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Abstract— **We experimentally demonstrate a 400 GHz carrier wireless transmission system with real-time capable detection and demonstrate transmission of a 60 Gbit/s signal derived from optical Nyquist channels in a 12.5 GHz ultra-dense wavelength division multiplexing (UD-WDM) grid and carrying QPSK modulation. This is the highest data rate demonstrated for carrier frequencies above 300 GHz and also validates the feasibility of bridging between next generation 100 GbE wired data streams and indoor wireless applications.**

Keywords— THz photonics, THz wireless communication, ultra-dense WDM, uni-travelling carrier photodiode.

I. INTRODUCTION

Optical fiber communication technologies have enabled spectrally efficient high data rates in wired networks, and 100 GbE and 400 GbE links will soon be deployed in the backbone by telecommunication service providers [1]. In comparison, wireless data rates grow even faster and are quickly approaching 100 Gbit/s [2], particularly driven by an increasing demand for high bit-rate wireless services, such as 5G and beyond, wireless access content-rich media, wireless transmission of ultrahigh definition video, wireless download of large volume data, and so on. Supporting such fast wireless data rates at tens of Gbit/s and eventually beyond 100 Gbit/s, would require very large radio frequency (RF) bandwidth, and the radiation spectrum naturally falls into the THz (0.1-10THz) range. Therefore, there has been an increasing interest in exploring THz frequencies for accommodating bandwidth-hungry high-speed wireless communications.

Figure 1 summarizes the up-to-date research efforts on the progress of high-speed THz wireless communication systems [3]-[19]. Carrier frequencies have been increased from W-band (75-110 GHz) to 600 GHz, attempting to explore more available frequency bandwidth. So far the highest single-transmitter bit rates of 100 Gbit/s has been demonstrated at 100 GHz [8] and 237 GHz [13], but only tens of Gbit/s and a few Gbit/s in the frequency range of 300-400 GHz and above have been reported. In addition, although off-line digital signal processing (DSP) is advantageous in investigating those very high data-rate communication systems, real time detection for instant information exchange with negligible latency, is necessary for implementing practical telecommunication systems.
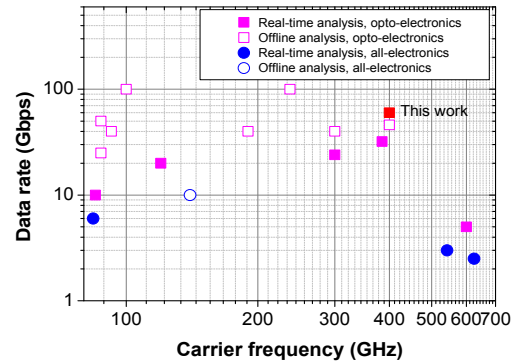

Fig. 1. State-of-the-art of data rate per antenna vs carrier frequency in the range of 100-700 GHz.

In this paper, we experimentally demonstrate a real-time capable THz wireless communication system operating on a 400 GHz carrier frequency, and carrying up to 60 Gbit/s Nyquist-QPSK data derived from four optical signals in a 12.5 GHz ultra-dense wavelength-division-multiplexing (UD-WDM) grid. The THz carriers are generated by heterodyne photo-mixing of free-running optical sources. This photonic generation method is transparent to modulation formats used in existing WDM optical networks. To demonstrate this compatibility of our system with advanced modulation formats, spectrally efficient optical Nyquist channels with quadrature phase shift keying (QPSK) data, planned for commercial 100 GbE [20] is employed in this demonstration experiment. Real-time heterodyne down conversion [21] at the receiver side is used to demodulate the signals after wireless propagation. To the best of our knowledge, THz wireless transmission of 60 Gbit/s data is so far the highest in the frequency range above 300 GHz. This work not only pushes data rates beyond the envelope of state-of-the art, but also paves the way to deploy THz wireless communication for very high data rate indoor radio applications.

II. EXPERIMENTAL SETUP

The experimental system is shown in Fig. 2. We create a four-channel QPSK optical signal by employing a continuous-wave (CW) laser array. In order to decorrelate neighboring channels, 25 GHz-spaced even-order and odd-order
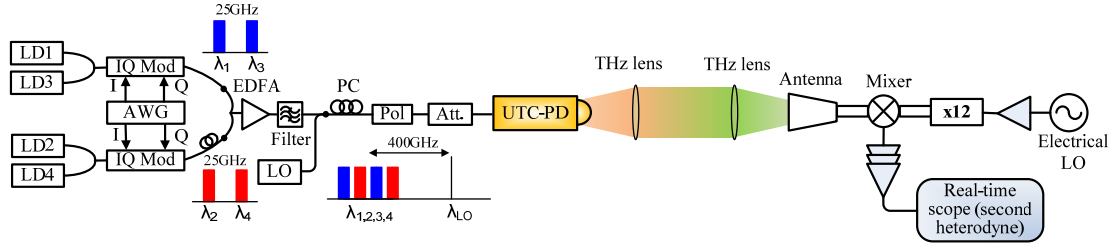
Fig. 2. (a) Experimental setup. LD: laser diode, AWG: arbitrary waveform generator, Pol: polarizer, Att.: attenuator, LO: local oscillator.

wavelengths are separately modulated by in-phase (I) and quadrature (Q) baseband signals from an arbitrary waveform generator (AWG), and a fiber-based delay line is used. Nyquist pulse shaping is electrically performed by applying a square root raised cosine filter with 0.1 roll-off factor in the AWG, and the data sequence has a PRBS length of 2^7-1. Interleaving the WDM channels creates a four-channel data stream in a 12.5 GHz UD-WDM grid. Subsequently, all the optical channels with baseband modulation are boosted by an Erbium-doped fiber amplifier (EDFA), filtered by a 1 nm optical filter for suppressing out-of-band noise, and then coupled with an optical local oscillator (LO) 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 uni-travelling-carrier photodiode (UTC-PD) is used as a THz photo-mixing emitter, due to its extremely fast photo-response [22][23]. Before launching into the UTC-PD, the optical signals are polarized to minimize the polarization dependency of the UTC-PD. In the wireless domain, we use a pair of THz lenses with 25 dBi gain to collimate the THz beam for 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.

At the receiver side, a 12-order harmonic THz mixer operating in the frequency range of 325-500 GHz is used to down-convert the received THz signal into an intermediate frequency (IF). The mixer is driven by a 31-36 GHz electrical LO signal and has 22 dB conversion loss. The IF output is amplified by a chain of electrical amplifiers with 68 dB gain, and then measured and demodulated with a real time sampling scope (63 GHz Keysight DSOZ634A Infiniium).

III. EXPERIMENTAL 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 optical power (equal power for the baseband and the optical LO) is 13 dBm, the THz emission power is estimated as -21 dBm. 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 a real-time scope and DSP processing in the vector signal analyzer software (VSA) is employed. The embedded DSP algorithms include frequency down-conversion (second heterodyne detection), I-Q separation, carrier recovery, synchronization,

equalization, data recovery, and bit error rate (BER) estimation, similar to a real-time coherent receiver. Here, the BER is evaluated from the error-vector magnitude (EVM) of the processed constellations.

We measure the performance for both single channel and 4-channel THz wireless transmission. Fig. 3 shows the BER performance of a single THz channel at different baud rates. The THz carrier generated from the photo-mixing of two CW wavelengths is 403 GHz (see optical spectrum in Fig.3(a)). While keeping the optical power to the UTC-PD constant at 14 dBm, we see error-free (BER<1e-9) QPSK operation achieved at 5 Gbaud, and performance below the forward error correction (FEC, 2e-3 with 7% overhead) at 18 Gbaud. The increasing the baud rate results in more closed eye-diagrams. Examples of constellation diagrams are given in Fig. 3(c) for 7.5 Gbaud to 17.5 Gbaud QPSK. Fig.3(b) displays the measured BER performance of a single THz channel vs optical power at 7.5 Gbaud and 10 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 the photocurrent, so a lower signal-to-noise ratio is encountered at higher symbol rates. BER below the FEC limit can be achieved at 10 dBm and 10.7 dBm for 7.5 Gbaud and 10 Gbaud, respectively, i.e. with a penalty at higher rates.
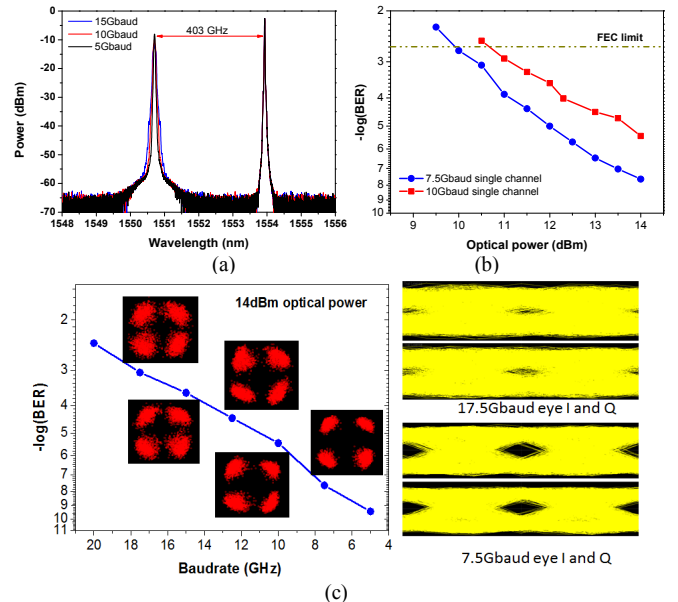

(a)

(b)

(c)

Fig. 3. (a) Optical spectra of single THz channel at different baud rates. (b) BER performance of single THz channel at 7.5 Gbaud and 10 Gbaud, (c) BER performance of single THz channel vs symbol rate. Right: I-Q eye-diagram for 17.5 Gbaud and 7.5 Gbaud rates.

Multi-channel THz performance is shown in Fig. 4. In the experiment, we generate four channels with 12.5 GHz wavelength spacing. All channels are modulated with 7.5 Gbaud Nyquist QPSK baseband data. The optical and electrical spectra are shown in Fig.4 (a) and (b). The four carrier frequencies after photo-mixing are 390.5GHz, 403GHz, 415.5GHz and 428GHz, respectively. From the BER results in Fig.4(c), we can see performance below the FEC limit is achieved for all channels, with channels 1, 2 and 3 with similar performance. Compared to single channel BER performance at 7.5 Gbaud, there is an approximately 5 dB receiver penalty caused by SNR degradation, as the four channels share the EDFA output power, which is constant. Channel 4 has 1 dB better BER performance, which is mainly caused by the frequency-dependent response of the THz mixer, as this channel is down-converted by a 440 GHz electrical LO.
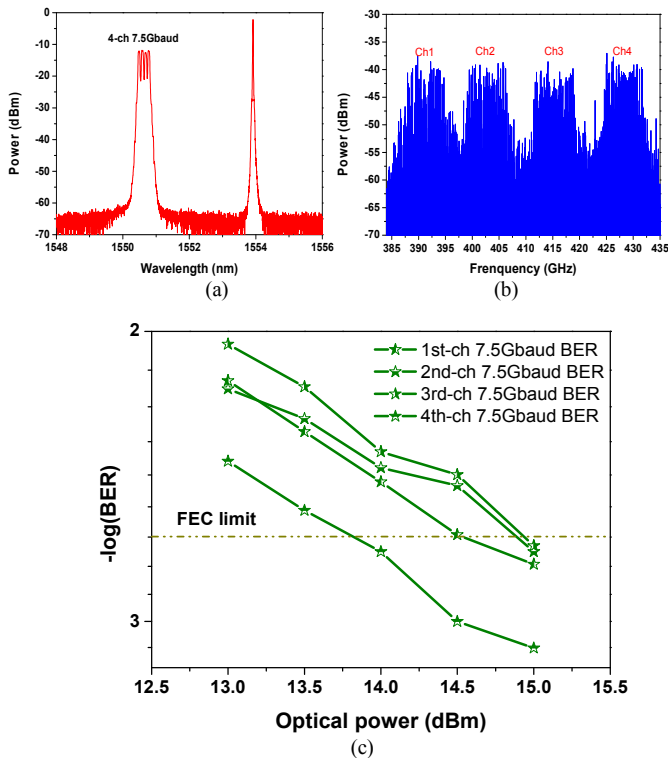

Fig. 4 (a) and (b) are optical spectrum and electrical spectrum of the 4-channel THz signals, respectively. (c) BER performance of four THz channels after 50 cm wireless transmission.

IV. CONLUSION

We have successfully demonstrated a real-time capable high-speed 400 GHz wireless communication system with an aggregated data rate of up to 60 Gbit/s. This constitutes the highest data rate at frequencies above 300 GHz demonstrated to date. The suggested scheme is fully compatible with WDM optical networks by simply inserting an additional optical heterodyne wavelength for generation of THz carriers by photo-mixing. The successful THz wireless transmission of Nyquist QPSK signals in a 12.5 GHz UD-WDM grid makes this scheme very promising in bridging to next generation 100 GbE data rates.

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