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1.2-Gbit/s Data-Rate Free-Space Optical Communications with Terahertz Laser

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Abstract—Terahertz quantum cascade lasers offer promising capabilities for free-space optical communication, bridging the gap between microwave electronics and optical fiber technologies. We report the first experimental demonstration of free-space optical communication at terahertz frequencies, utilizing a quantum cascade laser transmitter and a room temperature Schottky barrier diode receiver at 1.2 Gbit/s data rate. We achieve reliable data transmission over a 0.5 m free-space distance, with bit error rates dropping below the hard-decision forward error correction threshold (3.8×10^{-3}) as the received optical power increases. This gigabit-scale communication link highlights the potential of THz photonic devices for high-speed, short-range wireless communications in 6G and beyond.

I. INTRODUCTION

Next-generation 6G networks demand data rates in the range of hundreds of gigabits to terabits per second, far exceeding current wireless capacities [1]. Pushing carrier frequencies into the THz band (0.1–10 THz) offers unprecedented channel bandwidths and promises to meet these extreme data rate requirements. In contrast to traditional diode lasers, terahertz quantum cascade lasers (THz QCLs) operate based on band-to-band electron transitions. These QCLs utilize specially designed quantum well structures to facilitate intersubband transitions, where electrons move through a sequence of wells, emitting a photon with each transition. This design enables QCLs to be tailored for nearly any wavelength, spanning from the mid-infrared to the THz range. THz QCLs exhibit intrinsically fast carrier dynamics, allowing direct modulation at multi-GHz speeds in free-space optical (FSO) links, bridging the gap between microwave electronics and optical fiber systems. The sub-THz range (0.3–0.6 THz) spectral region is accessible using electronics-based devices, and various wireless communication links have been demonstrated [2], [3]. For instance, a wireless link at 237.5 GHz (sub-THz) has achieved 100 Gb/s over 20 m using photonic generation and mm-wave electronics [3]. However, extending wireless communications >1 THz has been challenging due to the lack of compact, high-power sources and fast detectors operating at ambient conditions. Significant work has been invested in sources, modulators, and receivers within this frequency band, improving output power, modulation bandwidth, and detector sensitivity. Recent reviews of these devices can be found in references [4]. Despite these technological advancements, QCL-based FSO systems have remained constrained to low

data rates. The fastest THz FSO system so far reached a data rate of 20 Mbit/s using a cryogenically cooled quantum well detector [5]. A more recent FSO system that utilizes a cryocooler for QCL operation and a room-temperature graphene-based receiver offers a data rate of 1 Mbit/s [6]. Nevertheless, establishing a THz FSO communication link with higher data rates continues to be a significant goal.

In this work, we demonstrate a THz FSO communication link using non-return-to-zero on-off-keying (NRZ-OOK) format with a data rate of 1.2-Gbit/s utilizing a 2.4 THz QCL transmitter and a room-temperature Schottky barrier diode as a receiver over a transmission distance of 0.5 m. This work demonstrates Gbit/s data transmission, offering a promising solution for next-generation communication networks.

II. RESULTS

Fig. 1 shows the experimental setup. A 2.4 THz QCL enabled an FSO link to transmit digital data at 1.2-Gbit/s. The THz QCL was biased at 300 mA and produced an optical power of $75 \mu\text{W}$. The QCL was modulated by an NRZ-OOK electrical data signal using a high-speed bias-tee and a Schottky barrier diode that acts as a direct detector to demodulate the received signal.

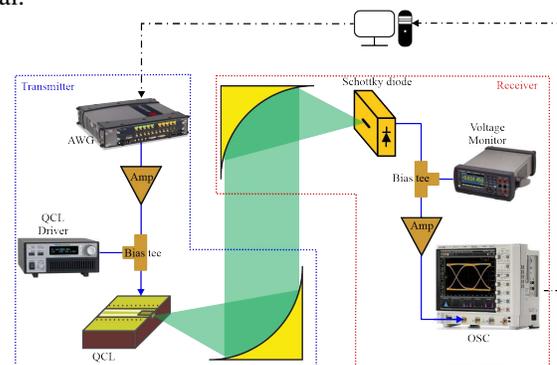


Fig 1. Experimental arrangements of THz FSO communication system includes a transmitter (blue box) with an arbitrary waveform generator for NRZ-OOK signal generation, an RF amplifier, and a QCL via a bias-tee, plus a 90° parabolic mirror for beam collimation. The modulated THz signal travels to the receiver (red box), focusing on a Schottky barrier diode for detection. The demodulated signal passes through another bias-tee and a low-noise amplifier, recorded on an oscilloscope for digital sampling and offline evaluation performance.

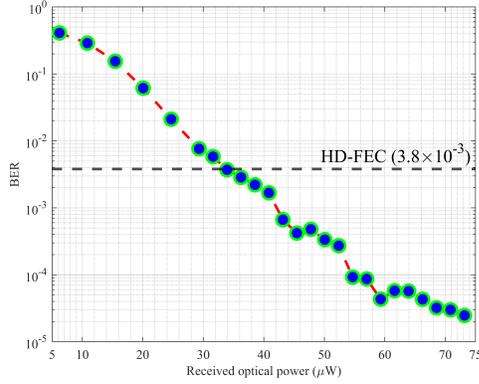


Fig 2. BER as a function of ROP for NRZ-OOK signals transmitted at 1.2-Gbit/s.

Fig. 2 shows the measured BER obtained by offline processing of the real-time oscilloscope (OSC) samples lasting 2 ms, as a function of received optical power (ROP). The BER was calculated using the direct error counting method for a total of 1.44×10^6 bits. The ROP was varied using a pair of crossed polarizers to attenuate the signal. The value of ROP is obtained by relating the QCL absolute power to the voltage values monitored at the DC voltage port of the receiver bias-tee. The HD-FEC limit, indicated by the dashed horizontal line at a BER of 3.8×10^{-3} , represents the threshold below which reliable data transmission can be ensured with the 7% overhead FEC. The BER decreases as the ROP increases.

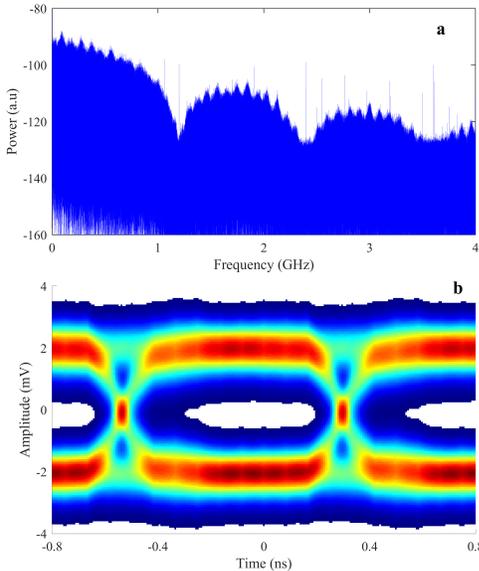


Fig 3. (a) Power spectrum of the demodulated signal. (b) The eye diagram is plotted across the bit interval, capturing the temporal characteristics of the transmitted data stream and received signal amplitude, indicating the levels of the “0” and “1” bits.

The system achieves a BER below 3.8×10^{-3} at a received power of approximately $34 \mu\text{W}$. When ROP exceeds $54 \mu\text{W}$, BER significantly improves, dropping well below 1×10^{-4} .

This highlights the importance of demonstrating excellent transmission performance and highlighting the critical role of adequate ROP for high-quality data transmission in THz free-space links. Fig. 3a. displays the power spectrum of the demodulated signal captured by an electrical spectrum analyzer at $75 \mu\text{W}$ ROP. The minima in the spectrum at 1.2, 2.4 and 3.6 GHz are the most significant features indicating NRZ-OOK modulation of 1.2 Gbit/s (1.2 Gbaud/s) of operation. The sharp peaks at 1.2, 2.4, and 3.6 GHz reflect distortion in the received signal. The broad peaks between the minima decrease in optical power as a function of frequency, reflecting the pulse shape. From the power spectrum of the demodulated signal, we can validate the reliability of the THz FSO communication system despite the low optical power of $75 \mu\text{W}$ from the QCL, which is sufficient for good signal reception. Fig. 3b displays the eye diagram of the received signal. A total of 2×10^7 symbols were used to plot the eye diagram over a 2 ms time span of the received signal without any filtering process. The diagram exhibits a clear eye with well-defined transitions between “0” and “1” bits, indicating minimal distortion and inter-symbol interference. The eye pattern demonstrates the system’s ability to maintain timing precision and amplitude integrity over the free-space transmission path. These figures clearly demonstrate that the NRZ-OOK modulation format at 1.2-Gbit/s is highly effective for short-range THz communication systems, provided the ROP is sufficiently high to maintain an acceptable BER below the HD-FEC limit.

III. SUMMARY

We experimentally demonstrate a 1.2-Gbit/s free-space optical communication link using a 2.4 THz QCL transmitter and a room temperature Schottky barrier diode receiver, constituting the first gigabit demonstration with a THz QCL. The system achieved reliable data transmission with BER performance reaching below 3.8×10^{-3} for the ROP above $34 \mu\text{W}$. The THz QCL-based FSO communication represents an exciting frontier bridging photonics and wireless technology. Further data on multi-Gbit/s data transmission and optimization of the THz communications link will be presented.

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