Advanced Photonics Congress (BGPP, IPR, Networks, NOMA, PVLED, SOF, SPPCom) © Optica Publishing Group 2022

Enhanced four-wave mixing dynamics in epitaxial quantum dot laser on silicon

Shihao Ding[1], **Bozhang Dong**[3], **Weng Chow**[2], **John Bowers**[3], **Frédéric Grillot**[1,4]

1. LTCI, Télécom Paris, Institut Polytechnique de Paris, 19 Place Marguerite Perey, Palaiseau, 91120, France
2. Sandia National Laboratories, Albuquerque, NM 87185, USA
3. Institute for Energy Efficiency, University of California Santa Barbara, Santa Barbara, CA 93106, USA
4. Center for High Technology Materials, University of New-Mexico, 1313 Goddard St SE, Albuquerque, New-Mexico 87106, USA
shihao.ding@telecom-paris.fr

Abstract: The four-wave mixing conversion efficiency of quantum dot laser is much higher than that of quantum well. These results are important for self-mode-locked pulse production and high-bandwidth optical frequency comb generation.

1. Introduction

Quantum dots (QD) are considered as an important choice for monolithic integrated light sources and photodiodes because of their improved tolerance to dislocations generated during epitaxial growth of group III-V on silicon compared to quantum wells (QW) [1]. In addition, the three-dimensional charge carrier confinement in QDs contributes to high material gain, low noise and significant temperature stability [2,3]. It also results in a low linewidth enhancement factor (α_H-factor) in QD, even approaching zero. The extraction of α_H-factor above threshold using phase modulation method is further evidence of the excellent performance of QD lasers [4]. In addition, the extensive optical non-linearities of QDs in particular the $\chi^{(3)}$ coefficient, was found to improve the efficiency of four-wave mixing (FWM) conversion significantly.

2. Results

Semiconductor frequency comb lasers driven by the FWM process exhibit a significant dependence on the α_H-factor [4]. Hence, investigations of the effect of different modulation frequencies on the α_H-factor is of significance. Corresponding studies are performed on a silicon-based Fabry-Perot (FP) QD laser which contains 5 QD layers with p-doped spacer. The details of the structure of silicon-based QD laser are shown in Fig. 1(a) and in this paper [5]. The results for the α_H-factor were also compared with those of a QW laser grown heterogeneously on silicon as shown in Fig. 1(b). This silicon-based epitaxial QD laser exhibits an excellent α_H-factor with the values between 1.0 and 1.6 for 19 longitudinal modes at twice threshold current and 30 °C. Furthermore, silicon-based QW lasers with the same epitaxial structure exhibit an α_H-factor extracted by the ASE method that is more than three times larger than that of QD lasers.

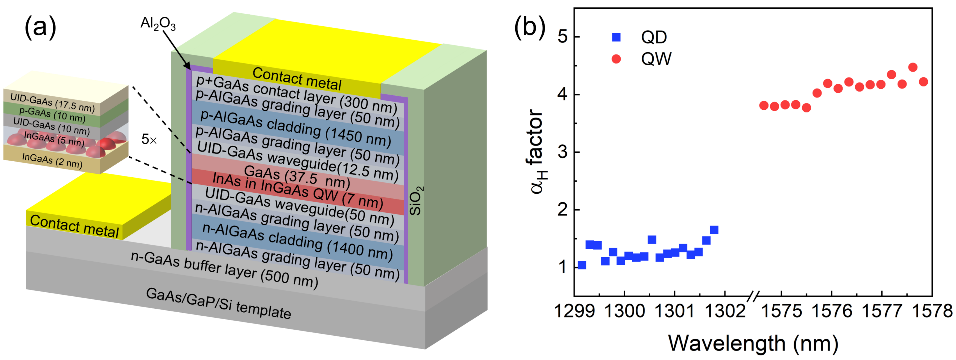

Fig. 1. (a) Schematic of quantum dots laser device structure. (b) Spectral dependence of the α_H-factor of both QD and QW lasers.

QD laser exhibits a much smaller α_H-factor than the QW laser, so this will provide the basis for the FWM dynamic characteristics of QD lasers. The intracavity drive-probe measurements are performed at 25 °C. The experiment is designed as shown in Fig. 2(a). Two narrow linewidth tunable lasers are used as drive laser and probe laser which are injected into the QD or QW laser through an optical circulator and a lens-end fiber. The optical spectrum is recorded by an optical spectrum analyzer (OSA). The drive laser is used to lock the laser cavity mode to 30 dB, which allows for the generation of FWM coherent beating. To obtain maximum frequency conversion efficiency, the probe signal needs to be adjusted to exactly match one of the suppressed FP cavity modes in the stable locking regime.

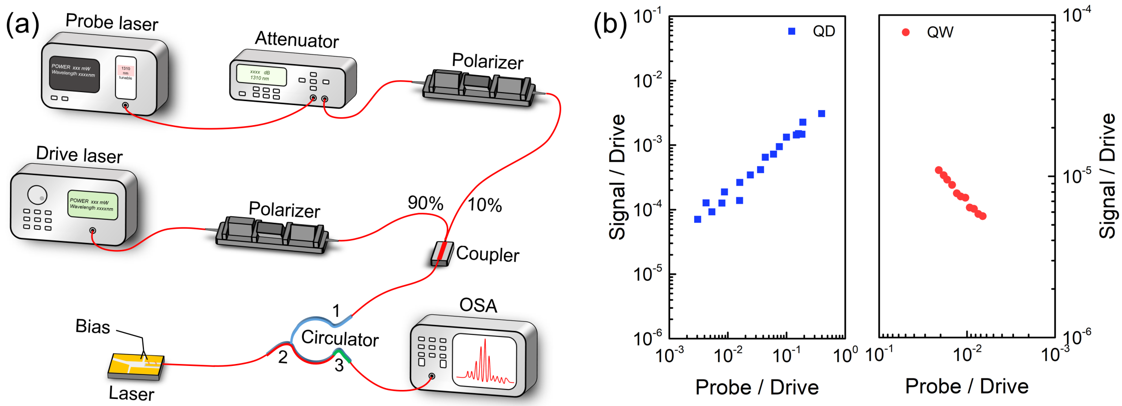

Fig. 2. (a) Experimental setup for FWM by Optical injection locking. The FP modes of the QD laser is locked by the drive laser. The tunable probe laser is used to generate the probe signal. (b) Four-wave mixing efficiency under the stokes condition as a function of frequency detuning of QD and QW.

The three-dimensional carrier confinement in the QD enhances the third-order nonlinear hence causing an improvement in FWM conversion efficiency. The FWM conversion efficiency is dependent on the ratio of signal power to drive power and the ratio of probe power to drive power. Fig. 2(b) displays the results for an epitaxial QD laser epitaxially grown on Si with p-doped in the active region and a QW laser at the frequency detuning, i.e. the difference between the frequencies of the probe and the drive sources (-300 GHz) under Stokes conditions, with the bias current fixed at twice the threshold. The FWM conversion efficiency of QD lasers is more than 10 times higher than the efficiency of QW devices. It is the superior third-order optical non-linear and p-type doping of the QD laser that significantly improves the FWM conversion efficiency.

3. Conclusion

This work shows a lower linewidth enhancement factor and higher FWM conversion efficiency, which leads to promising QD lasers for self-tuning phase-locked pulse generation and high bandwidth optical frequency comb generation.

References

1. Andrew D Lee, Qi Jiang, Mingchu Tang, Yunyan Zhang, Alwyn J Seeds, and Huiyun Liu. Inas/gaas quantum-dot lasers monolithically grown on si, ge, and ge-on-si substrates. *IEEE Journal of Selected Topics in Quantum Electronics*, 19(4):1901107–1901107, 2013.
2. Justin C Norman, Daehwan Jung, Zeyu Zhang, Yating Wan, Songtao Liu, Chen Shang, Robert W Herrick, Weng W Chow, Arthur C Gossard, and John E Bowers. A review of high-performance quantum dot lasers on silicon. *IEEE Journal of Quantum Electronics*, 55(2):1–11, 2019.
3. Jianan Duan, Yueguang Zhou, Bozhang Dong, Heming Huang, Justin C Norman, Daehwan Jung, Zeyu Zhang, Cheng Wang, John E Bowers, and Frédéric Grillot. Effect of p-doping on the intensity noise of epitaxial quantum dot lasers on silicon. *Optics Letters*, 45(17):4887–4890, 2020.
4. Shihao Ding, Bozhang Dong, Heming Huang, John Bowers, and Frédéric Grillot. Spectral dispersion of the linewidth enhancement factor and four wave mixing conversion efficiency of an inas/gaas multimode quantum dot laser. *Applied Physics Letters*, 120(8):081105, 2022.
5. Jianan Duan, Heming Huang, Bozhang Dong, Justin C Norman, Zeyu Zhang, John E Bowers, and Frédéric Grillot. Dynamic and nonlinear properties of epitaxial quantum dot lasers on silicon for isolator-free integration. *Photonics Research*, 7(11):1222–1228, 2019.