Chaos Bandwidth in Mid-infrared Quantum Cascade Photonic Devices with Interband and Intersubband Transitions

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Abstract: We experimentally display temporal chaotic waveforms in the mid-infrared domain with two different types of semiconductor lasers. The generated high-dimensional non-linear dynamics are of prime interest for private communications and physical random number generation. © 2021 The Author(s)

1. Introduction

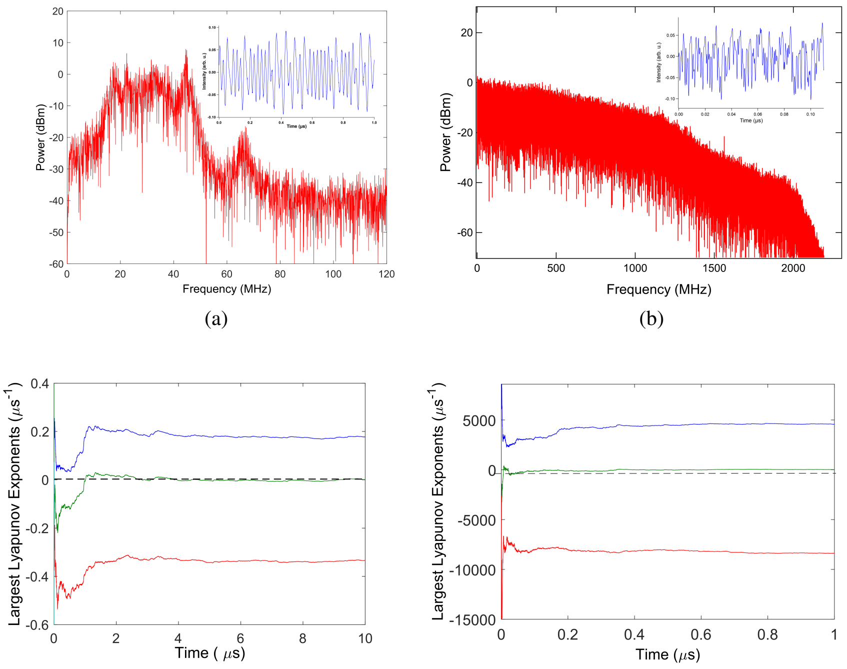
Available semiconductor sources in the mid-infrared (mid-IR) domain showed an accelerated development in recent years, both with intersubband devices and interband devices. On the one hand, quantum cascade lasers (QCLs), which are quasi-class A lasers, now achieve power-plug efficiency above 20% at room temperature and in continuous wave operation [1]. On the other hand, interband cascade lasers (ICLs), which are class B lasers, offer an alternative with lower power-consumption and wavelength up to 7 µm [2]. The versatility of these sources makes them desirable for a wide range of applications, from free-space communications in one of the transparency windows of the atmosphere (3-5 µm) [3] to mid-IR frequency combs [4]. When subjected to external optical feedback, QCLs exhibit several non-linear dynamics encountered in other semiconductor lasers: low-frequency fluctuations, chaos, extreme events [5] . . . Amid these phenomena, high-dimensional chaos is useful for applications such as private communications where the message is hidden within the chaotic carrier and physical random bit (PRB) generation [6]. For these two applications, the bandwidth and flatness of the generated chaos are key parameters because they set the maximum data rate of the private transmission [7] and increase the performance of optical chaos-based PRB [6], respectively. We present the first non-linear dynamics in an ICL which outputs chaotic waveforms very promising for the aforementioned applications. Indeed, our experimental efforts show that the chaotic bandwidth can range up to 50 MHz in the case of a QCL and up to 1.2 GHz in the case of an ICL. ICLs have consequently a greater advantage compared to QCLs. Still, QCLs can emit high output-power and reach wavelength up to 15 µm and are thus challengers of choice when one of the two previous conditions is required.

2. Experimental setup

External optical feedback is a common tool to display non-linear dynamics in semiconductor lasers [6] and the experimental setup we used is similar to the one deployed in our previous efforts [5]. The laser under study is mounted within a Newport LDM-4872 socket and a mid-IR lens allows collimating the laser beam. An external cavity with a gold-plated mirror is used to produce the external optical feedback. The light emitted by the laser is retrieved with a Vigo Mercury-Cadmimum-Telluride (MCT) detector with a 3 dB-bandwidth of 700 MHz. The electrical signal is subsequently analyzed by a fast oscilloscope at 25 GS/s. The QCL under study is a distributed-feedback (DFB) laser emitting at 5.7 μm and the ICL under study is a Fabry-Perot (FP) laser emitting around 4.2 μm. Similar experiments with FP QCLs did not show a wider chaos bandwidth compared to the DFB case.

3. Results and discussion

When feedback is strong, the lasers emit developed chaos as can be seen in Fig. 1 (a) and (b). The chaos spectrum has a 20 dB-cutoff frequency of 50 MHz in the case of the QCL. In the case of the ICL, the RF spectrum of the chaotic waveform is very flat and its 20 dB-cutoff frequency is 1.2 GHz. Moreover, the ICL's chaos analysis



(a) (b)

(c) (d)

Fig. 1: (a) RF spectrum of the QCL's chaos with chaotic timeserie (inset); (b) System dynamics analysis of the experimental QCL's waveform, showing one positive LE; (c) RF spectrum of the ICL's chaos with chaotic timeserie (inset); (d) System dynamics analysis of the experimental ICL's waveform, showing one positive LE.

is limited by the bandwidth of the MCT detector and consequently, the real bandwidth might be larger. Up to date, very few high-speed detectors in the mid-IR exist, and it is even more challenging to have some working at room-temperature. Further studies of the ICL chaos will be performed using wavelength up-conversion sensors and quantum well infrared photo-detectors [8] in order to access the whole characteristic of the signal.

For both semiconductor lasers, the chaotic nature of the waveform is assessed by the derivation of the largest Lyapunov exponents (LEs) [9]. The basic idea of the Lyapunov exponent λ is to measure the rate at which two originally nearby trajectories diverge in time, which is one of the peculiarities of chaos dynamics. To be considered as chaotic, a waveform must exhibit, at least, one positive Lyapunov exponent. As the time evolves, curves in each panel converge to the values of LE exponents, namely the three largest LEs (Fig. 1 (c) and (d)). For the calculated spectrum, the curves converge to values λ_1 = 0.180 μs^{-1}, λ_2 = 0.001 μs^{-1}, λ_3 = -0.330 μs^{-1} for the QCL's output and λ_1 = 4552.1 μs^{-1}, λ_2 = 32.7 μs^{-1}, λ_3 = -8179.4 μs^{-1} for the ICL's output. The LE values for the two components are very different because the time scales of the non-linear dynamics are not in the same range.

We have reported the first analysis of wideband chaotic waveforms with mid-IR ICLs. The advantage of ICLs lies within their interband structure while still emitting in the mid-IR domain. Future work will focus on generating PRBs and on realizing private communications by taking advantage of the wideband chaos we displayed.

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