High-speed free-space transmission at room temperature with an RF-mounted quantum cascade laser emitting in the long-wave infrared domain

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***Abstract*—We report on a room-temperature transmission with a long-wave infrared quantum cascade laser emitting at 8.1 μm. With 4-level pulse amplitude modulation and digital signal processing, maximum data rate of 4.8 Gbps is achieved.**

***Index Terms*—quantum cascade laser, free-space communication, long-wave infrared photonics**

I. Introduction

Optical free-space communication is well positioned to become a key technology in the race for high-speed data transmission, more specifically in configurations where fiber systems are too expensive or complex to implement. In order to optimize the free-space communication link, two wavelength domains are of paramount importance: one between 3-5 μm called the mid-infrared (MIR) window and another one between 8-12 μm called the long-wave infrared (LWIR) window. The former can be accessed by various methods and room-temperature transmissions have already been demonstrated using native MIR semiconductor lasers, such as interband cascade lasers (ICLs) or quantum cascade lasers (QCLs) [1], or using difference frequency generation [2]. This method is very promising in terms of data rate because it relies on mature technology at near-infrared wavelength that is subsequently up-converted to the MIR domain. However, the up-conversion process gives access to a limited panel of MIR wavelengths and does not allow higher wavelength emission. This means that transmission in LWIR domain must rely on native LWIR lasers, and one of the most relevant options is to work with QCLs because of their potential high output power with a wavelength of emission that can be tuned up to the terahertz domain. Unfortunately, LWIR experiments have only been carried out at cryogenic or Peltier-cooled temperatures [3], except for one recent effort about Stark-effect modulators [4]. LWIR wavelengths are more relevant than MIR wavelengths for long-distance propagation applications because of reduced beam scintillation, scattering and wandering at higher wavelengths [3]. Yet, the development of LWIR QCLs has been lagging behind that for MIR semiconductor lasers due to much complex technological challenges in laser design, power extraction and thermal management [5]. This explains the lack of experimental communication efforts in the LWIR domain despite an optimized wavelength for transmission through the atmosphere. In this experimental work, we take advantage of the low current threshold of a distributed feedback (DFB) QCL emitting at 8.1 μm to transmit a message with a 4-level pulse amplitude modulation (PAM-4). The low power consumption allows placing the laser on a water-cooled finger without the use of Peltier heat sink. With this configuration, we can achieve a transmission at a maximum data rate of 4.8 Gbps by direct modulation, with an error rate in the order of 10^{-3}. We anticipate that this finding can have a significant impact on the development of novel applications based on high-speed LWIR QCLs.

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II. Experimental setup

The QCL under study is a DFB laser emitting at 8.1 μm with a dedicated RF-mount compatible with a MMCX connector. This design has shown strong improvements in the bandwidth response [6] in comparison with conventional package for MIR semiconductor lasers [1]. Details about the bandwidth characteristics of this QCL can be found in Ref. [7], which also describes the wavelength and LIV properties of this laser. The structure shows a typical low-pass behavior with a 6-dB frequency cut around 300 MHz. Another peculiarity of this LWIR QCL is a short ridge length of 500 μm that induces a low current threshold, which is below 120 mA even at 303 K. The maximum output power is in the order of 10 mW at 140 mA. In the following, the laser is placed on a cold copper finger whose temperature is set by a water flow at 286 K. This temperature was chosen in order to maximize the optical power of the laser. The QCL is biased at 140 mA with a low-noise current source for the DC part and the AC signal is produced by a programmable arbitrary waveform generator

(AWG Tektronix 7122B) with a sampling rate of 12 GSa/s and an analog bandwidth of 3.5 GHz. The DC and AC signals are combined with a bias-tee prior to the connection to the MMCX wire, whose core is directly bounded to the QCL ridge. The optical signal retrieved by the fast detector (Vigo UHSM-I-10.6) is subsequently analysed with an oscilloscope (Tektronix MSO72004C) with a sampling rate of 12.5 GSa/s, and then recorded for post-processing. The sequence used in this transmission experiment is a 127-bit (2^7-1) long PRBS sequence Gray mapped to the 4 PAM symbols.

III. Results and discussion

In order to optimize the data rate that we can achieve with the aforementioned setup, a static pulse shaping digital filter was applied at the transmitter side and the acquired signal was equalized using a feed-forward equalizer at the receiver side. The equalizer coefficients were learnt using a least mean squares algorithm. After this step, the processed signal is compared with the seed signal and the bit error rate (BER) is computed. Figure 1 shows the evolution of the best BER we can achieve as a function of the number of feed-forward taps (n-tap), when the signal is pulse shaped by a root-raised-cosine (RRC) filter with a given roll-off factor, for a symbol rate of 2.4 Gbaud. The best configuration, leading to the lowest BER of 7×10^{-4}, corresponds to 101 taps and a roll-off factor of 0.4. It is relevant to note that, without signal post-processing, the BER at the receiver level is 3×10^{-1} (not shown in this paper) and this obviously hinders message recovery.
An example of the process to improve eye diagram, and thus message recovery, of the PAM-4 signal after transmission is shown in Fig. 2. The detected signal is the real-time signal that is observed with the oscilloscope and this corresponds to a configuration with only RRC filtering with a roll-off factor of 0.4 and no post-equalization. In that case, the signal is detrimentally degraded. The equalized signal eye diagram corresponds to the recorded timetrace that is subsequently post-processed and this allows achieving a BER of 1.6×10^{-3} with 49-taps. This transmission at 4.8 Gbps marks an important milestone in far-infrared communications systems because this result was obtained at room temperature, low bias current and direct modulation of the QCL emitting at 8.1 μm.
Further investigation will focus on longer distances with a Herriott cell of 30 meters instead of the current short path between the laser and the detector. The long-term goal is to implement our QCL setup in telescopes [8] for long-haul beam shaping that would allow achieving free-space transmissions over several kilometers. Future improvement can also be expected with more advanced equalization or use of soft-decision FEC decoders allowing for BER thresholds above 10^{-2} while still being considered an error-free transmission.

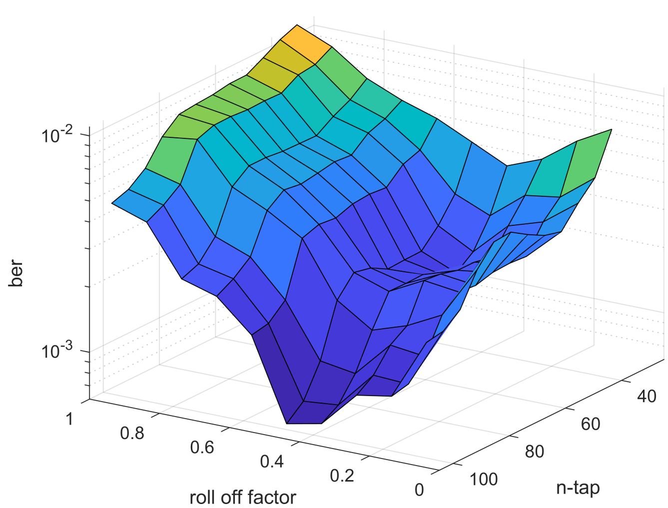

Fig. 1. Evolution of the BER for a PAM-4 signal at 2.4 Gbaud when varying the number of equalizer taps, and the roll-off factor driving the electrical bandwidth occupancy of the signal.

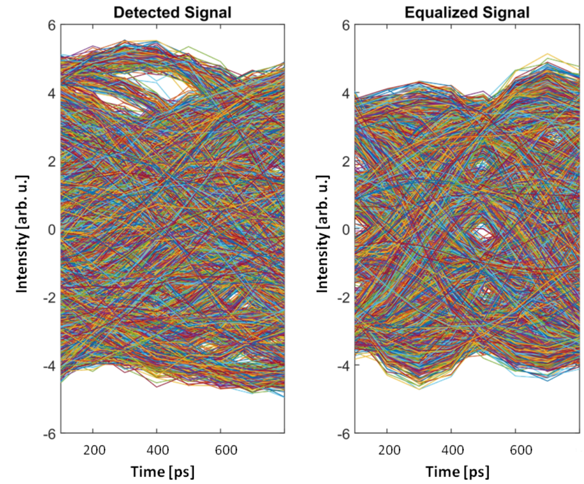

Fig. 2. Example eye diagrams; the left chart is the original signal detected with the real-time oscilloscope; the right chart is the signal after equalization and offline post-processing, leading to a minimum BER of 1.6×10^{-3}. The two diagrams were obtained for 2.4 Gbaud and a roll-off factor of 0.4.

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