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O. Spitz, L. Durupt, F. Grillot, "Towards a turnkey private communication system using a quantum cascade laser emitting at 4 microns," Proc. SPIE 11693, Photonic Instrumentation Engineering VIII, 116930K (5 March 2021); doi: 10.1117/12.2578238

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Event: SPIE OPTO, 2021, Online Only

Towards a turnkey private communication system using a quantum cascade laser emitting at 4 microns

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ABSTRACT

Quantum cascade lasers (QCLs) are optical sources exploiting radiative intersubband transitions within the conduction band of semiconductor heterostructures.[1] Mid-infrared QCLs have been thoroughly considered for applications such as spectroscopy,[2] free-space communications[3] and countermeasure systems.[4] Under self-optical feedback, QCLs have been proven to operate in several non-linear dynamic regimes,[5] including low-frequency fluctuations and deterministic chaos, which are suitable for private communications taking advantage of both chaos masking and background stealth. However, the previous experiments focused on distributed feedback (DFB) quantum cascade lasers emitting at 5.7 μm, which is not an optimized wavelength for free-space applications. Indeed the atmosphere is characterized by two transparency windows between 3-4 μm and 8-12 μm, which are called bandpass L and bandpass N, respectively.[6] Furthermore, the 5.7 µm lasers were studied at the chip level, which means that end users must own the dedicated mounts, connectors and mid-infrared optics in order to take advantage of these quantum cascade sources. This work extends our knowledge by exploring the non-linear dynamics of a packaged Fabry-Perot (FP) QCL emitting at 4 µm. The advantage of the FP configuration is an increased output-power compared to DFB sources, though the FP configuration is not well-known yet.[7] Moreover, this laser comes in a handy environment with embedded focusing optics and high-heat load (HHL) packaging for plug-and-play operation. Consequently, the current findings pave the way for off-the-shelf private applications at mid-infrared wavelength where high-power and compact turnkey systems are required.

Keywords: Quantum cascade lasers, mid-infrared photonics, non-linear dynamics, applications of laser chaos

1. INTRODUCTION

Optical feedback in quantum cascade lasers (QCLs) has been investigated in order to address beam quality properties[8] as well as stabilization or destabilization issues.[9] By re-injecting part of the emitted light of the QCL into its own cavity, the QCL can operate within five different non-linear dynamics regimes.[10] Among them, low-frequency fluctuations and coherence-collapse dynamics are chaotic waveforms[11] which can be used to hide a secret message within an unpredictable signal. This experimental work focuses on the non-linear dynamics of a HHL-packaged FP QCL pumped with a continuous bias and emitting at 4 μm. At this wavelength, the message can be transmitted through the atmosphere since two transparent windows have been highlighted in the mid-infrared, which overall means upper transmission properties.[12] Previous experimental efforts only dealt with unmounted QCL chips, thus forcing the end-user to own dedicated mounts and mid-infrared optics. This work pushes one step further the opportunities offered by compact off-the-shelf systems emitting in the mid-infrared. We investigate the effect of optical feedback on the temporal non-linear dynamics displayed by this FP-QCL when varying the feedback strength.

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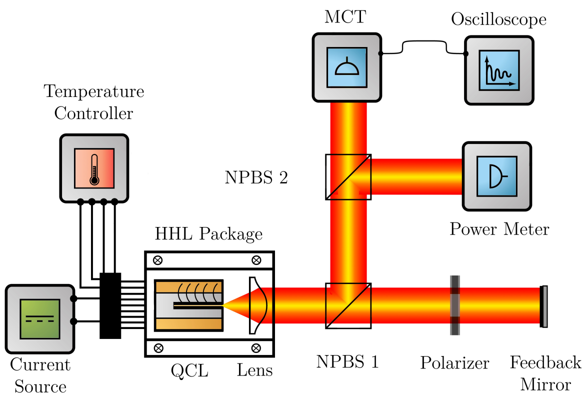
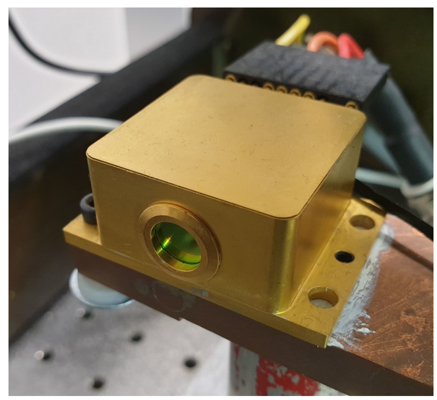
Photonic Instrumentation Engineering VIII, edited by Yakov Soskind, Lynda E. Busse, Proc. of SPIE Vol. 11693, 116930K · © 2021 SPIE · CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2578238

2. EXPERIMENTAL RESULTS

Figure 1 (a) depicts the light travel in our experimental setup. The QCL is biased with a continuous wave by a current source. The HHL packaging (fig. 1 (b)) provides the lens required to collimate the QCL light beam. Above the current threshold, the light emitted by the laser passes through a first non-polarizing beam splitter (NPBS 1) from which 55% of the light is transmitted into a polarizer and then is reflected back into the laser cavity by a mirror. 45% of the light is reflected towards a second non-polarizing beam splitter (NPBS 2) where the light is once again split between two paths: 70% of the light is transmitted to be analysed by a Mercury-Cadmium-Telluride (MCT) detector which is connected to an oscilloscope for real-time study, while 30% of the light is reflected and collected by a power-meter to perform the alignment and to record the output power. Contrary to our previous experiments,[5] we minimize the distance between the packaged QCL and the feedback mirror. The corresponding external cavity length is 14 cm roundtrip, which theoretically represents an external-cavity frequency of roughly 2 GHz. The expected frequency should be lower, as already pointed out in other experimental efforts,[7] but will be difficult to determine because the MCT detector has a 3 dB-bandwidth of 700 MHz.



(a)



(b)

Figure 1: (a) Experimental setup: the light from the QCL is focused by the lens and sent towards a beam splitter, the transmitted beam is used for the optical feedback while the upper part of the setup shows the analysis of the mid-infrared light, split between a power meter and a MCT detector; (b) Picture of the HHL package with the mid-infrared window, the QCL is enclosed inside the golden case.

The intensity output of the QCL under optical feedback is shown in fig. 2 for various feedback ratios. When the feedback is suppressed, the QCL does not produce non-linear dynamics and the timetrace is stable, with a low-level noise. By increasing the feedback strength, one can trigger various non-linear dynamics. The first that is visualized in fig. 2 (b) is a periodic sine pattern, which is also encountered in other semiconductor lasers with optical feedback or optical injection. The frequency of this sine wave is 13 MHz. A puzzling characteristic of the sine pattern we retrieved is that the frequency of the pattern is not equal to the external cavity frequency and is not equal to the relaxation oscillation frequency of the QCL (because QCLs are highly damped semiconductor laser and do not exhibit such relaxation oscillations). So the destabilization of this QCL occurs in a non-conventional way compared to other semiconductor lasers.[13,14] A possible explanation would be to consider the opto-thermal coupling effects in a QCL to support a destabilization at a very low frequency (dozens of MHz instead of hundreds or thousands of MHz) but, so far, the numerical models for QCLs have not considered this effect. An increase of the feedback strength from the destabilization point leads to a conventional evolution of the laser output. Figure 2 (c) shows a period-doubling pattern that is still governed by a very low frequency. The two periodic oscillations we just described are non-linear phenomena but they are not relevant for the applications detailed hereafter, because these phenomena have strong periodic components. Further increasing the feedback strength shows the boundaries between a phenomenon that is mostly periodic and a chaotic phenomenon. This configuration is visualized in fig. 2 (d). In order to get rid of the regular oscillation component, one needs to increase the feedback ratio even more to obtain a fully developed chaotic behavior with unpredictability and no

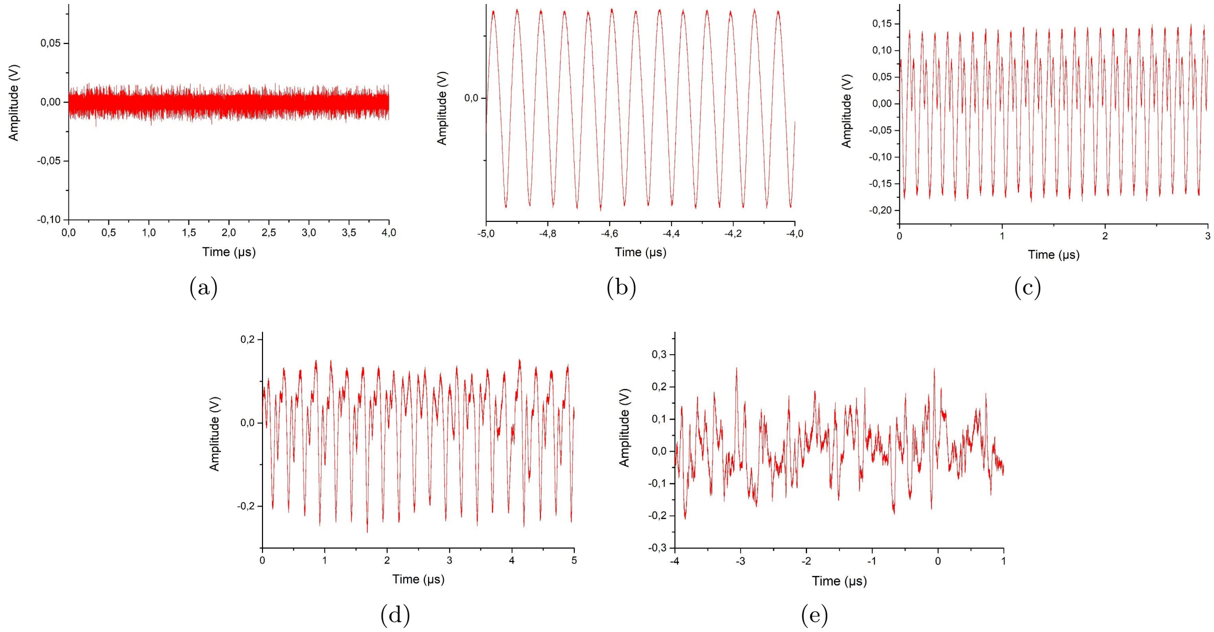
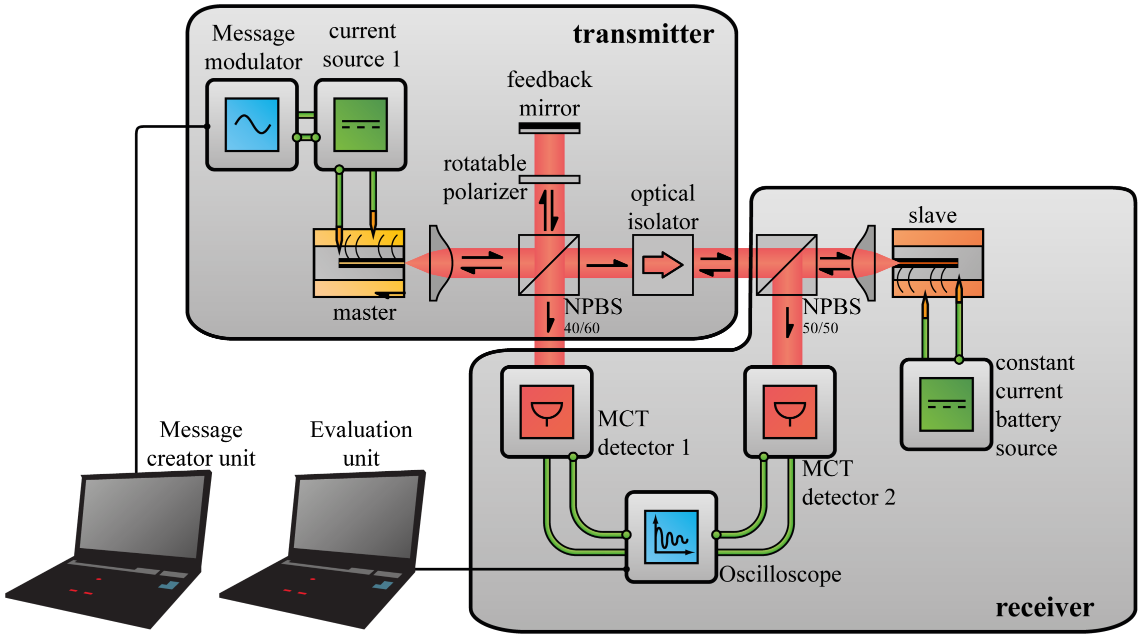


Figure 2: Typical experimental time traces retrieved when increasing the feedback strength; (a) case corresponding to the free-running QCL exhibiting a stable signal; (b) optical feedback induces a periodic oscillation in the output of the QCL; (c) further increasing the feedback strength leads to a period-doubling phenomenon; (d) corresponds to the configuration where the output of the laser transits from a periodic signal to a chaotic signal, the period-doubling phenomenon is still visible but with unpredictable perturbations; (e) fully developed chaos for the maximum feedback strength.

dependence on the previous outcome, as seen in fig. 2 (e).

3. APPLICATIONS OF SEMICONDUCTOR LASER CHAOS

In the following, we will describe how to implement a private communication based on chaos synchronization, because this is one of the main applications one can target with a packaged chaotic QCL. However, other applications exist and will be briefly described here, as they could be promising in future broadband technologies such as autonomous vehicles.[15] Over time, QCLs will likely become one of the main infrared laser sources for LIDAR (light detection and ranging) applications and in this case, high-duty-cycle waveforms are required since QCLs cannot be Q-switched to obtain high-energy pulses. More generally, chaos can be used in order to improve the efficiency of LIDAR. LIDAR is similar to RADAR (radio detection and ranging) in the detection process but offers increased resolution and better field of view due to shorter wavelengths. This is of paramount importance in order to ensure a reliable detection in an autonomous car driving on a road with a large incline, for example. Another advantage of LIDARs, compared to video cameras, is that LIDAR gives access to parameters of first importance such as the distance of the detected targets, as well as their speed thanks to Doppler effect. There are two categories of LIDARs: one based on lasers with ultra-short pulses and the second one based on frequency chirp. For the latter, the information about the target are recovered from the correlation between the back-reflected signal on the target and the delayed emitted signal. Several methods can be implemented in order to generate a signal with no repetition of the delayed outcome, because a repetition could lead to the measurement of a wrong target's distance. Lin and Liu developed chaotic LIDARs[16] and chaotic RADARs,[17] taking advantage of the chaos properties of laser diodes in order to create a signal at high frequency, which means high resolution, and with no dependence on any previous outcome. The detection step can be of the order of the centimeter and the range can be extended to several meters. Furthermore, the use of chaotic signals instead of modulated waves leads to detection systems resistant to noise and jamming.[18]
Another application strongly supported by optical chaos is physical random number generation (RNG).[19,20]



(a)

Figure 3: Setup for chaotic secure communications with QCLs. The apparatus is split into two parts: one (with the master QCL) is dedicated to chaos masking and transmission whereas the other (with the slave QCL) is dedicated to synchronization and recovery. Abbreviations are the same than those used in the previous section.

Random numbers are vital ingredients in many applications ranging, in a non-exhaustive list, from computational methods such as Monte Carlo simulations and programming,[21] to the large field of cryptography for the generation of enciphered messages, as far as to commercial applications like lottery games and one-arm bandits.[22] Even though different by nature, chaos and randomness share a common feature in that they produce entropy. Chaos in semiconductor lasers thus provides an ideal physical source of random bits, as it combines outcome-unpredictability with no dependence on any previous outcome. These two requirements are of paramount importance for RNG.[23] Using chaos from a laser diode, random bits can therefore be produced at very high bit-rates,[24] exceeding those obtained with other physical sources of entropy, including quantum random number generators, which are currently limited at approximately one Gbits/s[25] and may achieve a few dozens of Gbits/s in the coming years.[26,27] After the first successful demonstration in 2008,[28] the field of RNG using chaotic laser diodes has benefited from several developments, in terms of sampling rates and number of generated bits.[29] Recent experiments have confirmed the possibility to excess a sampling rate of one Tbits/s.[30,31]

The chaos emitted by semiconductor lasers under external optical feedback can also be used to transmit hidden messages, in the case of private communications.[32] The recovery process is based on chaos synchronization[33] and fig. 3 describes this concept in the case of a free-space transmission. The master QCL is electrically pumped with a current source and the small-amplitude message is added to the current bias. The resulting optical signal is sent towards a feedback mirror so that chaos builds on the seed signal and subsequently conceals the message to be transmitted. As we saw, the non-linear dynamics displayed by the QCL is linked to the feedback strength and a mid-infrared polarizer is placed between the master QCL and the mirror to obtain the desired chaotic dynamics. The optical signal, containing both the predominant chaos and the hidden message, is transmitted through the atmosphere towards two different components. On the one hand, the signal is gathered by the first MCT detector and, on the other hand, the signal is injected inside the slave laser's cavity. Provided that the message remains small compared to the chaotic waveform and provided that the slave QCL is a copy of the master QCL, the slave QCL will synchronize and, in turns, emit the same chaotic signal, without the initial message. A second MCT detector retrieves the signal of the slave QCL and, eventually, a subtraction between the signal of the first MCT detector and the signal of the second MCT detector allows recovering the concealed signal. This ideal configuration can however be complex to implement, because the QCL technology is less mature than that for near-infrared laser diodes, which means that key properties like threshold current, power output and optical wavelength can be different in two QCLs even if they come from the same manufacturing batch. Yet, this scheme is very promising QCLs can emit in the mid-infrared and this optical domain is known for being more resistant to atmospheric optical perturbations, such as scintillation and scattering, and for being less attenuated than visible or near-infrared wavelength, even in the event of degraded weather conditions, for instance fog or heavy rain.

4. CONCLUSION

The chaotic dynamics emitted by QCLs under optical feedback is of utter interest for several applications. In particular, free-space private communications can take advantage of the high output power of Fabry-Perot QCLs and their emission wavelength in bandpass L. We showed that such laser, embedded in an user-friendly package, exhibits the same route to chaos than the 5.7 μm distributed feedback QCLs we had studied beforehand. Further work with this HHL-QCL will consider the realization of long-range transmission, either private or conventional, as well as chaotic LIDAR applications. Switching to wavelengths in bandpass N, with another device, will also be relevant because atmospheric perturbations are further reduced in this optical domain and because the background environment enhances the stealth of the directional QCL beam. These advances will pave the way for a democratized use of mid-infrared and long-wave infrared QCL which are currently limited to spectroscopic and countermeasure applications.

Acknowledgments

This work is supported by the French Defense Agency (DGA), the French ANR program (ANR-17-ASMA-0006), and the European Office of Aerospace Research and Development (FA9550-18-1-7001). Authors thank Lukas Drzewitzki for the device to compute interfaces as well as Dr. Andreas Herdt and Prof. Wolfgang Elsäßer for their initial help in the experimental efforts.

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