Up to 6 Gbps Mid-Infrared Free-Space Transmission with a Directly Modulated Quantum Cascade Laser

Xiaodan Pang[(1,2)], Richard Schatz[(1)], Mahdieh Joharifar[(1)], Aleksejs Udalcovs[(2)], Vjaceslavs Bobrovs[(3)], Lu Zhang[(4)], Xianbin Yu[(4)], Yan-Ting Sun[(1)], Sergei Popov[(1)], Sebastian Lourdudoss[(1)], Oskars Ozolins[(1,2,3)]

[(1)] Appl. Phys. Depart., KTH Royal Institute of Technology, Sweden xiaodan@kth.se, rschatz@kth.se
[(2)] Network Unit, RISE Research Institutes of Sweden, Sweden oskars.ozolins@ri.se
[(3)] Institute of Telecommunications, Riga Technical University, Latvia
[(4)] College of Information Science and Electronic Engineering, Zhejiang University, China

Abstract *We report on an experimental demonstration of a mid-infrared free-space communication link enabled by a directly modulated quantum cascade laser operating at room temperature. A record high transmission rate up to 6 Gbps over 50-cm link distance is demonstrated at 4.65 µm wavelength.*

Introduction

Terrestrial free-space optical communication (FSO) has been proposed, studied, and even developed since decades ago. However, it has not been widely recognized and adopted as a reliable part of the modern ICT infrastructure. The main concern of current terrestrial FSO technologies, most operating in the near-infrared (NIR) telecom band (1 – 2 µm), is their limited tolerance of the dynamic atmospheric conditions. Recently, the mid-infrared (MIR) spectral region (4 – 12 µm) is attracting increasing interests, owing to its intrinsic merits of larger robustness against various weather conditions: scattering by aerosols, rain and snow, as well as beam broadening and scintillation by turbulence effects, compared with the NIR FSO[1]. Moreover, this unlicensed region can potentially offer extra spectral resources and complementary propagation properties for future wireless applications, with similar high-directional properties with the extensively studied sub-millimetre and terahertz (THz) technologies[2]. However, the MIR FSO technologies are currently underexploited, as there has been a lack of a viable semiconductor laser source until recently. Several demonstrations are reported with bulky and energy-inefficient nonlinear wavelength conversion approaches[3,4]. Quantum cascade laser (QCL), which can cover from the MIR to the THz range by exploiting inter-subband transitions[5,6], have appeared promising for MIR FSO transceivers with the recent breakthrough in continuous-wave (CW) and room-temperature operation[7]. A few QCL-based FSO demonstrations are reported lately[8,9]. The state-of-the-art studies include experimental demonstrations of up to 4 Gbps transmission with various multi-level modulation formats using a directly modulated MIR QCL operating at room temperature[10,11]. However, the reported link distance was limited to 5 centimetres due to the lack of adequate collimation, resulting in an insufficient receiver signal-to-noise ratio (SNR).

This paper reports on our recent demonstration of FSO transmissions based on directly modulated MIR QCL at 4.65 µm. By improving on the custom bias-tee design to drive the QCL chip on the laser mount, proper collimation is implemented to extend the transmission distance to 50 cm with a large power margin for further increase. Up to 4 Gbps simple non-return-to-zero on-off-keying (NRZ-OOK), 5 Gbps 4-level pulse amplitude modulation (PAM4) and 6 Gbps PAM8 signals are transmitted over the bandwidth-limited link and successfully received with below the 7% overhead hard-decision forward error correction (HD-FEC) limit bit error rate (BER) performance. This demonstration sets a new record for the bit-rate distance product of QCL-based room-temperature MIR FSO transmission, to the best of our knowledge.

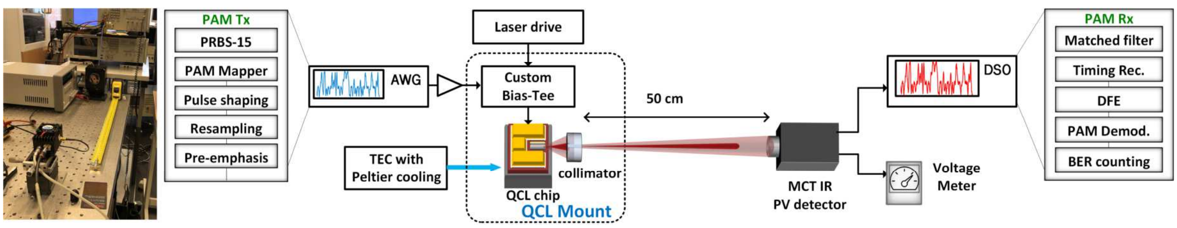

Fig. 1: Experimental setup with the configuration details of transmitter and receiver DSP. PRBS: pseudorandom binary sequence; AWG: arbitrary waveform generator; TEC: temperature controller; MCT: mercury cadmium telluride; DSO: digital storage oscilloscope; DFE: decision-feedback equalizer. (Inset: photo of the MIR FSO link setup).

978-0-7381-4679-9/21/$31.00 ©2021 IEEE

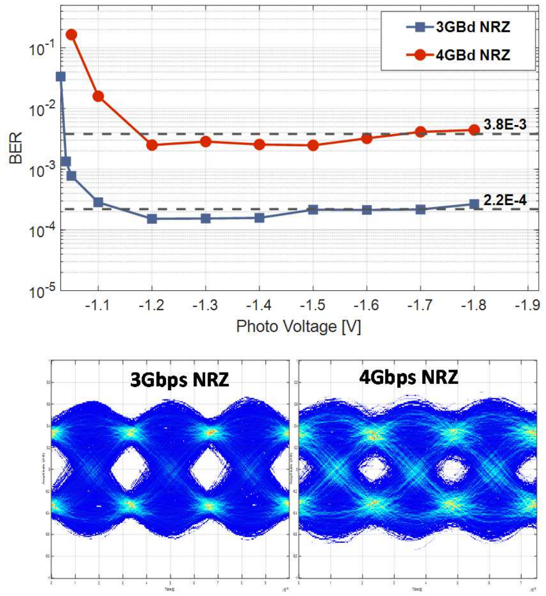

Fig. 2: BER as a function of the detector photo voltage for NRZ-OOK signals at 3 Gbaud (3 Gbps) and 4 Gbaud (4 Gbps), respectively. Selected eye diagrams are also shown for received signals at the optimal received power for both baud rates.

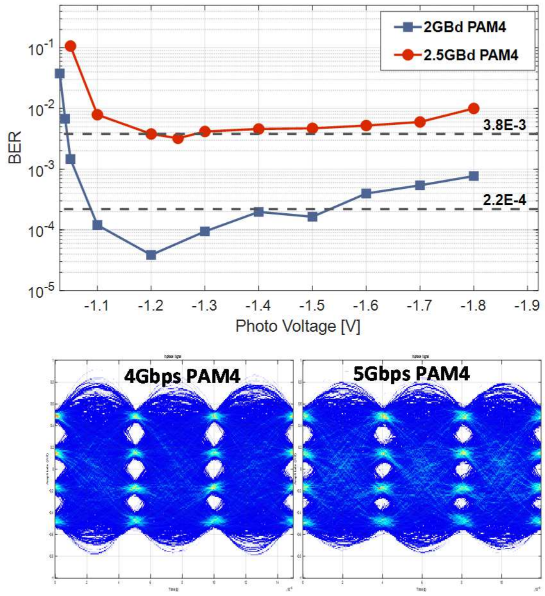

Fig. 3: BER as a function of the detector photo voltage for PAM4 signals at 2 Gbaud (4 Gbps) and 2.5 Gbaud (5 Gbps), respectively. Selected eye diagrams are also shown for received signals at the optimal received power for both baud rates.

Experimental setup

Figure 1 shows the experimental setup. The QCL chip used in the experiment was fabricated by mirSense, which is a distributed feedback (DFB) laser model from a previously reported design[7]. The QCL centred at a wavelength of 4.65 µm has a lasing threshold of 178 mA at 292 K (19 °C). The chip was mounted on a commercial QCL mount (ILX Lightwave LDM-4872) with a water-cooled Peltier element. The modulation signals are generated offline with a repeated pseudorandom binary sequence of the word length of 2^{15}-1 (PRBS-15), and converted to the analogue domain by a 50 GS/s arbitrary waveform generator (AWG). The modulation signals are firstly amplified to at least 2.5 Vpp (varied between different baud rates and modulation formats) by a linear driver amplifier before being coupled with the laser bias current at a custom-made bias tee and delivered to the QCL chip. The laser bias was set to 255 mA during the measurements, at which the QCL has an output power of 32.7 mW.

A beam collimator was installed at the QCL mount to guarantee a high directivity at the transmitter output. A MIR FSO link was established between the transmitter and a commercial mercury cadmium telluride (MCT, HgCdTe) photovoltaic (PV) MIR detector, which was mounted in a thermo-electrically cooled module with a built-in trans-impedance amplifier (TIA). The detector was placed 50 cm away from the transmitter. It is noted that the link distance in this experiment was only limited by the space constraint in our setup configuration. The characterized end-to-end system 3-dB bandwidth was around 320 MHz, and 6-dB bandwidth was around 450 MHz with a received optical power of below ~8 mW, corresponding to a detector photovoltage of ~1.3 V. The bottleneck of the system bandwidth is believed to be the detector, which per the manufacture's specification has a 3-dB bandwidth of 720 MHz. We also observed that the system bandwidth was correlated with the received power, and increasing the power into the detector beyond the optimal value causes a decrease in bandwidth. A real-time digital storage oscilloscope (DSO) operating at 10 GSa/s was used to convert the detector output into digital samples for offline digital signal processing (DSP). In this experiment, three modulation formats, namely, NRZ-OOK, PAM4 and PAM8 at different baud rates, were used to explore the link performance limit. A static two-tap pre-emphasis digital filter was placed at the transmitter to pre-compensate the bandwidth. A symbol-spaced adaptive decision-feedback equalizer (DFE) was used as a post-equalizer at the receiver to equalize the strongly filtered received signals further. After the post-equalizer, the signal was demodulated for BER counting.

Results and discussions

For each modulation format under test, we explore the highest bit rates achievable against two FEC thresholds, i.e., the 7% HD-FEC limit of

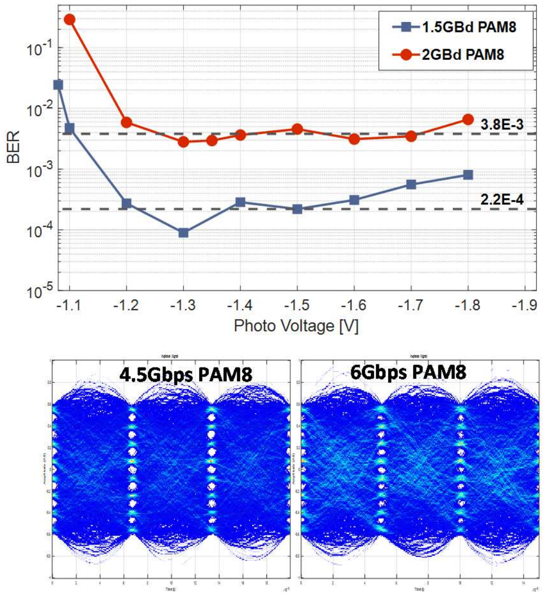

Fig. 4: BER as a function of the detector photo voltage for PAM8 signals at 1.5 Gbaud (4.5 Gbps) and 2 Gbaud (6 Gbps), respectively. Selected eye diagrams are also shown for received signals at the optimal received power for both baud rates.

3.8E-3 and the KP4-FEC limit of 2.2E-4. Figure 2 shows the measured BER results for NRZ-OOK signals as a function of the detector photovoltage. The signals are processed with DFE consisting of 33 feed-forward (FF) taps and 33 feedback (FB) taps. One can see that the KP4-FEC limit can be achieved with NRZ-OOK at 3 Gbaud, and the HD-FEC limit is achieved at 4 Gbaud. The optimal photovoltage range for both baud rates is found between -1.2 V and -1.4 V, corresponding to the received optical power of between 5.2 mW and 11 mW. Further increase of the received optical power degrades the BER performance, mainly due to the bandwidth shrinkage mentioned earlier. We also show the equalized signal eye diagrams at -1.2 V for both baud rates in Fig. 2. One can see clear eye openings thanks to the sufficient receiver SNR and effective equalization.

Figure 3 shows the BER performance for the PAM4 signals operating at 2 Gbaud and 2.5 Gbaud, corresponding to raw data rates of 4 Gbps and 5 Gbps, respectively. The same DFE configuration as the NRZ-OOK case is adopted to achieve performance below the respective FEC thresholds. The optimal detector photovoltage for 2 Gbaud PAM4 was found to be around -1.2 V, whereas for 2.5 Gbaud around -1.25 V. A slightly steeper BER degradation for PAM4 compared with NRZ-OOK can be observed when increasing the received power beyond the optimal values. We attribute it to the additional impairment caused by the saturation of the TIA at the detector, affecting the system linearity required by higher-order PAM signals. The eye diagrams for PAM4 signals at optimal power values for both baud rates are also shown in Fig. 3. Despite of the slight eye compression observed at 2.5 Gbaud, clear and adequately wide eye openings can be achieved to guarantee satisfying BER performance.

Figure 4 shows the BER performance for the PAM8 signals and the corresponding eye diagrams. 1.5 Gbaud and 2 Gbaud PAM8 signals are successfully transmitted and received through the MIR FSO link to reach below the respective KP4- and HD-FEC limits, corresponding to raw data rates of 4.5 Gbps and 6 Gbps. For an effective equalization, a DFE with 55 FF taps and 55 FB taps is used in the PAM8 cases. An optimal detector photovoltage of -1.3 V is identified for both baud rates, considering the tradeoff between required signal SNR and linearity. Clear eye openings are again observed after equalization. With a considerably large power margin of the current MIR FSO link, we can confidently expect that a much longer transmission distance can be achieved with the same data rates for all three tested modulation formats.

Conclusions

We have successfully demonstrated a directly modulated QCL-based MIR FSO link with a 50-cm distance, supporting up to 4.5 Gbps data rate to meet the KP4-FEC threshold and up to 6 Gbps data rate to reach the 7% OH HD-FEC threshold. Compared with the previous record of 4 Gbps data rate over 5 cm link distance, this demonstration shows a 50% higher achievable data rate with 10 times longer reach. Thanks to the improved custom bias-tee design allowing us to configure proper beam collimation, the received signal SNR is improved considerably with a large power margin to increase the link distance further for our next-phase explorations.

Acknowledgements

This work was supported in part by the Swedish Research Council (VR) projects 2019-05197 and 2016-04510, in part by the EU H2020 Project cFLOW under grant no. 828893, and in part by the ERDF-funded CARAT project (No. 1.1.1.2/VIAA/4/20/660). Gregory Maisons and Mathieu Carras from mirSense are acknowledged for providing the MIR QCL chip. Joakim Storck and Danya Mohamad are acknowledged for QCL mounting and characterization.

References

[1] A. Delga *et al.*, "Free-space optical communications with quantum cascade lasers," in *Proc. SPIE 10926*, 1092617, 2019.

[2] M. A. Khalighi, and M. Uysal, "Survey on Free Space Optical Communication: A Communication Theory Perspective," IEEE Commun. Surv. Tutor., vol. 16, pp. 2231-2258, 2014.

[3] Y. Su *et al.*, "10 Gbps DPSK transmission over free-space link in the mid-infrared," Opt. Express, vol. 26, pp. 34515-34528, 2018.

[4] W. Wang *et al.*, "5 Gbaud QPSK coherent transmission in the mid-infrared," Optics Commun., p. 466, 2020.

[5] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum Cascade Laser," Science, vol. 264, pp. 553-556, 1994.

[6] F. Capasso *et al.*, " Quantum Cascade Lasers: Ultrahigh-Speed Operation, Optical Wireless Communication, Narrow Linewidth, and Far-Infrared Emission," IEEE J. Quantum Electron. vol. 38, pp. 511–532, 2002.

[7] M. Carras *et al.*, " Room-temperature continuous-wave metal grating distributed feedback quantum cascade lasers," Appl. Phys. Lett., vol. 96, p. 161105, 2010.

[8] J.J. Liu *et al.*, " Mid and long-wave infrared free-space optical communication," in *Proc. SPIE 11133*, 1113302, 2019.

[9] O. Spitz *et al.* "Private free-space communications based on chaos synchronization of mid-infrared quantum cascade laser light." *Bulletin of the American Physical Society*, M08.00003, 2021.

[10] X. Pang *et al.*, "Gigabit free-space multi-level signal transmission with a mid-infrared quantum cascade laser operating at room temperature," Opt. Lett., vol. 42, pp. 3646-3649, 2017.

[11] X. Pang *et al.*, "Free-Space Communications Enabled by Quantum Cascade Lasers." physica status solidi (a), vol. 218, no.3 p. 2000407, 2021.