TeraHertz Photonics for Wireless Communications

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(Invited Tutorial)

***Abstract*—Optical fibre transmission has enabled greatly increased transmission rates with 10 Gb/s common in local area networks. End users find wireless access highly convenient for mobile communication. However, limited spectrum availability at microwave frequencies results in per-user transmission rates limited to much lower values, e.g., 500 Mb/s for 5-GHz band IEEE 802.11ac. Extending the high data-rate capacity of optical fiber transmission to wireless devices requires greatly increased carrier frequencies. This paper will describe how photonic techniques can enable ultrahigh capacity wireless data distribution and transmission using signals at millimeter-wave and TeraHertz (THz) frequencies.**

***Index Terms*—Broadband communication, microwave photonics, millimeter (mm)-wave generation, optical heterodyne, optical mixing, optical phase lock loops, photonic integrated circuits, semiconductor lasers.**

I. Introduction

There has been explosive growth in wireless data traffic over the last few years, due to both increased user adoption of higher bandwidth services, such as interactive computer gaming and video on demand, and to higher available wireless transmission rates. Extrapolating this growth into the future, we can expect that this category of data will soon represent a significant proportion of total backbone traffic, and that much higher wireless transmission rates will be required to support more sophisticated, bandwidth-intensive applications. Transmission rates in the widely used 2.4 and 5 GHz bands are restricted by the limited spectrum allocated (typically less than 500 MHz in total, depending on jurisdiction). To address this, wider spectral bands have been opened up at millimetre-wave (mm-wave) frequencies for unlicensed (60 GHz) and "lite license" (E-band, 70–95 GHz) use. However, the contiguous bandwidth available in these bands is 8.6 GHz or less, insufficient to support wireless data transmission at "wireline" speeds of, say, 100 Gb/s without employing very high spectral efficiency modulation formats (e.g., 512-QAM) which would reduce link length and which may be difficult to implement at symbol rates of several Gbaud. To enable ultra-high capacity wireless data systems, we therefore need to look to higher carrier frequencies, in particular at

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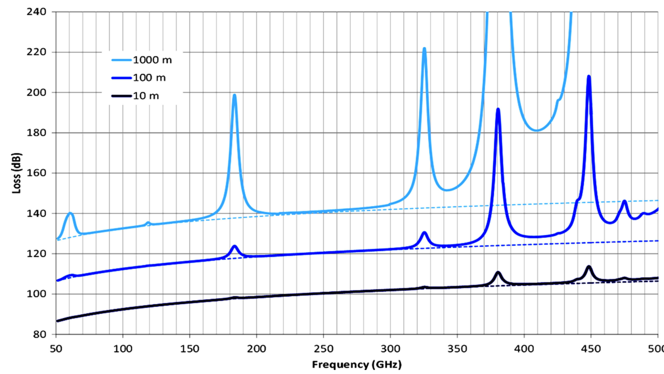

Fig. 1. Wireless link loss, showing free-space path loss only (dotted) and with water absorption (solid). (Water absorption data is for 2.59% $H_2 0$.) [2].

currently unallocated regions of the electromagnetic spectrum above 275 GHz (USA) or 300 GHz (Europe).

At millimetre-wave frequencies and above, wireless propagation characteristics require quite different system architectures to be employed compared to those used for omni-directional WiFi. Free-space path loss, governed by the Friis transmission equation, increases as the square of the carrier frequency and at least the square of the distance between transmit and receive stations. The increased loss at mm-wave frequencies compared to low GHz radio frequencies leads to the need for directional, line-of-sight wireless systems, to avoid the need for excessive power at the transmitter. This architecture is already deployed in the 60 GHz band, using high-gain, steerable, phased-array antennas.

At terahertz frequencies (>100 GHz), not only is the free-space path loss higher still, but absorption due to water vapour becomes an increasing problem [1]. However, as shown in Fig. 1, there are several spectral windows in the frequency range 200 to 450 GHz where the additional loss due to water absorption is low, at least for short transmission distances (100 m or less). Each of these windows has a bandwidth of several tens of GHz, making them suitable for ultra-high capacity wireless links.

Optical wireless communication (OWC) in the near infrared (IR) region is the other competitive wireless solution to THz communication systems for multi-Gbps data transmission. A 100 Gbit/s OWC system has previously been reported, employing higher order modulation formats and polarization multiplexing [3]. 1 Tbit/s was recently achieved in a free space system by multiplexing four beams with different values of orbital angular momentum [4]. However, OWC links are very susceptible to atmospheric environment conditions such as air turbulence and humidity fluctuation (the scintillation effect), fog, smoke, and rain [5]. Air turbulence and humidity fluctuations cause

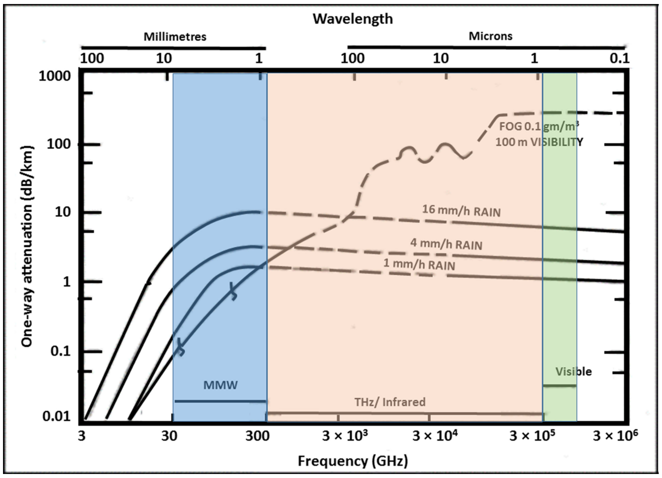

Fig. 2. Comparison of THz with optical wireless transmission [6].

TABLE I
REPRESENTATIVE LINK BUDGET CALCULATION

Data rate	20	Gb/s	
Source power	0	dBm	
Tx antenna gain	30	dBi	
Transmission loss	103	dB	At 340 GHz; link length = 10 m; absorption negligible
Rx antenna gain	30	dBi	
Received power	**−43**	**dBm**	
IF power	−53	dBm	10 dB down-conversion loss
IF input equivalent noise	−170	dBm/Hz	
E_b/N_0	**14**	**dB**	
System margin	7	dB	c.f. BPSK or QPSK at BER = 10^{-3} (E_b/N_0 = 6.8 dB)

refractive index changes, and in consequence distort the wave's phase front. Fog and smoke cause attenuation in the IR communication path more than two orders of magnitude higher than in a THz communication link at 300 GHz (see Fig. 2). On the other hand, THz waves are mainly attenuated by atmospheric water vapor, and oxygen absorption, while the smoke and dust particles have minor effects on the THz waves. This is due to their relative small size compared to the THz wavelengths. Other advantages of THz over OWC are that the sensitivity of THz detectors can be much greater than that of IR photodetectors, and that THz links are not affected by ambient light. In addition, precautions are required with OWC to ensure that the IR transmitted power is below eye-safe power levels.

II. THz Over Fibre System

Assuming a wireless transmission rate of several tens of gigabits per second, we can estimate the required power at the receiver input to be of the order of –50 dBm, while, as discussed in Section V, the emitted power from a photonics technology THz source at a frequency of approximately 300 GHz is unlikely to exceed 0 dBm. Yet Fig. 1 shows that the transmission loss at this frequency exceeds 100 dB, even for a 10 m link. Thus, even from an order-of-magnitude calculation, we can conclude that very high gain antennas (>25 dBi) will be required to construct an operational wireless system, and then only over short range. A more detailed representative link budget calculation is given in Table I, confirming these basic conclusions.

Given the limited range expected from such THz communication systems, and their directional nature, we propose the THz-over-fibre systems concept illustrated in Fig. 3. Optical fibres are used to connect to distributed THz wireless antennas, which give high-bandwidth capacity to fixed or mobile devices. The limited propagation distance at THz carrier frequencies allows well-defined microcells and frequency re-use. The architecture illustrated has already been used successfully for lower frequency wireless-over-fibre systems [7]–[10]. Possible applications include high-resolution multimedia services

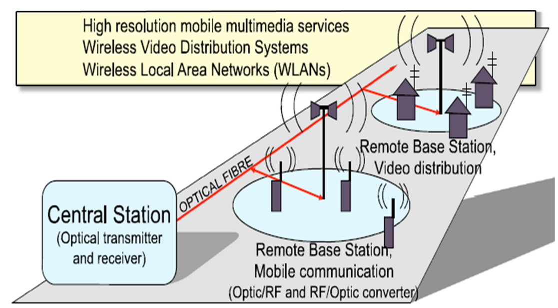

Fig. 3. THz-over-fibre systems concept.

to mobile devices, wireless video distribution, and very high-speed wireless LANs. Clearly, this scenario calls for the remote THz antenna units (AUs) to be low cost, since large numbers will be required. Transmitting baseband data to the AUs requires complex frequency generation and modulation technology to be placed in the hostile outdoor environment with severe cost implications. The alternative approach of centralised THz wireless signal generation reduces AU functionality to photo-detection and amplification, with the lower data rate uplink requirements met by simple modulation schemes [7], [9], [10]. This approach will now be described in more detail.

III. Heterodyne Signal Generation

Currently, the most widespread commercial systems for broadband THz generation are based on femtosecond (fs) pulse sources using mode-locked lasers and photoconductive switches. The application for these systems is mainly high-resolution 3-D imaging based on the time and depth resolution enabled by the short pulses. However, these systems have large power consumption (in the kilowatt range), and their spectral purity in the THz band is limited by laser jitter. In addition, the cost and the size of most short-pulse systems are also considered a drawback. Wireless communications and related applications require compact, low-power consumption sources, and high spectral purity. Nevertheless, recent progress in photonic technologies for optical communication systems can enable the

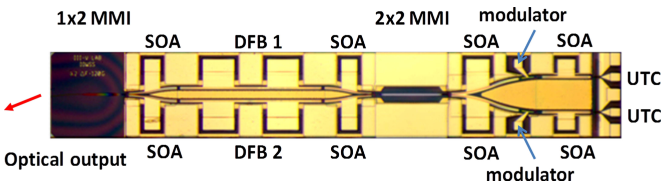

Fig. 4. Microscope view of the dual DFB dual wavelength source [13].

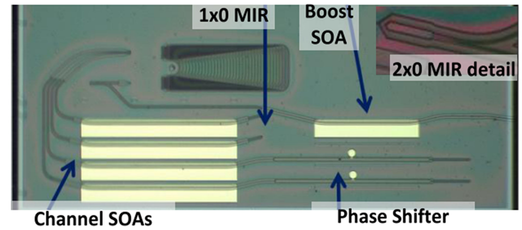

Fig. 5. Microscope view of the fabricated AWG laser dual wavelength source [12].

generation of compact and power-efficient coherent THz systems with high spectral purity. The most promising photonic technique for optical signal generation is the heterodyning of two optical sources with different wavelengths that are mixed in a photodiode (PD) or photomixer. The generated signal is an electrical signal at a frequency equal to the frequency difference between the two optical sources, and exhibits phase noise fluctuations resulting from linewidth and relative frequency fluctuation of the two laser sources.

Photonic integration of a monolithic dual-wavelength source for mm- and THz-wave generation is attractive as it results in more compact sources and can give improved spectral purity. One approach is based on the monolithic integration of distributed feedback (DFB) lasers, where two DFB lasers were grown side by side and the wavelengths combined using a Y-junction [11]. This approach is compact and both lasers encounter the same environmental fluctuations, thus reducing noise in the heterodyne signal. Fig. 4 shows a fully monolithically integrated mm-wave transmitter, where two DFB lasers and optical combiners for the dual wavelength generation, electro-optic modulators (EOM) for data modulation, and integrated high-speed photodiodes for millimetre-wave generation are all integrated on the same chip [12]. In addition to these components, semiconductor optical amplifiers (SOAs) are also implemented to compensate for the optical losses. A major advantage of this design is that it provides continuous tuning of wavelength spacing between the two monolithically integrated DFB lasers, with tuning of the mm-wave signal over the frequency range from 5 to 110 GHz demonstrated. However, its drawback is the relatively broad line-width of the optical modes (>300 kHz) [13].

Another approach to photonic integration of dual wavelength sources is based on an arrayed waveguide grating (AWG) laser using multimode interference reflectors (MIR). The AWG was initially used as the wavelength selector with a fixed frequency spacing in a wavelength division multiplexing (WDM) system. Fig. 5 presents one realization of this AWG laser approach, produced using an InP technology multi-project wafer run [12], [14], [15]. The structure shows four AWG channels with 1 mm long SOAs in each channel, providing the laser gain medium. The AWG central wavelength is 1550 nm, the channel spacing is 0.96 nm (120 GHz), and the free spectral range is ∼6 nm (700 GHz). The two bottom channels are combined with an electro-optic phase shifter (PHS) to allow wavelength tuning. All the channels are terminated with MIRs, allowing the cavity length to be defined independently of the chip dimensions, and reducing optical losses in the channels. Although the emission of the wavelengths is fixed by the channel pass-bands of the AWG, this structure shows very narrow optical mode linewidths (<200 kHz) without the need for any additional phase noise reduction scheme. This structure was demonstrated to generate a RF carrier at 95 GHz with a 250 kHz linewidth, which is the narrowest RF linewidth from a free-running, dual-wavelength semiconductor laser [14], [15].

IV. Uni-Travelling Carrier PhotoDiode

One of the key enabling technologies for the development of photonics enabled THz communications has been the uni-travelling carrier (UTC) PD [16]. Its importance can be assessed through the key technical requirements for THz photonic systems: high saturation power, high responsivity and high 3 dB bandwidth. Indeed it has been shown that moving the absorber into the highly p-doped region where holes are the majority carrier offers the advantage that only electrons will drift through the depletion region with their much higher velocity than holes and as a consequence the space charge effect will not be as strong. Therefore UTC devices inherently offer higher bandwidth and higher saturation power.

The next key element is responsivity, as to offer the required enhanced bandwidth, UTC devices require a thin absorber, which limits responsivity in vertically illuminated designs. The obvious solution to the problem is to use edge-coupled waveguide devices that offer several advantages in addition to enhanced responsivity, including distributed power dissipation, giving higher saturation powers, and the possibility of using travelling wave (TW) design to enhance frequency response. Several solutions have been described in the literature with the object of optimizing different aspects of the design. Here, we summarise their performance and assess them comparatively using a figure of merit $\eta_{\mathrm{THz}} = \mathrm{P}_{\mathrm{THz}}/\mathrm{P}_{\mathrm{opt}}^2$, that combines output power and responsivity in one useful parameter.

First one should look at commercially available detectors for the mm-wave and THz range, where only two manufacturers are offering devices. One set of devices based on waveguide-based PIN phtodetectors can operate up to 100 GHz with responsivities up to 0.5 A/W and output powers of up to 1 mW. The other device is a vertically illuminated UTC-PD that can emit good levels of power up to 2.5 THz but with a relatively low responsivity compared to waveguide devices. Recent work

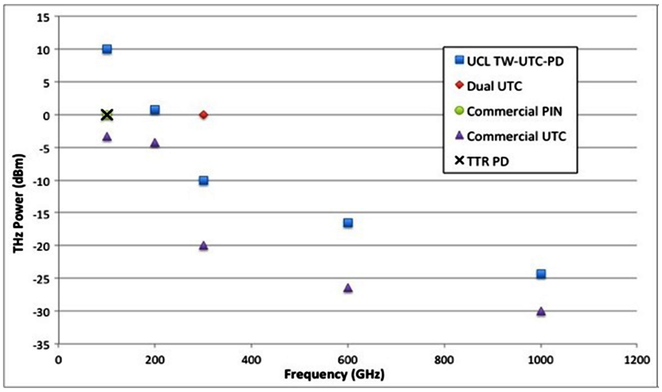

Fig. 6. Summary of best output power from selected published emitters [17]–[20]. (PD: photodiode, TTR: triple transit region, UTC: uni-travelling carrier, UCL TW-UTC-PD: travelling wave UTC-PD designed in University College London (UCL)).

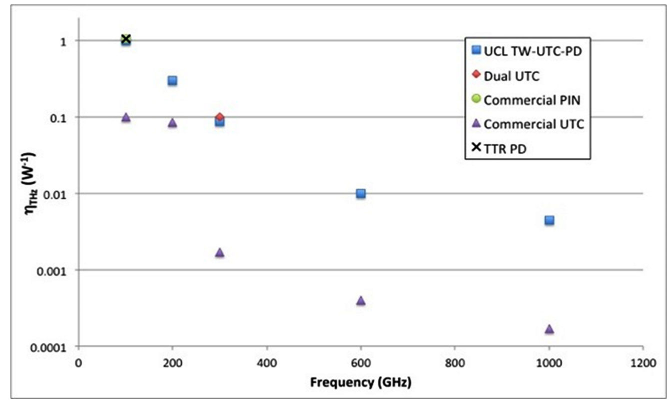

Fig. 7. Figure of Merit of selected published PD emitters [17]–[20]. (PD: photodiode, TTR: triple transit region, UTC: uni-travelling carrier, UCL TW-UTC-PD: travelling wave UTC-PD designed in University College London (UCL)).

integrated two UTC devices on the same chip and their combined power output showed record high power of 1 mW at 300 GHz [17]. To date, the best results in waveguide based devices have been obtained in work when the standard UTC structure was used in combination with an optimized pseudo TW design [18], [19]. The devices were not full travelling wave structures as this can only be achieved in periodic structures. However the quasi match of optical and electrical velocities in the device still enabled an improvement in the frequency response roll-off from 40 to 30 dB/decade. These devices were demonstrated both with coplanar contacts for integration into 50 Ω systems and with integrated antennas. They have demonstrated record output power up to 1 THz. Finally, recent work has resulted in further optimization of the carrier transport within the photodetector to enable higher non-linearity and higher bandwidth. The work looked into clamping the field in the absorber to help accelerate the electron towards the depletion region thus enhancing the overall response of the photodetector [20]. Interestingly, this work demonstrated a 3 dB bandwidth higher than 110 GHz and output power up to 1 mW with no sign of saturation.

In Fig. 6, the performance of different selected devices (representing the best results published to date) are shown in terms of output power. It is clear from this that the combination of TW design and UTC structures offer an advantage compared to UTC-only structures or PIN waveguide structures. One should also note that for triple-transit region (TTR) PDs these are the first published results and the power is not saturated so higher power should be achievable from such devices. The TTR-PD has been designed to ensure the carriers drift at saturation velocity or faster which maximizes the output power and increases the bandwidth limitation. However, as mentioned above, from the system point of view it is important ultimately to assess the efficiency of the device and look at the figure of merit (see Fig. 7). From that figure it is clear that waveguide devices have a further advantage in terms of efficiency particularly at frequencies above 200 GHz. One can also note that at 100 GHz the use of UTC structure or PIN structure does not affect the figure of merit and only the waveguide design is the cause of the increased efficiency.

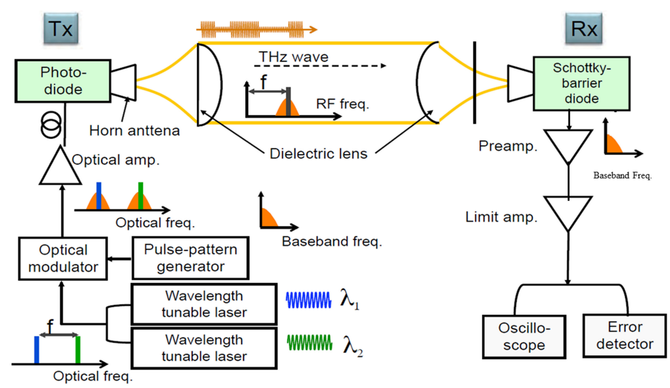

Fig. 8. Sub-THz wireless transmission at 300 GHz using Schottky barrier diode [28].

From this set of results it is clear that structures with fast carrier transport (such as UTC or TTR) combined with travelling-wave design offer the best performance overall as THz emitters that could be used in communication systems.

V. Heterodyne System Demonstration

Over the past few years, high-speed sub-THz communication links have developed quickly due to the availability of the necessary hardware components. Modulation of the optical sources using modulators developed for optical-fibre communication systems allows high symbol rate complex modulation formats to be easily generated at mm-wave and sub-THz frequencies. At the receiver, Schottky barrier diodes (SBDs) are available that can be used for either direct or heterodyne detection. In the direct detection scheme, SBD detectors are used as square-law detectors for amplitude-modulated signals. Many research works have demonstrated using OOK modulation at W-band and over 100 GHz [21]–[29]. Recently, real-time error-free data transmission was demonstrated for a 40 Gbps channel at 300 GHz and less than 1 m wireless transmission by heterodyning two tuneable optical light sources as shown in Fig. 8 [28]. Polarization multiplexing was also used to double the bitrate in a multiple

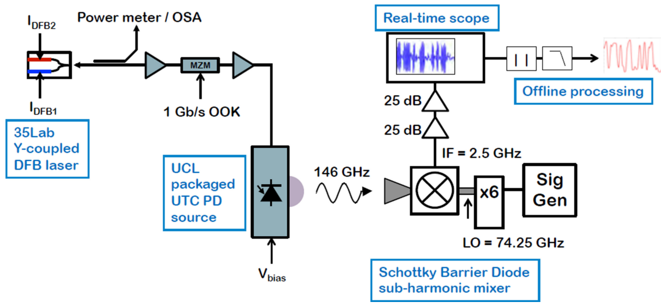

Fig. 9. 146 GHz THz wireless link using offline digital coherent detection [42].

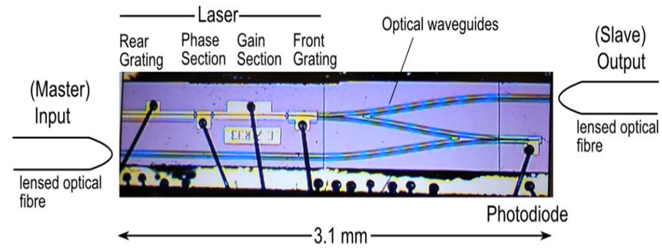

Fig. 10. Microscope picture of the PIC of the OPLL [63].

input multiple output (MIMO) system for 48 Gbps dual channel at 300 GHz [28]. However, these polarization-multiplexed systems suffer from a significant cross interference between the wireless channels, which in turn reduces the transmission quality of the system.

The direct detection scheme is very popular for THz wireless communication due to its simple and cost-effective configuration, but has lower sensitivity and needs the use of mm-wave amplifiers to extend the transmission range. Heterodyne detection, on the other hand, improves the receiver sensitivity and allows the use of vector modulation schemes. Thus, the transmitted data rate increases, and the system impairments can be removed through digital processing functions. In many recent experiments, the received THz is first down-converted to an intermediate frequency (IF), typically using an harmonic mixer. Then, the IF signal is recorded and processed offline. Several research groups have reported systems based on digital signal processing and off-line demodulation [30]–[52]. Using an integrated dual-wavelength laser similar to those discussed in Section IV, a transmission system using heterodyne detection of a 1 Gbps OOK at 146 GHz was reported, as shown in Fig. 9 [42]. Both wavelengths were modulated externally, and converted into mm-waves using UTC-PD packaged with a 6 mm diameter Si-lens. Data rates up to 100 Gbps (QPSK or 16 QAM) were demonstrated at 237.5 GHz using a microwave monolithic integrated circuit (MMIC) receiver at the receiver [46]. At 240 GHz, a successful transmission of 30 Gbit/s using 8 PSK modulation was achieved, and recently a THz wireless communication system for higher carrier frequency at 400 GHz was developed operating at up to 46 Gbps OOK by using a THz photo-mixer integrated with a broadband antenna [48], [53]. However, these systems suffer from the phase noise on the generated THz waves due to the uncorrelated phase noise of the two optical sources.

VI. Coherent Signal Generation

The spectral purity of the generated THz signal is limited by the linewidths and the frequency precision of the heterodyned lasers. It is desirable to have a THz source with high spectral purity for high-resolution spectroscopy and communication systems. If two free-running lasers are used, the linewidth of the THz signal will be determined by the sum of the linewidths of the two lasers [54]. For tunable semiconductor lasers, the full width at half maximum (FWHM) linewidth ranges from a few MHz to perhaps a few tens of MHz. Widely tunable external cavity lasers with FWHM linewidths of about 100 kHz are readily available, allowing a considerable improvement in the linewidth of the THz signal, but they are significantly larger and more expensive, and are best suited to laboratory use. To give the desired ‘synthesiser’ performance, the difference between the frequencies of the heterodyned lasers needs to be precisely set, while large improvements in the phase noise (linewidth) of the THz source can be achieved if the two lasers are phase locked.

An optical frequency comb generator (OFCG) provides an attractive solution for generating a number of phase-correlated optical signals, the spacing between the comb lines being set with high precision by a microwave synthesizer. Several techniques have been developed over recent years and compact sources are now available, either fiber or semiconductor based [55]–[57]. A simple approach is to use a phase modulated laser. This can be combined with a resonator to extend the span to over 4 THz in a compact package.

The comb lines required for heterodyning can be selected using conventional optical filters, but more effective filtering can be achieved by using optical phase locking techniques such as optical injection locking (OIL) [58] or optical phase lock loops (OPLLs) [59]–[61]. OIL is a simple technique achieved by injecting coherent photons into a slave laser cavity. Above a certain threshold, dependent on the detuning between the lasers, the slave source will be fully phase locked to the master through the stimulated emission process. A drawback of OIL is its narrow and asymmetric stable locking bandwidth, but the tracking range can be improved by use of the optical injection phase lock loop (OIPLL) technique [62]. However, locking with a frequency offset between the slave and the master laser, required to produce a heterodyne signal that is not a multiple of the comb spacing, is not possible. Where this is required, an OPLL can be used, comparing the phase of the beat signal between the master and slave lasers against an external RF reference to derive a feedback signal to lock the slave to the master with a tunable offset defined by the reference signal. Delay around the loop is critical to achieving suppression of heterodyne phase noise, and photonic integration can help here. The OPLL photonic integrated circuit (PIC) shown in Fig. 10 reduces the optical delay to a few tens of picoseconds, although a carefully designed low-delay external electronic feedback circuit is also required to close the loop to achieve phase locking. The InP-based monolithic PIC contains

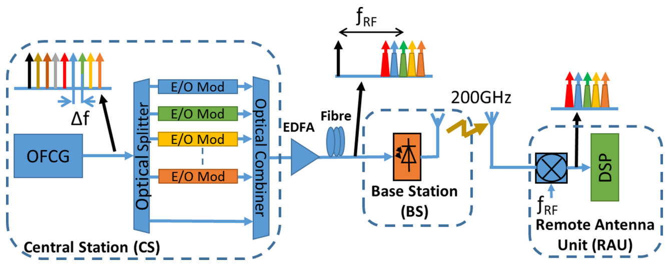

Fig. 11. Schematic diagram for photonic multichannel system.

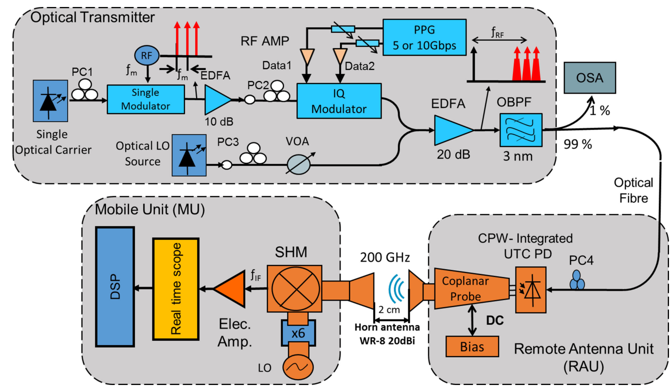

Fig. 12. Schematic diagram for multichannel THz signal experiment.

a broadly tuneable (∼8 nm), buried distributed Bragg reflection (DBR) laser, a PIN photodiode, passive optical waveguides and Y-junction couplers and splitters used as interconnections [63].

VII. Coherent System Demonstration

A coherent communications system using advanced modulation formats was first demonstrated in a compact broadband photonic wireless 60 GHz transmission system based on a cascaded RF and data modulation approach [64]. When two optical tones from a comb source are separated through optical filters, then modulated and recombined, their relative phase can change due to temperature and vibration induced refractive index changes in the optical path length and due to phase noise generated by optical amplifiers. This causes phase instability and degrades the system performance. To counter this, phase correlation between the two optical carriers can be improved by using the piezo phase shifters with closed loop control at the transmitter [28]. In order to use all the effective bandwidth, all of these systems require high bandwidth electro-optic components to use the large available THz bandwidth.

Other researchers have shown interest in increasing the data rate by using multiple channels at sub-THz frequencies. These have been demonstrated for long-haul WDM systems to increase the spectral efficiency, where two or more optical carriers are modulated and spaced by the baud rate, referred to as coherent optical orthogonal frequency division multiplexing (CoOFDM) [65], [66]. Fig. 11 shows the block diagram of the concept of a generic multichannel THz wireless on fibre system. At the central station, the optical carriers are generated using OFCG techniques. These optical carriers are then separated and individually modulated. An unmodulated line is used as a remote local oscillator (LO) at the remote antenna unit (RAU) for heterodyne detection. The modulated carriers and the LO are photomixed at the RAU and produce a multichannel modulated wireless signal at sub-THz frequencies. Then, these sub-THz channels are 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 with that required for the same aggregate data if only one carrier is used. This has been first realized in the 60 and 75–110 GHz wireless band showing bitrates up to 24 Gbps using three subcarriers modulated with 5 Gbaud QPSK [31]. This approach was also applied at 237.5 GHz to transmit single input and single output (SISO) wireless communication for a bit rate of 100 Gbps using three subcarriers modulated with different modulation formats (QPSK and QAM) [47]. MIMO transmission was also demonstrated using these multichannel system combined with polarization multiplexing at 92 GHz to achieve 120 Gbit/s. In such systems, the use of multiple channels can significantly enhance the transmission capacity to multi-gigabit or even terabit wireless transmission and relax the requirement for the optoelectronic component bandwidth. Nagatsuma *et al.* have explored the use of extremely large available bandwidth from 450–720 GHz using 1.6 Gbps modulated with OOK [28].

Recently, we have experimentally demonstrated the generation and detection of a multichannel THz wireless system at 200 GHz using baseband photonic technology and digital coherent detection at the receiver [67]. Fig. 12 shows the experimental system for the multichannel THz signal generation, modulation and detection. The system was evaluated for three subcarriers modulated with 5 Gbaud QPSK, or two subcarriers modulated with 10 Gbaud QPSK, giving total bit rate of 30 and 40 Gbps, respectively. Optical subcarriers were generated by modulating a single light source using an external intensity Mach–Zehnder modulator (MZM) with an electrical RF source. The spacing between the subcarriers was controlled by the driving RF frequency and the modulator DC bias. The optical signal was then amplified and fed into an external IQ MZM modulator for data modulation with 5 or 10 Gbaud QPSK modulation per subcarrier. The THz signal was generated by optically heterodyning the modulated optical signal with a tuneable LO source spaced by the desired THz frequency. The combined signal was then amplified using an erbium doped fibre amplifier (EDFA) and filtered using a 3 nm optical bandpass filter to remove out-of-band amplified spontaneous noise. At the RAU (no fibre transmission), the optical LO source mixes with the multichannel optical signal and generates the THz modulated multichannel signal. 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. The received THz signal was initially down-converted to a microwave IF by using a sub-harmonic mixer, operated with an electrical LO, and then was amplified and captured by the real-time scope whose sampling rate and bandwidth were 80 GSample/s and 36 GHz, respectively. The digitized signal was then processed offline using DSP in Matlab.

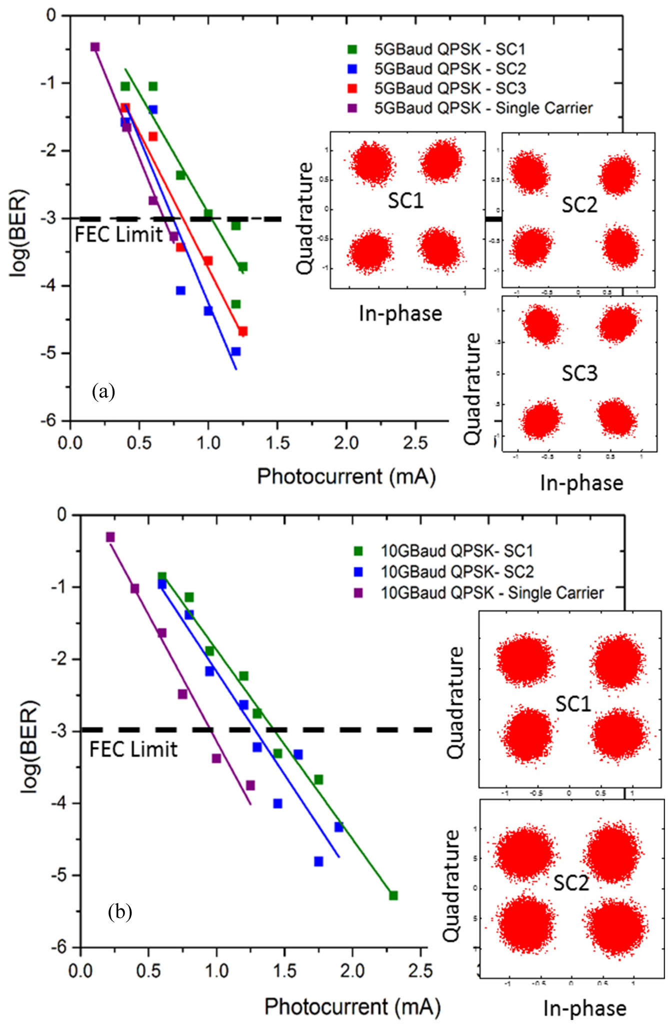

Fig. 13. BER versus photocurrent for (a) 3 subcarriers $\times$ 5 Gbaud, and (b) 2 subcarriers $\times$10 Gbaud QPSK.

The performance of the system was measured using BER versus photocurrent compared with the single channel as shown in Fig. 13 for both cases and the constellation diagrams are displayed as insets for the lowest BER values. The transmitted electrical power is proportional to the photocurrent squared. Based on measurements on similar UTC-PDs, we expect the power emitted from the UTC-PD at 200 GHz and 1 mA photocurrent to be $\sim$1–2 microwatts [68]. The measured BER was obtained below the forward error correction limit of 10^{-3} at 0.6 mA photocurrent for the single THz carrier, with a small penalty for the subcarriers in a multicarrier system. The first subcarrier has the worst performance due to the non-uniform response of the UTC-PD and the receiver responses [67].

VIII. Conclusion

The use of the THz spectral region for wireless communications offers the possibility to achieve transmission rates comparable to those achieved in wired local area networks. However, the properties of the free space channel require different approaches to those adopted for lower frequency lower capacity systems. In particular, THz wireless systems will have shorter free space ranges and will require beam steered rather than omni-directional antennas. Optical fiber transmission provides a convenient method for extending the overall reach of a THz wireless system and builds on extensive commercial use of wireless over fibre systems at microwave frequencies. THz wireless signal generation can leverage technologies used for coherent optical fiber transmission, with consequent off-the-shelf component cost savings. Photonic integration technology can play a key role in improving the phase noise performance and reducing the size and cost of THz wireless over fiber systems.

A key component of THz wireless over fiber systems is the photomixer. Quasi-travelling wave UTC-PDs offer the highly desirable combination of high optical responsivity, large bandwidth and high THz output power.

Future work will be needed on the development of low cost electronic technologies for mobile units and on the development of active antenna array technology to give the required antenna gain and beam-steering capabilities for THz wireless over fiber systems. MIMO systems based on wavelength division multiplex are a further possible area for investigation although path and scattering loss considerations are likely to constrain the application of MIMO techniques at THz frequencies.

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