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Terahertz technologies: present and future

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Abstract: A number of technical breakthroughs in electronics and photonics made since the early 1990s have started to bring terahertz (THz)-wave technologies from laboratory demonstrators to industrial applications such as non-destructive testing, security, medicine, communications, etc. This paper overviews the latest progress in THz-wave technologies in terms of components such as sources and detectors, and system applications, and discusses future challenges towards market developments.

Keywords: terahertz, source, detector, spectroscopy, imaging, communication

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

The electromagnetic waves at frequencies from 0.1 THz (100 GHz) to 10 THz is referred to as terahertz (THz) waves, which are located between microwaves

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and infrared light waves as shown in Fig. 1. The THz waves have long been a big concern mainly in the astronomy, because 98% of total photons emitted in the history of the universe since the Big Bang lie in the THz region of the electromagnetic waves. Thanks to tremendous efforts of research and development over two decades, THz technologies have proven lots of capabilities which are not available with conventional radio waves and/or light waves. In particular, use of pulsed THz waves generated and detected with ultrashort-pulse-lasers opened the first practical and powerful applications of THz waves both in spectroscopy and imaging in the early 1990s [1, 2]. In addition to such photonics-based approaches, we have seen a steady progress in semiconductor electronics with respect to operation frequency, output power in sources and sensitivity in detectors in the 2000s.

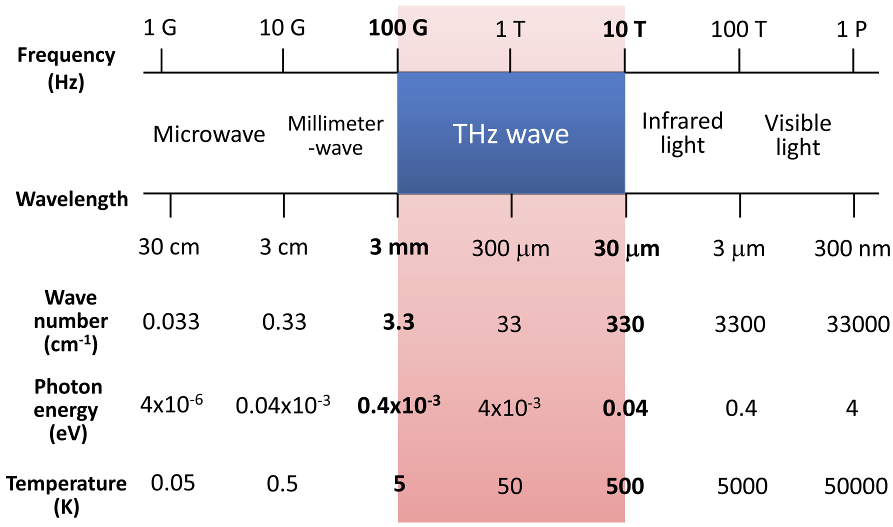

Fig. 1. Definition of THz waves.

The objective of this review paper is to provide readers, who are not so familiar with THz technologies, with advances in enabling technologies and their applications primarily in the last 3-5 years. Since the progress in THz technologies is too rapid, this paper covers limited portions of recently developed capabilities.

2 Advances in THz sources

2.1 Overview of sources

One of the obstacles to developing applications of THz waves is a lack of solid-sate signal sources, rather than detectors. In fact, the frequency band in this region is often referred to as the *terahertz gap*. Since the THz regions are located between microwaves and infrared light waves, there are two enabling technologies, that is, electronics and photonics. The trigger for the THz technology to break in the early 1990s is a photonic generation of THz waves, that is, optical-to-THz signal conversion technology with use of lasers. We have seen a significant progress in the increase of output power and/or

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efficiency with respect to conversion media. In the following, we will review the latest topics of THz sources including semiconductor electronic devices and lasers operating in the THz region.

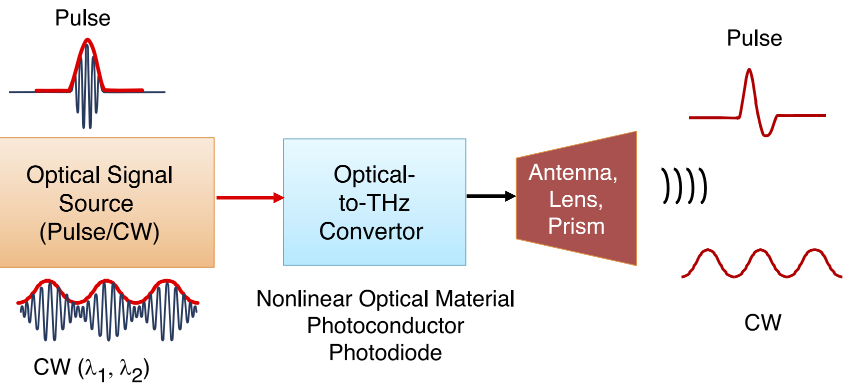

Fig. 2. Conceptual illustration of photonic generation of THz waves.

2.2 Optical-to-THz conversion

Figure 2 shows a concept of optical-to-THz conversion using interaction media such as nonlinear optical (NLO) materials, photoconductors, and photodiodes.

THz generation technology using NLO materials has attracted a great deal of attention, since the intensity and/or conversion efficiency are increasing dramatically within a few years. There are two approaches; one is to use an optical rectification process to generate "pulsed waves", which contain ultra-wide frequency components, by injecting femtosecond laser pulses into the NLO materials. The other is to use difference frequency generation (DFG) or optical parametric process in the NLO materials to generate "monochromatic" continuous or quasi-continuous THz waves. Typical NLO materials are crystals with large nonlinear susceptibility such as CdTe, ZnTe, GaP, $LiNbO_3$, and DAST (4-dimethylamino-N-methyl-4-stilbazolium tosylate).

As for the former pulsed techniques, "tilted-pulse-front pumping (TPFP) technique" provides electric field strengths approaching 1 MV/cm and pulse energies on the 10-μJ scale, up to 50 μJ, have been reported with $LiNbO_3$ crystals [3, 4] (Fig. 3). This energy level is more than three orders of magnitude higher than that achieved in the early 2000s, and is expected to be very useful for real-time imaging of large-area objects, and to pave the way for nonlinear spectroscopy. In place of NLO materials, intense THz pulses can be generated from the air plasma, where ambient air and different selected gases, excited by a dual-color femtosecond laser beam, exhibit a remarkable ability to radiate pulsed THz waves through the higher order nonlinear effect [5].

Single-frequency generation based on DFG or optical parametric process, where a frequency can be continuously tuned over wide range, is more attractive for spectroscopy applications, since it provides a higher signal-to-noise

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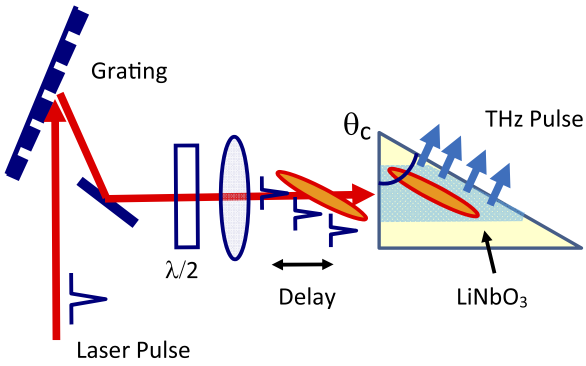

Fig. 3. Tilted-pulse-front pumping (TPFP) technique. $\theta_c = \cos^{-1}(n_g/n_{THz})$, where n_g and n_{THz} are refractive indices for a laser beam and a THz beam, respectively.

ratio (SNR) and spectral resolution. When the frequency band of interest is targeted for the specific absorption line of the objects being tested, CW systems with the selected frequency-scan length and resolution are more practical in terms of data acquisition time as well as system cost. Recently, a so-called prism-coupled Cherenkov phase-matching method, where a prism with a suitable refractive index at THz frequencies is coupled to $LiNbO_3$ or DAST, has been developed to generate widely tunable THz signals up to 10 THz over a wide excitation laser wavelength from 1250 to 1450 nm [6]. The above mentioned single frequency generation required high-peak pump power with Q-switched lasers, which leads to pulsed-CW sources. Pure CW sources based on intracavity difference frequency generation have been demonstrated with an average power as high as tens of milliwatt at 1 and 1.9 THz [7].

The other technique for photonics-based THz generation is to use photoconductors and photodiodes. Most common photoconductors, which are also commercially available, are made on low-temperature-grown GaAs (LT-GaAs) for 700∼900-nm laser wavelength and on LT-InGaAs for 1300∼1600-nm wavelength. Photoconductors are used for both pulsed and CW THz sources, while photodiodes are more suitable for the CW generation in terms of output power. As for the CW THz generation, two lightwaves with different wavelengths are injected onto the photoconductors or photodiodes. This technique is usually referred to as "photomixing" [8]. For the application to industrial instrumentation, use of 1550-nm laser wavelength is essential, since matured and cost-effective telecom-based components can be used including low-loss and low-dispersion optical fiber cables. Among 1550-nm photodiodes, uni-traveling-carrier (UTC) photodiodes and their modifications have exhibited the highest output power; >500 μW at 350 GHz, >100 μW at 350∼450 GHz, >10 μW at 1 THz [9, 10]. More than one order of increase in the output power at >500 GHz is desirable for practical applications.

Figure 4 shows the structure of modified UTC photodiodes which optimize a tradeoff between the bandwidth and the responsivity [9]. One of the remaining practical issues in the high-power UTC and UTC-like photodiodes

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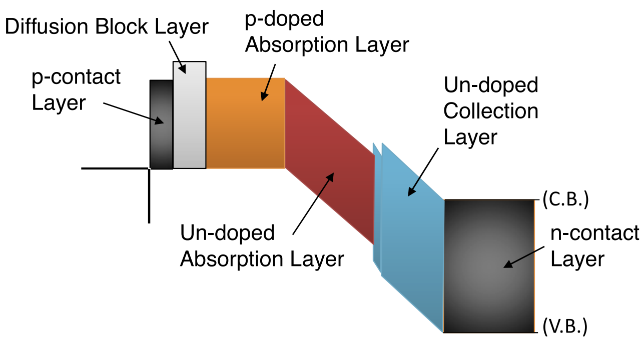

Fig. 4. Band diagram of modified UTC photodiode.

is thermal management. These photodiodes often face burnout before they reach their saturation condition due to thermal effects. Power combining technique is another practical solution to increase the output power.

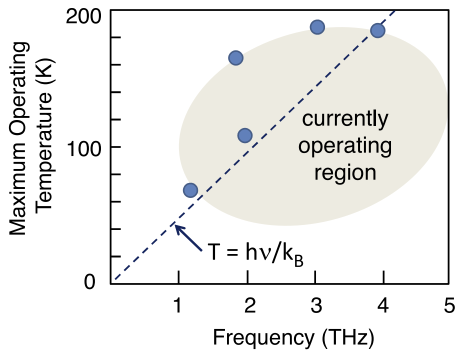

Fig. 5. Operating temperature of THz quantum cascade lasers reported without an applied magnetic field.

2.3 Quantum cascade lasers

The quantum cascade laser (QCL) is a semiconductor laser based on intersubband transitions in quantum wells. The photon energy of THz waves is extremely low as shown in Fig. 1, e.g., 50 K at 1 THz, which generally makes it difficult for THz-QCLs to operate at a room temperature. Since the first operation of THz-QCL at 4.4 THz in 2002 [11], lots of efforts have been made in order to decrease the operation frequency as well as to increase the operation temperature. Figure 5 shows the highest temperatures reported. They are a little bit over $h\nu/k_B$ (h: Plank constant, k_B: Boltzmann constant, ν: frequency), but are still far below a room temperature.

The QCL is the only semiconductor device whose output power exceeds a milliwatt level at over 1 THz. >2 mW is obtained at 1.8 THz at 155 K [12]. Currently, a practical use of THz-QCLs is to cool down to the liquid nitrogen temperature, which contributes to increase the output power. Application of strong magnetic field to the QCL is effective to be operated below 1 THz [13].

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2.4 Electronic sources and oscillators

Most of the signal generators and related instruments operating at frequencies from 100 GHz to 2 THz are based on frequency multiplication [14]. By using millimeter-wave power amplifiers, the output power from, for example, GUNN diode oscillators operating at 30∼100 GHz is boosted and is fed to diode-based frequency multipliers with a multiplication factor ranging from 2 to 18 ($2 \times 3 \times 3$). The output power of 20∼40 μW is achieved at 1.7∼1.9 THz [15]. Use of high-power amplifiers with GaN-related materials will increase the THz power up to a milliwatt level [16].

Resonant tunneling diodes (RTDs) are promising solid-state electronic oscillators, which operate at fundamental frequencies from 100 GHz to 1 THz or higher. Optimized device structure and circuit design including a careful antenna integration scheme have led to record performances; 200 μW at 443 GHz, >1 μW at 831 GHz, 7 μW at 1.04 THz [17, 18].

As the cutoff frequency of semiconductor transistors steadily increases, integrated oscillator circuits have recently been reported with compound semiconductor [19], Si bipolar [20], and Si-CMOS transistors [21]; 100-300 μW at 250-350 GHz with InP DHBT, and 160 μW at 482 GHz with CMOS.

3 Advances in THz detectors

3.1 Overview of detectors

Figure 6 categorizes configurations of detectors to receive THz signals. Comparing to signal generation technologies, detection technologies have several established components and techniques, because of historically long-run needs in passive detection technologies such as radio astronomy.

Direct detection (Fig. 6 (a)) using Schottky-barrier diodes (SBDs) or bolometers is the most widely used technique for the detection of amplitude or power of THz electromagnetic waves. The cutoff frequency of the SBD can be made more than 10 THz with GaAs materials [22, 23], and 1.5 THz with 130-nm CMOS [24]. Heterodyne detection with the SBD mixer and a local oscillator (LO) signal source (Fig. 6 (b)) provides higher sensitivity and phase information of THz waves, which is important for network analyzers, radars, etc. The sensitivity can be further enhanced when the superconductor-insulator-superconductor (SIS) mixer or superconducting hot electron bolometer (HEB) mixer is used. Another advantage of the superconducting mixer is that it requires an extremely small LO power (10 nW∼1 μW). Choice between the SBD and bolometer should be made considering the sensitivity, the response speed, and the operation temperature.

Figures 6 (c) and (d) show heterodyne detection systems which use photonically generated THz LO signal sources. An advantage of the scheme of Fig. 6 (c) is that we can not only deliver THz LO signals with optical fiber cables at some distances, but also increase a receiver bandwidth because of the inherently wider frequency tunability in photonic signal generation. Together with photonic mixers, the heterodyne (or homodyne) system of

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Fig. 6 (d) provides the largest bandwidth, which is useful for spectroscopy. Typical photonic mixers are photoconductors (PCs), electro-optic (EO) materials, and photodiodes (PDs).

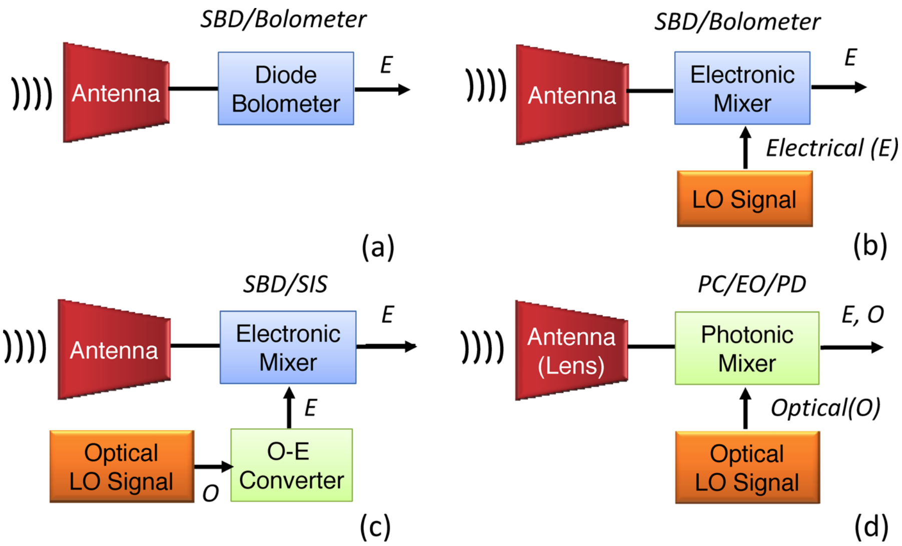

Fig. 6. Configuration of THz detection system.

In addition, ultimately sensitive THz detection technique is to detect a single THz photon with semiconductor quantum dot detectors and semiconductor charge-sensitive infrared phototransistors [25]. The noise equivalent power (NEP) on the order of $10^{-21}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ has been obtained, which is about ten orders of magnitude lower than those of the other detectors described below.

Among the latest detection technologies, we will describe two notable topics related to THz cameras in the following.

3.2 Plasma-wave detectors and arrays

One of the promising candidates, which are expected to surpass the sensitivity of the SBD detector, is a plasma-wave detector. Terahertz resonant and non-resonant detection (and/or emission) using plasmon resonances in two dimensional electron gas field-effect transistors was predicted in the early 1990s [26], and successful demonstration of THz signal detection and emission have been reported with compound semiconductor transistors [27, 28] and Si-CMOS transistors [29].

Array of detectors has been successfully fabricated to form a focal plane. Recently, by using microstrip patch antenna-coupled FETs with 150-nm CMOS transistors, multi-pixel (5×10) detector arrays operating between 550 and 600 GHz have been developed, and the arrays display a minimum optical noise equivalent power (NEP) of $43\,\mathrm{pW}/\sqrt{\mathrm{Hz}}$. For comparison, NEPs for the SBDs are $1.5\,\mathrm{pW}/\sqrt{\mathrm{Hz}}$ near 150 GHz and $20\,\mathrm{pW}/\sqrt{\mathrm{Hz}}$ at 800 GHz [30].

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3.3 Un-cooled bolometer detectors and arrays

The bolometer is a temperature sensitive device whose resistance varies with temperature, and consists of an absorptive element, such as a thin layer of metal, connected to a heat sink. Thus, the bolometer measures the energy of incident electromagnetic radiation. A cooled bolometer operating at 4 K is commercially available and widely used as a highly sensitive THz power meter, especially in laboratories; the NEP is $0.1{\sim}1\,\mathrm{pW}/\sqrt{\mathrm{Hz}}$.

Most recently, an un-cooled THz focal plane array (FPA) with 320×240 format and 23.5-μm pitch, and a THz imager (camera) have been developed [31]. By optimizing the device structure and the absorption element, the obtained NEP is 20 pW at around 3 THz.

4 Advances in applications

4.1 Spectroscopy

Figure 7 shows a typical configuration of THz spectroscopy system, by combining THz sources (Fig. 2) and detectors (Fig. 6 (d)). Laser-pulse-assisted THz-wave technology has proven to be powerful and useful in spectroscopy applications because of its unprecedented capability to control ultrashort timing [1]. In particular, the THz time-domain spectroscopy (THz-TDS) system has been established as a laboratory standard for THz spectroscopy [32] and is commercially available from a number of companies. In the THz-TDS system, frequency characteristics are obtained by Fourier transforming the time-domain data, and the frequency resolution is limited by the time window given by the optical delay shown in Fig. 7. The typical frequency resolution of the THz-TDS system is around 100 MHz–1 GHz and is determined by the repetition frequency of the pulse laser and the scan length of the optical delay line.

Recently, spectroscopy systems based on CW technology, which use monochromatic sources with an accurate frequency control capability, have attracted great interest [33, 34, 35]. The CW source-based systems provide

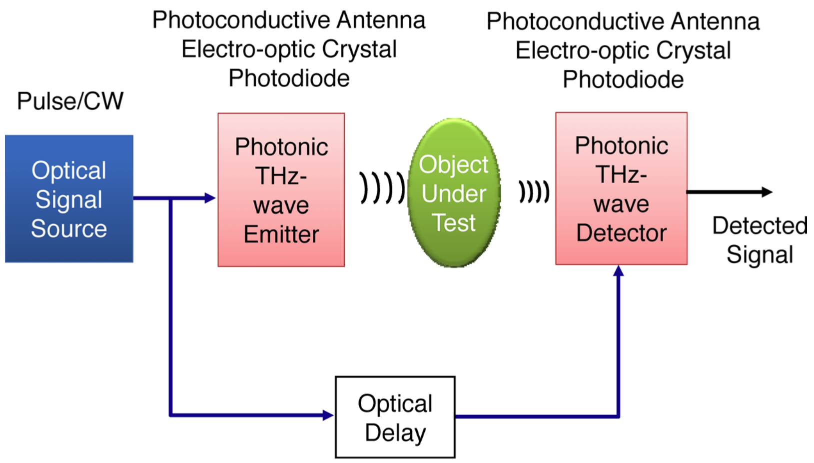

Fig. 7. Configuration of THz spectroscopy/imaging system based on photonic techniques.

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a higher signal-to-noise ratio (SNR) and spectral resolution. When the frequency band of interest is targeted for the specific absorption line of the objects being tested, CW systems with the selected frequency-scan length and resolution are more practical in terms of data acquisition time as well as system cost. A CW spectroscopy system with a photonic THz-wave emitter and detector is often referred to as a homodyne system, and its configuration is the same as that of the THz-TDS system (Fig. 7) except for the optical signal source.

One of the interesting aspects of THz-waves is in their interaction with matters via the motion of groups of relatively large molecules such as biological molecules like proteins and DNA, and chemicals. Pharmaceutical inspection of tablets with THz-waves is expected to have a large market opportunity [36]. Other potential profitable applications for THz spectroscopy would be targeted to material inspection and evaluation during or after manufacturing process of semiconductors, solar cells, polymeric films, dielectric composite, plastics, paint, etc. [37]

4.2 Imaging

THz-waves have an ability to penetrate a wide variety of non-conducting materials such as clothing, paper, cardboard, wood, plastics and ceramics, but are strongly absorbed by polar molecules, such as water, and also reflected by metals. THz imaging would become more unique and powerful when combined with its capability of spectrometer as mentioned above.

Examples of lately reported spectroscopic imaging applications include medical imaging of tissues [38], label-free protein detection [39], distribution of polymorphic forms in pharmaceutical tablets [40], on-chip THz spectroscopy systems [41].

One of the most recent and attractive progress in THz imaging is three-dimensional imaging or tomographic imaging. Both pulsed and CW THz waves can be applied to tomographic imaging of layer structure of tablets, internal structures of objects, material inspection, security applications, etc. [42, 43, 44, 45, 46, 47, 48]

In addition to the above limited examples, a wide range of nondestructive inspection and testing applications have been reported in order to find real and specific needs which cannot be duplicated by competing technologies.

4.3 Communications

Demand has been increasing for higher data rate in wireless access systems in order to keep up with the remarkable speed-up of fiber-optic networks. 10-Gbit/s data rate is an urgent need for the wireless transmission of 10-Gigabit Ethernet (10GbE) signals, and multiplexed uncompressed high-definition television (HDTV) signals. In the future, 20, 40, and 100 Gbit/s will be required for the wireless technologies, which can transmit Super Hi-Vision (SHV)/Ultra High Definition (UHD) TV data, having 16 times the resolution of HDTV (at least 24 Gbit/s), OC-768/STM-256 data (43 Gbit/s), and 100GbE (100 Gbit/s). In addition to these access network applications,

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there has also been a need in close proximity wireless transfer of large amount of data, for example, between mobile terminals and storage devices. Such a near-field data transfer technology will possibly evolve to wireless interconnections in devices and equipments.

To achieve such high data rates in wireless communications, there has been an increasing interest in the use of electromagnetic waves at frequencies above 100 GHz by making use of extremely large bandwidth, in contrast to improving spectral efficiency at microwave frequencies [49]. In particular, development of frequency bands from 100 GHz to 500 GHz is of great importance by the following reasons.

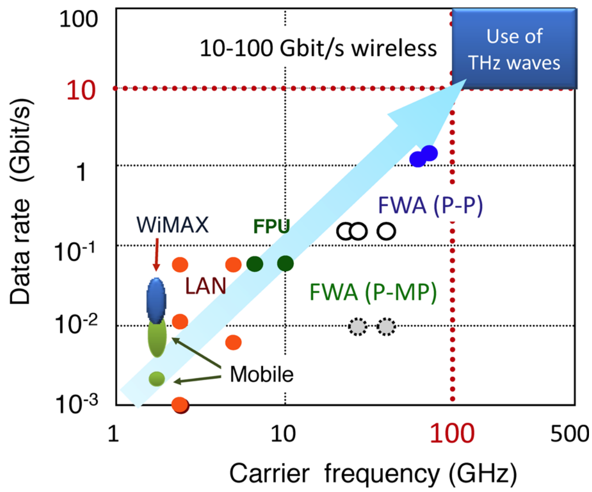

Fig. 8. Relationship between data rate and carrier frequency.

First, Fig. 8 shows the relationship between carrier frequency and data rate in various wireless communications technologies. As can be seen in the figure, the data rate increases with the carrier frequency. From this empirical trend, in order to achieve the data rate of 10∼100 Gbit/s, it is efficient to use the carrier frequencies of 100 to 500 GHz.

Second, the use of terahertz waves at frequencies above 275 GHz has attracted a great deal of interest for wireless communications, mainly because these frequencies have not yet been allocated to specific applications and thus will possibly be used for extreme bandwidth high-speed communications.

Third, developments in the 100 to 500 GHz region are most realistic in terms of enabling technologies such as semiconductor electronic devices and integrated circuits. Currently, oscillators and amplifiers with the operation frequency of 200 to 400 GHz have been developed by compound semiconductor technologies such as InP HEMTs and HBTs, and Si-CMOS will catch up within 10 years.

Fourth, from the viewpoint of atmospheric attenuation of electro-magnetic waves, 500 GHz is nearly an upper limit even for short range (∼100 m) applications. The attenuation is 1 dB per 10 m below 500 GHz as shown in Fig. 9.

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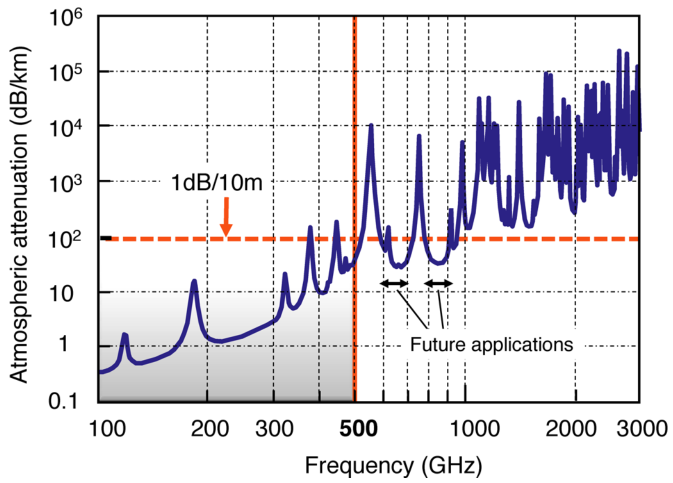

Fig. 9. Atmospheric attenuation of radio waves above 100 GHz.

Table I. Summary of wireless communications above 100-GHz frequencies.

Frequency	Technology		Bit rate	Application	Affiliation
	Tx	Rx			
120 GHz	Photonics-based	MMIC (direct det.)	10 Gbit/s	6ch HDTV	NTT
120 GHz	MMIC	MMIC (direct det.)	10 Gbit/s	5 km with FEC	NTT
200 GHz	Photonics-based	Disc. comp. (heterodyne det.)	1 Gbit/s	NA	IEMN (France)
220 GHz	MMIC	MMIC	~100 Mbit/s	Digital TV	Fraunhofer IAF
250 GHz	Photonics-based	Disc. comp. (direct det.)	8 Gbit/s	NA	NTT Osaka-U
300-400 GHz	Photonics-based	Disc. comp. (direct det.)	~20 Gbit/s	NA	Osaka-U NTT
300 GHz	Discrete components	Disc. comp. (heterodyne det.)	~100 Mbit/s	Analog / Digital TV	TU Braun-schweig
300 GHz	Resonant-Tunneling Diode	Disc. comp. (direct det.)	1.5 Gbit/s	HDTV	Rohm Osaka-U

In addition to the device speed, there is an important merit in choosing higher carrier frequencies. At frequencies of over 300 GHz, the antenna size becomes an order of sub-millimeter, which is smaller than that of lens used in the common IrDA module. For example, size of the array antenna unit in the commercially available 60-GHz wireless home link, which is used between the DVD player and HDTV display, is about 25 mm $\times$ 25 mm. At 300 GHz, the array antenna will be 5 mm $\times$ 5 mm. This leads not only to the dramatic decrease in the cost of transceiver modules, but also to the wide spread of wireless terminals used in the last access to the network, and in the short range data transfer [50].

Table I summarizes recent development of wireless links using radio waves at frequencies of over 100 GHz. Details of each technology have been described in the recent review articles [51, 52, 53].

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5 Conclusions

The field of THz science and technology has been growing at a tremendous speed, as evidenced by the exponentially increasing number of publications and conference presentations. This paper has provided an overview of latest trends in fundamental component technologies and their applications.

Of special notes which have occurred within the last five years are:

1) More than 20 companies over the world have started to produce THz-related instruments like spectroscopy and imaging systems, but the volume in the market is still small.

2) Commercial availability of key components such as emitters, detectors and lasers is increasing, which accelerates new researchers and engineers to join this field.

3) A number of field demonstrations of THz instruments and equipments have been conducted in order to attract more interest of potential users and market, and to find profitable applications.

Today's development of THz technologies was triggered by photonics technologies such as photonic generation and detection of THz waves, but commercially available photonic components like short pulse lasers are still expensive and bulky. Integration of photonic components, particularly with use of telecom-based components, is essential to hurdle cost and size issues. Fortunately, we have seen a steady progress of semiconductor electronic devices and circuits operating at THz frequencies, and they will replace some of the photonic components with purely electronic ones, except QCLs. Metamaterials, photonic crystals and MEMS technologies, which have also been making rapid progress, will help THz technologies to enhance their performance, functionality and usability.

THz technologies are now seriously facing a turning point from technology-push to market-driven phase. Of course, breakthrough technologies to overcome bottlenecks for practical use should continue to be developed to meet real market demands.

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