8-2 Stand-off Gas Sensing System Based on Terahertz Spectroscopy

SHIMIZU Naofumi, FURUTA Tomofumi, KOHJIRO Satoshi, SUIZU Koji, KADO Yuichi, and KOMIYAMA Susumu

We launched into a development of a new stand-off gas sensing system that can detect hazardous gases in disaster areas utilizing terahertz technology. This paper gives the outline of the system under development. The latest results of our research on terahertz transmitter and receiver are also presented.

Keywords
Terahertz electromagnetic wave, Remote, Stand-off sensing, Spectroscopy, Hazardous gas, Absorption line

1 Introduction

A number of remarkable characteristics of terahertz electromagnetic waves in relation to stand-off sensing applications include: (1) the frequencies of these waves are an order of magnitude or more higher than those of microwaves and millimeter waves (so-called short-wavelength frequencies) such that it is easy to focus their energy at a small spot on the target; (2) the wavelengths of terahertz waves are larger than those of infrared and visible light, and are less scattered by dust, soot, and smoke during propagation in air, with fewer effects on the human body; and (3) many materials have characteristic absorption lines (so-called fingerprint spectra) within this frequency range.

By making use of these characteristics of terahertz electromagnetic waves in sensing and imaging, a new method for collecting information, which could not otherwise be achieved with conventional technologies (involving X-ray, infrared, microwave, and millimeter waves), may become possible in disasters such as large-scale earthquakes. Furthermore, immediate distribution of the acquired information will help in the rescue of disaster victims, the prevention of secondary disasters, and in the minimization of primary disaster damage. Based on these schemes, we are currently conducting a project of research and development for terahertz technologies to provide safety and security through information and communication technology (ICT) sponsored by the National Institute of Information and Communications Technology (NICT). This project is scheduled to continue for five years, beginning in 2006.

The sections below present an overview of a stand-off sensing system based on terahertz spectroscopy. Then, the status of development of a terahertz transmitter and receiver that are important components of the system are presented. Finally, we also propose the possibility of effective collaboration with research groups of NICT performing research on terahertz-wave technologies.

2 Overview of stand-off sensing based on terahertz spectroscopy

Both passive and active methods are available in realizing a stand-off sensing system based on terahertz spectroscopy that will enable detection of hazardous gases in disaster areas. The passive method identifies these gases using the spectra of the electromagnetic waves emitted from the gas molecules themselves. The active method irradiates terahertz waves to buildings in disaster areas from a distance and performs spectroscopy on the received reflected waves. In a disaster area, various high-temperature objects are present in the background of the hazardous gases to be observed. Thus, in these cases, the active method is expected to provide higher sensitivity than the passive method. Taking into account the propagation loss of terahertz waves in air[1], the characteristics of the absorption lines of gases in the terahertz range[2], and the prospects of improvements in transmitter and receiver operating frequencies following five years of research and development, the present research and development project aims to construct a spectroscopic system based on terahertz waves in the range of 0.2 to 1 THz.

Figure 1 illustrates the conceptual operating principle of the stand-off spectroscopic sensing system currently under development. Terahertz waves at frequencies of f_1 to f_3 transmitted from the terahertz transmitter are reflected from the wall and received by the receiver. If a gas with absorption lines near the specific frequency of f_2 is present between the wall and the transmitter, the relative intensity of the received terahertz waves at this frequency will be weaker than that at other frequencies. Thus, by irradiating the terahertz waves covering the frequency range containing the absorption lines of the gases to be detected and by observing the spectrum of the reflected terahertz waves, we can detect the gases generated near the target object.

To construct the hardware required for this stand-off spectroscopic sensing system, we need a high-power, stable terahertz transmitter that can provide continuous tenability of the frequency with a narrow line width. We also need a high-sensitivity terahertz receiver that enables short-period measurement. For the terahertz transmitter, we adopted a method of generating high-power terahertz waves that begins with the generation of an optical sideband signal in an optical modulator. After this signal is generated, any two wavelengths (i.e., frequencies) are selected from the optical sideband signal using an optical filter. Using these two optical signals and a uni-traveling carrier photodiode (UTC-PD)[3][4], we generate a CW terahertz wave with the photomixing scheme. For the receiver, we adopted the heterodyne detection based on the use of a superconductor-insulator-superconductor mixer (or "SIS" mixer), which offers the lowest noise performance among available devices in the terahertz range[5]. We decided to develop the transmitter and receiver technology in the frequency range of 200 GHz to 500 GHz to establish the fundamental technological basis for

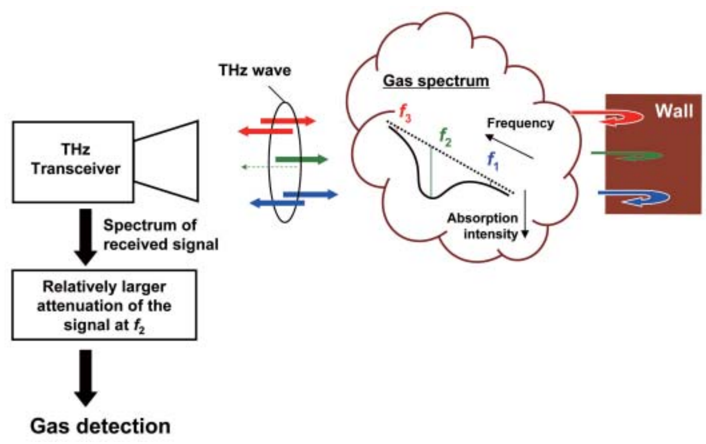

Fig. 1 *Operational principle of stand-off sensing system based on terahertz spectroscopy*

the first two years of this project. We report on the present status of development below.

3 Development status of system component technology

(1) Optical sideband signal generator

Figure 2 shows the configuration of the terahertz transmitter. The device generates a broadband optical sideband signal from light generated in the single-mode laser, using the phase modulator (PM) and the self-phase-modulation effect in the nonlinear optical fiber (DDF). Figure 3 illustrates the DDF output when the PM is operated at 25 GHz. The level difference in the optical sideband signal up to 500 GHz is within ± 4 dB. The arrayed wave-guide grating (AWG) divides the optical side-band signal into optical signals for each mode. Then, the optical switches in the next stage select two optical signals from the sets of signals within each mode, and the coupler combines the two signals. When this configuration is employed, we can perform continuous-frequency tuning of the optical beat signal by combining two processes: (i) selecting the modes using optical switches, and (ii) shifting the frequency of the PM modulation signal and finely adjusting the frequency difference between the selected signals. Figure 4 shows the output of the optical coupler. Here, an optical beat signal at a frequency of 277 GHz is generated. The carrier-to-noise (CN) ratio of the optical signal is 50 dB or more, and the spurious suppression ratio (desired signal intensity/undesired optical signal intensity) is also 25 dB or more. From the relationship $P_{THz} \propto P_{in}^2$ between the photomixer input power P_{in} and the terahertz wave radiation power P_{THz}, we can estimate that the spurious sup-

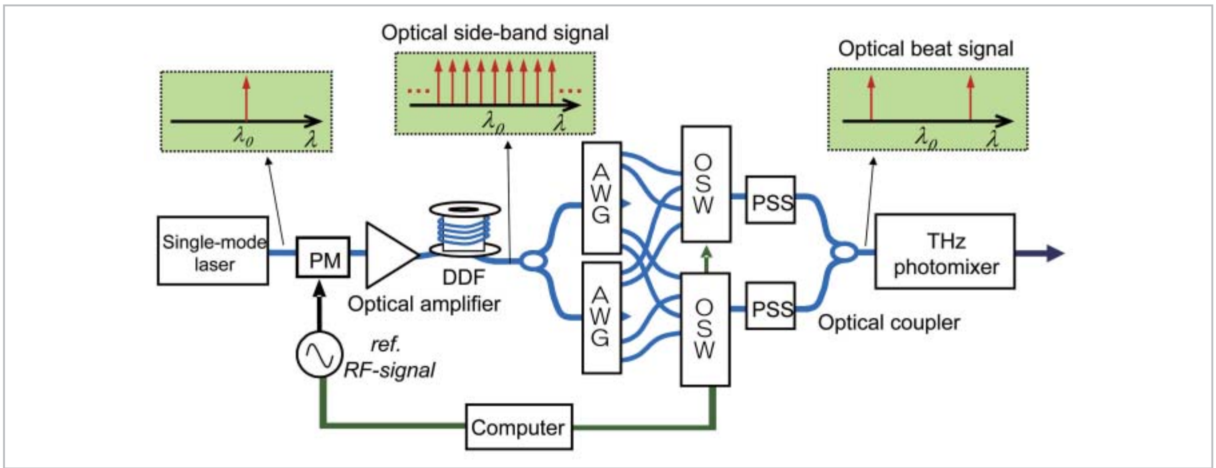

Fig.2 Configuration of terahertz transmitter

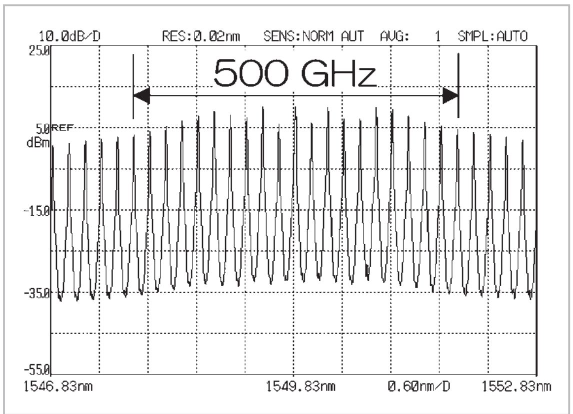

Fig.3 DDF output spectrum

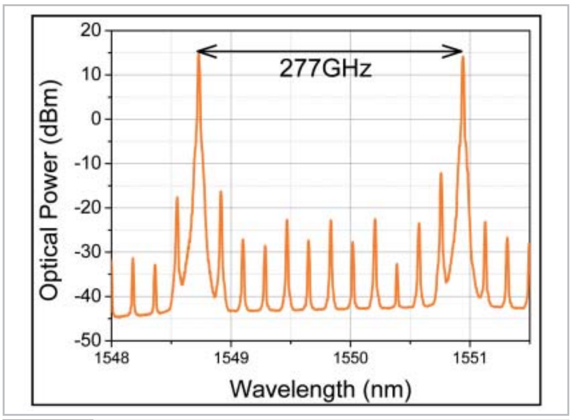

Fig.4 Optical coupler output

pression ratio of the terahertz waves generated with this configuration is 50 dB or more.

(2) Terahertz photomixer module

In the research and development discussed here, a UTC-PD module with high output power in the terahertz range is indispensable. Taking practical applications into account, we have adopted a configuration that combines a butterfly-type package, waveguide output configuration, and over-mode operation. For implementing over-mode operation with a waveguide output configuration, it is important for us to suppress the generation of higher-order modes. Accordingly, we have optimized the module configuration using a three-dimensional electromagnetic field simulator and have suppressed generation of the higher-order modes to 30 dB or over in the range of 200 GHz to 500 GHz. Figure 5 presents the characteristics of the J-band UTC-PD module. This module, covering the operating frequency range of 200 GHz to 500 GHz, shows maximum output power of 200 μW at 350 GHz.

(3) SIS mixer receiver

The SIS mixer features a sandwich structure with an extremely thin electron tunnel barrier (approximately 1 nm of aluminum oxide) between two superconductor (Niobium) electrodes. The nonlinear current-voltage characteristics of the mixer convert the terahertz electromagnetic waves to an output signal in the microwave range. To operate the SIS mixer in a broad frequency range from 200 GHz to 500 GHz, we have adopted a method that generates N-1 resonance frequencies, which are positioned closely on the frequency axis, with the junction capacitor and the inductance of microstrip lines in N multi-junction devices connected in parallel. Figure 6 shows the top view of the developed SIS mixer chip (N = 8) and the measured receiver noise temperature. We obtained a noise temperature of 700 K (30 times of the quantum limit) or less in the range from 230 GHz to 444 GHz. The 3-dB bandwidth, corresponding to 63% of the center frequency, is comparable to the widest RF bandwidth ever reported for SIS mixers. This measurement was performed with the support of Dr. Wang Zhen, Dr. Shingo Saito, and Dr. Masanori Takeda of the NICT Kobe Advanced ICT Research Center.

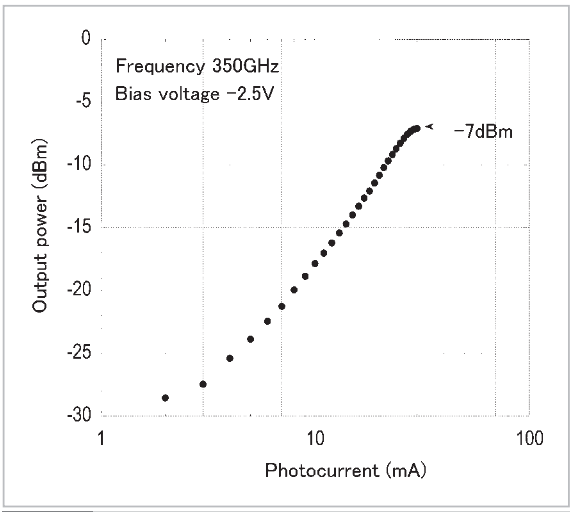

Fig.5 *Output characteristics of photomixer*

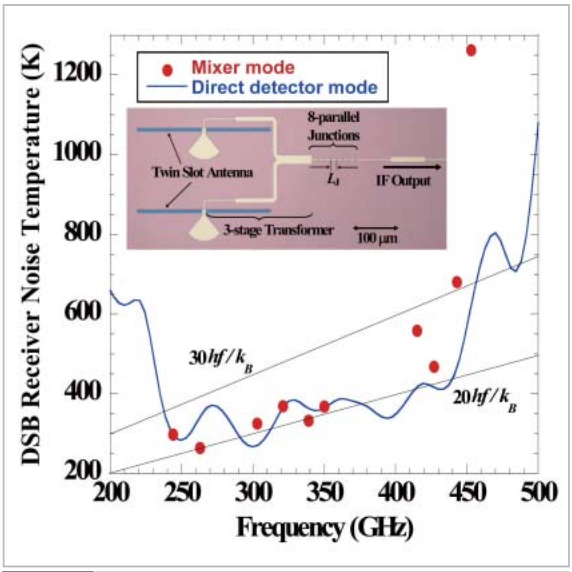

Fig.6 *Frequency dependence of receiver noise temperature and top view of SIS mixer chip (inset)*

(4) Terahertz gas spectroscopy

Utilizing the developed terahertz transmitter based on the optical sideband signal generator and the photomixer module, we evaluated the absorption characteristics of “laughing gas” (N_2O). N_2O features 25-GHz interval periodic absorption lines due to the transition between rotational states in the terahertz range[6]. As shown in Fig. 7, these

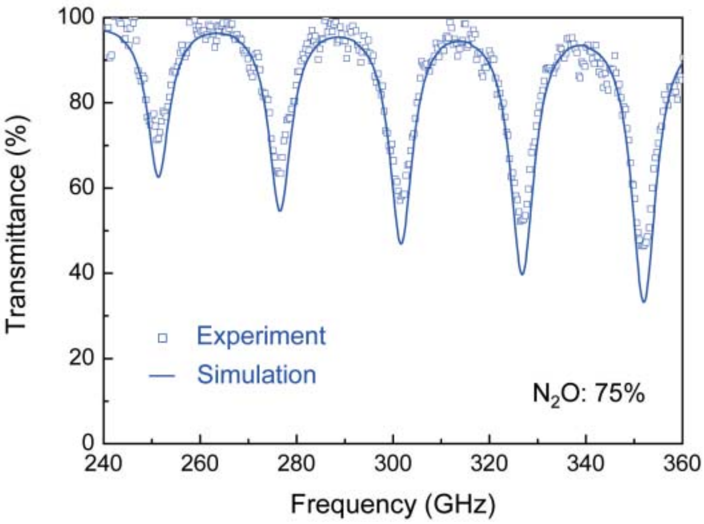

Fig.7 *Absorption spectrum of laughing gas*

absorption lines are clearly observed. The results also agree well with the spectrum calculated from the Hitran spectroscopic database for molecular transmission and absorption[7]. The results demonstrate that the developed terahertz transmitter offers high precision in terms of frequency and that the line width of the generated terahertz wave is narrow enough for applying to gas spectroscopy measurement.

4 Collaboration with NICT research groups

A precise atmospheric propagation model for terahertz waves and terahertz spectral databases for various materials are indispensable for accurately obtaining gas concentrations from measured spectra. The model and databases are also fundamental technological groundwork. Therefore, we believe that developing these technologies in collaboration with research groups of NICT will not only yield a profit for this project but will also contribute to the development in various terahertz applications including measurement, communications, inspections, and so forth. The energy gap of niobium electrode in our SIS mixer corresponds to 700 GHz in the frequency unit. Thus, the mixer performance may deteriorate above 700 GHz. The research group of NICT has developed a technique to fabricate electrodes of an SIS mixer using niobium nitride that does not show similar degradation in performance, even at frequencies of 700 GHz or greater[8]. For these reasons, we anticipate that collaboration with research groups of NICT will promote more efficient progress in the development of a terahertz receiver for the 0.5- to 1-THz range.

5 Conclusions

This article presents an overview of a stand-off sensing system, which we intend to develop based on terahertz technology with the scheme for providing safety and security through ICT. This research began in 2006 as a five-year project sponsored by NICT. We also report on the present status of hardware development. We thank Dr. Tadao Nagatsuma, the professor of Osaka University and research professor of NTT, who has expended much effort in the initiation of this research project, Dr. Ryoichi Fukasawa of Spectra Design, Ltd., and Dr. Osamu Mitomi of NGK Insulators, Ltd., who joined our discussions in system development as participants of the sponsored research.

References

1 "Trend Survey Report on Terahertz Technology", Support Center for Advanced Telecommunications Technology Research, 2005. (in Japanese)

2 S. Svanberg, "Atomic and Molecular Spectroscopy: Basic Aspects and Practical Applications", Fourth Edition, Springer, 2004.

3 H. Ito, T. Furuta, Y. Muramoto, T. Ito, and T. Ishibashi, "Photonic millimetre- and sub-millimetrewave generation using J-band rectangular-waveguide-output uni-travelling-carrier photodiode module", Electron. Lett. Vol.42, p.1424, 2006.

4 A. Hirata, H. Togo, N. Shimizu, H. Takahashi, K. Okamoto, and T. Nagatsuma, "Low-Phase Noise Photonic Millimeter-Wave Generator Using an AWG Integrated with a 3-dB Combiner", IEICE Trans. Electron, Vol.E88-C, No.7, pp.1458-1464, 2005.

5 S. Kohjiro, Y. Uzawa, J. Inatani, T. Nagatsuma, H. Ito, Z. Wang, and A. Shoji, "Quasi-optical Superconducting Heterodyne Receiver Using a Photonic Local Oscillator in the Submillimeter-wave Region", Ext.-Abstract 18B-6, International Workshop on Terahertz Technology, 16-18 Nov. 2005, Osaka, Japan.

6 H. Harde and D. Grischkowsky, "Coherent transients excited by subpicosecond pulses of terahertz radiation", J. Opt. Soc. Am. B, Vol.8, No.8, pp.1642-1651.

7 HITRAN homepage, http://cfa-www.harvard.edu/hitran/welcometop.html

8 Zhen WANG, "THz detectors with superconductive devices", OYO BUTURI, Vol.75, No.02, 2005.

***SHIMIZU Naofumi**, Dr. Eng.*

Senior Research Engineer, Smart Devices Laboratory, NTT Microsystem Intgration Laboratories, Nippon Telegraph and Telephone Corporation

High-speed Devices, Microwave Photonics

***FURUTA Tomofumi**, Dr. Eng.*

Senior Research Engineer, Advanced Opto-Electronics Laboratory, NTT Photonics Laboratories, Nippon Telegraph and Telephone Corporation

High-Speed Optical Receiver

***KOHJIRO Satoshi**, Dr. Eng.*

Senior Researcher, National Institute of Advanced Industrial Science and Technology

Superconducting Electronics

***SUIZU Koji**, Dr. Eng.*

Assistant Professor, Nagoya University

Nonlinear Optics

***KADO Yuichi**, Dr. Eng.*

Executive Manager, Smart Devices Laboratory, NTT Microsystem Integration Laboratories, Nippon Telegraph and Telephone Corporation

Low Power CMOS, Ubiquitous Communication System

***KOMIYAMA Susumu**, Ph.D.*

Department of Basic Science, The University of Tokyo

Condensed Matter Physics