Photonic generation for multichannel THz wireless communication

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Abstract: We experimentally demonstrate photonic generation of a multichannel THz wireless signal at carrier frequency 200 GHz, with data rate up to 75 Gbps in QPSK modulation format, using an optical heterodyne technique and digital coherent detection. BER measurements were carried out for three subcarriers each modulated with 5 Gbaud QPSK or for two subcarriers modulated with 10 Gbaud QPSK, giving a total speed of 30 Gbps or 40 Gbps, respectively. The system evaluation was also performed with three subcarriers modulated with 12.5 Gbaud QPSK (75 Gbps total) without and with 40 km fibre transmission. The proposed system enhances the capacity of high-speed THz wireless transmission by using spectrally efficient modulated subcarriers spaced at the baud rate. This approach increases the overall transmission capacity and reduces the bandwidth requirement for electronic devices.

OCIS codes: (060.5625) Radio frequency photonics; (060.0060) Fiber optics and optical communications.

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1. Introduction

There has been enormous growth in demand for high-speed wireless communication over the last few years. This is due to the existence and development of new wireless applications and changing ways of accessing and sharing information. The terahertz frequency range (0.1 – 30 THz) can provide largely unoccupied and unregulated bandwidth for fast data transmission, which is not available in the extremely limited spectrum below 60 GHz [1]. Therefore, there are many research groups working towards exploring the spectrum bands at these high frequencies, in order to fulfil the demands for high-speed wireless data transmission and to reduce the speed gap between fibre optic and wireless communications [2–13]. Fibre-wireless in the W-band (75 – 110 GHz) has been the subject of much research work on developing photonics-based systems [2–7]. These are based on two electronic approaches at the receiver, either by using direct or heterodyne detection. In the direct detection scheme, the receiver uses a diode detector for envelope detection such as 20 Gbps on-off keying (OOK) modulation at 93 GHz carrier frequency [2]. On the other hand, heterodyne detection uses a diode mixer and a local oscillator signal source to down- convert the THz signal to a lower intermediate frequency (IF). This enables the use of advanced modulation formats, and increases the bandwidth and sensitivity of the receiver. Several systems have been demonstrated based on this approach for bit rates up to 100 Gbps by using spectrally efficient modulation formats and optical polarization division multiplexing (PDM) for multiple input and multiple output (MIMO) systems [3–5]. A multicarrier channel consisting of two or more optical carriers spaced at exactly the baud rate, i.e. under the orthogonal frequency division multiplexing (OFDM) condition, was demonstrated in optical WDM links to maximise the overall channel data rate and therefore achieve high spectral efficiency [14,15]. This multicarrier approach was also demonstrated for wireless transmission at 60 GHz and in the 75 – 110 GHz band, based on all-optical OFDM to allow the use of highly spectrally efficient optical channels [6]. Data transmission of up to 120 Gbps was also demonstrated in the W-band using three sub-channels and PDM [7].

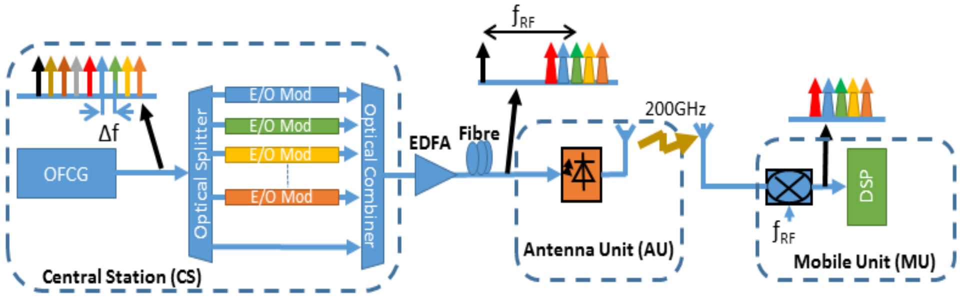

Fig. 1. Block diagram of photonic multichannel system.

The wireless transmission window between 200 GHz and 300 GHz is of strong interest due to low atmospheric transmission losses [8–12]. Data rates of up to 100 Gbps have been achieved in a multichannel THz system at 237.5 GHz by using different modulation formats for each channel and a monolithic millimetre-wave integrated circuit (MMIC) receiver [13]. The wireless transmission at this high frequency is limited to shorter transmission distances than at microwave frequencies due to higher free-space and atmospheric absorption losses. Therefore, the use of well-known wireless over fibre (WoF) technology provides a very good solution to increase the system distribution range and capacity for indoor wireless applications at these high frequencies. This approach also simplifies and reduces the cost of the system antenna units (AUs).

Figure 1 shows the block diagram of a generic multichannel THz wireless over fibre system. At the central station (CS), the optical carriers are generated using optical frequency comb generation (OFCG), which is a very convenient way to create a number of phase correlated optical carriers. These optical carriers are then separated and individually modulated. An unmodulated line is used as a remote local oscillator (LO) at the AU for heterodyne detection. The modulated carriers and the LO are photomixed at the AU and produce a multichannel modulated wireless signal at sub-THz frequencies. This is received by a mobile unit (MU), down-converted to the baseband, and demodulated. Using such a multichannel scheme increases the speed of the data link and reduces the bandwidth requirement for each sub-channel compared to that required for the same aggregate data if only one carrier is used.

In this paper, we demonstrate experimentally a THz wireless communication system operating at rates up to 75 Gbps with a multicarrier scheme using optical heterodyne techniques and a digital coherent receiver. These subcarriers are spaced at the baud rate of the modulation. Wireless transmission at 200 GHz was achieved by using optical heterodyne beating for three optical subcarriers modulated with 5 or 12.5 Gbaud QPSK or for two optical subcarriers modulated with 10 Gbaud QPSK. The system performance was also evaluated back-to-back (B2B) and after 40 km fibre transmission for the three subcarrier 12.5 Gbaud QPSK modulation case. In this system, we used an independent LO laser source for remote heterodyne generation at the AU. At the receiver, the full multicarrier signal was down converted to an IF and then digitized using an analog-to-digital converter (ADC) in a high-speed real-time oscilloscope (RTS). Demodulation was then realized using offline digital signal processing (DSP).

2. Experimental arrangement

The experimental arrangement used to demonstrate the multichannel photonic THz wireless communication WoF system is shown in Fig. 2. A single laser with a linewidth less than 15 kHz at a wavelength of 1554.98 nm was used to generate multiple optical subcarriers, by using an external Mach-Zehnder modulator (MZM). The spacing between the subcarriers was controlled by the MZM driving RF frequency. The optical signal was amplified using an

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erbium-doped fibre amplifier (EDFA) and filtered using a 1 nm bandwidth optical bandpass filter (OBPF).

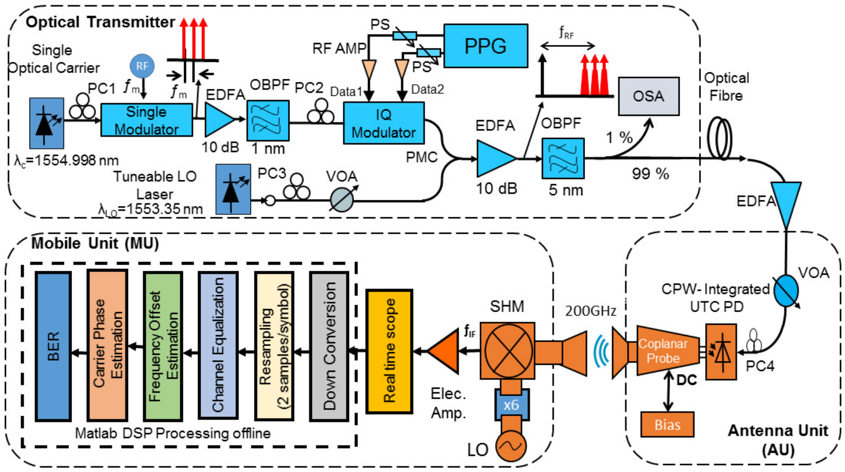

Fig. 2. Schematic diagram of multichannel THz signal experiment.

The output was then fed into an IQ MZM modulator. All subcarriers were simultaneously modulated with QPSK modulation. The I and Q signals driving the MZM were 2^{11}-1 pseudo-random bit sequence (PRBS) patterns obtained from independent outputs of a pulse pattern generator (PPG). The THz signal was generated by optically heterodyning the modulated optical signal with a tuneable LO source spaced by the desired THz frequency. The optical LO source was an external cavity laser with 100 kHz linewidth and 1553.35 nm wavelength, giving a 200 GHz frequency offset between the signal and LO laser. The polarization of the LO source was aligned to that of the signal using a polarization controller (PC) and combined with the optical signal using a polarization maintaining coupler (PMC). The combined signal was then optically amplified and filtered using a 5 nm OBPF to remove out-of-band amplified spontaneous emission (ASE). A 99%-1% optical coupler was used to capture the optical spectrum on an optical spectrum analyser (OSA). After that, the combined optical signal was transmitted over standard single mode fibre to the AU. An optical amplifier and variable optical attenuator (VOA) were used before the AU to evaluate the system performance. At the AU, the optical LO source beats with the multichannel optical signal on an unpackaged uni-travelling carrier (UTC) photodiode with integrated coplanar waveguide (CPW) [16] to generate the THz modulated multichannel signal. The output of the photodiode was coupled to a 20 dBi horn antenna (WR-5.1) using a coplanar millimetre-wave probe.

The modulated THz signal was radiated from the AU antenna and propagated through air to a receiving 20 dBi horn antenna. The received THz signal was initially down-converted to a microwave IF by using a sub-harmonic mixer (SHM) operated with an electrical LO. The electrical LO source was obtained from an RF signal generator using an electronic multiplier to obtain the sixth harmonic of the input RF signal. The SHM mixes the second harmonic of the electrical LO with the received THz signal. The frequency of the RF signal generator was adjusted to place the IF signal within the frequency band of the ADC in the oscilloscope. The mixer, multiplier and horn antenna were mounted on a different stage from the AU assembly to allow the transmission distance to be varied. The received IF signal was then amplified and captured by the RTS whose sampling rate and bandwidth were 80 GSample/s and 36 GHz, respectively. The digitized signal was then processed offline using DSP in Matlab. The detailed DSP block diagrams for signal processing algorithms are shown in Fig. 2. The digitized signal was first filtered to remove the out of band spectral components and limit the added noise. Then, each sub-channel was down converted from the IF by using a digital LO to generate in-phase and quadrature (IQ) baseband signals.

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The digitized IQ baseband signals were demodulated in subsequent steps for each sub-band using methods similar to those used in an optical digital coherent receiver. Signal resampling to twice the baud rate (2 samples/symbol) was performed to reduce the calculation complexity. After that, the third block in the DSP applies a blind adaptive finite impulse response (FIR) filter based on the classical constant modulus algorithm [17]. This filter uses 15 taps and compensates for the frequency selective multipath and interference on the constant envelope modulated signal. The subsequent steps are carrier recovery, which includes frequency offset estimation (FOE) and carrier phase estimation (CPE). The FOE is based on an FFT method while the CPE is based on the fourth power Viterbi-Viterbi algorithm [18,19]. After that, the bit error ratio (BER) was calculated after elimination of the $\pi/2$ phase ambiguity. Based on the robustness of the digital receiver, it is possible to compensate for uncorrelated laser phases and non-ideal link response.

3. Results and discussion

The photonic multichannel wireless THz communication WoF system was demonstrated for three cases by modulating the optical subcarriers with 5, 10, and 12.5 Gbaud QPSK giving a total wireless data rate of 30 Gbps, 40 Gbps, and 75 Gbps. The subcarriers were generated by using a single MZM driven by a 5 or 12.5 GHz RF source. The modulator DC bias was adjusted to obtain three optical subcarriers spaced by 5 GHz or 12.5 GHz for 5 or 12.5 Gbaud QPSK modulation, respectively, or two optical subcarriers spaced by 10 GHz for 10 Gbaud QPSK modulation, by using the optical carrier suppressed (OCS) scheme. Figure 3 shows the optical spectra for the modulated optical subcarriers for the three cases: 3 subcarriers at 5 Gbaud QPSK, 2 subcarriers at 10 Gbaud QPSK, and 3 subcarriers at 12.5 Gbaud QPSK, in each case combined with the optical LO source at 200 GHz frequency offset.

The radiated THz signal was transmitted over a 2 cm free space link. The distance was limited due to the low output power of the transmitter. At the MU, 10 μs long samples of the received IF signal were recorded using the RTS. The received IF signal spectra were obtained by using fast Fourier transform (FFT), and are shown in Fig. 4(a) and (b). Figure 4(a) is the electrical spectrum for three subcarriers with 5 Gbaud QPSK, and Fig. 4(b) is the spectrum for the two subcarriers with 10 Gbaud QPSK. The performance of the system was characterised by measuring BER versus photocurrent squared for the three cases (where the transmitted THz power is proportional to the square of the photocurrent), as shown in Fig. 5; constellation diagrams for the lowest BER values are displayed as insets. Figure 5(a) shows the BER for three subcarriers modulated with 5 Gbaud QPSK (30 Gbps total) at 200 GHz RF signal, with the result for a single carrier shown for comparison. In this case, the optical transmitter was connected to the RAU with just a few metres of fibre (back-to-back, B2B).

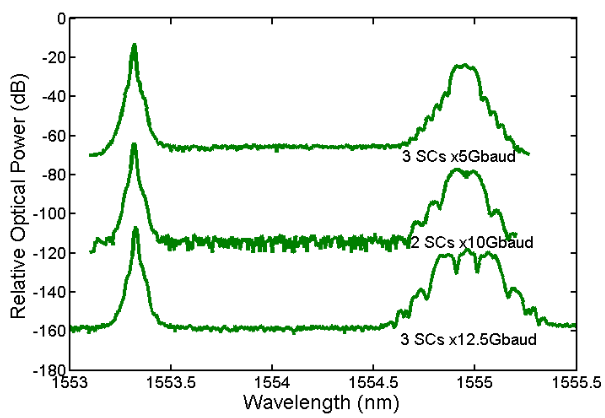

Fig. 3. Optical spectra for, 3 subcarriers 5 Gbaud, 2 subcarriers 10 Gbaud, and 3 subcarriers 12.5 Gbaud QPSK signal.

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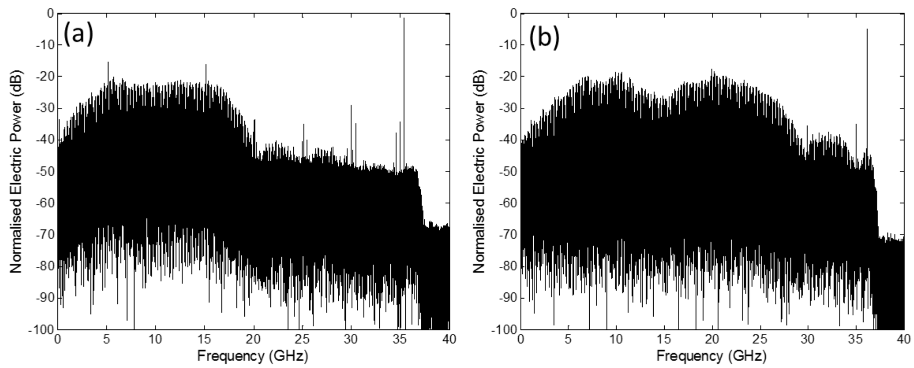

Fig. 4. Electrical spectra using FFT for (a) 3 subcarriers x 5 Gbaud QPSK, and (b) 2 subcarriers x 10 Gbaud QPSK.

The BER of 10^{-3}, which is below typical forward error correction (FEC) levels, was obtained at 0.75 mA photocurrent for the single THz carrier. There is a small increase in photocurrent to achieve the same BER with three subcarriers. The first subcarrier has the worst performance due to the lower subcarrier power compared to the other subcarriers resulting from the non-uniform response of the UTC-PD and the receiver responses. In order to verify this explanation, the combined frequency response for the UTC-PD, coplanar probe, antennas and SHM was measured, as displayed in Fig. 6. This was done by measuring the down converted RF signal after the harmonic mixer. The THz frequency was generated at the UTC-PD by photomixing two free running lasers, tuning one of them to give a frequency difference ranging between 170 and 240 GHz. The response of the UTC-PD and receiver as shown in Fig. 6 is not ideal and causes amplitude distortion and deterioration for the modulated subcarriers. In Fig. 5(b), BER measurements for a single carrier and two subcarriers modulated with 10 Gbaud QPSK (40 Gbps) are shown for B2B operation. The behaviour of the first subcarrier can be seen to be degraded, and this is due to the roll off of the frequency response over 200 GHz. The B2B performance of the system was also evaluated for 12.5 Gbaud QPSK (75 Gbps) for three subcarriers compared with the single carrier (Fig. 5(c)), and after 40 km fibre transmission between the optical transmitter and the AU (Fig. 5(d)). A small penalty after fibre transmission is observed due to dispersion. The constellation diagrams are shown as insets for B2B and after 40 km transmission for subcarrier 2.

It has previously been shown that a similar UTC-PD emitted power of 1 mW at 200 GHz for 23 mA photocurrent [20]. It is interesting to calculate the wireless transmission distance for the various modulation cases if the transmitted THz power were increased by increasing the photocurrent to 23 mA and inserting 30 dBi gain lenses. The THz received power is assumed to be proportional to the photocurrent squared and inversely proportional to the square of the distance (Friis equation). Thus, the wireless distance can be calculated for the low power required for possible data transmission at the FEC limit. Figure 7 shows the calculated wireless distance versus bitrate. As expected, the transmission distance decreases with the bitrate. This shows a trade-off for system complexity and bit rate with transmission distance.

4. Conclusion

We experimentally demonstrated the generation and detection of a multichannel THz wireless system at 200 GHz using photonic signal generation technology and digital coherent detection at the receiver. The system was evaluated for three subcarriers modulated with 5 and 12.5 Gbaud QPSK, or two subcarriers modulated with 10 Gbaud QPSK, giving total bit rates of 30 Gbps, 75 Gbps and 40 Gbps, respectively. The performance of the system was limited by the bandwidth limitations of the UTC-PD and the receiver. In this system, we have shown the capability to transmit high-speed wireless data with high spectral efficiency by forming a multichannel THz signal with subcarrier spacing equal to the channel baud rate. This approach decreases the baud rate on each subcarrier, and eases bandwidth requirements for the electronic components for higher order modulations. Moreover, this system is attractive for small numbers of subcarriers in order to reduce the system complexity and cost.

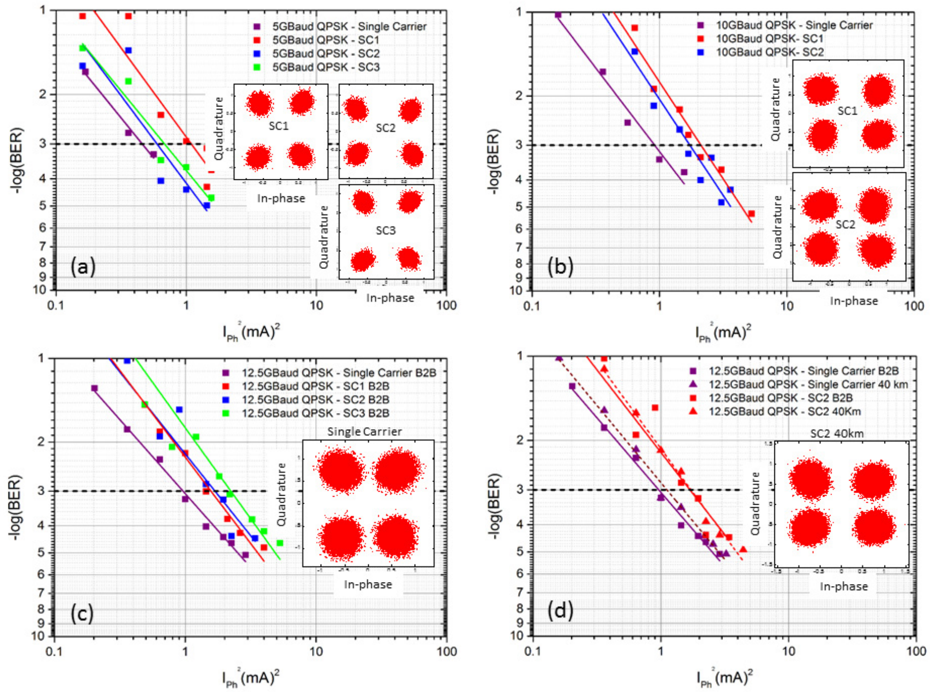

Fig. 5. BER versus photocurrent squared for (a) 5 Gbaud QPSK B2B, (b) 10 Gbaud QPSK B2B, (c) 12.5 Gbaud B2B, and (d) 12.5 Gbaud QPSK B2B and after 40 km.

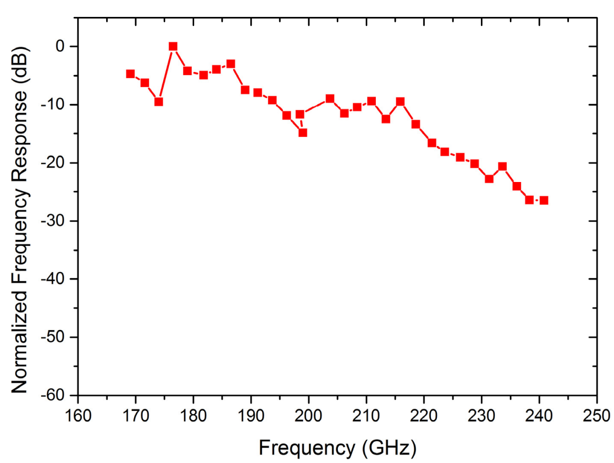

Fig. 6. Normalized RF response for the combined effect of UTC-PD, coplanar probe, antennas and SHM.

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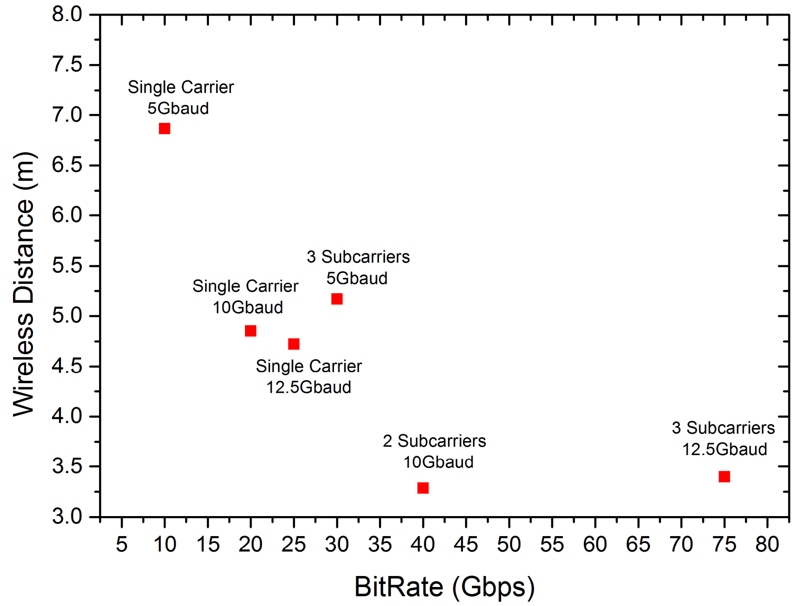

Fig. 7. Calculated wireless distance versus bit rate.

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