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 impulse and continuous waves. THz technologies have recently gained greater interest and expectations to meet an ever-increasing demand for the speed of wireless communications. This article reviews a latest trend of THz communications research focusing on how photonics technologies have played a key role in the development of first-age THz communication systems and how they compare with other competitive technologies such as THz transceivers enabled by electronic devices as well as free-space light-wave communications.

Trends in wireless communications

It is known that data traffic is increasing exponentially with Internet Protocol (IP) 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, etc. The prospective data rate for wireless communications in the market place will be 100 Gbit/s within 10 years[2]. Historically, since the first microwave wireless link developed by G. Marconi in early 20th 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 GHz~95 GHz[5]. However, the total allocated bandwidth is less than 7 GHz~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 even higher carrier frequency in the THz range (0.1 THz~10 THz) is required when the bandwidth is at a minimum several tens of GHz. The initial demonstrations of THz wireless communications were conducted using both impulse and continuous waves, which were generated from photoconductors and photodiodes excited by pulse lasers and intensity-modulated lasers, respectively[6-8]. The latter continuous-wave wireless link, which employs a 120-GHz band, is the first commercial THz communication system with an allocated bandwidth of 18 GHz (116 GHz~134 GHz), which offers 10 Gbit/s with an On-Off-Keying (OOK) modulation and 20 Gbit/s with a Quadrature Phase Shift Keying (QPSK) modulation at a transmission distance actually demonstrated of over 5 km[9, 10]. Now, lots of worldwide research groups have developed communication links at frequencies over 100 GHz. In particular, above 275 GHz, there is a possibility to employ extremely large bandwidth of over 50 GHz for radio communications, since these frequency bands have not yet been allocated to active services in the world.

General consideration and expectations of THz waves for communications

From Shannon formula[11], the information capacity, C, or the data rate is associated to the bandwidth, W, and the signal-to-noise ratio, S/N, as is given by C [bit/s] = $W \log_2 (1 + S/N)$. 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 applications; 100 GHz~150 GHz for long distance (1 km~10 km), < 350 GHz for medium distance (100 m~1 km), < 500 GHz for in-door (10~100 m). Above 600 GHz, there are two windows also for in-door communications; 625 GHz~725 GHz, and 780 GHz~910 GHz. When the frequency exceeds 1 THz, the radio wave undergoes a 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 (NFCs; <0.1 m). In addition, one cannot ignore attenuation from rainfall[13]. This attenuation is mostly independent on frequency in the range above 100 GHz, and the attenuation is about 10 dB/km in the case of heavy rain condition (25 mm/h), 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 GHz~320 GHz) and for up to km-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 system 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 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 free-space path loss 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 in 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[15, 16].

Depending on the above link distance criteria, promising applications of THz communications include front- and back-hauling of base stations (BSs) in femto cells, wireless local area networks in smart offices, wireless personal area networks in smart homes, near-field communications (NFCs) such as kiosk downloading, wireless connections in data centers, device-to-device communications (D2D), etc. (Fig. 2a). In these applications, another key aspect is the power consumption, directly related to transmitter and receiver architectures, and strongly impacting 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[17] in order to limit interference with established systems[18]. For indoor links, where frequencies can be re-used over several rooms for example, simple amplitude coding/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 to free-space optics (FSO) communications using infrared light (IR) waves. As we described in the beginning of the section, it would be logical to multiply the carrier frequency by several order of magnitudes and use optics as the carrier[19-21]. This would definitely offer more bandwidth while using the same base technology as photonics-based THz for the modulation of signals. However, the FSO faces lower tolerance in alignment, and requires stronger beam-steering control systems, though the development of MIMO-based system is promising[22]. For outdoor applications, the optics suffers more than 2 orders of magnitude higher losses in foggy conditions than THz waves[23], which again would limit the use of the FSO systems[24]. Ultimately, cost, size, performance and usability would determine which becomes more adopted in the marketplace.

Photonics-based approaches to realizing THz communications

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 obtained with optical-to-THz conversion using photomixing, high-speed amplitude and/or phase coding introduced from optical coherent network technologies, which has been widely developed since 2000's and now has become a mature technology for fiber-optic core networks[25]. A unique feature of using photonic devices relies on the possibility to address multi-carrier transmission very easily by adding optical laser lines to the optical driving signals. In the THz range, photonic III/V (InP) devices have been led by uni-travelling carrier photodiodes (UTC-PDs) pushed up to the order of mW power levels around 300 GHz in several laboratories[26, 27], paving the way for the realization of first indoor THz radio links with 'optical' data rates: for example, 50 Gbit/s at 300 GHz using real-time amplitude signaling[28], 60 Gbit/s at 200 GHz[29], 46 Gbit/s at 400 GHz[30] and up to 100 Gbit/s in the 100 GHz band[31] using digital signal processing and complete solid-state receiver with active elements working at such carrier frequencies[32]. The way towards 100-Gbit/s systems is now paved, and future developments towards this target will drive the THz communication systems developments. 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 to 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 of the large developments of silicon (Si) photonics-based systems, for example at 180 GHz a Ge-based photomixer in Si photonics process have shown EIRP (effective isotropic radiated power) > - 15 dBm from 170 GHz~190 GHz[33].

Since the early ages of THz communication, 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 (Rx's). Among THz receivers, several options have been tested for data wireless links in THz regime. The most common is a waveguide-integrated detector using GaAs Schottky barrier diodes (SBDs)[34] initially developed for radio-astronomy applications. Harmonic mixers using GaAs SBDs have also been investigated, featuring not only efficient real-time amplitude signaling[35] but also efficient down-conversion from high level THz modulation to microwave/MMW domain[36], opening the way to 'coherent fiber networks to THz radio bridges' which could be used in a future network convergence (fiber and ultra-high speed radio), as described later.

In the perspective of photonics-based THz transmitters for spectrally-efficient data links, the optical feed or source is requiring special attention[28]. Indeed, the spectral content of 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 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[37] or integrated lasers[28], independent lasers with frequency stabilization[38] dual mode lasers[39-41], Brillouin fiber lasers[42, 43] comb generation of a single laser line and active phase stabilization[44] or III-V on Silicon dual mode lasers[45].

Some features can be highlighted in these systems for THz communications 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 get $N f_0$ at a carrier frequency, requires an active phase stabilization to tackle random phase drifts in fiber cables. This kind of scheme has already been used to achieve real-time performance at 100 GHz[44], 200 GHz[35] and 300 GHz[28]. As the frequency increases, the frequency comb technique is limited by the increasing number of teeth to be generated in continuous wave regime (rather than common pulsed regime). In this case, a high modulating power to generate the required number of teeth and/or the use of highly non-linear optical modulators is mandatory.

Other techniques use dual-frequency tunable lasers producing the two required lines by design (i.e., without the optical frequency comb), with tunable spectral separation from microwave[39] up to sub-THz[41] or THz[40] 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. In ref. 40, the tuning from DC to 900 GHz is achieved by the use of an electro-optic effect inside cavity. This electro-optic effect can also be used to frequency lock the THz emission thanks 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, in order to reduce the constraints on the phase locking circuits, fiber lasers can be considered in order to reduce natural optical linewidth of the free-running optical source (usually MHz performance from standard lasers used in optical communications). For example, Brillouin fiber lasers[46] have been shown to reduce the intrinsic linewidth of an optical feed, down to kHz level[43] around 300 GHz and below 100 Hz around 1 THz[47].

Trends in all electronics-based approaches

From electronic side, beyond the use of electronic receivers combined with photonic Tx, first full electronic demonstrations have been realized using standard waveguide devices that were initially developed in GaAs technology for radio-astronomy (Herschel, ALMA programs). Using commercially available sources (multiplier chains), mixers, detectors, researchers have experienced first 'lab level' THz links, in many configurations: direct amplitude modulation of the source input[48] 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 behavior can be obtained and first complex signals have been transmitted using THz range[49]. In those systems, the major limitations in Tx and Rx are: (i) the nonlinear behavior of multiplier chains which limits to amplitude coding at input, (ii) the limited modulation index if the modulation is realized with a sub-harmonic mixer at source output and (iii) the relative high impedance (~kΩ) of Schottky barrier diode-based direct detectors that limit achievable bandwidths, even if some trans-impedance amplifiers integration can partially overcome this limitation.

From these 'first-age' systems, dedicated THz circuits or sub-systems have been developed since several years, first in III/V (for THz front ends only) but silicon developments will certainly compete III/V very fast as featuring higher integration level (front-end, baseband, digital). As first demonstrations use only THz front ends and Si devices currently not fully available in THz range, and III/V have driven the first dedicated circuit-level demonstrations. For example, at reception side, fully-integrated 300-GHz receiver MMIC using InP HEMT[50], a complete I/Q receiver at 237.5 GHz[32] using GaAs HEMT technology, these systems being evaluated using photonics at Tx. Fully-integrated QPSK emitter and receiver chipsets using InP HEMT at 300 GHz have also now been successfully validated on-wafer[51] for up to 50 Gbit/s phase modulated signals, opening the way to future systems. Recently, full waveguide integrated MMIC chipset based on GaAs metamorphic HEMT at 300 GHz have been proposed[52] to handle up to 64 Gbit/s (off-line detection) in QPSK signaling over meter ranges. Fully-integrated modulation and demodulation circuits have also been achieved using DHBT in "D band" (110 GHz~170 GHz)[53].

Up to now, at frequencies above 100 GHz, GaAs and InP ICs 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/1000 GHz with InP DHBT[54] and 660 GHz/>1 THz with 20-nm mHEMT[55]). 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 IC technologies have started to show their THz potential in the last 2-3 years. For example, SiGe HBTs are now expected to reach 700-GHz cut-off frequencies[56], and first chipsets have been already achieved: at 160 GHz with 10-mW power levels (1-W total consumption) and at 240 GHz[57], featuring output powers beyond 100 μW, 20-GHz bandwidth for Tx and 10-dB conversion gain for Rx. First simple tests have been achieved in free space using planar antennas and silicon lenses, over 0.3 m[56]. Also, wireless links using Si-CMOS are also now reported: for example, full demonstration of 11-Gbit/s links over 3 m have been reported at 130 GHz with real-time performance[58]. All of these potential technologies for THz communication systems will participate to the development of the field. According to the International Technology Roadmap for Semiconductors (ITRS), the half pitch of the wiring in Si-LSIs is expected to become 10~12 nm by 2020, enabling the maximum operation frequency of the mass-production level of Si-CMOS devices reach 1 THz, as well as various RF ICs in excess of 300-GHz operation could be realized in Si-CMOS. GaN and InP ICs, however, have the ability to significantly surpass Si devices in terms of the break-down 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 an output power in Si-CMOS transmitter ICs[59, 60]. Ultimate THz ICs would be a fusion of compound semiconductor and Si semiconductor ICs.

THz link demonstrations and photonics in network convergence

Considering all the aforementioned technologies, one can separate the types of systems in 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 off-line techniques to be analyzed. In that case, the real-time bit error rate (BER) 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 second category, amplitude coding, or multi-level modulation schemes (amplitude and phase coding) can also be combined with a wideband heterodyne receiver. Using further baseband of RF digital signal processing ('off-line detection'), the lack of active locking between THz emission and reception can be tackled, at the price of time latency. However, these 'off-line' techniques and systems have enable researchers to experience THz propagation of complex THz signals and lead to the first advanced multi-level format links. In a general data-link perspective, it contributes to increasing the knowledge in the research field, and future developments may focus on real-time systems for practical/usable systems. This 'first-age' of THz communication links can be summarized in Table 1[61-65].

One of the key features enabled by THz photonics technologies is the possibility to take benefit of the very low losses of optical fibers in order to remotely feed the THz emission circuits, which is useful in the case of backhaul applications as shown in Figs. 2a and 2b. Other key advantage of photonic-based solutions is the amazing facility to handle multi-carrier and multi-format THz channels as well as carrier switching (Fig. 2c), which has no equivalence in electronics-based solutions. This unique feature of photonics-based transceivers is in phase with optical network evolution towards 'flexgrids'[66, 67] that will expand core networks bandwidth beyond traditional WDM (wavelength division multiplex) systems. By essence, photonics could play a major as a convenient 'optical-to-high speed radio' interface in mixed network technologies context.

Figure 3 shows examples of THz link demonstrators based on photonics-based transmitters. 32-Gbit/s data transmission with 16-QAM modulation has been demonstrated with a link distance of 25 m at a carrier frequency of 385 GHz using a setup of Fig. 3a, while 50-Gbit/s real-time transmission with OOK modulation has been performed with a link distance of 100 m at a carrier frequency of 330 GHz using a setup of Fig. 3b. In the latter case, reflector antennas were used to realize a gain of over 53 dBi.

Future prospect and challenges

The full deployment of a THz-based wireless communication technology is facing multiple challenges. As discussed in the previous section while photonic technologies can help in term of link efficiency, generating high data rate 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 a kilometre. For example, a state of the art photonic emitter will offer about 1-mW output power at 300 GHz[26] and easily 40-Gbit/s data rate in a 50-

GHz DSB bandwidth, while a state of the art room temperature operating receiver (Schottky-diode mixer based[68]) would offer a detection sensitivity of $4 \cdot 10^{-19}$ W/Hz. With such characteristics and 40-dBi gain antennas, the maximum distance achievable in a worst case scenario (10-dB/km[69] attenuation for heavy rain) would be 280 m; short of the needed 1 km. While modulating in optics could easily reach very high data rate (for example 100 Gbit/s[70]) 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 of the traffic will soon be the highest consumption of energy per habitant in the world[71]. 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 are discussing 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 system 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[72] and a large research investment in American institutes for manufacturing integrated photonics[73]. 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 1W including cooling[74, 75]. That chip was also used successfully in transmission systems[76]. 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[26] (Fig. 4b) is promising to overcome the limitation.

Further to these recent progress in integration the development of active Si photonics integrated technology[77-80] 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 integrated on Si substrates with higher saturation due to the better thermal properties of Si offers a lot of prospect[81].

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 amplifiers based on InP HBTs with a record high bandwidth of 235 GHz developed by UCL with Chalmers University[82]. Also the hybrid/monolithic integration of UTC-PDs with HEMT/HBT amplifiers for emission at 100 GHz seems to demonstrate an interesting potential for future components of the system[83-85].

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 hollow waveguide with loss lower than 0.2 dB/m have been developed[86]. However, considering the architecture of a photonic chip, a planar solution would be more interesting, and developments in photonic band-gap structures that have been integrated directly with photonic chips and antenna[87] (Fig. 4c) would offer great prospect. Further development in plasmonic-based waveguides[88] could offer both low enough loss, field enhancement for interaction with a modulator or detection system and size reduction that are all desirable features in a future THz system. Further to such structures, the development in metamaterials can enable enhanced THz manipulation in devices[89], in particular interesting work has been done on THz modulators using metamaterials[90, 91].

The development of graphene-based technology for THz is also a promising area of development in particular for enhanced detection and emission using graphene-based field effect transistors[92, 93], and modulators in graphene-based metamaterials[94] (Fig. 4d), though in most cases the current performances are not at the state of the art compared to photonics-only-based technologies, the physical properties of a graphene and the level of results are indeed encouraging. In particular, the developments of room temperature detectors would be interesting in order to enhance the detection sensitivity of the system[95].

Also, plasma-based transistors have been shown to be potential candidates for THz detecton[96-97], mainly for imaging, but have also been investigated in data communication for 300 GHz short-range links[98]. The main limitation issue of these devices is the output interconnection: as the plasma is enhanced near 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 below 3 THz should be regulated and be got global consensus in its use for passive and active services. The effort on standardization and spectrum regulation issues for THz communications has been initiated and led by Kürner et al.[2, 18] by considering use cases, channel/propagation models, interference effects with other services such as, for example, radio astronomy and earth observation, enabling technologies, etc.

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Figure/table legends

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 applications such as long distance, medium distance, in-door, and near-field communications (NFCs). Above 600 GHz, there are two windows for in-door communications; 625 GHz~725 GHz, and 780 GHz~910 GHz. **b**, Link budget at THz frequencies for the isotropic case (Tx and Rx antennas with 0-dBi gain) for 23°C and 2.59 % water content in air composition (tropical climate).

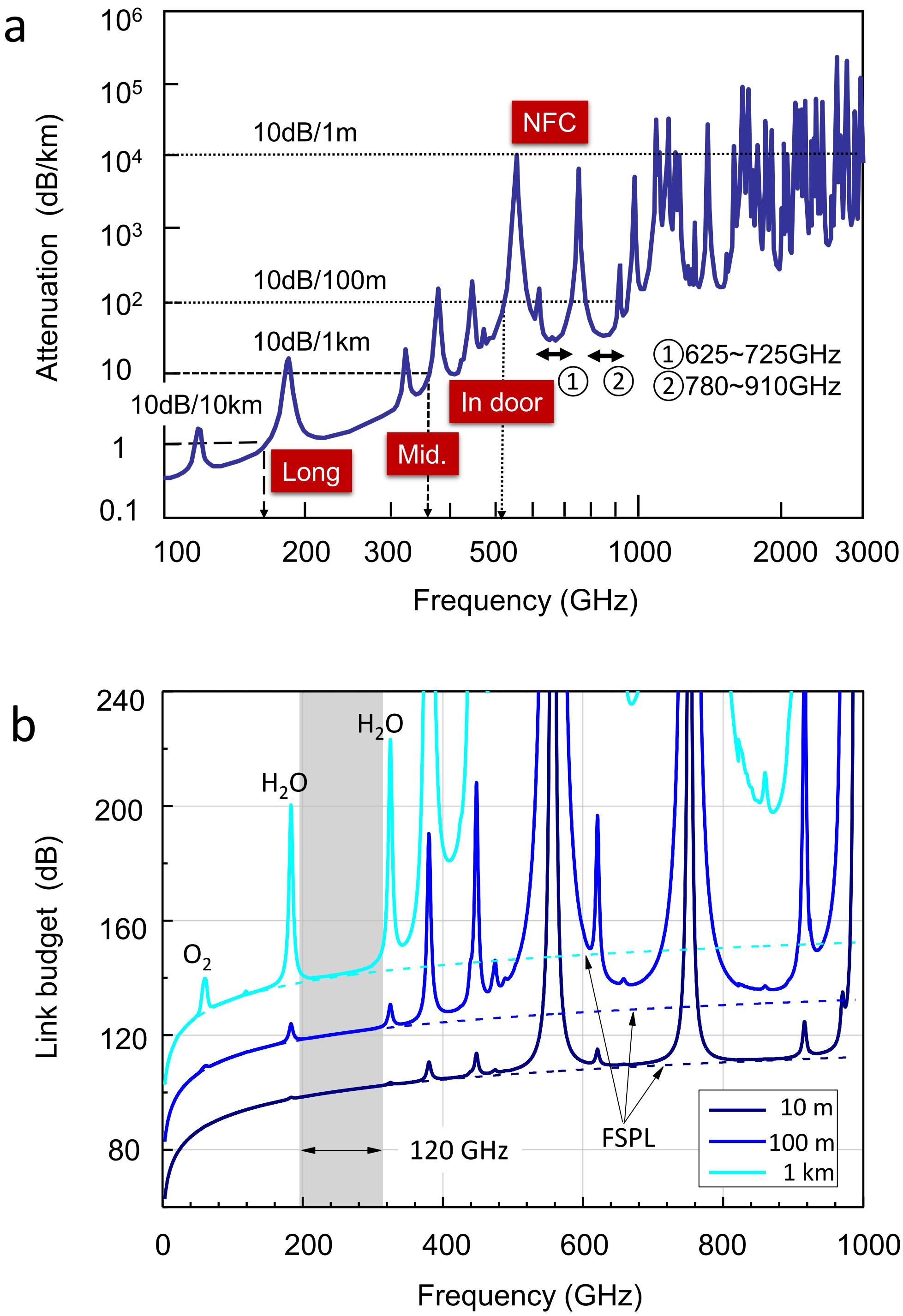
Figure 2 | Application of THz link in networks. **a**, Prospective view of THz link to connect base stations (BSs) for backhauling as well as device-to-device (D2D) interface. **b**, Concept of fiber-to-THz radio bridges for seamless connection between fiber-optic link and THz link ensuring the same data modulation formats with no latency. **c**, Configuration of multi-carrier reconfigurable and frequency-agile THz links using photonics.

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

Figure 4 | Enabling technologies for future THz communications. **a**, Integrated photonic transmitter at 100 GHz[75]. **b**, Integrated photodetectors with 1mW output at 300 GHz[26]. **c**, Photonic band-gap THz waveguides for interconnects[87]. **d**, Graphene-based, metamaterial structured THz modulator[94].

Table 1 Reported THz systems and actual highest performances achieved using several technologies. CDP is the capacity×distance product, in Gbit/s.km. CDP is a figure of merit for communication systems assuming the maximal regeneration-free distance in real-time conditions[67]. Most of highest data-rate of THz wireless systems have been achieved using the THz photonics technologies at transmitter, mainly based on high speed photodiodes. Combination of polarization, frequencies are now investigated to increase data-rate in the available THz bandwidth. SHM: Sub-Harmonic Mixer, UTC: Uni-Travelling Carrier, HEMT: High Electron Mobility Transistor, MMIC: Monolithic Microwave Integrated Circuit, SBD: Schottky Barrier Diode, ASK: Amplitude Shift Keying, QPSK: Quadrature Shift Keying, QAM: Quadrature Amplitude Modulation.

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



a
Attenuation (dB/km)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10dB/1m
10dB/100m
10dB/1km
10dB/10km
NFC
In door
Mid.
Long
①625~725GHz
②780~910GHz
100
200
300
500
1000
2000
3000
Frequency (GHz)
b
Link budget (dB)
240
200
160
120
80
H_2O
H_2O
O_2
120 GHz
FSPL
10 m
100 m
1 km
0
200
400
600
800
1000
Frequency (GHz)

Figure 1

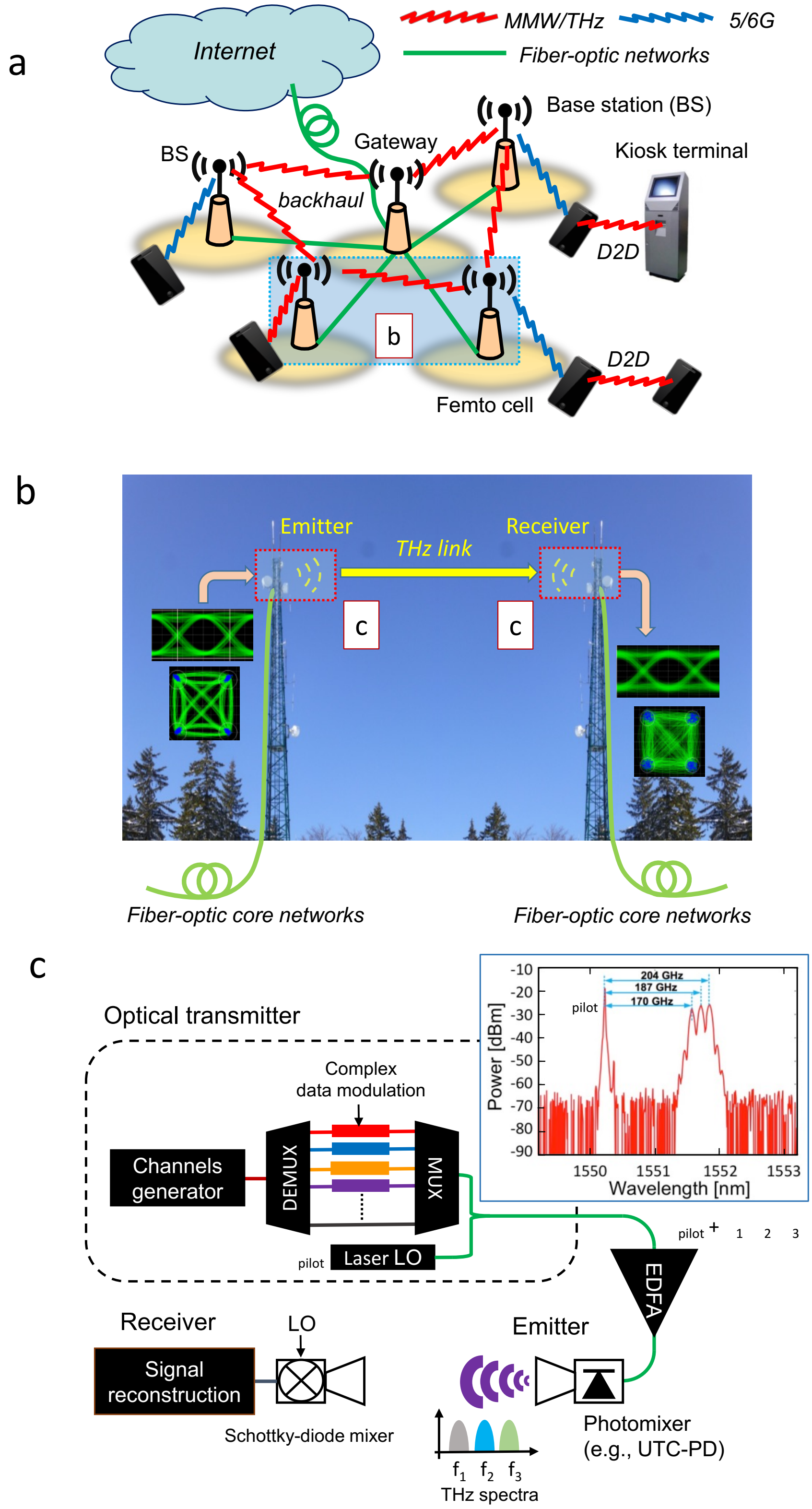

a
MMW/THz
5/6G
Fiber-optic networks
Internet
Base station (BS)
Gateway
BS
Kiosk terminal
backhaul
D2D
b
D2D
Femto cell
b
Emitter
Receiver
THz link
c
c
Fiber-optic core networks
Fiber-optic core networks
c
Optical transmitter
Complex
data modulation
Channels
generator
DEMUX
MUX
pilot
Laser LO
Power [dBm]
Wavelength [nm]
pilot
204 GHz
187 GHz
170 GHz
pilot
EDFA
Receiver
LO
Emitter
Signal
reconstruction
Schottky-diode mixer
THz spectra
Photomixer
(e.g., UTC-PD)

Figure 2

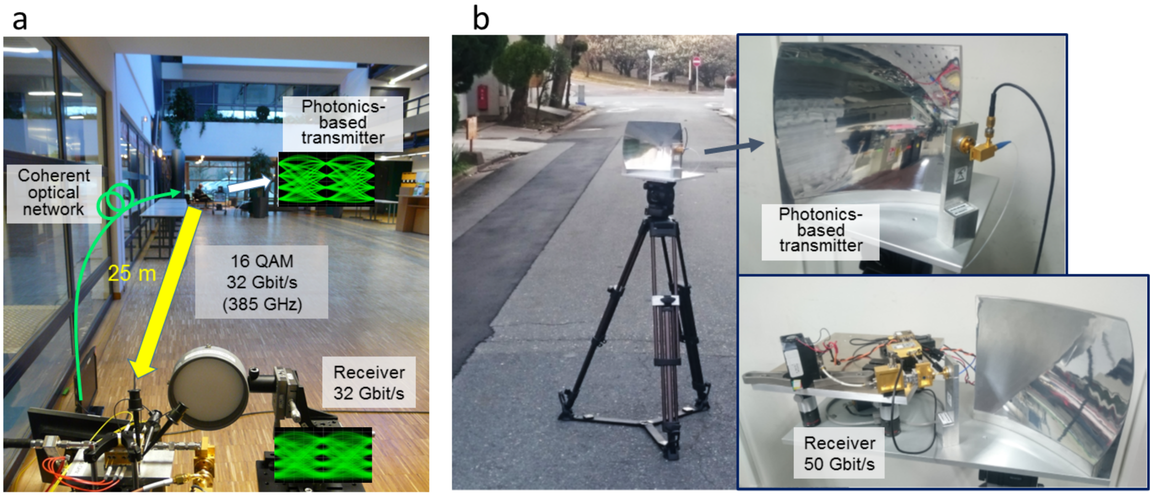

a
Photonics-based transmitter
Coherent optical network
25 m
16 QAM
32 Gbit/s
(385 GHz)
Receiver
32 Gbit/s
b
Photonics-based transmitter
Receiver
50 Gbit/s

Figure 3

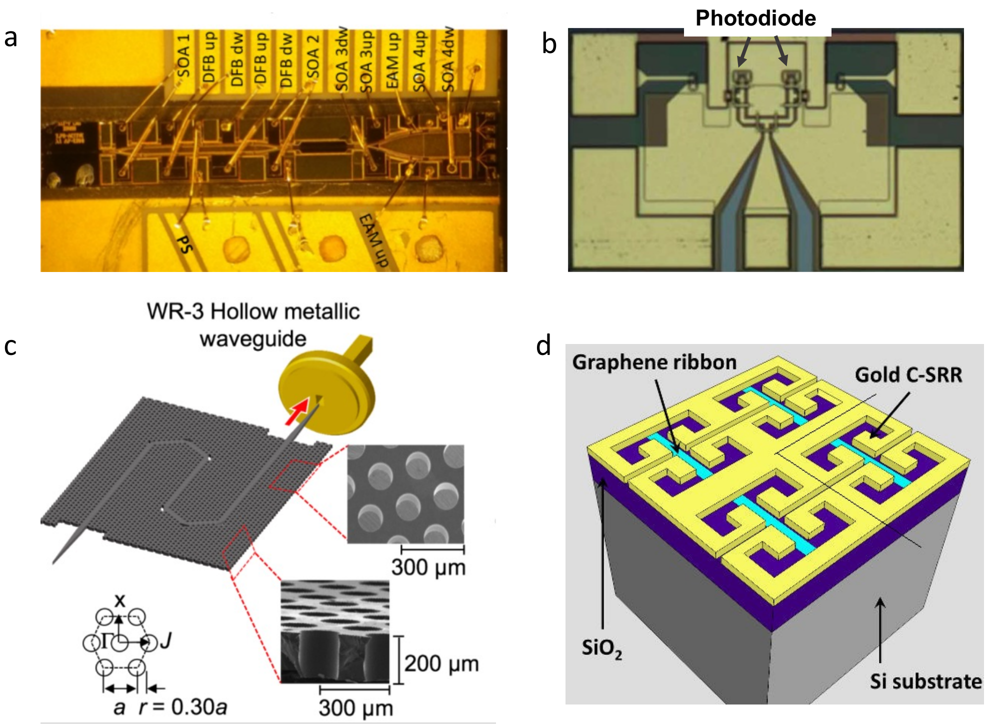

a
SOA 1
DFB up
DFB dw
DFB up
DFB dw
SOA 2
SOA 3dw
SOA 3up
EAM up
SOA 4up
SOA 4dw
PS
EAM up
b
Photodiode
c
WR-3 Hollow metallic waveguide
300 μm
200 μm
300 μm
x
Γ
J
a
r = 0.30a
d
Graphene ribbon
Gold C-SRR
SiO2
Si substrate

Figure 4

Table 1

Data rate (Gbit/s)	Distance (m)	Freq. (GHz)	Multiplexing	Technology (Tx/Rx)	Modulation	BER (Type)	Ref.	CDP (Gbit/s.km)	Year
200	0.5	100	Polarization (2 ch)	PD / SHM	QPSK	10^{-3} / off-line	[31]	-	2013
10	1000	120	-	UTC + HEMTs / HEMT	ASK	**< 10^{-9} / real-time**	[9]	**10**	2012
11	3	130	-	40nm CMOS (Tx/Rx)	ASK	**< 10^{-9} /real-time**	[58]	0.033	2015
75	0.02	200	Frequency (3 ch)	UTC-PD / SHM	QPSK	10^{-5} / off-line	[29]	-	2014
100	20	237.5	Frequency (3 ch)	UTC-PD / HEMT Rx	Up to QAM-16	2.10^{-3} / off-line	[32]	-	2013
64	850	240	-	mHEMT - MMIC	QPSK	5.10^{-3} / off-line	[61]	-	2015
64	1	300	-	MMIC (Tx/Rx)	QPSK	- / off-line	[52]	-	2015
40	10	300	-	UTC-PD / SHM	QPSK	10^{-4} / off-line	[36]	-	2015
48	0.5	300	Polarization (2 ch)	UTC-PD / SBD	ASK	**10^{-10} / real-time**	[34]	0.024	2013
3	50	340	-	SHM / SHM	QAM-16	**10^{-10} / real-time**	[65]	0.15	2014
32	0.5	385	-	UTC-PD / SHM	QPSK	10^{-5} / off-line	[62]	-	2015
46	2	400	-	UTC-PD / SHM	ASK	10^{-3} / off-line	[30]	-	2014
30 / 50	20 / 0.5	300 / 330	-	UTC-PD / SBD or SHM	ASK	**10^{-9} / real-time**	[28]	0.6/0.025	2015
60	0.5	400	Frequency (4 ch)	UTC-PD / SHM	QPSK	10^{-3} / off-line	[63]	-	2015
2.5	3	625	-	Multiplier / SBD	Duobinary (ASK)	**< 10^{-9} /real-time**	[64]	0.0075	2011

Table 2

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