2 General Discussion: Position and Prospect of Research and Developments for the Terahertz Technology in National Institute of Information and Communications Technology (NICT)

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Active research and development are now progressing on the application of electromagnetic waves known as terahertz waves. Universities, national research institutions, venture companies, and even major corporations are now beginning research and development in this area. Many examples demonstrate the usefulness of sensing and imaging with terahertz waves in various aspects of industry and society. Discussions have also begun on new high-bit-rate ultra-short-distance wireless technology that takes advantage of the ultra-high-frequency characteristics of terahertz waves. At this stage we cannot even imagine the eventual number and kinds of terahertz applications that will emerge. According to the March 2005 “Terahertz Technology Trend Report” of the Ministry of Internal Affairs and Communications and the “Terahertz Technologies, R&D, Commercial Implication and Market Forecast” of Fuji-Keizai USA Inc. issued in August 2007, the question is not whether the market for terahertz technology will increase – it inevitably will – but by how much. Given this background, the National Institute of Information and Communications Technology (NICT) launched its “Terahertz Project” in April 2006. The Terahertz Project aims to develop fundamental terahertz technologies at the national level for expanding applications in diverse fields. These fundamental technologies include those incorporated in small high-performance devices and measurement systems and high-precision light sources, as well as those required in the construction of an atmospheric propagation model, the construction of spectral databases of materials, and the standardization of measurement procedures. This special issue reports on the achievements obtained to date in independent research and development conducted directly by NICT (including semiconductor device technology, system technology, databases, and atmospheric propagation) as well as in contract research undertaken by external organizations. In this discussion, we indicate the direction in which each project is heading, in view of the important benchmarks in the future development of terahertz technology.

Keywords

Terahertz-wave, Semiconductor device, Terahertz time domain spectroscopy,
Spectral database, Atmospheric propagation model

1 Introduction

The Radio Law defines radio waves as electromagnetic waves with a frequency of three million megahertz or less. In other words, with a boundary at 3 THz (= 3 million megahertz), we refer to the lower-frequency electromagnetic waves as “radio waves” and the higher-frequency electromagnetic waves conventionally as “light”. There is as yet no final definition of terahertz-waves, but the definitions, which vary from person to person, differ only slightly. Generally, terahertz waves can be regarded as the range of electromagnetic waves spanning two orders of magnitudes in the frequency range from 0.1 THz to 10 THz. Thus, terahertz waves include millimeter waves [up to approximately 300 GHz (wavelength: λ = 1 mm)] at the lower edge and cover the boundary range between radio waves and light. These boundaries include both the upper frequencies of radio waves [from 300 GHz to 3,000 GHz (or 3 THz, with a wavelength: λ = 0.1 mm)] — previously referred to as “sub-millimeter-waves”— and the lower frequencies of light from 3 THz to 10 THz (wavelength: λ = 30 μm).

Terahertz waves are situated in the artificial, legally established boundary between radio waves and light. Nevertheless, we conclude that the natural boundary of electromagnetic waves also lies within the terahertz range. For example, Fig. 1 shows the relationship between maximum output power and frequency for oscillators based on semiconductor devices. On the left, the figure shows the relationship between oscillation frequency and the power of the electronic oscillator devices based on semi-classical electronic transport phenomena. These devices incorporate transistors and various two-terminal devices (such as a Gunn diodes and resonant tunneling diodes). As the frequency increases, the output power rapidly decreases. On the other hand, the figure shows, on the right, the relationship between output power and frequency in semiconductor lasers based on optical transitions of electrons described by quantum theory. In this range, output power decreases with a decrease in frequency (i.e., light energy). Looking at this figure, the boundary between the two appears to be situated near 1.5 THz. Near this boundary, the output values of the oscillators of the semiconductor devices are extremely small (with the exception of the terahertz quantum cascade laser). As such, phenomena determined by the laws of physics also seem to illustrate a progression from classical theory toward quantum theory in the terahertz range. This overlap is considered to have contributed to today's lack of high-power oscillators in the terahertz range. This range is referred to as the “terahertz gap”, and it is our belief that the light sources that will bridge this gap will form the key to development in the terahertz range.

The energy range of terahertz waves includes various elemental excitations of solids, rotational modes of molecules, internal vibration modes of macromolecules, hydrogen bonding, and van der Waals bonding. Diverse substances and materials have characteristic spectra (so-called “fingerprint” spectra) in this range. The thermal energy of room temperature is also within the terahertz range. Thus, this range is particularly interesting in terms of spectroscopic analysis, both in crucial engineering applications and in pure science.

In recent years, terahertz time-domain spectroscopy (THz-TDS) has emerged as a

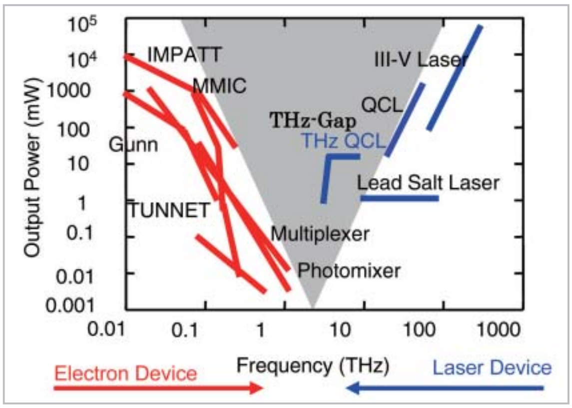

Fig. 1 Outout power of the semiconductor devices (Continuous wave mode) in the terahertz frequency region. In the “THz-Gap” (around 2 THz), It is difficult to realize a device with high output power

new spectroscopic technique. Tunable monochromatic terahertz light sources based on nonlinear optics and small high-intensity semiconductor light sources (terahertz quantum cascade lasers) have also been developed. With these new technologies, the terahertz waves conventionally used only in scientific research are now beginning to reveal prospects of diverse applications in fields close to daily life. As these technologies are developed, application demonstrations are also beginning in various fields (material analysis, security, medical treatment, pharmaceuticals, biotechnology, agriculture, industry, communications, and scientific instrumentation). To establish fundamental technologies at the national level for the growing and varied range of terahertz-technology applications, the National Institute of Information and Communications Technology (NICT) conducts its own independent research and development aimed at small high-performance devices and measurement systems, high-precision light sources, construction of an atmospheric propagation model, establishment of spectral databases for materials, and the standardization of measurement procedures, among others. Although these studies are all considered vital elements in disseminating terahertz technology, they would be difficult to implement in universities and private companies. In contract research conducted in close collaboration with independent research activities, NICT is developing stand-off (i.e., remote) spectroscopic sensing systems and camera systems to be used in disasters and similar situations. This special issue reports on the achievements obtained to date in both independent and contract research. Before the discussions in Chapter 3 and subsequent chapters, in this article, research and development issues are identified with respect to the technologies described in each chapter. In these cases we suggest a specific direction in which each project is heading, with a focus on the essential elements of the future development of terahertz technology.

2 Significance of each research and development issue

To date, R&D or demonstrations have been aimed at a variety of applications based on terahertz technology. Some of these studies or efforts are expected to develop into practical applications within several years — including, for example, security applications such as passenger screening in airports and at important facilities, and inspection of international articles of mail. These examples will be put to practical use even if the measurement costs (a function of the price of the equipment and the duration of measurement) are high. If the prices of the measurement equipment come down and usability increases, terahertz technology will face a very large number of potential applications in diverse fields. With these new applications, it will become even more essential to overcome an array of known challenges: reducing the price and size of the terahertz devices, enabling robust measurement (specifically allowing field use), establishing spectral databases that allow for spectroscopic analysis in the terahertz range, constructing an atmospheric propagation model (which will be essential in determining the specifications of devices), preparing measurement procedures that guarantee absolute values and precision of the measured values, and ensuring traceability. With these points in mind, NICT is pursuing research and development surrounding the issues below.

2.1 Semiconductor devices

It is generally characteristic of semiconductor devices that they are small, can provide usable power, and lend themselves to significantly cost-effective mass production. Among the diverse terahertz light sources available, solely the terahertz quantum cascade laser satisfies these characteristics. Thus, developing this laser represents an important step in the dissemination of terahertz technology. Although relative to other countries Japan came late to research and development of the terahertz quantum cascade laser, NICT was the first to commence development of the device in Japan, and these efforts were successful. As the semiconductor materials must be epitaxially grown to a thickness of more than 10 micrometers, and as high-sensitivity measurement of oscillation characteristics requires conventional detectors cooled by liquid coolants, the development of this laser raised a host of difficulties, both in technical terms and in terms of costs. Moreover, the size of the market for terahertz technology was not initially clear. These circumstances rendered it unsuitable and difficult for universities and private companies to perform the requisite research and development. Accordingly, this is the sort of initiative that falls naturally to national research institutions, which are poised to play important roles in taking up the challenge of such research and development.

On the other hand, the development of terahertz detectors is also imperative. In this area as well, universities and private companies are not in a position to undertake active research and development. The detectors to be used in terahertz applications must be large-scale (i.e., with more than 100 × 100 elements), feature high sensitivity (noise equivalent power, or NEP, of approximately 10^{-14} W/Hz$^{1/2}$), and must be able to operate at normal temperatures (approximately 300 K). Armed with such a detector, we will be able to implement a “terahertz camera” that will be able to detect blackbody terahertz components emitted from an object at normal temperatures (approximately 300 K) and instantly generate a corresponding image. In the fabrication of such a camera, semiconductor technology is key — in particular, the superior device-integration technology incorporated in these devices. However, it is widely accepted that significant hurdles lie in the way of implementation of all of these specifications. Accordingly, NICT set aside the requirement of normal-temperature operation in its independent research. As a result, development is now underway to develop a semiconductor quantum-well detector intended for a terahertz camera based on a large-scale (more than 100 × 100 elements), high-sensitivity (NEP of approx. 10^{-14} W/Hz$^{1/2}$) array detector. In corresponding contract research, NICT aims to develop a normal-temperature, stand-off camera system with a supplementary lighting source, by modifying the uncooled microbolometer array detector previously employed in the mid-infrared range so that it can be used for the terahertz range. We are also considering using a terahertz quantum cascade laser that we are developing in the course of our independent research as a supplementary light source.

2.2 Spectroscopic and imaging systems

The invention and development of terahertz time-domain spectroscopy (THz-TDS) have greatly simplified terahertz spectroscopy and imaging, with a superb S/N ratio. It is particularly meaningful that we can now perform measurements in a range in which conventional Fourier spectroscopy (several hundred GHz to several THzs) cannot provide a satisfactory S/N ratio; moreover, these measurements can be performed within a short time and across a large dynamic range, without the need for high-sensitivity detectors that require liquid coolants. It is also an advantage unique to this method that the complex dielectric constant can be directly derived based on the measured amplitude and phase information without using the Kramers-Kronig conversion, which is required in Fourier spectroscopy to obtain the complex dielectric constant. In Japan, the Kansai Advanced Research Center (KARC) of the Communications Research Laboratory (CRL, the predecessor of NICT) began research and development of terahertz time-domain spectroscopy in the 1990s. The technologies developed at KARC then spread to research and development in terahertz time-domain spectroscopy in numerous universities and private companies.

The bandwidth of terahertz time-domain spectroscopy depends on the pulse width of the excitation pulse laser. Using an excitation laser with a shorter pulse can produce terahertz signals in a larger bandwidth. Today, NICT is developing a terahertz time-domain spectroscopic system featuring a bandwidth of over 10 THz, offering stable operation while maintaining broadband characteristics. In addition, within a bandwidth as small as 2 THz, NICT is developing an ultra-short pulse light source based on the device technologies used in the optical communication band, as part of efforts to establish technologies for terahertz time-domain spectroscopy that will allow for flexible system configuration according to the measured object. Terahertz time-domain spectroscopy using this source is expected to provide stability, high precision, and compact size. We have high hopes that this device will take terahertz time-domain spectroscopy out of the laboratory and into the field.

Recent years have seen rapid developments in millimeter-wave imaging technology. It seems clear that part of the driving force for these developments arises from the search for new uses of millimeter-wave technology, which had previously been aimed primarily at communications and in-vehicle radar applications. New uses are particularly anticipated in the field of security. Apart from the pulsed terahertz technologies discussed above, terahertz technology as a simple extension of millimeter technology (involving simply increasing the applied frequency in existing contexts) also appears to hold significant potential. By increasing the frequency, the distance of the visible range decreases (mainly due to atmospheric absorption), but spatial resolution increases. As a result, a practical approach would involve conducting research on a given system in the millimeter range, waiting for the device technology to evolve to accommodate higher frequencies, and then promoting the application as a terahertz imaging technology. Given these possibilities, NICT is developing a millimeter-wave imaging technology using the near field, which we expect will then be extended to the existing terahertz band.

2.3 Material — spectral database

A defining feature of the terahertz range is seen in the presence of “fingerprint spectra” characteristic to various substances within this range. In the X-ray to mid-infrared ranges, for which spectroscopic analysis technology is already mature and applied to diverse purposes, spectral databases are established, are classified for different industries and application fields, and are used to obtain customized data. In the terahertz range, on the other hand, data have long been accumulated for pure substances, but there is no general spectral database for materials used in diverse fields. We are currently at a stage in which each separate organization that conducts research and development in the terahertz range is accumulating data according to its own specific purposes. NICT has constructed a spectral database related to a specific field (materials used in classic Western art), has pointed to examples of analyses made possible with this database, and generally demonstrated the usefulness of a terahertz spectral database. In addition, NICT has opened this database to the public and is inviting researchers throughout the world to take part. In the process of collecting this sort of data, precision is an issue of concern. In order to guarantee the precision and to increase the reliability of the database, we must standardize the relevant measurement procedures and calibration samples. By disseminating the network worldwide through the database and by promoting discussion of standardization of the measurement procedures in the process, we believe that we can increase the value of terahertz spectroscopy technology overall.

2.4 Constructing propagation model of electromagnetic waves

Constructing an atmospheric propagation model of terahertz waves is essential in designing various terahertz measurement systems in which terahertz waves travel through air. When we observe the atmospheric transmission characteristics of electromagnetic waves, we see extremely large absorption values in the terahertz range. Due to this absorption, it has commonly been assumed that terahertz waves are electromagnetic waves that cannot be used for communications and similar purposes. Atmospheric absorption in the terahertz range consists of the absorption lines of water molecules and a large broad peak referred to as the “continuum”. Each of these absorption lines forms an additional natural “terahertz gap” between radio waves and light. No available propagation model can simulate these characteristics with high precision. Radio-wave propagation models and light propagation models are often expanded to terahertz waves. However, the propagation characteristics reflected in these models do not agree with each other or with measured values in the terahertz range. As generation and detection techniques were previously immature in the terahertz range, it was not possible to measure the absorption lines with high precision. Similarly, measurement of the “continuum” was inherently difficult. For these reasons, we lacked a sufficient understanding of the atmospheric propagation of terahertz waves, resulting in our current lack of a propagation model, as discussed above. We must solve these problems and clarify how far waves propagate in the various frequency ranges. We anticipate that the completed terahertz atmospheric propagation model will challenge the common belief that lumps terahertz waves together in an “unusable range”, replacing this belief with the acknowledgement that certain ranges are indeed useful, depending on the purpose. With these aims in mind, NICT measures atmospheric transmittance using terahertz time-domain spectroscopy, collecting data to be used in the construction of the model.

2.5 Remote sensing

Terahertz-wave remote-sensing technology has raised high expectations as a tool for the observation of Earth’s environment, and as a means of remote sensing of hazardous substances and gases. NICT is currently promoting contract research and development of a terahertz stand-off sensor system that can be used for on-the-ground remote sensing. This system will be capable of detecting hazardous gases generated at disaster sites and similar locations from a distant base of operation. The system generates continuous terahertz waves (<1 THz) based on the device and system technologies developed for fiber-optic communications and their peripheral technologies. The system then detects the reflected waves with highly sensitive detectors, and infers presence of a toxic gas based on variation in the electromagnetic waves. As the frequency of terahertz waves is tunable in principle, this stand-off sensor system can be used in a wide range of applications, including detection of various hazardous substances other than toxic gases, spectroscopic analysis, and imaging.

On the other hand, given the immaturity of device and measurement-system technologies, environmental observation using terahertz waves stands as a significant challenge for the future. Thus, to construct an observation system based on device and measurement-system technologies presently available or anticipated, NICT is now conducting research on the radiative transfer model and the feasibility of observation from a space station. The data acquired for the construction of the propagation-characteristic model can also be used to simulate planetary atmospheres other than that of Earth. The data collected to date are beginning to highlight the potential value of future terahertz observation of planets. In order to create the remote sensors that could be used for these purposes, we must develop a superconductor mixer as well as a terahertz quantum cascade laser as the local oscillator. Accordingly, we are promoting development in these areas in collaboration with the Kansai Research Center.

3 Conclusions

In its independent research, NICT is studying fundamental technologies and conducting research for future technological development and applications, including terahertz quantum cascade laser technology, terahertz quantum-well detector technology, terahertz time-domain spectroscopic system technology, millimeter-wave imaging technology, a terahertz materials database, a terahertz atmospheric propagation model, feasibility studies for terahertz Earth environment observation, and studies on the superconductor mixer. In its contract research, NICT is developing highly generic technologies, including a terahertz camera system based on an uncooled microbolometer array detector and a stand-off sensor system that together enable the detection of toxic gases. Terahertz technology is advancing every day. All of the technologies discussed above are positioned as fundamental or seed technologies for future terahertz applications.

Millimeter waves were first used in communications, then incorporated into radar technology, and finally applied to new uses in imaging technology. In the terahertz range, higher in frequency than the millimeter range, applications were first implemented in spectroscopic analysis, followed by uses in connection with imaging technology. These different paths clearly reflect the differences in the physical nature of these two ranges of electromagnetic waves. The millimeter range contains few "fingerprint spectra", so this range will rarely be used for spectroscopic analysis. On the other hand, whether communication technologies will emerge that use the terahertz range depends on whether the market comes to demand such technology. However, there is no doubt that the application of semiconductor device technologies and fiber-optic technologies to the terahertz range will reduce the size and improve the performance of terahertz devices. Terahertz communication may simply lie on the other side of such development. It is notable that the US IEEE802.15 WPAN committee, which is preparing short-distance wireless communication standards, established a "Terahertz Interest Group (IGthz)" as a new working group in January 2008.

The next and following chapters discuss the details of the research and development topics that NICT is currently pursuing. We hope that you will enjoy reading through them.

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Terahertz Semiconductor Devices and Their Application to Measurement Systems