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Dynamic regimes and damping of relaxation oscillations in III-V/Si external cavity lasers

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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 turbulent and self-pulsing regimes. The different regimes are reached by detuning the lasing wavelength respect to the mirror effective reflectivity peak and are the consequence of the dispersive narrow band reflectivity of the silicon photonics mirror, the linewidth enhancement factor and four-wave mixing in the gain medium.

1. Introduction

Integrated lasers in silicon photonic are key components for the development of small and low cost optical transmitters for both datacom and telecom, sensors and LIDAR. In this context, the laser structure typically consists in a III-V gain material coupled to the rest of the silicon photonic chip, which provides the mirrors to form an extended cavity laser (for example Fig.1a). The design of the mirror relay on a bunch of silicon photonics components (micro-rings, DBR reflectors, Mach-Zehnder interferometers, delay lines, etc…) which provide designs of long effective length external cavities and narrow band dispersive mirrors. Thanks to these designs, lasers with very narrow linewidth and wide tunability has been realized [1,2]. In these structures, the reduction of the laser linewidth has been extensively studied both theoretically and experimentally, but very few works have been dedicated to the analysis of other dynamic characteristics. We demonstrate here that due to the narrow band dispersive silicon photonics mirror the laser can go through different dynamic regimes: from ultra-stable regimes, characterized by the reduction of the relaxation oscillation frequency and strong damping of the relaxation oscillations, to self-pulsing and turbulent regimes. These regimes were found experimentally in [1,2] by tuning the lasing wavelength via the phase control section. To the best of our knowledge modelling and theoretical work to explain the experimental finding is still missing. The aim of this work is demonstrating that the different dynamic scenarios are due to the long effective external cavity, the narrow bandwidth of the reflector and the linewidth enhancement factor (α-parameter) and the four wave mixing in the RSOA.

2.Method

The hybrid laser in Fig 1a consists in an off-the-shelf MQW 1mm long RSOA, butt-coupled to a silicon photonic reflector with Si3N4 rings. The rings are designed to set the FWHM bandwidth of the effective reflection coefficient ($|r_R(\omega)|^2$. in Fig.1a) to 6GHz. The peak of $|r_R(\omega)|^2$is 3% with Tc,out =73% designed to optimize the WPE at output power of 20mW [3]. The lasing frequency can be detuned respect to the peak by tuning the phase $\Delta\phi$ of control section PS. The numerical method applied in our analysis is based on [4] and consists of an integral equation for the propagation of the optical electric field in the RSOA and delayed differential equations to account for the time-response of the rings. The equation of the field is coupled with the rate equation of the average carrier density of the RSOA. We perform a linear stability analysis (LSA) of the CW solution of the system [4] and we calculate the complex roots of the determinant of the linearized system. The two main roots are associated to the relaxation oscillation resonance (RO) and the photon-photon resonance (PPR) and give the frequency (real part of the roots) and damping (imaginary part of the roots) of these resonances. We employ this approach to quantify the impact of the external cavity, of dispersive mirror bandwidth and tuning of the phase control section in determining the characteristics of the RO and PPR. The numerical solution of the equation system gives the temporal evolution of the dynamic regime (e.g: output power versus time, RIN spectra and integrated RIN, optical spectra etc …)

3. Results

Fig. 1b reports the map of the RIN (integrated over a bandwidth of 25GHz) calculated at different RSOA bias current and detuning $\Delta\nu$ of lasing frequency respect to the peak of $|r_R(\omega)|$. The blue region corresponds to stable regime with single mode output while the yellow region of high RIN corresponds to a self-pulsing or turbulent regime. The white dashed line is obtained by LSA and it marks the border between the stable regime (with positive imaginary part of the RO roots) and the unstable regime (with negative imaginary part of the RO roots). At fixed RSOA bias current of 230 mA, we report in Fig.2a the lasing wavelength and the average output power by varying $\Delta\phi$ and in Fig. 2b the optical spectra in region 1 (turbulent regime), region 2 (stable single mode regime) and region 3 (self-pulsing regime). To understand the transition from the stable to the self-pulsing regime we plot the damping (Fig. 2c) and the frequency (Fig. 2d) of the RO: when the damping gets negative, we enter in the unstable regime characterized by undamped relaxation oscillations that, when resonant with another longitudinal mode, lead to the self-pulsing. The undamped RO is explained as follows: for detuning $\Delta\nu<0$ the phase noise caused by spontaneous emission and non-null α-parameter turns into intensity noise due to the narrow band reflector making the RO less damped. When the poorly damped RO is resonant with another longitudinal mode of the cavity, it reduces the threshold of this mode that turns on and beats with the main lasing mode. This effect decreases when increasing wavelength toward the peak of $|r_R(\omega)|$ because the contrasting effect of detuned load [5]. Indeed, at $\Delta\phi/2\pi=0.35$ we reach the detuning corresponding to the maximum slope of $|r_R(\omega)|$ and therefore the maximum of the damping of the RO. The progressive reduction of the damping by further increasing $\Delta\phi/2\pi$ is therefore explained by the progressive reduction of the detuned loaded effect. The scenario would be completely different if the LEF was neglected (purple lines in Fig.2c and d) because of the reduced phase noise.

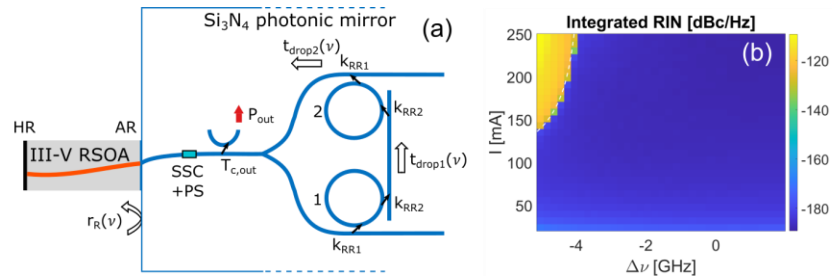

Fig. 1- III-V/Si hybrid laser (a) and (b) Integrated RIN for different detuning $\Delta\nu$ of lasing wavelength and RSOA bias current. $\Delta\nu=0$ corresponds to lasing at the reflectivity peak which is centred at 1310 nm.

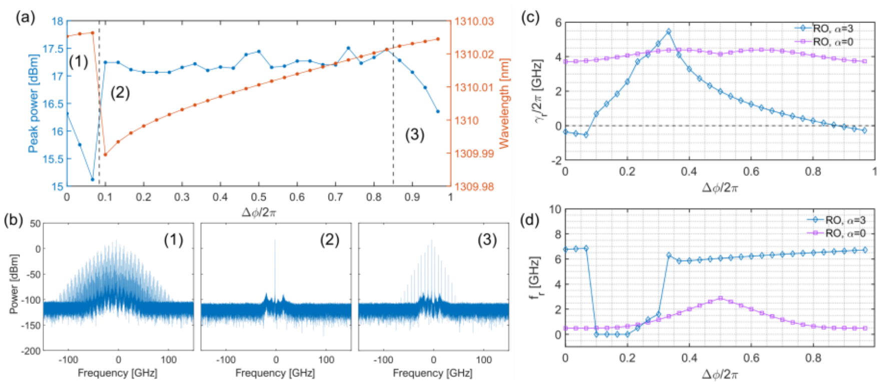

Fig. 2- Simulated lasing wavelength and output power by tuning the phase section (a), optical spectra in the three dynamics regimes (b) and damping (c) and frequency (d) of the roots associated at the RO by varying $\Delta\phi$. RSOA bias current is fixed at 230 mA.

The results in Fig.2 are in line with the experiments in [1,2] and can be a valuable approach to interpret the experimental findings. By designing effective mirrors with different bandwidth of $|r_R(\omega)|$ we have also found that the narrow bandwidth can give higher damping factor as compared to the case of a broad band reflector. The approach has also been employed to analyze the stability of these lasers to external optical feedback and evaluate the impact of PPR in destabilizing the laser in presence of external optical feedback.

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