Towards private optical communications with mid infrared chaotic light

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ABSTRACT

Free-space optics constitutes a growing technology offering higher bandwidth with fast and cost-effective deployment compared to fiber technology. Multiple applications are envisioned like private communications. In such a case, the secret message is encoded into a chaotic waveform from which the information is extremely hard for an eavesdropper to extract. For free-space optics applications, the operating wavelength is an important parameter that has to be chosen wisely to reduce the impact of the environmental parameters. In this context, quantum cascade lasers are highly relevant semiconductor lasers because the lasing wavelength can be properly adjusted in the mid-infrared domain, typically at wavelengths for which the atmosphere is highly transparent. The simplest way to generate a chaotic optical carrier from a quantum cascade laser is to feed back part of its emitted light into the device after a certain time delay, beyond which chaos synchronization between the drive and the response lasers occurs. In this paper, we discuss about how quantum cascade laser's chaos can be used to develop private communication lines. We also give realistic perspectives for further developing mid-infrared private communications using chaotic waves.

Keywords: Quantum cascade lasers, chaotic waves, synchronization, cryptograhy

1. INTRODUCTION

Owing to its fast and cost-effective deployment compared to fiber technology, free-space optics (FSO) has become a ramping up technology offering a higher bandwidth associated to a lack of regulation unlike radio frequencies.[1] Several applications are envisioned including, but not limited to, campus-scaled network, substitution for a fiber network after a disaster (e.g., earthquake, attack, etc.), connecting a drone as a relay in white spots, and private communications. The latter is the fundamental cornerstone towards unbreakable global and space networks providing the platform to build trusted nodes in continental and intercontinental networks. In this case, the secret message is to be encrypted into a chaotic waveform which means that the information is impossible to retrieve for an eavesdropper. This property mostly results from the fractal dimension and complexity of the strange attractor where multiscale similarity of the density of trajectories exists.[2] Chaos-based communication was originally proposed and demonstrated in electronic circuits,[3] and then extended to optical fibered systems.[4] However, its application to FSO is fundamentally restricted by the atmospheric phenomena (e.g., turbulence, fog or scattering).[5] Therefore, the operating wavelength is an important parameter that has to be chosen wisely so as to reduce the impact of the environmental parameters. In order to improve the FSO availability, performance and range, the investigation of the cross relation between the climatic conditions and the wavelength is highly required.

In this context, quantum cascade lasers (QCLs) are unipolar semiconductor lasers based on intersubband transitions that emit light in the mid-infrared domain. This optical domain is of prime interest for free-space communications because the atmosphere is highly transparent between 3-5 microns and between 8.5-11 microns.[6] Indeed,

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it is relevant to notice that not only the absorption but also the signal distortion is lower at higher wavelength. Indeed, it is known that turbulence on the propagation path significantly deteriorates the optical signal causing e.g. beam spreading, beam wandering, scintillation or loss of spatial coherence.[5] In this case, the scintillation will be the predominant phenomenon, corresponding to intensity fluctuations of the propagating beam. This effect evolves as a function of $\lambda^{-7/6}$, and will therefore be less significant at higher wavelength hence the advantage of mid-infrared waves for FSO communications.[7] The first tests were conducted shortly after the experimental proof-of- concept of QCLs, and as soon as 2001, a Peltier-cooled device showed the possibility of a data transmission up to 300 MHz over several hundred meters at 9.3 micron.[8] Recent investigations showed the relevance of a similar transmission but at room temperature and 4.65 micron.[9] The versatility of this method, combined with the QCLs' potential for high speed modulation up to 10 GHz,[1] demonstrates that these lasers are poised to be the cornerstone of very high speed free-space data transmissions. At lower frequency rates, QCLs are also of paramount importance for secure communications that can be obtained through chaos synchronization.[4] QCLs have indeed been proven to emit a chaotic output when subject to external optical feedback.[10] Indeed, depending on the amount of external optical feedback and the length of the external cavity, the QCLs can operate within five different regimes including one where low-frequency fluctuations (LFF) take place.[11] The LFFs are a type of chaotic oscillations known as intermittent chaos observed in semiconductor lasers with external optical feedback manifesting by a sudden power dropout with a following gradual power recovery.[10] Here, we give insights on the development of private communication lines based on mid infrared QCLs. To do so, we describe what are the potential levers in order to improve the performances of our future communication system, both in terms of chaos bandwidth and transmission quality. The concept of optical injection is also introduced and the non-linear dynamics obtained with that scheme is compared with that retrieved with conventional optical feedback. As opposed to quantum communications where the range and rate of the secure channel are currently limited, this work unveils how chaotic waves at mid infrared wavelengths can create unconditionally secure free-space communications environment between a drive laser and a response laser, even in a high-photon-flux environment.

2. DESCRIPTION OF THE APPARATUS

The chaotic secure transmission system is described in Fig. 1.

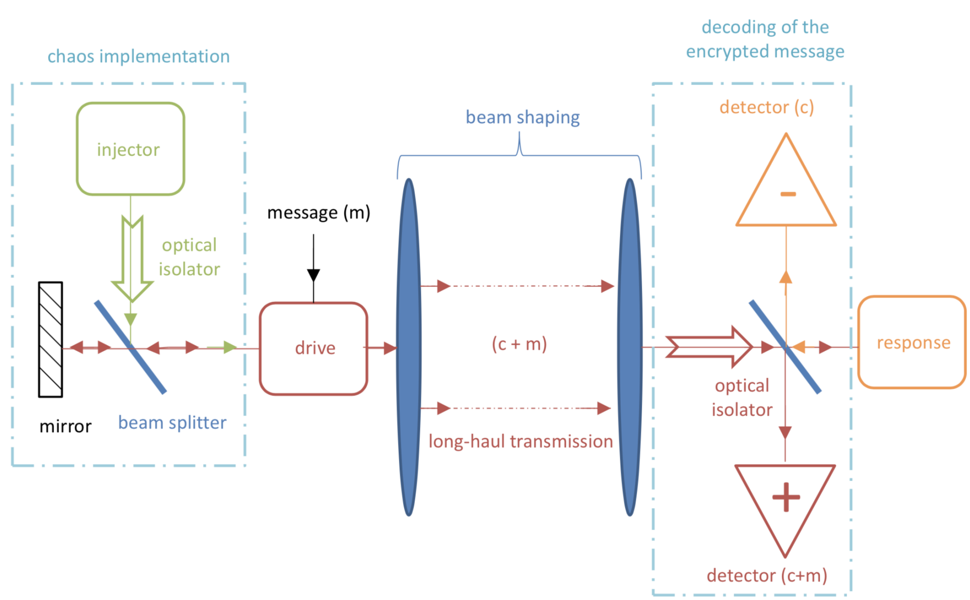
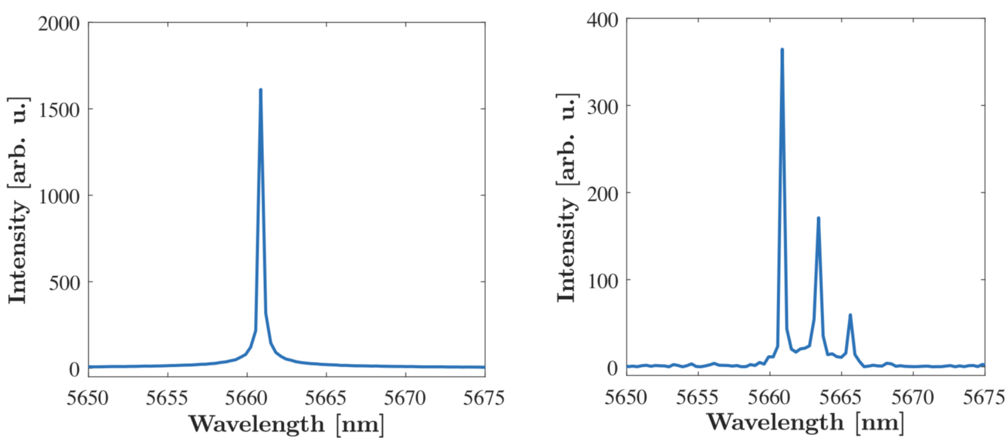


Figure 1: Schematic of optical chaos synchronization and secure communication between a drive QCL and a response QCL.

The apparatus includes QCLs that are distributed feedback lasers (DFB) emitting single mode at ≈ 5.7 micron. The drive QCL (ie. master) is made chaotic with external optical feedback and/or injection. In the former, prior studies have shown that QCLs can exhibit a LFF-like pattern.[10] The chaotic light of the drive QCL is then injected into the response QCL (ie. slave) through an optical isolator so that the light from the response does not interfere with the drive. Contrary to some schemes found in laser diodes,[12] when the drive and the response laser are not coupled, the response laser is not chaotic because there is no mirror in front of it. The output of the drive laser is sent towards the response laser through an optical isolator to avoid back-reflections and the signal of the drive and the response are detected with a MCT detector. The signal from the MCT detectors are analyzed with a fast oscilloscope and a RF spectrum analyzer. Apart from the chaotic features observed with the RF spectrum analyzer and the digital oscilloscope, it is possible to confirm that the drive signal is well injected into the response by observing the behavior of the optical spectrum with a FTIR. Indeed, under free-running operation, the response laser can be single-mode and it turns to be multi-mode when the synchronization is effective, as shown in Fig. 2.



(a) **(b)**

Figure 2: (a) Optical spectrum of the free-running response laser when it is biased at 512.4 mA. (b) Optical spectrum of the response laser after injection of the output of the drive laser when the response laser is biased at 512.4 mA.

For secure communications, the purpose is to have chaotic fluctuations with the broadest RF spectrum possible because this means that the maximum frequency of the message to be transmitted, as well as the privacy of the process, can be increased. The first idea is trying to synchronize chaos obtained between the drive laser and the response laser. Synchronization between periodic oscillators has been observed in a multitude of fields ranging from biology,[13] chemical reactions,[14] to high-precision clocks,[15] frequency stabilization[16] and quantum information processing.[17] Dynamical chaos synchronization may seem counter-intuitive at first, in that two wildly divergent chaotic signals can now be marching in step, but has since seen verification in electronic circuits[3] and lasers.[4,18]

In our case, when the QCL is pumped with a quasi-continuous wave (QCW), the best results are obtained in term of chaos complexity.[19] However, this configuration may not always be suitable because it can be difficult to include the message to be transmitted while the laser is already pumped with a QCW. Furthermore, the transmission tentative can become easier to detect for an eavesdropper, thus destroying the benefit of the stealth. Also, slight changes in temperature occur when operating the drive laser in QCW mode. If, on the one hand, the drive laser is driven chaotic in this configuration and, on the other hand, the response laser is pumped with a continuous bias, it is not possible to synchronize the chaotic fluctuations of the drive for the entire period of the QCW, as shown in Fig. 3. This is due to the wavelength detuning because temperature shifts and this is a fundamental result for QCLs which are proved to be highly temperature dependent. Indeed, we experimentally observed that the drive laser and the response laser can be synchronized only if they have the same wavelength, with an uncertainty of a few dozens of MHz. The synchronization is also effective when the drive QCL has the same wavelength than one of the side modes of the response QCL, and vice versa. However, it seems that the best case for synchronization occurs when the DFB peak of the drive coincides with that of the response. Consequently, it is not possible to take advantage of the chaos studied with a quasi-continuous bias because it detrimentally degrades the synchronization. It is interesting to notice that we did not try to apply a QCW on both the response and the drive QCL to see if it could improve the overall quality of the chaos synchronization. As it is possible to have islands of chaos with a CW pumping,[20] we investigated the possibility of chaos synchronization and secure communication with this scheme also because it could be compared with the pioneering studies.[21]

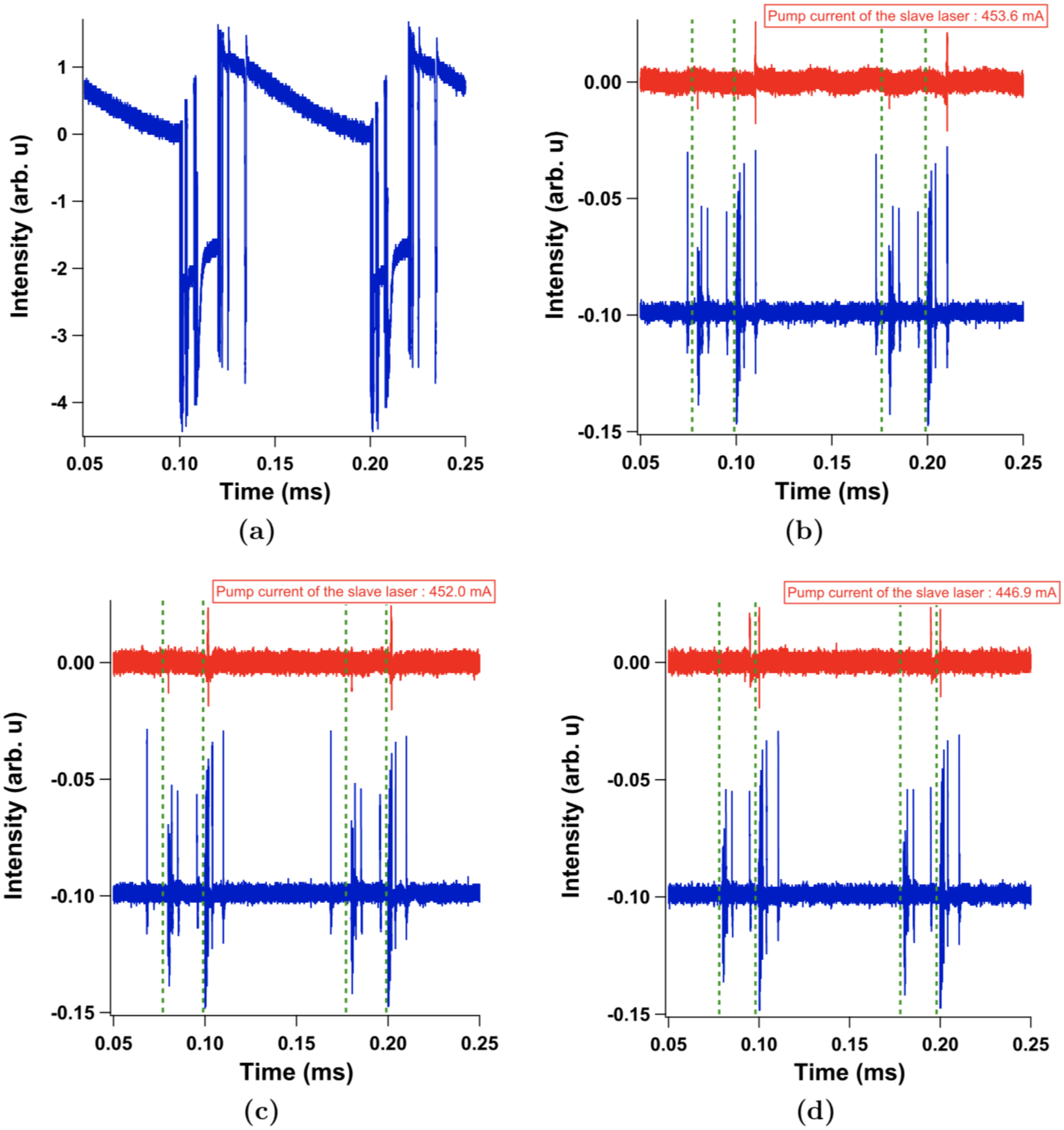


Figure 3: Synchronization trial when the drive QCL (blue) is pumped with a QCW bias and driven chaotic. The response QCL (red) is pumped with a CW bias. (a) Output of the chaotic drive laser pumped with a QCW before low-frequency filtering. (b - d) Response QCL is pumped with several continuous biases.

When the optical frequency of the drive and the response are matched, partial or full synchronization can occur. For example, Fig. 4 shows an example of a synchronization. The drive QCL (blue) outputs a typical LFF-like pattern which is perfectly copied by the response QCL (red). Beyond that, modifying some of the parameters

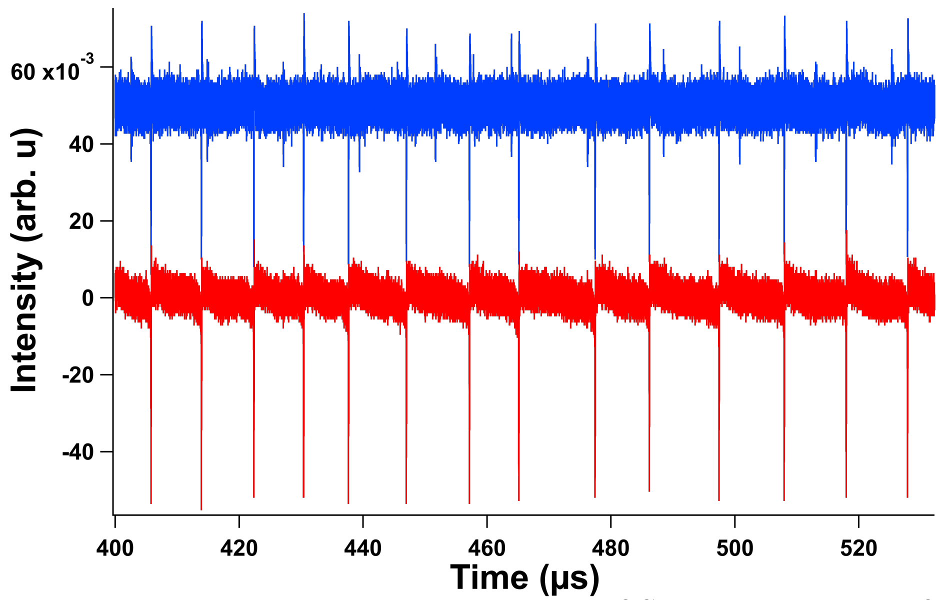


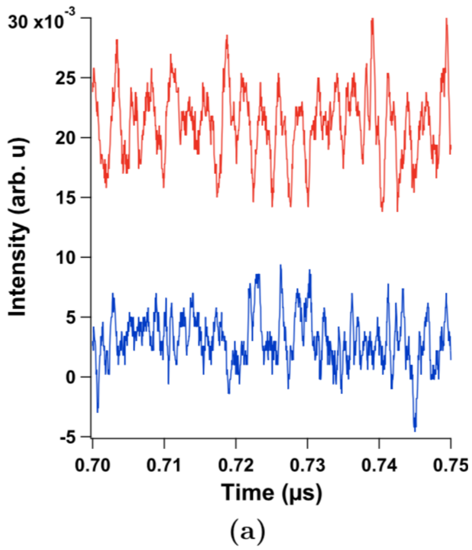
Figure 4: Partial synchronization. In blue the drive QCL, in red the response QCL.

can also lead to anti-synchronization.[22]

3. IMPROVING CHAOS IN QCLS WITH OPTICAL INJECTION

Another relevant option is to replace external optical feedback by optical injection. Similarly to what has been described for chaos synchronization, optical injection consists in injecting the light of an injector laser into a drive laser, as illustrated in green in Fig. 1. However in this case, the injector laser is not driven chaotic. To this end, an optical isolator is required between the injector and the drive laser to avoid optical feedback of the injector after reflection on the drive facet, or optical injection of the drive inside the injector. In laser diodes, optical injection was found useful in enhancing the chaos bandwidth of a drive laser subject to optical feedback.[23] If the injector is strongly injected towards the drive laser already rendered chaotic because of optical feedback, the non-linear dynamics is not changed. For instance, the chaotic fluctuations do not turn into periodic oscillations but the bandwidth of the observed chaos is strongly increased. This technique, is also very relevant in terms of secure communications if a third laser (ie., the response laser) is used for the synchronization of the expanded chaos.[24]

Using the optical injection configuration, the chaotic frequencies emitted by the drive QCL can be well increased up to 500 MHz as shown in the following. The initial non-linear phenomenon observed in Fig. 5 shows a LFF-like pattern with the main frequency centered around the value of the detuning. But even if this value is centered around the frequency detuning, the RF spectrum is quite large, with a bandwidth of roughly 50 MHz. So it is not easy to determine if what we observed was a periodic pattern as the one derived from the simulations[25] or a deterministic form of chaos similar to what already described regarding LFFs. Further investigation is needed to derive the Lyapunov exponents[26] of the retrieved signal and analyze whether it is possible to synchronize this signal in a scheme with another QCL. However, a recent study pointed out that it could be difficult to generate chaos solely with optical injection in QCLs.[27] In other semiconductor lasers, the behavior of the laser under injection varies a lot depending if it is a highly damped semiconductor laser[28] or not. In our case, the pattern is visible from a near-zero detuning up to a detuning of 600 MHz, as can be seen in Fig. 6. The peak frequency for each case corresponds to the frequency detuning between the injector laser and the drive laser. The influence of the injector laser is strong for detuning values below 100 MHz and around 400 MHz. Further investigation is needed to understand why some frequencies are likely to have a stronger influence on the drive laser. However it seems possible to increase the maximum frequency of chaos in QCL up to a frequency of 400 MHz, providing that the observed phenomenon is deterministic chaos. A thorough experimental mapping is required to determine what are the most suitable regions in order to use injection as a chaos driver. The long-term purpose is to inject the chaotic signal created by the injection process into a third laser which will thus be synchronized or anti-synchronized with the chaotic signal which is used to hide the message and prevent any eavesdroppers to retrieve it. This method has already been implemented to achieve secure communications in fibers for near-infrared lasers[24] and we plan to extend it to free-space communications by taking advantage of the two transparency windows of the mid-infrared domain. In our case, the injection configuration will also allow faster data transmission compared to conventional optical feedback.



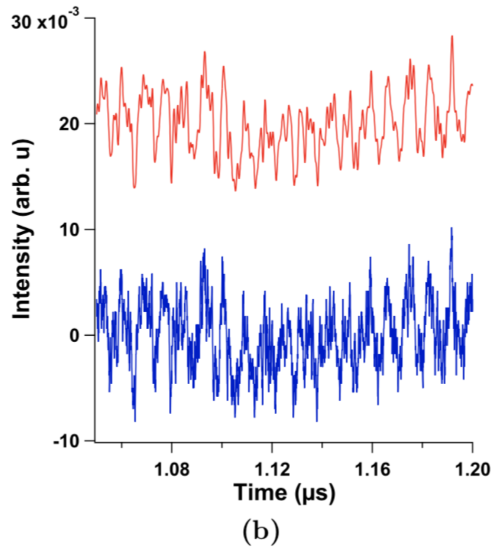


Figure 5: (a) Experimental time traces of the output of the drive QCL when the bias current of the drive QCL is at (a) 485.8 mA showing a LFF-like pattern (red) and control waveform showing only noise (blue); (b) 486.5 mA after low-pass filtering (red) and before (blue).

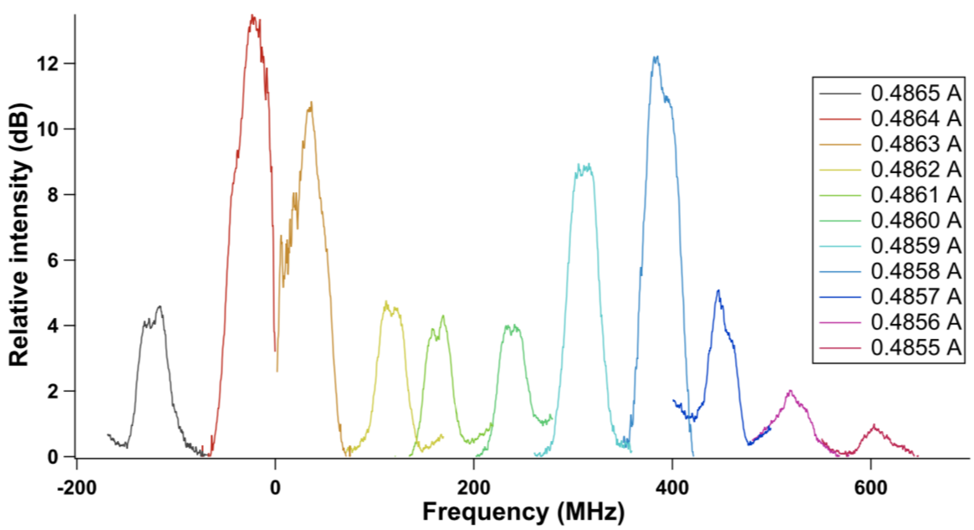


Figure 6: RF spectrum of the drive QCL when varying the pump current of the drive QCL while the injector laser is biased with a constant current.

4. TOWARDS MID INFRARED PRIVATE COMMUNICATIONS

In most cases, private communication is achieved via a drive and a response laser with similar parameters and operating conditions in order to allow the synchronization.[29] So far, only numerical efforts have proven the possibility of a secure free-space communication but in the near-infrared domain, with laser diodes.[30] As aforementioned, the drive laser is chaotically driven with external control methods (e.g. optical injection, optical feedback), then synchronized with the response laser, and eventually, the message to be transmitted is hidden inside the chaotic signal of the drive laser.[31] The chaotic output of the drive laser is thus the carrier in which the message is encoded. Using this technique with chaos-based message encryption methods, such as chaos masking or chaos modulation, a secure message can be transmitted from a transmitter to a receiver. The decoding is divided into two steps: a detector records the signal (with the encrypted message) from the drive laser and another detector records the one from the response laser, which is a mirror image of the drive's chaos. Subtracting the intensities of the first detector with that of the second detector allows recovering the hidden message.[32] However, synchronization may somewhat be difficult to achieve in the case of quasi-continuous pumping, because the thermal shift inside the laser's structure leads to a shift in the emission wavelength of the QCL. On the other hand, pure continuous wave pumping leads to a more regular spiking dynamics that can be controlled by adding current modulation.[19] This entrainment phenomenon studied by adding sine and square wave modulations allows finely triggering the spiking that is suitable for secure communications where the chaos itself contains the secret message.[33] Moreover, developed chaos can also be found in this configuration for narrow ranges of feedback ratios. Even if these specific spots can be difficult to reach, they can be candidates of choice for chaos synchronization and secure communications because the temperature of the device remains steady.

In the view of developing a communication link of several kilometers, it is mandatory to switch towards wavelengths that are more suitable for optimal transmission through the atmosphere, for instance 4 μm and 10 μm. While the latter can almost solely be achieved with QCLs, the former can be emitted in other semiconductor lasers like interband cascade lasers (ICLs).[34] The best option between these two lasers could be the one that is able to generate chaos with the largest bandwidth. The data rate of the hidden message is also relevant and the choice of either a QCL or an ICL can be of paramount importance depending on the targeted transmission rate (ie. typically ranging from a few hundreds of Mbits/s to a few hundreds of Gbits/s). In the slower cases, the best option can be to transmit only a secret key with the chaotic scheme and then use another mean to achieve the very high-speed transmission. As the key can be as small as a few kilobytes,[35] the data rate is not an issue because it is possible to reach nearly 1 Mbits/s in our configuration, but in this case, chaotic secure communication is challenged by quantum key distribution (QKD).[36]

5. CONCLUSIONS

In summary, this work is of paramount importance for the development of compact private high-speed communication systems in the mid-infrared domain. We point out the importance of the pumping conditions, namely the QCW versus continuous waves. Thus, even if the most relevant chaos is obtained under QCW conditions, this configuration may not always be the best to secure the transmission because of the difficulty to include the message and the temperature variations when operating the laser in the QCW mode. In addition, if the drive laser is driven chaotic in this configuration while having the response laser pumped with a continuous bias, it turned out that the chaotic fluctuations of the drive cannot be synchronized for the entire period of the QCW. Finally we also showed that optical injection can complement the optical feedback with the view of generating optical chaos with larger bandwidth. The initial findings can be implemented in applications ranging from civil to defense with a focus on airborne communications, spaceborne communications (such as transmissions between satellites or transmissions between space rovers) and last-mile connections in remote or devastated areas. Our final goal is the implementation of a private QCL transmission channel operating at high-speed in the outdoor environment, that is to say, for a transmission through a 4-km horizontal line of sight in an urban environment. Last but not least, as opposed to QKD, chaos based communication provides a pathway to achieve secure communications, in long-distance channel links and in scalable repeater modules outside the single-photon flux-limited environment.

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).

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