11 Gb/s LWIR FSO Transmission at 9.6 µm using a Directly-Modulated Quantum Cascade Laser and an Uncooled Quantum Cascade Detector

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Abstract: Record 11 Gb/s LWIR FSO transmission is demonstrated with a 9.6-µm directly-modulated QCL and a fully passive QCD without cooling, surpassing the previous bitrate record of DM-QCL-based FSO in this spectral window by 4 times.

1. Introduction

Free-space optical (FSO) communications in the mid-infrared (IR) region, particularly the two atmospheric transmission windows at the Mid-Wave IR (MWIR, 3-5 µm, 60-100 THz) and the Long-Wave IR (LWIR, 8-12 µm, 25-37 THz), contain rich potential but are currently underexploited. Compared with the extensively studied THz band (0.03-3 mm, 0.1-10 THz), the MWIR/LWIR spectrum contains over tenfold broader bandwidth with two orders of magnitude lower atmospheric propagation attenuation and is unlicensed [1]. Compared with the 1.5-µm telecom band in the short-wave IR (SWIR) where most commercial FSO systems adopt, the MWIR/LWIR has much lower sensitivity to particle scattering, atmospheric turbulences, and lower risk for eye safety.

Recently, very high data rates are demonstrated in the < 4-µm region by using wavelength conversions from the telecom band before and after the mid-IR FSO link [2,3]. However, from the energy efficiency point of view, direct-emission semiconductor lasers and photodetectors are more attractive. Quantum cascade laser (QCL) and quantum cascade detector (QCD) based on inter-subband transitions emerge as promising candidates thanks to breakthroughs in broad bandwidth and high-temperature operation. In the MWIR window, several transmission demonstrations have been reported with room-temperature directly-modulated (DM)-QCLs with bitrates up to 6 Gb/s [4-6]. However, a cooled Mercury-Cadmium-Telluride (HgCdTe) detector operating at 200 K was used to guarantee low-noise characteristics to achieve such high bitrates [6]. The LWIR window encounters even more stringent requirements for the device power and noise characteristics due to the smaller energy bandgap. To the best of our knowledge, the highest reported room-temperature LWIR FSO bitrate with DM-QCL was up to 2 Gb/s with bit-error rate (BER) below the 2×10^{-2} soft-decision FEC limit [7]. Very recently, a 9-µm FSO link supporting up to 10 Gb/s non-return-to-zero on-off keying (NRZ-OOK) signals was demonstrated based on an external free-space Stark modulator and an unbiased QCD without any active cooling [8]. Notice that the external modulator scheme requires extra LWIR optics and a delicate beam alignment, necessary to increase the modulation depth and therefore the signal-to-noise ratio (SNR) on the detector. Therefore, DM-QCL is a simple and efficient solution that can speed up commercial LWIR FSO solutions.

In this paper, we report on a record LWIR FSO bitrate of 11 Gb/s achieved with a 9.6-µm DM-QCL and an uncooled and unbiased passive QCD. The highest bitrates of both binary NRZ-OOK and multilevel PAM4 signals are explored against the 6.25% overhead (OH) hard-decision (HD) FEC limit [9]. This work sets a significant landmark on the uncharted territory of > 10 Gb/s LWIR FSO and shows promising potential of DM-QCL and QCD for the future ICT infrastructure.

2. Experimental configuration

Figure 1(a) shows the experimental setup. A 64 GSa/s arbitrary waveform generator (AWG) is used to generate the modulation signal. The OOK and PAM4 symbols are mapped from random binary sequence of >1 million unrepeated bit-length generated from MATLAB based on Mersenne Twister with a shuffled seed number. A root-raised-cosine (RRC) pulse shaping filter of 0.15 roll-off factor and a static pre-emphasis filter are applied to pre-

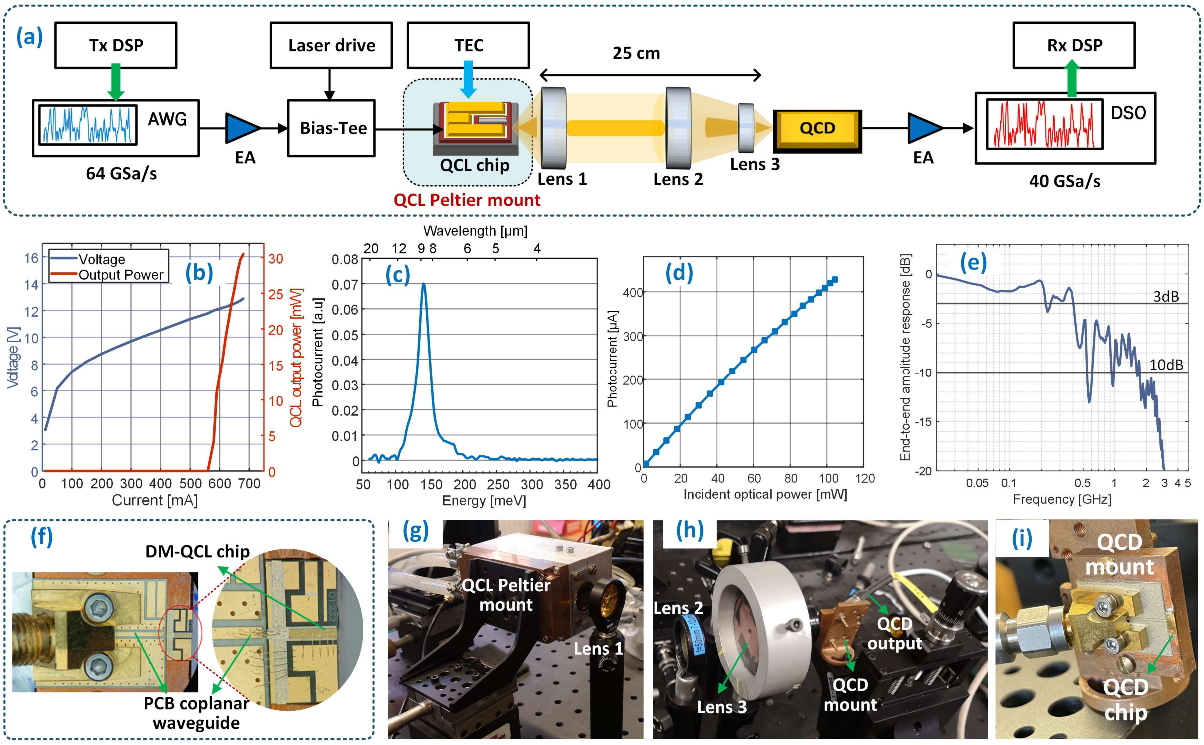

Fig. 1. (a) Experimental setup. (b) P-I-V curve of the 9.6-μm DM-QCL. (c) Measured photocurrent spectrum of the QCD at room temperature. (d) Measured photocurrent of the uncooled QCD as a function of incident CW laser power. (e) Characterized end-to-end amplitude response including the QCL, QCD, all the electrical and RF components. The pictures of (f) the QCL chip wire bonded to a printed circuit board (PCB) coplanar waveguide delivering the bias and RF modulation signal, (g) the transmitter with the QCL Peltier mount and the beam collimating lens, (h) the cascaded beam focusing lenses and the mounted QCD chip, and (i) the mounted QCD chip.

compensate for the system bandwidth limit. The DM-QCL is a 3 mm distributed-feedback ridge laser processed epi-down so that it can be operated at room-temperature using a Peltier cooling module with few tens of milliwatts of continuous wave infrared light at wavelength of 9.6 µm. In this measurement, we operate the DM-QCL at 0°C to ensure sufficient incident power for the detector. The P-I-V curve of the DM-QCL measured at 0°C is shown in Fig. 1 (b). At this temperature, the lasing threshold is around 560 mA, and the saturation appears around 675 mA. The DM-QCL chip is soldered on a submount, and wire bonded to a high-frequency capable coplanar waveguide, as shown in Fig. 1 (f). The cut-off modulation frequency of the device is around 3 GHz, after which the frequency response drops sharply. The laser is biased and modulated through an external bias-tee.

For the FSO transmission, we used a ZnSe aspheric lens at the QCL output to collect and collimate the beam. The detector is a GaAs/AlGaAs QCD mesa, based on a diagonal transition with a 45° polished facet to fulfil polarization requirements for inter-subband transitions. This unipolar detector operates in the photovoltaic regime and exhibits a very wideband frequency response with a first order roll-off. The frequency response of the QCD is almost flat up to the device cut-off at 6 GHz [8]. Fig. 1 (c) shows the measured photocurrent spectrum of the QCD at room temperature. The peak responsivity is observed at 141.6 meV, corresponding to a wavelength of 8.75 µm, and the efficiency drops to approximately 45% of the peak at 9.6 µm. Therefore, we can expect further improved performance with a slightly shorter laser wavelength closer to the peak. As shown in Fig. 1 (d), the photocurrent linearly increases with the injected power up to 50 mW with a responsivity of 4.5 mA/W at 9 µm at room-temperature. In the current experiment, the highest optical power on the detector was 30.5 mW and hence well within the linear region. An optical element consisting of two lenses is used to focus the light on the detector to achieve the small spot size needed to maximize the QCD photocurrent. The detected signal is amplified and captured with a 40 GSa/s real-time digital storage oscilloscope (DSO). Figure 1 (e) shows the calibrated end-to-end frequency response of the channel, including the AWG, QCL, QCD, DSO, and all the electrical components in between. The photos of the LWIR transmitter and the receiver are shown in Fig. 1 (g) and (h). The mount where the QCD chip wire-bonded to coplanar waveguide is shown in Fig. 1 (i). Finally, the signal is processed with a matched filter, a timing recovery and down-sampling process based on maximum variance, a symbol-spaced decision-

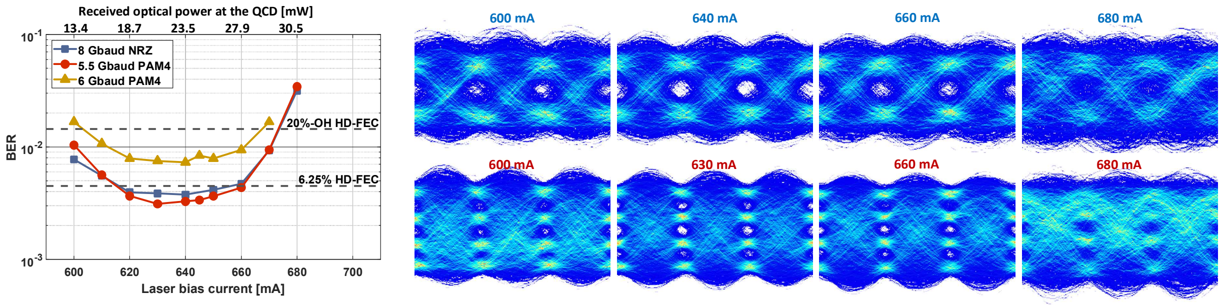

Fig. 2. BER results as a function of laser bias. Selected eye diagrams for 8 Gbaud NRZ and 5.5 Gbaud PAM4 at different bias points.

feedback equalizer (DFE) with 55-feedforward taps and 55-feedback taps, and the BER performance is evaluated after the demodulation.

3. Experimental results

Three modulation configurations, i.e., 8 Gbaud NRZ, 5.5 Gbaud PAM4 and 6 Gbaud PAM4 were tested. As there is no variable attenuator in the setup and tuning the optomechanics lacks accuracy, we evaluate the transmission performance by sweeping the laser bias current, which translates into the change of received optical power at the QCD. The modulation linearity is also correlated with the laser bias point. Figure 2 shows the measured BER results as a function of the laser bias for all three modulation formats, and the corresponding incident power onto QCD is shown in the top axis. A clear trade-off between the SNR and modulation linearity is observed. The optimal bias point was found to be between 630 mA and 640 mA to simultaneously obtain a sufficient SNR and signal linearity, where both the 8 Gbaud NRZ and the 5.5 Gbaud PAM4 achieve the BER below the 6.25%-OH HD-FEC limit of 4.5×10^{-3}. Further increase of the PAM4 baud rate to 6 Gbaud severely degrade the BER performance and the 6.25%-OH HD-FEC limit could not be achieved. A higher coding-gain FEC configuration, e.g., with 20%-OH, may be used to further increase the data rate, but is not desirable due to the increased latency and complexity. We also show the selected signal eye diagrams after post-equalization for 8 Gbaud NRZ and 5.5 Gbaud PAM4 at different laser bias points. One can clearly observe the compression of lower-amplitude levels at 600 mA for the PAM4 signal as it is too close to the QCL lasing threshold. On the other hand, increasing the bias current beyond the optimal region causes compression on the upper-amplitude levels and cause severe signal distortion at 680 mA, despite of the high achievable SNR at this point.

4. Conclusion

We demonstrated a record bitrate LWIR FSO transmission at 9.6 µm with a directly-modulated QCL and a fully passive QCD without any cooling or bias voltage. The system supports up to 8 Gbaud NRZ and up to 5.5 Gbaud PAM4 signals with BER performance below the 6.25%-OH HD-FEC limit, verifying the excellent performance in terms of the bandwidth and linearity of both the DM-QCL and the QCD. This work is a significant step towards a fully connected high-speed LWIR FSO network, envisioned to be a promising alternative to the RF-based wireless systems.

5. Acknowledgement

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