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Published in:
IEEE Transactions on Terahertz Science and Technology

Link to article, DOI:
10.1109/TTHZ.2016.2599077

Publication date:
2016

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

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400-GHz Wireless Transmission of 60-Gb/s Nyquist-QPSK Signals Using UTC-PD and Heterodyne Mixer

Xianbin Yu, Senior Member, IEEE, Rameez Asif, Molly Piels, Darko Zibar, Michael Galili, Toshio Morioka, Peter U. Jepsen, and Leif K. Oxenløwe

Abstract—We experimentally demonstrate an optical network compatible high-speed optoelectronics THz wireless transmission system operating at 400-GHz band. In the experiment, optical Nyquist quadrature phase-shift keying signals in a 12.5-GHz ultradense wavelength-division multiplexing grid is converted to the THz wireless radiation by photomixing in an antenna integrated unitravelling photodiode. The photomixing is transparent to optical modulation formats. We also demonstrate in the experiment the scalability of our system by applying single to four channels, as well as mixed three channels. Wireless transmission of a capacity of 60 Gb/s for four channels (15 Gb/s per channel) at 400-GHz band is successfully achieved, which pushes the data rates enabled by optoelectronics approach beyond the envelope in the frequency range above 300 GHz. Besides those, this study also validates the potential of bridging next generation 100 Gigabit Ethernet wired data stream for very high data rate indoor applications.

Index Terms—Photomixing, THz photonics, THz wireless communication, ultradense wavelength-division multiplexing (UD-WDM), unitravelling carrier photodiode (UTC-PD).

I. INTRODUCTION

OPTICAL fiber communication technologies have enabled spectrally efficient high data rates in the wired networks, and 100- and 400-GbE links will be soon deployed in the backbone by telecommunication service providers [1]. In comparison, wireless data rates grow even faster and are quickly approaching 100 Gb/s [2], particularly driven by an increasing demand for high bit-rate wireless services, such as wireless access of rich content media, wireless transmission of ultra high definition video (UHD), wireless download of large volume data, etc. Fig. 1 illustrates some potential application scenarios of high-speed photonic-wireless communication technologies, typically in the population-intensive, and, hence, data-intensive areas. For instance, future E-health systems transporting large volume of reliable medical data would be one of the scenarios. Beside those, newly emerging ultrafast wireless applications, e.g., superfast wireless downloading and supercomputing, superfast board-to-board interconnecting, and superfast wireless smart home [see Fig. 1(b)] are also driving wireless techniques towards extremely high speed beyond 100 Gb/s. As an example, transmission of uncompressed UHD requires up to 80-Gb/s data rate. Supporting such fast wireless data rates would definitely require very large radio frequency (RF) bandwidth, the radiation spectrum naturally falls into the THz (0.3–10 THz) range. Therefore, there has been an increasing interest in exploring THz frequencies for accommodating bandwidth-hungry high-speed wireless communications.

We summarize up-to-date research efforts on the progress of high-speed THz wireless communication systems [3]–[28], as shown in Fig. 2. In the footprint map, RF carrier frequencies have been increased from W-band (75–110 GHz) till 600 GHz,
in order to explore more available bandwidth in higher frequency bands for carrying high-speed information. There are two main approaches adopted to develop these THz wireless communication systems: all-electronics approach employing electronic devices for both THz emitter and receiver [10]–[16] and optoelectronics approach based on photonic generation of high-speed THz signals. We can see that the optoelectronics approach has made significant contributions on delivering very high data rates, particularly above 10 Gb/s. So far the highest single-transmitter bit rate of 100 Gb/s has been achieved at the W-band [8] and 237 GHz [13], and maximum 64 Gb/s based on all-electronics approach [25] and 50 Gb/s based on optoelectronics approach [26] in the frequency range of 300–400 GHz and above have been reported.

In this paper, we experimentally demonstrate an optoelectronics THz wireless communication system operating at 400-GHz band, and carrying scalable data rates derived from optical signals in a 12.5-GHz ultradense wavelength-division multiplexing (UD-WDM) grid. THz carriers are generated by heterodyne photomixing of free-running optical sources. This photonic generation of millimeter wave and THz signals is transparent to photomixing emitter, due to its extremely fast photoresponse [30]. Before launching into the UTC-PD, the optical signals are polarized to minimize the polarization dependence of the UTC-PD. In the wireless domain, we use a pair of THz lens with 25-dBi gain, effective focal length of 54 mm, and diameter of 37 mm to collimate the THz beam for free-space transmission. The first lens collects the THz emission from the UTC-PD and collimates it into a parallel beam, and the second lens focuses the parallel THz beam onto a THz diagonal horn antenna.

In the receiver, a THz mixer operating in the frequency range of 325–500 GHz (Virginia Diodes) is used to down convert the received THz signal into intermediate frequency (IF) range. The mixer is driven by a 12-time frequency multiplied 31–36 GHz electrical LO signal and has 22-dB conversion loss. The IF output is amplified by a chain of electrical amplifier with 6-dB gain, effective focal length of 54 mm, and diameter of 37 mm to collimate the THz beam for free-space transmission. The first mixer is driven by a 1-nm optical filter for suppressing out-of-band noise, and then coupled with an optical local oscillator (LO) with 100-kHz linewidth for heterodyne generation of THz signals. In this experiment, a single channel is generated by simply switching on one CW laser, but keeping the others off. In our experiment, a commercially available broadband bow-tie antenna integrated unitravelling photodiode (UTC-PD) from Nippon Telegraph and Telephone Electronics (NTT-Electronics) is used as THz photomixing emitter, due to its extremely fast photoresponse [30].

In the wireless domain, we use a pair of THz lens with 25-dBi gain, effective focal length of 54 mm, and diameter of 37 mm to collimate the THz beam for free-space transmission. The first lens collects the THz emission from the UTC-PD and collimates it into a parallel beam, and the second lens focuses the parallel THz beam onto a THz diagonal horn antenna.

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III. RESULTS AND DISCUSSIONS

In the experiment, the THz wireless propagation distance is fixed at 50 cm, and the path loss is less than 2 dB when the THz beam is collimated by the THz lenses. When the incident total optical power to the UTC-PD (equal power for the baseband and the optical LO) is 13 dBm, THz emission power is estimated as −21 dBm by using a Pyroelectric THz power meter. After the electrical heterodyne at the receiver mixer, the IF channels are individually down converted into the 20-GHz band. This IF signal is measured using the real-time scope and real-time processed by digital signal processing (DSP) algorithms in the vector signal analyzer software employed [31]. The embedded...
real-time DSP algorithms include frequency down conversion (second heterodyne detection), bandpass filtering, I-Q separation, carrier recovery, synchronization, equalization, data recovery, and bit error rate (BER) estimation, similar as a real-time coherent receiver. Here, the BER is evaluated from the error-vector magnitude of the processed constellations.

The link budget of such a THz wireless communication system can be usually calculated by the Friis formula [32]

\[
PR_x = PT_x + GT_x + GR_x - L_{\text{Free-space}}.
\]

Here, \(PR_x\) is the received power and \(PT_x\) the transmitted power in dBm, \(GT_x\) and \(GR_x\) are the gains of transmitter and receiver in dBi respectively, and \(L_{\text{Free-space}}\) represents the free space path loss in dB. In this case, the signal-to-noise ratio (SNR) for a channel with a bandwidth of \(B\) can be expressed as [33]

\[
\text{SNR} = \frac{PR_x}{kTB \cdot N_f}.
\]

where \(k\) is the Boltzmann constant, \(T\) is the temperature, and \(N_f\) is the receiver noise figure denoting additional noise in a nonideal receiver. From (2), it is obvious that a narrower bandwidth \(B\) (lower baud rate) naturally results in a larger SNR.

In our system, besides two antennas for the transmitter and receiver, gain of two THz lenses in the free-space propagation path is also taken into account. The estimation of link budget is illustrated in Table I. We can see the employment of 50-GHz bandwidth makes 400-GHz wireless transmission of QPSK modulation with high data rates possible in such a system. In this context, we first measure the overall system frequency response in the 370–460-GHz band, as shown in Fig. 4.

We measure the BER performance for both single-channel and multichannel THz wireless transmission in the experiment. Different cases are experimentally demonstrated for the multichannel, including three channel and four channel, as well as line rate mixed three channel. Fig. 5 shows the BER performance for both single-channel and multichannel 400-GHz wireless transmission.
performance of single THz channel at different baud rates. The THz carrier generated from the photomixing of two CW wavelengths is 403 GHz (see optical spectrum in Fig. 5(a)). While keeping the optical power to the UTC-PD constant at 14 dBm, error-free (at BER of $10^{-9}$) QPSK operation can be achieved at 5 Gbaud, and performance below the forward error correction (FEC, corresponding to a BER of $2 \times 10^{-3}$ with 7% overhead) at 18 Gbaud, as shown in Fig. 5(c). Higher baud rate results in more closed eye diagrams, and examples of constellation diagrams are also given in Fig. 5(c) for 7.5- to 17.5-Gbaud Nyquist QPSK signals. Fig. 5(b) displays the measured BER performance of a single THz channel versus optical power for 5 to 17.5 Gbaud. The photocurrent generated in the UTC-PD is proportional to the input optical power, and the THz emission power is proportional to the square of photocurrent, so a lower SNR is encountered at higher baud rates. BER below the FEC can be achieved for all cases here, while with a penalty at higher rates, i.e., at 10 and 10.7 dBm for 7.5 and 10 Gbaud, respectively.

Fig. 6 depicts the measured performance for three THz channels with 5-, 7.5-, and 10-Gbaud line rates. In this measurement, three 12.5 GHz-spaced carrier frequencies are 390.5, 403, and 415.5 GHz. From the optical spectra in Fig. 6(a), we can observe the optical SNR degradation when increasing the applied symbol rates, due to constant output power from the EDFA. The measured optical and electrical spectra are shown in Fig. 6(a) and (b). In this case, the four carrier frequencies after photomixing are 390.5, 403, 415.5, and 428 GHz, respectively. From the BER results in Fig. 8(c), we can see performance below the FEC is achieved for all four channels, with similar performance for channels 1, 2, and 3. Compared to the three-channel BER performance at 7.5 Gbaud presented in Fig. 6(b), there is an approximately 2.5-dB receiver penalty caused by SNR degradation when the shared EDFA output power is constant. Similarly,
frequency-dependent response of the THz mixer causes 0.5-dB penalty between the 4th-channel and others.

IV. CONCLUSION

We have successfully demonstrated a high-speed 400 GHz photonic wireless communication system with an aggregated data rate of up to 60 Gb/s. This pushes the data rate envelope enabled by optoelectronics approach at frequencies above 300 GHz. To further extend the wireless coverage of such a system, enhancement of THz link budget from the device level will be highly appreciated, specifically improvement of photodiode responsivity and receiver sensitivity, as well as development of THz amplifiers and very high-gain THz antennas. This optoelectronics scheme is fully compatible with WDM optical networks by simply inserting an additional optical heterodyne wavelength with improved spectral efficiency," IEEE Trans. Microw. Theory Tech., vol. 55, no. 12, pp. 2813–2821, Dec. 2007.


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Dr. Yu held a Marie Curie Fellowship within the 7th European Community Framework Program (2009–2011).

Rameez Asif, photograph and biography not available at the time of publication.

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