CW and comb regimes in III-V SiN hybrid lasers with frequency-selective narrow band mirror

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***Abstract*— We investigate the stability of III-V SiN hybrid lasers. By detuning the lasing frequency with respect to the narrowband mirror reflectivity peak, we observe regimes of ultra-damped relaxation oscillations, turbulence, and combs, caused by the interplay of four-wave mixing, Henry alpha-parameter and the narrowband reflectivity.**

Keywords—Silicon photonics, hybrid lasers, optical feedback, frequency comb, self-pulsing

I. Introduction

Laser sources integrated in Silicon Photonic (SiPh) platforms are essential for the realization of low-cost optical transmitters for optical interconnects, as well as for sensing and LIDAR applications. These lasers are usually composed of a III-V gain material for light generation and amplification coupled to the rest of the silicon photonic chip, which acts as the laser mirror facet and extends the laser cavity. The design of the SiPh mirror can include several components, such as micro-rings, delay lines, Mach-Zehnder interferometers, and DBR reflectors, all providing very narrow band dispersive reflectors (with bandwidths of a few GHz) [1], allowing for long external cavity narrow linewidth lasers with wide tunability [2,3]. While many works have been investigating the laser linewidth reduction of these devices, both from an experimental and theoretical point of view, few studies have been dedicated to the analysis of other dynamical features.

In this paper, we theoretically explore the impact of dispersive narrow-band reflectors on laser dynamic performance, and we analyze in detail the causes leading CW emission to a multimode regime. We demonstrate that several dynamical regimes can be observed, ranging from ultra-stable CW emission (where the laser relaxation oscillations are strongly damped) to self-pulsing or turbulent regimes. Similar dynamics have been experimentally observed [2,3] through the tuning of the lasing frequency, however they lack, to the best of our knowledge, a theoretical description able to explain the reasons behind their occurrence. Our work proves that such regimes are due to the interplay between the non-null linewidth enhancement (Henry) factor and four-wave mixing in the reflective semiconductor optical amplifier and that their occurrence depends on the narrow bandwidth of the SiPh mirror and on the laser effective length. The presented work provides a versatile tool for the analysis of external cavity hybrid lasers and the illustrated results can potentially be extended to other hybrid laser configurations.

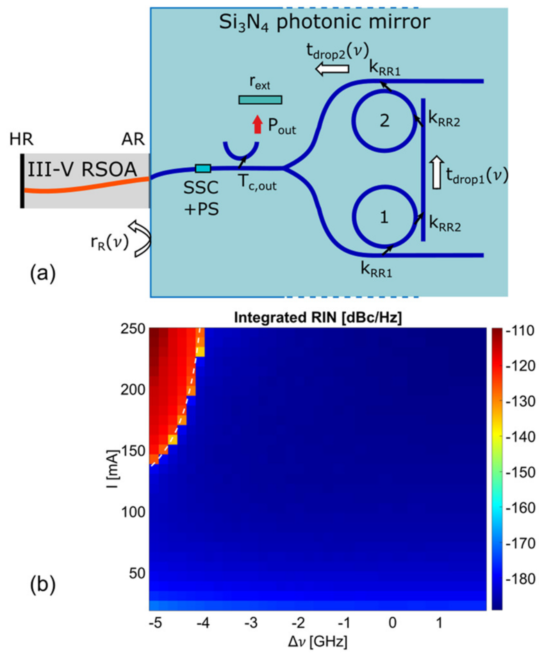

Fig. 1. Schematics of the III-V/SiN hybrid laser (a) and integrated RIN for different detuning $\Delta\nu$ of lasing frequency and RSOA bias current (b). $\Delta\nu=0$ corresponds to lasing at the reflectivity peak, which is centered at 1310 nm.

II. Methods

The hybrid laser in this study is illustrated in Fig 1(a). This laser consists of an off-the-shelf III-V MQW 1mm long HR/AR RSOA edge-coupled to a silicon photonic circuit based on two coupled Si_3N_4 micro-rings, which provide narrowband dispersive reflectivity and wide tunability through Vernier effect. The ring radii are chosen in order to maximize the tuning range and minimize the overlap of the ring resonance peaks near the lasing one. Ring coupling coefficients are selected equal to achieve maximum mirror reflection in the critical coupling regime. This configuration has been analyzed in [5,6]. The overall effective reflectivity of the SiPh mirror ($|r_R(\nu)|^2$ in Fig.1(a)) has a bandwidth with FWHM 6 GHz obtained through ring design. The peak of $|r_R(\nu)|^2$ is 3% and the output power is collected through the output coupler $T_{c,out}$=73% [5]. Detuning of the lasing frequency with respect to the effective reflectivity peak is possible through the tuning of the phase $\Delta\phi$ of the control section PS. The numerical model applied in our analysis is based on [7] and consists in a set of time-delayed algebraic differential equations at the reference plane of the AR-coated facet of the

RSOA. The model accounts for the frequency-selective mirror, assuming a Lorentzian response for the rings around the reference frequency, as well as for the competition between laser sidemodes. In particular, an integral equation for the propagation of the optical electric field in the RSOA is coupled to the delayed differential equations accounting for the response of the rings and to the rate equation for the average carrier density of the RSOA. A linear stability analysis (LSA) of the CW solutions of the laser [7] allows to address the impact of the dispersive mirror bandwidth and the tuning of the phase control section on the laser dynamics. Here, the main complex roots of the determinant of the linearized system for the CW perturbations are associated to the relaxation oscillation (RO) resonance and the photon-photon resonance (PPR) and give the frequency and damping of these resonances. Numerical simulations of the dynamical equations give the time evolution of the laser in terms of output power versus time, RIN spectra, integrated RIN, and optical spectra.

III. Results and Discussion

In Fig. 1(b) we show the map of the integrated RIN (over a bandwidth of 25 GHz) computed for different values of RSOA bias current and detuning $\Delta\nu$ of the lasing frequency with respect to the effective reflectivity $|r_R(\nu)|$ peak. The blue region of low RIN (<-160 dBc/Hz) corresponds to a stable single-mode (CW) regime, while the red region of high RIN (>-130 dBc/Hz) corresponds to a multimode regime (which we will characterize as self-pulsing or turbulent in the following). The asymmetry in the detuning Δν with respect to the reflectivity peak is due to the non-null Henry α-factor, which leads to a larger region of emission with negative detunings. The white dashed line is obtained through LSA and highlights the boundary beyond which single mode emission becomes unstable (which occurs when the imaginary part of the RO root becomes negative, leading to undamped ROs). Figure 2(a) shows the lasing frequency (in green) and the average output power (in blue) for varying $\Delta\phi$ and fixed RSOA bias current of 230 mA, well above threshold. In Fig. 2(b) we report the optical spectra related to region 1 (turbulent regime), region 2 (stable single-mode emission), and region 3 (self-pulsing regime). As a result of LSA we are able to justify the transition between single mode and multimode regimes, which occurs when the damping of the perturbation becomes negative and we enter a CW unstable regime, characterized by undamped relaxation oscillations. The linewidth enhancement factor together with the narrowband SiPh effective mirror allow for the efficient conversion of phase noise into intensity noise, which can cause another longitudinal mode to reach the lasing threshold. When the beating frequency between competing modes becomes resonant with the laser relaxation oscillations (which occurs for larger negative detunings) the latter become undamped and the laser typically enters in a self-pulsing regime characterized by a frequency comb in the spectral domain. For small negative detunings Δν, detuned loading [8] has a contrasting stabilizing effect, leading to the presence of an optimal detuning condition for which maximal RO damping is observed. For even smaller detunings, such damping is reduced due to the progressive decrease of the detuned loading effect. Note that when the effect of the linewidth enhancement factor is neglected, this scenario is completely altered because of the reduced phase noise conversion: self-pulsing and turbulent regimes are unachievable in this case. The results in Fig. 2 are in accordance with experimental findings in [2,3] and can exemplify a valuable approach to interpret experimental results. As a general trend, we observe that narrow bandwidths can give higher damping factors in comparison with the case of a broad band reflector. On the other hand, since these narrow bandwidths are experimentally achieved by acting on the coupling coefficients of the two rings, they are also associated with longer cavity effective lengths, implying a reduction on the laser free spectral range, the emergence of a second resonance due to PPR and a potential additional cause of instability e.g. when addressing the laser tolerance to spurious back-reflections. Consequently, proper design of the SiPh mirror is necessary to guarantee the laser stability while reducing the mirror bandwidth.

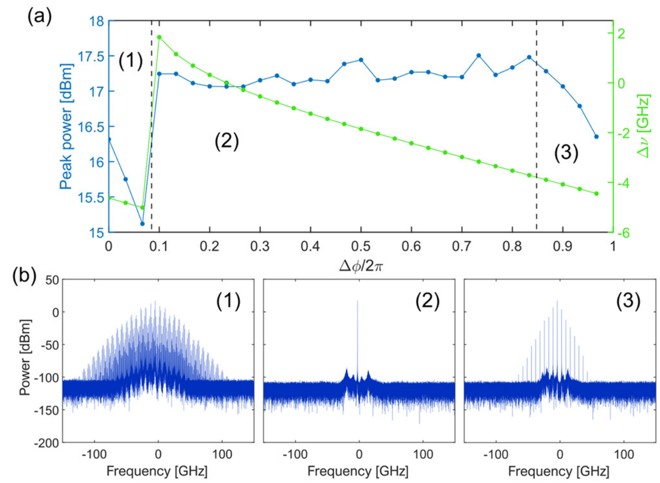

Fig. 2. Simulated lasing frequency and output power obtained through tuning of the phase section PS (a), optical spectra for the three dynamics regimes (b). The RSOA bias current is fixed at 230 mA.

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