THz Laboratory Measurements of Atmospheric Absorption Between 6% and 52% Relative Humidity

by
Andriy Danylov

Submillimeter-Wave Technology Laboratory
University of Massachusetts Lowell
175 Cabot Street, Suite 130
Lowell, MA 01854

http://stl.uml.edu

September 2006
Abstract

Atmospheric transmissions of terahertz radiation were measured over 0.3 – 3.9 THz spectral range at sea-level over 1.7 m path length for relative humidity values ranging from 6% to 52%. Absorption coefficient values were calculated as a function of relative humidity, for the atmospheric windows in this region.

Introduction

THz radiation has been finding more and more applications because of its interesting properties. It penetrates through materials that are opaque to visible light and it excites the rotational motions in many molecules. The first property can be used in such applications as a security screening to detect concealed drugs and weapons (1), quality control, and nondestructive testing (2). The second one can provide spectroscopic information about materials (3).

A primary obstacle to THz applications is the attenuation by the ambient atmosphere due mainly to intense rotational transitions of the water molecules (4,5). In gases like water vapor the relative isolation of the molecules leads to sharp resonant peaks of absorption centered at specific frequencies with “transmission windows” between them. Three parameters: center of the line, strength of the line, and line broadening fully describe the absorption lines. While the first parameter is well determined for all of the lines because it depends only on the molecule inner structure, the other two are much more difficult to predict because they depend on the molecule interactions. It has been known for a long time that the line contribution is not enough to reproduce the experimentally measured atmospheric absorption, with calculated absorption being as much as an order of magnitude too small. In order to explain the discrepancy the so-called continuum absorption was introduced (6-8). The physical mechanisms of the continuum absorption are still not well explained. The dependence of the THz continuum absorption and the H2O line parameters on relative humidity, temperature and pressure are accounted for in atmospheric transmittance codes such as the high-resolution transmission molecular absorption database (HITRAN) (9). Despite the significant progress in theoretical predictions of atmospheric absorption (10-12), direct experimental measurements are still the most reliable method. Even for a short stand-off range, careful selection of operating frequencies will be necessary to avoid extreme degradation of system performance under adverse environmental conditions, particularly high water vapor content. In order to evaluate the utility of any window frequencies of the THz region for short-range surveillance applications, it is necessary to measure the broadband THz atmospheric transmittance as a function of water vapor content. Surprisingly, to our knowledge, data of this type is not available in the open literature.

In this work, the measurements of terahertz atmospheric transmission at varying relative humidity levels (6 – 52% RH) were carried out under known conditions of path length, temperature, and pressure. All measurements were made at sea level (1 atm), room temperature (27 C), and path length of 1.7 m. From these data, atmospheric
absorption coefficient values were calculated for various relative humidity levels using the Beer-Lambert law.

Experiment

A variable path or long path cells with controlled partial pressures of N₂, O₂ and H₂O in conjunction with conventional spectrometer are usually used for such measurements. However, such cells are not commercially available at the long wavelengths (50µm-1000µm) and time constraints prevented the design, construction and testing of a suitable absorption cell. However, as the results will indicate the use of an open FTIR spectrometer and conventional room humidifier provides a practical alternative.

The data were obtained with the Bruker model IFS 66V FTIR spectrometer at a resolution 0.15 cm⁻¹ (4.5 GHz). A mercury lamp was a broadband source of the THz radiation. The system has a dynamic range about 25 dB. The 1.7 m inner pathlength of the spectrometer was used for all measurements. The radiation that passed through the spectrometer was detected with a liquid-helium-cooled silicon bolometer of a composite type with an inner collective optics in the form of a Winston cone. In order to acquire transmission data a reference and sample spectra were required. The first was obtained with the 1.7 m pathlength of the Bruker FTIR under vacuum. After opening the spectrometer to room air, the second (sample) spectrum was obtained. The ratio of these two spectra yields the percentage transmission of the air as a function of the frequency. Since the experiments were carried out in winter when the relative humidity at room temperatures was low, a conventional humidifier was used to increase the amount of water in air. Relative humidity and temperature were measured with traceable hydrometer/thermometer with an accuracy 3% RH and 1 °C. The temperature and pressure were roughly constant at 27 °C and 760 mm Hg. The relative humidity values investigated were 6%, 12%, 22%, 26%, 40%, and 52%.

Measurements and analysis

The spectra for the above mentioned values of relative humidity in the wavenumber range 10 – 130 cm⁻¹ (0.3-3.9 THz) are shown in Fig.1. These spectra represent the total absorption, consisting of spectral line and continuum contributions. Because of the poor signal-to-noise ratio, data below 0.3 THz is not presented. Data in the spectral regions around 0.8 THz (26.5 cm⁻¹) and 3.27 THz (109 cm⁻¹) is not valid because of instrument artifacts caused by the beam splitter, which results in low signal-to-noise ratio near these two frequencies. Spectrally expanded views of this crowded plot are presented in Fig.2a - Fig.2g.
Figure 1. Measured atmospheric THz transmission at different levels of relative humidity. Blue, red, green, purple, orange, and black lines correspond to 6%, 12%, 22%, 26%, 40%, and 52% RH, respectively.
The spectra consist of about 75 absorption lines caused by rotational transitions in water molecules. They all were well-resolved and analyzed by R. Hall and J. Dowling (4). There is a good agreement in position of the lines with data obtained by R. Hall. The transmission data also was compared with the theoretical predictions made by MPM model (10) for the frequencies below 1 THz. The agreement is within 1% for the frequencies at the plateau of the “windows” between lines. Five distinct and relatively broad transmission windows 3.39-3.47 THz, 2.51-2.55 THz, 2.09-2.12 THz, 1.96-2.0 THz, 1.47-1.56 THz as well as narrower ones can be used for short-range surveillance applications. In order to estimate the attenuation of the THz radiation due to water vapor absorption over a certain distance the attenuation constant has to be calculated. It was done, for above mentioned five windows, by using the Beer-Lambert’s law $T = \exp(-\alpha x)$, where $\alpha$ is the attenuation constant, $T$ is the transmission, and $x$ is the propagation distance. The results are presented in Fig. 3 as the curves of $\alpha$ versus relative humidity.
Once $\alpha$ is known, one can predict the signal attenuation over any relatively small range of distance. These data should be used carefully to avoid a large uncertainty in prediction of atmospheric attenuation over long path lengths. A simple example illustrates the problem. Assume that 1.96-2.0 THz window is used at 26% RH, where the attenuation constant is $\alpha=0.072$ m$^{-1}$. Since $\alpha$ is measured by spectroscopic means over 1.7 m pathlength and the intensities of the radiation were measured to a precision about 1.5%, then $\alpha$ will be uncertain by about 12.3% or $\delta\alpha=0.0088$ m$^{-1}$, i.e. $\alpha = 0.072 \pm 0.0088$m$^{-1}$. The corresponding range of estimated attenuation factors for a 25 m path would be 6.9 dB, 7.8 dB, and 8.8 dB, respectively, for $\alpha = 0.063$m$^{-1}$, $\alpha = 0.072$m$^{-1}$, and $\alpha = 0.0808$m$^{-1}$.

**Conclusion**

Experimental atmospheric transmission data is still the most reliable source for obtaining the attenuation coefficient. The measurements presented in this paper were carried out at sea-level over the 0.3 – 3.9 THz spectral and 6 – 52% RH ranges. From this data the attenuation constants were plotted as a function of water vapor content. Five distinct windows with relatively high level of transmission were identified as the frequencies that might be used for short-range surveillance systems to avoid significant degradation of the THz signal.

**References and links**

5. Darrell E. Burch, “Absorption of infrared radiant energy by CO$_2$ and H$_2$O. Absorption by H$_2$O between 0.5 and 36 cm$^{-1}$”, Journal of the Optical Society of America, volume 58, number 10, October 1968.


