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Chaos-based mid-infrared communications

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ABSTRACT

The advantage of mid-infrared wavelength is that it is less affected by atmospheric conditions than conventional near-infrared wavelength, and this optical domain is thus envisioned to play a key role in the 6G standard under development. The directivity of the beam, as well as the stealth conferred by the background emission, makes communication systems based on long-wave infrared quantum cascade lasers (QCL) highly desirable. However, some applications require a further level of privacy. Protecting the communication link against eavesdroppers is possible with chaos-based enciphering. Using this concept, a chaotic master QCL is used to conceal the private message while deciphering is achieved with a second, identical, remote QCL that is called the slave. The deciphering process relies on chaos anti-synchronization where the slave only reproduces the reversed chaotic pattern of the master, thus allowing the recovery of the private message by adding the slave signal and the master signal. The privacy of our system is also assessed and shows that an illegitimate receiver would end with a detrimental error rate during translation, even in the unlikely case this eavesdropper knows the coding format of the private message. We believe our private communication system brings a cost-effective, reliable and versatile alternative for free-space data links, especially in harsh environments where mid-infrared lasers strongly outperform their near-infrared counterparts. Features such as room-temperature operation and high-speed transmission further advocates for a large deployment, and we anticipate that this finding can have a significant impact on the development of novel applications based on QCLs.

Keywords: quantum cascade laser, mid-infrared photonics, free-space communication, data transmission

1. INTRODUCTION

In the early days of quantum cascade lasers (QCLs), these mid-infrared optical sources were already considered for free-space communication and Gbits/s data rate were achieved in cryogenic configuration,[1] for both the emitter and the receiver. The intersubband technology of QCLs combined with the absence of relaxation oscillations[2] was a promising peculiarity for achieving high-speed data rate. Furthermore, the performances of lasers emitting at telecom wavelengths were comparable with those of QCLs at that time.[3] The following years showed strong development of fiber networks, whereas the technology of telecom wavelength devices, such as modulators and amplifiers, became very mature.[4] Meanwhile, mid-infrared communication efforts with QCLs were lagging behind. This field has experienced a renewed interest since 2017 and the demonstration of a multi-Gbits/s transmission with room temperature emitter and receiver.[5] Recently, many groups have published results involving short-range mid-infrared communication systems[6–11] and the next challenge is now to increase the distance between the QCL and the detector with the help of adaptive optics.[12] Though the directivity of laser beam can be enough for communication requiring a low level of privacy, extra enciphering can be implemented with optical chaos. QCLs were proven able to emit complex non-linear dynamics when they are subject to strong optical feedback.[13,14] Typical bandwidth of the mid-infrared chaos emitted by QCLs can be between MHz and dozens of MHz and this will limit the maximum data rate of the private communication. Chaos-based communication relies on chaos synchronization which requires two lasers with similar properties: a master laser and a slave laser.[15] The master laser is forced into a chaotic state and the message to be transmitted is added to the chaos

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output to conform a new optical signal. The latter is send unidirectionnaly (in order to avoid cross-talk) towards the slave laser and this slave laser will, in turn, generate a copy of the master chaos only, which allows recovering the chaos-concealed message by subtraction. This synchronization property where the slave laser reproduces the chaotic output of the master laser can only be achieved if the characteristics of the slave laser are compatible with those of the master laser. The slave laser is thus a mandatory physical key in the deciphering process.

2. OPTIMIZING BIT-ERROR-RATE FOR THE LEGITIMATE RECEIVER

In this section, we give details about the filtering process of the private transmission described in Ref. 16. Early efforts about communication based on chaos synchronization highlighted the importance of filtering, either in electrical or optical configurations,[17,18] and in our case, mid-infrared optical wavelength is elected for its relevance in a free-space communication scheme. One of the key features of the chaotic signal is that both its amplitude and frequency bandwidth must be much more important than those of the message to be hidden, otherwise an eavesdropper can potentially decipher this message by analyzing the optical signal from the master laser. Figure 1 shows the electrical bandwidth characteristics of the four signal of interest: the 0.5 Mbits/s message to be transmitted privately (green), the master signal (red) that contains both the chaotic carrier and the small amplitude message, the slave signal (blue) which is supposed to be a copy of the chaotic carrier as the master QCL is unilaterally injected into the slave QCL, and the difference signal (purple) which gives access to the message, provided that a relevant filter is applied as demonstrated hereafter. The master and the slave spectra show that most of the chaos frequencies are within a 5 MHz range, and the most notable difference between these two spectra is a bump around 20 MHz in the slave spectrum. This bump (that is also present in the difference spectrum) appears because of optical frequency mismatch between the master and the slave QCL. The maximum of the bump corresponds to the optical detuning between the two monomode lasers, as explained in Ref. 19. In the message spectrum, another bump can be seen for higher frequencies but is of little interest as in return-to-zero (RZ) coding, one can focus on the electrical frequencies with a value lower than six times the data rate (0.5 Mbits/s in our case).[20] Figure 2 shows the same unfiltered spectra but for a maximum frequency of 5 MHz. Except for the green spectrum, the traces were obtained from the electrical signal of the MCT detectors (or subtraction between the signal of two MCT detectors for the purple trace). The tabulated

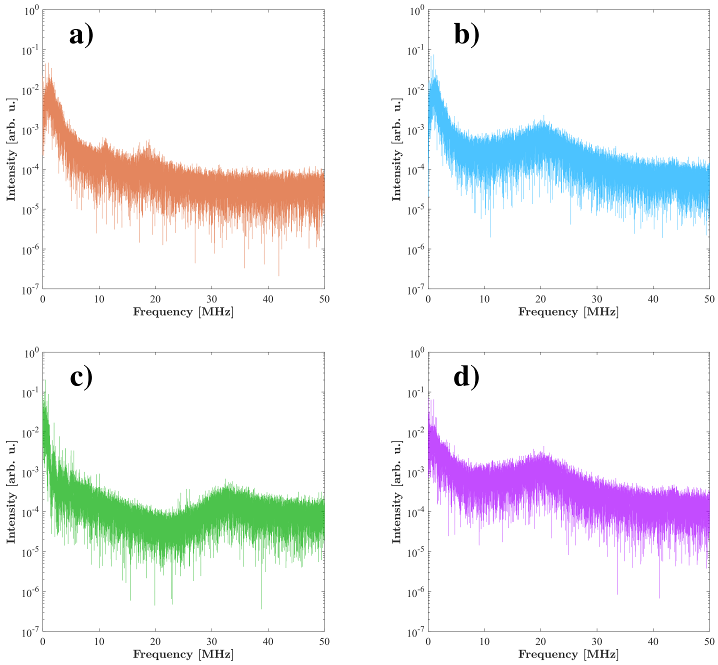

Figure 1. Electrical spectra obtained with fast Fourier transform for a) the master signal, b) the slave signal, c) the message to be transmitted and d) the difference signal.

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low cut-off bandwidth for these detectors is 1 MHz and the spectra show distortion around 100 kHz. This is the reason why, in the following, we will numerically cut the high-frequency components of these spectra and

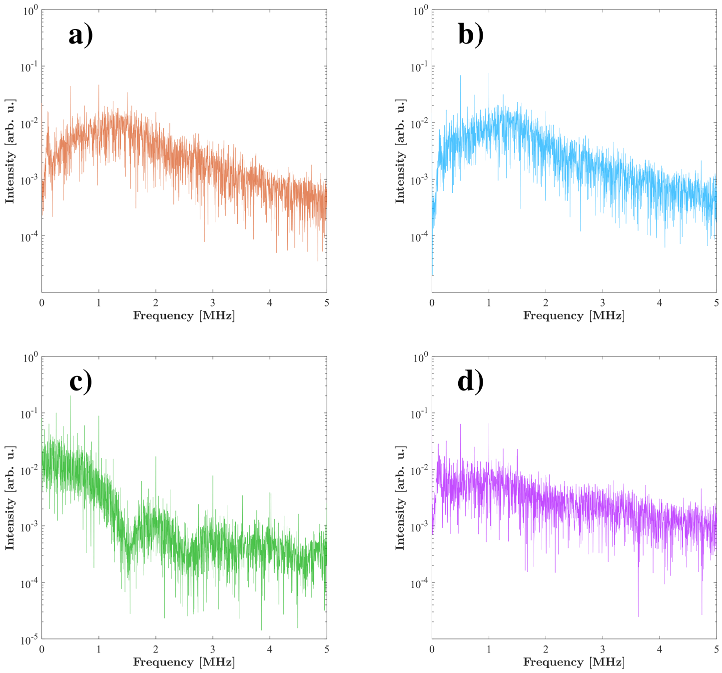

Figure 2. Same spectra as in the previous figure with a focus on frequencies below 5 MHz that are relevant for the private transmission.

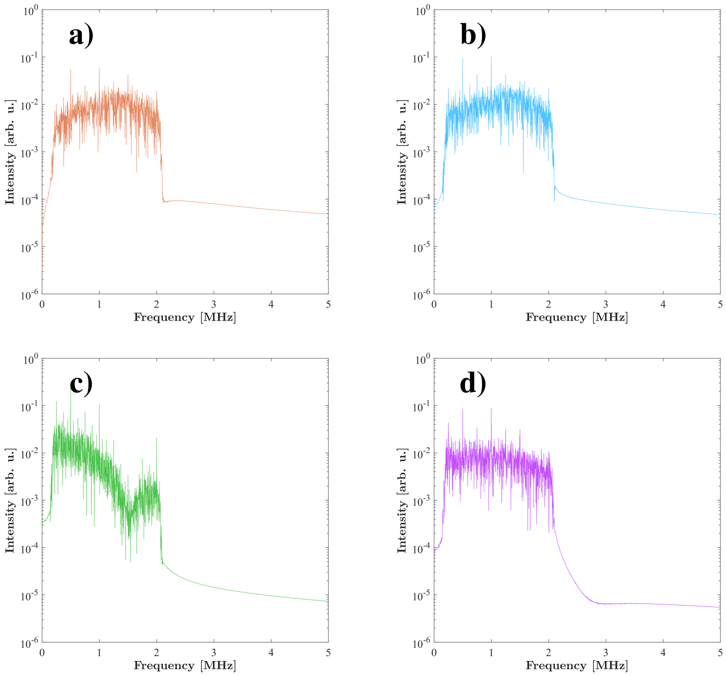

Figure 3. Electrical spectra after a band-pass filter is applied. This is a key step for improving the quality of the transmission for the legitimate receiver.

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also the low-frequency components to get rid of this distortion at low frequency. Despite this feature, one can see that the slave spectrum is very similar to the master spectrum and, moreover, one cannot distinguish the

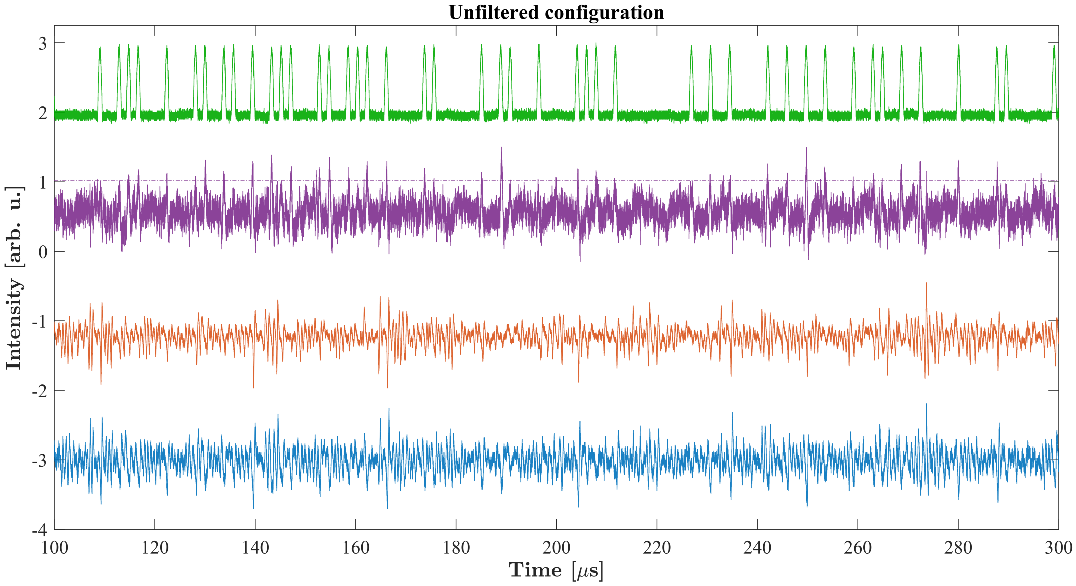

Figure 4. Part of the bit sequence to be transmitted (green), the master chaos trace with embedded message (red), the synchronized slave chaos (blue) and the difference between the master and the slave signal purple that is supposed to be a copy of the green trace. In this unfiltered configuration, high-frequency noise deteriorates the quality of the transmission and comparing the full 191 bits message with the purple trace leads to 24 errors. The purple dash-dot line is the threshold used to discriminate '0' and '1' in the difference signal.

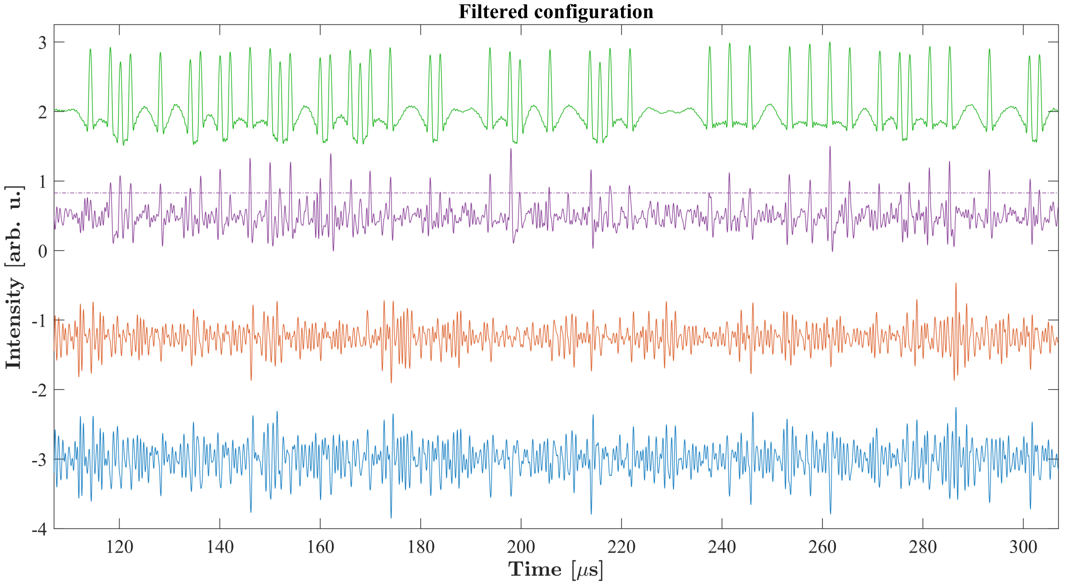

Figure 5. Same sequences as in the previous figure after filtering each trace, including the initial message. Suppressing the high-frequency noise in the purple trace improves message recovery with now 12 errors out of 191 bits. The purple dash-dot line is the threshold used to discriminate '0' and '1' in the difference signal.

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spectrum of the message within the master spectrum. Even in the difference spectrum, one can only guess typical features of the message, such as the dip around 1.5 MHz and around 2.5 MHz. This means that the message is very well concealed within the chaotic carrier. Yet, with this difference time trace, it is possible to recover most of the bits of the initial message. Finally, we show in Fig. 3 the filtered spectra for the same frequency range. Parameters of the band-pass filter are given in Ref. 16 and this filter is of paramount importance to improve the bit-error-rate for the legitimate receiver. If this filter is not applied, the recovery process leads to 24 errors in a sequence of 191 bits. Figure 4 shows part of the time trace for the message, difference, master signal and slave signal (same color code as in the previous figures). In the purple trace, one can visualize the high-frequency noise (mainly due to the bump in Fig. 1) with an amplitude that is much more important than in the blue trace because the amplitude of the hidden message is small compared to the initial chaos amplitude. When using the aforementioned filter, the recovery process leads to 12 errors in the same sequence and the filtered time traces can be observed in Fig. 5. The comparison with the initial bit serie (which is also filtered in this figure to confirm that it is not detrimentally altered by filtering) is now easier though filtering did not correct all the errors. An option to decrease the bit-error-rate for the legitimate receiver would be to increase the amplitude of the initial message that is concealed within the chaotic carrier. However, in our current configuration, this would result in a message that can be partially extracted by an illegitimate receiver[21] and that is the reason why our experimental effort focused on a configuration with 12 errors out of 191 bits to be transmitted.

3. CONCLUSION

Free-space communication using QCLs is under strong development and recent progress in external modulators[22] can pave the way towards long-haul mid-infrared communications at hundreds of Gbits/s without being restricted in terms of optical frequencies by wavelength up-conversion processes.[23] One of the options to increase the privacy of the free-space mid-infrared transmission is to take advantage of the optical chaos that can be generated in QCLs under external optical feedback. If a receiver wants to decipher the message that is concealed within the chaotic carrier, he must own a second laser that is (to the best extent) a copy of the laser that was used for optical chaos generation. During the chaos synchronization process, filtering is an essential step to remove the high-frequency noise and to obtain the lowest bit-error-rate, which means a correct translation of the private message.

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