2021 27th International Semiconductor Laser Conference (ISLC) | 978-1-6654-4133-9/21/$31.00 ©2021 IEEE | DOI: 10.1109/ISLC51662.2021.9615828

Analysis of the relative intensity noise in a Fabry-Perot interband cascade laser revealing relaxation oscillations

Pierre Didier[1,2*], Olivier Spitz[1], Daniel Andres Diaz-Thomas[3], Alexei N. Baranov[3], Laurent Cerutti[3], Frédéric Grillot[1,4]

[1]LTCI, Télécom Paris, Institut Polytechnique de Paris, 19 place Marguerite Perey, 91120 Palaiseau, France
[2]mirSense, Centre d'intégration NanoInnov, 8 avenue de la Vauve, 91120 Palaiseau, France
[3]IES, Université de Montpellier, CNRS, 34000 Montpellier, France
[4]Center for High Technology Materials, University of New-Mexico, 1313 Goddard SE, Albuquerque, NM, USA

*Email: pierre.didier@telecom-paris.fr

Abstract – ICLs are promising mid-infrared semiconductor lasers that could address many applications. However, current knowledge about their intrinsic properties is scarce. Here, we demonstrate a clear relaxation process when studying the noise properties of an ICL, which contributes to the fundamental characterization of this semiconductor structure.

I. Introduction

The mid-infrared domain has attracted attention because of the many promises it holds in terms of high-precision molecular spectroscopy [1], non-invasive analysis of blood-serum [2] and free-space transmission that are resistant to degraded conditions such as fog or heavy rain [3]. Most of the current application developments in the mid-infrared currently rely on quantum cascade lasers (QCLs) technology. QCLs are semiconductor lasers exploiting radiative intersubband transitions within the conduction band of semiconductor heterostructures. They now achieve low-linewidth and high-power operation while coming in user-friendly packages. However, QCLs often require large bias currents and voltage which are detrimental to their implementation in light portable systems. Furthermore, due to their highly-damped behavior, they are very limited in terms of non-linear dynamics bandwidth and this hinders the maximum transmission speed in the case one wants to use QCLs for private chaos-synchronized communication [4]. Interband cascade lasers (ICLs) offer an alternative pathway for low consumption mid-infrared semiconductor sources, even though they are not yet widely used for applications. These lasers take advantage of broken interband gap, which allows mid-infrared emission up to 7 µm at room temperature. Recent publication with ICLs have shown frequency comb operation [5], large chaos bandwidth [6] and precision spectroscopy of methane [7]. Contrary to QCLs whose properties have been thoroughly studied [1], basic knowledge about ICL intrinsic properties is still lacking. For instance, very few papers discuss the noise properties of ICLs [8] and the relaxation frequency is never clearly extracted from experimental data. In this work, we experimentally unveil the relaxation oscillation of an ICL from the measurement of the relative intensity noise (RIN) for various currents above threshold. The frequency shift that we observe when changing the bias current is compatible with existing simulation efforts [8]. Overall, this work deepens the understanding of the physics of ICLs and shed the light on the potential limitations in terms of electrical modulation bandwidth and non-linear dynamics in these novel semiconductor lasers.

II. Results

The ICL is grown by molecular beam epitaxy on a GaSb substrate. The active region is made with seven-stage cascade periods composed of type-II "W" quantum wells whose design is optimized for lasing emission at 4.1 µm at room temperature. The active medium is surrounded by GaSb optical confinement layers and claddings with AlSb / InAs superlattices.

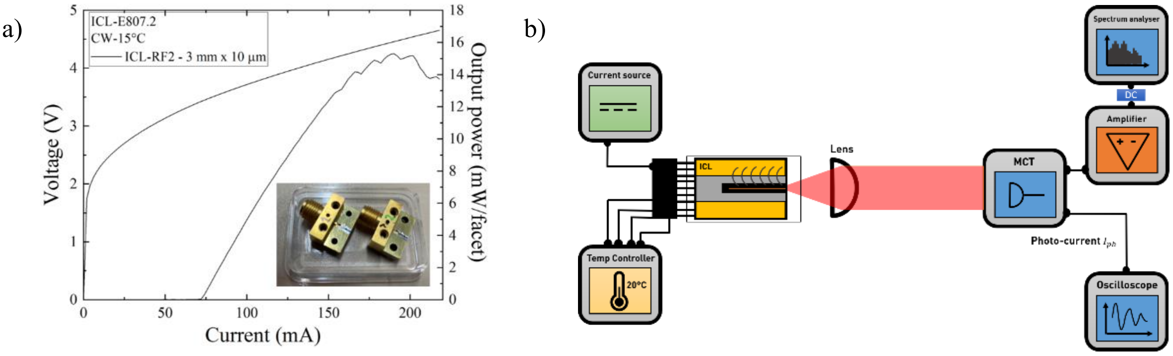

Fig. 1. (a) Power-current-voltage (PIV) curve obtained when the ICL is kept at a temperature of 288K; the bottom right insert shows two ICLs mounted on a mount suitable for high frequency electrical modulation. (b) Experimental scheme for determining the intensity noise of the ICL, which subsequently leads to the determination of the relaxation frequency.

The processing of the ICL is performed by following different technological steps to form a Fabry-Perot cavity. The ridge waveguide is 3 mm long and 8 µm wide. The ICL is then soldered with indium on a copper block and mounted on a package suitable for radio frequency modulation. Fig. 1. a) displays two RF-mounted ICLs as well as the static characteristics of the ICL under continuous wave at 15 °C. The threshold current is 72 mA and the output optical power maximum is 15 mW. The ICL is maintained at a constant temperature of 20 °C by a temperature controller and a Peltier system and this increases the threshold current to 75 mA. The laser is powered with a low noise source (QCL 2000 Lab Wavelength Electronics). Changing the current source (ILX Lightwave LDX-3210) does not mainly change the displayed results. The beam collimated by a lens is detected with a MCT (Mercury-Caladium-Teluride) detector with 700 MHz-bandwidth per manufacturer's specification.

The noise spectral density of the photocurrent fluctuations at the output of a photodectector is the sum of two distinct contributions:

$$S(f) = 2qI_{ph} + I_{ph}^{2}\, RIN(f)$$

where I_{ph} is the average value of the photo-current, q is the electron charge, and S(f) the power spectral density of the optical intensity fluctuations. The first term is related to the shot noise due to the quantum nature of electrons and photons whereas the second corresponds to the power spectral density of the relative fluctuations of the optical source that is to say the RIN. The MCT is sensitive enough to detect signals down to a few hundreds of µW. The signal of the MCT is sent towards a bias-tee with a bandwidth of 100 kHz-12GHz allowing us to recover the DC and AC component of the laser beam. For the AC part, we use an electrical amplifier (SHF 826H) with 25 dB gain and a spectrum analyzer (Rohde & Schwarz FSU). For each bias current, we assess the spectral noise power of the signal of the illuminated detector. We then subtract the dark power which includes the white thermal noise of our setup. The photovoltaic current corresponds to the DC part of the signal and is retrieved with an oscilloscope to evaluate the shot noise. A sketch depicts our experimental setup in Fig. 1 b).

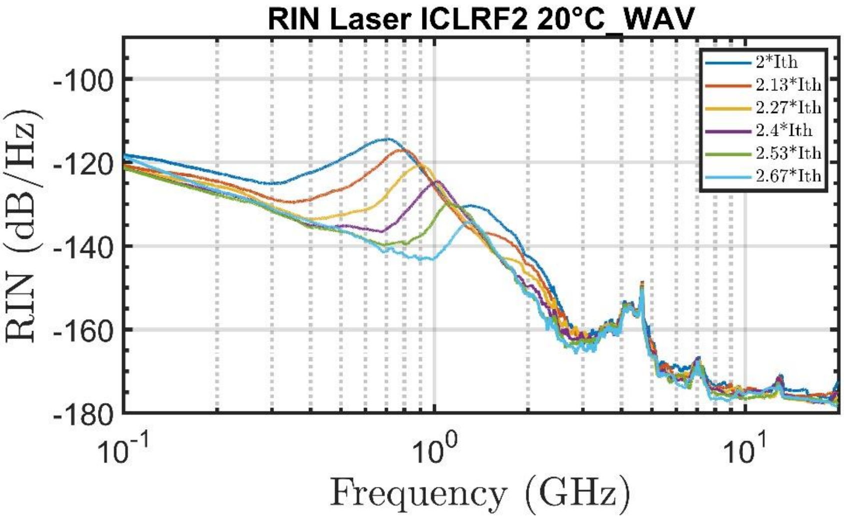

Fig. 2. (a) RIN value over the 10MHz-20GHz interval at 293K. Evidence of a peak in the spectrum at the relaxation frequency of the laser around GHz.

The final result is illustrated in Fig. 2. The RIN of the ICL is a function of frequency; it peaks around relaxation oscillation frequency because of the interaction between carrier density and photon density. The RIN decreases as the current increases, which agrees well with the literature. Moreover, we find that as opposed to quantum cascade lasers which do not have relaxation oscillation due the intersubband dynamics, the ICL exhibits a clear relaxation frequency in the order of 1 GHz that increases with the bias current. To the best of our knowledge, this result constitutes the first experimental evidence of relaxation oscillation in such interband cascade laser sources which is of first importance to better understand their high-speed capabilities. The 3dB-bandwidth of the detector used hinders a thorough characterization of the spectral behavior and further experimental studies will take advantage of the very large bandwidth of quantum cascade detectors (QCDs) to extend the presented results. Future work will also focus on exploring other fundamental parameters, with the long-term goal of producing squeezed light at mid-infrared wavelength, which is of utter interest for quantum applications in an almost uncharted optical domain.

III. References

[1] C. Mann et al., Advances in Solid State Physics. Springer, 351–358 (2003)
[2] M. Brandstetter et al., Applied Physics B, Volume 110, 233–239 (2013)
[3] P. Corrigan et al., Optics Express, Volume 17, 4355–4359 (2009)
[4] O. Spitz, Mid-infrared Quantum Cascade Lasers for Chaos Secure Communications, Springer (2021)
[5] J. Hillbrand et al., Optica, Volume 6, 1334–1337 (2019)
[6] O. Spitz et al., in CLEO: Science and Innovations, STu1H.4, Optical Society of America (2021)
[7] N. Li et al, Optics Express, Volume 29, 7221–7231 (2021).
[8] Y. Deng & C. Wang, IEEE Journal of Quantum Electronics, Volume 56, 1–9 (2020).