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Dynamics and tolerance to external optical feedback of III-V/Si hybrid lasers with dispersive narrowband mirror

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Abstract – We report how external cavity III-V/Si hybrid lasers operate in regimes of ultra-damped relaxation oscillations or in unstable regimes as consequence to the dispersive mirror, non-zero linewidth enhancement factor and four-wave mixing in the gain medium. Tolerance to external optical feedback is also discussed.

I. Introduction

In the development of laser sources compatible with the silicon photonics platform, many laser structures based on III/V hybrid or heterogeneous integration have been investigated. Some of them consists in a III-V RSOA butt coupled to a silicon photonic mirror with integrated micro-rings. An example structure is shown in Fig. 1a. These lasers have been intensively studied in the context of reducing the laser linewidth thanks to the long effective cavity length and the detuned loading effect both provided by the dispersive silicon photonic mirror [1]. In [2] we have demonstrated a design trade-off between the reduction of the linewidth, the power available at the output port and the laser wall plug efficiency WPE. We have also studied the tolerance to external optical feedback of these devices [2] in the frame of the well-established Lang-Kobayashi model, which has however the limitation of investigating only the stability of the lasing mode by neglecting the competition with the other longitudinal modes of the hybrid laser cavity and the dispersion of the mirror. These are not negligible in the case of the hybrid lasers having high Q narrowband reflector and small longitudinal mode free spectra range (FSR).

In this work we present a more rigorous approach, based on an in-house Time-Domain Travelling-Wave (TDTW) numerical simulator with the aim of studying the dynamics of both the solitary hybrid laser and the laser in presence of spurious external optical feedback. This unwanted back reflection may come from other components integrated in the same chip and/or from the fiber collecting power out of the chip. We employ high-Q SiN rings (Fig. 1a) to get a dispersive narrowband reflector such that the -3dB reflectivity bandwidth is smaller or comparable with laser relaxation oscillation frequency at the typical output power requested by the application (in this work set to 20mW). We investigate the dynamics of the solitary hybrid laser evidencing various dynamic scenarios: from very stable one, with ultra-damped relaxation oscillations and reduced photo-photon resonance (PPR), to very unstable regimes including self-generation of optical frequency combs as experimentally found in [3]. The unstable regimes are triggered by the linewidth enhancement factor (LEF) and the four-wave mixing (FWM) of the RSOA and they can be controlled via the design of the SiN reflector and/or by the thermal tuning of phase control section (PS in Fig. 1a).

II. Results

The TDTW model couples the distributed propagation of the optical field in the RSOA with the carrier rate-equation of the III-V active region and the time-domain response of the optical narrowband mirror with each ring approximated with a Lorentzian response.

The hybrid laser is shown in Fig 1a: it consists in an off-the-shelf MQW 1mm long RSOA, butt-coupled to a silicon photonic reflector with Si_3N_4 rings. The output power is collected by the output coupler with transmission coefficient $T_{c,out}$. The ring coupling coefficients $k^2_{RR1,2}$ are designed to set the FWHM bandwidth of the effective reflection coefficient $|r^2_{eff}|$ to 3GHz ($k^2_{RR1,2}=0.08$), 6GHz ($k^2_{RR1,2}=0.15$) and 10GHz ($k^2_{RR1,2}=0.25$) respectively. The peak of $|r^2_{eff}|$ is 3% with $T_{c,ou}$ is 73% designed to optimize the WPE at output power of 20mW [2]. The lasing frequency can be detuned respect to the reflectivity peak by tuning the phase control section PS. We plot in Fig.1b the calculated integrated RIN versus this detuning $\Delta\nu$: in the case of LEF=3 and $k^2_{RR1,2}=0.08$ we have a stable CW lasing with low RIN only in the range $-2.4\text{GHz} \leq \Delta\nu \leq -0.6\text{GHz}$.

For $\Delta\nu<-2.4\text{GHz}$ stable CW lasing is replaced by a regime characterized by the dynamic competition among the hybrid laser side modes triggered by the phase-amplitude coupling mechanism provided by LEF and the FWM [4]. This regime disappears for LEF=0 (empty circles in Fig.1b). When the mirror bandwidth is very narrow (ie: $k^2_{RR1,2}\leq 0.08$) and LEF=3, it is also impossible to get emission with $\Delta\nu\geq 0$. This is associated to the narrow bandwidth of the mirror and non-zero LEF. Indeed, when $k^2_{RR1,2}$ is higher ($k^2_{RR1,2}=0.15$ or 0.25 and LEF=3 in Fig.1b) and/or LEF=0 the emission is possible and stable also at $\Delta\nu\geq 0$. In Fig.2 we compare the simulated intensity modulation (IM) response of the laser to RSOA current modulation in the cases of i) (top panel) CW lasing with $\Delta\nu=-0.88$ GHz corresponding to the minimum RIN and ii) (bottom panel) CW lasing with detuning $\Delta\nu$ corresponding to the maximum derivative of the effective reflectivity (which is the condition for detuned loaded effect and minimum optical linewidth [1]). The IM response always shows two maxima: one is associated with the photon-photon resonance (PPR) with the nearest, below threshold, hybrid cavity longitudinal mode and the other one to the relaxation oscillation frequency of the laser. Interestingly, we note that the latter is significantly damped respect to what is obtained assuming $|r^2_{eff}|$ constant in frequency. This demonstrates that the narrow bandwidth reflector is beneficial in over-damping the relaxation oscillations of the laser and suppressing the PPR. As the bottom panel demonstrates, the intensity of the damping of the relaxation oscillation is also reduced with increasing Δν and the PPR is enhanced.

To study the stability of the hybrid laser when an external optical feedback (with reflection coefficient R_{ext}) is present at the output port, we simulate the laser dynamics by inserting a reflector at 5cm distance. According to Lang-Kobayashi model, this is the worst case when the critical feedback level is the minimum and is independent on the optical feedback phase. The integrated RIN versus R_{ext} for CW lasing at Δν=-0.88 GHz is shown in Fig.3a. In all the three cases the maximum back reflection ($R_{ext,max}$) to avoid feedback induced instability is between -25dB and -20dB. As a comparison, a 1mm laser with 3% facet reflectivity has $R_{ext,max}$=-35dB [2]. We get therefore an improvement of more than 10dB on the tolerance to optical feedback. By analyzing the RIN spectra at $R_{ext,max}$, we have observed a peak centered at the relaxation oscillation frequency and we conclude that the destabilization mechanism if yet due to the undamped relaxation oscillations. The achieved improvement in feedback tolerance is the consequence of combined effects: 1) the increase of the effective cavity length [2] that leads to the reduction of the relaxation oscillation frequency as compared to flat reflector case [4] and 2) the increase of the damping factor.

We conclude that this analysis sets the basis for designing stable hybrid lasers that could be easily integrated in silicon photonic optical transceivers without the need of expensive and bulky optical isolators.

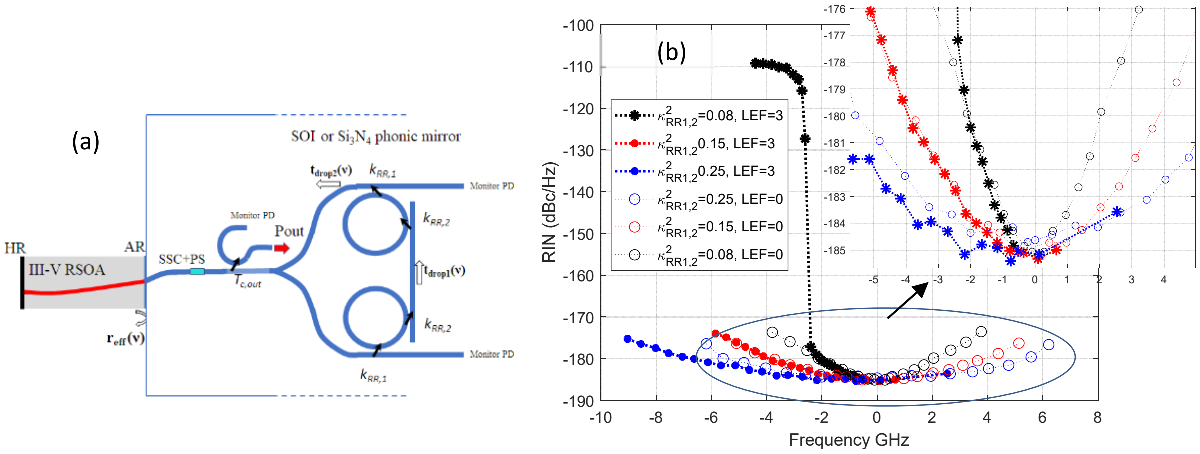

Figure 1 (a) Laser structure and (b) Integrated RIN of the output power (<Pout>=20mW and RSOA bias current of 104 mA) versus the detuning of lasing frequency respect to the peak of the effective reflectivity. The inset is a zoom of the region evidenced by the circle.

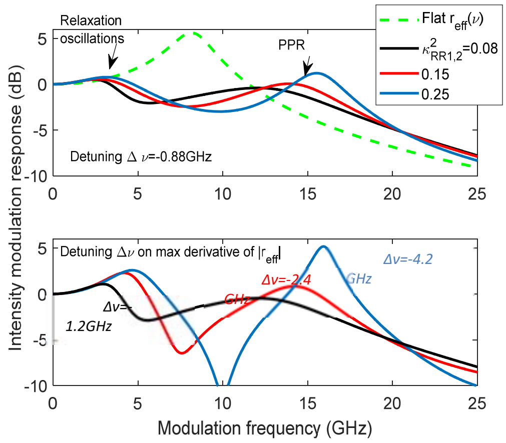

Figure 2 Laser IM response for lasing with i) detuning Δν=-0.88GHz and minimum RIN (top panel) and ii) Δν for CW lasing in the condition of detuned loaded and minimum optical linewidth (bottom panel)

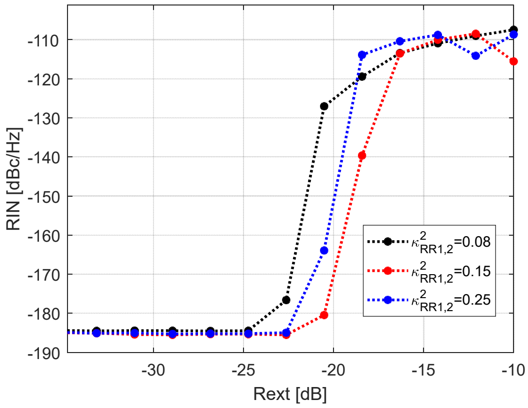

Figure 3 Integrated RIN versus external optical feedback Rext at 5cm from the output port, RSOA bias to get Pout=20mW and LEF=3.

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