Addressing experimental self-generation of frequency combs in III-V/SiN hybrid integrated tunable lasers

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Stefania Cucco[1], Anzal Memon[2], Cristina Rimoldi[1], Marco Novarese[1], Lorenzo L. Columbo[1], Klaus-Jochen Boller[2], and Mariangela Gioannini[1]

[1]Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Torino, Italy
[2]Department of Science and Technology, University of Twente, Enschede, Netherlands

ABSTRACT

We present experimental results featuring the self-generation of optical frequency combs in a III-V/SiN hybrid integrated laser with a frequency selective mirror. We model the laser through a set of time-delayed algebraic equations accounting for longitudinal mode competition, non-zero alpha factor and the narrowband SiN mirror. We are able to produce frequency combs matching the experimental case in terms of bandwidth, free-spectral range and optical frequency spectrum. Supported by our model, we demonstrate that the optical frequency combs occur when the laser becomes CW unstable due to the resonance between the relaxation oscillation frequency and the frequency separation between cavity modes, and efficient four-wave mixing allows for the locking mechanism between optical lines. The comb is characterized by both amplitude and frequency modulation.

Keywords: Silicon photonics, hybrid integrated laser, multimode dynamics, optical frequency combs.

1. INTRODUCTION

Optical frequency comb (OFC) lasers generate a source with a series of equally spaced frequencies in the optical spectrum. The implementation and optimization of frequency comb lasers remain a scientific and technological challenge. One important goal is to make these devices more compact by integrating them into silicon photonic integrated circuits to facilitate their wider use in application fields.

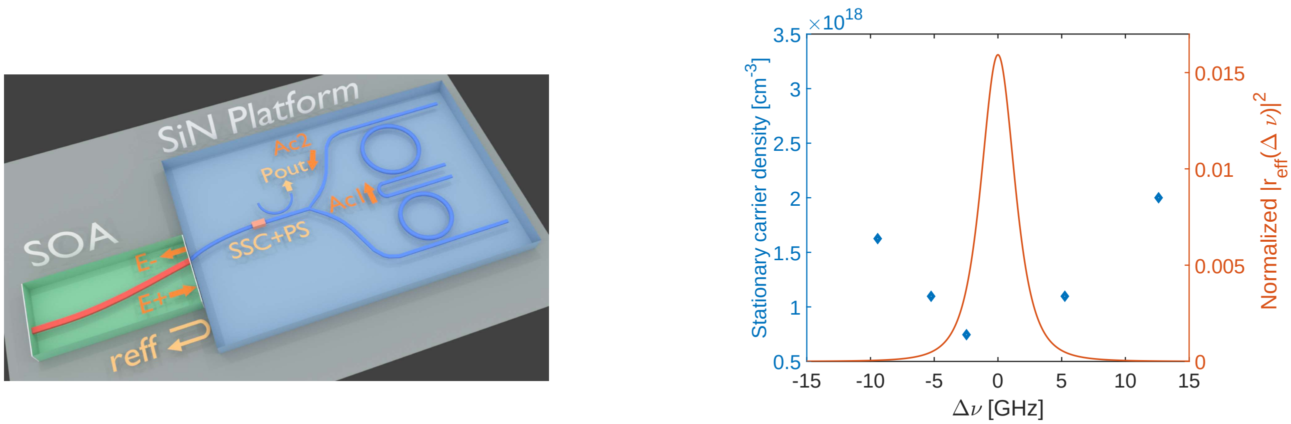
In this study, we examine experimentally and theoretically the generation of optical frequency combs within a hybrid integrated tunable laser.[1] We then establish a link between the onset of the OFC and the intensity modulation (IM) response measured at different currents and lasing wavelengths just before the comb starts. To simulate this device, we apply the model[2] that implements a set of time-delayed algebraic equations, which was originally designed to analyze the stability of continuous wave (CW) regimes and their resilience to unwanted back reflections.[3] The proposed model can also effectively address the competition between longitudinal modes and simulate the formation of OFCs.[4] Specifically, we demonstrate the emergence of OFCs when the laser modes are asymmetrically detuned from the reflectivity peak, under a simple DC bias applied to the gain regions (i.e. self-generated combs) in the hybrid integrated laser. The model provides an accurate representation of the experimental findings, including the optical spectrum. Then, we focus on the study of the IM response[2] in CW conditions, to assess whether relaxation oscillations or photon-photon resonance play a role in the instability mechanism of OFC generation.

2. RESULTS

The device under consideration is a hybrid tunable laser shown in Fig. 1(a). It consists of two parts: an active MQW HR/AR reflective semiconductor optical amplifier (RSOA, which provides the III-V gain material) and a passive component which is a silicon nitride photonic integrated circuit designed as the front mirror of the laser cavity.[1] The platform has been realized through TriPleX technology, involving Si3N4 / SiO2 waveguides with low propagation losses of 0.001 dB / cm and a high-index contrast of 0.5. The detuning of the lasing wavelength

Further author information: (Send correspondence to M.N. and M.G.)
M.N.: E-mail: marco.novarese@polito.it
M.G.: E-mail: mariangela.gioannini@polito.it

with respect to the peak of the mirror reflection coefficient (Fig.1(b)), indicated by $\Delta\nu = \nu_s - \nu_0$, is achieved by applying a current to the integrated Phase Control Section (PS) within the passive circuit. The mirror has been designed with two microring resonators and waveguides to achieve widely tunable lasing and a very narrow linewidth when the lasing frequency approaches the peak of the reflection coefficient. The configuration of two coupled rings (with radii of approximately 140 μm, a power coupling coefficient of 0.07, and a quality factor of around 40,000) provides an effective reflectivity with a bandwidth of a few GHz, as shown in Fig. 1(b), due to the Vernier effect. The effective reflectivity has a full width at half-maximum (FWHM) of 3.1 GHz. In Fig. 1(b), the solutions to the oscillation condition are also plotted. Each blue diamond in the figure represents a possible CW solution with a frequency detuned from the reflectivity peak by $\Delta\nu_s$, and the associated carrier density N_s required to reach the threshold of that CW solution. Based on the detuning, controlled via the PS, the laser operation can be single mode with narrow linewidth, OFC, or quasi-chaotic. In this work, we focus on the OFC regime.



(a) (b)

Figure 1. (a) A schematic representation of the III-V/SiN hybrid laser is presented. (b) The diagram illustrates, in orange, the narrow-band effective reflectivity (left y-axis) with a FWHM of 3.1 GHz, as well as the single-mode solutions of the oscillation condition (illustrated with blue diamond markers) and the associated carrier density at threshold (right y-axis).

Fig. 2(a) presents a comparison between the optical spectrum measured in the experiment and the result of the numerical model.[2] In both cases, the pump current is 3.6 times the threshold current. At this current, the self-generation of OFCs is observed, as predicted by the model. The experimental comb line separation of 3.1 GHz is close to the simulated value of 3.3 GHz. In this configuration, CW instability occurs because the frequency separation between the lasing mode ($\Delta\nu = -2.468$ GHz) and another cavity mode ($\Delta\nu = -5.244$ GHz) starts to become resonant with the frequency of relaxation oscillation (at 3.1 GHz, as shown approximately in Fig. 2(b) and 2(c)). In addition, the signal-to-noise ratio of the beat note in the experimental radio frequency spectrum is about 36 dB.

When the laser operates in the CW regime, controlled by frequency detuning and/or RSOA bias current, we calculate numerically the IM response. We analyse the IM response to observe at what frequency the Relaxation Oscillations (RO) peak and the Photon-Photon Resonance (PPR) peak are located in the CW regime and assess which of the two approximates the OFC Free Spectral Range (FSR), when the bias current and/or the detuning are changed, approaching the condition for the OFC formation. This analysis provides insight into which mechanism contributes to the laser CW instability. In Fig. 2(b), the IM numerical response[2] at a bias current of 50 mA is shown as a function of the detuning in the single-mode regime. Two peaks can be observed, associated to relaxation oscillation and photon-photon resonance, respectively. When the detuning is in proximity to the reflectivity peak, the peaks are damped, with the RO frequency at 1.55 GHz and the PPR frequency 11.45 GHz. Conversely, an increase in detuning leads to a reduction in the damping of the RO frequency peaks, with RO shifting to a frequency of 3.1 GHz and PPR maintaining its position at 11.45 GHz. Consequently, the frequency of the RO peak coincides with the line spacing of the comb, as shown in Fig. 2(a). In this scenario, the OFC form as a consequence of efficient proliferation of modes, due to parametric gain and phase locking between

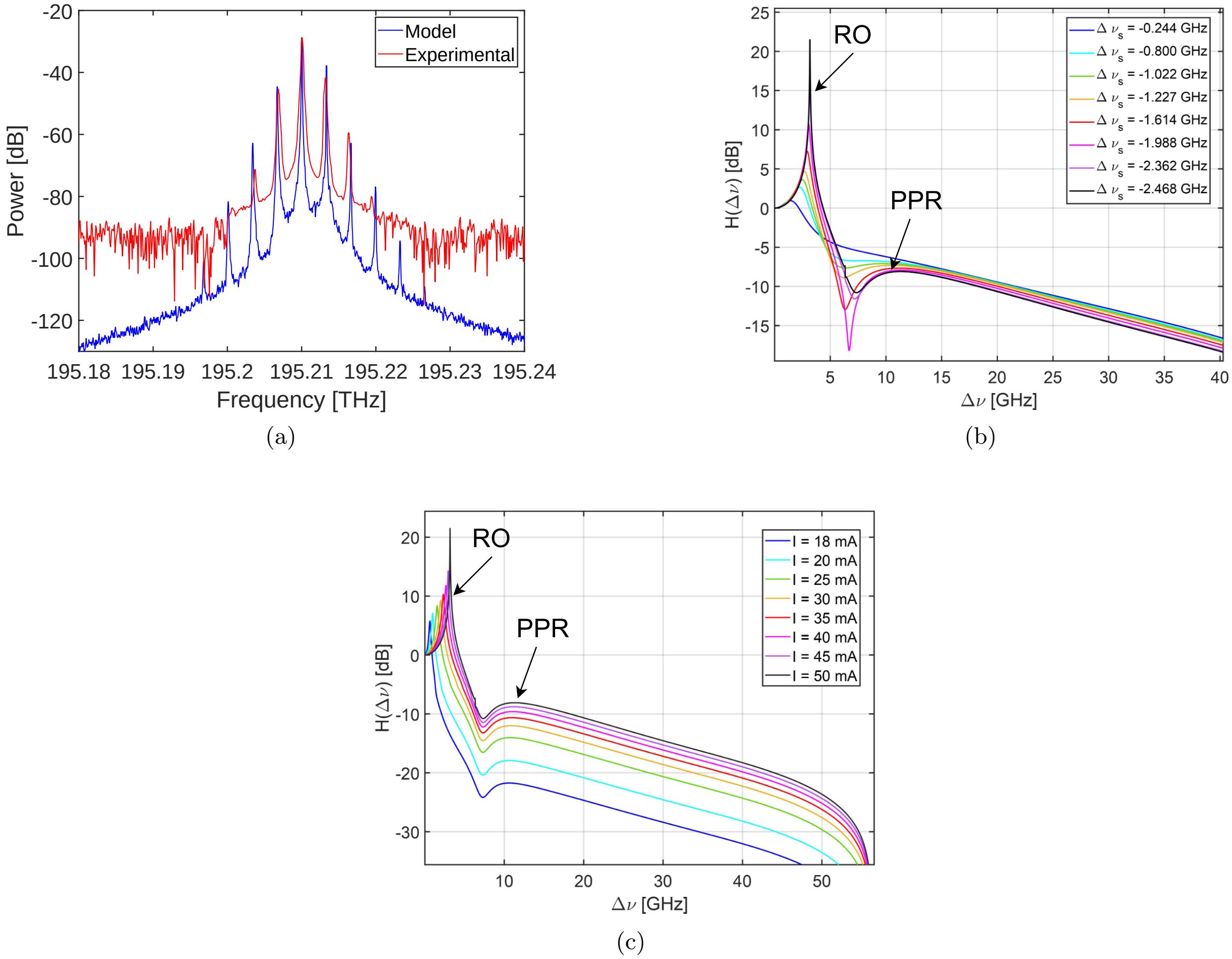


Figure 2. (a) The experimental and theoretical optical spectra are presented in an OFC regime at $I = 3.6 I_{th}$ and $\Delta\nu = -2.468$ GHz. (b)The IM response is presented for a bias current of 50 mA, with varying laser frequency detuning. (c) The IM response is analyzed for a fixed detuning of $\Delta\nu = -2.468$ GHz, while varying the bias current.

optical lines. Fig. 2(c) shows the IM response with detuning $\Delta\nu_s$ set at -2.468 GHz for different bias currents. This graph displays two peak,RO and PPR, similar to those in Fig 2(b). Here, the RO frequency varies with the bias current and becomes less damped as the current intensity increases, while the PPR frequency remains unchanged. This is different with respect to the standard FP or DFB lasers where the RO is more and more damped as the bias current increases. On the contrary, in the laser considered in this work, the undamping of the RO with increasing current triggers the OFC formation, as we have also observed in experiments. In fact, at current of 50 mA, we are at the threshold of the comb self-generation where the RO frequency coincides with the comb line separation of Fig.2(a). Furthermore, the IM response highlights that the photon-photon resonance does not induce CW instability in this chip configuration.

In summary, we explored the generation mechanism of optical frequency combs in a hybrid tunable laser and demonstrated a good matching between experimental observations and theoretical predictions. The instability of CW operation originates from the resonance between the frequency of relaxation oscillations and the frequency spacing of the modes that satisfy the oscillation condition.

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