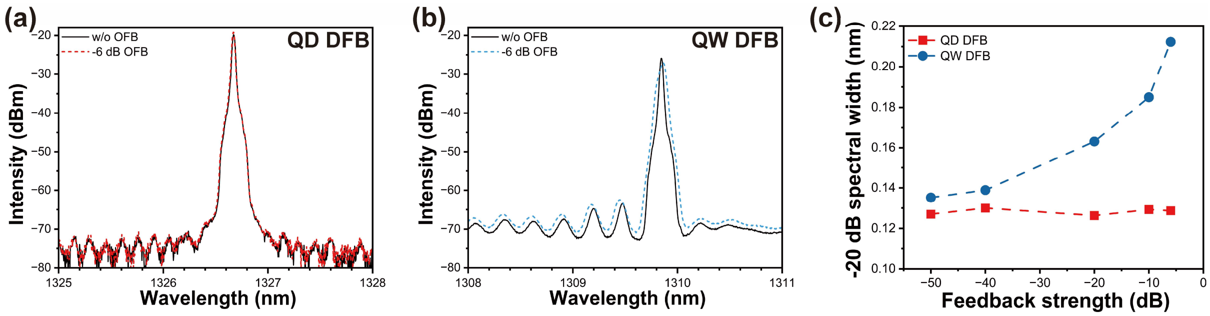

Figure 2. Optical spectra of the (a) QD DFB laser operating under OFB-free (black solid line) and OFB strength of -6 dB (red dashed line) conditions. The injection current is 80 mA, working temperature is 40 °C. (b) Commercial QW DFB laser operating under OFB-free (black solid line) and OFB strength of -6 dB (Blue dashed line). It operates at 40 °C with an output power comparable to that of the QD laser. (c) The -20 dB spectral width evolutions of the QD (red) and QW (blue) DFB lasers with varying OFB strengths.

Figure 2(a) shows the optical spectra of the QD DFB laser without external OFB and under -6 dB OFB, respectively. The single-mode wavelength and power remain stable under -6 dB OFB, and a high side-mode suppression ratio (SMSR) over 50 dB is maintained. In contrast, the commercial QW DFB laser shows a decline in SMSR under OFB due to the reduction of single-mode output power and the increase of side mode intensity. The spectral width of the QW DFB laser broadens under -6 dB OFB, compared to the state without external OFB. Figure 2(c) illustrates the -20 dB spectral width evolutions of the QD (red) and QW (blue) DFB lasers with varying OFB strengths. The point on the horizontal axis of -50 dB corresponds to the OFB-free state. The spectral width of QD DFB laser remains around 0.127 nm as the OFB strengths increase to -6 dB. However, under the same OFB condition, the spectral width of the commercial QW DFB laser increases by 57%, from 0.135 nm to 0.212 nm.

These above results indicate that the QW DFB experiences optical spectral quality deterioration under external OFB of -20 dB and above, while QD lasers maintain a stable single-mode output and can resist external OFB up to -6 dB. Considering that the critical OFB tolerance of a DFB laser increases with the higher injection current and decreased the optical wavelength tuning (OWD)[2], further increasing the injection current and adjusting the longitudinal mode wavelength can achieve higher OFB tolerance.

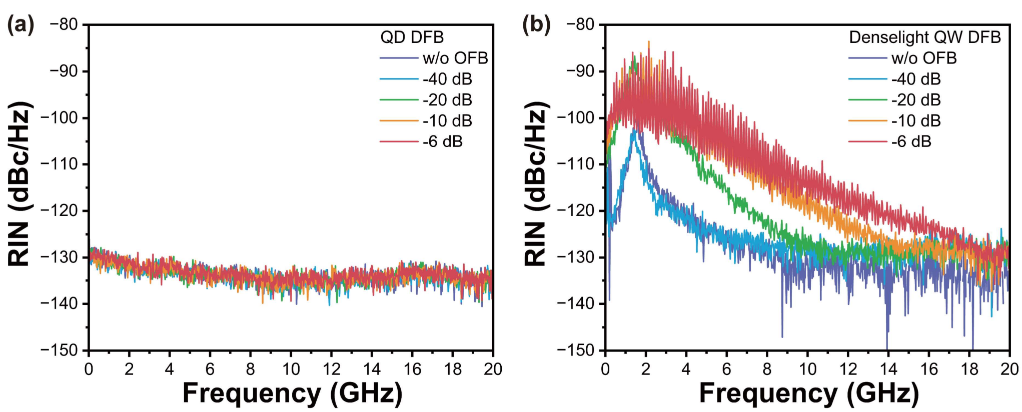

Figure 3. The RIN evolutions with different OFB strengths for the spectra of (a) QD laser and (b) QW laser operating under the same output power conditions. The RBW = VBW = 200 kHz for the ESA.

For further optical communication applications, such as light sources for transmission systems, the relative intensity noise (RIN) of the laser is a crucial indicator that affects amplitude modulation (AM) and constrains the modulation rate. As a consequence, the RINs of DFB lasers at different OFB strengths are characterized and shown in FIG 3. The injection current of the QD laser is 80 mA, and the operating temperature is 40 ℃, while the QW one operates at the same temperature and output power state. As illustrated in Fig. 3(a), the RIN of QD DFB laser reaches -135 dBc/Hz, and remains stable under OFB up to -6 dB. RIN is directly related to the output power of the laser. By increasing the injection current thus the output power, RIN is expected to reach a lower value. The resonance peak around 2 GHz shown in Fig. 3(b) corresponds to the relaxation oscillation of the QW laser. At an OFB strength of -20 dB, the RIN shows a significant increase before 10 GHz, reaching a maximum of -87 dBc/Hz. With further increase in the OFB strength to -6 dB, the relaxation oscillation peak continues to broaden, and the RIN exhibits a significant increase across the entire frequency range (up to 20 GHz). This deterioration of RIN indicates the negative impact of external OFB on QW lasers. In contrast, our QD DFB laser can operate stably under at least -6 dB OFB, making it a promising isolator-free light source for optical interconnects systems.

4. CONCLUSIONS

We experimentally studied the external OFB influence on our O-band InAs/GaAs QD DFB lasers. In terms of optical spectrum, our DFB laser can maintain a stable wavelength and power output under external OFB strengths of up to -6 dB. The SMSR remains above 50 dB, and the spectral width at -20 dB remains at 0.127nm. As for the RIN, as the OFB strengths increase to -6 dB, the RIN maintains a level of -135 dBc/Hz. Further increasing the output power is expected to reduce the RIN. In summary, the high reflection tolerance of our QD DFB laser enables it to serve as an isolator-free single-wavelength light source in hybrid-silicon photonic integrated circuits.

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