Characterization of Dielectric Material at 300 GHz for Vacuum Window Applications

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Abstract— **This paper describes the experiments that have been used to characterize dielectric samples applicable for a low-loss vacuum window at 300 GHz. The complex refractive indices of the samples were measured with a Quasi-Optical Vector Network Analyzer (QO-VNA). The loss tangents were further confirmed with the Method of Intersecting Lines using a Superconductor-Insulator-Superconductor (SIS) receiver. Finally, leak rates of the samples were compared using long term monitoring on a small vacuum chamber.**

***Index Terms*—Dielectric materials, dielectric measurements, superconductor-insulator-superconductor (SIS) receivers, sub-millimeter wave technology, vacuum window.**

I. Introduction

VACUUM windows form an important component for ultra-low noise submillimeter cryogenic receivers. Recent developments in receiver technology have driven the quest for wide aperture, low-loss, broadband, and reliable vacuum windows. Although there exists a wealth of information in the literature on the electrical and mechanical properties of different dielectric materials, the aim of our work is to explore new material and to confirm the properties of material from different vendors.

Future wideband Submillimeter Array (wSMA) receivers [1] require windows with a clear aperture diameter of 105 mm, covering an octave frequency range centered at 300 GHz. Large format receivers for Cosmic Microwave Background (CMB) observations necessitate windows with much larger diameter [2]. Quartz windows in use for the SMA receivers and ALMA offer only narrow band coverage and are somewhat smaller in size. That is why our focus is on thin but relatively strong window material that can be coated with an effective anti-reflection (AR) coating.

II. QUASI-OPTICAL VECTOR NETWORK ANALYZER

We have set up a Quasi-Optical Vector Analyzer (QO-VNA), operating between 210 and 370 GHz, to measure the complex refractive indices of different materials. Fig. 1 shows the QO-VNA set up. The material under test is placed on the sample holder, attached to a translation stage located between two 90-degree off-axis parabolic mirrors with focal lengths of 50.8 mm. Efforts are made to ensure the sample is as flat and perpendicular to the incoming wave as possible. A bi-directional coupler on the source side uses harmonic mixers to monitor the amplitude and phase of the incident wave as well as the reflected wave for reflection measurements. The transmitted wave is measured by another harmonic mixer connected to the receiving horn. To reduce back reflections from the receiving horn and harmonic mixer, a reflective neutral density filter, which acts as an attenuator (of -12.5 dB at 300 GHz), is placed between the sample holder and the receiving mirror at a roughly 45-degree angle. Fundamental Gaussian analysis of this setup shows that the beam waist, where the wave front is planar, is located very close to the sample holder. The value of the beam waist radius is about 12 mm.

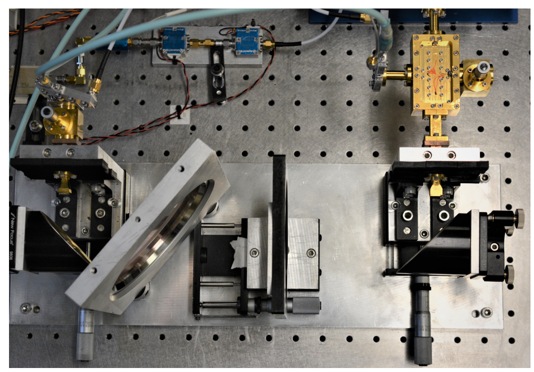

Fig. 1. 210-370 GHz QO-VNA setup. The sample holder is placed midway between a pair of off-axis parabolic mirrors. A partially reflective mesh, placed at 45° to the optics path, is put behind the sample holder for transmission measurements.

In order to derive the refractive index, a pair of transmission measurements are made using the QO-VNA: one with no sample and one with the sample under test mounted in the sample holder. The complex ratio of these two vector measurements, *R*, describes the geometric series of multiple reflections and loss, and can be written as follows [3]:

$$R = \frac{S_{21}^{sample}}{S_{21}^{thru}} = \frac{(1-\Gamma^2)e^{-j(n-1)\beta_0 d}}{1-\Gamma^2 e^{-j2n\beta_0 d}} \quad (1)$$

In the above equation, Γ is the reflection coefficient at the interface between air and the sample, the reflective index of

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which is n. n is a complex quantity, and its imaginary part is related to the loss tangent ($\tan\delta$) of the material.

$$n = n' - jn" = n'(1 - j\frac{\tan\delta}{2}) \quad (2)$$

In a first order approximation, the phase of the complex ratio R varies linearly with frequency, and n' can be derived from the slope. The imaginary part of n can also be extracted from a plot of the magnitude of R vs. frequency, provided that the sample is thick enough to present measurable losses for the QO-VNA, the threshold of which is 0.1 – 0.2 dB. Once an approximate value is established for n' and n'', a final round of complex data fitting yields the final experimental value of n together with an estimation of experimental errors. The measured refractive indices and loss tangents of selected materials are listed in Table 1.

TABLE 1
REFRACTIVE INDICES AND LOSS TANGENTS OF SELECTED MATERIALS MEASURED WITH A QO-VNA

Material	Refractive Index, n	$tan\partial \times 10^{-3}$
High Density Polyethylene (HDPE)	1.5327 ± 0.0005	0.6 ± 0.1
Honeywell Spectra (Dyneema)	1.552 ± 0.001	1.4 ± 0.3
Polypropylene (PP)	1.502 ± 0.001	0.5 ± 0.3
Polystyrene (PS)	1.594 ± 0.007	3 ± 1
Polytetrafluorethylene (PTFE)	1.434 ± 0.001	
PREPERM 225	1.605 ± 0.005	6 ± 1
Polymethylpentene (TPX)	1.45 ± 0.01	
Ultra-High Molecular Wt. Polyethylene (UHMW-PE)	1.515 ± 0.002	
Z- Cut Crystalline Quartz	2.107 ± 0.002	
Zitex G-108	1.22 ± 0.02	

III. METHOD OF INTERSECTING LINES

The loss tangent of selected materials measured with the QO-VNA have been confirmed with an *in-situ* loss measurement using the Method of Intersecting Lines with an SIS receiver. This method was first proposed by Blundell [4]. Using the procedure outlined in [5], Y-factor measurements are performed using hot and cold loads for a range of Local Oscillator (LO) levels. From this, the equivalent input noise temperature of the RF input section of the receiver can be derived. Repeating this procedure with the sample placed close to the vacuum window of the SIS receiver yields a new input noise temperature; the difference between the pair of measured input noise temperatures is directly proportional to the insertion loss due to the sample, which is accurate down to about 1%. Since this is a more sensitive method, we were able to measure thinner samples, the thicknesses of which are closer to what we will likely use for a vacuum window. Results utilizing this technique are comparable to those obtained with the QO-VNA for thicker samples. These results are included in Table 2.

TABLE 2
INSERTION LOSS AND LOSS TANGENTS OF SELECTED MATERIALS MEASURED WITH THE METHOD OF INTERSECTING LINES

Material	Thickness (mm)	Loss (%)	$tan\partial \times 10^{-3}$
High Density Polyethylene (HDPE)	2.37	1.3 ± 0.2	0.9 ± 0.2
Honeywell Spectra (Dyneema)	1.84	4.7 ± 0.07	3.2 ± 0.1
Polypropylene (PP)	1.48	1.1 ± 0.3	0.8 ± 0.2
Z- Cut Crystalline Quartz	4.97	1.1 ± 0.03	0.5 ± 0.1

IV. LEAK RATE TESTS

We have also conducted vacuum leak rate tests of some selected material samples using a small chamber with a 51 mm diameter aperture. The vacuum window sample under test is pressed against the aperture O-ring, and a vacuum pump, connected to a shut valve, evacuates the chamber. Once a desirable base pressure is reached, the shut valve is closed and a pressure gauge monitors the rising internal pressure. Fig. 2 shows the results of the conducted leak-rate measurements, which is a relative measure of how effective the sample functions as a vacuum window.

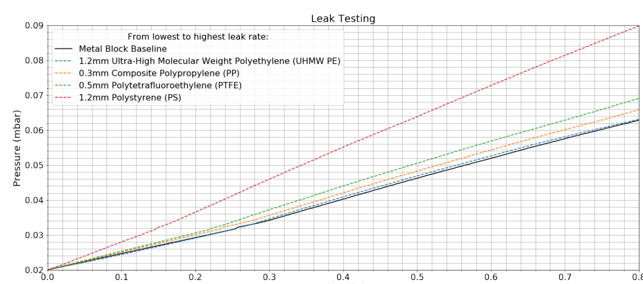

Fig. 2. Leak testing of various plastic materials on a 51mm diameter aperture vacuum chamber over a 0.8 hour time span.

V. CONCLUSION

Using the QO-VNA, we were able to determine the refractive indices and loss tangents of a variety of materials at around 300 GHz. The insertion losses of a number of sample windows have also been measured using the Method of Intersecting Lines with an SIS receiver. We have started to study the mechanical properties of these materials, including the leak rate and tensile modulus. Final selection of a window design will be a function of the refractive index, loss, mechanical strength, and the ease in which an effective anti-reflection coating can be implemented on the material.

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