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THz photonic wireless links with 16-QAM modulation in the 375-450 GHz band

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Abstract: We propose and experimentally demonstrate THz photonic wireless communication systems with 16-QAM modulation in the 375-450 GHz band. The overall throughput reaches as high as 80 Gbit/s by exploiting four THz channels with 5 Gbaud 16-QAM baseband modulation per channel. We create a coherent optical frequency comb (OFC) for photonic generation of multiple THz carriers based on photo-mixing in a uni-travelling carrier photodiode (UTC-PD). The OFC configuration also allows us to generate reconfigurable THz carriers with low phase noise. The multiple-channel THz radiation is received by using a Schottky mixer based electrical receiver after 0.5 m free-space wireless propagation. 2-channel (40 Gbit/s) and 4-channel (80 Gbit/s) THz photonic wireless links with 16-QAM modulation are reported in this paper, and the bit error rate (BER) performance for all channels in both cases is below the hard decision forward error correction (HD-FEC) threshold of 3.8e-3 with 7% overhead. In addition, we also successfully demonstrate hybrid photonic wireless transmission of 40 Gbit/s 16-QAM signal at carrier frequencies of 400 GHz and 425 GHz over 30 km standard single mode fiber (SSMF) between the optical baseband signal transmitter and the THz wireless transmitter with negligible induced power penalty.

OCIS codes: (060.5625) Radio frequency photonics; (060.2330) Fiber optics communications.

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1. Introduction

There has been an explosive growth of the demand for data rates in both wired and wireless communications over recent decades, mainly driven by increased user adoption of higher speed services, such as ultrahigh definition (UHD) data, download of large volume of data, ultrafast intra/inter-chip data exchange, fast restoration of network connections in disaster areas, and so on, and a trend seems likely to continue for the coming decade [1–4]. High-speed connections based on fiber to the home (FTTH) have been widely deployed, however they cannot provide global coverage due to various limitations such as geographical condition, provider's strategy, and damage situation in the case of disaster. Wireless networks based on optical fiber links are therefore becoming a key building block to enable the next

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generation networking providing anywhere, anytime services [5, 6]. From a technical point of view, optical fiber links with large capacity and wireless links with the superior characteristics of flexible arrangement and easy installation, can be synergistically integrated to realize agile provision of larger capacities [7, 8]. To enable seamless optical-to-wireless access networking, wireless transmission systems require a significant capacity enhancement to match well beyond 100 Gbit/s data rates in fiber-optic communications. In the field of wireless transmission, the conventional radio bands up to 60 GHz are almost fully exploited [9, 10], therefore a lot of effort has been directed to explore the large bandwidths available in the millimeter-wave and THz terra incognita [11–15].

Several wireless propagation demonstrations in higher frequency bands have been reported, such as 11 Gbit/s on-off keying (OOK) data wireless transmission at 100 GHz carrier frequency [16], a 40 Gbit/s wireless link at 300 GHz based on OOK data modulation and direct detection [17], real-time 50 Gbit/s OOK 300 GHz wireless transmission at over 20 m distance [18], a wireless OOK link operating at a carrier frequency of 220 GHz with a data rate of 25 Gbit/s [19], 24 Gbit/s amplitude shift keying (ASK) data wireless transmission at 300 GHz using a uni-travelling carrier photodiode (UTC-PD) emitter and a Schottky barrier diode detector [20], 200 GHz multicarrier wireless transmission using a quadrature phase-shift keying (QPSK) baseband signal and a gain-switched laser comb source [21], 25 Gbit/s QPSK hybrid fiber-wireless transmission in the W-Band (75–110 GHz) with a remote antenna unit for in-building wireless networks [22], and 60 Gbit/s QPSK wireless transmission with real-time capable detection at 400 GHz carrier [23]. Furthermore, spectrally efficient quadrature amplitude modulation (QAM) signals have also been implemented, such as 100 Gbit/s and 40 Gbit/s 16-QAM signals in the 75-110 GHz band [24, 25] and single-input/single-output (SISO) QPSK, 8-QAM and 16-QAM signals at 237.5 GHz [26, 27]. Up to date, the fastest reported 16-QAM wireless system in the THz frequency range (>300 GHz) is operating at 340 GHz with a data rate of only 3 Gbit/s [28], meaning less than 1 GHz exploited bandwidth. Therefore, combining the employment of spectrally efficient modulation format 16-QAM and the exploration of more THz bandwidth is expected to significantly improve the THz wireless capacity.

In this context, we propose and experimentally demonstrate a four-channel THz photonics communication system in the 375-450 GHz band with 5 Gbaud 16- QAM baseband data modulation per channel, reaching an overall throughput as high as 80 Gbit/s. The transmitter consists of a coherent optical frequency comb (OFC) for photonic heterodyne mixing in a UTC-PD integrated with an ultra-wideband bow-tie antenna for generating multiple THz carriers with low phase noise and high stability. The phase-correlated OFC is created by employing a continuous wave (CW) light modulated by two cascaded phase modulators (PMs), both of which are driven by an amplified 25 GHz sinusoidal radio frequency (RF) signal. The multi-channel THz signals are generated by photo-mixing the modulated 16-QAM optical wavelengths with one un-modulated optical tone spaced by 375-450 GHz (the desired THz signal frequencies). In this work, we demonstrate wireless transmission of two channels with 5 Gbaud 16-QAM modulation, reaching an overall throughput of 40 Gbit/s, and four channels with 5 Gbaud 16-QAM modulation resulting in an 80 Gbit/s capacity. In case of the 40 Gbit/s, both back to back (BTB) and 30 km of standard single mode fiber (SSMF) transmission between the optical baseband signal transmitter and the THz wireless transmitter are experimentally demonstrated. The 40/80 Gbit/s wirelessly transmitted 400 GHz band signals are received by an electrical receiver based on a Schottky mixer. Such high capacities in the THz link are enabled by the ultra-wideband behavior of the involved THz transceiver. In both 40- and 80 Gbit/s demonstrations, the bit error rate (BER) for the 16-QAM signal in each channel after 0.5 m free-space transmission is achieved below the hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} with 7% overhead. In addition, the employment of the OFC offers advantages such as reconfigurable frequency selection and long-term stability of frequency spacing, for the desired phase-correlated optical local

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oscillator (LO) and carrier tones selection. Then since the path difference between the optical LO and the carriers with modulation can result in phase decorrelation between them, we compensate the optical LO path by using a matched piece of fiber to reduce the complexity and processing time of digital signal processing (DSP) at reception.

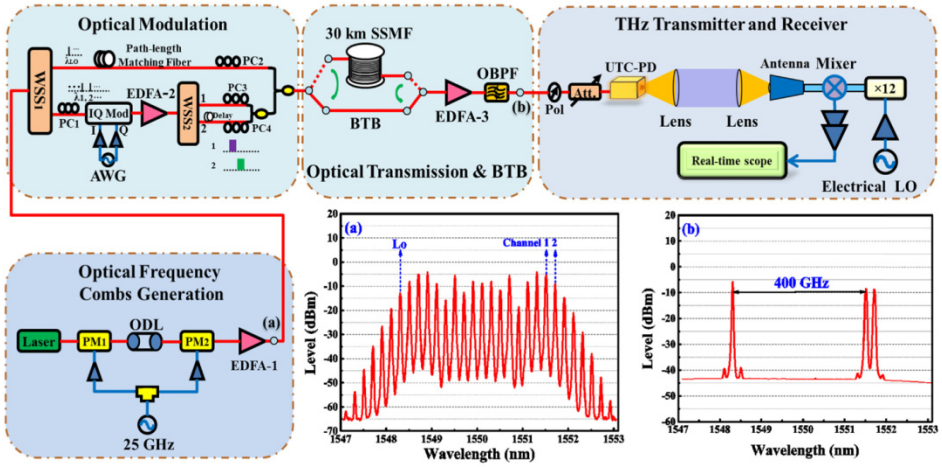

Fig. 1. Experimental setup of the dual-channel THz communication system with and without 30 km optical fiber transmission. PM: phase modulator, ODL: optical delay line, EDFA: erbium-doped fiber amplifier, WSS: wavelength selectable switch, PC: polarization controller, AWG: arbitrary waveform generator, IQ Mod: in-phase and quadrature modulator, SSMF: standard single mode fiber, BTB: back to back, OBPF: optical band pass filter, LO: local oscillator, Pol: Polarizer, Att.: attenuator, UTC-PD: uni-travelling carrier photodiode. 1(a) The spectrum of generated optical frequency comb. 1(b) The combined spectrum of optical tones launching into the UTC-PD for photo-mixing generation of THz signals.

2. Experimental demonstration of dual-channel THz fiber wireless transmission

As shown in Fig. 1, the experimental configuration is organized as follows. The first section describes the coherent generation of the OFC, and the second section presents the optical modulation of 16-QAM data and the phase correlation compensation between the optical LO and the modulated optical tones. The third section shows that the combined optical signal containing one LO tone and two modulated tones, is either delivered directly to the UTC-PD (back-to-back, BTB), or transmitted over 30 km SSMF before converting to the THz wireless signal in the UTC-PD. The last section deals with the THz transmission link, consisting of a UTC-PD as the photo-mixing emitter, a 0.5 m THz wireless transmission path and a Schottky mixer as the electrical receiver at the reception side.

First of all, a continuous wave (CW) light from a laser at a wavelength of around 1550 nm, is modulated by two cascaded phase modulators (PMs) with a tunable optical delay line (ODL) in-between, in order to generate a coherent OFC. Both PMs are driven by a 25 GHz RF signal, which determines the comb line spacing of the OFC. The amplified RF driving power on the two PMs ($V\pi$ of 3V) are 31 dBm and 22 dBm, thus the corresponding modulation indices are $3.8V\pi$ and $1.4V\pi$, respectively. By optimizing the delay of the ODL, timing match between the two PMs can be achieved to broaden the spectrum for generating the desired multiple THz frequencies. After amplification by an Erbium-doped fiber amplifier (EDFA-1), the OFC with 25 GHz line spacing is fed into a wavelength selective switch (WSS-1, Finisar WaveShaper 4000S). WSS-1 is employed to select several appropriate phase-locked comb lines and split them into two different optical output ports. In one port, a single optical tone is selected to act as a remote LO for THz signal generation. At the output of the other port, two optical tones positioned at 400 and 425 GHz respectively from the optical LO tone, are selected and launched into an in-phase (I) and quadrature (Q) optical

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modulator (IQ Mod), where the 2 optical carriers are modulated with 5 Gbaud 16-QAM baseband data electrically generated from an arbitrary waveform generator (AWG). After the modulation and amplification (EDFA-2), the 2 optical baseband channels are separated by WSS-2, and a fiber delay line is added to de-correlate adjacent channels. Note that a fiber with an optimized length is inserted in the optical LO path to match the path length difference between the LO and the 2 modulated tones, before they are combined together. The unmodulated and modulated tones are polarization aligned by employing three polarization controllers (PC-2, 3 and 4). Then, the combined optical signal is transmitted either over 30 km SSMF or in BTB before the THz link. EDFA-3 is employed to amplify the optical signal, followed by a 9 nm optical band-pass filter (OBPF) to reject out-of-band amplified spontaneous emission (ASE).

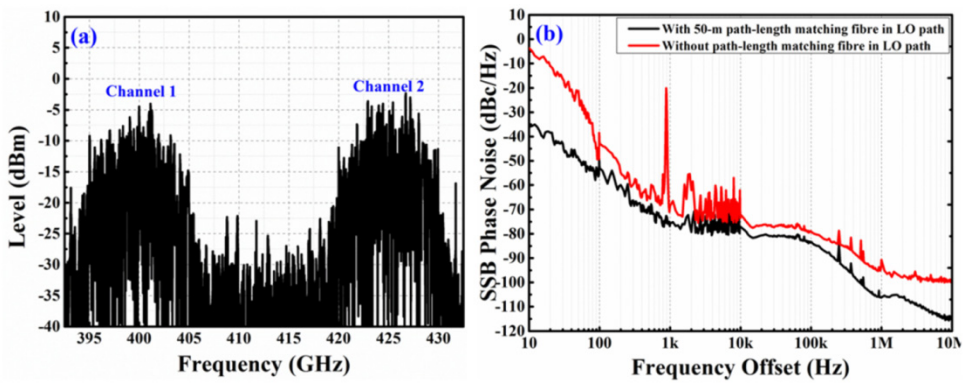

Fig. 2. (a) The combined electrical spectrum of 2-channel generated THz signals. 2(b) The phase noise measurement of THz carrier without modulation.

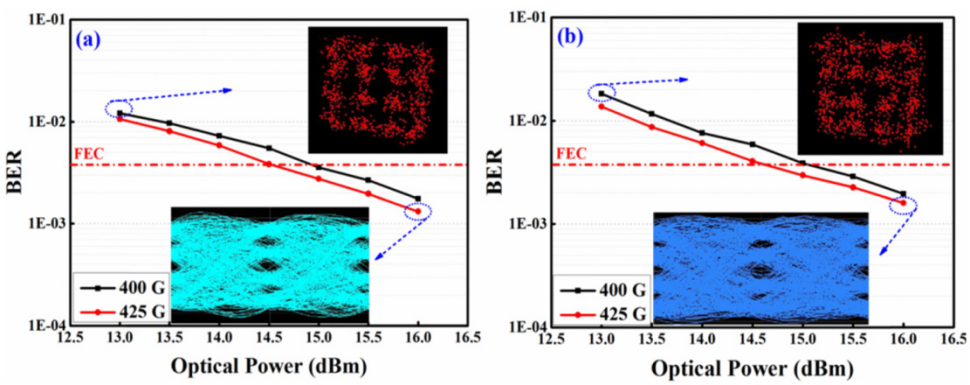

Fig. 3. (a) The measured BER performance for two channels in BTB. 3(b) The measured BER performance for two channels with 30 km SSMF transmission.

Finally, a polarizer ensures the modulated optical tones and the un-modulated LO are copolarized before launching them into the UTC-PD for photo-mixing, resulting in two-channel THz signals at around 400 GHz and 425 GHz respectively. The incident optical power is controlled by an optical attenuator. After a 0.5-m free-space transmission link, where a pair of THz lenses is employed to collimate the THz beam, THz signal in each channel is individually down-converted to the intermediate frequency (IF) domain with a carrier of 6 GHz by using a Schottky mixer. The mixer is driven by a 12-time frequency multiplied electrical LO in the frequency range of 32.83 - 35.92 GHz. After amplification by a chain of RF amplifiers, the overall gain and bandwidth of which are about 42 dB and 40 GHz respectively, the IF output is sent into a broadband real-time sampling oscilloscope (Keysight

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DSOZ634A Infiniium) with 160 GSample/s sampling rate and 63 GHz analogue bandwidth for analog-to-digital conversion, demodulation and performance analysis.

The generated spectrum of the 25 GHz spaced OFC at point (a) of Fig. 1 is shown in Fig. 1(a). The tones labelled by blue arrows correspond to the optical LO and 2 optical tones for optical baseband modulation. It can be seen that the SNR of the desired tones is higher than 50 dB. As illustrated in Fig. 1(b), the combined spectrum at point (b) consists of one un-modulated LO tone and 2 optical carriers with modulation. Each optical carrier is modulated with 5 Gbaud 16-QAM, resulting in an overall capacity of 40 Gbit/s. The photo-mixing of all the 3 tones in the UTC-PD generates 2-channel THz signals at 400 and 425 GHz carrier frequencies, respectively. The combined electrical spectrum is shown in Fig. 2(a). Here the combined THz electrical spectrum is measured from the down-converted IF signal after the 0.5 m THz wireless transmission. We can see that the response of the whole THz link in the 425 GHz band is a bit better than 400 GHz band. Moreover, we measure the phase noise performance of the 425 GHz carrier in the cases of with/without path-length matching fiber, in order to characterize the THz phase noise degradation induced by the path difference. It can be seen from Fig. 2(b) that the measured phase noise without the matched compensation fiber is much worse than that with 50 m path-length matched fiber in the LO path, especially at a frequency offset close to the carrier, i.e. around 30 dB worse at 10 Hz frequency offset.

The measured BER performance for two channels in BTB case can be seen in Fig. 3(a). An eye diagram and a constellation corresponding to the BER of 1.3×10^{-3} and 1.2×10^{-2} are also exhibited. The BER measurement for two channels after 30 km SSMF optical baseband transmission is shown in Fig. 3(b), where an eye diagram and a constellation corresponding to the BER of 1.6×10^{-3} and 1.8×10^{-2} respectively are displayed. In both cases, we can observe that the BER performance of all channels has been achieved below the HD-FEC threshold of 3.8×10^{-3} with 7% overhead. The power penalties between the 425 GHz and 400 GHz channels in both Figs. 3(a) and 3(b) are around 0.5 dB. This can be explained by the un-even frequency response of the THz link reflected in Fig. 2(a). By comparing BTB and fiber transmission performance, we can see that the power penalty induced by the 30 km SSMF fiber transmission is negligible for both two channels. This is because the loss of the 30 km SSMF transmission can be compensated by using low-noise EDFA-3 followed by a 9-nm OBPF.

3. Experimental demonstration of four-channel THz wireless communication

The experimental setup for the four-channel THz wireless transmission system is shown in Fig. 4, where the section of OFC generation is same as that in Fig. 1. In the part of optical modulation, five phase-locked comb lines are selectively filtered by WSS-1, into two output arms. One arm transmits only one optical tone used as the LO, and the other arm delivers a group of four optical tones positioned at 375, 400, 425 and 450 GHz from the optical LO tone for IQ modulation. Here we modulate the same 5 Gbaud 16-QAM baseband data onto all the 4 channels. The decorrelation between even- and odd-order channels is implemented by WSS-2, incorporating with a fiber delay line in between. The optimized path-length matching fiber is also added in the optical LO arm to compensate the two-path length difference. In this experiment, only the BTB case is demonstrated and the section of THz transmitter and receiver is same as that in Fig. 1.

The combined optical spectrum before launching into the UTC-PD is inserted in Fig. 4. The optical signal contains one un-modulated LO tone and four 25 GHz gridded wavelength division multiplexing (WDM) channels with 5 Gbaud 16-QAM modulation for each channel. The overall throughput therefore reaches 80Gbit/s. The combined electrical spectrum of the generated 4-channel THz signals at 375-, 400-, 425- and 450 GHz respectively, is shown in Fig. 5(a), by measuring the individually down-converted IF signal after the wireless path. It is noted that the overall frequency response of the THz link can also be explained by the spectrum in Fig. 5(a), where the 425 GHz channel is obviously better than other three.

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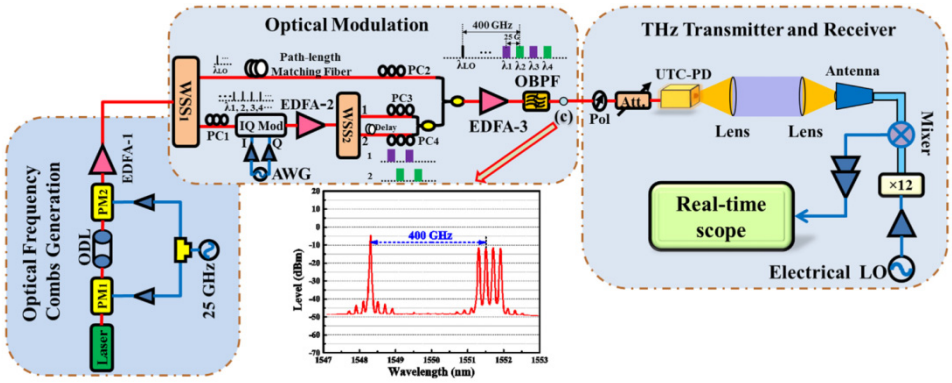

Fig. 4. The experimental setup of the 4-channel THz data wireless transmission.

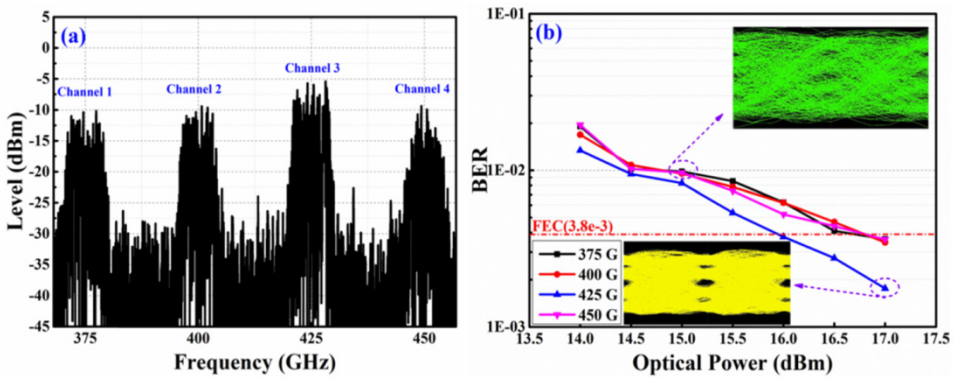

Fig. 5. (a) The combined electrical spectrum of generated 4-channel THz signals. 5(b) The BER performance measurement for 4 channels.

The BER performance measurement for 4 channels is shown in Fig. 5(b). We can observe that the BER performance of all channels has been successfully achieved below the HD-FEC threshold (3.8×10^{-3} with 7% overhead). There is around 1 dB power penalty between the best and worst channels, which can be explained by the un-even frequency response of the THz link and hence different received signal-to-noise-ratio, as reflected in Fig. 5(a). Amongst them, the 425 GHz channel is evidently the best, which agrees well with the BER performance. Two eye diagrams corresponding to the BER of 1.7×10^{-3} and 9.6×10^{-3} are also illustrated in Fig. 5(b).

4. Conclusion

We have successfully demonstrated a THz photonics communication system in the 375-450 GHz band with four-channel 16-QAM modulation. The employment of 16-QAM modulation and ultra-broadband THz transceivers enables a throughput as high as 80 Gbit/s in the THz band above 300 GHz. The combination of the high-order modulation formats and ultra-broad bandwidth in accordance with higher THz frequencies, is promising to provide a path to scale wireless communications to Tbit/s rates.

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