Telecommunications technology-based terahertz sources

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A review is presented of continuous-wave terahertz sources based on the optical heterodyne generation (photomixing) technique, that make use of optical components and fabrication techniques originally developed for the 1550 nm optical fibre telecommunications window. The uni-travelling carrier photodiode is identified as a key component for conversion of optical to terahertz power, and the state of the art is summarised in terms of terahertz power generated at various frequencies. An approach based on phase locking the heterodyned lasers is described, which enables terahertz signals to be generated with extremely high spectral purity and frequency accuracy, and progress in developing the photonic integrated circuits required for its implementation is reported. Finally, possible future developments in the field are discussed.

Introduction: The terahertz (THz) band of the electromagnetic spectrum (100 GHz to 10 THz) is of great interest for understanding various chemical, biological, and astronomical phenomena through spectroscopic analysis [1, 2], and has a range of technological applications [3], including materials, medical and security imaging and screening [4–6], and short-range, high capacity wireless communications [7]. A major impediment to rapid progress in these areas is the lack of availability of compact sources of THz radiation at low cost and with low power dissipation. This is particularly true of high spectral purity, high output power continuous-wave (CW) THz sources [8]. In this Letter, we summarise recent work on CW THz generation by photonic techniques, which leverages the mature, reliable components and fabrication and optical integration techniques that have been developed for optical fibre telecommunications.

Optical heterodyne generation: Many existing THz systems already rely on photonics-based sources, in the form of the Auston switch [9], in which a femtosecond pulse of light generates a correspondingly short burst of photocurrent in a photoconductor across which an electric field is applied. The pulse of photocurrent has a spectrum with components extending through the THz band. The photoconductor is commonly made from low-temperature-grown GaAs (LT-GaAs), requiring the optical pulse source to operate at a wavelength of 850 nm or less. Titanium-sapphire femtosecond lasers are often used, but these are bulky, power hungry, and expensive. However, the pump-probe time-domain spectroscopy (TDS) configuration usually employed allows the amplitude and phase of the THz signal to be obtained with high sensitivity.

An alternative, CW, photonic generation technique is optical heterodyne generation (OHG), sometimes called photomixing. The outputs of two lasers are combined, perhaps amplified, and directed onto a suitable photomixer (a square-law detector). The resulting photocurrent contains a component at the frequency corresponding to the difference in frequency between the two lasers, which can easily be set to be in the THz band. OHG at THz frequencies was first demonstrated using an LT-GaAs photomixer, with power detected at frequencies as high as 3.8 THz [10]. The maximum CW power achieved at 1 THz with LT-GaAs photomixers is 2 μW [11].

Compared to the GaAs wavelength of around 850 nm, components and technologies for the 1550 nm optical communications band are far more numerous and mature. InP-based active devices developed at 1550 nm include widely tunable, singlemode semiconductor lasers, high-speed optical detectors, and semiconductor optical amplifiers (SOAs). There has been huge effort directed at developing techniques for integrating active semiconductor components with passive optical waveguides, splitters/combiners, etc., in order to create photonic integrated circuits (PICs). Erbium-doped fibre amplifiers (EDFAs) are also readily available, as are fibre-based femtosecond modelocked lasers suitable for 1550 nm TDS systems.

The main spectral bands used for long-haul optical fibre communications (the C- and L-bands), defined by the operating bandwidths of EDFAs, are each 4 THz or more wide. Thus, a single EDFA can be used to amplify the combined outputs of the two lasers in an OHG system prior to photomixing, making generation of high optical powers (100 mW or more) straightforward. SOAs, which can be easily integrated with lasers, etc., also have gain bandwidths of several THz, although output powers are generally limited to tens of milliwatts. Tunable semiconductor lasers with tuning ranges exceeding the width of the C-band have been developed, while simpler designs can give around 1 THz tunable range [12]. Thus, two tunable lasers centred on appropriate wavelengths can be combined to give an OHG source with output frequency tunable from DC to several THz. Such a tunable narrowband source, when used with an appropriate detector, could be used to probe the transmission or reflectivity of a sample directly. Compared to the pulsed TDS approach, such a system has potential for being cheaper and more compact, and may enable more rapid scanning [13]. However, if incoherent detection is used, less information is obtained.

LT-InGaAs photoconductors have been investigated as photomixers for operation at 1550 nm [14], but it is difficult to achieve performance approaching that of LT-GaAs at 850 nm. Specifically, the dark conductivity of LT-InGaAs is generally too high to allow the use of the high bias voltages required to give the necessary high electric field. One proposed solution involves more complicated, multilayer epitaxial structures [15]. Alternatively, we can draw on high-speed photodiode (PD) technology similar to that employed in optical communications systems [16], which can now deliver waveguide coupled *pin* PD modules with responsivity higher than 0.7 A/W and a −3 dB bandwidth of 100 GHz. For photomixing, we are not constrained to operate within the −3 dB bandwidth, but can make use of the reduced response at higher frequencies.

The frequency response of a PD is ultimately determined by the interplay between transit time and device capacitance. A short transit time calls for a thin absorber region, but this increases capacitance, which can result in performance being resistance capacitance (RC) time constant limited. In addition, in conventional PD designs, the photocurrent is carried by both electrons and holes, and the lower velocity of holes can further reduce performance. Uni-travelling carrier (UTC) PDs [17] address both of these issues by using separate absorber and depletion (transport) layers, with the transit time determined only by the faster electrons. A further advantage of having a single travelling carrier is the significant reduction of the space charge phenomenon, leading to enhanced optical power handling capabilities. The highest −3 dB bandwidth reported for any 1550 nm photodiode, 310 GHz, was obtained with a UTC photodiode with a very small area (5 μm^2) and terminated with a 12.5 Ω load [18]. The frequency response was obtained by taking the Fourier transform of the pulse response of the UTC, and further showed that the relative response remained above −15 dB to more than 1 THz.

There is an intrinsic trade-off between bandwidth and efficiency for PDs where the light is incident in the direction normal to the epitaxial layers of the device, since high speed requires a thin absorbing layer. Waveguide coupled PDs ease this limitation, by allowing longer interaction lengths and thin absorber layers to be combined. They also allow the use of travelling-wave designs [19], which give a slower frequency response roll-off, and are more compatible with integration. Record levels of THz figure of merit (P_{THz}/P_{opt}^2, where P_{THz} is the THz power generated and P_{opt} is the applied optical power) ranging from 1 W^{-1} at 110 GHz to 0.0024 W^{-1} at 914 GHz have recently been reported using waveguide-fed travelling-wave UTC PDs [20].

PDs can be integrated with THz antennas to give compact emitters, with the overall dimensions determined by the antenna design and the minimum operation frequency. Resonant designs can give higher output over a limited frequency range. Examples of these are shown in Fig. 1.

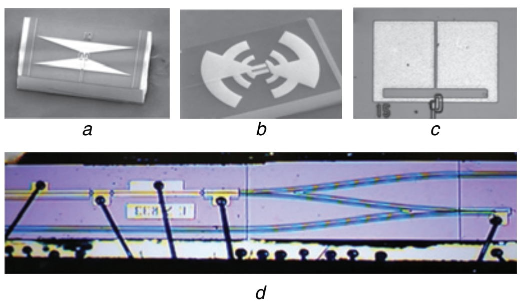

Fig. 1 *Integrated components for THz sources: travelling-wave UTC PDs integrated with bow-tie antenna (Fig. 1a), log-periodic antenna (Fig. 1b),*

narrow band resonant antenna (Fig. 1c), monolithically integrated OPLL (Fig. 1d)

Fig. 2 summarises key results for the power generated using the OHG technique at various frequencies in the range 100 GHz to 1.5 THz [17, 20–24]. All of these results have been obtained with UTC PDs; conventional *pin* PDs have been found to give powers between 10 and 20 dB lower [17, 21]. Below 150 GHz, power measurements were made by conventional RF techniques, using coplanar probes or rectangular waveguides to extract the signal from the PD chip. At higher frequencies, PDs with integrated antennas were used, with the power measured using an InSb hot-electron bolometer or a Thomas Keating power meter. In the frequency range 100 to 120 GHz, output powers of 10 to 20 mW have been obtained [17, 22], at mean photocurrents of around 30 mA, demonstrating the power handling capabilities of the UTC. The detected power falls rapidly with frequency (at 30–40 dB/decade), owing to the reduced PD frequency response. Nonetheless, broadband sources have demonstrated outputs of 300 μW at 300 GHz and 2.6 μW at 1.04 THz [17]. UTC-PDs with integrated narrowband antennas, which allow the transit-time limited performance to be approached, have been demonstrated with output powers of 148 μW at 457 GHz and 24 μW at 914 GHz [23]. Approximately 1 μW of power has been obtained at 1.53 THz by OHG using 1550 nm band components [21], and frequencies as high as 1.8 THz have been reported [25]. The detection of higher frequency signals is currently limited by the ability to resolve the signal against background noise.

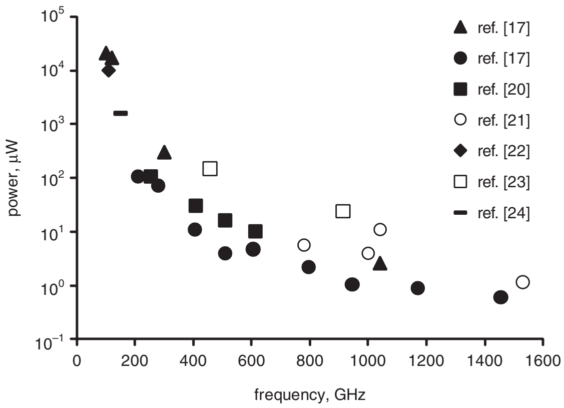

Fig. 2 *THz power generated by OHG at different frequencies*
Open symbols, narrowband antennas; filled symbols, broadband antennas

THz synthesisers: The basic OHG technique described above has limitations with regard to its frequency precision and spectral purity. The accuracy of the frequency generated depends on a precise knowledge of the frequency difference between the two lasers being heterodyned. Wavemeter measurements would allow arbitrary frequency THz signals with a precision of perhaps 100 MHz (0.8 pm), while interferometric frequency control can give resolution of the order of 1 MHz [26]. In addition, the spectral purity of the THz signal generated is limited by the linewidths of the heterodyned lasers. For high-resolution spectroscopy and communications systems, it is desirable to have a THz source with the precision, spectral purity, and ease of use of a microwave synthesiser. When combined with coherent detection techniques, as described below, this would also give higher sensitivity.

If free-running lasers are used, the linewidth of the THz signal will be determined by the sum of the linewidths of the two lasers. For tunable semiconductor lasers, giving the most compact implementation, each laser might have a full width at half maximum (FWHM) linewidth of a few MHz to perhaps a few tens of MHz. Widely tunable external cavity lasers with FWHM linewidth 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. A scheme which makes this possible is illustrated in the left-hand side of Fig. 3. An optical frequency comb generator (OFCG) provides a frequency reference, the spacing between the comb lines being set with high precision by a microwave synthesiser. The two lasers used for the heterodyne source are phase locked, using optical phase-lock loops (OPLLs), to two of the comb lines, separated by an appropriate frequency difference. Since the comb lines are phase locked to each other, so are the two heterodyne lasers, giving a low phase noise THz signal after photomixing. To generate arbitrary THz frequencies (not just those defined by multiples of the comb line spacing), the lasers can be phase locked to their respective comb lines with a frequency offset determined by further microwave synthesisers. Thus by appropriate choice of comb lines and offset frequencies, any THz frequency can be generated, with an absolute accuracy determined by that of the microwave synthesisers, which can be a few tens to hundreds of Hertz. Similarly, the phase noise of the THz source at low offset frequencies can be reduced to close to the combined phase noise of the microwave synthesisers, making THz sources with sub-hertz linewidth a possibility.

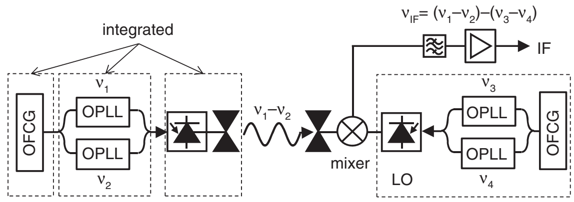

Fig. 3 *Coherent-detection CW THz spectroscopy system, using OHG source and local oscillator*

There are various OFCG schemes which can give spectra extending over 1 to 2 THz, but most promising because of their small size and potential for integration are approaches based on semiconductor laser technology, e.g. modelocked [27] or frequency modulated [28] laser diodes.

The OPLL acts as an ultra-narrow filter to select the required comb line and additionally provide the required frequency offset. For low phase noise performance when using lasers with linewidths of the order of 1 MHz, a short propagation delay (approximately 1 ns) around the OPLL feedback loop is essential [29]. This requires a micro-optics [30] or integrated optics approach to reduce the optical delay as far as possible and hence ease the delay requirement on the electronics section of the loop.

There have been several recent demonstrations of OPLLs implemented using PIC fabrication technologies that were originally developed for 1550 nm telecommunications applications. Ristic *et al.* report a monolithic OPLL PIC based on InP, and demonstrated homodyne and offset phase locking of one of the on-chip lasers to the other [31]. Two such OPLLs, capable of being locked to an external source, would be required for the optical heterodyne synthesiser application proposed here.

Within our own group at UCL, we have been pursuing two photonic integration technologies for OPLLs. The first is also a monolithic approach, which integrates a DBR laser with approximately 1 THz tuning range with waveguides, MMI couplers and a photodiode [32]. The output of the DBR laser is combined with an external input on an integrated photodiode (Fig. 1). The heterodyne signal from the photodiode is mixed with an external RF reference in the electronic feedback circuit to give offset locking. We have also demonstrated a similar scheme using hybrid integration of InP-based components on a silica-on-silicon motherboard with waveguide optical interconnections [33]. Since our aim is to use two OPLLs to create a phase-locked heterodyne source, two DBR lasers are integrated on the same InP chip, mounted on a silica-on-silicon daughterboard, and then flip-chip bonded onto the motherboard. A frequency offset between the tuning ranges of the two DBR lasers is designed in, enabling frequency differences of up to about 2 THz to be obtained. Both monolithic and hybrid integrated approaches result in low optical delays (3 and 50 ps, respectively), although the monolithically integrated approach results in a much more compact PIC. The short optical path length enables the overall loop delay requirements to be met when combined with suitable low-delay electronics [33].

Fig. 4 shows the spectrum of a signal synthesised by OHG, locking to two lines in an OFCG separated by 99 GHz. One comb line is selected by using one half of a hybrid dual OPLL PIC, while the other comb line is selected by optical injection locking of a discrete DBR semiconductor

laser [33]. A travelling-wave UTC PD with −3 dBe bandwidth of 110 GHz was used to generate the millimetre-wave signal. The next step for both monolithic and hybrid integrated OPLLs is to demonstrate a dual OPLL PIC and show that this gives a low phase noise THz heterodyne signal that can be precisely tuned.

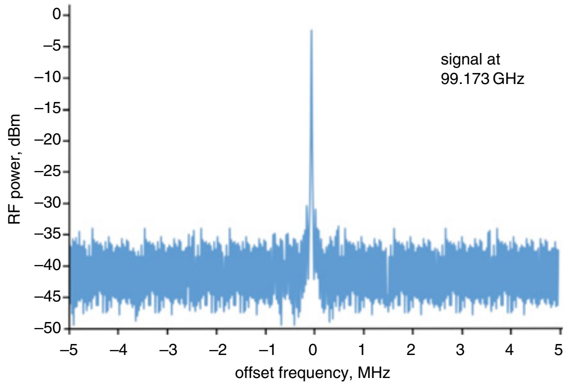

Fig. 4 *Spectrum of high-purity millimetre-wave signal synthesised by OHG, using OPLL to lock to optical frequency comb*

Future prospects: As described in this Letter, the key building blocks required to construct a compact, low power consumption THz synthesiser are nearly in place. However, a full detection system with the same characteristic is not fully demonstrated yet. Therefore, the immediate future goal is to use these blocks to demonstrate applications such as heterodyne detection spectroscopy and wireless communications, using the complete scheme illustrated in Fig. 3. This uses photonic heterodyne generation both as a source in the transmitter section and to generate a THz local oscillator in the receiver and as such takes full advantage of the high spectral purity of the signal for increased detection sensitivity. By using different source and LO frequencies, the signal is downconverted in the mixer to an RF or microwave intermediate frequency, simplifying recovery of the signal compared to homodyne detection [34]. Possible mixer technologies include Schottky diode mixers, superconductor-insulator-superconductor mixers and hot electron bolometer mixers [35], and LT-InGaAs [15]. UTC-PDs have been used as optically pumped upconversion mixers at 60 GHz [36], and may also prove useful for downconversion of THz signals.

Beyond that, we envisage the whole THz source (i.e. the OFCG, dual OPLL, PD and antenna) being integrated into a single component with dimensions of a few millimetres (for monolithic integration) or a few centimetres (hybrid integration). Indeed, it may be possible to fully integrate the photonic and THz components of the spectrometer in Fig. 3 on a single chip, enabling ‘lab-on-a-chip’ spectroscopic analysis of small samples [37, 38].

Wireless communications in the THz band presents great opportunities for very high bit rate transmission, because of the high carrier frequency and available wide spectral windows, particularly in the unregulated spectrum above 300 GHz. A wireless link using a 120 GHz carrier generated by OHG has already been demonstrated [39]. However, the enormous free-space path loss at these frequencies dictates that such links will be short-range and highly directional. To achieve useful transmission distances, higher output power sources will be required. The integrated sources discussed here are limited in their output power by a combination of the optical power available from the lasers, and the responsivity and frequency response of the PD. Whilst improvements in all of these can be expected over coming years, they are likely to be relatively modest, perhaps collectively amounting to an order of magnitude at frequencies of around 1 THz. Ultimately, the THz power that can be generated by a single PD will be limited by the electrical power dissipation that can be tolerated. At RF frequencies (below 6 GHz), output powers of over 250 mW have been generated using PDs with diameters of 34 μm or more, for power dissipation of around 1 W [40]. However, generation of signals at THz frequencies will always require smaller PDs, to reduce the RC limitation, reducing the power dissipation at which device damage occurs by perhaps an order of magnitude. To get around this problem, higher total optical power could be distributed to an array of PDs [41] with integrated antennas, thus also allowing shaping and steering of the THz beam by phased-array techniques. The THz power generated then becomes limited by the optical power available. With fibre amplifier technology capable of delivering watts of optical power, increases in power by at least an order of magnitude could be possible at all frequencies, with larger gains at higher frequencies as improvements to the PD frequency response are made in parallel. Output powers at 1 THz exceeding 1 mW are therefore not implausible. However, the use of external high-power fibre amplifiers will result in sources being larger and having higher power consumption. To overcome this, one could imagine arrays of complete OHG sources, all phase locked to the same OFCG, and with their outputs combined using phased array techniques. A compact, high output power, THz source such as this is in principle achievable using the integration techniques outlined in this review, but represents a step change in the complexity of PICs, posing significant challenges for researchers and developers.

Acknowledgments: The authors acknowledge the important contribution of the Centre for Integrated Photonics to this work in terms of devices and integrated systems fabrication and useful discussions on the design. Financial support from the European Commission (within the framework of the European integrated project IPHOBAC under grant 35317) and from EPSRC under grants EP/E027520/1 (PHITSIN), EP/D502233/1 (PORTRAIT) and GR/S86631/01 (PRINCE) is acknowledged for aspects of the work reported in this Letter.

12 July 2010
doi: 10.1049/el.2010.1917

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