Thermally controlled frequency comb generation in hybrid silicon quantum dot lasers

(Student paper)
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This work investigates the spectral properties of a hybrid silicon InAs/GaAs quantum dot comb laser. Experiments show that the comb bandwidth can be nicely improved through a proper thermal-control. They also unveil the possibility to achieve comb operation without pulses as a direct consequence of the background dispersion. As discussed hereinafter, these effects result from different contributions of both materials and device parameters of the quantum dot laser. Overall, these results provide novel findings for the conception of next-generation multi-channel optical transceivers for short-reach inter-chip communications.

Keywords: Quantum dots, frequency combs, optical interconnects, silicon photonics

INTRODUCTION

Over the past two decades, high performance computing (HPC) has been deeply incorporated in the network infrastructure as the global Internet usage is ramping up1. Nowadays, hyperscale data centers and supercomputers are installed around the world to share the extensive loads of demands on intense computing power and high-volume transmission. However, current Von Neumann architecture of modern computers requires frequent exchanges between computing and storage units and is becoming an explicit limiting factor of the performance of the global network2, as off-chip communications are commonly established over electric wires/cables, where the transmission capacity per link is dependent on data rate and distance, and the general energy efficiency is less than ideal. Moreover, when considering distributed systems, intensive inter-server and inter-rack hardware resource sharing can further exacerbate the bandwidth bottleneck problem3. One viable solution to overcome such obstacle, is to replace inter-chip, inter-server, and inter-rack electric wires and cables with high-performance optical interlinks, that are considerably more energy-efficient and rather independent on reach. To fully leverage the transmission capacity of optical carrier, photonic integration technology enabled integrated Dense Wavelength Division Multiplexing (DWDM) system has been proposed, allowing to lay out data line array through a single optical waveguide/fiber, and reducing circuit complexity by removing redundant footprints. Thanks to the major breakthroughs in silicon-based photonic integrated circuits (PICs) over recent years, compact optical transmitters that incorporate DWDM functionalities can be envisioned in the near future4. On this stage, it is preferable to use one single optical frequency comb (OFC) laser as light source instead of multiple single-mode lasers to keep the chip design simple, however, manipulating the OFC to provide required number of channels is a rather challenging task.

To this end, semiconductor lasers made with quantum dots (QD) as an active gain media are considered as an attractive candidate, hence providing high optical gain with a low threshold current density, which are all desired properties for achieving high performance integrated sources. Moreover, owing to the dot size dispersion, QD lasers often exhibit a wide gain spectrum, ideal for OFC generation5. In this work, we investigate the comb properties of a hybrid silicon InAs/GaAs QD comb laser. By varying the temperature from 20°C to 50°C, the comb width is found to increase with respectively 20, 22, 30 and 40 lines above floor level. We believe that this thermally controlled frequency comb generation is achieved from the linewidth enhancement factor ($\alpha_i$) and the homogenous broadening which are both temperature-dependent. On another hand, our beat note measurements point out the possible to achieve frequency comb enhancement without pulses in the time domain. This phenomenon is explained through the group velocity dispersion (GVD) which is not fully compensated by the optical nonlinearities of the saturable absorber. Overall, these results bring new insights on QD comb lasers and can therefore be utilized for the conception of future DWDM optical transceivers for short-reach optical interlinks.

LASER STRUCTURE

The studied laser has a multi-section cavity design, schematically represented in Figure 1(a). Two mirrors with 50% and 100% reflectivity define the 2.6-mm-long laser cavity. The 1.4-mm-long active region includes a semiconductor
optical amplifier (SOA) with a 176-µm-long saturable absorber (SA) placed in a middle, in a colliding pulse configuration. Such SA placement allows to take advantage of the second harmonic, providing richer channel spacing at high bit-rate\(^6\). The epitaxial structure consists of 8 layers of InAs QDs in GaAs, integrated on silicon. The optical mode transfer between the III-V and Si waveguides is realized by modes converters at the edge of the active region. A grating coupler (GC) couples the light out of the chip, to be collected in a micro-lensed optical fiber.

The epitaxial structure is obtained by taking an unpatterned wafer of InAs/GaAs QDs and wafer-bonding it to a Silicon-on-Insulator (SOI) wafer with already patterned Si passive devices. Standard III-V processing techniques are then used to etch the QD material and deposit the p- and n-contacts. A more detailed explanation of the epitaxial processes and laser structure can be found elsewhere\(^4,6\).

**RESULTS AND DISCUSSION**

Figure 2(a) shows the optical spectra of the laser under increasing temperatures of 20°C, 30°C, 40°C and 50°C, for bias conditions of I = 2 × \(I_{th}\) and \(V_{SA} = -6V\). The emission wavelength of the different spectra is respectively centered around 1297 nm, 1299 nm, 1303 nm and 1305 nm, which is attributed to the thermal redshift of the gain envelope. The comb width appears to increase with the temperature, with respectively 20, 22, 30 and 40 lines above floor level, and 6, 8, 11 and 12 lines within a -10 dB power variation from the highest power mode of each spectrum, as delimited by the arrows in figure 2(a). While the reason for this temperature-dependence comb spectrum is not fully understood yet, we believe that both the \(\alpha_H\) and the homogeneous broadening play a determinant role in this behavior. These two parameters are indeed temperature dependent\(^7\). Assuming a QD as a two-level atomic system and that the entire gain media of the QD laser is composed of uniform nanostructures, we demonstrated in a prior work\(^8\) that the comb bandwidth \(\Delta \nu \propto \Gamma \times \alpha_H\) with \(\Gamma\) being the homogeneous broadening.
of the QD transition and the $\alpha_H$ calculated on the entire comb spectrum. In the laser under study, the $\alpha_H$ is found to increase with temperature from about 1 to 6 (not shown here) whereas the increase of the homogeneous broadening with temperature makes the coupling among the dots much stronger.

Since lasing photons can therefore be emitted not only from energetically resonant dots but also from other non-resonant ones, these effects can result in a dependence of the comb properties with temperature. The strengthening of the comb properties is also further highlighted by Figure 2(b), which displays the corresponding intermode beat note along with the peak power at different temperatures. The beat note frequency of 31.5 GHz is found at twice the free-spectral range of the cavity, which is coherent with the optical comb spectrum where alternates between lasing and suppressed comb lines are observed. Such second-harmonic generation directly results from the colliding pulse configuration of the laser cavity. Finally, although the beat note appears quite stable over temperature, the linewidth of 3MHz results in an incomplete mode-locking. We checked the corresponding temporal dynamics and no pulses were clearly observed whatever the operating conditions (not shown here). This effect directly results from the GVD that is not compensated by the optical nonlinearities in the cavity, hence preventing phase-locking of the modes. Indeed, in order for the beatnotes to lock, some optical nonlinearity coming from saturable absorption or from four-wave mixing within the gain medium is necessary to overcome the dispersion.

**CONCLUSION**

This work investigates the influence of external conditions on a multi-section hybrid silicon InAs/GaAs QD comb laser. Particularly, we found that the comb properties are thermally-controlled at high reverse bias, that can be translated into a wider comb. These results also unveil the possibility to achieve comb operation without pulses as a direct consequence of the background dispersion which is useful for future DWDM optical transceiver in short-reach inter-chip communications. Further work will concentrate on the modelling our QD comb laser taking into account the GVD. We will also measure how the GVD behaves with temperature.

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**References**


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![Fig. 2. Thermal dependence of (a) the optical spectrum and (b) the RF beatnote of the laser at $I = 2 \times I_{th}$ and $V_{sa} = -6V$.](image-url)