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Influence of the cavity design on the differential gain and linewidth enhancement factor of a QD comb laser

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ABSTRACT

This work investigates the effects of the confinement factor on the linewidth enhancement factor in hybrid silicon quantum dot comb lasers, which is a key parameter involved in frequency comb generation. Experiments are performed on two laser devices sharing the same gain material with slightly different cavity designs resulting in different confinement factors. The results highlight that a lower confinement factor leads to a smaller carrier-induced refractive index variation and a larger differential gain, together resulting in a smaller linewidth enhancement factor, which in turn translates into different sets of performance regarding the feedback applications. This paper brings novel insights on the fundamental aspects of quantum dot comb lasers and provides new guidelines of future on-chip light sources for integrated wavelength-division multiplexing applications.

Keywords: Quantum dots, frequency combs, linewidth enhancement factor, laser dynamics, silicon photonics

1. INTRODUCTION

Data transfers have been recently increasing greatly for smaller and smaller distances, in particular in High Performance Computing (HPC) systems where they can reach up to several petabits per second between the memory and the different compute nodes.[1] Relying on on-chip wavelength division multiplexing (WDM) technology, optical interconnects allow the transmission of multiple wavelengths that can be separately modulated to greatly improve the data transfer speed for data center applications. Although this approach can be achieved by allocating one single-wavelength laser per channel, it is not very appropriate for integrated WDM solutions in photonics integrated circuits (PICs) as it results in a larger footprint and energy consumption along with a lower stability of the modes frequencies that are not always perfectly equally spaced. Another possibility relies on using a single laser made with quantum dots (QD) and producing an efficient optical frequency comb (OFC) wherein the phase of each line cannot shift independently from the others.[2] Thanks to their wide gain bandwidth and narrow linewidth,[3] QD lasers are meaningful for enhancing the performance of OFC. In addition, while in bulk materials carriers are distributed to higher energy states at high temperature, no such redistribution takes place in QD devices since the energy difference between the excited states and the ground state is beyond the thermal energy k_BT. Therefore, all carriers contribute to the inversion at lasing energy, hence leading to a great thermal stability. The figure of merit of a comb laser is the linewidth of each line and the bandwidth of operation. The former can be fundamentally reduced by minimizing the linewidth enhancement factor (α_H-factor), while the latter scales up with α_H.[4,5] To this end, design rules must be found to address this tradeoff. Furthermore, it is known that the α_H-factor impacts the sensitivity of the comb laser to external optical feedback,[6,7] which is also a serious problem for integrated technologies where the inclusion of an optical isolator remains bulky and expensive. In this work, we investigate experimentally the α_H-factor in two carefully chosen hybrid silicon InAs/GaAs

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QD comb lasers operating under different operating conditions. The lasers share the same gain material, but have slightly different cavity designs resulting in different values of the confinement factor Γ_{QD}. We show that a lower confinement factor leads to a smaller carrier-induced refractive index variation and a larger differential gain, together resulting in a lower α_H, which translates into an improved resilience to external optical feedback. We believe that this paper brings further insights on comb lasers, which is of paramount importance for future on-chip light sources for integrated WDM applications in data centers and in supercomputers.

2. LASER STRUCTURE & EXPERIMENTAL SETUP

The multi-section laser is depicted schematically in Figure 1(a). The structure consists of a 2.6-mm-long cavity with mirrors having 50% power reflectivity on both sides, and a 1.4 mm active region in the center. The semiconductor optical amplifier (SOA) section is made with 8 layers of InAs QDs on GaAs and a 45-μm-long saturable absorber (SA) is included in a colliding configuration. The optical mode is transferred from active waveguide down to the passive silicon waveguide through mode converters. Then, the light is coupled out through a grating coupler (GC). Further information about the epitaxial structure is available elsewhere.[8,9]

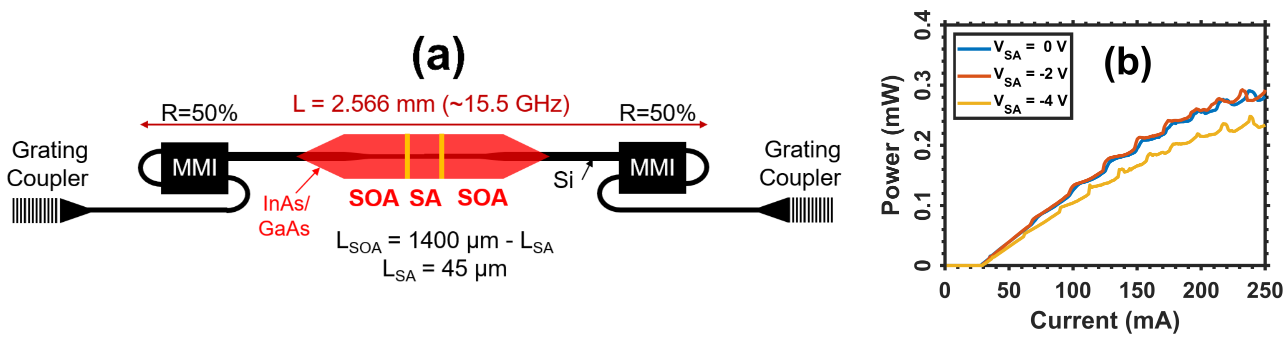

Figure 1. (a) Schematics of the laser design. SOA: semiconductor optical amplifier; SA: saturable absorber; GC: grating coupler; MMI: multi-mode interferometer. (b) LI characteristic of laser A at voltages of 0V, -2V and -4V on the SA.

In this study, two lasers with different confinement factors Γ_{QD} are investigated, that is to say two lasers with different overlaps of the optical mode with the whole active region. The confinement factor is of 35% (corresponding to 0.9% in a single QD layer) for laser A and of 58% (corresponding to 0.55% in a single QD layer) for laser B. Figure 1(b) depicts the LI curves under different SA voltages (0V, -2V and -4V) measured in laser A at room temperature of 20°C. Surprisingly, the threshold current I_{th} remains constant at 29 mA whatever the reverse voltage conditions.

3. RESULTS AND DISCUSSION

The α_H-factor drives the coupling between the phase and the amplitude of the electrical field or, in a similar manner, the coupling between the gain and the refractive index. This parameter is described as the ratio of the derivatives of the gain and optical index with respect to the carrier density, such as

$$\alpha_H = -\frac{4n\pi}{\lambda^2}\frac{d\lambda/dI}{dG/dI} \tag{1}$$

where n is the effective group index, λ the photon wavelength, G the net modal gain, and I the bias current. The α_H has often been measured in single-section devices with respect to the pumping condition, but little is known for multi-section devices especially in presence of an absorber section. In the following experiments, all values of the α_H are measured at threshold through the amplified spontaneous emission (ASE).[10–13] First, a set of optical spectra is captured below and above the laser's threshold with a high resolution (10 pm) optical spectrum analyzer (OSA). Then the differential gain dG/dI and the wavelength shift $d\lambda/dI$ are calculated for each longitudinal mode.

In semiconductor lasers, the wavelength shift below threshold $d\lambda_1$ is caused by carrier-induced refractive index change (band filling), while above, since the gain is clamped, only the thermal effects persist in the wavelength shift $d\lambda_2$.[12] Both can be expressed as follows:

$$d\lambda_1 = \left(\frac{dn}{n} + \frac{dn_t}{n} + \frac{dL}{L}\right)\lambda, \qquad d\lambda_2 = \left(\frac{dn_t}{n} + \frac{dL}{L}\right)\lambda \tag{2}$$

where dn is the refractive index change due to the injection of carriers, dn_t the refractive index change induced by the active region temperature increase, and dL the thermal expansion of the laser cavity.

In the devices studied here, the thermal red-shift is predominant to the carrier-induced blue-shift, resulting in a slight red-shift even below threshold, as visible in Figure 2(a). Therefore, to avoid any underestimation of the α_H-factor, thermal effects must be properly eliminated in Eq. 1. To do so, the carrier blue-shift $d\lambda = \lambda_1 - \lambda_2$ is extracted by subtracting the slope above threshold from the one below.

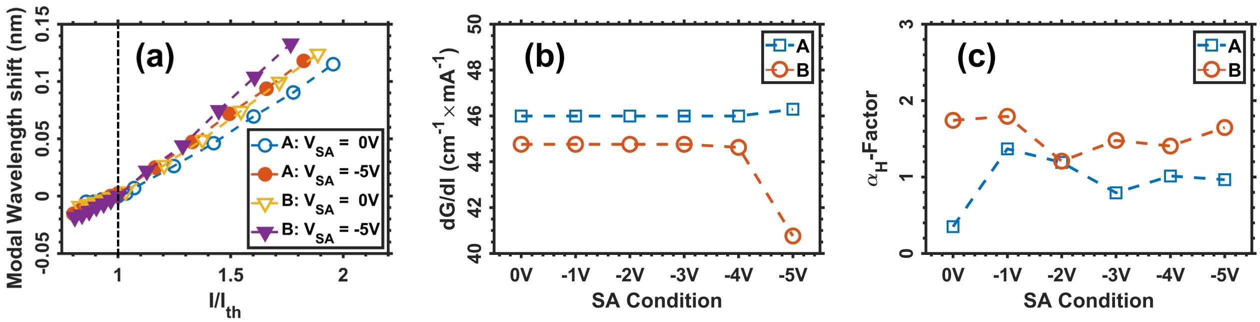

Figure 2. (a) Wavelength shift with respect to the normalized current I/I_{th} for both lasers at $V_{SA} = 0$V and -5V. (b) Differential gain of both lasers for V_{SA} from 0V to -5V. (c) Measured α_H-factor at threshold of both lasers for V_{SA} from 0V to -5V.

Figure 2(a) shows the wavelength shift of the first lasing mode with respect to the normalized current I/I_{th} for each laser at $V_{SA} = 0$V and -5V. The first lasing mode is defined as the mode with the highest intensity just above threshold. Both lasers display a higher thermal red-shift at -5V compared to 0V, which is related to the heating from the increased losses of the SA. Moreover, for each SA voltage laser B shows an increased red-shift above threshold compared to laser A, while they both exhibit similar wavelength shifts below. This indicates a higher carrier-induced blue-shift in laser B. The higher thermal load in laser B can be explained by the increased photon density in the active region, where the SA is located. Figure 2(b) represents the differential gain dG/dI of the first lasing mode of both lasers for SA voltages from 0V to -5V. The dG/dI appears to be consistently higher for laser A than for laser B, which is somewhat counter-intuitive since a lower confinement factor should result in less gain. Further investigations are needed to explain such a difference. Finally, Figure 2(c) displays the α_H-factor of the first lasing mode of both lasers at SA voltages from 0V to -5V. It can be noted that α_H is lower for laser A than for laser B, which is consistent with Figures 2(a) and (b) showing a lower carrier-induced wavelength shift and a higher differential gain. Furthermore, apart from the $V_{SA} = 0$V case, we found that the value of the α_H-factor at threshold is quite stable whatever the SA condition, for both lasers.

Figure 3 highlights the impact of the SA voltage on the OFC of both lasers. Laser A displays a nicely formed comb even at $V_{SA} = 0V$, however in laser B, lasing modes are less grouped. Moreover, the optical spectrum of laser A shows a reduction of the side modes when the SA voltage is increased from 0V to -5V, while the main lasing modes remain mostly unaffected. Such as situation is quite different for laser B, for which a few main modes are suppressed as well. This could explain the dip observed at -5V in Figure 2(b).

As aforementioned, the α_H-factor is also linked to the effects of the external optical feedback on the laser.[6,7] To demonstrate this, Figure 4 shows two spectra for each laser under free-running operation (namely no feedback) and at the maximum feedback strength achievable with our setup (estimated to be around -17dB).

Laser A shows a very good resilience of the comb against external optical feedback, with only a few modes losing around 1 dB of peak power. This can be explained by the lower value of the α_H-factor found for laser A in Figure

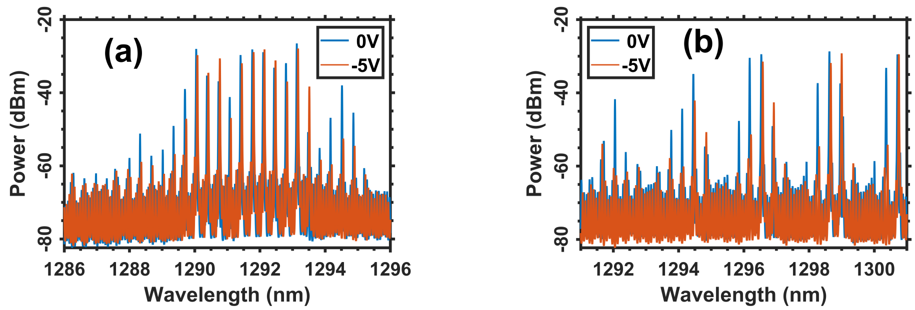

Figure 3. Free-running optical spectra of (a) laser A and (b) laser B at 20°C, with bias conditions of $2 \times I_{th}$ and $V_{SA} = 0$V and -5V.

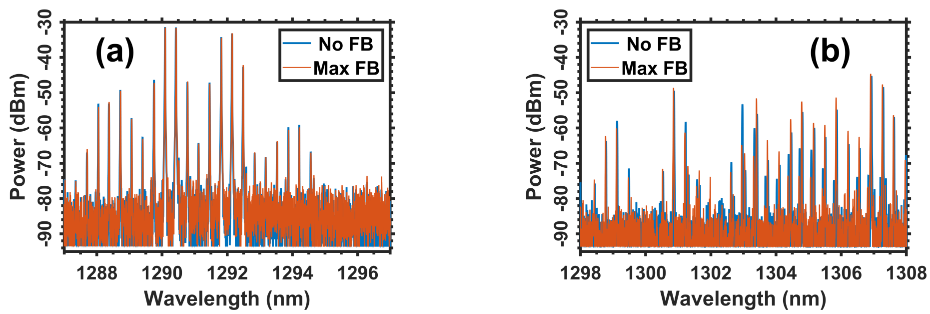

Figure 4. Impact of the external optical feedback on the optical spectra of (a) laser A and (b) laser B, at room temperature (20°C) with bias conditions of I = 240mA and $V_{SA} = -5V$.

2(c). Furthermore, these results are also attributed to the lower confinement factor Γ_{QD} in laser A leading to a smaller fraction of the feedback being coupled back into the active region. On the contrary, the laser B is found more affected by the feedback, with some modes either loosing or gaining several decibels of peak power (up to -15dB) while the whole comb spectrum is slightly blue-shifted by the feedback. For simplicity, we only present here the spectra corresponding to a specific set of bias conditions (I = 240 mA and $V_{SA} = -5V$), but it is important to stress that the same results are observed at most operating conditions.

4. CONCLUSIONS

This work investigates the role of the SA and the confinement factor in multi-section hybrid silicon QD lasers. In particular, we focused on the wavelength shift and differential gain, which both impact the α_H-factor. The experimental results show a stable α_H over various reverse voltage conditions, the smallest value being achieved for the laser having the lowest Γ_{QD}, as a consequence of a higher differential gain. Together, these properties gives the highest resistance to optical feedback. As a conclusion, this work provides a good understanding of the impact of the design of the cavity of QD comb lasers on the α_H-factor and thus provide further guidelines for future on-chip multi-wavelength light sources in integrated WDM applications.

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