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Advances in terahertz communications accelerated by photonics

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Almost 15 years have passed since the initial demonstrations of terahertz (THz) wireless communications were made using both pulsed and continuous waves. THz technologies are attracting great interest and are expected to meet the ever-increasing demand for high-capacity wireless communications. Here, we review the latest trends in THz communications research, focusing on how photonics technologies have played a key role in the development of first-age THz communication systems. We also provide a comparison with other competitive technologies, such as THz transceivers enabled by electronic devices as well as free-space lightwave communications.

It is known that data traffic is increasing exponentially, with Internet protocol traffic expected to reach over 130 exabytes per month by 2018[1]. The fastest-growing part of that increase is on wireless channels, as mobile users increasingly make use of online services. Such an increase in the network capacity requires much higher wireless transmission rates in numerous connection links between each base station, between a base station and an end-user device, between each end-user device, and so on. The prospective data rate for wireless communications in the market place will be 100 Gbit s^{-1} within 10 years (ref. 2). Historically, since the first microwave wireless link developed by Guglielmo Marconi in the early twentieth century, carrier frequencies used for wireless communications have been increasing[3,4] to meet bandwidth requirements, up to the recent development of wider spectral bands at millimetre-wave (MMW) frequencies, such as 60 GHz and ~70–95 GHz (ref. 5). However, the total allocated bandwidth is less than a regulation bandwidth, that is, 7–9 GHz, which will ultimately limit the total throughput of the channel to an insufficient level for the increasing demand.

It is obvious that the use of an even higher carrier frequency in the THz range (0.1–10 THz) is mandatory when the minimum bandwidth reaches several tens of GHz. The initial demonstrations of THz wireless communications were conducted using both pulsed and continuous waves, which were generated from photoconductors and photodiodes excited by pulse lasers and intensity-modulated lasers, respectively[6–8]. The continuous-wave wireless link, which employs a 120-GHz band, is the first commercial THz communication system with an allocated bandwidth of 18 GHz (that is, between 116–134 GHz), which offers 10 Gbit s^{-1} with an on–off keying (OOK) modulation and 20 Gbit s^{-1} with a quadrature phase shift keying (QPSK) modulation for a demonstrated transmission distance of over 5 km (refs 9,10). Now, lots of research groups worldwide have developed communication links at frequencies over 100 GHz. In particular, above 275 GHz, there is a possibility to employ extremely large bandwidths of over 50 GHz for radio communications, as these frequency bands have not yet been allocated to active services in the world.

General considerations and expectations

From the Shannon formula[11], the information capacity, C, or the data rate is associated with the bandwidth, W, and the signal-to-noise ratio, S/N, as is given by C (bit s^{-1}) = $W\log_2(1 + S/N)$. High data-rate THz wireless systems could be possible due to the large available bandwidth, W, even though the signal power, S, generally tends to decrease with the carrier frequency. However, one of the big obstacles in the use of THz waves in wireless communications is the atmospheric attenuation[12], as shown in Fig. 1a. Transmission distance is limited by the attenuation, and the appropriate carrier frequency or frequency band should be determined by application: ~100–150 GHz for long-distance (~1–10 km), <350 GHz for medium-distance (~100 m–1 km) and <500 GHz for indoor (~10–100 m) communications. Above 600 GHz, there are another two windows for indoor communications: ~625–725 and ~780–910 GHz. When the frequency exceeds 1 THz, the radio wave undergoes significant absorption by water vapour and oxygen molecules in the atmosphere, and is attenuated by less than one-tenth at only 1-m propagation distance, which is still useful for near-field communications (<0.1 m). In addition, one cannot ignore attenuation from rainfall[13]. This attenuation is mostly independent of frequency in the range above 100 GHz, and the attenuation is about 10 dB km^{-1} in the case of heavy-rain conditions (25 mm h^{-1}), and should be considered for outdoor applications.

A free-space path loss (FSPL)[14], L_B, which is given by $L_B = (4\pi df/c)^2$ with link distance, d, carrier frequency, f, and the velocity of light, c, is physically inevitable. In the first THz communication window (~200–320 GHz) and for up to kilometre-range systems, the link budget is very close to the FSPL, and is not really degraded by the atmospheric contribution (Fig. 1b). For 1 km (usual backhaul size in cellular networks), THz systems will have to deal with 140 dB total losses at a carrier frequency of 300 GHz. High-gain antenna structures have to be considered to compensate for this fundamental limitation. Indeed, since the antenna gain, G_A, is given by $G_A = 4\pi A\eta(f/c)^2$ with antenna area, A, and antenna efficiency, η, the FSPL can be compensated by the gain of both transmitter and receiver antennas; total antenna gain in the link can easily be made more than 100 dBi at 300 GHz, though such antennas are highly directive. Even if technology will increase the output-power capability, isotropic THz links may not be practically feasible. Beam steering or beam forming with phased array antennas would be useful, as has already been introduced in 60-GHz wireless technologies (www.sibeam.com/Products.aspx and ref. 15).

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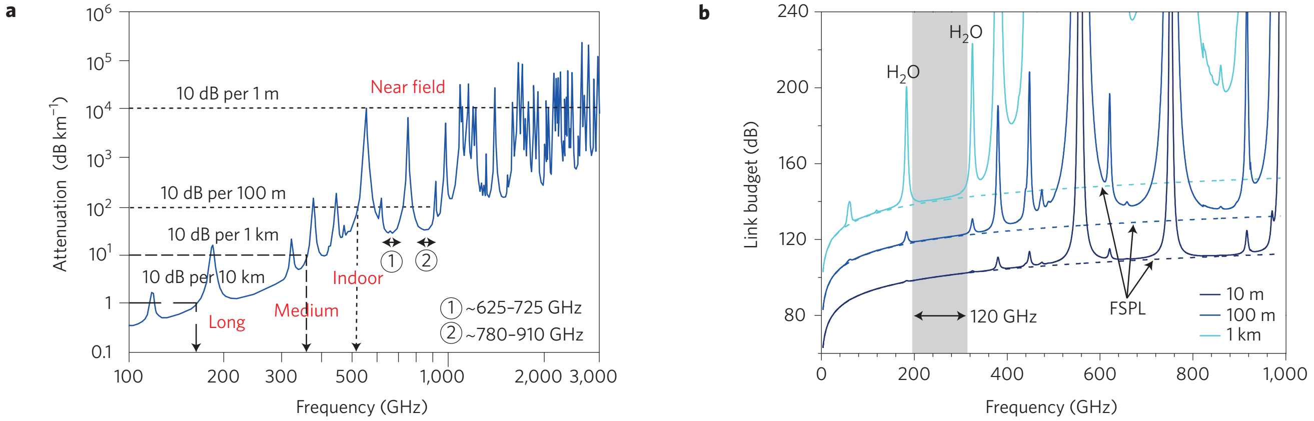

Figure 1 | Impact of atmospheric attenuation of THz waves. a, Transmission distance is limited by the attenuation, and the appropriate carrier frequency or frequency band is chosen by application, for example, long-distance, medium-distance, indoor and near-field communications. Above 600 GHz, there are two windows for indoor communications: ~625–725 GHz and ~780–910 GHz. **b**, Link budget at THz frequencies for the isotropic case (Tx and Rx antennas with 0 dBi gain) at 23 °C and 2.59% water content in air composition (tropical climate). The grey-shaded area highlights the first useful band for THz communications, featuring a total 120-GHz bandwidth. FSPL, free-space path loss.

Depending on the above link-distance criteria, promising applications of THz communications include front- and backhauling of base stations in femto cells, wireless local area networks in smart offices, wireless personal area networks in smart homes, near-field communications such as kiosk downloading, wireless connections in data centres, device-to-device communications, and so on (Fig. 2a). In these applications, another key aspect is the power consumption, which is directly related to the transmitter and receiver architectures, and strongly impacts the real THz link scenario (mobile user or fixed point to point). For an outdoor link, spectral efficiency has to be taken into account, both for point-to-point and Earth-to-space links[16], to limit interference with established systems[17]. For indoor links, where frequencies can be re-used over several rooms, for example, simple amplitude coding and duobinary can be used not only to drastically simplify the receiver architectures using primitive direct detection but also to limit the receiver energy requirements.

One of the frequently raised concerns for THz communications is the comparison with free-space optics (FSO) communications using infrared light waves. As we described in the beginning of this section, it would be logical to multiply the carrier frequency by several orders of magnitudes and use optics as the carrier[18–20]. This would definitely offer more bandwidth while using the same base technology as photonics-based THz technologies for the modulation of signals. However, FSO faces lower tolerance in alignment, and requires stronger beam-steering control systems, although the development of a multiple-input multiple-output-based system is promising[21]. For outdoor applications, the optics suffer more than two orders of magnitude higher losses in foggy conditions than THz waves[22], which again would limit the use of FSO systems[23]. Ultimately, cost, size, performance and usability would determine which becomes more adopted in the marketplace.

Photonics-based approaches

From the various THz technologies continuously developed, system-level efforts have led to the use of both photonics- and/or electronics-based technologies. First key advances have been realized using III–V semiconductor technologies at a ‘lab’ integration level, where each device or component separately developed is optimized to show the highest performance. Among this scheme, the highest data rates have been reached using photonic devices as transmitters, combined with cutting-edge III–V THz electronic devices as receivers.

Photonics-based techniques offer the unique opportunity to ensure a high modulation index is obtained with optical-to-THz conversion using photomixing, high-speed amplitude and/or phase coding introduced from optical coherent network technologies, which have been widely developed since 2000s and are now a mature platform for fibre-optic core networks[24]. A unique feature of using photonic devices relies on the possibility to address multi-carrier transmission easily by adding optical laser lines to the optical driving signals. In the THz range, photonic III–V semiconductor (InP) devices have been led by uni-travelling carrier photodiodes (UTC-PDs) pushed up to the order of milliwatt power levels around 300 GHz in several laboratories[25,26], paving the way for the realization of first indoor THz radio links with ‘optical’ data rates: for example, 50 Gbit s^{-1} at 300 GHz using real-time amplitude signalling[27], 60 Gbit s^{-1} at 200 GHz (ref. 28), 46 Gbit s^{-1} at 400 GHz (ref. 29) and up to 100 Gbit s^{-1} in the 100-GHz band[30] using digital signal processing and a complete solid-state receiver with active elements working at such carrier frequencies[31]. Future developments towards the 100 Gbit s^{-1} target will drive the progress of THz communication systems. To tackle the power limitation of photonic devices, the future of photonics-based THz systems may be based on the combination of power amplifiers associated with photomixers, but performances would require a monolithic association of the two devices, which has not been achieved in the THz range. Also, THz links development may also benefit from the large developments of silicon photonics-based systems, for example, at 180 GHz a Ge-based photomixer in a Si photonics platform has shown an effective isotropic radiated power of >−15 dBm from ~170–190 GHz (ref. 32).

Since the early ages of THz communications, photonics has played a key role as a ‘technology driver’ for the THz transmitter (Tx). At the reception side, electronics-based approaches remain more efficient to achieve usable receivers (Rxs). Among THz receivers, several options have been tested for data wireless links in the THz regime. The most common is a waveguide-integrated detector using GaAs Schottky barrier diodes (SBDs)[33] initially developed for radio-astronomy applications. Harmonic mixers using GaAs SBDs have also been investigated, featuring not only efficient real-time amplitude signalling[34] but also efficient down conversion from high-level THz modulation to the microwave and MMW domains[35], opening the way to ‘coherent fibre networks to THz radio bridges’ that could be used in a future network convergence (fibre and ultrahigh-speed radio), as described later.

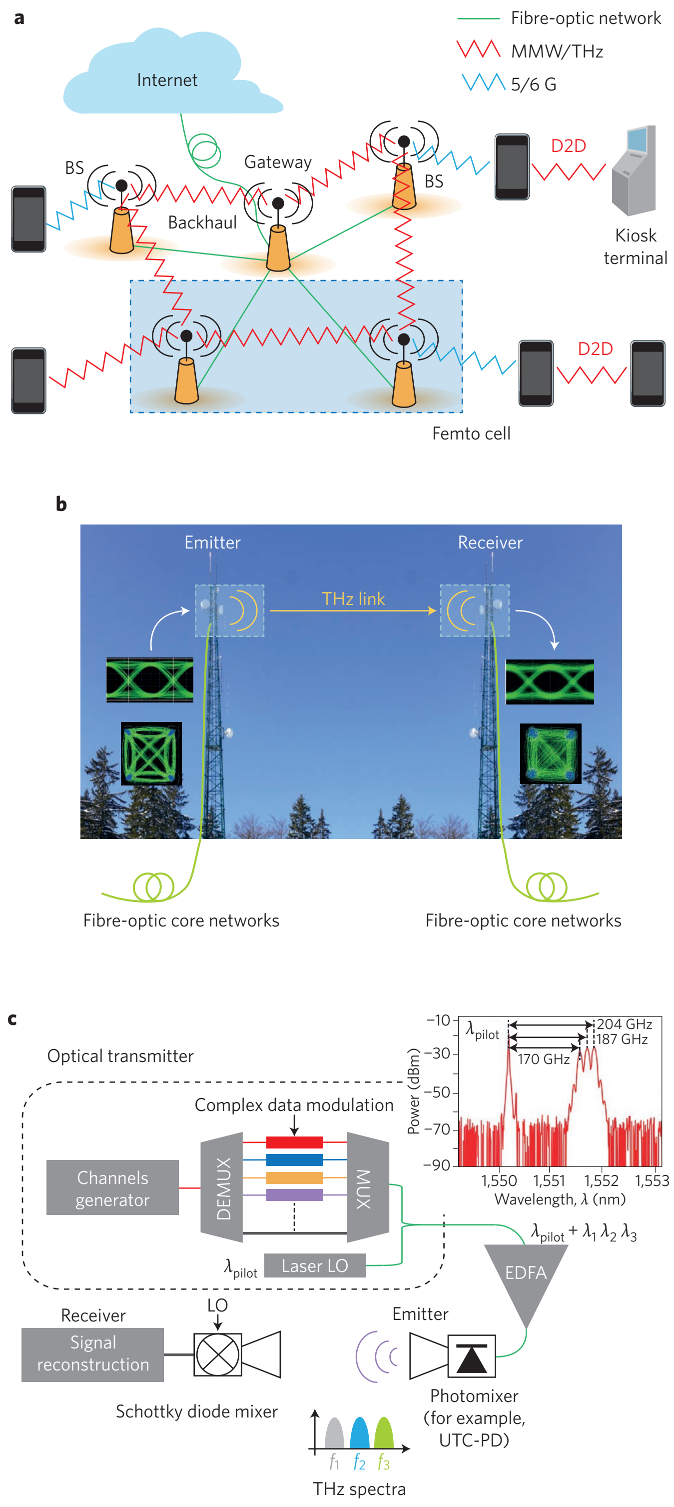

Figure 2 | Application of THz links in networks. a, Prospective view of THz links to connect base stations (BSs) for backhauling, as well as the device-to-device (D2D) interface. **b**, Concept of fibre-to-THz radio bridges for a seamless connection between a fibre-optic link and a THz link ensuring the same data modulation formats with no latency. **c**, Configuration of multi-carrier reconfigurable and frequency-agile THz links using photonics. DEMUX and MUX are optical demultiplexer and multiplexer, respectively; EDFA, erbium-doped fiber amplifier; LO, local oscillator; UTC-PD, uni-travelling carrier photodiodes. Inset: Optical spectrum at the input to the photomixer containing one pilot laser line and three data modulated signals.

From the perspective of photonics-based THz transmitters for spectrally efficient data links, the optical feed or source requires special attention[27]. Indeed, the spectral content of a THz signal is directly related to the two optical laser lines driving photomixing devices such as photodiodes. Ultimate performance would require the optical feed featuring low jitter and narrow linewidth in the optical domain. Practically, at least the spectral separation between two laser lines have to be locked; in other words, optical laser lines should be correlated with each other to ensure a low phase noise and a limited frequency drift of the beating frequency used as a carrier in the THz domain. Several techniques have been demonstrated to achieve spectrally narrow photomixing based on laser heterodyning: for example, microchip[36] or integrated lasers[27], independent lasers with frequency stabilization[37], dual-mode lasers[38–40], Brillouin fibre lasers[41,42], comb generation of a single laser line and active phase stabilization[43], or III–V semiconductors on silicon dual-mode lasers[44].

Some features can be highlighted in these systems for THz communication applications. First, the use of one single laser line, modulated at f_0 (from a microwave reference) to create an optical frequency comb, further filtered using optical components to obtain Nf_0 at a carrier frequency, requires an active phase stabilization to tackle random phase drifts in fibre cables. This kind of scheme has already been used to achieve real-time performance at 100 GHz (ref. 43), 200 GHz (ref. 34) and 300 GHz (ref. 27). As the frequency increases, the frequency comb technique is limited by the increasing number of teeth to be generated in a continuous-wave regime (rather than a common pulsed regime). In this case, a high modulating power to generate the required number of teeth and/or the use of highly nonlinear optical modulators is mandatory.

Other techniques use dual-frequency tunable lasers producing the two required lines by design (that is, without the optical frequency comb), with tunable spectral separation from microwave[38] up to sub-THz[40] or THz[39] frequencies. In these techniques, the common mode noise is decreased as two laser modes experience a single cavity and the spectral content is relatively invariant with frequency. Thus, the same phase noise performance (free running) can be obtained from 100 GHz to beyond 1 THz, which is a major advantage of photonics. Tuning from d.c. to 900 GHz is achieved by the use of an electro-optic effect inside the cavity[39]. This electro-optic effect can also be used to frequency lock the THz emission owing to an external phase-locked loop, fed by the down-converted signal of a THz heterodyne detection. Thus, the phase noise achieved is also limited by the multiplied electrical reference used to down convert the THz wave. Moreover, to reduce the constraints on the phase-locking circuits, fibre lasers can be considered to reduce the natural optical linewidth of the free-running optical source (usually MHz performance from standard lasers used in optical communications). For example, Brillouin fibre lasers[45] have been shown to reduce the intrinsic linewidth of an optical feed, down to the kHz level[42] around 300 GHz, and below 100 Hz around 1 THz (ref. 46).

All electronics-based approaches

Beyond the use of electronic receivers combined with a photonic Tx, first full electronic demonstrations have been realized using standard waveguide devices that were initially developed using GaAs technology for radio astronomy (Herschel, ALMA programmes). Using commercially available sources (multiplier chains), mixers and detectors, researchers have demonstrated the first ‘lab level’ THz links, in many configurations, for example, direct amplitude modulation of the source input[47], which is very simple but bandwidth limited and not suitable for phase coding of the THz beam, as the frequency multiplication is essentially nonlinear. Using harmonic mixers as up-converters, linear behaviour can be obtained and the first complex signals have been transmitted in the THz

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Table 1 | Reported THz systems and actual highest performanes achieved using several technologies.

Data rate (Gbits^{-1})	Distance (m)	Frequency (GHz)	Multiplexing	Technology (Tx/Rx)	Modulation	Bit error rate (type)	Reference	CDP (Gbits^{-1} km)	Year
200	0.5	100	Polarization (two channels)	PD/SHM	QPSK	10^{-3}, offline	30	-	2013
10	5,800	120	-	UTC + HEMT/ HEMT	ASK	$<10^{-9}$, real time	9	58	2012
11	3	130	-	40-nm CMOS (Tx/Rx)	ASK	$<10^{-9}$, real time	57	0.033	2015
75	0.02	200	Frequency (three channels)	UTC-PD/SHM	QPSK	10^{-5}, offline	28	-	2014
100	20	237.5	Frequency (three channels)	UTC-PD/HEMT	Up to 16 QAM	2×10^{-3}, offline	31	-	2013
64	850	240	-	Metamorphic HEMT/MMIC	QPSK	5×10^{-3}, offline	60	-	2015
64	1	300	-	MMIC (Tx/Rx)	QPSK	-, offline	51	-	2015
40	10	300	-	UTC-PD/SHM	QPSK	10^{-4}, offline	35	-	2015
48	0.5	300	Polarization (two channels)	UTC-PD/SBD	ASK	10^{-10}, real time	33	0.024	2013
3	50	340	-	SHM/SHM	16 QAM	10^{-10}, real time	64	0.15	2014
32	0.5	385	-	UTC-PD/SHM	QPSK	10^{-5}, offline	61	-	2015
46	2	400	-	UTC-PD/SHM	ASK	10^{-3}, offline	29	-	2014
30 or 50	20 or 0.5	300 or 330	-	UTC-PD/SBD or SHM	ASK	10^{-9}, real time	27	0.6 or 0.025	2015
60	0.5	400	Frequency (four channels)	UTC-PD/SHM	QPSK	10^{-3}, offline	62	-	2015
2.5	3	625	-	Multiplier/SBD	Duobinary (ASK)	$<10^{-9}$, real time	63	0.0075	2011

CDP is the capacity × distance product. It is a figure of merit for communication systems assuming the maximal regeneration-free distance in real-time conditions[66]. Most of the highest data rates of THz wireless systems have been achieved using THz photonics technologies at the transmitter (Tx), mainly based on high-speed photodiodes. A combination of polarization and frequencies are now investigated to increase the data rate in the available THz bandwidth. ASK, amplitude shift keying; HEMT, high-electron-mobility transistor; MMIC, monolithic microwave integrated circuit; PD, photodiode; QAM, quadrature amplitude modulation; QPSK, quadrature shift keying; Rx, receiver; SBD, Schottky barrier diode; SHM, sub-harmonic mixer; UTC, uni-travelling carrier.

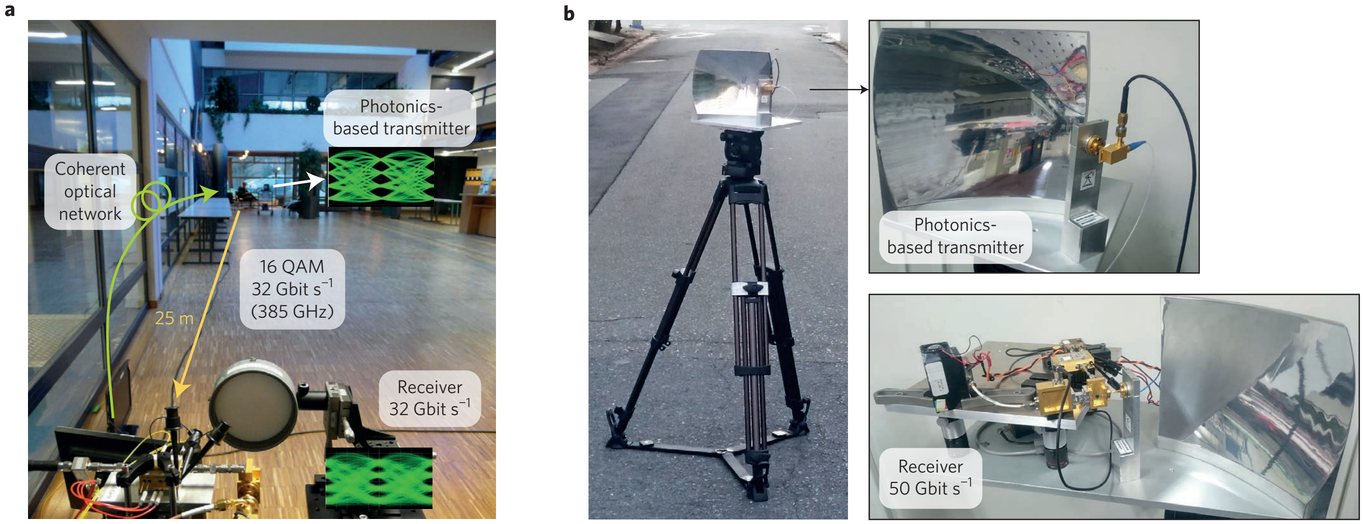

Figure 3 | Examples of THz links using photonics-based transmitters. a, Multi-level 32 Gbit s^{-1} link over 25 m with 16 QAM modulation delivered by a fibre-optic network. **b**, Real-time 50 Gbit s^{-1} link over 100 m with OOK modulation.

range[48]. In those systems, the major limitations in the Tx and Rx are: (i) the nonlinear behaviour of multiplier chains, which limits the amplitude coding at input; (ii) the limited modulation index if the modulation is realized with a sub-harmonic mixer at the source output; and (iii) the relative high impedance (~kΩ) of SBD-based direct detectors that limit achievable bandwidths, even if the integration of some transimpedance amplifiers can partially overcome this limitation.

From these ‘first age’ systems, dedicated THz circuits or subsystems have been developed over several years, first in III–V semiconductors (for THz front ends only), but Si developments will certainly compete with III–V semiconductors very quickly, as they feature higher integration levels (front end, baseband, digital). As first demonstrations use only THz front ends and Si devices are currently not fully available in the THz range, III–V semiconductors have driven the first dedicated circuit-level demonstrations. For example, on the reception side, a fully integrated 300-GHz receiver monolithic microwave integrated circuit (MMIC) using an InP high-electron-mobility transistor (HEMT)[49] and a complete in-phase and quadrature receiver at 237.5 GHz (ref. 31) using GaAs HEMT technology have been evaluated using photonics at the Tx. Fully integrated QPSK emitter and receiver chipsets using an InP HEMT at 300 GHz have also now been successfully validated on-wafer[50] for up to 50 Gbit s^{-1} phase-modulated signals, opening the way to future systems. Recently, a full waveguide-integrated MMIC chipset based on a GaAs metamorphic HEMT at 300 GHz has been proposed[51] to handle up to 64 Gbit s^{-1} (offline detection) in QPSK signalling over metre ranges. Fully integrated modulation and demodulation circuits have also been achieved using a double-heterojunction bipolar transistor (DHBT) in the 'D band' (110–170 GHz)[52].

To date, at frequencies above 100 GHz, GaAs and InP integrated circuits have been key players in all-electronic THz communications research. This is mainly due to the high cut-off and maximum frequencies of transistors (for example, f_{t} and f_{max} of the order of 400–500 GHz up to 1,000 GHz with InP DHBT[53] and 660 GHz up to >1 THz with a 20-nm metamorphic HEMT[54]). However, other technologies are also expected to open the way to practical THz communications, and mass production-compatible chipsets are now required and rapidly developing. Si integrated-circuit technologies have started to show their THz potential in the past two to three years. For example, SiGe heterojunction bipolar transistors (HBTs) are now expected to reach 700-GHz cut-off frequencies[55], and first chipsets have already been achieved: at 160 GHz with 10-mW power levels (1 W total consumption) and at 240 GHz (ref. 56), featuring output powers beyond 100 μW, 20-GHz bandwidth for the Tx and 10-dB conversion gain for the Rx. First simple tests have been achieved in free space using planar antennas and Si lenses, over 0.3 m (ref. 55). Also, wireless links using Si-CMOS (complementary metal-oxide–semiconductor) devices are now reported: for example, full demonstration of 11 Gbit s^{-1} links over 3 m have been reported at 130 GHz with real-time performance[57]. All of these potential technologies for THz communication systems will participate in the development of the field. According to the International Technology Roadmap for Semiconductors (ITRS), the half pitch of the wiring in Si large scale integrations is expected to become ~10–12 nm by 2020, enabling the maximum operation frequency of the mass-production level of Si-CMOS devices to reach 1 THz, as well as the realization of various radiofrequency integrated circuits in excess of 300-GHz operation in Si-CMOS devices. GaN and InP integrated circuits, however, have the ability to significantly surpass Si devices in terms of the breakdown voltage, and are still indispensable in applications where a high output power is required. A power combining technique using integrated array antennas has proven to be effective to increase the output power in Si-CMOS transmitter integrated circuits[58,59]. Ultimate THz integrated circuits would be a fusion of a compound semiconductor and Si semiconductor integrated circuits.

Table 2 | Summary of requirements and challenges for future THz communications technologies.

Item	Target	Technology options
Data rate	~100 Gbit s^{-1}–1 Tbit s^{-1}	Multi-band (multi-carrier) system Ultra-wideband optical modulators
Link distance	~1–5 km	Integrated photodiode arrays Use of amplifiers and integration
Efficiency and cost	-	Photonic integration (III–V semiconductor photonics and Si photonics)
Key components	-	Low-loss waveguide and interconnect Wideband, low-loss and reconfigurable antennas Wideband passive devices (filter, coupler, diplexer, absorber) New materials and devices (metamaterials, graphene, plasma wave, and so on)
Miscellaneous	-	Propagation and interference (model, real THz channels emulation, testing) Standardization Spectrum regulation

Terahertz link demonstrations

Considering all the aforementioned technologies, one can separate the types of system into two categories; 'real time' systems and systems with post processing. The first category, real-time systems, considers essentially a 100% time availability (no latency), as the signal does not require any signal processing or offline techniques to be analysed. In that case, the real-time bit error rate is the usual figure of merit of the link. These real-time systems have been achieved with direct detection or coherent detection (Tx and Rx have the same phase reference). As for the post-processing category, amplitude coding or multi-level modulation schemes (amplitude and phase coding) can also be combined with a wideband heterodyne receiver. Using further baseband processing of the radiofrequency digital signal ('offline detection'), the lack of active locking between THz emission and reception can be tackled, at the price of time latency. However, these offline techniques and systems have enabled researchers to conduct experiments of THz propagation of complex THz signals and led to the first advanced multi-level format links. From a general data-link perspective, investigations into complex signal transmission contribute to increasing the knowledge in the research field, and future developments may focus on real-time systems for practical and usable systems. This 'first age' of THz communication links is summarized in Table 1 (refs 60–64).

One of the key features enabled by THz photonics technologies is the possibility to take advantage of the very low losses of optical fibres to remotely feed the THz emission circuits, which is useful in the case of backhaul applications, as shown in Fig. 2a,b. Another key advantage of photonics-based solutions is the facility to handle multi-carrier and multi-format THz channels as well as carrier switching (Fig. 2c), which has no equivalent in electronics-based solutions. This unique feature of photonics-based transceivers is in phase with optical network evolution towards 'flexgrids'[65,66] that will expand core networks' bandwidth beyond traditional wavelength-division multiplex systems. In essence, photonics could play a major role in realizing a convenient 'optical-to-high-speed radio' interface in a mixed network technologies context.

Figure 3 shows examples of THz link demonstrators based on photonics-based transmitters. A data transmission of 32 Gbit s^{-1} with 16 quadrature amplitude modulation (QAM) has been demonstrated with a link distance of 25 m at a carrier frequency of 385 GHz using the set-up in Fig. 3a, while 50 Gbit s^{-1} real-time transmission with OOK modulation has been performed with a link distance of

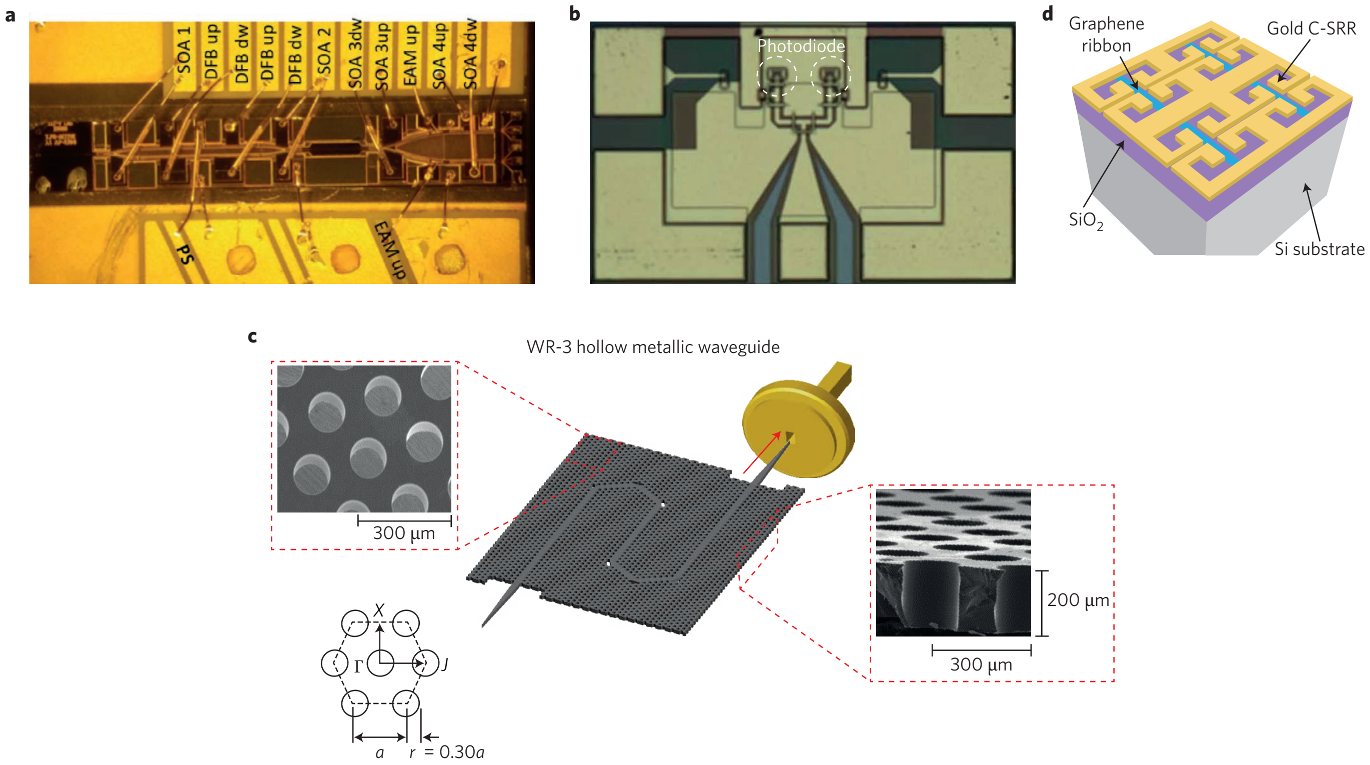

Figure 4 | Enabling technologies based on photonics and new materials for future THz communications. **a**, Integrated photonic transmitter at 100 GHz (ref. 72). **b**, Integrated photodetectors with 1 mW output at 300 GHz (ref. 25). **c**, Photonic bandgap THz waveguides for interconnects[85]. *a*, lattice constant; *r*, hole radius. **d**, Graphene-based metamaterial structured THz modulator[92]. C-SRR, complementary split-ring resonator. Figure adapted with permission from: **a**, ref. 72, OSA; **b**, ref. 25, IEEE; **c**, ref. 85, OSA; **d**, ref. 92, Nature Publishing Group.

100 m at a carrier frequency of 330 GHz using the set-up in Fig. 3b. In the latter case, reflector antennas were used to realize a gain of over 53 dBi.

Future prospects and challenges

The full deployment of a THz-based wireless communication technology is facing multiple challenges. As discussed in the previous section, while photonics technologies can help in terms of link efficiency, generating high data rates and coherence, the system still needs more output power at the transmitter, in particular for applications such as backhaul, where the distance will have to reach 1 km. For example, a state-of-the-art photonic emitter will offer about 1-mW output power at 300 GHz (ref. 25) and easily a 40 Gbit s^{-1} data rate in a 50-GHz double-sideband bandwidth, while a state-of-the-art room temperature operating receiver (Schottky-diode mixer based[67]) would offer a detection sensitivity of 4×10^{-19} W Hz^{-1}. With such characteristics and 40-dBi gain antennas, the maximum distance achievable in a worst case scenario (10 dB km^{-1} (ref. 68) attenuation for heavy rain) would be 280 m — short of the needed 1 km. While modulating in optics could easily reach a very high data rate (for example, 100 Gbit s^{-1} (ref. 69)), making the modulator a lower priority, it is clear that a better transmitter and/or receiver are required together with higher antenna gains. Another challenge is related to energy consumption, as data traffic, especially the wireless part, will soon be the highest consumption of energy per habitant in the world[70]. Such challenges will still require developments of technologies to generate more power at the transmitter while increasing the overall system efficiency. In this section, we discuss the different prospects that could potentially fully enable the future THz wireless network, as summarized in Table 2.

The first technology that could improve both the power at the transmitter and the overall efficiency of the system is 'photonic integration'. Photonic integration will naturally reduce coupling losses, such as the loss from fibre to chip and in particular the loss between the laser and the photomixer. It should also enable the use of multiple antenna systems that would lead to advanced active array antennas to compensate the path loss and allow for some tracking. It is interesting to see that photonic integration is now progressing fast in the world, with a multi-wafer foundry platform system in Europe[71] and a large research investment in the American Institute for Manufacturing Integrated Photonics (www.aimphotonics.com). These have led to important progresses for the field of THz communications, with highlights such as the development of a single chip transmitter (Fig. 4a) emitting 100 μW at 100 GHz from a total electrical consumption of 1 W including cooling[72,73]. That chip was also used successfully in transmission systems[74]. However, one can note that in such a case, the power is still limited for long-distance transmission, and recent development of integrated multiple photodiodes[25] (Fig. 4b) is promising to overcome the limitation.

Further to this recent progress in integration, the development of active Si photonics integrated technology[75–78] would enable potentially even better efficiency, easier integration with Si electronics technology and lower loss waveguides. Interestingly, knowing that the best photomixer saturation limit is mostly thermally driven, the performances at lower frequencies of UTC-PDs integrated on Si substrates with higher saturation due to the better thermal properties of Si offers potential[79].

However, even with such developments, there is still a clear need for amplification at both the emitter and receiver, thus low-noise and wide-bandwidth THz amplifiers for both transmitters and receivers are also a key priority. One example of such progress in amplifiers is a THz amplifier based on InP HBTs with a record high bandwidth of 235 GHz (ref. 80). Also the hybrid and monolithic integration of UTC-PDs with HEMT and HBT amplifiers for emission at 100 GHz seems to demonstrate an interesting potential for future components of the system[81–83].

THz technologies could benefit further if a strong interconnect technology is created to direct the THz wave on-chip between different components. For that, we could highlight low-loss waveguide technology, where a hollow waveguide with loss lower than 0.2 dB m^{-1} has been developed[84]. However, considering the architecture of a photonic chip, a planar solution would be more interesting, and developments in photonic bandgap structures that have been integrated directly with photonic chips and antennas[85] (Fig. 4c) are promising. Further development in plasmonic-based waveguides[86] could offer both low enough loss, field enhancement for interaction with a modulator or detection system, and size reduction, which are all desirable features in a future THz system. Further to such structures, the developments in metamaterials can enable enhanced THz manipulation in devices[87], in particular, interesting work has been done on THz modulators using metamaterials[88,89].

Graphene-based technology for THz technologies is also a promising area of development, in particular for enhanced detection and emission using graphene-based field-effect transistors[90,91], and modulators in graphene-based metamaterials[92] (Fig. 4d). Although in most cases the current performances are not at the state of the art compared with photonics only-based technologies, the physical properties of graphene and the level of results are indeed encouraging. In particular, the development of room-temperature detectors would be interesting to enhance the detection sensitivity of the system[93].

Furthermore, plasma-based transistors have been shown to be potential candidates for THz detection[94,95], mainly for imaging, but have also been investigated in data communication for 300-GHz short-range links[96]. The main limitation issue of these devices is the output interconnection: as the plasma is enhanced near the transistor pinch-off voltage, the channel impedance value is quite high and far from usual wideband amplifier impedances (50 Ω). In the future, innovative interconnects need to be developed to take full benefit of the plasma effects.

Finally, every radio wave at frequencies <3 THz should be regulated and a global consensus for its use for passive and active services needs to be reached. The effort on standardization and spectrum regulation issues for THz communications has been initiated and led by Kürner *et al.*[2,17] by considering use cases, channel and propagation models, interference effects with other services, for example, radio astronomy and Earth observation, enabling technologies, and so on.

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Competing financial interests

The authors declare no competing financial interests.