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Single Channel 106 Gbit/s 16QAM Wireless Transmission in the 0.4 THz Band

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Abstract: We experimentally demonstrate a single channel 32-GBd 16QAM THz wireless link operating in the 0.4 THz band. Post-FEC net data rate of 106 Gbit/s is successfully achieved without any spatial/frequency multiplexing.
OCIS codes: (060.5625) Radio frequency photonics, (060.4080) Modulation

1. Introduction

Recently, photonic-assisted millimeter wave (MMW) and THz technologies have elevated the capacity of wireless transmissions to a new level, of over 100 Gbit/s. This is mainly enabled by employing spectrally efficient modulation formats, advanced multiplexing techniques, and fully exploiting the available ultra-broad bandwidth at high carrier frequencies of over 100 GHz [1]. System demonstrations with wireless bitrates of the order of 100 Gbit/s have been reported at different carrier frequencies. In the W-band (75-110 GHz) and D-band (110 - 170 GHz), up to 400 Gbit/s wireless transmissions have been demonstrated using wireless spatial multiple-input multiple-output (MIMO) and/or frequency multiplexing techniques, with up to 100 Gbit/s per frequency/spatial channel [2-5]. However, the proposed solutions cannot fit in the lately regulated available bandwidth below 200 GHz [6]. In the sub-THz band (200-300 GHz), transmissions of over 100 Gbit/s with single pair of antennas have been achieved by frequency multiplexing of multiple sub-channels [7, 8]. In the THz band (>300 GHz), we have recently reported a series of high-speed wireless demonstrations in the 0.3-0.5 THz regime with multi-channel QPSK/16QAM signals, reaching a net data rate of up to 260 Gbit/s [9-11]. However, both the spatial MIMO and the frequency multiplexing techniques will increase the system's size, power consumption and the complexity of both the hardware and the DSP module. Therefore, a single channel wireless link without spatial and frequency multiplexing techniques operating over 100 Gbit/s has the potential to relax the system complexity, while fulfilling the capacity requirements of emerging bandwidth intensive wireless applications.

In this paper, we experimentally explore the achievable transmission rate of single channel photonic-wireless link in the 0.4 THz band with a single pair of THz emitter and receiver. The transmitter consists of a coherent optical frequency comb for photonic heterodyne mixing in a uni-travelling carrier photodiode (UTC-PD) integrated with an ultra-wideband antenna [12], generating a THz signal with high carrier frequency stability. We have successfully recovered up to 32 Gbaud 16QAM signals after a 0.5 m THz link, which results in pre-FEC line rates of up to 128 Gbit/s and a post-FEC error-free bit rates of up to 106 Gbit/s in a single frequency channel.

2. Experimental setup

Figure 1 shows the experimental setup of the high-speed single channel THz transmission system. We launch the output of an external cavity laser (ECL) of <100-kHz linewidth into two cascaded intensity and phase modulators, with a tunable optical delay line in-between, to generate a coherent optical frequency comb. Both modulators are driven by a 25 GHz radio frequency (RF) signal, which determines the line spacing of the optical frequency comb. By optimizing the optical delay, a timing match between the two modulators can be achieved to improve the signal-to-noise ratio (SNR) of the optical comb lines and to broaden the spectrum for generating the desired THz carrier signal. After amplification, a programmable wavelength selective switch (WSS) is used to select, separate and equalize two comb lines with 425 GHz spacing at its two output ports. One of the optical tone is used as signal carrier for data modulation and the other tone is served as an optical local oscillator (LO) for heterodyne mixing. A 2-channel arbitrary waveform generator (AWG, 64 GSa/s) is employed to map and modulate two shifted PRBS 2^{15}-1 sequences into a 16QAM signal at an IQ modulator. The 16QAM signal waveform is pulse shaped with a root-raised-cosine (RRC) filter of 0.15 roll-off factor. Static digital pre-equalization is performed prior to the modulation to pre-

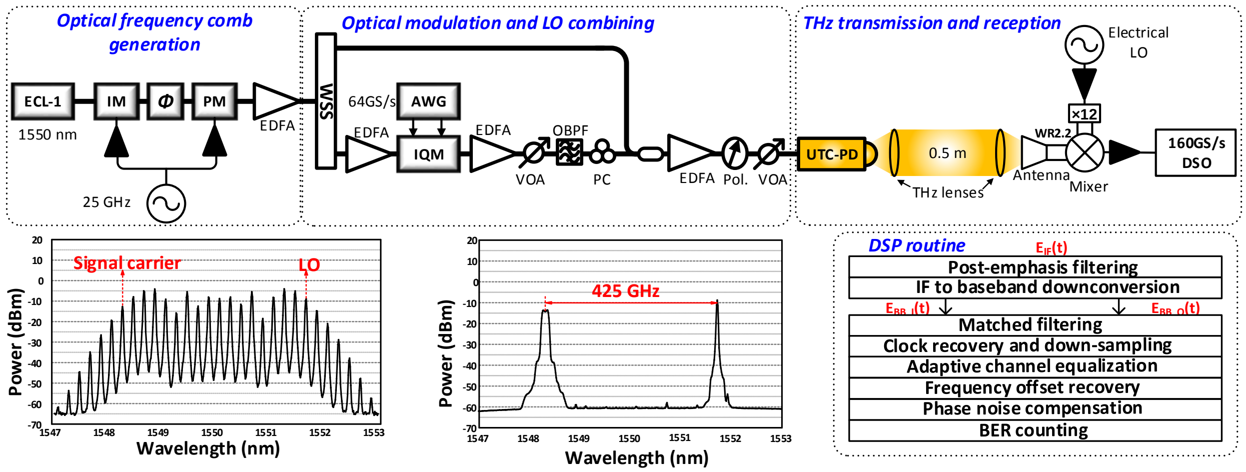

Fig. 1 Experimental setup of the single channel photonic-wireless link in the 0.4 THz band. IM: intensity modulator, PM: phase modulator, EDFA: erbium doped fiber amplifier, WSS: wavelength selective switch, AWG: arbitrary waveform generator, VOA: variable optical attenuator, PC: polarization controller, UTC-PD: uni-travelling carrier photodiode, DSO: digital sampling oscilloscope. Insets: optical spectra of the generated optical frequency comb and combined modulated signal and LO, and the DSP routine structure at the receiver.

compensate the AWG output frequency roll-off and the skew between the electrical cables. The optical 16QAM signal is amplified and filtered before combining with the optical LO branch.

An ultra-broadband UTC-PD is used for heterodyne mixing. Two critical technical rules need to be noted for an efficient THz generation with heterodyne mixing: firstly, the optical power ratio between the signal and the LO needs to be balanced; secondly, the polarization states between the two branches need to be aligned. Both factors are found to have significant impacts on the generated THz signal power and SNR thus requiring precise optimization [13]. Therefore, a variable optical attenuator (VOA) and a polarization controller (PC) are placed in the signal branch before a polarization maintaining 3-dB coupler. After combining with the LO, the EDFA, polarizer and VOA placed after the 3-dB coupler are all polarization maintaining to match the input state of the UTC-PD. The optical spectra of the optical frequency comb and the combined signals after the 3-dB coupler are shown in insets of Fig. 1. At the output of the UTC-PD, a single channel THz signal with carrier frequency centered at 425 GHz are generated and sent into free space. A pair of THz lenses is used to collimate the THz beam in a 0.5 m line-of-sight (LOS) link. At the receiver, the signal is down-converted to an intermediate frequency (IF) signal using a 12-order harmonic THz Schottky mixer operating in the range of 300-500 GHz. The mixer is driven by a 33.8-34.3 GHz tunable electrical LO signal, resulting an IF carrier frequencies of 13-19 GHz, depending on the transmitted signal baud rate.

The IF signal is amplified and converted to digital samples at a 160 GSa/s real-time digital sampling oscilloscope (DSO) with 63 GHz analog bandwidth. The digital signals are processed and analyzed offline with a specifically designed DSP routine in a quasi-real-time manner with a loop probing the captured samples every ~6 seconds. The structure of the DSP chain is also shown in Fig.1 inset. We observe a strong filtering effect to the IF signal at high baud rates due to the bandwidth limit of the mixer output. To equalize this filtering roll-off, a 2-tap static post-emphasis filter is employed. This needs to be performed before the IF down-conversion because the receiver low-pass filtering effect to the IF signal is not symmetrical around the IF carrier but around DC. After down-conversion, the baseband complex signal is processed through matched filtering, resampling and clock recovery, 29-tap multi-modulus algorithm (MMA) based adaptive channel equalization, blind phase search (BPS) based 2-stage frequency and phase noise compensation, before being differentially decoded. The bit-error-rate (BER) is evaluated by counting errors within a total number of ~400k bits per trace.

3. Results and discussions

In this work, we experimentally evaluate single channel 16QAM THz wireless transmissions at symbol rates of 16 Gbaud, 20 Gbaud, 28 Gbaud and 32 Gbaud, corresponding to line rates of 64 Gbit/s, 80 Gbit/s, 112 Gbit/s and 128 Gbit/s. We measure BER as a function of launched optical power into the UTC-PD for all four baud rates, as shown in Fig. 2 (a), and successfully show below-FEC threshold performance in all cases. As shown in the figure, both 16 Gbaud and 20 Gbaud transmissions achieve BER performance below the 7% overhead hard-decision forward error correction (7%-OH HD-FEC) threshold, yielding error-free post-FEC net bit rates of 59 Gbit/s and 74 Gbit/s, respectively. In the cases of the 28 Gbaud and 32 Gbaud transmissions, BER performances below the 20% overhead soft-decision FEC (20%-OH SD-FEC) limit are achieved, resulting in overall post-FEC error-free net bit rates of 93 Gbit/s and 106 Gbit/s, respectively. Corresponding signal constellations captured at 14 dBm for all symbol rates

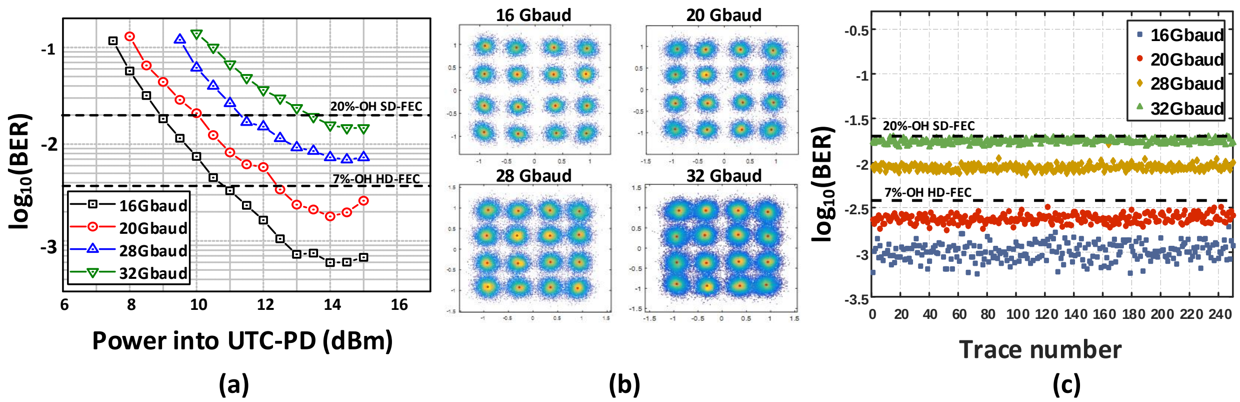

Fig. 2 (a). BER performance versus launched optical power into the UTC-PD. (b). Constellations for all 4 baud rates at 14 dBm optical power. (c). System stability tests for all 4 configurations (250 traces (~25 min) per channel, 800 k Sa/Trace).

are shown in Fig. 2 (b). The system performance is mainly limited by the SNR of the received signals and the receiver's bandwidth. The former is primarily due to the conversion efficiency of the UTC-PD (0.15 A/W) and the THz Schottky mixer. And the latter further enhances the high frequency noise after post-emphasis equalization. The performance difference between different symbol rates can also be seen from the spreading clusters of corresponding constellations. It is also noted that further increase of launched optical power into the UTC-PD above 14 dBm does not yield better BER performance. We attribute this to the saturation of the UTC-PD in terms of output THz signal power. However, it is expected that in the future, a larger margin can be achieved by employing multi subcarrier modulation formats with higher noise tolerance, and improved hardware.

Finally, we evaluate the performance stability of the THz communication link in the lab environment and show the results in Fig. 2 (c). For each symbol rate we run the system continuously over 25 minutes, collecting 250 traces with 800 k samples per trace and counting errors. From Fig. 2 (c) it is observed that for all cases the system could maintain the BER performance within a small fluctuation range, below the corresponding FEC limits. This result indicates that the demonstrated THz wireless link operating at high symbol rates has a stable performance because of the sophisticated DSP algorithms employed in this work.

4. Conclusion

We have experimentally demonstrated a high speed single channel THz photonic-wireless link operating in the 0.4 THz band using a single pair of THz transmitter and receiver. The employment of 16QAM modulation format, ultra-broadband THz transceivers and advanced DSP routine enables the high throughput up to 106 Gbit/s net data rate in the THz band without spatial or frequency multiplexing techniques. The demonstrated THz link also shows high transmission performance stability, indicating its potential to support upcoming bandwidth intensive short range wireless applications.

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