Dynamic and Noise Properties of High-Q Hybrid Laser

A. Gallet[1, 3], K. Hassan[2], C. Jany[2], T. Card[2], J. DaFonseca[2], V. Rebeyrol[2], A. Shen[1], J-G. Provost[1], F. Van Dijk[1], N. Girard[1], V. Muffato[2], A. Coquiard[2], S. Malhouitre[2], S. Olivier[2], G. Baili[4], H. Debrégeas[1], G.-H. Duan[1], F. Grillot[3] and A. de Rossi[4]

1 III-V Lab, a joint lab of 'Nokia Bell Labs', 'Thales Research and Technology' and 'CEA Leti', Campus Polytechnique, 1, Avenue A. Fresnel, 91767 Palaiseau Cedex, France,
2 CEA LETI, Minatec, 17 rue des Martyrs, F-38054 GRENOBLE cedex 9, France.
3 LTCI, Telecom ParisTech, Université Paris-Saclay 46 rue Barreau, 75634 Paris Cedex 13, France.
4 Thales Research and Technology, 1, Avenue A. Fresnel, 91767 Palaiseau Cedex, France,
antonin.gallet@3-5lab.fr

Abstract: *This paper describes a high quality factor III-V on silicon hybrid laser consisting in a harmonic optical potential well cavity. We measured a photon lifetime as high as 103 ps and a relative intensity noise below 147 dB/Hz with a constant level over 20 GHz.*
Keywords: *Hybrid laser, Silicon Photonics, High quality factor*

1. INTRODUCTION

III-V on silicon heterogeneous integration platform can provide ultra-low loss waveguides and gain material [1-2], hence making a laser with high quality factor (Q) resonator becomes possible [3]. As described by the extended Schawlow-Townes formula [4] lowering cavity losses reduces the laser linewidth. To obtain a high Q laser, one needs to severely limit the confinement in the III-V region, have a high grating strength to close the cavity and a special tailoring of the grating to reduce coupling to leaky mode and spatial hole burning. This paper reports on a high-Q hybrid laser made in the 500/300 nm SOI standard platform of Leti. Fig. 1a displays the cross section of the cavity. The mode is buried into a rib silicon waveguide with large width W_{wg} of 2 µm to limit the absorption in the III-V p-doped region as well as the scattering in the silicon waveguide. The grating is made by etching a 30 nm deep tooth into the rib waveguide. In a grating, a photonic band gap is opened in the waveguide dispersion, corresponding to the Bragg reflection. As described in [3], it is possible to make a single mode laser by a spatial modulation of the grating band gap. Here, this results in an effective photonic parabolic potential formed in the lower frequency band (VB). The spatial dependence of the edge of the VB is shown in figure 1b. Using coupled mode theory, a single localized mode is found in the valence band, 43 GHz above the band edge of the barrier section of the grating. The envelope of the mode is close to a Gaussian, which is related to a parabolic photonic potential.

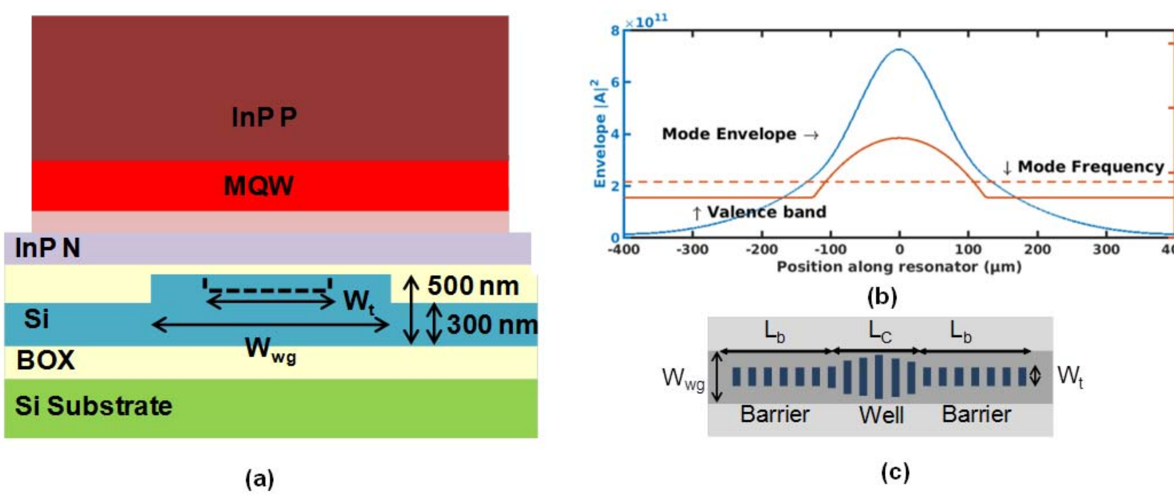


Fig.1: **(a)** Cross section of the device showing the silicon waveguide. **(b)** High Q laser spatial structure. The variation of valence band frequency as a function of position in the cavity is presented in solid orange. The mode frequency is found at 43 GHz from the unperturbed band edge (dashed orange). The power in the cavity calculated by couple mode theory is depicted in blue. **(c)** Schematic top view of the high Q DFB laser showing the barrier and well regions. The 300 nm slab is in light grey, the 500 nm waveguide in grey and the 30 nm-deep etched regions in dark blue.

The band diagram modulation presented in fig.1b is achieved by varying the teeth width W_t with a Gaussian profile on a “Well” length L_C = 250 µm as depicted in fig.1c. This feature limits the coupling to leaky modes of the grating. The Length L_b determines the external quality factor Q_{ext} of the resonator and thus the total Q factor [5]. This offers the possibility to optimize the external quantum efficiency by adjusting Q_{ext}. Here, the confinement in the quantum well is limited to 0.5%, which is much smaller than typical DFB design, however, it is enough to overcome the very low cavity losses inherent to a large Q factor.

2. STATIC AND DYNAMIC CHARACTERISTICS OF HIGH Q HYBRID LASERS

The dependence of the L-I curves with respect to the Q-factor is represented in fig. 2a, where the barrier length varies from 125 to 325 µm in steps of 50 µm. The maximum fiber coupled power ranges from 0.3 mW to 2.5 mW. In this range of barrier length, the calculated Q factor increases exponentially with L_b as it is dominated by Q_{ext} (fig. 2b). As a consequence, the laser threshold decreases exponentially with the barrier length. The optical spectrum is plotted in fig. 2c for various drive currents. We obtain a side mode suppression ratio (SMSR) better than 55 dB and constant over the whole drive current range.

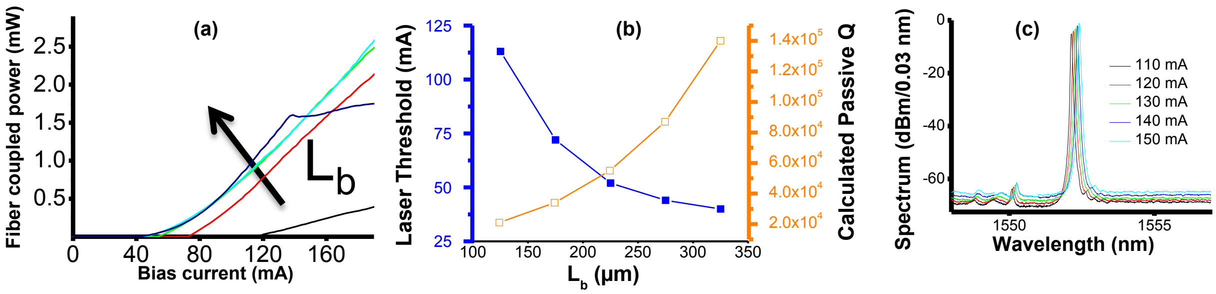
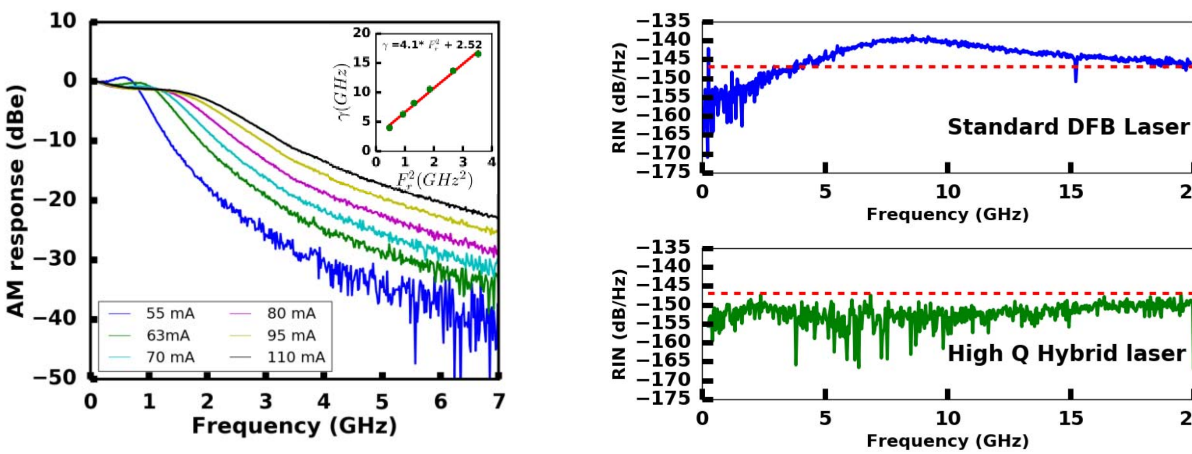


Fig.2: **(a)** L-I curve for L_C = 250 µm for L_b parameter ranging from 125 to 325 µm by 50 µm steps. **(b)** Variation of laser threshold and passive Q factor with the barrier length L_b. **(c)** Optical spectra for L_C = 250 µm and L_b= 275 µm showing SMSR > 55 dB.

3. DYNAMICS AND NOISE PROPERTIES

The main specificity of high Q hybrid lasers is their high photon lifetime, that we characterized with small signal modulation bandwidth. As seen from fig.3a, the modulation response is highly damped and the relaxation oscillation frequency F_r is low. Inset of fig. 3a shows the damping factor γ as a function of F_r^2. Solid line in red represents a curve-fitting using the relationship $\gamma = KF_r^2 + \gamma_0$ from which a K-factor as high as 4.1 ns is extracted leading to a photon lifetime of 103 ps. The interception with the y-axis gives an inverse differential carrier lifetime γ_0 of 2.5 GHz. Relative intensity noise (RIN) is then measured for a bias current of 120 mA and displayed on fig. 3b. A flat RIN is obtained, with level below 147 dB/Hz. A very little increase of the RIN due to the F_r is obtained. For comparison, the RIN of a λ/4 phase shifted hybrid DFB with classical laser design is plotted above.



(a) (b)

Fig 3: **(a)** Measured small signal bandwidth of the laser. The fitted damping factor versus square of relaxation oscillation frequency is displayed in the inset. **(b)** RIN measurements for a λ/4 phase shifted hybrid DFB laser with classical laser design (top) and a high Q hybrid laser (bottom). Both lasers have similar threshold and measurements are done for a same bias current of 120 mA.

4. CONCLUSION

This paper presents a high-quality factor hybrid laser. Influence of external Q factor on laser threshold is studied. The laser fiber output power reaches 2.5 mW with a SMSR greater than 55 dB for the best design. High photon lifetime of 103 ps is extracted, in agreement with the calculated quality factor. The high damping of the relaxation oscillation frequency is confirmed by RIN measurements remaining below -147 dB/Hz over 20 GHz.

REFERENCES

[1] G. H. Duan et al., "Hybrid III--V on Silicon Lasers for Photonic Integrated Circuits on Silicon," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 20, no. 4, pp. 158-170, July-Aug. 2014
[2] M. J. R. Heck et al., "Hybrid Silicon Photonic Integrated Circuit Technology," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 19, no. 4, pp. 6100117-6100117, July-Aug. 2013.
[3] C.T Santis et al., High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III-V platforms. Proceedings of the National Academy of Sciences of the United States of America (2014).
[4] C. Henry, "Theory of the linewidth of semiconductor lasers," in IEEE Journal of Quantum Electronics, vol. 18, no. 2, pp. 259-264, February 1982.
[5] H. Haus, “Waves and Fields in Optoelectronics”, Prentice-Hall Series in Solid State Physical Electronics, 1983