Quantum Dots for Photonic Integrated Circuits: From Isolation-Free to Amplitude Noise Squeezing

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2022 IEEE Photonics Society Summer Topicals Meeting Series (SUM) | 978-1-6654-3489-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/SUM53465.2022.9858311

***Abstract*—This paper reports on an InAs/GaAs quantum-dot (QD) laser for uncooled and isolation-free photonic integrated circuits. All lasing properties are improved with the increase of temperature by applying a design of optical wavelength detuning. The QD laser can also be used for squeezed light generation.**

***Index Terms*—quantum dot laser, isolation-free, uncooled application, light squeezing, photonic integrated circuit**

I. Introduction

The developments of 5G, artificial intelligence, and quantum technologies rely on high-performance photonic integrated circuits (PIC). Despite the huge progress in monolithic silicon photonic integration technologies, the performance of PICs suffer from their high power consumption and the chip-scale parasitic back-reflections. The chip-scale back-reflections are responsible for the unstable oscillations generated from laser sources. To address those issues, it is of significant importance to develop energy-efficient, thermally stable, and reflection-resistant lasers. In particular, a high performance single-frequency source is a promising solution for a range of applications, including high-resolution LIDAR systems, high-speed optical networks, and quantum states of light generation. Recently, quantum-dot (QD) lasers on silicon that are made with zero-dimensional nanostructures demonstrate a low threshold current, a high thermal stability, a strong tolerance for parasite reflections, and a high four-wave mixing (FWM) efficiency [2]. All these properties make the QD laser promising to serve as the sources for both classical and quantum PICs.

This paper reports on high performance QD lasers for PIC applications. Experimental results demonstrate that a QD distributed feedback (DFB) laser with a design of optical wavelength detuning (OWD) is a promising solution for uncooled and isolator-free applications. A following simulation reveals that QD lasers are ideal candidates for amplitude-noise squeezed light generation, which is useful for making precision oscillators.

II. Results and Discussions

The active region of the laser studied is made of 8-layer InAs QDs on (100) GaAs substrate that are grown by molecular beam epitaxy. The high dot density of $\sim 6 \times 10^{10}$ cm^{-2} per layer allows for a high optical gain. To further increase the modal gain, p-type doped GaAs spacers are added between each dot layer. As a result of the low dot size dispersion, the luminescence width at half-maximum of the active region is as narrow as $\sim$ 24 meV at room temperature. To realize single-frequency emission, the corrugated structure above the active region is fabricated with electron beam lithography and wet etching, whereas the InGaP/GaAs gratings on top are formed by metal organic vapour phase epitaxy. The longitudinal spatial hole burning of the DFB laser is finely controlled by applying a normalized coupling coefficient of the DFB grating κL at 1.2. To further improve the output power, the rear and the front facets are coated with high-reflection (HR) and antireflection (AR), respectively. To improve the laser performance at a high operating temperature, the DFB laser is designed with an OWD fixed to 25 nm at 25°C, which refers to the difference between the DFB lasing peak and the optical gain peak. Figure 1 depicts the optical spectra of the DFB laser under different temperatures. The positive OWD decreases with the increase of temperature from 15 to 55°C, due to the different temperature induced wavelength shift of the DFB mode (burgundy) and the gain peak (jade). The optimum operating temperature T_m of the device studied is 75°C, where

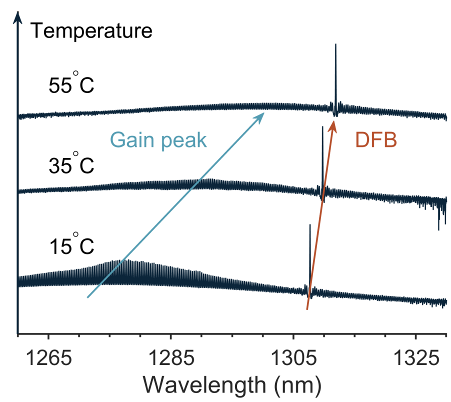

Fig. 1. (a) Optical spectra at $2 \times I_{th}$ under different temperatures. The variations of gain peak and DFB peak are marked by the jade and the burgundy lines, respectively.

the OWD approaches zero. As a result of the reduction of OWD below the T_m, the gain is increased, which results in the decrease of threshold current I_{th} from 10.5 to 6 mA with the increase of temperature from 15 to 55°C. Additionally, the gain will decrease if the operating temperature is higher than T_m, where the OWD becomes negative. The laser performance will suffer a degradation in that operating regime.

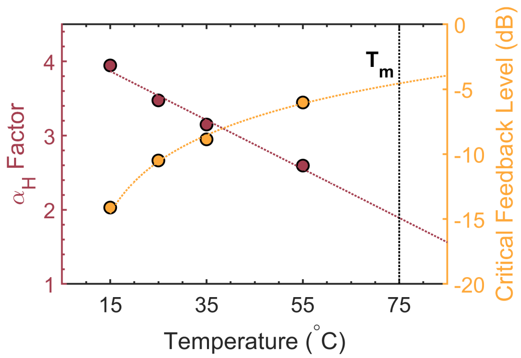

Fig. 2. Linewidth enhancement factor (red) and critical feedback level (yellow) at $6\times I_{th}$ as a function of the temperature. The optimum operating temperature at 75°C is marked by the dotted black line.

The feedback sensitivity of laser is dependent on the linewidth enhancement factor (α_H factor) of its active region [4]. Therefore, it is of importance to control the α_H factor to improve the laser's tolerance for parasite back-reflections. The red markers shown in Fig. 2 represent the α_H factor of the device studied in different temperature conditions while keeping the bias current at $6\times I_{th}$. The above-threshold α_H factors are measured by sinusoidal optical phase modulation method [5]. With the increase of temperature from 15 to 55°C, the α_H decreases from 4 to 2.5, which is due to the increase in differential gain. As a consequence of the decrease of α_H factor, the feedback insensitivity of laser is improved. To analyze the tolerance of the laser to back reflection, one of the commonly used approaches is the critical feedback level r_{crit} that is associated with the onset of coherence collapse [4]. The yellow markers shown in Figure 2 depict the r_{crit} of the DFB device when it operates at $6\times I_{th}$. In the full range of temperature, the DFB laser exhibits a high degree of tolerance for back-reflections in presence of r_{crit} much beyond the IEEE 802.3 standard at -21 dB. It is worth stressing that the α_H factor, the feedback resistance, and the modulation dynamics such as the K-factor (not shown in this paper) can all be improved when the operating temperature approaches T_m, which is marked by the dotted black line in Fig. 2.

The QD laser is an ideal source for silicon PICs because of its reflection insensitivity and its high tolerance to defects, which enables growth on Si and high volume, low cost fabrication [2]. In this context, utilizing a QD laser as a quantum state of light generator would be a low-cost and compact solution for integrated quantum technologies. QD lasers are also beneficial for light squeezing owing to their low population inversion factor. A squeezed state saturates the Heisenberg uncertainty principle with reduced uncertainty

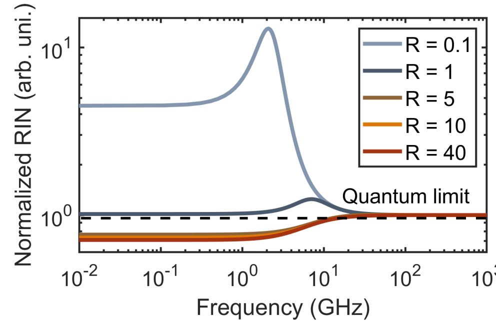

Fig. 3. Calculated normalized relative intensity noise spectra under different normalized noise-suppressed pump level R.

in one of its quadrature components (E_1, E_2) and increased uncertainty in the other hence $\Delta E_1 \times \Delta E_2 \geq \hbar\omega/2$. In a laser system, the two quadrature components thus refer to the amplitude and the phase, respectively. Therefore, based on a semiclassical model that was reported in an earlier work [6], amplitude squeezed light can be generated from a QD laser by utilizing a noise-suppressed pump. Although based on the particle character of radiation, this model remains classic because photons are considered as classic particles and without mutual interaction. Figure 3 depicts the calculated normalized relative intensity noise (RIN) spectra under different normalized pump level R with $R = I/I_{th} - 1$, in which I accounts for the pump current. The parameters for simulation are all measured from a Fabry-Perot QD laser. By ensuring $R > 1$, the RIN at low frequencies is squeezed below the quantum limit (i.e., shot noise level), which is approximated by the RIN level at high frequencies. This theoretical model also reveals that the degree of light squeezing can be improved by better optimizing the QD laser configuration in particular by increasing the quality factor of the cavity and considering InAs/GaAs QD lasers wherein low internal loss can be achieved.

III. Conclusions

This study highlights the potential of QD lasers for developing the uncooled and isolation-free high-speed photonic integrated circuits. Theoretical analysis also gives initial insights for generating non-classical states of light which is of paramount importance for the development of novel quiet optoelectronics sources using QD technology.

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