Experimental and theoretical study of frequency combs in hybrid lasers with a narrow-band mirror.

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***Abstract*— We present experimental and theoretical evidence of a self-pulsing regime in III-V/SiN hybrid integrated lasers featuring a frequency-selective mirror. While such a regime has been previously theoretically predicted in microcavity laser, as in the case of Fano laser, our research demonstrates its occurrence in a simpler and more accessible silicon photonics platform. Our findings demonstrate that these lasers can generate narrow free spectral range (FSR) frequency combs, with FSR of just a few gigahertz and smaller than the cavity FSR. The experimental observations are also supported by a theoretical model.**

Keywords*— *Silicon photonics, hybrid integrated laser, multimode dynamics, optical frequency combs, self-pulsing regime.

I. Introduction

The recent focus on optical frequency combs (OFCs) is motivated by the many applications they find in various photonic systems. Here we investigate generation of OFC in semiconductor lasers integrated in silicon photonic (SiPh) platform. Indeed recent progress in the field of optical communication has driven the development of hybrid and heterogeneous integration of laser sources in this platform. This facilitates the development of low-cost, CMOS-compatible devices suitable for scalable deployment. Specifically, on-chip OFCs realised with SiPh integration, a development that represents significant progress towards scalable and fully integrated photonic circuits.

In this contribution, both experimental and theoretical investigations are presented about the generation of OFCs in a hybrid integrated tunable laser. We investigate the relation between the onset of OFC generation and the intensity modulation (IM) response of the laser, measured for various injection currents and lasing frequencies before the comb formation. The device is simulated using a model based on time-delayed algebraic equations [1]. We previously theoretically predicted that OFCs can emerge when the laser emission frequency is asymmetrically detuned from the reflectivity peak of the purely passive mirror, under a simple DC bias applied to the gain sections and without the need of a saturable absorber [2]. This process is known as self-pulsing and it has also been theoretically predicted in Fano lasers [3]. Principles in [3] and [2] are very similar, but they have never been experimentally proved. While the realization of the Fano laser based on photonic crystals proposed in [3] is quite complicated, we rely here on a simpler and more accessible hybrid laser in silicon photonics. (see Fig.1 (a)). The experimental and numerical IM responses in CW conditions are analyzed to investigate the role of relaxation oscillations (RO) just before self-pulsing occurs. The comb regime observed in simulations is in good agreement with experiments.

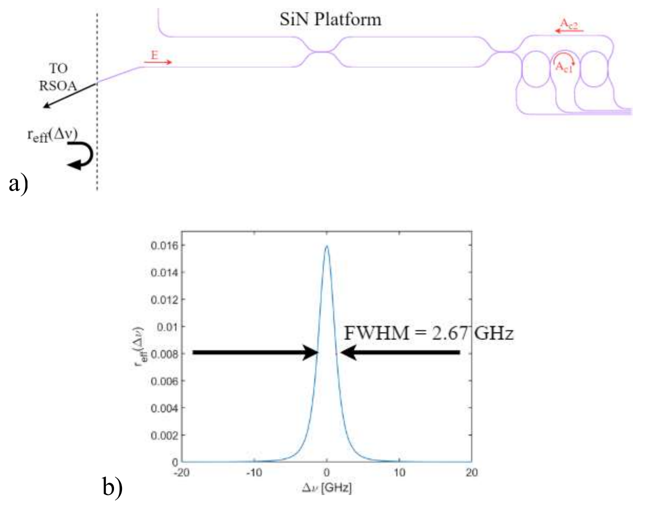
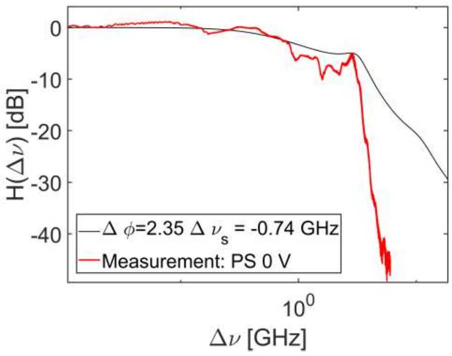


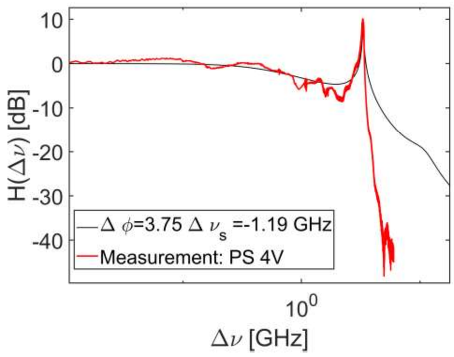
Fig. 1. (a) Schematic of the right mirror of the III-V/SiN hybrid laser. The laser cavity is composed by a MQW reflective SOA (RSOA and closed on the right by the SiPh passive mirror here displayed. (b) Reflection coefficient of the passive mirror with FWHM of 2.7 GHz.

II. Results.

The device under test is a hybrid tunable laser, illustrated in Fig. 1 (a), integrating an active MQW HR/AR reflective semiconductor optical amplifier (RSOA) and a passive silicon nitride photonic integrated circuit (PIC) that functions as the front narrow band passive mirror. The PIC is fabricated using TriPleX technology with low-loss Si_3N_4/SiO_2 waveguides [4]. Lasing frequency detuning from the mirror reflection peak, defined as $\Delta\nu = \nu s - \nu 0$, is controlled via current injection into an integrated phase control shifter (PS). The mirror incorporates two coupled microring resonators which, generate a narrow band reflection via Vernier effect (full width at halfmaximum (FWHM) ~2.67 GHz, as shown the Fig. 1 (b)). By studying the numerical IM response in the CW regime for increasing frequency detuning and fixed bias current at 195 mA, we are able to identify the frequency of RO. We compare this with the experimental measurements, as shown in Fig. 2. We observe that the RO peak is at a frequency of 3.3 GHz and this peak becomes less damped as the detuning increases. Subsequently, increasing the current and detuning leads to the comb regime shown in Fig. 3. In Fig. 3 (a), we compare the numerical and experimental optical spectrum, showing an FSR of the comb lines equal to 3.4 GHz, while in Fig. 3 (b) we compare the numerical radio frequency spectrum with the experimental measurements.



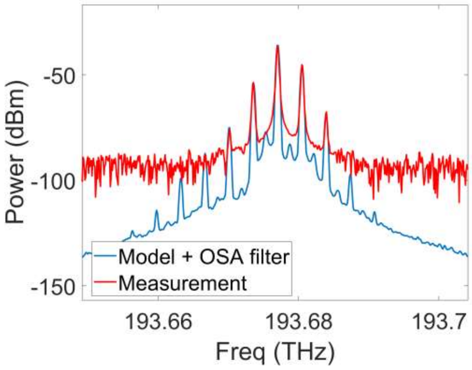
a)



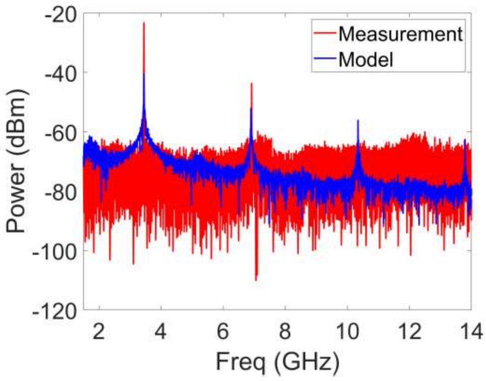
b)

Fig. 2. Simulated (black) and experimental (red) intensity-modulation response (IM) at a current of 195 mA, when the laser is in single mode. a) phase control section equal to 0 V corresponding to stable CW single mode emission; b) Phase control section at 4 V close to comb formation. Measurements are limited at about 5 GHz due to the RF modulation bandwidth.

In conclusion we see that the comb is at an FSR comparable with the RO frequency and hence we prove for first time that undamped RO can lead to combs. This is possible only thanks to the very narrow band passive reflector and to the rather high (about 5) α-parameter of the RSOA.



a)



b)

Fig. 3. (a) Experimental (red) and numerical (blue) optical spectrum in OFC regime at a current of 200 mA and detuning -1.60 GHz. (b) Experimental (red) and numerical (blue) data of radio-frequency spectrum for the same current and detuning.

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REFERENCES

[1] Rimoldi, C., Columbo, L. L., Bovington, J., Romero García, S., and Gioannini, M., “Damping of relaxation oscillations, photon-photon resonance, and tolerance to external optical feedback of iii-v/sin hybrid lasers with a dispersive narrow band mirror.,” Opt Express (2022 Mar 28).

[2] Rimoldi, C., Columbo, L. L., and Gioannini, M., “Optical frequency combs in external cavity sin hybrid lasers,” IEEE Photonics Journal 16(2), 1–5 (2024).

[3] Seegert, K., Heuck, M., Yu, Y., & Mørk, J. (2024). Self-pulsing dynamics in microscopic lasers with dispersive mirrors. Physical Review A, 109(6).

[4] Mak, J., et al., “Linewidth narrowing via low-loss dielectric waveguide feedback circuits in hybrid integrated frequency comb lasers,” Opt. Express 27, 13307–13318 (Apr 2019)