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Dielectric Constant of Goretex RA7956/7957 Radome Material in the Frequency Range 1 MHz-2 THz

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Goretex radome material RA7956/7957 has been used in several applications at the CDL of the NRAO. To characterize its properties, careful measurements have been made of the dielectric constant, ε_r, which was found to be between 1.2 and 1.3, somewhat higher than previously determined values. As some concern exists about the future availability of thin Goretex sheets, the product is not recommended for any future designs or for use in ALMA.

Some NRAO test receivers have vacuum windows consisting of a plastic film vacuum barrier supported by a 1/8" sheet of Goretex RA7956/7957 radome material. Chips of Goretex have also been used to plug the waveguide openings in SIS mixer blocks to prevent contamination. Additionally, designs for new "5-layer" quartz vacuum windows considered for use in ALMA and the VLBA have made use of Goretex matching layers. Test receivers in the CDL also incorporate Goretex sheets as cold IR filters. Several samples of RA7956/7957, in thicknesses of 40 mils, 1/16", 1/8" and 1/4", were obtained around 1996. An order was placed in 1999 for 25 square feet of 20-mil thick Goretex sheet for use on the quartz windows.

Goretex RA7956/7957 is expanded polytetrafloroethylene (PTFE, *aka* Teflon) sheet, produced by W. L. Gore in a proprietary manufacturing process [1]. It has approximately ¼ the density of solid Teflon. There is some confusion regarding the part number. According to the company, samples thinner than 40 mils are referred to as RA7957, while thicker sheets are RA7956. Gore, however, has not been consistent in using this definition. The material is referred to as "Radome Material" or alternatively as "Hyper-sheet gasket material." It should be noted that as of 1999, W. L. Gore no longer makes Goretex thinner than 20 mils, and it was exceedingly difficult to obtain the 20-mil thick material. Numerous calls to the sales office of W. L. Gore went unanswered and there were at least 3 major delays in obtaining the product, resulting in a lead time of about 4 months.

The Measurements

Network Analyzer

The 20-mil thick Goretex was purchased to test a preliminary 5-layer window design. The window, designed using MMICAD [2], for the 90-116 GHz band, consists of a 226-mil thick, Z-cut quartz crystal plate (ε_r = 4.5 [3]). On each face is bonded a 17-mil thick sheet of high-density polyethylene (HDPE, ε_r = 2.31 [4]), and on each outer surface of the polyethylene is bonded a 20-mil sheet of Goretex. Previous measurements gave ε_r = 1.2 for the Goretex [5], [6], and the window design was thus expected to cover the entire 90-116 GHz band with 0.05 dB loss at the band edges.

Measurements were carried out on an HP8510 network analyzer using time-domain gating to eliminate the effects of spurious reflections [7]. Due to the limitations of the instrument, a single free-standing sheet of Goretex could not be measured with sufficient accuracy, leaving information about the Goretex to be extracted from a model fit to the transmission data for the complete window. During application of the Goretex to the window, the nominal thickness of 21.4 mils was reduced to approximately 20 mils, as measured under a microscope. However, even allowing the thickness of the Goretex to vary, the best fit to the MMICAD model could only be obtained for $\varepsilon_r = 1.295 \pm 0.005$.

The dielectric constant of the quartz was precisely determined by modeling the network analyzer data for a blank quartz crystal plate. Data were also taken on the incomplete window after application of the polyethylene layers. The window model was then used to fix the ε_r of the polyethylene. Small changes in any of the values resulted in a mismatch between the measured and modeled channeling fringes in the reflection spectrum. The unexpectedly high value of ε_r for the Goretex and the resulting shift of the window passband to lower frequencies led to the detailed investigations of the Goretex described below.

Capacitance Bridge

A simple way to determine the dielectric constant of a material is to sandwich a sheet of it between two parallel plates and measure the capacitance of the structure. Knowing the spacing between the plates and the area of the sheet, the dielectric constant can be extracted. To this end, a precision jig was constructed to allow stable and reproducible capacitance measurements to be made. The jig consists of two steel tool blocks, 2"x2"x5/8" thick, with the large surfaces ground flat and parallel to better than 0.0001". The spacing of the plates is adjusted by micrometers on three of the four corners, which bear on 6-mm sapphire balls partly sunk into the lower plate. The remaining corner is left open so as to be able to remove the sample without disturbing the jig. A Boonton Model 75G capacitance bridge was used to measure the capacitance of the assembly. The bridge operates at 1 MHz.

In practice, a piece of material 1.5"x1.5" square is placed in the jig. The upper plate is lowered carefully until the material is flattened, eliminating air gaps, without actually compressing the material. For soft material, such as Goretex, the method insures complete filling between the plates, and determines the plate separation precisely. The capacitance is then measured. Afterward, the material is carefully pushed out from between the plates without disturbing the plate spacing and the capacitance is measured again with the jig empty. This method allows the fringing fields of the plates to be cancelled out of the calculation of the dielectric constant, which is given by

$$\varepsilon_r = 1 + \Delta C D / \varepsilon_0 A$$

ΔC is the difference in capacitance of the jig with and without the sample present, D is the spacing between the plates, and A is the area of the material to be measured (not the plates). The area of the Goretex sheets was measured precisely using a microscope with digital micrometers attached to the stage. The plate spacing was determined using a digital micrometer measuring the position of the top plate directly.

The Boonton bridge generally yielded measurements of ΔC, repeatable to within 2%-3%, and sets the overall accuracy of the measurement. The 20-mil, 40-mil and 1/16" Goretex samples were measured, yielding values of $\varepsilon_r = 1.22$, 1.24 and $1.21 \pm 3\%$, respectively, consistent with the earlier measurements, $\varepsilon_r = 1.2$, for the 40-mil [5] and ¼" Goretex [6].

Fourier Transform Spectroscopy

The 20-mil Goretex sample was further analyzed using Fourier transform infrared (FTIR) spectroscopy to obtain Far-IR spectra. Fitting the spectra to a MMICAD model, the dielectric constant can be extracted. For these measurements, extreme care was taken to determine the free-standing thickness of the Goretex sheet very accurately. Because the material is so soft, simply applying calipers to the sheet is enough to distort the surface and render the measurement inaccurate. Instead, the spring force of a digital micrometer was calibrated as a function of displacement. By adjusting the overall micrometer height to obtain different spring compressions, and using various sizes of measurement feet, many thickness measurements were obtained at different measurement pressures. Extrapolating to zero pressure, as shown in Figure 1, the uncompressed thickness of the 20-mil Goretex was found to be 21.4 mils.

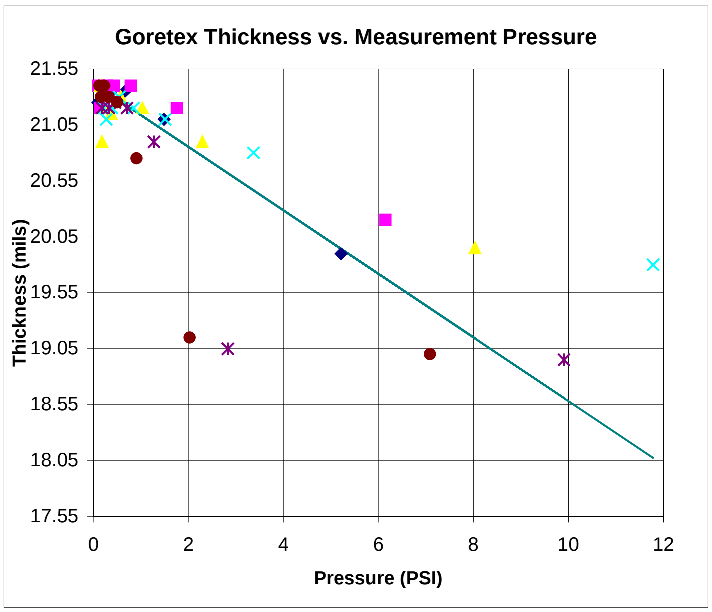

Figure 1. Thickness of "20-mil" Goretex RA7956.

The best fit to the IR data did not necessarily occur for a sample thickness of 21.4 mils. Instead, the sample thickness was allowed to vary in the MMICAD model, and the fit was often improved using a thickness of approximately 22 mils, consistent with the sample thickness used for the capacitance bridge measurements. It is quite possible that the material has expanded in time after its thickness was measured. All of the 20-mil samples measured were obtained from the same batch, though it is possible that variation exists across the sheet. Due to the complexity of the thickness measurement, the discrepancy has not been resolved. However, varying the thickness from 21.4 to 22 mils has a relatively small effect on the fits, altering ε_r by only 3%. The attenuation coefficient was also allowed to vary as one of the fitting parameters in the model.

Two different sets of measurements were made on the 20-mil Goretex sample, each run yielding good data over a limited frequency range. A Bruker IFS66V FTIR spectrometer at UVA with a mercury arc lamp source and a helium-cooled bolometer was used to cover the lowest frequency range of 300-700 GHz [8]. The best fit was found for $\varepsilon_r = 1.29$ with a sample thickness of 22.2 mils. Fixing the thickness at 21.4 mils, the dielectric constant increased to 1.32, and the fit to the data was not as good. Fits were also attempted with a lower dielectric constant of 1.2, but the amplitude of the interference fringes could not be matched at all. ε_r = 1.25 gave an acceptable fit, but the amplitude was still too low, thus setting a lower bound for ε_r.

Measurements were also made at the Advanced Light Source Synchrotron Facility at Lawrence Berkeley National Labs, coincidentally also on a Bruker IFS 66V/S spectrometer [9]. The internal mercury arc lamp was used as the source along with an He-cooled bolometer having a 100 cm^{-1} (3 THz) cutoff, and a 23-micron mylar beamsplitter. Data were obtained at a resolution of 3 cm^{-1} (90 GHz). While data were obtained over the entire range from ~400-3000 GHz, only two narrower frequency ranges could be fitted to the MMICAD model. From 500-1000 GHz, the best fit was obtained for ε_r = 1.28 and D = 20.6 mils. Fixing thickness at 22 mils produced ε_r = 1.26, though the fit was much worse. From 1800-2250 GHz, a best fit resulted in ε_r = 1.21 and t = 22.4 mils. Decreasing t to 22 mils increased ε_r to 1.26, though the fit also deteriorated.

A second measurement was run on the same instrument, this time with a 50-micron beamsplitter. The thicker beamsplitter produced a dropout in the spectrum from ~58 to 63 cm^{-1}. A good fit was only possible from 900-1600 GHz, resulting in ε_r = 1.25 for a thickness of 21.7 mils. An acceptable fit was obtained for t = 22 mils, yielding ε_r = 1.22.

It is not known why the thickness of the sample appears to vary for the best fit from run to run, or even within different frequency regions of the same spectrum. However the maximum variation is less than ± 3%. Since it is the optical thickness, $\sqrt{\varepsilon_r}$ x D, which is relevant here, the derived values for ε_r are presumed to be within ~ ± 3%.

The results for the best fits to the 20-mil Goretex are summarized in Table 1, and ε_r is plotted as a function of frequency in Figure 2, for all the data. The three points at 0 frequency correspond to the 1 MHz capacitance bridge measurement for the 40 mil, 20 mil and 1/16" Goretex samples, from top to bottom, respectively. ε_r =1.295 at 100 GHz from the HP8510 network analyzer data. Thickness was allowed to vary to obtain the best fit for all of the IR derived data and the middle of the fitting range was taken for the frequency. The best fits are plotted as dark diamonds. The fixed-thickness fits are plotted with lighter-shaded symbols.

Table 1. Dielectric constant of 20-mil Goretex RA7956.

Frequency (GHz)	Dielectric Constant (ε_r)	Data Source
0.001	1.22	Capacitance Bridge
100	1.295	HP 8510 Network Analyzer
500	1.29	UVA
750	1.28	ALS first run
1250	1.25	ALS second run
2025	1.21	ALS first run

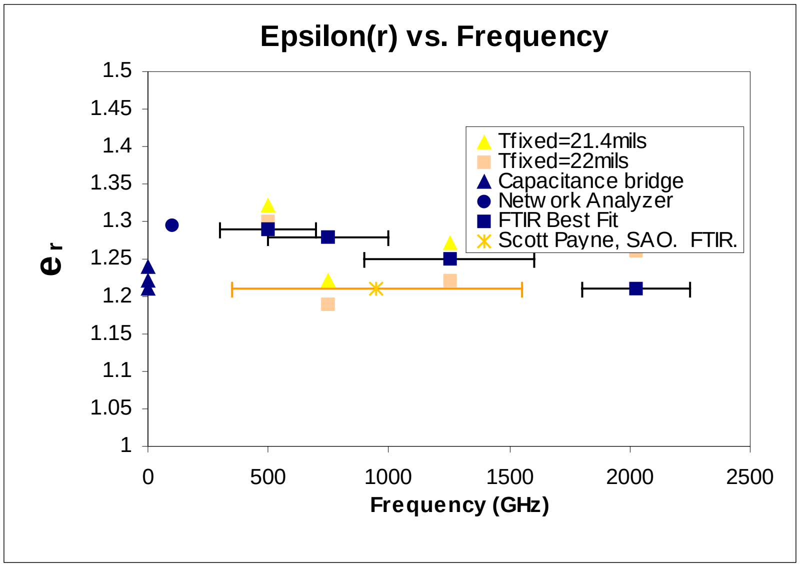

Figure 2. Dielectric constant of Goretex from several measurements.

Conclusion

Despite the variation in the data, a frequency-dependent trend is evident in the best fits. To better define the behavior of the dielectric constant, more measurements are needed, particularly below 500 GHz, at the very low frequencies, and also above 2000 GHz. Very low frequency FTIR (to 200 GHz or less) and higher frequency network analyzer measurements (to 200 GHz or higher) would help eliminate any systematic errors existing in the two lowest data points. A mid-IR measurement would also help confirm the slow decrease in the dielectric constant seen as frequency increases.

It should be noted that the ¼" sample measured by the SAO [6] and the other samples may not have the same properties. Without knowing the details of the proprietary manufacturing process, it is possible the samples are significantly different materials. The difficulty in obtaining information about Goretex, and in purchasing samples to work with, suggests that alternative materials be found. To this end, various different samples of "Zytex" sheet are being investigated [10]. Zytex G, which is also expanded Teflon, is easily available in a wider range of thickness than Goretex.

References

[1] W. L. Gore and Associates, Inc., 1901 Barksdale Rd., P. O. Box 9236, Newark, DE 19714-9236.

[2] MMICAD is a microwave circuit analysis and optimization program available from Optotek Ltd., 62 Steacie Drive, Kanata, Ontario, Canada K2K 2A9. http://www.optotek.com/.

[3] $\varepsilon_r = 4.45$, refined from the MMICAD fit to the network analyzer data. See also S. Roberts and D. D. Coon, "Far-Infrared Properties of Quartz and Sapphire," *J. Opt. Soc. Am.*, v. **52**, pp. 1023-1029 (1962). E. E. Russell and E. E. Bell, "Measurement of the Optical Constants of Crystal Quartz in the Far Infrared with the Asymmetric Fourier-Transform Method," *J. Opt. Soc. Am.*, v. **57**, pp. 341-348 (1967). E. V. Loewenstein, D. R. Smith, and R. L. Morgan, "Optical Constants of Far Infrared Materials. 2: Crystalline Solids," *Appl. Opt.*, v. **12**, pp. 398-406 (1973).

[4] ε_r = 2.31, refined from the MMICAD fit to the network analyzer data. See also M. N. Afsar, "Dielectric Measurements of Common Polymers at Millimeter Wavelength Range," *1985 IEEE MTT International Microwave Symposium Digest*, pp. 439-442, 1985.

[5] Nancy Jane Bailey, while at NRAO, used capacitance bridge measurements similar to those described here to measure the dielectric constant of a 40 mil Goretex sheet. ε_r was found to be 1.2, but the precision of the measurement was not stated.

[6] Scott Payne and Jon Kawamura, Smithsonian Astrophysical Observatory, Cambridge, MA. Personal communication of 10/24/1995. The refractive index for a ¼" piece of Goretex from NRAO was found to be n = 1.10 (ε_r = 1.21), essentially constant over a range of 350-1500GHz, using dispersive FTIR measurements.

[7] G. A. Ediss, A. R. Kerr, D. Koller, "Measurements of Quasi-Optical Windows with the HP 8510," ALMA Technical Memo #295, March 2000. Available on-line at http://www.alma.nrao.edu/memos/.

[8] Thanks to Tatiana Globus of the UVA Physics Dept. for these measurements.

[9] Thanks to Michael C. Martin of Berkeley National Labs for the measurements on Goretex and other materials.

[10] Norton Performance Plastics, 150 Dey Road, Wayne, NJ. Zytex G is available in thicknesses of 4, 6, 8, 10, 15 mils, and larger thicknesses up to 150 mils.