High-speed transmissions with direct-modulation room-temperature semiconductor lasers emitting in the transparency window around 4 μm

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Abstract: We experimentally realize a free-space transmission over one meter with room-temperature quantum cascade lasers and interband cascade lasers. With direct electrical modulation and raw analysis, the data-rate of the real-time transmission outperforms similar reported schemes. © 2021 The Author(s)

1. Introduction

Available semiconductor sources in the mid-infrared (mid-IR) domain showed an accelerated development in recent years with cascade photonic devices. On the one hand, quantum cascade lasers (QCLs) experimentally demonstrated for the first time in 1994, are optical sources exploiting radiative intersubband transitions within the conduction band of semiconductor heterostructures. On the other hand, interband cascade lasers (ICLs), offer an alternative with lower power-consumption and wavelength up to 7 μm. The wide range of wavelengths achievable with these novel devices leads to a large number of applications, including free space communications that are less affected by atmospheric phenomena (e.g., turbulence, fog or scattering) compared to short-wave infrared and visible light transmissions [1, 2]. Besides, conventional channels for high-speed communications with near-infrared fiber components are close to saturation. It is thus of paramount importance to extend the current knowledge about near-infrared optics to the mid-IR domain and to assess the performances of long-haul free-space transmissions. For instance, recent progress have shown integrated platform for mid-IR photonics [3] or optical fibers designed for the long-wave infrared domain [4]. These technologies are very promising for the future of communications though their performances are still well behind those of near-infrared components. In this paper, we demonstrate a free-space communication with an ICL and with a packaged QCL, both emitting around 4 μm, which corresponds to one of the transparency atmospheric windows. In this experiment, the distance between the laser and the mid-IR detector is roughly one meter. The real-time transmission data-rate reaches 550 Mbits/s in the case of the QCL, and that is a lower rate than the one achieved with previous configurations considering cryogenic temperatures [5] or bulky computer-assisted processes which only allow quasi real-time transmissions [2]. However, the data-rate we achieved is better than that retrieved in other similar configurations at room-temperature with direct electrical modulation of the QCL and raw analysis at the detector level [6]. The real-time data-rate reaches 110 Mbits/s in the case of the ICL and this surpasses, to the best of our knowledge, the previous record with this kind of semiconductor lasers [1]. In our experiment, for both the ICL and the QCL configuration, we did not perform any pre-processing or post-processing, which means that we did not study the full-system frequency response to encode the seed signal. Consequently, the rate improvement was only due to a combination of a low-noise current source, a low-noise oscilloscope, as well as a wide-bandwidth mid-IR detector with low gain-flatness.

2. Experimental setup

The QCL under study is a Fabry-Perot (FP) laser embedded in a high-heat load (HHL) package that is commercially available and the maximum optical power is 130 mW. The ICL is also a FP-laser but it is not enclosed in a HHL package. Instead, the ICL is mounted on a custom heat-sink and the maximum optical power is 5 mW. Unless stated, the temperature of the heat-sink for both lasers is 288K. The photonic devices are biased with a low-noise current source for the DC part and a pseudo-random binary sequence (PRBS) generator for the AC part. The DC and AC signals are combined with a bias-tee prior to the connection to the laser's probes. This allows the laser to

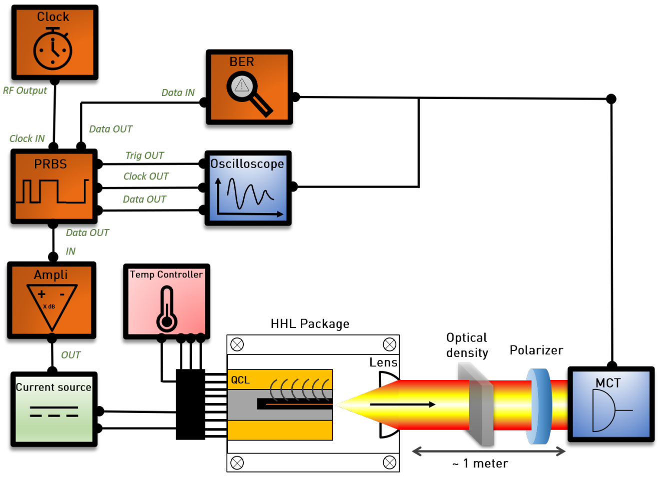

Fig. 1: Experimental setup to transmit an OOK message with a HHL-packaged QCL. The signal generation requires a reference clock, a PRBS generator and an electrical amplifier. The QCL is hermetically packaged and a 6-pin connector allows controlling the temperature and biasing the device with a low-noise current source. The only difference for the ICL's setup is that the laser is mounted on a custom copper heat-sink with a remote mid-IR lens for light-focusing. The raw analysis of the modulated beam is performed with a mid-IR MCT detector, a real-time oscilloscope and an error detector which is able to provide real-time bit-error rates.

be electrically modulated for optical signals transmission. The light generated by the laser is sent towards a 2.0 optical density foolowed by a polarizer to adjust the optical power received by the Mercury-Cadmium-Telluride (MCT) detector. We were able to perform the detection down to a few hundreds of µW at the detector level, compared with the multi-mW output power available at the emitting facet of the lasers. In the case of the QCL, we can perform the transmission with an attenuation up to 26 dB. This attenuation is equivalent to a real-field 4-km transmission with 0.5-km visibility (i.e. weather conditions with regular fog). The optical signal retrieved by the MCT is subsequently analysed with a fast oscilloscope and an error detector. The latter compares the bit of the seed PRBS signal and the bits of the received PRBS signal. The sequence used in this on-off keying (OOK) transmission experiment is 127-bit long (2^7-1). The full setup is described in Fig. 1.

3. Results and discussion

It is possible to achieve several Gbits/s transmission with QCLs. However, this feat requires either liquid helium [5] or a computer-assisted process based on a thorough analysis of the frequency response of the whole transmission system, before programming a dedicated transmission signal [2]. All in all, these two techniques are difficult to implement in a real-field environment. Besides, even if the second configuration works at room-temperature, the transmission was only performed in a back-to-back configuration with 5 cm between emitter and detector, without any subsequent attenuation. In our scheme with a commercial off-the-shelf QCL, several optical elements mimic the attenuation of a room-temperature atmospheric transmission. The result for the packaged QCL is displayed in Fig. 2 (a) and shows that we can achieve 550 Mbits/s without complex processing and obtain a bit-error rate (BER) that is compatible with the current standard of forward error correction (FEC). In the case of the ICL, the maximum data-rate is lower for a similar BER, as visualized in Fig. 2 (b). Furthermore, the output power of the laser is only 5 mW, and we did not apply any major attenuation on the optical path before retrieving the signal. This 110 Mbits/s data-rate is however the fastest in the literature so far, and further improvements could be expected since the ICL technology is less mature than the QCL technology.

In the configuration with the QCL, we also underline the role of the attenuation along the optical path. Figure 3 shows the evolution of the BER with the angle of the polarizer in front of the MCT detector. By increasing the angle of the polarizer, one decreases the optical power received by the detector because the QCL light is TM polarized. While the BER remains below the 3×10^{-2} threshold (marked with the dashed line), the transmission can be considered error-free with the help of FEC. In our case, this means that we can realize a 400-Mbits/s communication with a maximum attenuation of 26 dB. The conclusion is that quantum intersubband/interband cascade lasers are promising for realizing free-space transmissions in the mid-IR. Further improvement will consider optimized RF bondings of the devices in comparison with the bare chips we used in that experimental work. Mid-IR external modulators based on Germanium could also be of great help although they are currently limited to modulation speeds at a few dozens of MHz [7], which is lower that the ones we exhibited with direct electrical modulation.

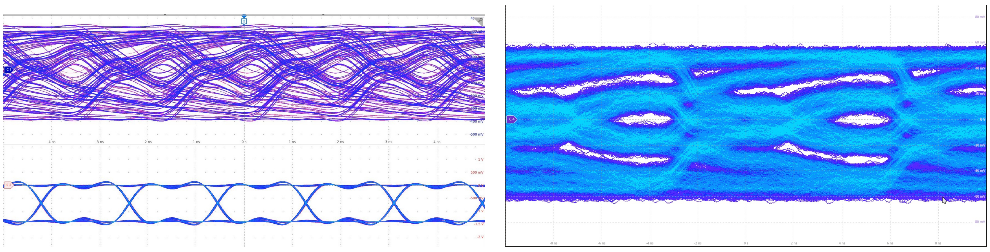
(a) (b)

Fig. 2: (a) Eye diagram in the case of a transmission at 550 Mbits/s with the QCL, the top trace is the signal recovered by the detector with a BER of 1×10^{-3} and the bottom trace is the seed signal; (b) Eye diagram in the case of a transmission at 110 Mbits/s with the ICL, showing a BER of 1×10^{-3}.

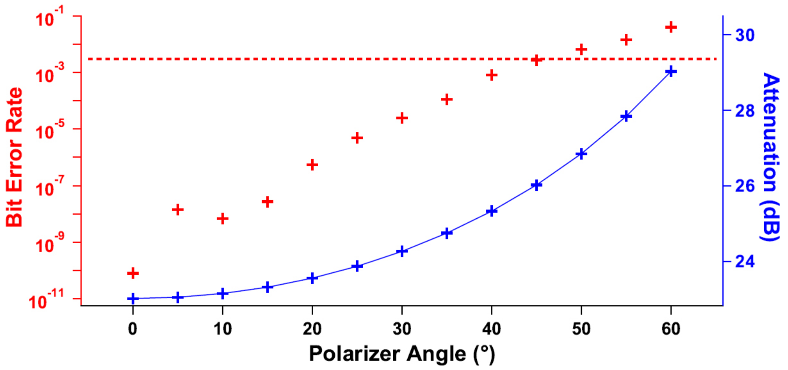

Fig. 3: Performance of the transmission with the QCL for a data-rate of 400 Mbits/s. The red crosses represent the BER retrieved with the error detector when varying the polarizer angle in front of the detector. The red dashed line corresponds to the maximum BER if one wants to perform error-free transmission with state-of-the-art FEC. The blue solid line is the total attenuation (taking into account optical density and polarizer) as a function of the angle of the polarizer and shows that error-free transmission can be achieved up to 26 dB of attenuation.

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