6 Terahertz-Wave Propagation Model

6-1 Atmospheric Propagation Model of Terahertz-Wave

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Knowledge of atmospheric propagation property of terahertz-wave is very important for terahertz technology and its applications. Our final goal is development of terahertz-wave propagation model, based on accurate spectroscopic parameters of the line and continuum parts. In this paper, we introduce the atmospheric propagation model of terahertz-wave and the results of our laboratory measurements of spectroscopic parameters needed for manufacturing the model.

Keywords
Terahertz, Atmospheric propagation, THz-TDS, Pressure broadening coefficient, Continuum absorption

1 Introduction

Terahertz waves are electromagnetic waves in the frequency range from 1 to 10 THz (0.3 to 0.03 mm). They cover the so-called “unexplored” range between visible light and radio waves, so named due to the difficulty of generating and detecting waves in this region. Basic research and development in terahertz technologies are now underway for applications in diverse commercial fields, including safety and security, the biomedical field, electronics and new-material industrial uses, medical treatment, the diagnostic and pharmaceutical areas, agriculture and fisheries (including food quality control), and ultra-high-speed high-capacity communications.

This rapid development can be attributed to the nature of terahertz waves, which offer the advantages of both radio waves and light waves. For example, the illuminating characteristics of terahertz waves enable imaging at high spatial resolution due to their superior directionality, while their penetrating radiowave-like characteristics enable imaging through objects such as paper and plastics. In addition, many agents have characteristic fingerprint spectra in the terahertz range, such that terahertz waves can be used to identify substances. Based on these advantages, terahertz waves are beginning to find use in a number of safety and security applications, including detection of illegal drugs and explosives in mail articles and airport luggage. Further, as they lie within a frequency range that is safe to the human body, a series of potential applications have been proposed that may introduce new technologies to the field of medical treatments, such as cancer screening, early diagnosis of tooth decay, and diagnosis of the depth of burn injuries. Taking all of these aspects into consideration, terahertz technology is expected to open up new worlds in the same way that nanotechnology opened a new era.

The atmospheric transmittance of terahertz waves now rank among the most critical issues in the societal implementation of terahertz technology. While some terahertz wavelengths can be used for communications between locations separated several hundred kilometers on the ground, other terahertz waves propagate less than 1 m due to significant attenuation. In diverse terahertz applications, it is essential to know the applicable attenuation characteristics under different atmospheric conditions.

Based on these considerations, we are currently conducting research aimed at clarifying how the transmittance of terahertz waves in air depends on frequency, gas components, and temperature, in order to construct a terahertz wave propagation model based on this basic data. Section **2** outlines the terahertz wave propagation model, and Section **3** describes an example of laboratory measurement required to construct the model.

2 Terahertz wave atmospheric propagation model

Generally, the atmospheric absorption of terahertz waves is roughly divided into two absorption components (Fig. 1). One of these components is comprised mostly of the absorption lines of water vapor present in air. The absorption lines of water vapor are characterized by spectroscopic parameters, including the center frequency of the absorption line, oscillator intensity, and the pressure broadening coefficient. These spectroscopic parameters are generally determined through precise, careful measurement in laboratory experiments. The precision of these spectroscopic parameters is extremely important, as it will directly influence the precision of the atmospheric propagation model. The spectroscopic data for major atmospheric molecules such as water vapor are found in databases such as JPL[1] and HITRAN[2], which are widely used in atmospheric simulations. However, known spectroscopic parameters in the terahertz range are presently scarce[3][4].

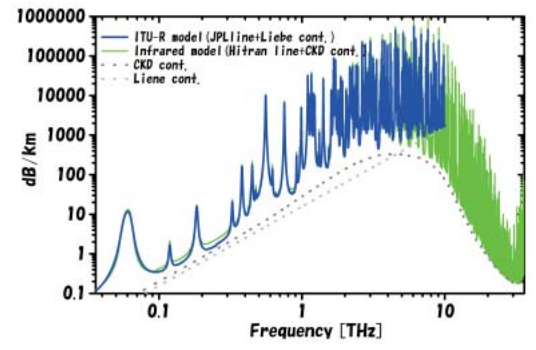

Fig. 1 Atmospheric propagation characteristics of terahertz waves

The remaining absorption component consists of a continuous absorption known as “continuum absorption” (Fig. 1). Continuum absorption is defined as excess absorption that cannot be described by water vapor absorption lines. It is known that the results of simulation under the assumption that the atmospheric absorption spectrum corresponds to the accumulation of water vapor absorption lines do not agree with experimental observation of atmospheric absorption. Such excess absorption is observed in a wide range of electromagnetic waves, from microwaves to the infrared region[5][6]. Today, continuum absorption is not sufficiently understood. Many theories have proposed various causes of this absorption, including the superposition of tails of numerous absorption lines, absorption by dimers and trimers of water vapor, and absorption by collisions between atmospheric molecules[7]-[9]. As such, the physical origin of continuum absorption remains unclear, and theoretical values of absorption intensity incorporate significant errors as a result. Clough, Kneizys, and Davis proposed a semi-empirical model applicable in a wide frequency range (CKD model), and this model has proven successful in some aspects[10]. Tipping and Ma et al. predicted continuum absorption based on an inter-molecular collision theory[9]. We must have experimental data to verify these predictions.

3 Atmospheric propagation measurement technique based on THz-TDS; measurement results

To construct an atmospheric propagation

model for terahertz waves, we will require highly precise spectroscopic parameters for both water vapor absorption lines and continuum absorption. Generally, when attempting to obtain such precise spectroscopic parameters, we must be extremely careful in determining the relevant values, employing two or more experimental systems of different types. Meshkov et al. developed a measurement system for continuum absorption in the millimeter and sub-millimeter wave range[11]. Their system is based on cavity ringdown spectroscopy. Meshkov and his associates measured broad absorption lines and continuum absorption of air in the frequency range from 0.17 to 0.26 THz[11]. Another technique often used in the terahertz and infrared ranges is known as Fourier-transform Infrared Spectroscopy (FT-IR). Gasster et al. measured the pressure broadening coefficient of the water vapor spectrum using FT-IR in the frequency range from 0.75 to 3.3 THz[3]. Podobedov et al. measured water vapor continuum absorption in air using FT-IR in the frequency range from 0.4 to 1.8 THz[12]. More recently, with the development of femtosecond lasers, terahertz time-domain spectroscopy (THz-TDS) has attracted a great deal of attention[7][13]. Grischkowsky et al. measured the terahertz spectrum of several gas molecules using THz-TDS. The further development of these experimental techniques will prove indispensable in the precise measurement of spectroscopic parameters.

In this study, we performed measurements using THz-TDS, which has recently seen dramatic advances and is expected as a result to produce results of higher sensitivity and higher precision. Here, we report on our measurement results concerning the pressure broadening coefficients, γ_{N2} and γ_{O2}, of nitrogen and oxygen, respectively, for the terahertz spectrum of water vapor.

THz-TDS is a spectroscopic technique that irradiates a pulsed terahertz wave to the sample, measures the time variation of the electric field of the transmitted wave, and obtains the amplitude magnitude and phase information of the electric field of the terahertz wave at each wavelength by Fourier transformation (Fig. 2). In this study, we performed measurements using a gas cell built into the pulse IRS-2300 (manufactured by Advanced Infrared Spectroscopy Co., Ltd.). The gas cell was at room temperature (23 °C ± 1 °C). We performed measurements for several pressure values with two types of samples: 500 to 2,500 Pa of water vapor mixed at a ratio of 23 to 70 kPa of nitrogen and mixed at a ratio of 43 to 90 kPa of oxygen. The frequency resolution was 1 GHz (0.03 cm^{-1}).

The time-domain spectrum measured is Fourier transformed into a frequency spectrum and then modified to an absorbance spectrum using the background spectrum measured directly prior to the main measurement. For the Fourier transformation, the data are multiplied by eight-fold zero filling. We used the Boxcar function for apodization. After checking that the obtained rotation lines of water vapor were not saturated, we performed least mean square fitting using the Lorentz function. We then performed analysis for 36 lines in a range from 0.5 to 3.1 THz.

Figure 3 shows an example of the absorption spectrum. The half width at half maximum, obtained by non-linear least mean square fitting to the Lorentz function, is plotted against the nitrogen and oxygen pressures. The values of γ_{N2} and γ_{O2} are determined from the slopes of the plots. In the range from 0.5 to 3.1 THz, we obtained γ_{N2} and γ_{O2} for the 36 rotation lines (Fig. 4). The horizontal

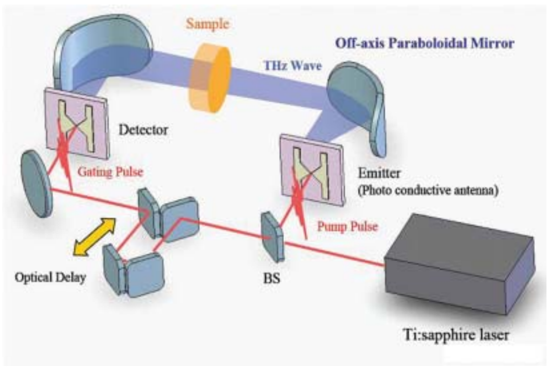

Fig.2 THz-TDS spectroscopic system

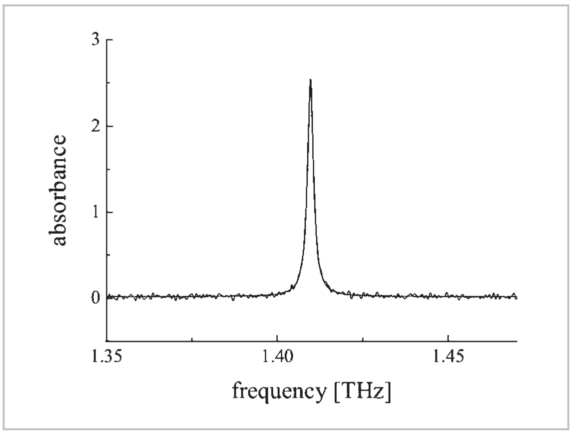

Fig.3 Example of measurement and analysis of water vapor spectrum by THz-TDS

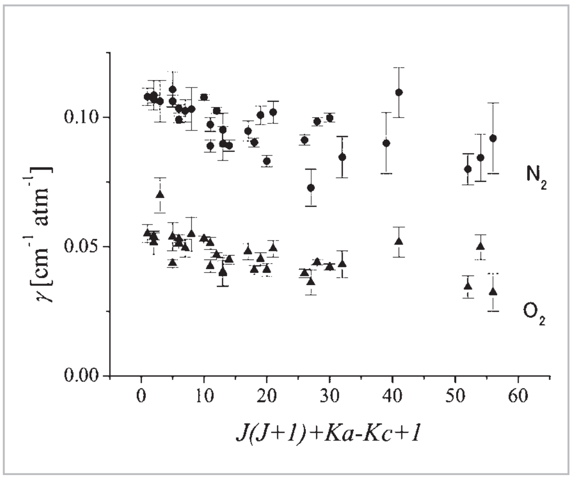

Fig.4 Measurement results of γ_{N2} and γ_{O2}

axis of Fig. 3 represents a quantity that depends on the rotational quantum number of water vapor, which has been theoretically suggested to correlate with the pressure broadening coefficient. Gasster et al. performed a similar measurement using FT-IR. While they were able to analyze 11 absorption lines in this frequency range[3], we were able to analyze more than three times as many. This is because THz-TDS is more sensitive and offers a wider dynamic range than FT-IR, and thus can measure many lines at once, from strong absorption to weak absorption.

4 Conclusions

This article briefly describes an atmospheric propagation model for terahertz waves. It also indicates the measurement results of atmospheric propagation characteristics based on THz-TDS, as an example of laboratory measurement of the spectroscopic parameters required to construct an appropriate model.

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