Wideband Permittivity Measurement System in the 67-116 GHz Range

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***Abstract*—In this study, we present an accurate permittivity measurement system for the 67-116 GHz band and measure dielectric properties of some low-loss polymers. The results obtained were in good agreement with other measurements reported in the literature, demonstrating the validity of the measurement system. The developed free space method allows the measurement of material characteristics with the same system over a large continuous bandwidth, which is key for accurate calibration and results. This is key for the design of high-performance receiver optics components to be used in high-performance application, such as radio astronomy receivers.**

***Keywords*— permittivity measurement, receiver**

I. Introduction

In radio astronomy, it is necessary to measure the permittivity accurately for the design of optical components in order to develop a highly sensitive telescope receiver. Accurate permittivity values are also essential for the optics design of the Atacama Large millimeter/sub-millimeter Array (ALMA) Band 2 receiver, which covers over 67-116 GHz [1].

The free space method has several advantages, such as the possibility of continuous measurement over a wide bandwidth, and the non-contact method, which does not require special jigs or high-precision processing of thin or small samples. In the development stage of an optical system, it is necessary to grasp as quickly as possible a wide variety of materials with different types, lots, and cut-out parts. Therefore, the free space method is suitable because of its ease of sample processing. However, there were few examples of measurements in the wide band of 67-116 GHz without changing the configuration of the equipment, and discontinuities occur in the band, making it difficult to measure accurately. In this study, we developed a system and measured the permittivity of some low-loss polymers in the wide band from 67 to 116 GHz continuously and accurately.

II. Permittivity extraction

A. Measurement Setup

The measurement setup consisted of a vector network analyzer (VNA), N5225B PNA Series, Keysight Technologies, frequency extender modules, VNAX WR-10+, Virginia Diodes Inc., and an optical system. The detailed optical system design was described in [2]. The optical system was designed with the Gaussian beam theory [3]–[5]. The corrugated horn was designed to have low-reflection loss and high-gaussicity in the operating frequency to make the system works as designed [6]. In the measurement process, *S*-parameters are measured with a metal plate or no object in the beam path. These *S*-parameters are needed to normalize the reflection and transmission coefficients of the sample and to derive the error terms for the 2-port network model.

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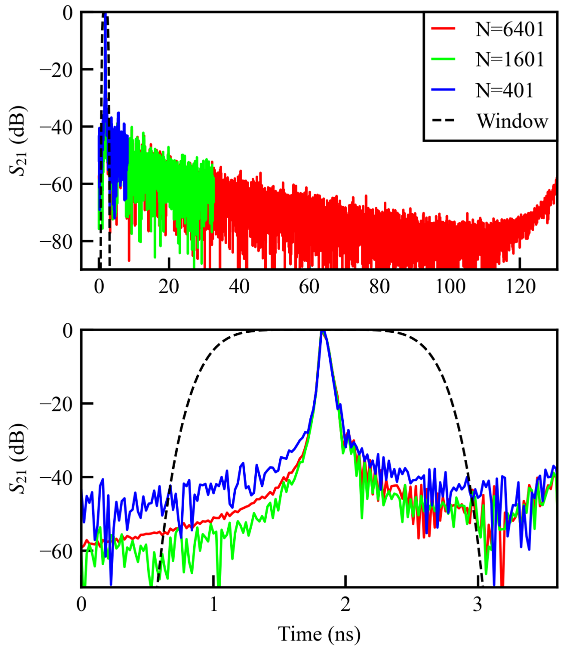

Fig. 1. Measured S_{21} in the time domain for each *N*.

B. Preprocessing

Before estimating the permittivity by applying the model equation to the measurement data, preprocessing is necessary because the raw data contains reflections due to impedance mismatching at the horn and multiple reflections in the optical system. Therefore, filtering with a window function in the time domain is performed to suppress these effects. First, the measurement data in the frequency domain is transformed into the time domain data using the Discrete Fourier Transform (DFT). After DFT, the time-domain data are multiplied by a window function to minimize the influence of undesired components. When applying DFT, we should carefully select the measurement bandwidth, Δf, and the number of points, N. The measurement range in the time domain is represented by $(N-1)/\Delta f$. Therefore, when Δf is constant, the measurement range in the time domain is proportional to N. According to Perceval's theorem shown in (1), the integral values of the noise power in the time and frequency domains are preserved before and after the Fourier transform. In other words, by selecting a large N, the noise level per unit of time becomes small. By multiplying a window function of appropriate width near the desired signal and performing the DFT, the noise in the frequency domain can be suppressed, resulting in an accurate estimation of the permittivity.

$$\sum_{n=0}^{N-1} |x[n]|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X[k]|^2 \quad (1)$$

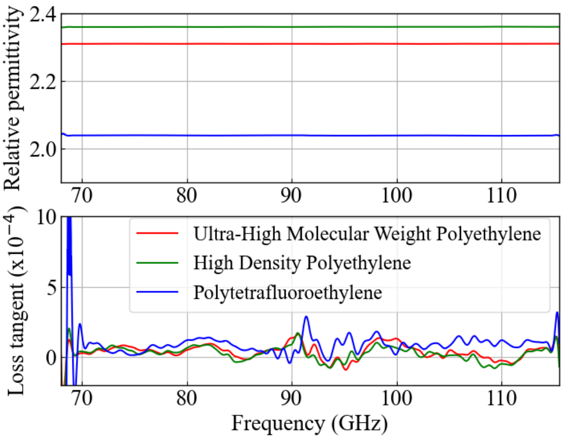

Fig. 2. Extracted relative permittivity (top) and loss tangent (bottom).

where n is the discrete time, k is the discrete angular frequency, $x[n]$ is the discrete-time signal, and $X[k]$ is the DFT of $x[n]$. To investigate the optimal N, we compared the noise level with varying N. Fig. 1 shows the measured S_{21} in the time domain for each N. Since the integrated noise power is preserved in the time domain, the noise level per unit of time decreases as N increases. The larger N, the smaller the noise level in the preprocessed data. However, a larger N increases the frequency sweep time and uncertainty due to the time stability of VNA, so the optimal N was set to 6401 points by balancing them. After preprocessing the above, we estimate the permittivity iteratively.

C. Data Analysis

The model formula used in this study was the 4-parameters method given by the following equations [7].

$$\det S = S_{11}S_{22} - S_{21}S_{12} = \frac{\gamma^2 - \tau^2}{1 - \gamma^2\tau^2} \tag{2}$$

with

$$\gamma = \frac{1/\sqrt{\varepsilon_r} - 1}{1/\sqrt{\varepsilon_r} + 1}, \qquad \tau = \exp(-jk_0 t\sqrt{\varepsilon_r}) \tag{3}$$

where ε_r is the complex relative permittivity, k_0 is the wave number, and t is the thickness of the dielectric slab. The permittivity is estimated by minimizing the difference between the determinant of the measured *S*-parameter and (2) using an optimization solver.

III. Experimental Results

Fig. 2 shows the measurement results for several types of low-loss polymers, ultra-high weight molecular weight polyethylene (UHMWPE), high density polyethylene (HDPE), and polytetrafluoroethylene (PTFE), which are commonly used for dielectric lenses or vacuum windows. The extracted permittivity of UHMWPE, HDPE, and PTFE are 2.307, 2.360 and 2.045, respectively. The measurement results are consisted with those of reported in [8].

IV. Conclusion

In this study, we measured the dielectric properties of low-loss polymers commonly used for optical components in radio telescopes with the permittivity measurement system in the 67-116 GHz band. The obtained results are in good agreement with previous studies in other bands, demonstrating the validity of the measurement system. This study will enable the high-accurate design of optical components, i.e., dielectric lenses, and vacuum windows, in the 67-116 GHz range.

References

[1] P. Yagoubov *et al.*, “Wideband 67 − 116 GHz receiver development for ALMA Band 2,” *Astron. Astrophys.*, vol. 634, 2020.

[2] R. Sakai *et al.*, “Accurate Free-Space Measurement of Complex Permittivity with the Angular Spectrum Method,” *IEEE Trans. Terahertz Sci. Technol.* (in press)

[3] Paul F. Goldsmith, *Quasioptical Systems: Gaussian Beam Quasioptical Propogation and Applications*. Wiley-IEEE Press, 1998.

[4] A. Gonzalez, “Frequency Independent LO Injection in Quasi-Optical Heterodyne Systems,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 5, no. 4, pp. 546–550, 2015, doi: 10.1109/TTHZ.2015.2434107.

[5] A. Gonzalez, “Frequency Independent Design of Quasi-optical Systems,” *J. Infrared, Millimeter, Terahertz Waves*, vol. 37, no. 2, pp. 147–159, 2016, doi: 10.1007/s10762-015-0205-1.

[6] A. Gonzalez, K. Kaneko, and S. Asayama, “Recent work on (Sub-)Mm-wave ultra wideband corrugated horns for radio astronomy,” *2017 11th Eur. Conf. Antennas Propagation, EUCAP 2017*, pp. 3327–3331, 2017, doi: 10.23919/EuCAP.2017.7928625.

[7] J. Baker-Jarvis, E. J. Vanzura, and W. A. Kissick, “Improved technique for determining complex permittivity with the transmission/reflection method,” *IEEE Trans. Microw. Theory Tech.*, vol. 38, no. 8, pp. 1096–1103, 1990, doi: 10.1109/22.57336.

[8] C. Y. E. Tong, K. Carter, and J. Connors, “Quasi-optical characterization of low-loss polymers at 300 GHz for vacuum window applications,” *IEEE Trans. Terahertz Sci. Technol.*, vol. 10, no. 6, pp. 713–720, 2020, doi: 10.1109/TTHZ.2020.3021352.