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160 Gbit/s photonics wireless transmission in the 300-500 GHz band

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To accommodate the ever increasing wireless traffic in the access networks, considerable efforts have been recently invested in developing photonics-assisted wireless communication systems with very high data rates. Superior to photonic millimeter-wave systems, terahertz (THz) band (300 GHz-10 THz) provides a much larger bandwidth and thus promises an extremely high capacity. However, the capacity potential of THz wireless systems has by no means been achieved yet. Here, we successfully demonstrate 160 Gbit/s wireless transmission by using a single THz emitter and modulating 25 GHz spaced 8 channels (20 Gbps per channel) in the 300-500 GHz band, which is the highest bitrate in the frequency band above 300 GHz, to the best of our knowledge. © *2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4960136]

According to the Cisco visual networking index forecast, mobile data traffic will increase 10-fold between 2014 and 2019, reaching 24.2 exabytes per month by 2019.[1] To accommodate the ever increasing traffic in the access networks, wireless connections in the foreseeable future are highly desired to operate at a data rate of well beyond 100 Gbit/s, eventually Tbit/s. With respect to the commercial industry development of optical networks, Cisco and Juniper deployed their first 100 Gbit/s Ethernet (100 GbE) systems in 2011,[2] and the IEEE 802.3 400 Gbit/s Ethernet (400 GbE) study group was established in 2013 to support the development of next speed of Ethernet and get prepared for the initial deployment of 400 GbE by using the existing single mode fiber deployed. Therefore wireless links, which are compatible with the existing optical Ethernet infrastructure and technically benefit from its large capacity, will be highly appreciated as a cost efficient solution for the next generation last-mile wireless access. Apart from backhauling mobile streams, ultrafast wireless communication technologies are in fact also expected to significantly benefit many other bandwidth-hungry applications, such as wireless transmission of ultrahigh definition video, wireless download of large volume data, ultrafast intra/inter-chip data exchange, fast restoration of network connections in disaster areas, and so on.

Recently, considerable efforts have been invested in developing photonics-assisted wireless communication systems targeting very high data rates.[3] So far, several wireless connections at data rates of 100 Gbit/s and beyond have been achieved in the sub-THz band (200-300 GHz) by using uni-travelling photodiodes (UTC-PDs) and comb sources,[4,5] and in the W-band (75-110 GHz) incorporating optical polarization division multiplexing (PDM)[6] and spatial multiple-input-multiple-output (MIMO) techniques.[7] To move beyond this, the THz band (300 GHz-10 THz) between the millimeter-wave and infrared radiation is considered as the "Next Frontier" to meet the eventual data rate target of Tbit/s,[8] due to its much larger unregulated bandwidth available comparing to the millimeter-wave band, as well as less atmospheric disturbances compared to optical wireless links.

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In this context, the development of THz photonics-wireless communication systems has recently attracted considerable attention, and progressive achievements at tens of Gbit/s in the past few years have been enabled by THz transceivers,[9–14] particularly the availability of ultra-broadband UTC-PDs[9] as efficient photo-mixing emitters and Schottky diodes as broadband electronic receivers. We have recently contributed to this development by demonstrating the highest reported bit rate in the frequency bands above 300 GHz, by showing 60 Gbit/s Nyquist-quadrature phase shift keying (QPSK) wireless transmission at 400 GHz using a UTC-PD and a Schottky receiver.[15] However, the capacity potential of THz wireless systems has by no means been achieved yet. The limitation is mainly associated with the typical opto-electronic approach of generating THz carriers by using free-running lasers for heterodyne photo-mixing in the UTC-PD, which intrinsically leads to a beat-note with high phase noise. However, it has been commonly known that spectrally efficient modulation formats are all susceptible to phase noise,[16,17] even if digital algorithm-based carrier phase estimation can to some extent mitigate the influence of phase noise. Therefore, generation of THz carriers with high purity and low phase noise will be expected to increase the capacity of THz wireless systems, from communication system viewpoint.

In this work, we optically create a coherent frequency comb instead of free running laser in our previous work,[15] for photo-mixing generation of THz carriers in the 300-500 GHz. Optical comb sources have been used in demonstrating photonic millimeter-wave communication systems;[4,5] however, a time delay between optical paths of delivering an optical local oscillator (LO) and optical baseband wavelengths will induce significant phase noise due to the phase decorrelation among them. Therefore, we examine this delay compensation in this work and reduce the THz phase noise by compensating the optical path difference. This scheme allows for exploitation of more THz bandwidth for data delivery, and up to 160 Gbit/s data generation, transmission and detection in the 300-500 GHz band are successfully achieved. To the best of our knowledge, this is a new record in the THz band above 300 GHz, and also pushes THz communication data rates beyond 100 Gbit/s.

The experimental configuration is shown in Fig. 1(a). We first optically generate a frequency comb based on two concatenated phase modulators (PMs), both of which are driven by an amplified 25 GHz sinusoidal signal. The phase modulation indexes are $7.5V_\pi$ and $2.7V_\pi$ respectively. An optical tunable delay line in-between is used to match the phase of the two-stage modulation, in order to improve the signal-to-noise ratio (SNR) of the optical tones in the comb needed for the 300-500 GHz carrier generation. Subsequently, a programmable wavelength selective switch (WSS-1, Finisar 4000S) based on solid-state liquid crystal on silicon (LCoS)[18] is employed to
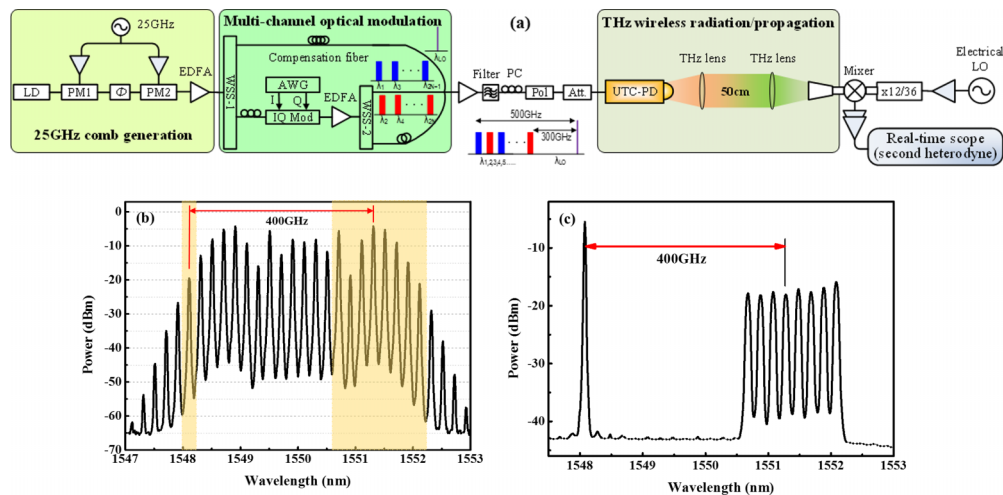
FIG. 1. (a) Experimental configuration of the 300-500 GHz photonics-wireless communication system. PM: phase modulator, WSS: wavelength selectable switch, AWG: arbitrary waveform generator, LO: local oscillator, Att.: attenuator, UTC-PD: uni-travelling carrier photodiode. (b) Generated 25 GHz spaced frequency comb spectrum and optical tones for THz generation. (c) WSS-prepared 8 WDM channels 25 GHz apart and centered 400 GHz from the LO before the UTC-PD.

separate one optical comb line, to be used as an optical local oscillator, from 8 other comb lines with 25 GHz spacing, to be used for optical multi-channel baseband modulation. The LO line and the 8 WDM data lines are 300-500 GHz apart, and the WSS-1 additionally equalizes the comb lines. The digital baseband data signal is generated from an arbitrary waveform generator (AWG) and optical baseband modulation is implemented by a Fujitsu lithium niobate (LN) in-phase (I) and quadrature (Q) modulator with 32 GHz 3 dB bandwidth. In the experiment, we modulate a Nyquist quadrature phase shift keying (QPSK) pseudorandom binary sequence (PRBS) $2^7 - 1$ signal and perform Nyquist pulse shaping electrically in the AWG by applying a square root raised cosine filter with 0.05 roll-off factor. The even-order and the odd-order channels after the IQ modulator are de-correlated by a second WSS (WSS-2) and a fiber delay line, and then combined again together with the optical local oscillator. With respect to the optical local oscillator, we compensate the path by using a piece of fiber, which matches the path difference between the optical LO and the 8 data lines de-correlating their phases. Then all the combined optical signals are boosted by an erbium-doped fiber amplifier (EDFA) with a noise figure of around 4 dB, and filtered by a 9 nm optical filter for suppressing out-of-band noise.

Eventually the optical LO and the 8 WDM data lines are directed onto the UTC-PD photo-mixing emitter, generating 8 carrier frequencies with 25 GHz spacing centered around 400 GHz. The UTC-PD has an extremely fast photo-response and high responsivity (DC responsivity of 0.15 A/W here). Before launching into the UTC-PD, the optical signals are polarized to minimize the polarization dependency of the UTC-PD, and the incident optical power is controlled by an optical attenuator. In the wireless domain, we use a pair of THz lenses with 25 dBi gain to collimate the THz beam, and hence reduce the free space propagation loss in a 50 cm line-of-sight (LOS) communication link, which is measured to be less than 2 dB in the experiment. At the receiver side, a THz Schottky mixer operating in the frequency range of 300-500 GHz is used to individually down-convert the received THz channels into an intermediate frequency (IF) signal within 20 GHz band. The mixer is fed by a 36-order frequency multiplier driven by an 8.3-13.9 GHz tunable electrical LO signal. The IF output is amplified by a chain of electrical amplifiers with 42 dB gain and is finally demodulated and analyzed by a broadband real time sampling oscilloscope (63 GHz Keysight DSOZ634A Infiniium).

The 25 GHz spaced optical frequency comb is shown in the inserted spectrum in Fig. 1(b). The comb extends beyond 5 nm and the desired optical tones (shaded regions) for heterodyne generation of 300-500 GHz carriers present more than 40 dB carrier-to-noise ratio, which is mainly limited by the 25 GHz electrical driving power. The data modulated 8 WDM channels are used with the optical LO to generate the THz signal around 400 GHz, which fully explores the bandwidth of THz mixer. The combined optical spectrum is displayed in Fig. 1(c).

In the experiment, 400 GHz emission power is estimated as −21 dBm for 13 dBm incident optical power, and THz transmitter and receiver antennas individually have 25 dBi gain. We first investigate the phase noise performance of the 350 GHz carrier after wireless propagation by measuring its down-converted IF component at 6 GHz, and the measured results are shown in Fig. 2. In order to examine the delay compensation and compare phase noise performance, the phase noise of the 350 GHz analogue signal generated in three different regimes is measured. The first case is coherent beating of the two optical tones without splitting at the WSS-1. In this case, both of the optical LO and the optical data line with 350 GHz frequency spacing are selected by a same port of the WSS-1, and thus there is no additional optical delay between them. This coherent beating is the reference to precisely compensate the path difference later. The second case is to accurately compensate the delay difference between two optical paths using 50 m optical fiber when they are split by the WSS-1. The third is without the delay compensation technique when split. It is noted that both the second and the third cases are implemented on the complete platform for later communication experiment, excluding the baseband modulation. From Fig. 2, we can learn that compared to an electrical sinusoidal signal from a synthesizer, photo-mixing of two coherent tones from the comb generates a THz carrier (blue curve in Fig. 2) with 10 dB higher phase noise at 10 kHz offset frequency. This is because the photo-mixing of the two phase-correlated harmonic tones, originating from the same laser, sums up their individual phase noise. When the path of optical LO after the WSS-1 is not compensated, the phase noise of the generated THz carrier is even worse and
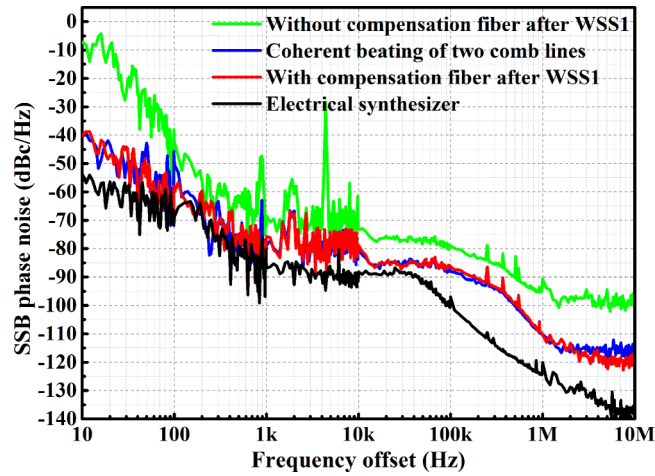
FIG. 2. Phase noise performance comparison of generated 350 GHz carriers in different regimes.

unstable due to the induced phase de-correlation, while the same phase noise performance as for coherent beating can be achieved when the path difference is accurately compensated with a 50 m fiber.

With respect to the wireless transmission performance, we measure bit error rate (BER) performance for single channel, 7-channel as well as 8-channel after 50 cm wireless transmission, all employing the delay compensation scheme. The data modulation in all these cases is 10 Gbaud Nyquist QPSK per channel. Optical spectrum of the single channel is shown in Fig. 3(a) with a THz carrier frequency at 400 GHz. The corresponding BER performance is shown in Fig. 3(c), and a BER performance below the hard decision forward error correction limit (FEC, BER 3.8×10^{-3} with 7% overhead) can be achieved at an optical incident power of 7.5 dBm. Note that the THz system with free running lasers in our previous work[14] requires more than about 10.5 dBm optical power for 10 Gbaud rate to obtain the same BER performance with the same receiver. This >3 dB benefit is attributed to significant deduction of THz carrier phase noise in this work. In this sense, further development of THz system with an enhanced capacity can be enabled. The optical spectrum of 7-channel before the UTC-PD is illustrated in Fig. 3(b). Photo-mixing of these 7 WDM tones with the optical local oscillator wavelength in the UTC-PD generates the 7-channel 25 GHz
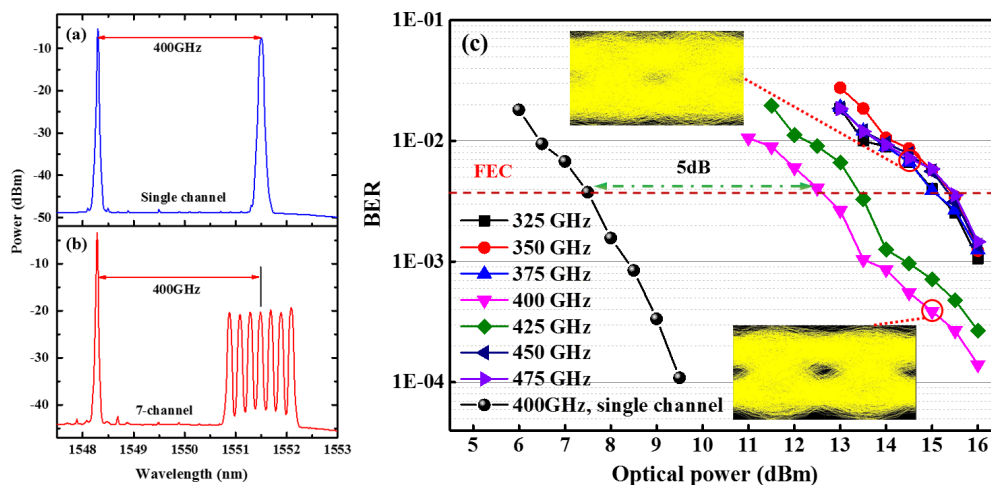

FIG. 3. Optical spectrum of single channel (a) and 7-channel (b). (c) Measured BER performance after 50 cm wireless transmission for single channel at 400 GHz and 7 channels in the 300-500 GHz band. Insets are eye-diagrams corresponding to BER of 4×10^{-4} and 7×10^{-3}, respectively.
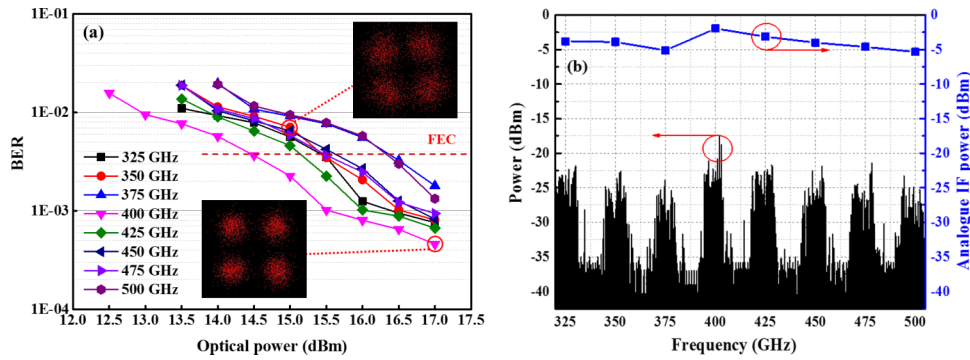
FIG. 4. (a) Measured BER performance after 50 cm wireless transmission for 8 channels in the 300-500 GHz band; (b) 8-channel electrical spectrum and frequency dependent conversion loss of the receiver.

spaced THz signals with a center frequency of 400 GHz. 10 Gbaud QPSK modulation per channel results in an aggregated bit rate of 140 Gbit/s. The baud rate is less than half of the channel spacing 25 GHz, for the sake of reducing interference from the neighbor channel in the down-conversion. The BER performance for all the 7 channels after wireless transmission is also shown in Fig. 3(c). It can be seen that all the channels have also achieved a BER performance below the FEC. There is about 5 dB penalty between the 400 GHz channel in the cases of 7-channel and single channel. This penalty is mainly caused by signal-to-noise degradation when multiple optical modulation channels share the constant EDFA output power. It is noted that launching of more channels into the EDFA by this means would lead to less signal to noise ratio for each individual channel, as indicated in Figs. 3(a) and 3(b). We also measure the BER performance for 8 channels after 50 cm wireless transmission by adding an additional 500 GHz channel, as shown in Fig. 4(a). The optical spectrum of 8-channel is displayed in Fig. 1(c) and these 8 tones occupy 200 GHz overall operation bandwidth. It can be seen that all the 8 channels have also obtained a BER performance below the FEC. Therefore, an overall capacity of up to 160 Gbit/s is successfully achieved. We can observe from Fig. 4(a) that the BER performance of 400 GHz channel among 8 channels in the 300-500 GHz band is the best, same as the 7-channel performance in Fig. 3(c).

In addition, the 375 GHz and 500 GHz channels in Fig. 4(a) are slightly worse than the 325-, 350-, 425-, and 450 GHz channels with a penalty of less than 1 dB. This penalty can be explained by the conversion loss of the Schottky mixer based receiver shown in Fig. 4(b). The receiver conversion loss fluctuates over the 300-500 GHz frequency range, 375 GHz and 500 GHz bands exhibit the largest conversion loss, and 400 GHz least, which comply well with the BER performance observation. Here the conversion loss is investigated by measuring the down-converted analogue IF power at 6 GHz without modulation and this loss is also reflected in the 8-channel electrical spectrum in Fig. 4(b). The BER performance in the experiment is evaluated from the error-vector magnitude (EVM) of the processed constellations. For illustration purposes, two eye-diagrams and constellations corresponding to BER of 4×10^{-4} and 7×10^{-3} are displayed in Figs. 3(c) and 4(a), respectively.

In conclusion, we have successfully demonstrated a 160 Gbit/s THz wireless link in the 300-500 GHz band using a single UTC-PD based transmitter and a Schottky mixer-based receiver. We improve the purity of the generated THz carriers by examining and compensating phase decorrelation between the photomixing tones derived from the same comb source. This scheme enables the exploration of more bandwidth in the THz band for communication, and the record 160 Gbit/s data rate above 300 GHz has been achieved in this work. Spectral efficiency improvement incorporating signal to noise ratio consideration and development of broadband THz transceiver, for instance, based on photonic crystal[19] and plasmonics,[20] would benefit this system to further increase the data rates. In addition, to extend the wireless reach of such a THz system, enhancement of THz device performance will be fundamentally essential, for example, improvement of photodiode responsivity and receiver sensitivity, as well as development of THz amplifiers and very high gain THz antennas, etc. This achievement shows that beyond 100 Gbit/s THz communication takes shape

and that there is great potential in bringing high capacity of optical communication to ultrafast wireless access.

[1] See http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.pdf for information about mobile data rate evolution.

[2] See http://www.uknof.org.uk/uknof19/Evans-Deploying-100Ge.pdf for detailed information about deployment of 100 GbE.

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