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Recent advances in high-speed data communications using mid infrared quantum cascade lasers

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ABSTRACT

Mid-Wave Infrared (MIR) free-space optical communication offers multiple advantages, such as improved transmission capacity through the atmosphere and immunity to electromagnetic interference. In addition, MIR transmission between 8-12 microns provides stealth for the communication signal thanks to the random thermal blackbody radiation having a strong background at these wavelengths, hence greatly reducing the probability of adversaries intercepting a MIR laser signal. Quantum cascade lasers (QCL) are optical sources of choice to target this wavelength domain. They are unipolar semiconductor lasers from which stimulated emission is obtained via electronic transitions between discrete energy states inside the conduction band. This work reports on a full unipolar quantum optoelectronics communication system based on a 9-micron QCL and on a Stark-effect modulator. Two different receivers are considered for high-speed detection, namely an uncooled quantum cascade detector (QCD) and a nitrogen-cooled quantum well infrared photodetector (QWIP). We evaluate the maximum data rate of our link in a back-to-back (B2B) configuration before adding a multi-pass Herriott cell so as to increase the transmission length of the light path up to 31 meters. By using pulse shaping, pre- and post-processing, we reach a record bitrate both 2-level (OOK) and 4-level (PAM-4) modulation scheme for a 31-meter propagation link and a bit error rate (BER) compatible with standard error-correction codes. Overall, we believe that our unipolar quantum system is of paramount importance for the development of cost-effective, reliable and versatile free-space optics data links.

Keywords: quantum cascade devices, unipolar quantum optoelectronics, mid-infrared modulator, high-speed photonics, free-space communication

1. INTRODUCTION

The beginning of the 21st century has seen the apogee of fiber telecommunication with wavelength division multiplexed systems exhibiting more than 100 Gbit/s per channel.[1] Yet, alternatives are sought after in order to deploy future generations of communication systems. One of the options relies on free-space optics (FSO) communication with either near-infrared lasers[2,3] that were initially optimized for fiber communications or with longer wavelengths.[4,5] The mid-infrared domain has two bands of interest (between 3-5 μm and between 8-12 μm, respectively) for FSO, which are called atmospheric transparency windows.[6] In particular, mid-infrared wavelengths are known for their resistance to degraded weather conditions, such as fog, and could thus be

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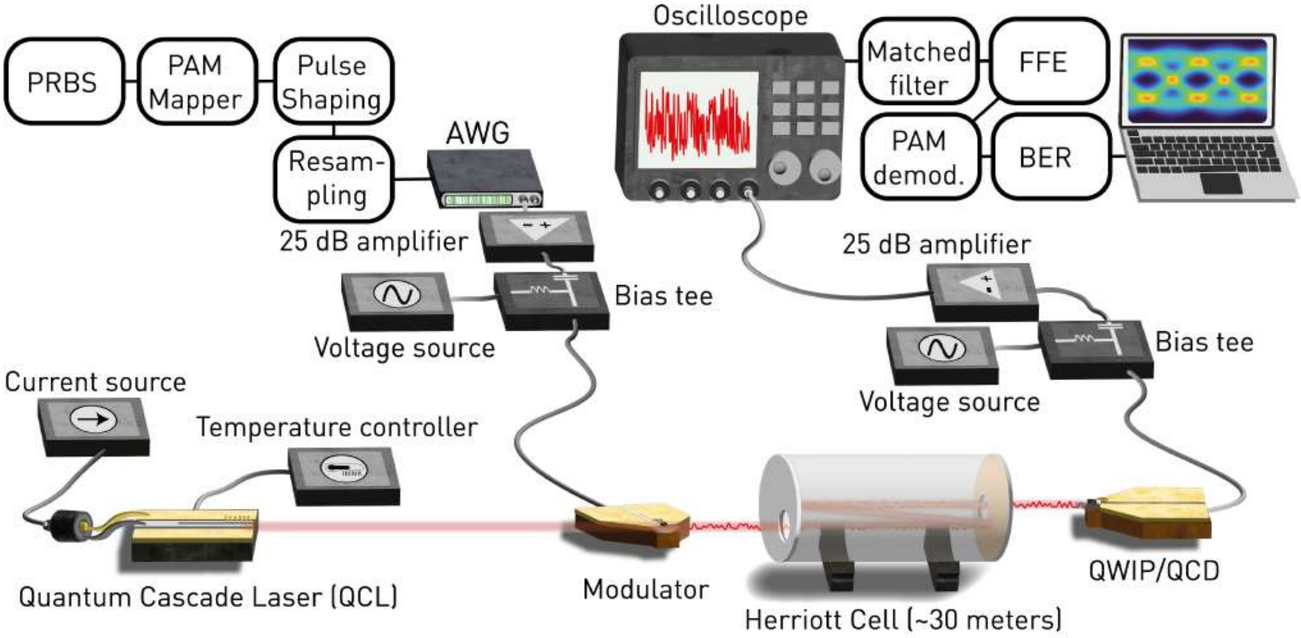

Figure 1. Experimental setup of the high-speed data communication at mid-infrared wavelength. The setup includes three unipolar quantum devices: a quantum cascade laser, an amplitude Stark-effect modulator and a quantum well infrared photodetector (or alternatively, a quantum cascade detector).

useful for communications in maritime environments where visible wavelength is also a potential candidate.[7] Despite a few proof-of-concept experiments of outside mid-infrared free-space transmissions,[8] those wavelengths still lack critical off-the-shelf components that are widely available at near-infrared wavelength, such as external modulators and optical amplifiers. Recent years have seen the development of various technologies for external modulation of mid-infrared light,[9–11] but their electrical bandwidth is lower than that of RF-optimized QCLs.[12,13] This explains why, so far, experiments demonstrating high-speed transmission with QCLs focused on direct modulation schemes.[14–16] With the latter, it is possible to achieve multi-Gbit/s data rates or uncompressed HD-video transmission.[17] However, some applications require faster data rates, up to 100 Gbit/s, equivalent to those already demonstrated with near-infrared semiconductor lasers. We recently unveiled novel amplitude Stark-effect modulators operating at a wavelength of 9 μm.[18] By modulating the voltage of these external modulators, one can change the wavelength of the maximum of absorption and thus attenuate or transmit the light coming from a QCL. These modulators combine a modulation bandwidth of several GHz with a large modulation depth, which are ideal for high-speed free-space communication at mid-infrared wavelength. In this work, we show that the combination of a room temperature QCL, an external Stark-effect modulator, a 31-meter multi-pass cell and a cryogenic intersubband detector allows one to achieve free-space data rates of several dozens of Gbit/s and this paves the way towards outdoors long-distance communication based on unipolar quantum technologies.

2. EXPERIMENTAL SETUP

We carry out the experimental demonstration with the setup presented in Fig. 1. The QCL is biased high above threshold so that it can emit roughly 100 mW of optical power at 9 μm. This optical power is more than enough to mitigate the optical losses of our channel at this wavelength and would be compatible with a transmission distance of hundreds of meters. The laser is kept at a stabilized room temperature thanks to a temperature controller. The mid-infrared beam first impinges the amplitude Stark-effect modulator that is linked to a custom coplanar waveguide and RF-mounted for high-speed operation. This modulator is both DC-biased and electrically driven with the message to be transmitted. The characteristics of the optical channel[19] must be taken into account in order to pre-map (i. e. voluntarily distort) the electrical signal to be transmitted so that it complies with the limited bandwidth of the full system. The signal is pre-mapped with a Matlab program and then loaded to the Socionext arbitrary waveform generator (AWG) with a fixed sampling per symbol. The AWG

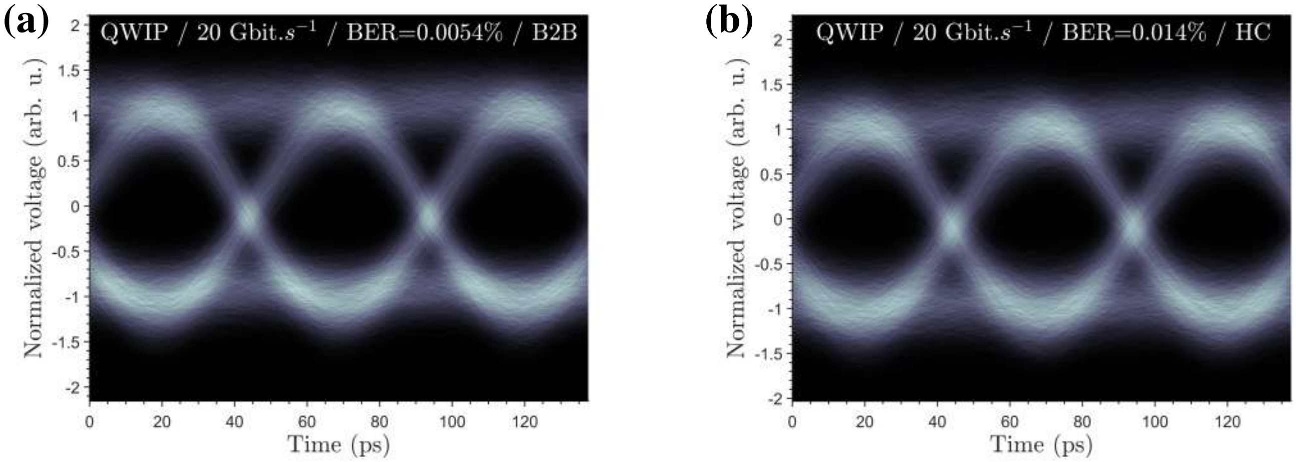

Figure 2. (a) Eye diagram of the transmission when a 20 Gbit/s OOK message is applied to the external modulator and the QWIP is located right after the modulator. (b) Eye diagram of the transmission when a 20 Gbit/s OOK message is applied to the external modulator and the Herriott cell extends the length of the optical path, as shown in Fig. 1. With this latter configuration, the BER shows a slight degradation but this does not affect the error-correction processing.

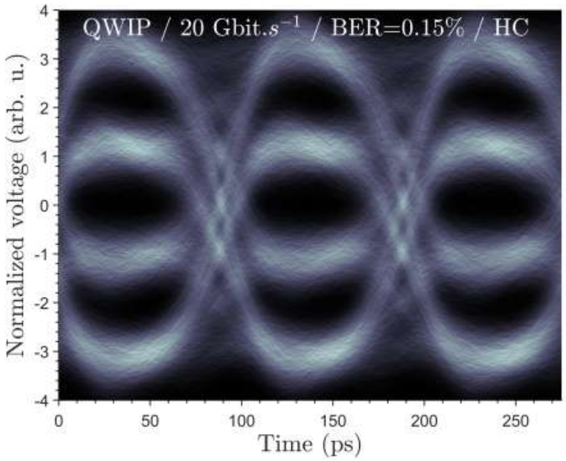

Figure 3. (a) Eye diagram of the transmission when a 20 Gbit/s PAM-4 message is applied to the external modulator and the Herriott cell extends the length of the optical path, as shown in Fig. 1.

acts as a digital-to-analog converter with a maximum bandwidth of 30 GHz and a maximum peak-to-peak output voltage of 1.5 V. Because there is a strong impedance mismatch between the AWG output and the modulator input, a 25-dB amplifier is required in order to achieve a large modulation depth. After the modulation step, the mid-infrared light escapes the modulator, enters the Herriott cell (HC) and bounces 80 times (that corresponds to a free-space propagation of 31 meters) before exiting and being collected by either a room-temperature quantum cascade detector (QCD) or a cryogenic quantum well infrared photodetector (QWIP). The detector converts the mid-infrared light into an electrical signal that is subsequently amplified with a 25-dB amplifier before being recorded with a 100 GS/s oscilloscope (Tektronix, DPO70000SX, 33 GHz bandwidth). The recorded signal is then post-processed with steps including resampling at a constant sampling per symbol and feed-forward equalization (FFE). Finally, the bit error rate (BER) is derived and the eye diagram is plotted. When the Herriott cell is not inserted between the modulator and the detector, the total propagation distance is roughly 2 meters and this corresponds to a back-to-back (B2B) configuration.

3. RESULTS

In the following, we apply PRBS (pseudo-random binary sequence) signals to the external modulator and the sequence length is 2^{15} symbols for the three configurations described hereafter. An increase of the transmission distance has an impact on the quality of the transmission and this can be analyzed with the bit error rate (BER). This is shown in Fig. 2 where the eye diagram of a 20 Gbit/s communication is shown, first for a back-to-back configuration (Fig. 2 (a)) and then for a Herriott cell configuration (Fig. 2 (b)) when considering a 2-level modulation format (OOK, on-off keying). The two eye diagrams look similar but a closer look at the BER shows that the error rate is 0.0054% in the short-range communication while it is 0.014% in the long-range communication. In a real-field experiment with propagation of hundreds of meters, the attenuation of the atmosphere should give a similar trend. In this experiment, the degradation of the BER does not mainly come from the free-space propagation but from the small absorption (in the order of 1%) of the two mirrors inside the Herriott cell. As the light is reflected 80 times by one of these two mirrors before reaching the detector, the mid-infrared power at the output of the Herriott cell is actually less than 50% of the mid-infrared power at the input of the Herriott cell. In other words, adding the multi-pass cell leads to a $\sim$ 3-dB attenuation. In comparison, this is roughly the attenuation caused by Mie scattering at 9 μm when the beam travels 900 meters when the visibility is 1 km (fog conditions).[20]

Apart from the OOK format, we also tested a 4-level modulation format (PAM-4, pulse amplitude modulation) at 10 Gbaud, which corresponds to 20 Gbit/s too (Fig. 3). When the Herriott cell is introduced in the optical path, the BER is now 0.15 %, corresponding to degraded conditions of operation compared to the OOK format. Yet, the BER previously shown for the OOK format and that for the PAM-4 format are low enough to be corrected with conventional error codes. Indeed, when the BER is below 0.38%, it is possible to get rid of all the remaining errors by adding a 7% bit overhead. For the 20 Gbit/s example shown here, this means that the error-free transmission rate becomes 18.6 Gbit/s. This data rate is sufficient to transmit uncompressed high-quality videos with 4K60 (3840 pixels × 2160 pixels at 60 frames per second) resolution and HDR (high dynamic range) format and this will improve our current direct-modulation setup that can only transmit videos with 720p30 (1280 pixels × 720 pixels at 30 frames per second) resolution.[17]

4. CONCLUSIONS

This paper demonstrates a novel free-space laser transmission system operating at 9 μm and based on unipolar quantum technology. We showed data transmission at 20 Gbit/s for both an OOK format and a PAM-4 format when the free-space propagation distance is roughly 30 meters. In those configurations, the BER is found fully compatible with standard error-correction codes working with a 7% bit overhead. Recent findings in intersubband technology are very promising for the development of new high-speed applications. QWIP detectors working up to 220 GHz are already available[21] and could be the cornerstone of hybrid photonics-wireless transmission systems based on mid-infrared heterodyne photomixing,[22] in combination with an amplitude Stark-effect modulator like the one presented in this proof-of-concept communication experiment. In addition, recent efforts about private free-space communication at mid-infrared wavelength[23] could take advantage of external modulators to increase the rate of the private datacom. Overall, the 20 Gbit/s FSO communication results shown here are of paramount importance for the development of cost-effective, reliable and versatile free-space data links in the mid-infrared.

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