Unipolar quantum technology enabling high-speed free-space communication in the long-wave infrared regime

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Abstract: A combination of unipolar quantum laser, modulator and detector allows us to demonstrate a free-space communication at 40 Gbits/s and 9 μm far-infrared wavelength. The distance between the emitter and the receiver is 31 meters.

1. Introduction

The mid-infrared (MIR) and long-wave infrared (LWIR) optical domains hold many promises in terms of free-space communication because of reduced absorption and atmospheric turbulence, especially between 3-5 μm and 8-12 μm [1]. Previous efforts (some of them more than two-decade old) exhibited proof-of-concept transmissions using quantum cascade lasers (QCLs) with direct electrical modulation [2, 3]. Yet, the need for cryogenic equipment and/or the limited data rate in the order of a few Gbits/s hindered the large-scale deployment of MIR/LWIR communication systems, and all results so far were obtained in back-to-back (i. e. centimeter scale) configurations. External modulators offer a relevant alternative but most of the experimental efforts currently lag behind the direct modulation schemes in terms of bandwidth [4,5]. Recently, we showed a way to bypass this two-decade old bottleneck by developing a full unipolar quantum system that includes a QCL emitting at 9 μm, a quantum well infrared photodetector (QWIP) and a quantum cascade modulator relying on Stark effect and working at room temperature. The first efforts showed that, even without signal processing, we could achieve data transmission at 10 Gbits/s in a back-to-back configuration [6]. Further integration of this breakthrough technology in a telecommunication environment allows us demonstrating a free-space communication at 40 Gbits/s with a distance of 31 meters between the emitter and the receiver by using a multi-pass Herriott cell. We anticipate that our unipolar quantum system brings a cost-effective, reliable and versatile alternative for free-space data links, and that large-scale deployment of this technology could benefit people in areas where broadband data connection is not yet available.

2. Experimental setup

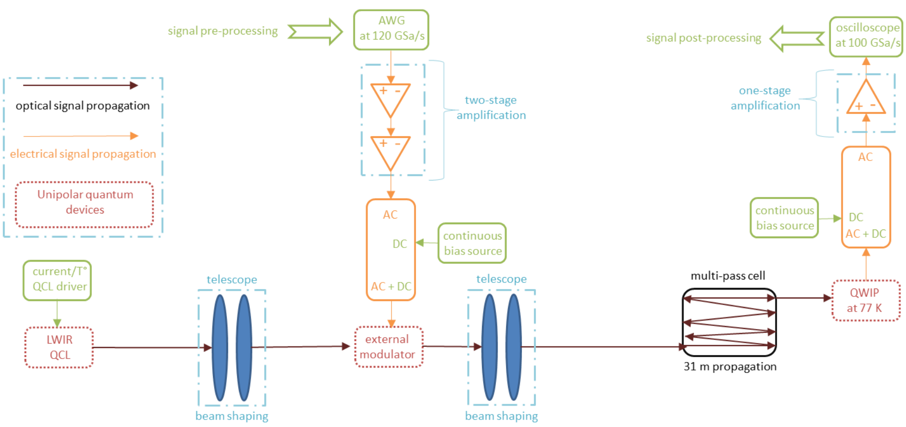

Fig. 1: Experimental setup for the high-speed transmission in the LWIR domain with unipolar quantum devices. A 9 μm wavelength QCL emits around 100 mW of optical power. The QCL's beam is intercepted by the Stark-effect modulator that is driven by the amplified signal of an AWG. The resulting signal passes through a 31 meter Herriott cell, is collected on a broadband detector and is processed with a high-speed oscilloscope.

The experimental setup of the LWIR free-space communication is described in Fig. 1. The QCL emits 97 mW of optical power at room temperature and the 9-μm wavelength beam is focused on the external modulator thanks to a telescope. This modulator has a dimension of 50 μm $\times$ 50 μm and is driven by a 15V peak-to-peak signal that is produced by an arbitrary waveform generator (AWG) at 120 GSa/s, followed by two stages of broadband amplifiers. Characterization of the frequency response of the full system (modulator, QWIP and amplifiers), gives a 4 GHz 3-dB bandwidth (not shown here) with a smooth 20dB/decades amplitude decay. Pre-processing of the signal occurs when uploading signal to the AWG. The 15V peak-to-peak signal is the 2^{15}-bit long message sequence to be transmitted and in our case, it is either a 2-level On-Off-Keying (OOK) modulation format or a 4-level Pulse-Amplitude-Modulation (PAM-4) format. After being modulated, the optical beam is shaped by a second telescope before entering the multi-pass Herriott cell. This device allows implementing a free-space propagation of 31 meters in a compact apparatus. At the output of the multi-pass cell, the beam has an optical power of 15 mW and is gathered by a cryogenic QWIP with a bandwidth of at least 25 GHz. The electrical signal from this fast detector is amplified and recorded by an 30GHz-bandwidth oscilloscope with a sampling rate of 100 GSa/s. Traces are then post-processed to account for the free-space channel perturbations and improve the bit error rate (BER).

3. 31-meter transmission using the multi-pass Herriott cell

Figure 2 a) shows that we can achieve data rates of 30 Gbits/s in the case of an OOK modulation scheme, while Figure 2 b) shows a transmission at 40 Gbits/s for a PAM-4 modulation scheme. The eye diagrams and histograms assess the quality of the transmission and allows determining a BER of 7.5×10^{-3} and 3.6×10^{-2} for the OOK signal and for the PAM-4 signal, respectively. These BERs are compatible with conventional error codes correction, which means that the transmission can be considered error-free provided that correction is implemented. The aforementioned eye diagrams and histograms were obtained using conventional pre- and post-processing. More precisely on the emitter side, PAM-4 electrical signal were pre-shaped by a digital Root-Raised-Cosine (RRC) filter to reduce the spectral bandwidth of the signal to be transmitted, in order to accommodate the limited bandwidth of our system. On the receiver side, we apply a 31-tap and 401-tap feed forward equalization for OOK and PAM-4 schemes, respectively.

Overall, we unveiled the potential of unipolar quantum technology for high-speed communication in the mostly uncharted long-wave infrared domain that is of utter interest for free-space propagation. This breakthrough paves the way for novel telecom systems and real-field deployment.

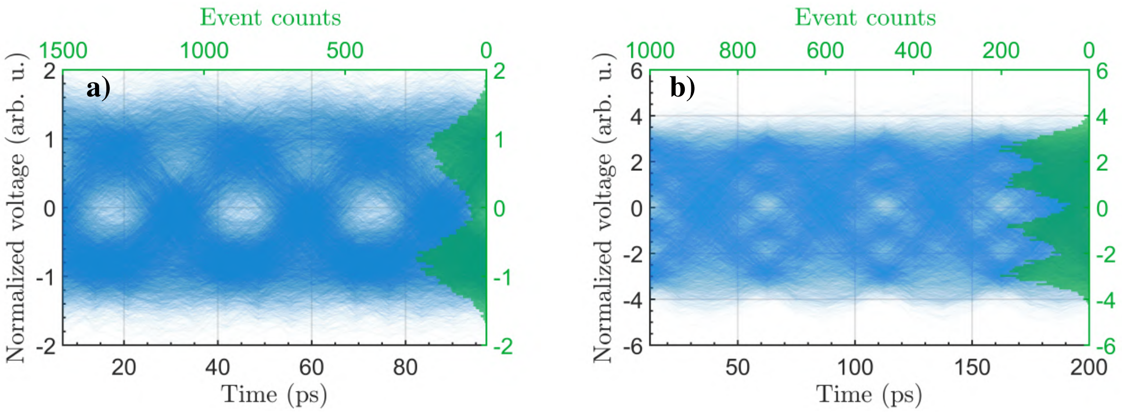

Fig. 2: Characteristics of the transmission after a free-space propagation of 31 meters for two different modulation formats. a) OOK format at 30 Gbaud exhibiting an error rate of 7.5×10^{-3}. b) PAM-4 format at 20 Gbaud exhibiting an error rate of 3.6×10^{-2}. In both cases, the blue diagrams show open eyes, with residual errors that could be corrected, and the green diagrams highlight the 2-level or 4-level intensity pattern, respectively.

References

1. Flannigan, L., et al., *Journal of Optics* 24, 043003 (2022).
2. Martini, R., et al., *Electronics Letters* 37, 1290–1292 (2001).
3. Pang, X., et al., *physica status solidi (a)* 218, 2000407 (2021).
4. Li, T., et al., *Photonics Research* 7, 828–836 (2019).
5. Montesinos-Ballester, M., et al., *ACS Photonics* 9, 249–255 (2022).
6. Dely, H., et al., *Laser & Photonics Reviews* 16, 2100414 (2022).

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