Free-Space Transmissions in the Upper- and Lower-THz Bands Assisted with Photonics

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Abstract *We report our recent studies in photonics-assisted free-space transmissions in both the lower- (0.3-0.5 THz) and upper- (~64.5 THz) terahertz bands. We adopt the hybrid electro-optical approach for the lower-THz signal transmission, whereas a directly modulated quantum cascade laser is used for the upper-THz band.*

Introduction

Nowadays, many prominent aspects of large-scale digitalization, such as the Internet of Things (IoT), autonomous vehicles, and augmented reality (AR), have already started and will continue to reshape society. Such digital transformation has been speeded up by the current COVID-19 pandemic, primarily coped with by virtual services like distance working and social activities. However, today's wireless communication technologies, which play an essential role in this transformation, are limited by insufficient spectral resources to continuously support the increasing demand for data in the Beyond 5G (B5G) and 6G era. A vision to unlock such a limit is to have a unified electromagnetic (EM) spectral resource pool, composing both optics and radio frequency (RF) bands, available to be allocated for all types of wireless services. Currently, transmission technologies' research and development status in different spectral bands are in different maturity levels. Particularly, wireless communication technologies in the terahertz (THz) region, which connects the radio and optics, are underexploited[1]. The THz region can be loosely categorized into the lower- (<10 THz) and upper-THz (>10 THz) bands. The former has properties like radio waves, and the latter is closer to optics. There have been many experimental demonstrations with over 100 Gbps transmissions in the lower-THz band, most of them based on the hybrid electro-optic approach [2-14]. On the other hand, transmission experiments in the upper-THz band, which is largely overlapped with the mid- and far-infrared region in its definition, support relatively lower data rates so far, yet have shown immense potential. Different methods, including both nonlinear wavelength conversion [15,16] and directly modulated quantum cascade lasers (QCLs) [17-22], are proposed and demonstrated.
This report summarizes our recent experimental studies in both frequency bands and discusses future challenges and directions.

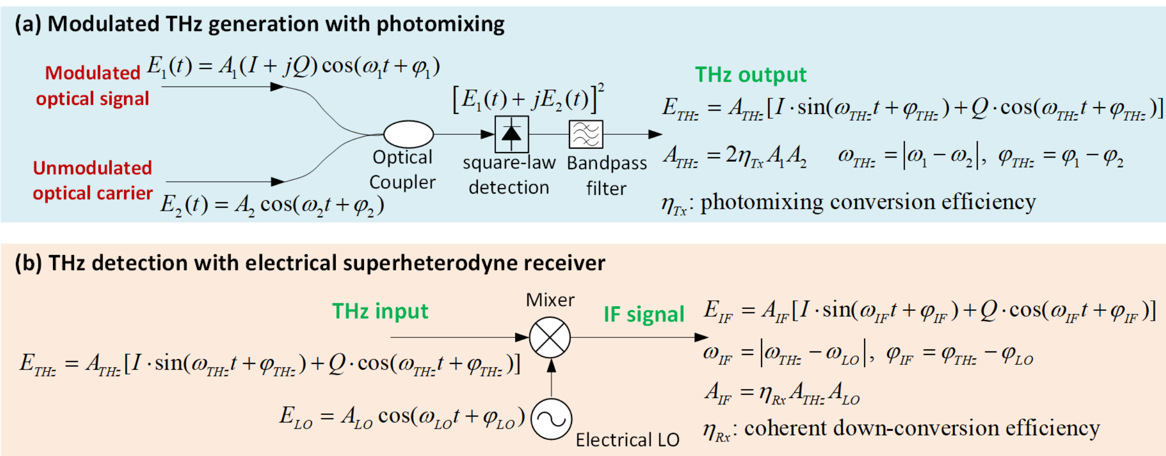

Fig. 1: Principles of (a) photomixing with square-law detection which "transparently" converts the phase and amplitude modulation from optical carrier to THz carrier, and (b) the coherent THz detection with electrical superheterodyne receiver.

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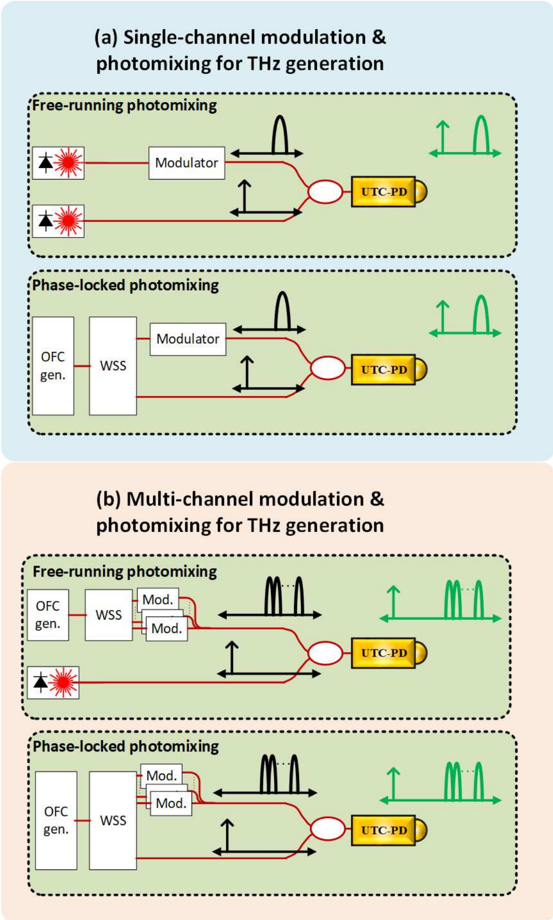

Fig. 2: Illustration of the modulated THz generation schemes with free-running and phase-locked photomixing in (a) single-channel and (b) multi-channel configurations. OFC: optical frequency comb; WSS: wavelength selective switch; UTC-PD: uni-traveling carrier-photodiode.

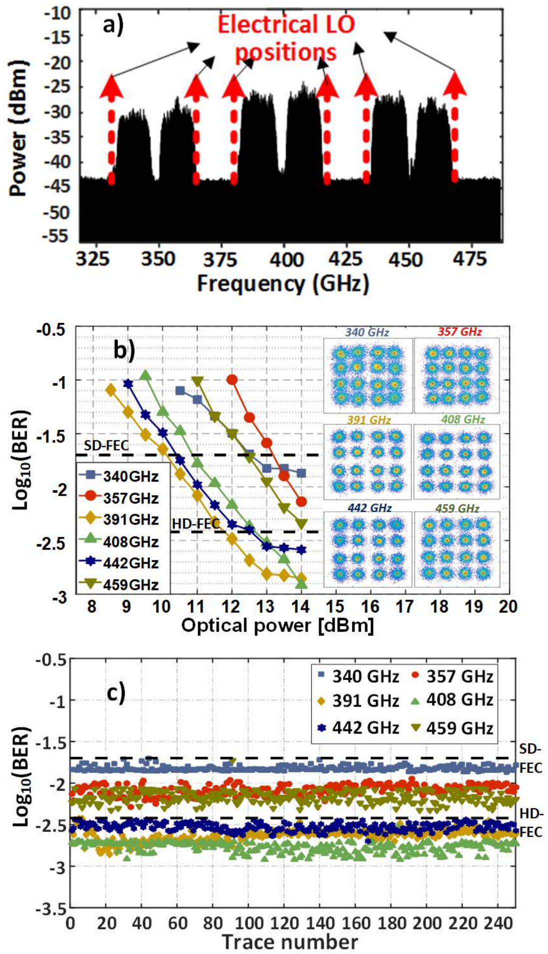

Fig. 3: Selected experimental results of a 6-channel transmission at the 0.3-0.5 THz band, resulting a total aggregation data rate of 300 Gbps. (a) Up-converted signal spectrum. (b) BER results and the constellation diagrams for all channels. (c) System stability test results.

High-speed transmissions in the 0.3-0.5THz bands with hybrid electro-optical methods

Figure 1 shows the principle of the hybrid electro-optical THz transmission system with heterodyne photomixing THz generation and all-electrical coherent THz detection. One can see from the short equations shown in the figure that the phase and amplitude modulation of the optical signal can be "transparently" converted to THz even through the nonlinear photomixing process and eventually preserved in the intermediate frequency (IF) signal after coherent down-conversion with a superheterodyne receiver. Based on this principle, we have recently carried out a series of high data rate transmission experiments with both free-running and phase-locked optical sources[8-14]. A few typical experimental configuration examples for the THz transmitters are collectively illustrated in Fig. 2, including generation of both single- and multi-frequency channels. A key semiconductor component to enable this scheme is a high bandwidth uni-traveling-carrier photodiode (UTC-PD)[23]. So far, we have explored different system dimensions, including achievable data rate and transmission distance, among others. Figure 3 shows some selected results from a multi-channel THz transmission demonstration as an example[10]. In this experiment, six optical channels in the C-band, each modulated with a 12.5 Gbaud 16-ary quadrature amplitude modulation (16QAM) signal, are simultaneously photomixed with a free-running optical carrier and successfully delivered from the THz emitter to the THz receiver over a 50-cm free-space link. An aggregated raw data rate of 300 Gbps and net data rate of 260 Gbps after subtracting the corresponding FEC overheads were demonstrated with high stability in the lab environment.

Multi-gigabit transmissions with a directly modulated QCL at room temperature

Figure 4 shows the experimental summary of free-space transmissions with a directly modulated QCL at 4.65 μm (64.5 THz). The QCL

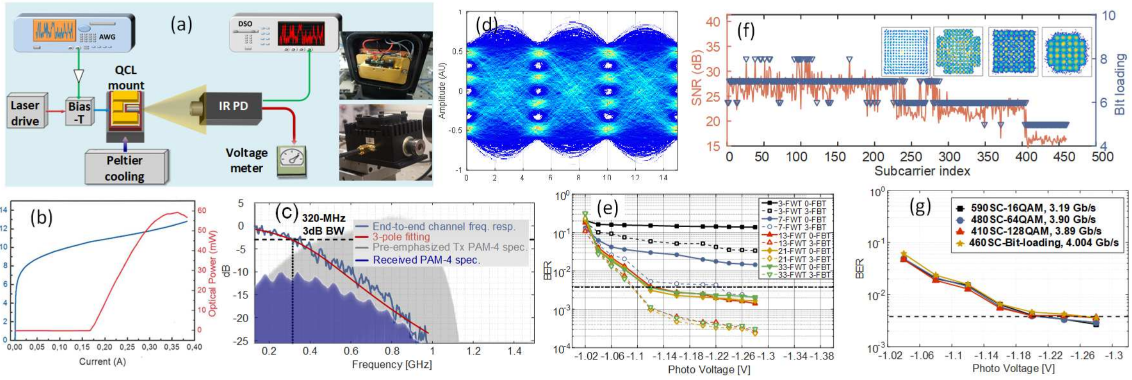

Fig. 4: (a) Experimental setup of 4 Gbps free-space transmission with directly modulated QCL at 65 THz. (b) P-I-V curve of the QCL. (c) End-to-end S21 response and equalized signal spectrum before and after transmission. (d) Eye diagram of the equalized 2 Gbaud PAM4 signal. (e) BER performance of 2 Gbaud PAM4. (f) SNR and bit-loading configuration of 4 Gbps DMT signal. (g) BER performance of DMT signals at various bit rates.

chip used in the experiment was fabricated by mirSense, which is a distributed feedback (DFB) laser model[24]. The P-I-V curve of the QCL is shown in Fig.4(b). An optimal linear modulation point was found around 250 mA, at which the QCL output power was around 30 mW. The receiver is a commercial mercury cadmium telluride (MCT) photovoltaic (PV) detector with a built-in trans-impedance amplifier (TIA). The 3-dB end-to-end system bandwidth was around 320 MHz, and strong pre-emphasis was found to be effective for single carrier pulse amplitude modulation (PAM) signals, as shown in Fig.4(c). The equalized eye diagram and the BER performance of 4 Gbps PAM4 signal transmission are shown in Fig.4(d) and (e), respectively. One can see that the 7%-OH HD-FEC limit can be well achieved assisted with pre- and post-digital equalizations. Similarly, around 4 Gbps free-space transmission with discrete multi-tone (DMT) signals were also demonstrated with effective bit- and power-loading, as shown in Fig.4(f) and (g). It is noted that the lack of beam collimation was found to be the limiting factor for both link distance (5 cm) and receiver signal-to-noise ratio (SNR) in this demonstration.

Challenges and outlook

Currently, for the hybrid electro-optical scheme in the lower-THz band, despite its capability to support ultrabroadband data transmission, achieving high power and high wall-plug efficiency are major challenges, compared with the CMOS and BiCMOS all-electronic solutions [25-27]. Therefore, besides continuing the research efforts towards fundamental breakthroughs in materials and devices, a possible way forward in the short term is to explore transceiver miniaturization through photonic integration.

For the upper-THz band, the main challenge on the transmitter side is to achieve higher-bandwidth modulation with a high extinction ratio and low chirp, which may be tackled by designing and developing novel broadband modulators operating in this frequency region. High-speed detectors have been reported on the receiver side[28,29], and the next phase target is to characterize their performance in high-speed free-space transmission systems.

Both frequency bands are expected to support non-line-of-sight (NLOS) scenarios and be capable of multi-dimensional multiplexing[30]. These requirements translate into the need for developing active/passive components such as transmissive/reflective beamformers, frequency multiplexer/demultiplexers, among others.

Finally, the two frequency bands that we chose for experimental demonstrations are far apart. Therefore, further research efforts to identify suitable technology options to bridge the gap are necessary to realize the envisioned wireless communication paradigm with a unified EM resource pool.

Conclusions

We summarize our recent transmission studies in two frequency bands around the THz region. In the 0.3-0.5 THz band, ultrabroadband signal generation can be realized with the hybrid electro-optical approach, whereas at 65 THz, DM QCLs appear promising. We believe that our demonstrations in both frequency bands are still far below their physical limits. Thus, further research and development efforts can be rewarding in the coming decade.

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