Galore New Applications of Terahertz Science and Technology

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Abstract: Terahertz science and technology is now receiving increasing interest around the world, and materials, devices and systems exploiting this waveband are set to play an important role in a very diverse range of applications. We give an overview of the current status of the technology and its future prospects.

Keywords: THz sources and detectors, THz-time-domain-spectroscopy, THz new applications, future prospect of THz technology

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1. Introduction

Terahertz (THz) science and technology develops new research field in the frequency gap between the infrared and microwaves, typically referred to as the frequencies from 100*GHz* to 30*THz*. The THz science and technology itself has long been studied in fields such as astronomy and analytical science. However, recent innovation in THz technologies is bringing a wide variety of applications in the field of information and communications technology (ICT); biology and medical sciences; non-destructive evaluation (NDE); homeland security; quality control of food and agricultural products; global environmental monitoring; and ultrafast computing among others [1].

THz-time domain spectroscopy (THz-TDS) has brought about a breakthrough in the middle of 80's, and followed by a THz imaging with THz-TDS. This has stimulated various kinds of THz research and applications [2]. Important platforms are classified into THz sources, THz detectors, modulators/manipulators, imaging methods, basic science such as interaction between THz waves and materials, application trials, THz standards/EMC, development of database, and so on. This paper reviews the recent progress of the THz science and technology and introduce some of the recent topics in the THz applications.

2. New twist of THz science and technology

Among fundamental technologies, breakthroughs in the field of THz sources and time-domain-spectroscopy have triggered THz research. Fig. 1 summarizes THz emission power as a function of frequency. There are three major approaches for developing the THz sources. The first is optical THz generation; the second is the recently developed THz Quantum Cascade Laser (QCL); the third uses solid-state electronic devices.

Optical THz generation methods can be broken into the generation by an ultrafast photocurrent in a photoconductive switch or semiconductor using electricfield carrier acceleration or the photo-Dember effect, and by nonlinear optical effects such as optical rectification, difference-frequency generation or optical parametric oscillation. The former steadily progresses such as development of photoconductive switches adapted for 1.5 μm wavelength excitation [3,4]. Photomixing is also a potential THz beam generation technique. Among many candidates of photomixers, Uni-traveling Carrier Photodiodes (UTC-PD) is a promising device. Nagatsuma et al. has succeeded to obtain over 20 μW at 1*THz*, which is available for short range wireless communication [5].

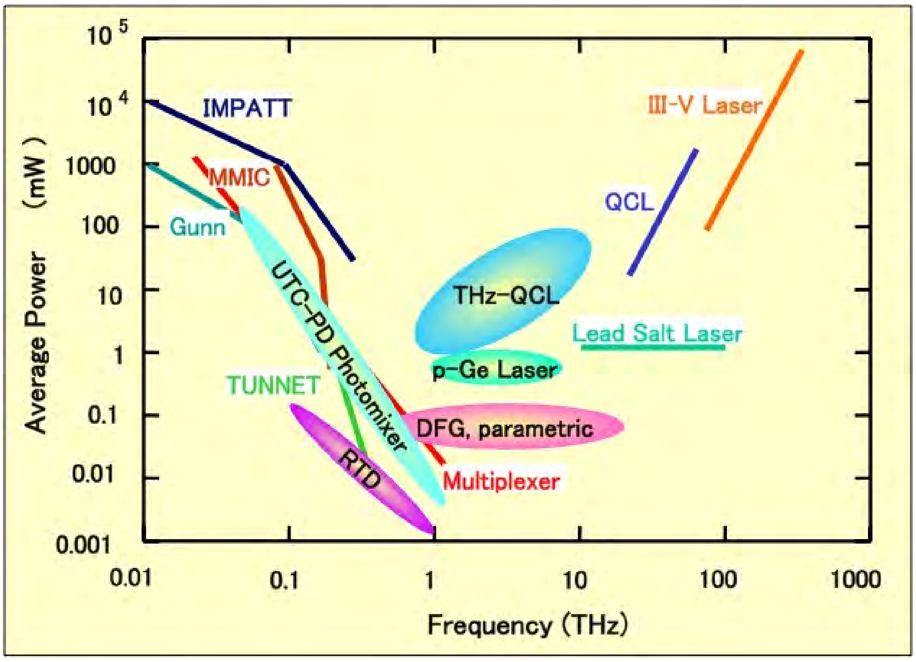


Fig.1 THz emission power from various devices as a function of frequency.

Very recent topics in the field of nonlinear optical-THz conversion are THz Cherenkov radiation [6] and air plasma generation [7]. The emission mechanism for the former is explained as follow. When femtosecond optical pulses travel in $LiNbO_3$ crystal, THz waves are generated by parametric fluorescence toward about 50-degrees-off angle from the incident pulse propagation direction. They are absorbed in $LiNbO_3$ severely. To avoid such absorption, Hebling et al. introduced tilted fs optical pulse wave front to excite THz waves at the Cherenkov radiation wave front, as shown in Fig.2, which enhances THz wave generation totally. M. Nagai et al. has improved the system and realized high field generation of monocycle terahertz (THz) pulse above 200 kV/cm, as shown in Fig. 3 [8,9].

The air/gas plasma also can produce high power THz beam. In addition to the high power, it covers wide broad bands up to 30 THz. Emissivity strongly depends on gaseous species, which increases with decreasing ionization potential. Thus Xe gas can produce much higher power THz beam than He.

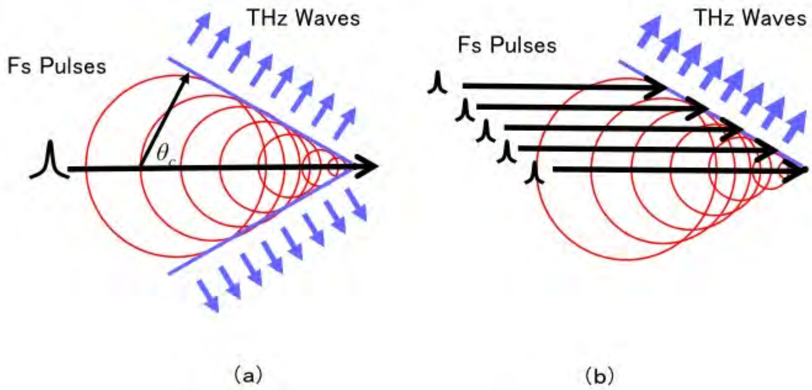


Fig.2 (a) Cherenkov radiation in $LiNbO_3$ crystal and (b) improved THz generation with tilted fs pulse wave front.

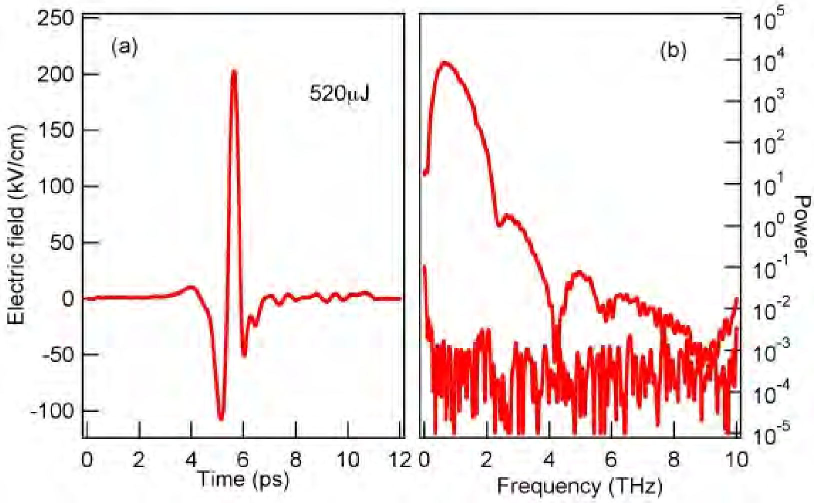
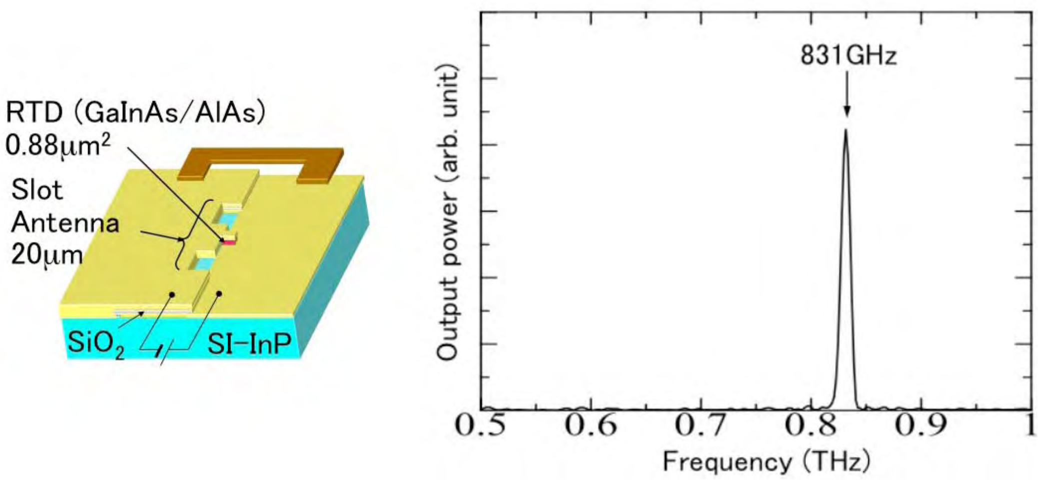


Fig.3 (a) Temporal THz waveform and (b) corresponding Fourier spectrum.

Remarkable progress in the development of THz-QCL has been achieved. State-of-the-art THz-QCL works at a lowest frequency of 0.68 *THz* and a temperature of 225*K* with external magnetic field, and a power of 140 *mW* and 250 *mW* at CW and pulsed operation, respectively [10,11].

Electronic THz wave generation is one of the key technologies for ICT to realize mobile, robust, and inexpensive system. Very recently Asada et al. succeeded to generate THz waves at a frequency of 0.83 *THz* from resonant tunneling diodes as shown in Fig.4 [12]. Otsuji et al. has also developed a plasmon-resonant THz emitters and succeeded to produce broadband THz waves up to 7 *THz* [13,14]. These solid state devices would bring a variety of applications.

Continuous efforts have been made to develop better THz detectors. As recent topics, Kawano et al., has developed near field THz detector, which consists of 2D electron gas THz detector, small aperture, and near field probe antenna in one chip as shown in Fig. 5 [15]. This detector enables us to image high resolution THz field. They are also developing a new type of THz detector utilizing graphene operating under magnetic field [16].



(a) (b)

Fig.4 (a) Schematic of RTD. (b) THz emission at 832*GHz* from RTD.

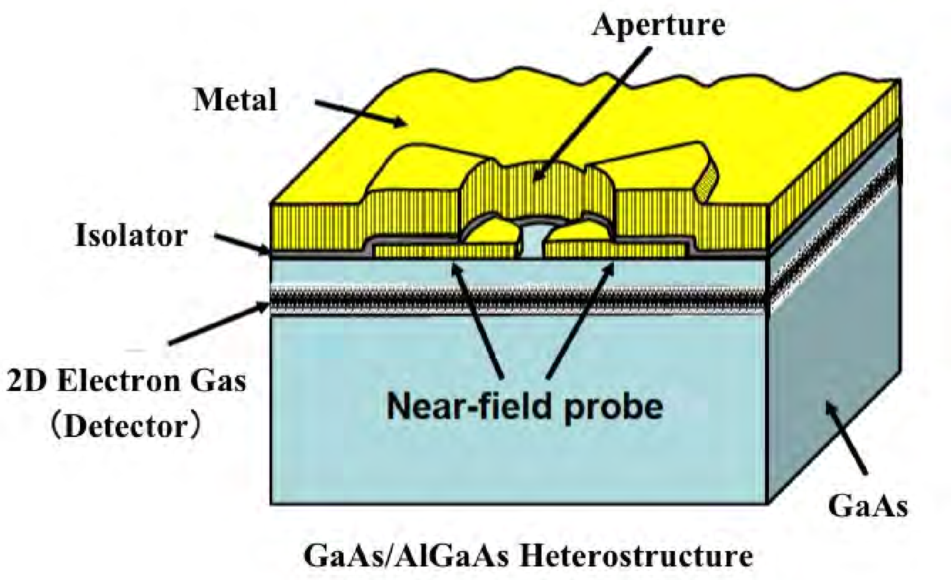


Fig.5 Schematic of all-one-chip near field THz detector.

Recently Oda et al. has optimized an operation frequency of infrared focal plane imaging arrays [17] at around 3 *THz* and obtained its NEP as small as 40 *pW* at a flame rate of 60 *Hz* for 320x240 pixels (Fig. 6). They optimized the resistance of the absorption layer and window materials. At moment, this shows a highest performance as the THz camera [18].

There are many other important components for THz applications such as THz fiber [19], waveguide, metamaterials [20] and so on. Recently porous fibers are found to have low dispersion medium as a THz waveguide. Also carbon nanotubes are found to be excellent THz wave polarizer [21].

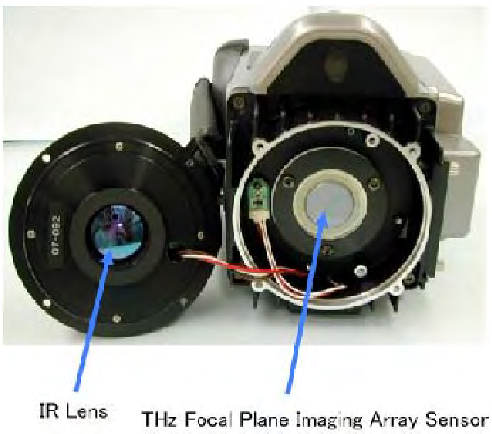


Fig.6 Developed THz camera.

Fig.7 Developed THz-TDS system.

Continuous efforts have been made to develop compact, high-sensitive, and robust THz-TDS for spectroscopy and imaging. As a source of TDS, organic crystals have high photon-THz-wave conversion efficiency. DAST is one of promising materials. Otsuka Electronics Co. Ltd. has recently commercialized compact THz-TDS system using fs fiber laser at a wavelength of 1560 *nm* and DAST, which covers the frequency range up to 7 *THz* (Fig.7). Since 1.5 *μm* laser matches to the phase condition at around 2.2 *THz* [22], conversion efficiency becomes maximum at over 2 *THz*, which enable us to utilize THz waves at higher frequencies. Fig. 8 shows an example of the evaluation. The dielectric parameters of $SrTiO_3$

thin films are characterized. The 370-*nm*-thick films grown by the laser ablation has a resonance at 3.3 *THz*, which is attributed to the LO photon scattering [23,24]. The results indicate that one can evaluate the optical constant up to 6 *THz*.

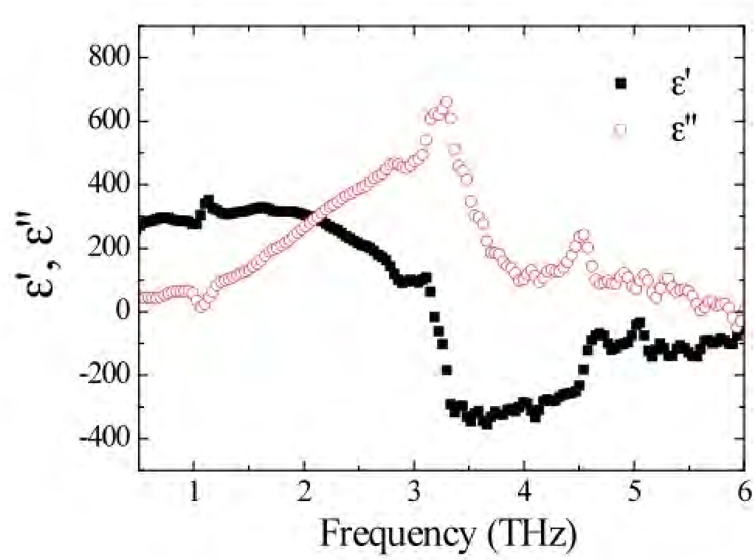


Fig.8 (a) Real and (b) imaginary parts of dielectric constant of the STO film on MgO substrate.

We are studying a unique application of THz waves. Femtosecond laser illumination induces THz wave generation from various kinds of materials. The observation of the THz waveforms enables us to explore ultrafast nature of electronic materials and devices as a THz emission spectroscopy. Thus construction of a laser-THz emission microscope (LTEM) would provide a new tool for material science and application [25]. The LTEM system is illustrated schematically in Fig. 9. Currently we obtained LTEM resolution down to be 0.6 *μm*. As explained in later, there are many applications of LTEM such as imaging of supercurrent distributions [26], ferroelectric domain [27], and so on.

3. New Trends of THz Applications

There has been an intense activity to develop THz-sensing and ICT applications. Here we introduce some of the recent new types of THz application re-search.

3.1 Conservation of Historic and Artistic Works

There have been the thousand applications of THz-TDS [1]. Fukunaga et al. has recently introduced THz-NDE for conservation of historic and artistic works, which gives us strong impact [18, 28]. She has found that different color pallet has different response to the THz waves. This is much more sensitive than that with light from the mid-and near-infrared regions. Thus THz-NDE is a potential tool to analyze artwork to obtain information useful for restoration and conservation.

Fig. 10 shows one of the observation parts in the Polyptych of Badia (ca 1300, Giotto, Uffizi Gallery). Existence of gold foil under paints was clearly observed at the outline of the head and wings of Angel. The layered structure of the painting was obtained non-invasively and without contact. Two gesso layers proved that this work was made by traditional medieval technique. The information obtained here using THz imaging is practically useful for conservators and would never be obtained by conventional methods.

Note that these techniques are also available for many other NDEs.

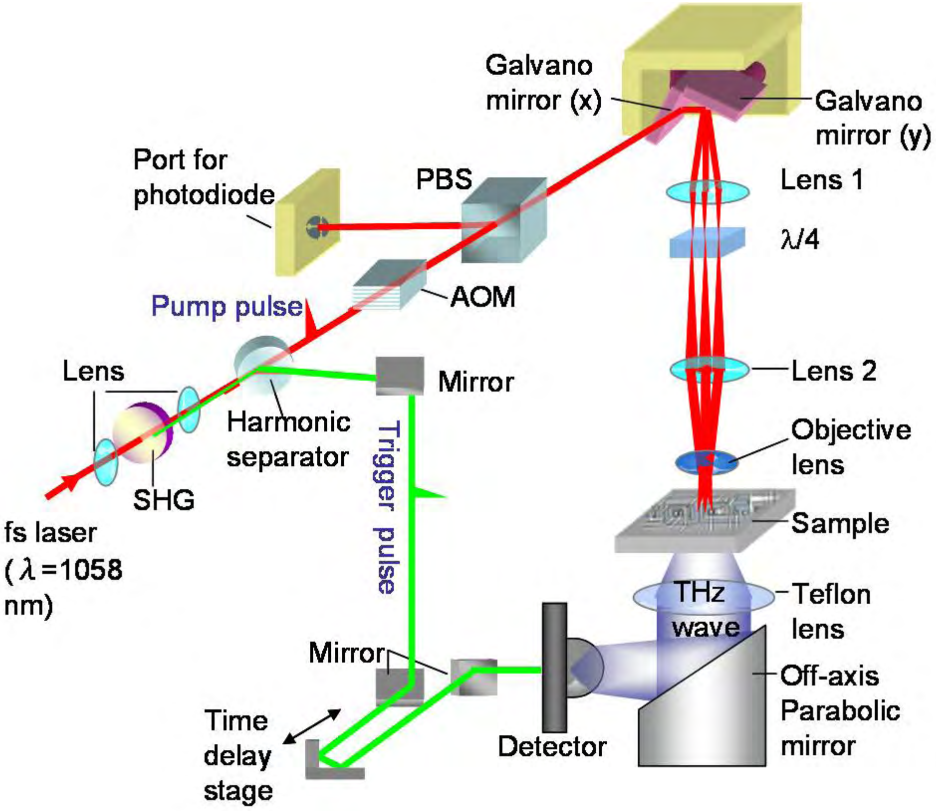


Fig.9 Schematic of LTEM.

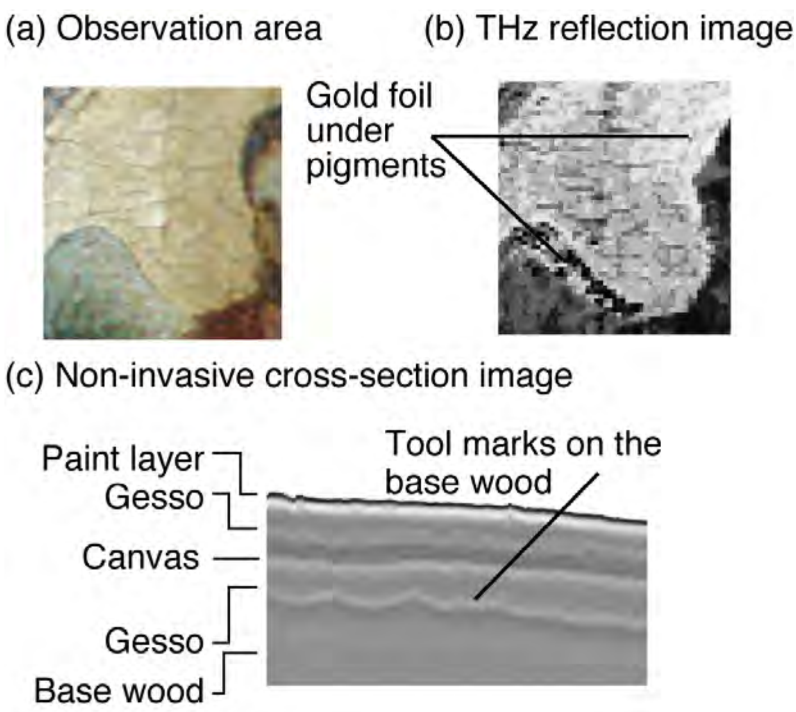


Fig.10 Visible(a) and THz (b) images of a part of Polyptych of Badia, and its tomographic view(c).

3.2 THz emission spectroscopy

One can observe THz emission from various materials upon femtosecond laser illumination, which reflects dynamic response of optically excited materials. Thus THz emission spectroscopy is one of the potential tools to study material physics. We have discovered unique THz emission from $BiFeO_3$ (BFO) [29]. The emission mechanism is attributed to direct optical modulation of spontaneous polarization Ps. BFO is well known to posses the strong Ps. Generally, THz emission is attributed to real space carrier acceleration/deceleration, or nonlinear down conversion due to optical rectification/difference frequency generation (DFG)/parametric generation through $\kappa^{(2)}$ or $\kappa^{(3)}$ effect. Different from conventional mechanism, THz generation from BFO is explained by the optical annihilation of Ps [30].

Fig. 11 (a) is an example of THz emission from photoconductive antenna made of BFO and Au electrodes. We use the fs laser at a wavelength of 400 *nm* doubled by SHG. BFO is polled once by an external electric field and the emission is observed after removal of the field. Maximum amplitude dependence on polling field shows clear hysteresis, representing Ps of the BFO film (Fig. 11(b)). Results indicate that polling with fs laser pulse illumination assists the spontaneous polarization switching whereas no saturation of polling is observed below an external field less than 200kV/cm. This proves that THz emission spectroscopy can be a strong tool for the noncontact evaluation of Ps nondestructively.

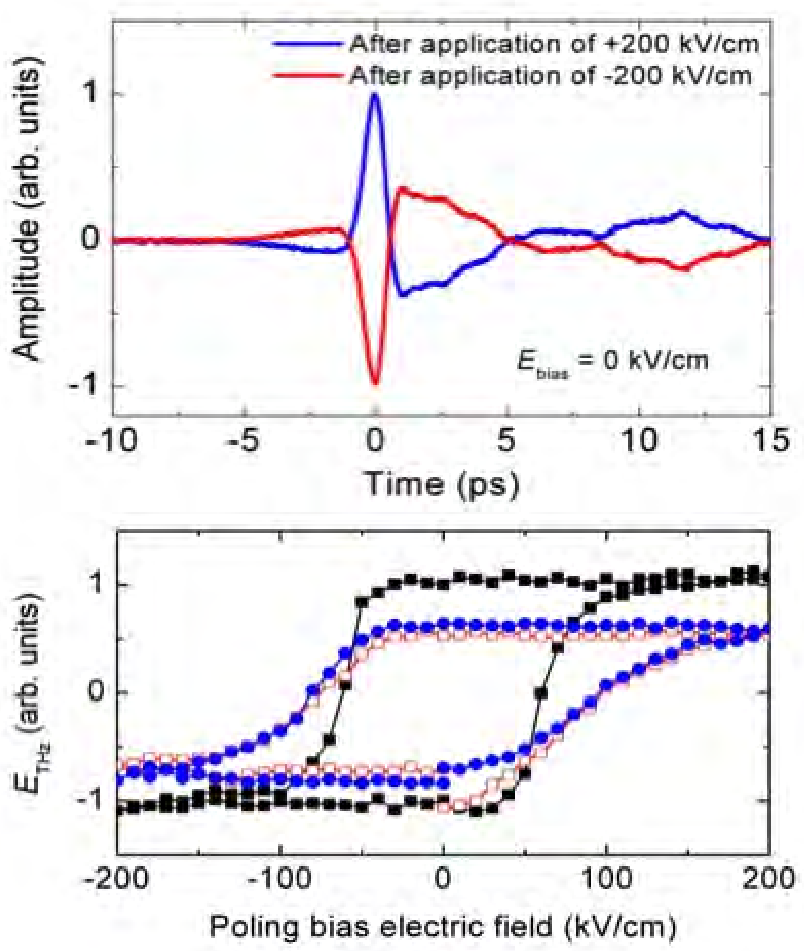


Fig.11 (a) Example of THz emission waveform radiated from BFO photoconductive switch, and (b) Maximum THz amplitude dependence on polling field. Black is for the data polled with illumination; red and blue for those without illumination.

Kiwa et al. has developed new application of THz emission to study chemical reaction and bio applications [31,32]. Fig. 12 (a) indicates the schematic of the sensing chip. SiO_2 and Si thin films were prepared on the substrate. The antibody was immobilized on the SiO_2 surface. When the femtosecond laser hits the Si film from the backside of the chip, the THz are generated and radiated to the free space as the result of the photo-Dember effect. If the antibody is combined with the anitigen, the surface potential of chip shifts and the peak amplitude of THz changes. Thus the reaction of the antibody and the antigen can be measured by monitoring the peak amplitude of THz. Fig. 12 (b) shows the peak amplitude of the THz from the chip. The avidin, which was strongly combined with the biotin, was immobized on the chip. A 4-(2-hydroxyethyl)-1- piperazineethanesulfonic acid (HEPES) solution was applied as the test solution. The THz amplitude was rapidly decreases by injecting the 5-pmol/L-biotin to the solution. This result indicates that high sensitive label free detection of the reaction of proteins can be possible using the sensing chip. This is the first demonstration of the detection of the proteins combinations in the water solutions using THz technology.

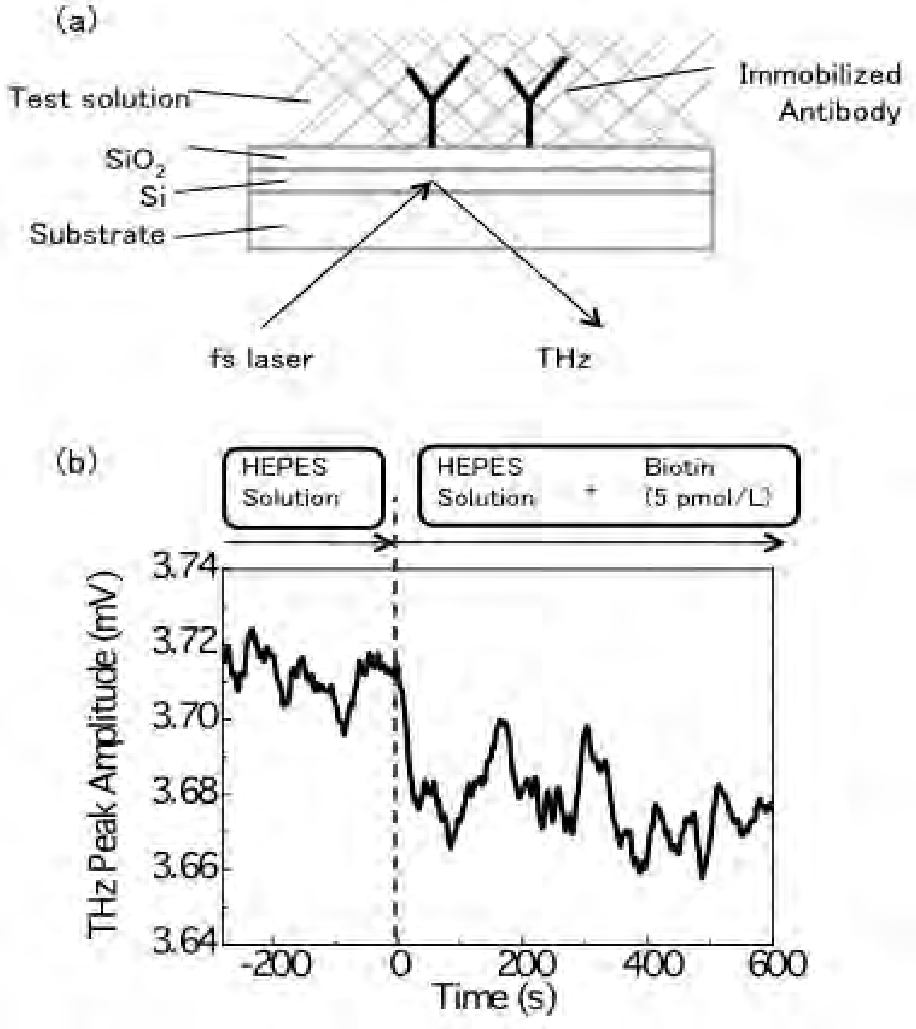


Fig. 12 (a) Schematic of the sensing chip and (b) time-dependent THz emission amplitude.

3.3 LTEM application to LSI defect analysis

We have developed LTEM utilizing excitation laser pulses at 1.06 μm wavelength for the inspection and localization of electrical failures in large-scale integrated (LSI) circuits with multilayered interconnection structures. The system enables to measure THz emission images from the backside of an LSI chip with a multilayered interconnection structure which prevents the observation from the front side. By comparing the THz emission images, we successfully distinguish a normal circuit from damaged ones with different positions of the interconnection defects without any electrical probing [33].

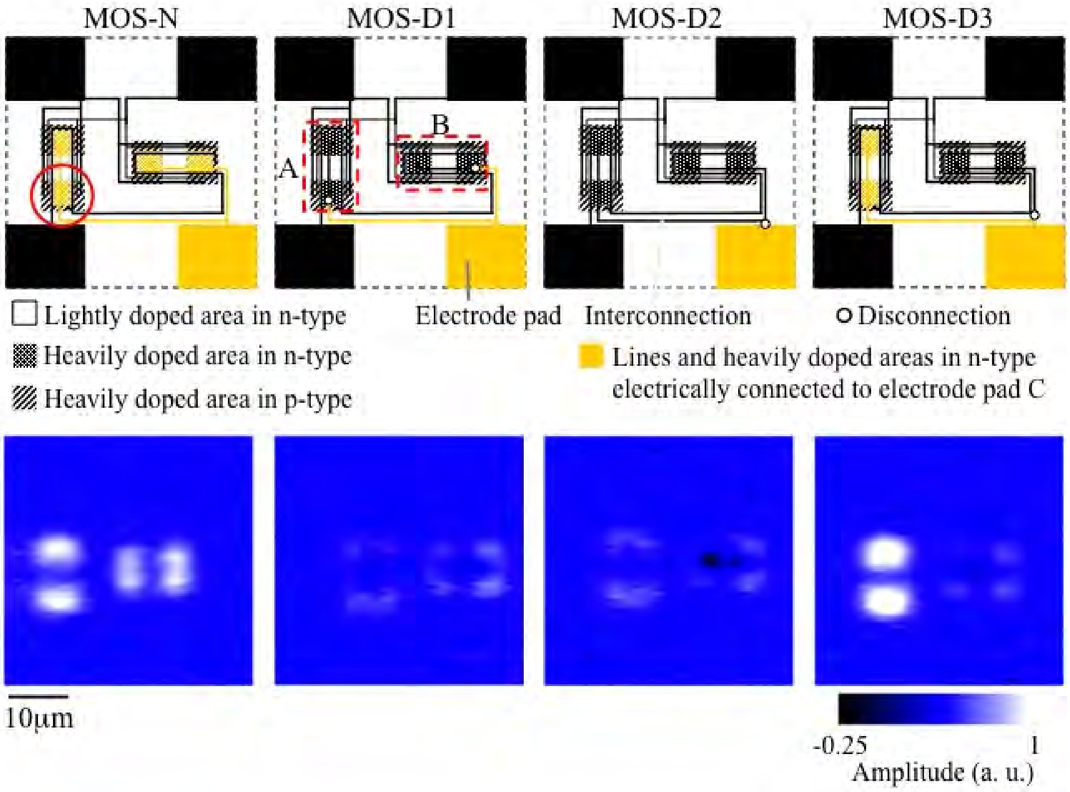


Fig.13 (a) Illustrations of the normal circuit (MOSN) and the defective ones (MOSD1-MOSD3) with different disconnection positions. (b) The corresponding THz emission images.

Schematic illustrations of test circuits composed of Si pMOSFETs are shown in Fig. 13 (a), which are measured from the backside of the chip. The normal circuit is labeled MOSN, and three defective ones (MOSD1-MOSD3) with a different position of the disconnection of the line between the heavily doped areas in n-type and the electrode pad as shown by circles in Fig. 13 (a) are prepared. MOSD1 and MOSD2 have disconnections on the lines from both areas A and B, differing in the fact that in MOSD1 the lines are interrupted near A and B, while in MOSD2 there is a single interruption near pad C. MOSD3 has a disconnection only on the line from the area B. The THz emission images of the test circuits from the backside of the chip are shown in Fig. 13 (b). By comparing the THz emission images in Fig. 13 (b), one can distinguish the normal circuit from the defective ones. It also can be seen that the THz emission signals from p-n junctions change depending on the position of the line disconnection. MOSD1 and MOSD2 radiate the smaller THz emission signals from heavily doped areas in n-type in both areas A and B than that from MOSN due to the disconnection. In the case of MOSD3, the THz emission signals from heavily doped areas in n-type of A increase but that from B decrease by the disconnection between the electrode pad C and the area B. This suggests that the increase of the transient photocurrent from A flowing into the electrode pad enhances the THz emission signal. It can also be seen that there is little influence of the disconnections to the THz emission signals from heavily doped areas in p-type. These results suggest that the interconnections and electrode pad enhance the THz emission efficiency by working as an antenna and the change of the THz emission images are useful for the localization of p-n junctions with interconnection defects in circuits.

3.4 THz spectrum analyzer

A spectrum analyzer is a fundamental frequency measurement instrument. Recently, new types of spectrum analyzers using a mode-locked fs laser, referred to as THz-comb-referenced spectrum analyzer, have been proposed and developed which can measure the absolute frequency and spectral shape of continuous-wave (CW) THz radiation without the need for cooling [34,35].

Fig. 14 shows a schematic diagram of the experimental setup. The output light of an Er-doped fiber laser was focused onto a gap of a photoconductive antenna (PCA) after passing through an optical fiber for delivery. This results in generation of a THz frequency comb of photocarriers (PC-THz comb) in the PCA. By precisely stabilizing a laser mode-locked frequency by referring to a rubidium (Rb) atomic clock, the PC-THz comb can be used as an accurate and stable frequency ruler in the THz region. When the CW-THz radiation from a test source was incident on the PCA, photoconductive heterodyne mixing between the CW-THz radiation and the PC-THz comb was occurred in the PCA and generates a group of beat current signals between them. The beat signal with the lowest frequency and the laser mode-locked frequency are measured with an RF spectrum analyzer and an RF frequency counter to determine the absolute frequency and spectral shape of the CW-THz radiation.

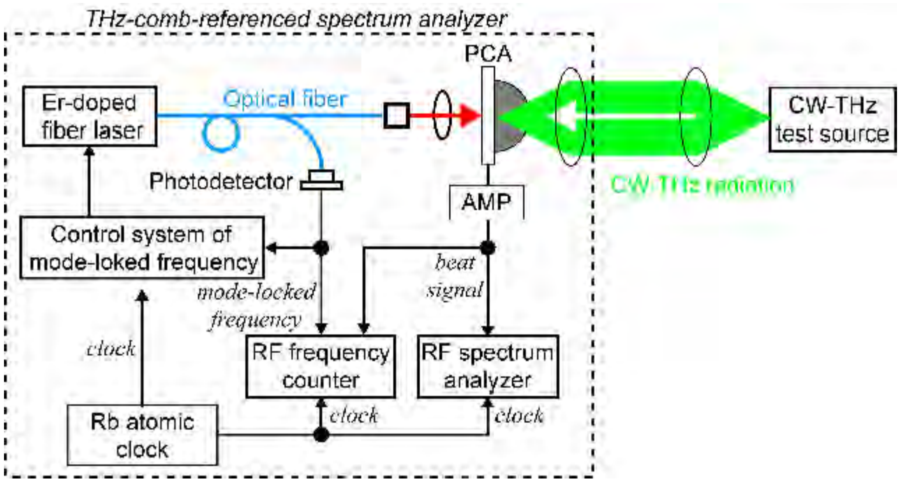


Fig.14 Schematic diagram of the experimental setup.

5. Summary

We report on the review of recent progress of THz science and technology, and introduce some of the new type of applications among the galore ones. THz sources are developing rapidly, and new type of detectors and camera are emerging. Promising applications such as art conservation, LSI defect analysis, and THz spectrometers are becoming ready to use. There are many other NDE and imaging applications [36], which will be coming soon. Large market applications are expected for THz wireless communication, and Bio applications, which would need a rather longer-term- strategy.

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