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***Abstract*—We model the dynamical behavior of a III-V SiN hybrid laser accounting for the narrowband mirror effective reflectivity. We characterize the laser as a function of bias current and detuning of the laser emission frequency with respect to the effective reflectivity peak. Numerical simulations allow to address the potential physical triggers for longitudinal multimode dynamics. Among these, we assess the mechanism of generation of frequency combs and we preliminarily characterize this regime in terms of bandwidth and line separation.**

Keywords—Silicon Photonics, semiconductor lasers, multimode dynamics, hybrid lasers

I. INTRODUCTION

In the past decade, the compatibility of laser sources with silicon photonic (SiPh) platforms has been a main topic of study for research and industry due to the entailed potential for the realization of low-cost optical transceivers for application in data centers. Among the proposed solutions, hybrid integration has been the most successful for out-of-the-lab applicability. While much effort has been dedicated towards the stabilization of single-mode narrow linewidth emission in hybrid laser platforms, only a few studies [1,2] have been dedicated to the characterization of multimode regimes emerging for high currents. On the other hand, optical frequency combs (OFCs) in multi-longitudinal mode semiconductor lasers have been attracting much interest both from industry and academia in recent years, with applications ranging from high-resolution spectroscopy to broad-band free space optical communication [3]. In this contribution, we aim to analyze frequency comb regimes in a hybrid laser consisting of a III-V Multiple Quantum Well HR/AR RSOA edge-coupled to a SiN circuit, including two coupled high-Q rings. Such a configuration provides an effective reflectivity that is selective in frequency due to Vernier effect. A phase section in the SiN circuit allows to detune the lasing frequency with respect to the effective reflectivity peak. We model this device via a set of algebraic rate equations with delay, based on the approach reported in [4], which properly accounts for longitudinal mode competition. The dynamical model allows to study the stability of single mode solutions as well as the physical mechanisms giving rise to multimode regimes. Recent contributions [1,2] have demonstrated the emergence of OFCs in similar platforms and have justified [1] their occurrence with the almost symmetric distribution of longitudinal mode solutions around the effective reflectivity peak. Here, we show that OFCs can also appear when the laser modes are asymmetrically detuned with respect to the reflectivity peak and demonstrate that the physical mechanism giving rise to this regime is a combination of longitudinal mode competition and four-wave mixing (FWM), non-null α-factor, and undamping of relaxation oscillations. The resulting frequency comb is characterized by both frequency and amplitude modulation. Our results are also qualitatively confirmed by a more rigorous Time Domain Traveling Wave (TDTW) dynamical simulator [5]. Preliminary results demonstrate bandwidths of about 90GHz within 20 dB from the comb peak frequency.

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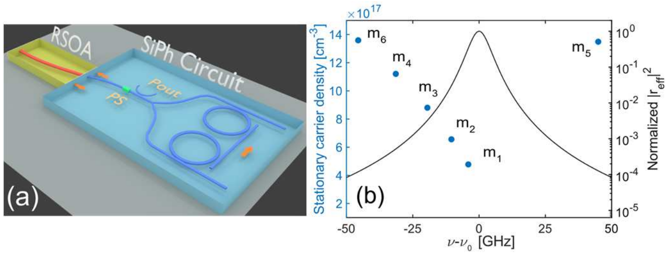

Fig. 1. (a) Sketch of the simulated III-V SiN hybrid laser, (b) plot of the single mode solutions of the oscillation condition (in blue) and of the narrowband effective reflectivity (in black).

II. MODELING AND RESULTS

The device we aim to describe is illustrated in Fig. 1(a). Due to Vernier effect the configuration with the 2 coupled rings allows to extend the laser cavity and provide an effective reflectivity $|r_{eff}|^2$ with a bandwidth of a few GHz, which we sketch in Fig. 1(b), e.g., in the case of an FWHM of 6 GHz. Detuning of the lasing frequency ω_s with respect to the effective reflectivity peak ω_0 is possible by acting on the phase control section PS, integrated in the SiN circuit. The power P_{out} is collected through an output coupler $T_{c,out}$ placed before the splitter. Our dynamical model [6] is based on a set of time-delayed algebraic equations and is able to account for such an effective mirror reflectivity: in particular

$$E(t) = \frac{e^{i(\omega_s-\omega_0)\tau_{in}}\exp\big(f(\omega_s,N_s)\big)}{r_{eff}(\omega_s)}A^-(t-\tau_{in}) + F(t)$$

$$\frac{dA_{c1}(t)}{dt} = \gamma_{c1}t_{SSC}^2\big(1-T_{c,out}\big)E\big(t-\tau_{in,SiN}\big)e^{-i\Delta\phi} - \gamma_{t1}A_{c1}(t)$$

$$\frac{dA_{c2}(t)}{dt} = \gamma_{c2}A_{c1}(t) - \gamma_{t2}\,A_{c2}\,(t)$$

$$\frac{dN(t)}{dt} = \frac{\eta_i I_{bias}}{eV} - \frac{N(t)}{\tau_e} - v_g g_N \ln\left(\frac{N(t)}{N_0}\right)\sigma\frac{|E(t)|^2}{V}$$

with

$$f(\omega_s,N_s) = \frac{1}{\tau_{in}}\int_{t-\tau_{in}}^{t} L\left(1+i\alpha\frac{\omega_s}{\omega_0}\right)g_N \ln\left(\frac{N(\bar{t})}{N_s}\right)d\bar{t}$$

$$A^-\,(\omega-\omega_0\,) = r_{eff}\,(\omega)E(\omega-\omega_0\,)$$

where $E(t)$ is the electric field exiting the SOA at the AR-coated facet, $A_{c1}(t)$ relates to the field out of the drop port of ring 1, $A_{c2}(t)$ is the field after propagation in the second ring, and $N(t)$ is the carrier density in the SOA. Coefficients $\gamma_{c1,2}$

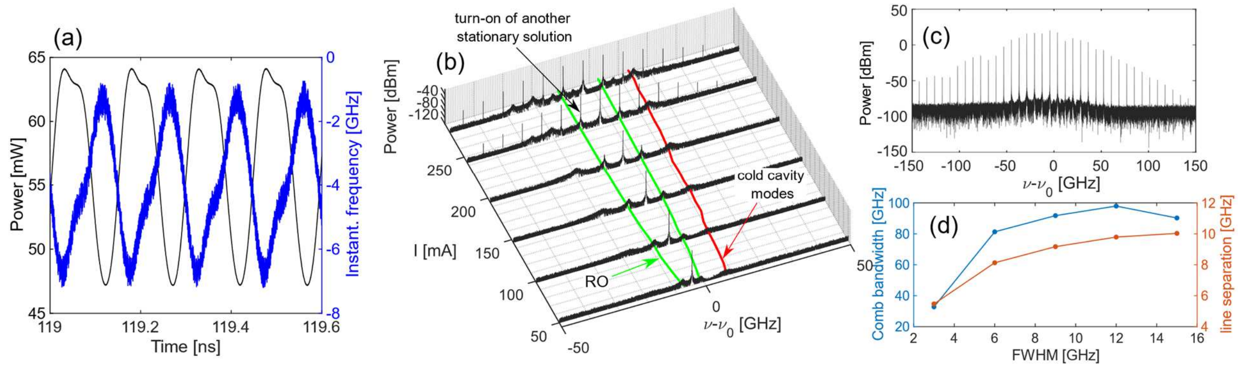

Fig. 2. (a) Laser temporal dynamics in power (black) and instant frequency (blue) for reflectivity FWHM=6 GHz and I_{bias}=240 mA. (b) Optical spectra for increasing currents (FWHM=6 GHz). (c) OFC example at FWHM=6 GHz obtained with the TDTW model. (d) Trend of maximum comb bandwidth (blue) and separation between comb lines (orange) for increasing reflectivity FWHMs obtained by scanning the detuning for fixed I_{bias} at 300 mA.

and $\gamma_{t1,2}$ represent the coupling rate of the electric field into the ring from the bus waveguide and the rate at which the electric field is lost, due to coupling out of the bus waveguide and to waveguide losses. While previous studies of similar laser configurations have been focused on its narrowband single mode emission linewidth [2] and feedback resilience [7,8], which was shown to be improved up to -10 dB for specific detuning and reflectivity bandwidth configurations, here we focus on the phenomenon of self-generation of OFCs, as recently shown in preliminary experimental findings [1,2]. The cavity modes m_i, in Fig. 1(b) are the single mode solutions of the laser oscillation condition, with angular frequency ω_s. In this detuning configuration mode m_1 is set at a frequency of -4 GHz with respect to $\nu_0=\omega_0/2\pi$, while the other solutions of the oscillation condition are asymmetric with respect to m_1, because of the non-null α-factor of the semiconductor amplifier. In Fig. 2(a) we show the laser temporal evolution of the optical power and instantaneous frequency at a bias current I_{bias}=240 mA. This regular dynamics at a frequency near the longitudinal mode separation is associated to the OFC regime in Fig. 2(b). More irregular temporal traces, eventually leading to chaotic regimes through period doubling can be observed either increasing I_{bias} or for larger detunings from the reflectivity peak [7]. To explain the self-generation of OFCs, in Fig. 2(b), we show the optical spectra for increasing I_{bias} leading to the frequency comb at 240 mA. For currents on the range between 50 and 100 mA, we have single mode emission at the main spectral peak: the secondary peaks are sidebands at the relaxation oscillation frequency (ROs, in green) and cold cavity modes (in red), which are different from m_i because of α=3 [6]. Then, by increasing the bias current it may occur that ROs become resonant with the frequency separation between the m_i modes, thus getting undamped and leading to single mode instability. Note that this phenomenon does not occur if (i) α=0 or if (ii) the lasing frequency is not detuned with respect to the effective reflectivity peak [6]. In fact, it is the efficient conversion of phase noise into intensity noise, leading then to the consequent enhancement of phase noise, aided by α, that is at the root of the destabilization of the single-mode regime. Then, FWM may provide efficient mode proliferation, due to parametric gain, and phase locking of the new generated optical lines with a separation close to the frequency distance between m_1 and m_2, which results in an OFC regime. These results are qualitatively confirmed through a more rigorous TDTW dynamical simulator [5], which has been then employed to obtain a more detailed analysis on the comb characteristics for varying reflectivity FWHMs. In Fig. 2(c), we show an example of an OFC regime at FWHM=6 GHz. While very narrow reflectivity bandwidths (e.g., 3 GHz) are characterized by a higher nonlinearity in the SiPh mirror r_{eff} phase, which can also lead to irregular regimes, they are effective in reducing the comb span (see Fig.2(d)), suggesting, as expected, that larger FHWMs will increase the comb bandwidth. On the other hand, when we increase the reflectivity bandwidth beyond e.g., 12 GHz, more longitudinal modes characterized by higher dispersion can reach threshold, leading to a more complex mode competition and eventually to irregular regimes. The interplay of these effects leads to somewhat of a bandwidth saturation observed in Fig. 2(d) at about 90 GHz.

CONCLUSIONS

We addressed the formation of OFCs in a III-V SiN hybrid laser. Investigation of OFC contrast, coherence, and bandwidth as a function of the properties of the mirror effective reflectivity, detuning, and bias current, of relevance for applications in the field of integrated sources for high-speed optical interconnects, is currently ongoing.

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