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Effects of external optical feedback in InAs/InP quantum dot frequency comb lasers on silicon

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ABSTRACT

On-chip integration of semiconductor lasers have shown a growing interest in recent years, especially for the development of photonic integrated circuits (PICs) which are of paramount importance for high-speed communication within and between data centers, and fast on-board data exchanges. For all these applications, a key challenge remains the stability of the laser sources integrated on a PIC in presence of external optical feedback with the view to avoid integrated bulky and costly optical isolation. In this study, the effects of external optical feedback are investigated in hybrid InAs/InP quantum dot comb lasers on silicon. The design of the cavity includes a semiconductor optical amplifier section, a saturable absorber and an on-chip external cavity incorporating a vertical coupler. We measured the resulting feedback properties with respect to the operation conditions (bias current and voltage) and to the length of the saturable absorber. We show that under most operating conditions, the laser remains stable against optical feedback, only few regimes of operation occur, which either improve or degrade the frequency comb and/or the radio-frequency beatnote power of the laser.

Keywords: Quantum dots, frequency combs, optical feedback, laser dynamics

1. INTRODUCTION

High Performance Computing (HPC) systems have seen a vast increase in data transfers in recent years, reaching 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. Despite that, using multiple single-wavelength lasers does not offer enough compactness which is a critical issue for silicon based-integrated technologies. In order to significantly reduce complexity and energy requirements in on-chip WDM systems, a single laser using quantum dots (QD) as an active medium and producing an efficient optical frequency comb (OFC) can be considered instead.[2] Thanks to their wide gain bandwidth and narrow linewidth,[3] QD materials are meaningful for enhancing the performance of OFCs whereas the ultimate carrier confinement within the nanostructures provides an excellent thermal stability. Nevertheless, for the aforementioned applications, a key challenge is the stability of the laser sources integrated on a PIC in presence of external optical feedback. In this study, the effects of external optical feedback are investigated on a hybrid InAs/InP QD comb laser. To do so, we measure the feedback properties with respect to the reverse voltage and bias current. The influence of the confinement factor in the active region, the mesa width and length of the saturable absorber (SA) is also studied. We show that under most operating conditions, the laser remains stable against optical feedback. Only few regimes of operation occur, which either improve or degrade the frequency comb performance. These inputs are of paramount importance for future PICs circuits without bulky and costly optical isolation as well as for HPC in next-generation supercomputers.

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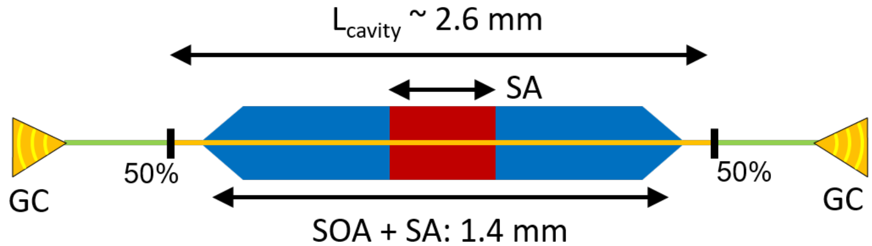
2. LASER STRUCTURE & EXPERIMENTAL SETUP

The multi-section laser design is depicted schematically in Figure 1. The structure consists of a 2.6-mm-long cavity that has mirrors with 50% reflectivity on both sides, and a 1.4 mm active region is placed in the center. The semiconductor optical amplifier (SOA) section incorporates 8 layers of InAs/InP QDs and the SA is positioned in the middle. The optical mode transfer from active waveguide down to the passive Si waveguide is ensured by mode converters and the output light is coupled out through a grating coupler (GC). More information about the epitaxial structure can be found elsewhere.[4,5]



Laser	L_{SA}	W_{mesa}	Γ_{QD}
A	45 μm	4 μm	35%
B	45 μm	6 μm	35%
C	45 μm	4 μm	58%
D	45 μm	6 μm	58%
E	176 μm	4 μm	35%

Figure 1. Schematics of the laser design, and table summarizing the values of L_{SA}, W_{mesa} and Γ_{QD} for all five lasers. SOA: semiconductor optical amplifier; SA: saturable absorber; GC: grating coupler. The inset table lists the differences in cavity design for all five studied lasers.

In this study, five lasers with different cavity designs are investigated. The waveguide width W_{mesa} is varied from $4\mu m$ for lasers A and C to $6\mu m$ for lasers B and D. The confinement factor Γ_{QD}, that reflects the overlap of the optical mode with the whole active region is of 35% (corresponding to 0.9% in a single QD layer) for designs A and B whereas it increases to 58% (corresponding to 0.55% in a single QD layer) for C and D ones. As for the last laser E, the design is identical to device A, except for its longer SA of 176 μm compared to 45 μm in all others. All parameters are summarized in the table in Figure 1. Figure 2(a) depicts the LI curves under different SA voltages (0V, -2V and -4V) measured in laser A at room temperature of $20°C$. The threshold current is of 21 mA for the three reverse voltage conditions. Figure 2(b) and 2(c) show the laser spectra (A) in both optical and radio frequency (RF) domain under 110 mA and $V_{SA} = 0V$ at $20°C$. At these conditions, the emitting wavelength is centered at 1307 nm, and the beatnote frequency is around 15.4 GHz.

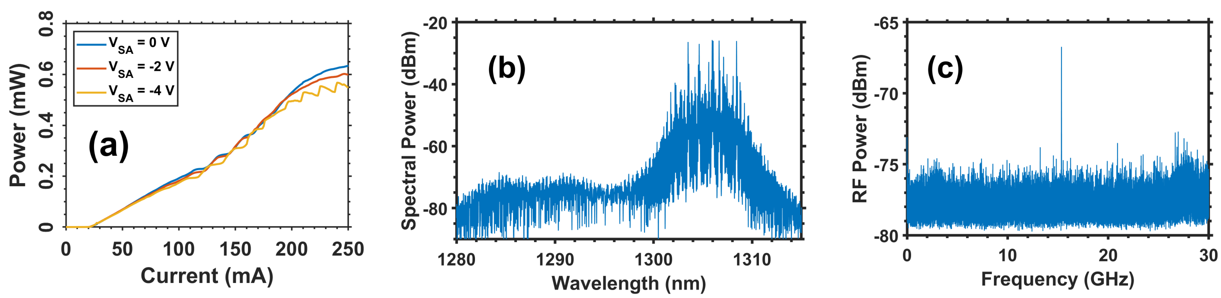


Figure 2. (a) LI characteristic of laser A at a voltage of 0V, -2V and -4V on the SA; (b) Optical and (c) RF spectra of the laser A at 110mA with $V_{SA} = 0V$.

The comb properties of the lasers are measured under external optical feedback for different bias currents and SA voltages. The light from the laser is coupled to a micro-lensed fiber, the coupled power is then split: 90% goes to a back-reflector with attenuation, allowing to adjust the feedback strength from -72 dB up to -17 dB, with the consideration of the losses from the fiber coupling and in the setup; the rest 10% is directed to either an optical spectral analyser (OSA) or an electrical spectrum analyser (ESA) by an optical switch, in order to characterize the comb bandwidth, number of modes and modal power variation, as well as RF beatnote power variation.

3. RESULTS AND DISCUSSION

In our experiment, the external optical feedback affects the comb properties in different ways. To distinguish the impact, we recorded the optical power of the lasing modes, the comb bandwidth, the number of modes displayed in the comb spectrum, and the RF beat-note power. Figure 3(a) shows an example of an improvement of the comb properties. One could argue that the lasing operation switches to another set of modes with different wavelengths, however, in this case the comb is clearly improved. For instance, the bandwidth at -10 dB increases from 2 nm to 3.1 nm, while the number of modes is improved from 11 to 18. On the contrary, Figure 3(b) shows a different situation where a more nuanced change in the comb is observed. Although the overall power of the lasing modes is increased, the bandwidth at -10 dB is slightly affected hence leading to a reduction from 13 modes to 9 modes.

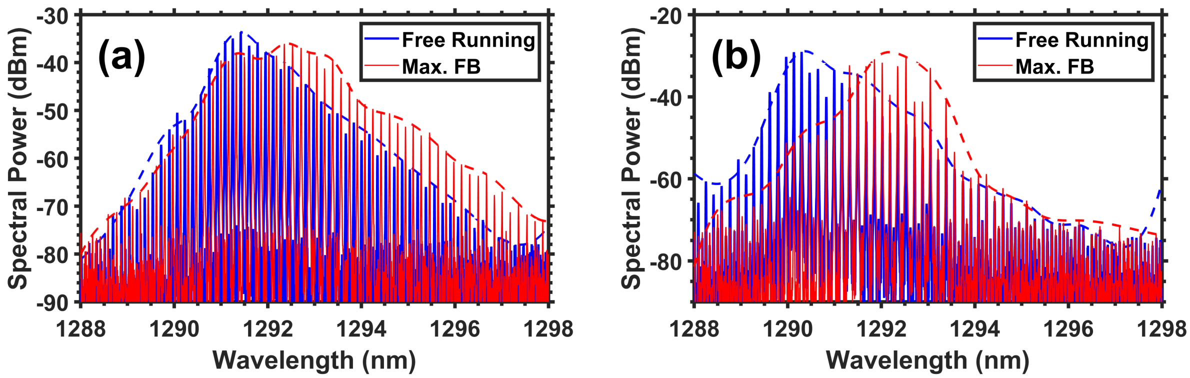


Figure 3. Optical spectra without feedback (in blue) and with maximum feedback strength (in red) for the laser E at (a) 60mA and $V_{SA} = -5V$; and at (b) 70mA and $V_{SA} = -3V$.

For each set of bias conditions, the impact on comb properties of the optical feedback is characterized as either leading to insensitivity or an improvement or a degradation of the comb, or a mixed situation between the two. Figure 4 shows two maps summarizing the results for lasers A and D. Here, the dark blue regions are bias conditions were the laser is found to be insensitive to optical feedback, i.e. the spectra remain the same regardless of the tested feedback strength; the green regions represent an improvement of the comb properties (comb width, number of modes, mode power, or RF beatnote power), red regions represent a deterioration of comb properties, and cyan regions correspond to the mixed situation where some properties are improved, others degraded (as in Figure 3(b)). Owing to the nature of the QD materials, these two lasers have good immunity against external feedback, as the dark blue region is highly dominant in both maps. Similar behaviors have been observed for the other lasers (not shown here). Furthermore, the two lasers having the lowest confinement factor Γ_{QD} (lasers A and B) show a stronger resilience to optical feedback than lasers C and D which is due to the lower optical power recoupled into the active region. Moreover, laser A is found to be the most resilient laser, with only one set of bias conditions where the comb is degraded by the presence of optical feedback. Finally, while the laser E with a longer SA displays similar results, it appears less immune to optical feedback at lower V_{SA}. This effect can be explained through the linewidth enhancement factor α_H which depends on the reverse voltage. Indeed, while this parameter is pretty constant for the lasers with short SA, it is found to slightly increase with V_{SA} for lasers with long SA section (not shown here).Overall, these results suggest that all lasers under study are robust against optical feedback with respect to the operating conditions whereas most of the changes in the comb dynamics appear at high biases (starting from around 150 mA) and/or high SA voltages.

4. CONCLUSIONS

In this work, we investigated the effects of optical feedback on InAs/InP qQD frequency comb lasers on silicon with a multi-section cavity design. All lasers under study display a very good resilience against external optical feedback. The devices were mostly affected at high bias currents and/or SA voltages whereas those with the lowest confinement factor showed the best reflection immunity. Also we observed that under some specific

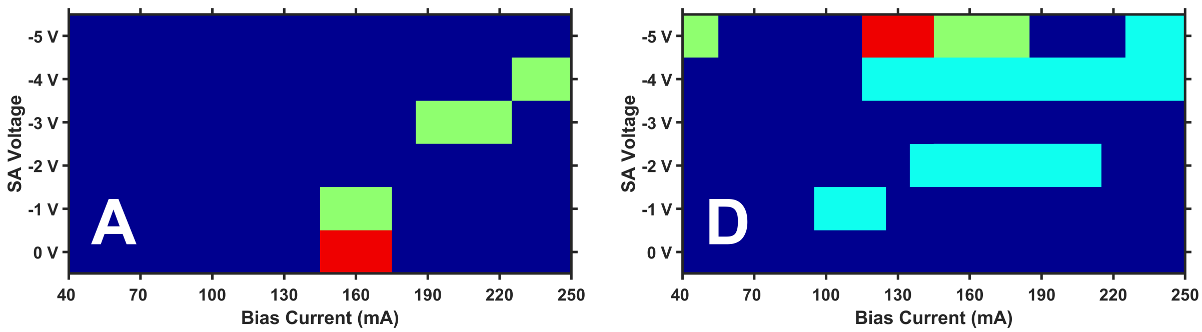


Figure 4. Map of the bias conditions tested for the A and D lasers. Dark blue: insensitive to optical feedback; green: comb improvement; red: comb degradation; and cyan: improves some comb properties and degrade some others.

feedback conditions, the comb can be improved in terms of bandwidth, number of lines emitted and output power. This initial work provides new guidelines for the conception of future on-chip WDM systems. Further work will involve comb improvement through optical injection,[6] time domain characterization, and extraction of the α_H factor for each comb line.[7]

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