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FEATURE

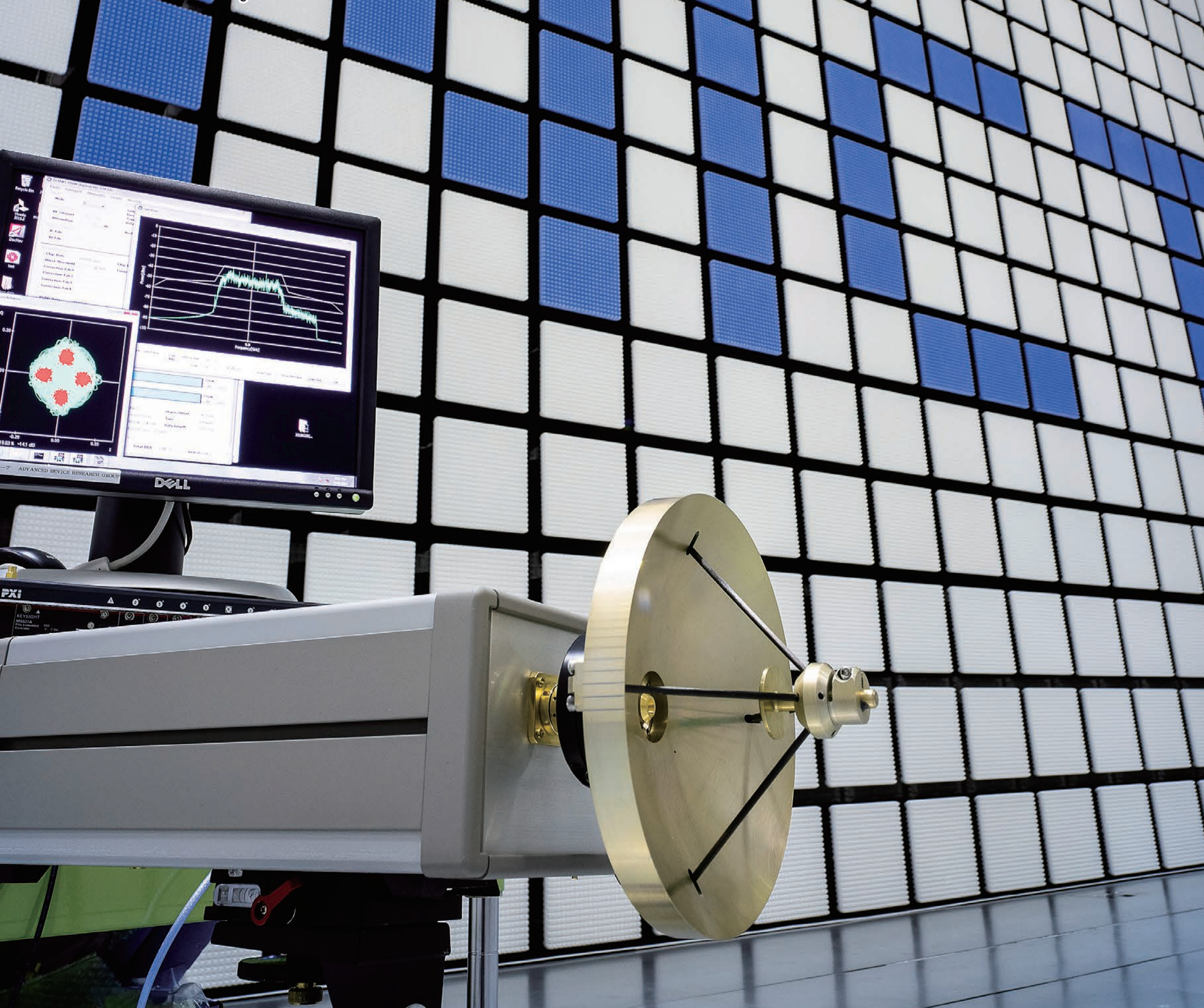
Towards Terahertz Open Innovation

—Expectations for a wide range of applications from space to communications—

Interview

Exploring the Terahertz Band, a Frontier between Radio and Light

Beyond 5G - and further



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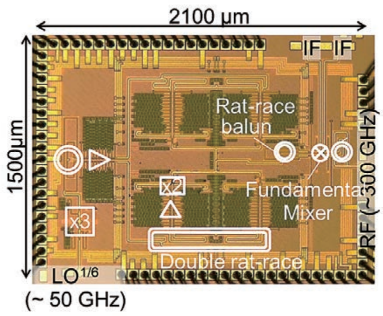

Cover photo: 300-GHz terahertz transmitter
NICT is developing transmitters and receivers in the 300-GHz terahertz band. The transmitters and receivers are evaluated in NICT's large-scale anechoic chamber with the assessment of radio transmission performances at distances of 10 meters and more extended.

Upper-left photo:
Chip micrograph of a 300-GHz-band receiver circuit fabricated in 40-nm silicon CMOS technology. High-speed terahertz band radiocommunication has been demonstrated in performance tests using that same chip.

Interview

Exploring the Terahertz Band, a Frontier between Radio and Light

Beyond 5G - and further

Terahertz Technology Research Center

HOSAKO Iwao

Director General
Terahertz Technology Research Center

After completing a doctoral program, Iwao HOSAKO worked for NKK Ltd. (currently JFE). In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT). He has been engaged in research and development of terahertz semiconductor devices and various application systems. Ph. D. (Science).

OGAWA Hiroyo

Terahertz Technology Research Center

After achieving a master's degree, Hiroyo OGAWA started working for Nippon Telegraph and Telephone Corporation (currently NTT). In 1998, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT). He has been engaged in research, development and standardization of millimeter-wave and terahertz systems. IEEE Fellow, Ph. D. (Engineering).

Ever since Guglielmo Marconi invented radio telegraphy, technologies that use radio waves have drastically altered our everyday lives, as well as society as a whole. One only needs to look at the smartphones people carry with them to see how this technology has benefitted us. Speaking of smartphones, 5G (fifth-generation mobile communication systems) service starts in Japan this year, and research institutes are already formulating development plans for Beyond 5G — and even more advanced systems.

The terahertz band, an almost unexplored frequency band, is now the focus of significant attention. With a frequency from 100 GHz to 10 THz — 3 mm to 30 µm, converted to wavelengths — one might ask: why do we need such high frequencies? Furthermore, how is this band being researched and standardized for use? For the answers to these questions and more, we sat down with HOSAKO Iwao, Director General of the Terahertz Technology Research Center, and OGAWA Hiroyo, who worked in standardization at the same Center.

Why the terahertz band

——Tell us about the current state of terahertz band development.

HOSAKO The terahertz band is a band of waves with an extremely high frequency. The band of several hundred GHz on the lower end of that spectrum appears to be very useful in future radio communications, so we've been engaged in research and development of the band for some time now.

NICT was originally a laboratory for researching radio waves, so we already have a lot of valuable data in terms of wireless research and development. Looking at radio use and research thus far, there is a trend toward using higher and higher frequencies, and we are just breaking into the terahertz band now. It's a frequency band that is about to become mainstream, so you could say that it's the frontier of radio research.

——Why is the terahertz band necessary?

HOSAKO Simply, to create faster, higher-bandwidth communication systems. 5G service starts here in Japan this year, and provides transmission speeds of more than 10 Gbps. That's more than ten times what 4G offers. There are always people who say we don't need any more speed, but surely the drive to reach ever faster speeds and greater bandwidths is part of our programming as humans.

Higher frequencies become necessary as you push toward higher speeds, and the 3.6 GHz band is the highest frequency band being used with the current 4G technology. 5G uses the 28 GHz band as well, which means that the frequency for 5G is ten times higher that used for the current 4G. At this rate, we'll probably be seeing frequencies around 300 GHz ten years from now, in the year 2030. Of course, that means we'll be using the terahertz band.

In that sense, you could say that the terahertz band frequencies being successfully identified at the WRC-19 in November of last year was very good timing.

Finalizing frequency identification

——Dr. Ogawa, you were instrumental in identifying the terahertz band frequencies, correct?

OGAWA The International Telecommunication Union (ITU), which is a United Nations (U.N.) specialized agency, publishes some-

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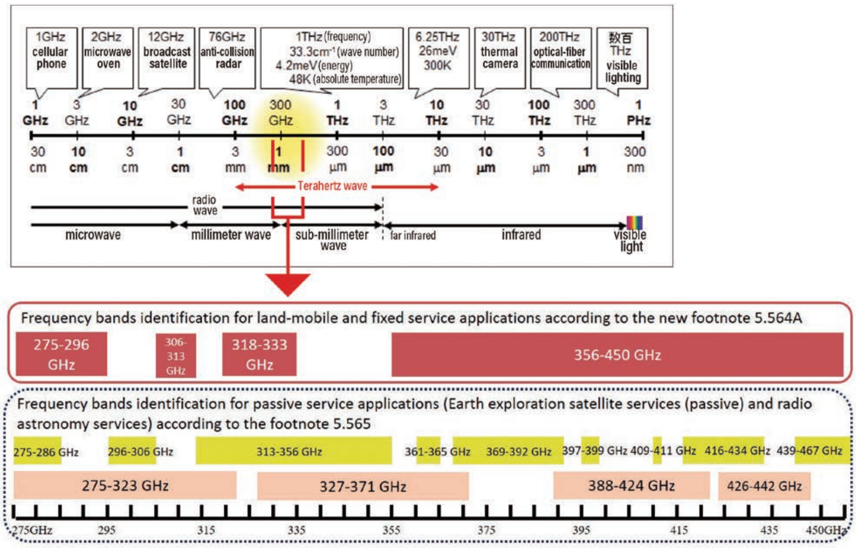


Figure: WRC-19 frequency identification results

thing called the Radio Regulations (RR), and frequencies are allocated here in Japan according to the Radio Regulations. This is revised basically every four years at the World Radiocommunication Conference (WRC). The WRC reviews frequency allocations in light of technological progress, societal needs, and so on.

In this case, the frequency identification was done at the World Radiocommunication Conference 2019 (WRC-19). Until then, frequencies higher than 275 GHz had not been allocated for radiocommunication services. The only frequencies identified were basically for radio astronomy and Earth exploration satellites services, which are passive services (receive-only services).

At this WRC, we added a new footnote identifying new frequency bands that can be used in radiocommunication active services to the Radio Regulations.

——And that was needed in order to start using the terahertz band?

OGAWA That's right. There is increased demand for both passive and active services. You could call it demand for short-range, high capacity radiocommunication systems.

We spent four years in discussions with the main authorities from each country through the ITU-R and were ultimately able to identify four bands and list them in the Radio Regulations. The four bands are 275 to 296 GHz, 306 to 313 GHz, 318 to 333 GHz, and 356 to 450 GHz, for a total bandwidth of 137 GHz (see figure).

This is a broad range of frequencies, the likes of which have never been provided for mobile communications. Having the frequencies identified means that they can now be used by wireless businesses. I admit that I'm rather proud of this major achievement by the Terahertz Technology Research Center.

HOSAKO The results of WRC-19 come from international agreements, and because each country uses radio differently, we needed to coordinate with various countries around the world. In this case, we organize the Asian region first, and submit a proposal representing Asia to the WRC. Representatives from all of the countries then gather for the main WRC conference, discuss the proposals, and make a decision. This time, the agenda was set in February of 2015, and those bands were identified in November of 2019, so it took more than four years. And of course, we did studies within Japan before the Asian conference, including consultations with groups using passive services, such as the National Astronomical Observatory of Japan and JAXA (the Japan Aerospace Exploration Agency).

——What changes once the frequencies have been identified?

OGAWA Deciding how the new bands will be used is the next step, but they will most likely be applied mainly in mobile radiocommunication systems, fixed radiocommunication systems, and so on.

HOSAKO That's exactly right. With the bands now being identified, they can be used in radiocommunication, which also makes it easier for companies to invest with an eye to new business ventures.

Cooperation with other groups

OGAWA The Terahertz Systems Consortium, of which I am the Deputy Chairman, played a major role in the frequency identification. The Consortium has some manufacturers as members as well, which made it possible for us to submit technical and operational characteristics, including antenna and propagation characteristics when working in the terahertz band, to the ITU-R.

—Have you collaborated with any universities or academic societies?

HOSAKO The Institute of Electronics, Information, and Communication Engineers has a Technical Group on Terahertz Application Systems. NICT is also sending out researchers to engage in research. The Japan Society of Applied Physics has a Terahertz Electromagnetic Wave Research Group, with which we have partnered as well. We are also actively collaborating with a technical exchange organization called the Terahertz Technology Forum.

For example, having a radio wave propagation model — called "channel modeling" — is an essential part of radiocommunication. As I mentioned earlier, NICT was formerly a radio wave research laboratory, and is thus very strong in this area. NICT has channel models for everything up to millimeter waves.

Terahertz waves have extremely short wavelengths. The propagation state changes subtly depending on objects, human movement, and more, which means the waves travel over an extremely high number of paths. This makes channel modeling quite complicated, and it won't be possible to apply terahertz waves in actual operations until we gather a lot of data.

Support for Beyond 5G

——Using terahertz will become a reality with Beyond 5G, the next-generation communication standard, correct?

HOSAKO Beyond 5G is expected to start in 2030, and a lot of ideas are being proposed around the world at this moment. Next year is the final year of NICT's 4th Medium- to Long-Term Plan, so we are in the process of considering how to approach Beyond 5G with an eye to our 5th Medium- to Long-Term Plan.

One of the characteristics of Beyond 5G garnering attention is this image of an efficient, low-power, "cool" network, which not only expands on higher bandwidths, lower latencies, and greater numbers of connections, but also does things like apply AI to network slicing (dividing a network virtually for more efficient operations). We will also likely see three-dimensional networks with drones, high-altitude platform stations (HAPS), Global Navigation Satellite Systems (GNSS), connected cars, IoT devices, and more. We think these areas offer opportunities to apply terahertz waves, and NICT will likely be pouring tremendous energy into collaborations focused on Beyond 5G terahertz technologies. I hope we can make good use of the cutting-edge techniques that only NICT can offer. One example is building compact atomic clocks into terminals. NICT is currently engaged in research for implementing atomic clocks in chip form, and is also researching micro-fabricated ion traps, which have an even higher level of accuracy than atomic clocks. Such technology enables device times to be synchronized with atomic clock-level accuracy, eliminating the process of synchronization when establishing communication and increasing speeds by that amount.

Additionally, quantum cryptography offers the ultimate in security. While photons are typically used, we are also researching physical-layer cryptography which dispenses with photons. We are considering how to create terrestrial, satellite, inter-satellite, aircraft, and other such networks using this physical-layer cryptography.

Although these technologies are still a ways off, they might be ready in time for whatever next-next-generation communication standards will start around 2040.

Image sensing using the terahertz band

HOSAKO Beyond communications, the terahertz band is proving useful in sensing applications such as passenger scanners in airports. This is an area garnering great interest as a counterterrorism measure.

We've started exploring whether this can be implemented in the W band (75 to 110 GHz), which includes part of the terahertz band. The technique uses a slightly lower frequency band than the terahertz band. This is because if the frequency is too high, the waves can't properly penetrate clothing, while a high spatial resolution brings up issues of privacy. Our solution is to use the W band to avoid such privacy issues while utilizing AI to increase the identification accuracy.

Future prospects

OGAWA By identifying the terahertz band frequencies, we've been able to secure a large band, around eight times the total bandwidth of 17.25 GHz identified for 5G at the World Radiocommunication Conference 2019. So I think this spectrum resource will be sufficient for another 20 years. But then in another 20 years, people might be saying that 137 GHz is not enough.

HOSAKO I think that would actually be more interesting. Japan has been somewhat behind the curve when it comes to 5G, so I'd like to focus all our energy on Beyond 5G. NICT has a large amount of basic research, applied research, and data in a broad range of related fields, so I want us to push forward as the driving force behind next-gen and next-next-gen communication technologies in Japan.

We received assistance from a lot of people during the standardization process. Within NICT itself, we had help from the Innovation Promotion Department's Standardization Promotion Office, and received support from the Terahertz Systems Consortium and relevant departments at the Ministry of Internal Affairs and Communications. It's our hope to use that accumulated knowledge and support as the seeds for even stronger research and development in the future.

ITU: International Telecommunication Union
ITR: International Telecommunication Regulations
WRC: World Radiocommunication Conference
ITU-R: ITU Radiocommunication Sector

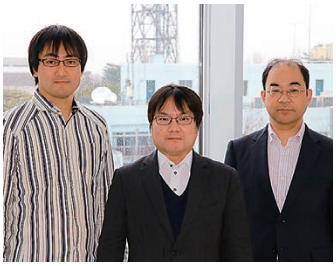
Helping identify a total frequency bandwidth of 137 GHz at WRC-19

Based on the results of research and development in terahertz radiocommunication fundamental technologies using frequencies over 275 GHz, the Terahertz Technology Research Center proposed and contributed to the establishment of WRC-19 agenda item 1.15 at WRC-15 in 2015, which identifies frequency bands for mobile and fixed service applications in the frequency range 275-450 GHz.

Subsequently, in the relevant Working Parties held from 2016 to 2019, the technical operational characteristics of terahertz radio systems and the results on sharing and compatibility studies with passive services were reflected in the work of WRC-19 agenda item 1.15, in cooperation with the Terahertz Systems Consortium's member companies. These results were provided as input at WRC-19, held from October 28 to November 22, 2019, and contributed to the revision of the Table of Frequency Allocations in the frequency range 275-450 GHz in the Radio Regulations, carried out during the conference. (See Figure.)

R&D on Terahertz-wave Testbed Platform

Toward Beyond 5G communication systems



From The left: MOROHASHI Isao, KANNO Atsushi, SEKINE Norihiko

KANNO Atsushi

Planning Manager, Strategic Planning Department, Strategic Planning Office / Research Manager, Network System Research Institute, Network Science and Convergence Devices Technology Laboratory

After completing graduate school, he joined NICT in 2006 after working with University of Tsukuba. He is engaged in research on high-speed optical modulation, radio over fiber technology, and microwave photonics. Ph. D. (Science).

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Senior Researcher, Advanced ICT Research Institute, Frontier Research Laboratory / Senior Researcher, Social Innovation Unit Terahertz Technology Research Center, Collaborative Research Laboratory of Terahertz Technology

After completing graduate school, he joined NICT in 2007 after working as a JST researcher. He is engaged in research on THz measurement systems. Ph. D. (Engineering).

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Director, Social Innovation Unit Terahertz Technology Research Center, Collaborative Research Laboratory of Terahertz Technology

After completing graduate school, he joined NICT in 2005 after working with a company and a university. He is engaged in research on physical properties of semiconductor nanostructures in terahertz-wave region and its applications. Ph. D. (Engineering).

Terahertz waves, which have higher frequencies than millimeter waves, are being explored for use in future wireless systems (e.g., Beyond 5G). In addition to increasing transmission capacity, using higher frequencies is expected to provide more precise radiolocation systems, better physical security using narrower beams, and more. NICT has been developing a testbed platform for communications, measurement, and imaging applications in terahertz-wave bands. This article will introduce technologies for evaluating terahertz-wave transmission systems, as well as signal generation technologies for Beyond 5G and further.

Building a terahertz-wave transmission infrastructure

With the start of 5G mobile wireless services, the frequencies used in wireless systems continue to move away from the traditional microwave bands, toward millimeter wave bands. Broader bandwidth in higher frequencies is available, which in turn makes it possible to achieve transmission capacity exceeding 10 Gbps. Further improvements in communication capacities are expected through the use of the higher-frequency radio waves, such as terahertz waves. Technologies for transmitting and receiving high-frequency radio signals are thus being developed rapidly. To evaluate the transmitters and receivers being researched and developed in parallel, it is, of course, necessary to verify whether or not high-frequency terahertz-wave systems themselves can be used. NICT has, therefore, been developing terahertz-wave testbed platform technologies for verifying terahertz-wave systems experimentally (Figure 1). This article gives an overview of the testbed technologies and introduces efforts underway toward attaining even higher frequencies.

Developing testbed platform technologies in terahertz-wave bands

The available frequency band of terahertz waves is more than ten times broader that of microwaves. Traditional transceivers and signal processing techniques, therefore, cannot be applied as-is. Signal propagation loss over air also rises in proportion to the square of the frequency, which means that new amplifiers, antennas, and the other components must be designed and developed. NICT is developing the terahertz-wave platform technology, including wideband signal generation, transmission, and reception based on high-speed fiber-optic technologies. The optical technology has an extremely broad bandwidth,

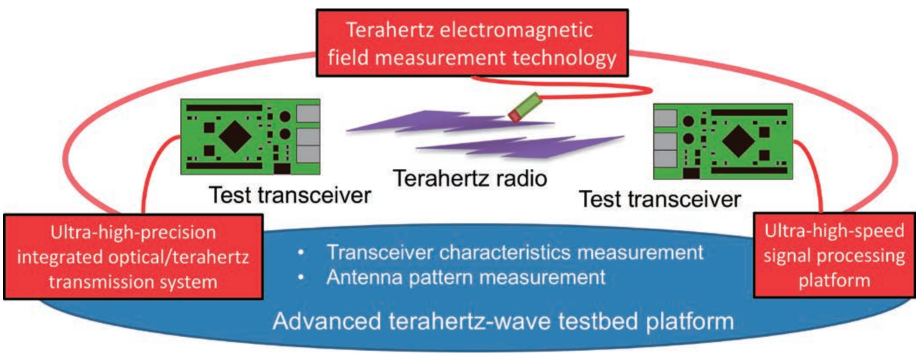

Figure 1 Overview of terahertz-wave testbed platform

and thus generated frequencies can be tuned and provide 100 Gbps-class high-capacity signals. Techniques for generating terahertz waves using optical frequency comb technology are being developed to ensure high-frequency stability. Meanwhile, radio signal transmissions in the 300 GHz and 600 GHz bands have been demonstrated through radio over fiber technology, which integrates fiber-optic communication systems with wireless communication technologies (Figure 2). NICT is also working on narrow-beam radio systems to both transmit and receive signals efficiently by suppressing transmission loss and optimize the irradiation areas to secure physical-link security. Employing the testbed platform based on optical technology is not only useful in developing and evaluating the 300 GHz-band systems expected to be used in the future but also contributes to research in advanced radio systems aimed at even higher frequencies and broader bandwidths.

Pushing the limits of radio wave use

Radio Regulations defines 3 THz as an upper limit for radio waves. In the ultra-high-frequency band of 2–3 THz, even simple generation and detection of signals is a difficult process, which has thus far limited applications to radio astronomy, spectroscopic measurement, and so on. The atmospheric absorption baseline is extremely high –100 dB/km– and molecular motion in the air produces many sharp absorption lines; however, there are several relatively low-loss windows with bandwidths of around 100 GHz. In other words, these ultra-high-frequency bands may be applicable in ultra-high-speed and broad-bandwidth communication, if used at short ranges. NICT is researching proprietary technologies such as terahertz-band semiconductor lasers, superconducting detectors, and more. Integrating these technologies will enable wireless communication systems that make use of extremely high frequencies exceeding 2 THz.

Figure 3 shows a terahertz-wave communication system currently being developed at a frequency greater than 1 THz. The transmitter is based on optical technologies, while the receiving system employs a superconductive electronic device. An optical frequency comb generator is used for signal generation. The signals of two terahertz frequency-separated components extracted from an optical frequency comb signal are data-modulated and input to a uni-traveling-carrier photodiode (UTC-PD) to generate the modulated signal in the terahertz bands. This method makes it possible to provide high stability and flexibility in terms of the terahertz wave frequency.

A heterodyne technique employing a high-sensitivity hot-electron bolometer mixer (HEBM) is used for the receiver system (see pp. 8–9). The local oscillator (LO) for frequency down-conversion in the receiver is a terahertz quantum cascade laser (THz-QCL). A terahertz-wave-band phase-locked loop (PLL) circuit was developed to stabilize the frequency, and finally, communication. Terahertz waves from the THz-QCL were received by a superlattice mixer (SLM) and compared with a microwave reference signal to obtain an error signal. The error signal was fed back into the system to stabilize the linewidth of the THz-QCL of approximately several MHz to less than 1 Hz (see pp. 6–7).

The HEBM receives the modulated signal in the terahertz bands from the transmitter, and the signal converted to the microwave band through integration with the frequency-stabilized THz-QCL is demodulated with a vector signal analyzer (VSA). This makes it possible to verify terahertz-wave radio systems in environments similar to traditional wireless communication even at extreme frequencies of several THz.

Future prospects

As millimeter waves continue to take on a primary role over microwaves in the 5G era, the demand for terahertz radio systems, which can realize even more advanced communications, radar, location measurement, and more, will continue to increase. However, a testbed platform for testing, evaluating, and providing feedback for terahertz radio systems is essential for exploring practical applicability for services. Developing the testbed platform technology based on optical technology has also enabled terahertz radio system verification, which goes beyond radio waves. The testbed platform technology is expected to be very useful in verifying new terahertz-wave systems in the future.

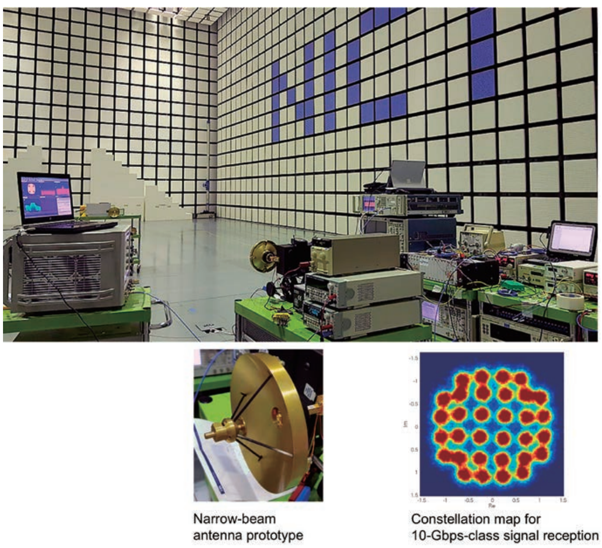

Figure 2 High-speed terahertz communication experiment using integrated optical/terahertz platform technology

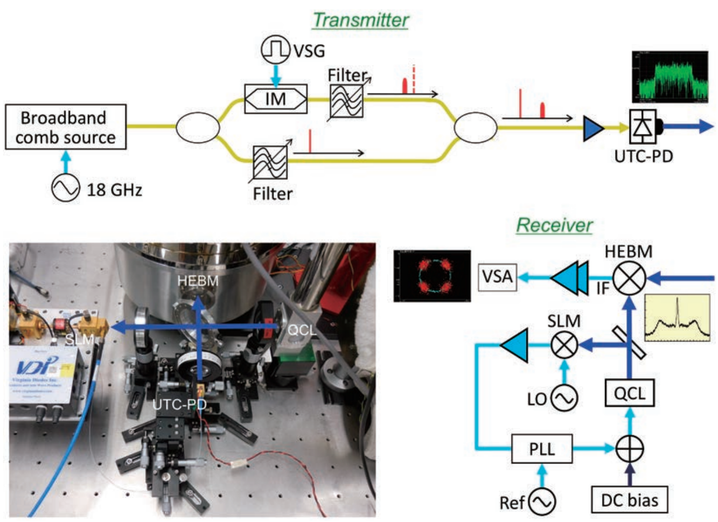

Figure 3 Overview of extreme-high-frequency terahertz communication system

Techniques of Measurement Standards for Terahertz Band

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After completing a doctoral course, joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT) in 2000. Since then, engaged in research on frequency standards, including primary frequency standard development and reference signal distribution using optical fiber. Ph.D. (Science).

As terahertz waves become practically applicable in communications, sensing techniques, and more, precise measurements of radio field strengths and frequencies is essential. NICT is engaged in R&D providing accurate standards with respect to radio field strengths and frequencies for terahertz wave measurements.

Why NICT measures terahertz waves

For the past 70 years, NICT has been offering a paid calibration service which articulates the relationships between the standard instruments maintained and managed by NICT, and the instruments used in inspections and maintenance checks required to obtain radio licenses in Japan. The calibration of RF power meters and frequency standard instruments, which are fundamental to determining the characteristics of radio waves, are the services into which NICT has poured the most energy. Meanwhile, in anticipation of an era where terahertz waves will be used extensively, NICT is pushing forward with R&D for techniques for the highly-accurate measurement of radio field strengths (for RF power), high-accuracy generation of terahertz frequencies, and more.*

Techniques for measuring radio field strengths

RF power meters are used to measure the strength of radio fields. NICT has offered an RF power meter calibration service, extending up to 0.11 THz (110 GHz), since 2007. Following in the footsteps of this service, in 2011 NICT began working with the National Institute of Advanced Industrial Science and Technology to research and develop a device known as a calorimeter, which can provide reference values for RF power for terahertz waves. NICT also began R&D into calibration services for calibrating RF power meters given by customers, so that they can use accurate values.

Thus far, we have developed power meter calibration devices like the one shown in Figure 1 and provided services for calibrating RF power meters up to 0.33 THz (330 GHz). As technologies which use radio waves become more advanced, the frequency range for our calibration service is expanding from lower to higher frequency bands; and although we are only just entering the terahertz band, after having no values to serve as standards, we have finally reached a milestone for reference values to measure the strengths of terahertz fields.

From now on, if we use power meters that have been calibrated correctly, we will be able to express the strength of terahertz fields as numerical values. For example, in research papers, it should be possible to take qualitative statements such as "we have developed a generator capable of emitting a stronger radio field than was traditionally possible" and express them quantitatively, e.g., "we have developed a generator capable of emitting a radio field at 0.484 mW ± 0.041 mW, an increase of 28 % over traditional techniques." One meter measured using a calibrated ruler is the same one meter throughout the world, so just as one can compare lengths from different locations. Similarly, we will be able to compare radio field strengths of the terahertz waves emit from the distant generators without needing to bring them to the same location.

Incidentally, an RF power meter measures the strength of radio waves propagating through a waveguide. An antenna is needed to measure the strength of the radio waves traveling through a space. The antenna can be thought of as a "converter" which enables the RF power meter to take a measurement by converting the radio waves traveling through the space into radio waves propagating through the waveguide. However, the conversion factor must be known at that time. To that end, we are researching and developing calibration for standard gain horn antennas, which serve as a reference for a variety of antennas; circular horn antennas, which show promise for use in IoT sensors for detecting obstructions; and more (Figure 2).

Techniques for measuring frequencies

NICT is a public institution which, in addition to the calibration services described earlier, also sets the national standard of frequency. Distributing the frequency standard based on the definition to real society is one of the institute's missions. The terahertz wave will likely be applied in more and more parts of our lives, and thus like the field strengths discussed above, terahertz frequencies will need to be measured with a high level of accuracy for frequency resources to be used effectively. In this section, we will introduce terahertz frequency measurement, as well as terahertz frequency reference generation and its measurement applications, based on an optical comb.

An optical comb, an ultrashort pulses laser whose oscillation modes have constant frequency intervals, is widely used for highly-accurate measurements of optical frequencies. Also, in terahertz frequency region, a combination of an optical comb and a photoconductive antenna enables direct frequency measurement of the terahertz wave. We have confirmed that, under certain conditions, the system we developed (Figure 3) is capable of measuring the absolute frequency of terahertz waves at the same level of accuracy as the national standard of frequency. Moreover, a terahertz frequency reference having the same accuracy as the national standard of frequency can be generated at any desired terahertz frequency by photomixing two arbitral oscillation modes extracted from an optical comb using the nonlinear effect of optical fibers. Combined with a superconducting frequency mixer (see pp. 8-9) highly-sensitive frequency measurement of terahertz waves is possible. We successfully demonstrated the frequency measurement of the remote terahertz wave (the narrow line width 3 THz quantum cascade laser discussed on pp. 4-5) at an optical fiber endpoint as shown in Figure 4.

In addition to measuring the absolute frequencies of terahertz waves, we are engaged in ongoing research for terahertz frequency standards in various areas. These include terahertz frequency reference transmission, which shows promise for application in remote calibration and frequency comparisons; the development of frequency standard based on quantum transitions in atoms/molecules, which can serve as an independent frequency reference in the terahertz band; and more.

Future prospects

Research & development is already underway for next-generation mobile communication systems aimed at Beyond 5G. Completely new services and applications using terahertz waves will likely begin appearing in the near future. NICT will continue to lead global R&D into techniques for precisely measuring radio field strengths and frequencies— the primitive measurand for using the terahertz band —and promote the spread of terahertz technologies throughout society through our calibration service.

＊ "Able to generate with a high level of accuracy" and "able to measure with a high level of accuracy" are synonymous, and which is made more accurate differs depending on physical quantities.

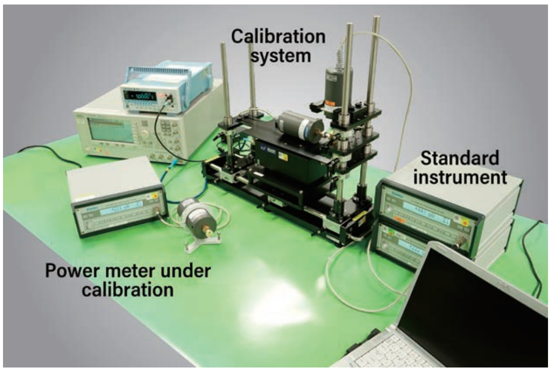

Figure 1 RF power meter calibration system
A calibration system of power meters for terahertz waves, owned by customers. The service is provided for individual frequency bands, based on the dimensions of the waveguide.

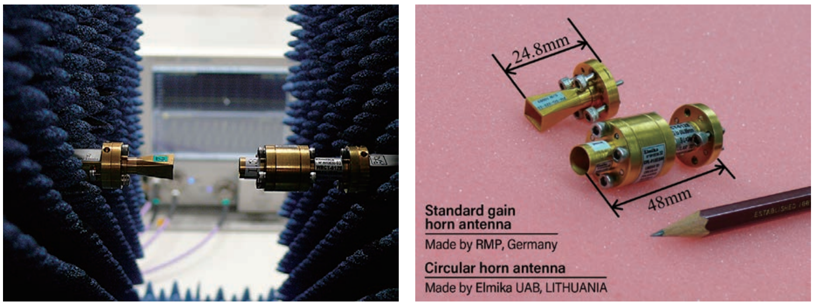

Figure 2 Research on antenna calibration
NICT is involved in R&D for determining the actual gain in antennas for measuring the strength of terahertz waves traveling through a space.

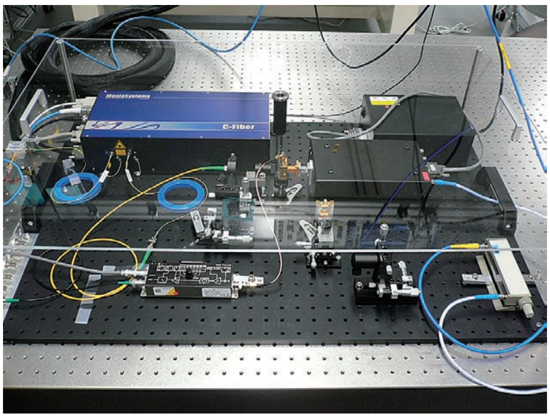

Figure 3 Terahertz frequency measurement system using an optical comb and a photoconductive antenna

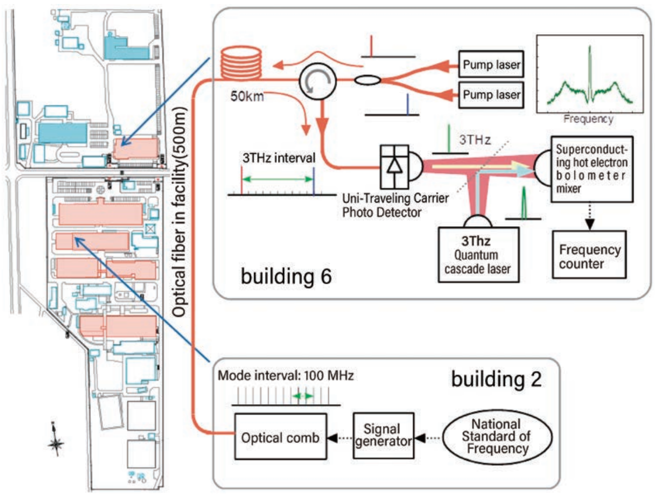

Figure 4 Terahertz frequency reference transfer and frequency measurement of the remote terahertz wave using an optical fiber link at the NICT site

Developing High-sensitivity Spectroscopic Technology for the Terahertz Band

Terahertz wave spectrum detection using a superconducting hot electron bolometer mixer

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After receiving Ph.D. degree in 1992 and working as researcher at Nobeyama Solar Radio Observatory, National Astronomical Observatory, Dr. Irimajiri joined Communications Research Laboratory (currently NICT) in 1993. His research interests include a terahertz wave transmitter and receiver system. Ph. D. (Science).

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After receiving M.S. degree, he joined Communications Research Laboratory (currently NICT) in 1988 and received Ph.D. degree in 1999. He has been engaged in research on superconducting high-frequency devices.
Ph. D. (Engineering).

"Terahertz waves" refers to electromagnetic waves in a frequency range of 100 GHz to 10 THz, which includes some millimeter waves and infrared rays. It is a relatively unexplored frequency band which has not yet been fully developed and used. High-speed radiocommunication, non-destructive inspections, frequency standards, security, medicine, and earth atmosphere/astronomical observation are some of the areas that hold promise for terahertz applications. To make such applications a reality, it is essential to develop the platform technologies of oscillation and detection. There is still insufficient technological progress, particularly for terahertz frequencies exceeding 1 THz. This section will introduce a 2 THz band high-sensitivity spectrum detector (hot electron bolometer mixer) created and developed from devices through laboratory collaborations with the Terahertz Technology Research Center.

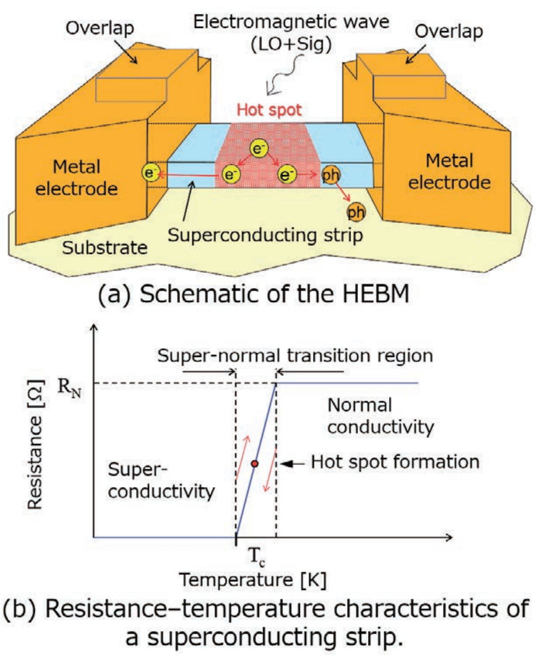


Figure 1 HEBM structure and operation overview

Terahertz band spectrum detection using a superconducting hot electron bolometer mixer

A superconducting hot electron bolometer mixer (HEBM), has a structure in which a microscopic piece of superconductive film (a superconductive strip) several hundreds of nm in length and width and less than 5 nm thick is placed between electrodes at a position corresponding to an antenna's power feed point (see Figure 1(a)). The mixer device uses strong nonlinear impedance produced when the superconductive strip transitions between superconductive and normal conductive states. Irradiating the HEBM with electromagnetic waves causes the electron temperature in the superconductive strip to rise, and a normal-conductive region (called a "hot spot") is formed in part of the superconductive strip in a temperature range exceeding the superconducting transition temperature (Tc) (see Figure 1(b)). When a local oscillation source (LO) along with a signal source (Sig) is used for the irradiated electromagnetic waves, the size of the hot spot is modulated according to the difference frequency (IF) signal component, and IF output can thus be obtained. The maximum operating frequency of the HEBM is limited only by its structure and dimensions, which makes mixer operations possible up to several tens of THz.

Novel hot electron bolometer mixer structure using magnetic material

Making bolometers smaller is normally useful in increasing detector sensitivity and achieving broader IF bands. However, there have been issues to be addressed when it comes to miniaturizing HEBMs. In the HEBM device structure, the metal electrodes overlap the superconductive strip in order to ensure reliable electrical contact between the strip and the electrodes (the "overlapping region" in Figure 1(a)). However, at this overlapping region, the superconductive strip is in a superconductive state even at normal mixer operating temperature, and furthermore is not directly suppressed by electromagnetic radiation due to being located under metal. The superconducting proximity effect from this region is thus expected to inhibit hot spot formation and reduce the sensitivity of the mixer. Attempting to make the device smaller will instigate superconductive bonding between the electrodes, which will instead negatively affect the mixer's performance (Figure 2(a)). We therefore proposed a new HEBM structure unique to NICT, in which a thin film of nickel (Ni)—a magnetic material—is inserted between the superconductor and metal electrode films. This Ni-HEBM, as it is called, suppresses superconductivity under the electrodes to ensure that only the superconductive strip between the electrodes remains superconductive (Figure 2(b)). We have already confirmed that superconductivity in a 5 nm-thick niobium nitride (NbN) superconductive thin film can be suppressed using a 0.6 nm ultra-thin Ni film. This structure makes it possible to further reduce the size of the HEBM, and is expected to be useful in improving the mixer performance by, for example, reducing LO power, increasing sensitivity, and broadening the IF bands.

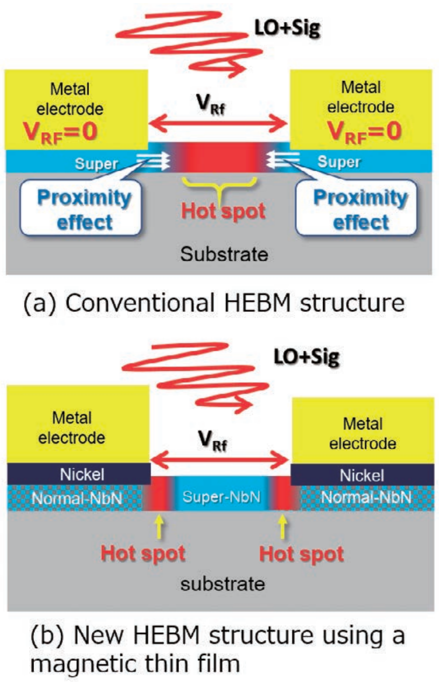


Figure 2 Schematics of a conventional and a new HEBM structure

In the 2 THz-band Ni-HEBM we constructed, the length and width of the NbN strip were set to 0.1 and 0.5 μm, respectively. At 2 THz, and with input optical system loss corrected, the Ni-HEBM achieves a mixer noise temperature of Trx = 570 K (DSB), as well as an IF bandwidth of about 6.9 GHz which was improved around 3 GHz more than the bandwidth of HEBMs having a traditional structure, demonstrating the improved performance the Ni-HEBM structure provides (Figure 3). Unlike measurements taken thus far, these results (and especially the IF bandwidth result) were obtained at the actual operating temperature of 4 K, which is easy to recreate using a typical cryogenic refrigerator. As a terahertz band HEBM, the performance is considered among the highest in the world.

Examples of applications for terahertz-band high-sensitivity mixers

Terahertz-band mixers using this device provide high sensitivity, high-frequency resolution, and real-time operability, and can therefore be used in as general terahertz-band spectrum analyzers for a variety of applications. Using this receiver, we succeeded in the detection of an approximately several hundred nW-terahertz spectrum created from an optical comb and a uni-traveling-carrier photodiode (UTC-PD), the high-sensitivity detection of the radio wave spectrum emitted from methanol molecular gas, and so on. We also detected THz waves from a THz Quantum Cascade Laser, or THz-QCL, and verified phase locking of the THz-QCL using that signal. Furthermore, we have also started developing communication experiments using high frequencies exceeding 2 THz (see pp. 4-5), terahertz wave frequency standards (see pp. 6-7), and the like by applying these techniques.

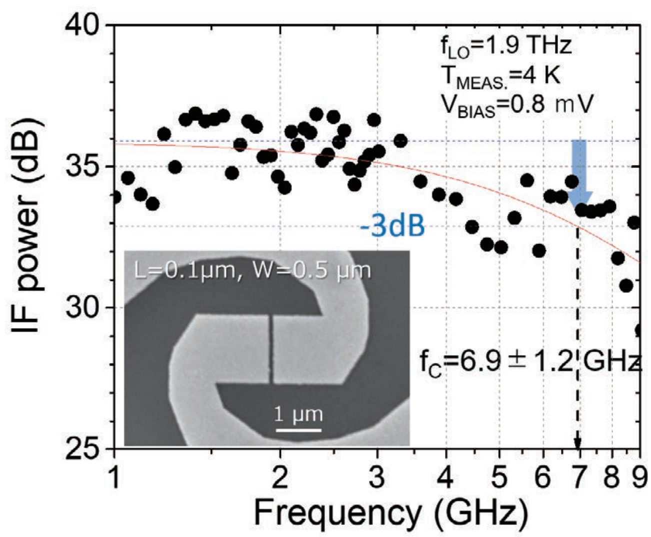


Figure 3 Measured IF bandwidth of a Ni-HEBM

Future prospects

Thus far, we have worked to develop an HEBM using a planar antenna, known as a "quasi-optical" type. We are currently working jointly with the Academia Sinica, Institute of Astronomy and Astrophysics (ASIAA), to develop a 2 THz-band waveguide-type HEBM as an even more advanced mixer with a cleaner beam pattern. The mixer is built on a 55 μm-wide, 800 μm-long, and 1 μm-thick silicon nitride thin-film bridge, which is supported by a 200 μm-thick silicon frame. The size (cross-section) of the waveguide is an extremely small 130 μm × 65 μm (WR - 0.51). As such, highly-precise microstructure creation, mechanical processing, advanced assembly techniques, and more are necessary.

Terahertz wave technology will continue to mature through the development—or actual application—of such receivers in areas such as remote sensing of the Earth's atmosphere, radio astronomy measurement, and so on from flying objects such as balloons or aircraft, or from space (e.g., high-sensitivity spectral measurement of trace amounts of molecules). We expect the technology to spread extensively to other fields in the future.

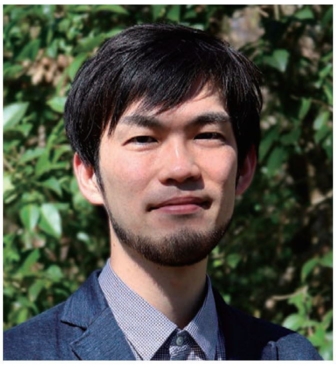
Space Terahertz Remote Sensing for Earth and Planets

KASAI Yasuko

Executive Researcher

Terahertz Technology Research Center

After receiving Ph. D in 1995, she joined CRL(currently, NICT) in 1999. Her interest is Terahertz remote sensing for Earth and Planets. Ph. D. (Science).



YAMADA Takayoshi

Researcher

Collaborative Research Laboratory of Terahertz Technology

Terahertz Technology Research Center

After receiving Ph. D degree, he joined NICT in 2018. He is developing radiative transfer model and building a terahertz measurement system for small satellite. Ph. D. (Science).

Remote sensing is a technique which enables one to "see" an object or phenomenon without making physical contact with the object by detecting electromagnetic waves. It not only allows us to see almost as far as the edge of the universe, but also allows us to penetrate matter and see inside. Light and radio waves have been mainstream in sensing applications thus far, but progress is being made on the use of terahertz waves, which are located in a frequency band between light and radio waves. In this article, we will discuss new scientific discoveries, the evolution of new space businesses, and more made possible by the use of space terahertz remote sensing.

Background

Traditionally, satellites carrying out remote sensing of the Earth from space have primarily employed image-based or spectrometric observation using optics/infrared light or radio waves. Terahertz (THz) waves, located in the boundary region between radio waves and light, only started being used in 2002—relatively recent in terms of the history of satellite observation. THz technology is advancing rapidly in recent years, and new technologies such as high-gain antennas and high-power output devices are rapidly being developed for terahertz-based Earth/planet remote sensing observation from space. These technologies are being applied in space remote sensing techniques as well. THz waves have specific characteristics which are a mix of the advantages of both light and radio waves, for example, sensing with high spatial resolution (a characteristic of light), high matter transmissivity (a characteristic of radio waves), and ultra-compact and lightweight sensors with ranges of several kilograms (a property of high frequencies). These technical revolutions have enabled measurement of physical quantities in a variety of areas, which have been difficult in traditional environmental observations, such as: estimating the size distribution of ice clouds; exploring the habitability of Jupiter's icy moon, Ganymede, by observing atmospheric molecular isotopes and surface water content; and investigating water resources in near-Earth space, such as on the Moon and Mars.

Terahertz remote sensing research at NICT

Figure 1 illustrates the progress NICT has made in developing THz remote sensing observation from space. We have continued to

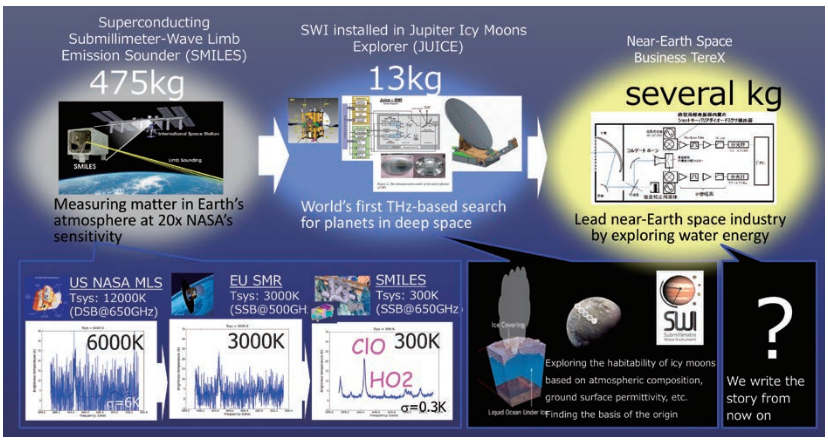


Figure 1 Progress of terahertz remote sensing at NICT

advance our research fields, from identifying actual environmental conditions on Earth, to searching for life in the Jupiter and its icy moons, to exploring water energy sources in near-Earth space (the Moon and Mars).

Development of the Superconducting Submillimeter-Wave Limb Emission Sounder (SMILES) began in 1998. The device was installed in the Japanese Experiment Module on an exposed part of the International Space Station, and used in observations for seven months, from October of 2009 to April of 2010. The project was a joint mission between NICT and JAXA for the purpose of exploring the use of THz electromagnetic waves for Earth environment diagnostics. SMILES features an ultra-sensitive and accurate calibration technique using a 4K superconducting mixer at 0.6 THz. The project presented many challenges for which we had neither precedents nor experience, including the launch of the first HTV, the development of a 0.6 THz superconducting mixer, HEMT low-noise amplifier, and THz optical system/calibration system (for which there were no terrestrial precedents), and the development of Japan's first THz space sensor. These challenges spurred some Western researchers to say "there's no way they will succeed." Ultimately, however, SMILES boasts the world's highest molecular detection sensitivity, which is about 20 times better than that of similar conventional satellites developed by NASA and in Europe, and even 10 years after its launch, SMILES' unique and highly-reliable data is still being reported by scholarly articles—even from letter journals which focus on prompt reporting.

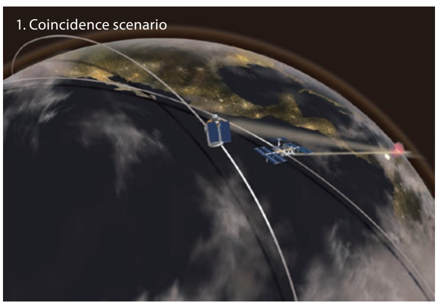
SMILES succeeded in capturing the spectrum of the short-lived and active "radical molecular HO_2," which is an ultra-trace species (around one part per hundred million at atmospheric pressure) in the Earth's atmosphere, by a single 0.5-second measurement. HO_2 radicals have an important role as strong oxidant which changes the atmospheric composition, such as H_2O, CO_2, and CH_4, which are the key species for radiative forcing and have indicated the possibility of an increase in the Earth's upper atmosphere by greenhouse gas emissions. We found spatial-temporal coincidence of SMILES HO_2 single scan observation with upper atmospheric transient discharge events called "sprite" by another imager satellite and ground-based lightning detections (Figure 2-1). Through this, we were able to prove that new HO_2 is being produced by lightning sprites and suggest that HO_2 concentration is increasing on a global scale (Figure 2-2). This research not only sounds a new alarm about climate change from a scientific point of view, but also paves the way for new types of science, which provide new knowledge by capturing "instantaneous phenomena" that do not appear in statistics, unlike the traditional data science, which primarily handles phenomena using statistical data.

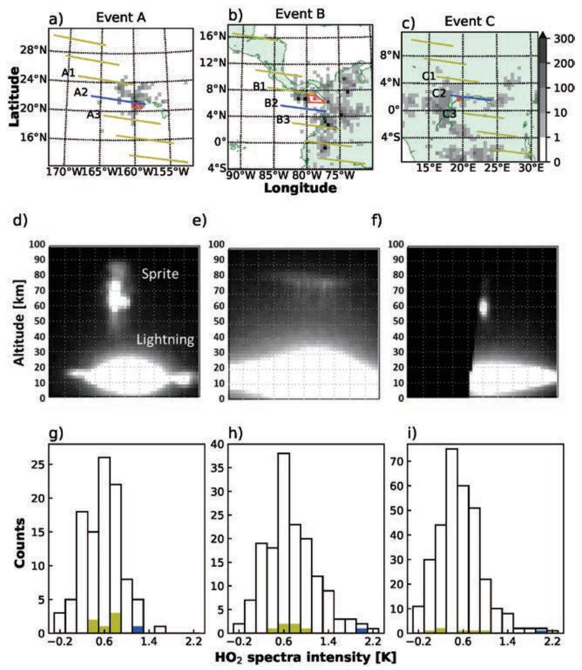
Future prospects: exploring water energy in near-Earth space

The Fourth Industrial Revolution brings about a paradigm shift in industrial restructuring on a global scale. Industries involved with space business are undergoing drastic structural changes as well. "New Space" — an area where no main industry players are currently positioned— holds great promise as a stage for disruptive innovation which, through new ideas and technology, will dramatically alter society, the economy, and more as we know. The global space industry has started working on the basic infrastructure for economic activities aimed at "three-dimensional space" seamlessly linking the Earth with New Space (stratospheric platforms, low-orbit satellites, stationary satellites, the Moon, etc.).

While oil is the main energy source for industrial and human activity on Earth, water fills that role for New Space. Water is broken down into hydrogen and oxygen by chemical reaction. Hydrogen and oxygen are used for energy sources in rocket fuel, factory power sources, and more. A characteristic THz waves is the detection of water with the highest sensitivity among all electromagnetic wave regions. We are currently developing an 8 kg-class THz remote spectrometer, which is vastly smaller than the 475-kg SMILES. This requires us to meet many new challenges, such as reducing weight through the use of CFRP components for THz antennas and calibration systems; short development time for compiling the flight model in a mere three years, compared to the ten required for SMILES; and more. It is our hope to discover water on the Moon or Mars and lead New Space businesses in the future. A further dream of ours is to apply our experience with space THz sensors in THz communication for the Beyond 5G era to create an "AI-Driven Space THz Network" connecting all of New Space through THz communications. We welcome anyone who is interested in our research activities to join us.

＊The Ministry of Internal Affairs and Communications "Panel on Space x ICT" Report (in Japanese)
https://www.soumu.go.jp/main_content/000502202.pdf





2. (a–c) Observation range of SMILES FOV at corresponding altitudes (yellow and blue lines), the estimated locations of sprites (red dots) and their ranges (red boxes), and lightning occurrence distribution between SMILES and ISUAL observations obtained from WWLLN data (grayscale mesh) for Events A, B, and C. Altitude ranges of the SMILES-FOV are 75–90, 77–90, and 80–90 km for Events A, B, and C, respectively. SMILES and ISUAL observed facing east (left to right in these figures).

(d–f) Images of sprites and their parent lightning emissions detected by the ISUAL for each event.

(g–i) Distributions of the mean intensity in the range of 649701.5 ± 0.8 MHz for the background atmosphere (white columns). Blue columns represent the mean line intensity near sprite events. Yellow columns represent the mean line intensity three scans before and after.

T. Yamada et al., JRL (2020)
doi.org/10.1029/2019GL085529

Figure 2 Schematic image and analysis of the coincident observation with SMILES-HO_2, sprite imaging satellite, and ground based lightning detection.

Building an Open Innovation Platform for International Development

— Advancing ICT collaborations with south-east Asian research institutes through ASEAN IVO —

Global Alliance Department, International Research Advancement Office
Manager EMOTO Hiroshi

In February of 2015, NICT, along with research institutes, universities, and other organizations in South-East Asia, established a global alliance called the "ICT Virtual Organization of ASEAN Institutes and NICT," or ASEAN IVO. The organization was created as a means to further develop partnerships based on research connections cultivated in the ASEAN region over many years. ASEAN IVO's mission is to solve problems common throughout the region, by promoting a mutual recognition of the cooperative efforts needed to address major issues shared by member countries and launching collaborative research projects in the field of ICT. The organization aims to construct an Open Innovation platform tightly integrated with the region. Membership has increased year on year, from 9 countries and 25 institutions at the time of its founding, to all 10 ASEAN countries, Japan, and 60 institutions, as of January 2020.

Figure 1 ASEAN IVO Forum 2019 (Manila, Philippines, November 20, 2019)

Figure 2 Kick-off meeting for the Asian language treebank construction project

Meanwhile, to solve social and regional problems from a global standpoint, NICT is driving efforts which leverage a diverse range of collaborative R&D projects with international organizations to develop its technologies into actual solutions for society, both in Japan and abroad. ASEAN IVO is one platform essential for furthering those efforts and provides the necessary environment for international development in the ASEAN region. This platform can also be used by industries, including those in Japan, and private firms are starting to join.

ASEAN IVO has a steering committee, which serves to set the overall policy and direction of activities and R&D topics, determine the adoption and execution of collaborative projects, and more. The organization also holds a forum each year for the purpose of forming collaborative research projects by giving researchers from ASEAN countries a channel for proposing ideas and networking with other researchers. For example, at the ASEAN IVO Forum 2019, 29 presentations (including posters) were given on 4 topics: ICT for food; ICT for environment protection and disaster prevention; ICT for a secure and smart community; and ICT-related technologies and applications (Figure 1).

Starting in 2016, ASEAN IVO also began establishing and advancing around five collaborative projects each year, with NICT's support. One feature of ASEAN IVO's projects is that at least 2 countries from the ASEAN region are required to participate in each project. This ensures that projects have ties across multiple countries and regions. As of March 2020, a total of 24 projects have been implemented. NICT researchers participated in 18 of these, and NICT in general has greatly contributed to the technological development of the ASEAN region in a wide range of ICT fields, e.g. constructing an Asian language treebank for multilanguage processing; building communication infrastructure in rural areas; applying tech in communication methods for moving subway cars; and sharing data for developing cybersecurity technologies. For example, in the construction of an Asian language treebank for multilanguage processing, treebanks have been built for 9 languages (Indonesian, Malay, Vietnamese, Khmer, Burmese, Tagalog, Thai, Japanese, and English), and some of these have been released for free use for nonprofit purposes (Figure 2).

The ASEAN region's population size exceeds that of other regional cooperative organizations and, over the next ten years, the number of new Internet users in the region is projected to increase by a number equivalent to Japan's entire user base each year. Users are moving toward formats that are more user-friendly, and expectations are high for faster access speeds. The ICT industry, which is one element of social infrastructure, is thus considered to be more important by countries, societies, regions, and communities—and there is no question that ASEAN IVO is playing a major part. While gaps still remain between ASEAN countries in terms of ICT infrastructure and R&D, ASEAN IVO hopes to help eliminate those gaps, as we move into the future.

ASEAN IVO: https://www.nict.go.jp/en/asean_ivo/
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Terahertz Wireless Communication using Silicon CMOS Integrated Circuits

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Ph. D. (Science)

Biography

1976 Born in Kanagawa Prefecture
1996 Graduated from Faculty of Science and Technology, Tokyo University of Science
2006 Completed Doctorial Course at Tokyo University of Science
2007 Researcher at Toyota Technological Institute
2008 Research Associate at Tokyo University of Science
2013 Joined NICT
2019 Current Position

Awards, etc.

2019 Institute of Electronics, Information, and Communication Engineers 2018 Best Paper Award
2017 International Symposium on Radio-Frequency Integration Technology RFIT Award

Q&As

Q What do you like the most about being a researcher?

A Being able to deepen my understanding of cutting-edge tech across disciplines. One of the advantages of being a researcher, I think, is that you have many opportunities to have in-depth conversations with other researchers.

Q What are you currently interested in outside of your research?

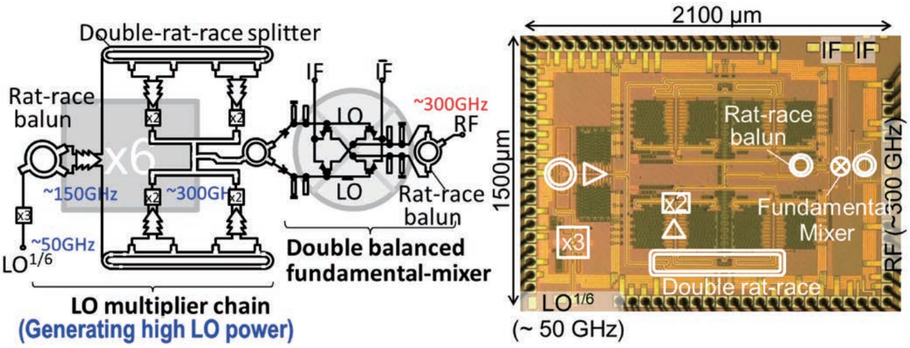
A Right now I'm trying to learn how to ride my child's two-wheeled skateboard. I also enjoy observing my pet praying mantis.

Q What advice would you like to pass on to people aspiringto be researchers?

A Don't be afraid of failure. Listen to the advice of your seniors and teachers, and devote yourself to your research. Let's all work together to create new technologies.

Electromagnetic waves including radio waves and light are used in a wide range of industrial fields. Among them, the frequencies of the radio waves are allocated based on their application according to the pertinent regulations, and wireless communication techniques used in wireless LAN, smartphones, and more are in widespread use based on those standards. However, new forms of ICT are being developed in areas like IoT, big data, and AI, and there is increased demand for high-speed wireless communication capable of sending and receiving large amounts of data. To make this a reality, techniques which use wide frequency bands all at once are being proposed as possible solutions.

Terahertz (THz) waves are electromagnetic waves located between radio waves and light, and are known as an "unexplored frequency resource." If frequency ranges with low atmospheric absorption can be utilized over a wide band, THz waves hold promise as a means for realizing high-speed wireless communication. A frequency spectrum from 275 to 450 GHz, for a total band of 137 GHz, was identified at the World Radiocommunication Conference (WRC) held in 2019 (see pp. 1-3).



Circuit diagram and chip photograph of 300 GHz silicon CMOS receiver circuit

We have been engaged in research aimed at making THz wireless communication a reality. Through joint research with Hiroshima University and Panasonic Corporation, we successfully developed a 300-GHz-band transmitter/receiver using a silicon CMOS technology. Silicon CMOS, which is widely used in information processing devices, is easily mass-produced and is therefore suited to handling the spread of THz wireless communications. However, typical silicon CMOS technologies have a problem in that it is difficult to design an amplifier in the 300 GHz band due to the limit of the FET performance. In our work, a 300-GHz CMOS receiver combining a down conversion mixer with a high-output local oscillation driver was developed with a high-output power transmitter, and we successfully verified high-speed wireless communication in the 300 GHz band.

Moving forward, we aim to further improve the properties of the THz transmitter/receiver and put ultra-high-speed wireless communication technology in the THz band into practical applications as soon as possible.

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