Design of hybrid lasers for silicon photonics: efficiency, optical feedback tolerance and laser dynamics

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ABSTRACT

We present the design and the simulation of the dynamics of hybrid lasers based on a reflective SOA edge-coupled to a silicon photonics integrated reflector realized with waveguide rings. We design the laser for high efficiency and tolerance to spurious optical feedback and we compare the best designs in SiN and SOI platforms. By simulating the laser dynamics with a Time Domain Travelling Wave approach we show that the hybrid solitary laser (ie: without feedback) can operate in various regimes from CW to self-pulsing. These regimes are triggered by the linewidth enhancement factor of the SOA and can be controlled by a phase control section. The tolerance to the optical feedback is also further enhanced by the damping of the relaxation oscillations filtered by the narrowband reflector.

Keywords: *hybrid laser, silicon photonics, optical feedback tolerance*

1. INTRODUCTION

It is well known that the integration of the laser source in a silicon photonics (SiPh) platform is one of the most challenging issues because the laser must be low cost, reliable, efficient, stable and robust against spurious optical back reflections coming from the rest of the SiPh circuit or from the output connectors. The technology closest to industrial commercialization is the hybrid integration technique consisting of flip-chip butt-coupling of a III-V gain chip with a SiPh mirror [1].

In this work we present the design of a hybrid laser realized via the edge-coupling of a commercial III-V MQW HR/AR reflective SOA (RSOA) with an integrated mirror implemented in a silicon nitride (SiN) platform as sketched in Fig.1. The SiN mirror forms an external cavity that can be designed to optimize the laser wall-plug efficiency (WPE), the tolerance to an external optical feedback [2], and the laser optical linewidth [3]. We show here that a trade-off between laser efficiency and feedback tolerance can be found with a proper selection of the mirror parameters [2], and we compare this design with a similar one in a Silicon-On-Isolator (SOI) platform. We also study the dynamics of these hybrid lasers both as solitary lasers and in the presence of spurious external optical feedback. As a final result, we demonstrate that the designed SiN hybrid laser can give an ultra-high tolerance to the external optical feedback thanks to the narrow bandwidth reflection coefficient of the SiPh mirror.

2. DESIGN

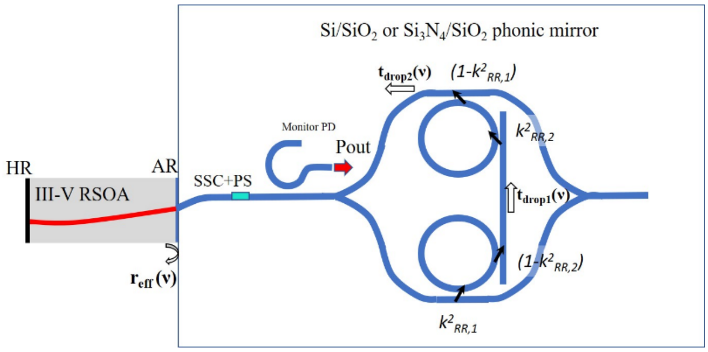

Figure 1: Sketch of the hybrid external-cavity laser structure. The mirror is based on a Mach Zehnder Interferometer (MZI) loaded by two rings providing a narrowband complex reflectivity $r_{eff}(v)$ and a Vernier tuning of about 150 nm. The symbols are: PS = phase control sections, $k^2_{RR1,2}$ = power coupling coefficient of the two ring resonators in the critical coupling configuration ($k_{RR1,2}$), $t_{drop1,2}$ = drop port transmission coefficients of the two ring resonators, SSC = spot size converter. The output power P_{out} is collected by the coupler with output coupling coefficient $T_{c,out}$.

Starting from a simple model based on textbook rate-equations and an effective Lang-Kobayashi (LK) approach [2], we demonstrated that by increasing the mirror cavity effective length (L_{eff}) the laser in a SiN platform is more tolerant to optical feedback (compared to an equivalent FP laser) thanks to the increase of the cavity round trip time. In Fig. 2 we plot, as function of the ring coupling coefficients ($k_{RR,1}$=$k_{RR,2}$) and the output coupler transmission coefficient $T_{c,out}$, the calculated WPE at fixed output power P_{out}=20mW (Fig. 2a), the corresponding

SiPh mirror L_{eff} and the resulting critical feedback level as predicted by the effective LK approach [2]. The RSOA is a commercial device, and we design the laser considering RSOA parameters extracted from measurements. In this work the design procedure of [2] for the SiN platform is extended also to the SOI platform by including the non-linear loss due to two-photon absorption (TPA) and free carrier absorption (FCA) in silicon straight waveguides and rings. TPA and FCA parameters are extracted from measurements. Fig.2(a) shows that high WPE of more than 19% can be reached in both platforms, even including silicon TPA and FCA of SOI waveguides. This is due to the design procedure that searches for the best design parameters to optimize the WPE and due to the high differential gain of the III-V gain material. On the contrary, Fig. 2(b) and (c) demonstrate that the choice of the platform significantly impacts on the L_{eff} and hence the maximum tolerated feedback ($R_{ext,max}$). In the SiN platform L_{eff} can be long because of large ring radii (>95 μm) and negligible non-linear loss. Fig. 2c also quantifies the impact of silicon non-linear loss on $R_{ext,max}$ showing that the high $R_{ext,max}$ achivable in SiN is significantly reduced in Si because of the TPA and FCA.

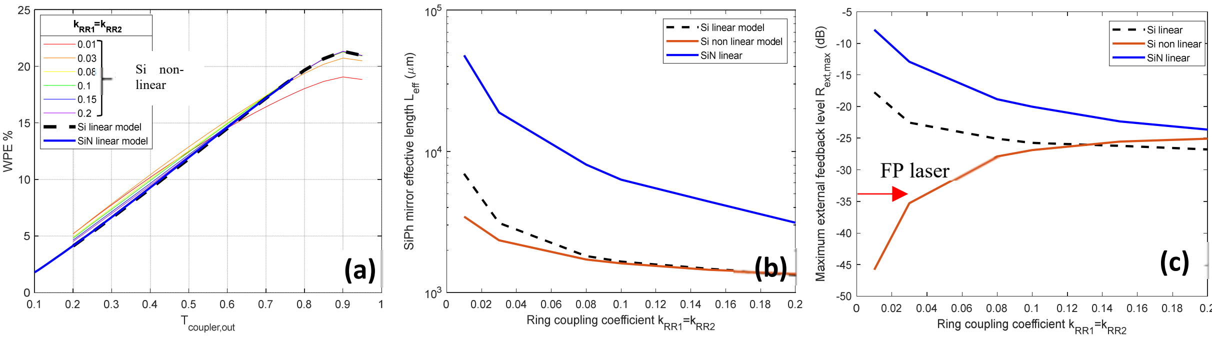

Figure2:(a) Laser WPE at Pout=20mW as function of the design parameters and platform (SiN or SOI); (b) SiPh mirror effective length and (c) maximum tolerated external feedback as function of the ring coupling coefficients $k_{RR1,2}$. In (b) and (c) $T_{c,out}$ is fixed at 72%. The red arrow indicates the $R_{ext,max}$ of an equivalent Fabry-Perot laser.

From this analysis we learned that the SiN design is more tolerant to the optical feedback thanks to the possibility of designing both long L_{eff} maintaining sufficiently large tuning range. However the question is now if the narrowband $r_{eff}(\nu)$ of the mirror can play an additional role in increasing further the tolerance to the feedback by damping the relaxation oscillation of the laser. To answer this question, we have studied the laser dynamics.

3. LASER DYNAMICS

To study the dynamics of the hybrid solitary laser and to validate the design presented above, we have simulated the laser structure in Fig.1 with a Time Domain Travelling Wave (TDTW) simulator including polarization dynamics and hence the gain dispersion and the linewidth enhancement factor (LEF) of the SOA. The advantage of this approach is the inclusion of the dynamic competition between the lasing mode and the other cavity longitudinal modes. The TDTW model can also investigate the role of the narrowband SiPh mirror in the dynamics of the solitary laser and in the ultra-high tolerance to the optical external feedback.

Via TDTW numerical simulations we first found that the various operation regimes of the solitary laser (ie: stable single mode, self-pulsing, chaotic etc..) are triggered by the LEF and can be controlled by the phase control section PS. As shown in Fig. 3a, the lasing mode of the SiN laser of Fig. 1 can be tuned via the PS section to operate at the reflectivity peak (marked with "TW0 case" in Fig.3a) or detuned with respect to it ("TW1 case" in Fig.3a) where $dr_{eff}(\nu)/d\nu$ is positive and maximum. The TDTW simulations showed that when LEF is small (e.g. LEF=1) the TW0 solution is stable but, for higher LEF (e.g LEF=3), it becomes unstable evolving toward a pulsing regime (Fig.3b) sustained by the beating of two cavity longitudinal modes. On the contrary, the TW1 solution is always stable even for large LEF (Fig.3c). In the TW0 case, any noise can shift the lasing mode to the high frequency side of the reflectivity peak with a consequent significant reduction of the $r_{eff}(\nu)$ seen by the laser. This leads to the consequent increase of the carrier density and, in the case of large LEF, this further pushes the lasing mode to higher frequencies until a point of stable operation is reached. This stable operation is usually self-pulsing caused by the beating of two other cavity longitudinal modes emerging from the (ν- ν_0)<0 side. On the contrary, in the TW1 case, a negative feedback control is installed: if the lasing mode shifts to smaller/higher frequency due to the noise, the effective reflectivity reduces/increases leading to an increase/reduction of the carrier density that pushes the lasing mode back to the stable TW1 position.

This TW1 solution turns out to be very stable also in the presence of external optical feedback. In Fig. 3d we report the stability of the TW1 solution in the presence of an external feedback for different SiN laser designs with Tcout=72% and various ring coupling coefficients. The green symbols indicate a stable TDTW solution whereas the red symbols are unstable TDTW solutions triggered by the photon-photon resonance with other cavity longitudinal modes. We observed an improved stability with respect to the solution predicted by the effective LK approach. In Fig.3e we compare the intensity modulation response of the solitary laser as predicted by a standard rate-equation model with spectrally flat $r_{eff}(v)$ and the one calculated with the TDTW approach including the narrowband $r_{eff}(v)$ with bandwidth narrower than the laser relaxation oscillation frequency. The peak of the relaxation resonance is significantly damped by the narrowband mirror and therefore the increased damping improves the $R_{ext,\,max}$ further with respect to the LK prediction. The drawback is however the turn-on of the photon-photon resonance appearing as second peak of the IM response. The PPR is indeed the cause of the red unstable TDTW solution in Fig. 3d.

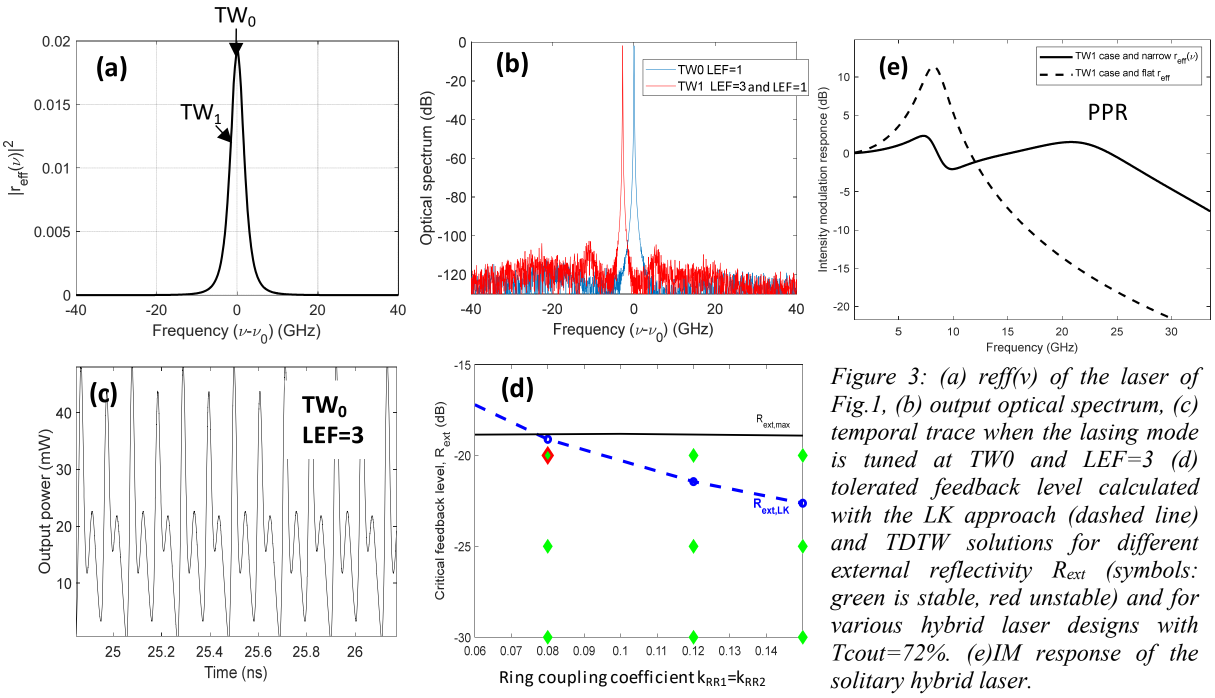

Figure 3: (a) reff(v) of the laser of Fig.1, (b) output optical spectrum, (c) temporal trace when the lasing mode is tuned at TW0 and LEF=3 (d) tolerated feedback level calculated with the LK approach (dashed line) and TDTW solutions for different external reflectivity R_{ext} (symbols: green is stable, red unstable) and for various hybrid laser designs with Tcout=72%. (e)IM response of the solitary hybrid laser.

CONCLUSIONS

We have presented the design of a hybrid laser based on RSOA and SiPh mirror. We have compared the laser performance in terms of efficiency and tolerance to the optical feedback for both SiN and SOI platforms demonstrating that both platforms can provide good WPE, but the TPA and FCA of silicon waveguides and rings significantly reduce the tolerance to spurious optical feedback. Studying the laser dynamics we have shown that the tolerance to spurious back reflections of the hybrid laser is significantly increased not only thanks to the long effective length of the SiPh mirror but also due to the very narrow bandwidth of the SiPh reflector that can damp significantly the laser relaxation oscillations that trigger the laser instability in the presence of spurious back reflection. This analysis demonstrates the potential of these structures for realizing lasers for a silicon photonics platform.

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