Measurement of Transmittance and Scattering of Radome Membranes from 30 to 1000 GHz

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***Abstract*—Transmittance of a number of woven and nonwoven radome membranes with various diameters of threads of the fabric and thickness of the laminate has been studied as a continuous function of frequency over the 30–1000-GHz range by utilizing Fourier transform spectroscopy (FTS). These woven and nonwoven radome membranes, now known as "Gore-Tex," were manufactured by W. L. Gore and Associates, Inc. In this paper and for the first time, the transmittance has been measured with various angles of incidence of the incident wave for both TE and TM modes. Strong diffractive scattering has been found above the frequency with wavelength comparable with the fabrics' period (240 GHz for the standard Gore-Tex product). Gore-Tex woven-membrane materials were found to be suitable for radome applications up to 1000 GHz.**

***Index Terms*— Antenna, Fourier transform spectroscopy, millimeter-wave, radomes, submillimeter-wave, transmittance.**

I. Introduction

LARGE microwave and millimeter-wave antenna systems have been used for over 20 years by radio astronomers. These systems are normally enclosed in radomes. For radio astronomy applications it is desirable that radomes are usable over a broad frequency band. Today, the receiver technology has significantly improved at higher millimeter- and submillimeter-wave frequencies (up to 1000 GHz). This new higher frequency application is a challenge for the designers of radomes. In the millimeter-wave region, radomes usually have a metal-space frame structure. This structure consists of metal thin frames and dielectric membranes tightened over them. The metal-space frame design allows the use of thin dielectric membranes. The use of thin dielectric membranes is a great advantage in radome designs: firstly, the period of channeling (the periodic changing of transmittance amplitude due to interference) increases with decreasing thickness and secondly the overall attenuation in the thinner layer become smaller.

The dielectric membranes should be durable and inert to most atmospheric chemicals, which suggests the use of a Teflon-based material for radomes. It is desirable in a woven membrane to have thin membranes with good mechanical strength. W. L. Gore and Associates, Inc., developed a Teflon-based material known as "Gore-Tex."[1] The commonly known Gore-Tex material is a fabric made up of threads on top of a flat layer, which are both made from specially treated Teflon. The flat Teflon layer is known as "laminate." A laminate layer normally consists of three sub-layers of an expanded Teflon and fully dense (pure high density) Teflon. The laminate holds the threaded piece together and provides additional protection from adverse weather conditions. The threads made with Teflon provide mechanical strength to the membrane. However, the periodical structure of these materials (threads) raises the concern about possible diffraction (scattering) at the high-frequency end of the millimeter-wave range.

The diffraction of radiation can increase the antenna temperature and deteriorate the performance of the complete antenna system. It is difficult to calculate and predict the magnitude of this deterioration effect because of the complicated structure of woven fabrics. One can calculate transmission characteristics for the woven structure at lower frequencies based on an analysis of the dielectric layers. However, it does not generate adequate precision in such calculations because of the mismatch of the reflection and transmission in the weave formation. Thus, electromagnetic properties of these materials should be experimentally measured (directly) in order to use this data in a radome design and to create an electromagnetic model for these materials. This paper presents experimental results obtained using the Fourier transform spectroscopy (FTS). The FTS is the only technique which allows one to perform such measurements over the entire required frequency band (as a continuous function of frequency) with sufficient precision [1]–[4]. In this paper, we are presenting accurate transmittance measurements on Teflon-based woven membranes manufactured by W. L. Gore and Associates, Inc. at different angles of incidence for TE and TM modes. Birch *et al.* [5] had measured the transmittance spectra at normal incidence of some Gore-Tex membrane specimens in 1983. This led to the use of the Gore-Tex radome membrane RA 7943 in the enclosure of the James Clark Maxwell telescope (JCMT) in Hawaii for radio-astronomy observations up to 1000 GHz. The same Gore-Tex radome membrane (RA 7943) has also been used in the radome of the Five College Radio Astronomy Observatory (FCRAO) in Amherst, MA.

II. Measurement Techniques

Data presented in this paper was measured with a specially constructed millimeter-wave FTS. The FTS is a well-known

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[1] Gore-Tex is a registered trademark of W. L. Gore, Inc. W. L. Gore and Associates, Inc., Elkton, MD 21922-1100 USA.

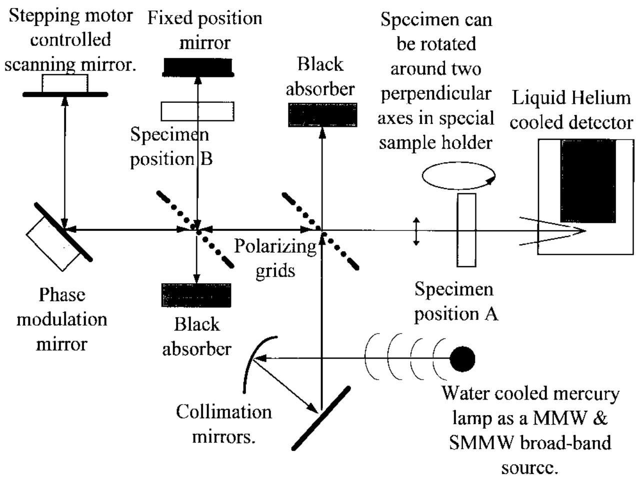

Fig. 1. The ray diagram of the two-beam interferometer (used for millimeter-wave FTS) shown in its polarization-mode configuration. A pair of wire-grid polarizes the incident radiation, splits, recombines, and analyzes the beams. The specimen can be placed at position A for conventional FTS and position B for dispersive FTS which provides phase information as well.

technique in the infrared spectral region. One advantage of the FTS technique is the frequency coverage over a broad continuous spectral band. In the millimeter- and submillimeter-wave region, we have developed a number of special FTS instrumentation and measurement methods [1]–[4]. The FTS measurements methods we developed are the only techniques which provide continuous broad-band (over the entire frequency region) measurements of the real and imaginary parts of dielectric permittivity, loss tangent, and insertion loss with high precision. In this paper, the transmittance of membranes was studied as a function of angle of incidence. A mylar film is used as beam-splitter material in most FTS interferometers for $\sim$50% transmission and $\sim$50% reflection in a Michelson-type two-beam interferometric configuration. The reflectivity of a mylar surface is almost constant, where as the absorption coefficient in a mylar film increases with increasing frequency. A thicker mylar film would absorb more energy at the shorter wavelength (higher frequency) and provide more transmission of energy at the longer wavelength region, whereas a thinner mylar film would have more transmission of energy at higher submillimeter-wave frequencies. The use of thicker mylar film generates a multiple interference, resulting in a channel spectrum in the near millimeter-wave region. It is almost impossible to have a continuous coverage of frequency from 30 to 1000 GHz utilizing mylar beam splitters. One may have to use four mylar beam splitters with thicknesses such as 50, 100, 200, and 500 μm to cover the frequency range of 30–1000 GHz. The alternative way to increase the signal performance at millimeter waves is to use a pair of freestanding wire-grid polarizers (made with 10-μm-thick tungsten wire with a 25-μm center-to-center wire spacing) as beam splitters in a two-beam interferometric configuration commonly known as a polarizing interferometer. A pair of freestanding wire-grid polarizers was used for beam division in our FT Spectrometers. The continuous spectral coverage of 30–6000 GHz can be achieved with such polarizing grids (with different detectors). At the millimeter-wave region, the spectral energy loss due to the channel behavior of a mylar beam splitter can be completely avoided in a polarizing interferometric configuration. The ray diagram of our polarizing FT interferometer is shown in Fig. 1. For transmission measurements, the conventional FT interferometric technique was employed in which the specimen was placed in the detector arm of the interferometer in front of the detector, shown as position A in Fig. 1. A specially designed sample holder was installed between the interferometer and the detector. This sample holder allows us to rotate a specimen around the axis that is perpendicular to the direction of propagation of the incident wave. The atmospheric absorption loss was reduced by flushing dry nitrogen gas inside the specimen holder (The rest of the interferometer was evacuated). The source of radiation is a mercury vapor lamp that essentially acts as a black body radiation source. However, the energy around 150 GHz is very low from such a mercury vapor lamp source. One, therefore, needs to use very sensitive detector and stabilize the interferometer and electronics to recover the energy around 150 GHz. A highly sensitive fast liquid-helium-cooled Indium Antimonide Rollin detector was used for detection of energy at the millimeter-wavelength region. This detector allows us to perform reliable measurements in the 1–34 cm^{-1} range (30–1020 GHz). One wire-grid polarizer used in the interferometer serves as a polarizer and a analyzer of radiation beam and the other wire-grid polarizer serves as a beamsplitter and beam recombiner. The polarization configuration of the interferometer behaves essentially like a passband filter allowing the interferometer to work from 30 to 6000 GHz (1–200 wavenumber per cm) in a single beam-splitting operation. Additionally, it provides us with polarized radiation in interferometer active arms (mirror arms) and in the output arm of interferometer. In the conventional FTS technique, the transmittance of the specimen is calculated as the ratio of power spectra with the specimen in the sample holder and without the specimen. Initially, the specimen was placed perpendicular to the incoming beam before the beam reaches the detector. It is to be noted that the polarization of the beam is in the plane of incidence (TE mode). We termed this position as the 0° (normal incidence) incidence orientation in the TE mode. Once one set of measurement was completed at this position, the specimen was rotated to 15° with respect to normal incidence position. The experiment was then repeated for 30° and 45° specimen orientations. The specimen holder was then rotated sideway by 90° to perform TM-mode measurements. The experiment was then repeated for 0°, 15°, 30°, and 45° in the TM mode. Each curve in our results is reproducible (For each mode and angle of incidence, we repeated the measurement at least three times).

III. Results

We have measured and studied the following four Gore-Tex membrane materials:

1) RA7943—heavy-duty radome laminate membrane;
2) RA7947 w/m—radome membrane with laminate based on a thinner fabric;

TABLE I
SPECIMEN SUMMARY

Specimen	average thickness, μm	structure	measurements
RA7943	350	fabric with laminate	TM and TE modes 0, 15, 30 and 45 degrees
RA7947w/m	270	fabric with laminate	TM and TE modes 0, 15, 30 and 45 degrees
RA7947	150	fabric without laminate	TM and TE modes 0, 15, 30 and 45 degrees
non-woven membrane	1690	non-woven material, dielectric slab	Normal incidence

3) RA7947—which is effectively a fabric-only version of the RA7947 w/m;
4) prototype (no product designation) nonwoven Gore-Tex membrane.

Some specifications of these specimens are outlined in Table I.

The heavy-duty radome laminate membrane (RA7943) is woven with 210 × 410 μm threads (400 denier) with 100-μm spacing between them. One side of this membrane is covered with an additional flat layer (laminate), and the total average thickness of the material (or entire membrane combination) is 350 μm. The term "heavy duty" was used since it utilized two almost equally thick layers composed of a Gore-Tex flat layer laminated to the woven Gore-Tex fiber fabric. Fig. 2 shows a set of data for the incident wave polarized in the plane of incidence. The lower thick solid line represents the data for the normal incidence. The dashed line represents spectrum for the 15° incident angle, the thin solid line, and dotted line represent spectra for 30° and 45° incident angles, respectively. The overall trend of these curves agrees well with the theoretical transmittance spectrum (calculated using absorption coefficient and refractive index data) for the dielectric layer. A number of unusual insertion loss (valleys in transmittance) peaks were observed at 330 and 420 GHz (11 and 14 wavenumbers per cm). These valleys in transmittance could be explained by absorption lines due to the laminate. We can see that these absorption peaks (valleys in transmittance) are too sharp and moving away from each other with increasing angle of incidence. It is most likely that these peaks are related to the structural scattering of the membrane.

Transmittance spectra for the Gore-Tex heavy-duty radome laminate membrane (RA7943) for the incident wave perpendicular to the plane of incidence are presented in Fig. 3, where one can clearly see unidentified peaks. These peaks also move away from each other with increasing angle of incidence. In Figs. 2 and 3, one can see the increasing absorption valleys above 600 GHz (20 cm^{-1}) for both polarizations. As mentioned earlier, this phenomenon could emerge from increasing scattering in this frequency range. The period of the threads in the material is comparable with the radiation wavelength.

Two other specimens (RA7947 w/m and RA7947) we studied have the same woven structure, but only one specimen has the lamination on one side (RA 7947 w/m). The woven fabric consists of Teflon-based threads, 130 μm in diameter (100 denier). The distance between threads is not uniform and varies in the range of 90–254 μm with a typical average value of approximately 100 μm. The average thickness of the specimen without the laminate layer is 150 μm (RA 7947), and for the specimen with lamination is 270 μm (RA7947 w/m).

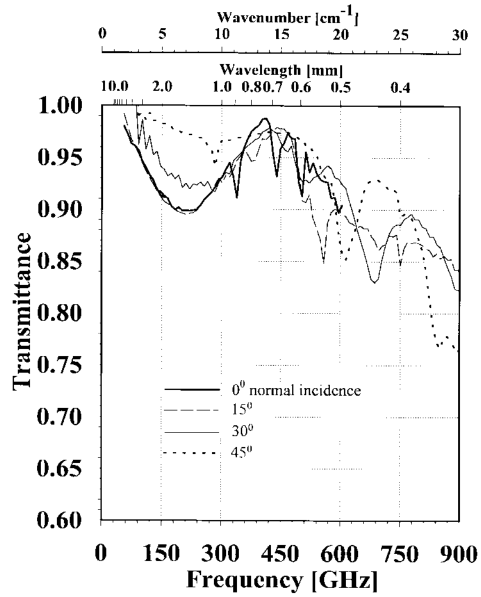

Fig. 2. Transmittance spectra for the heavy-duty radome membrane (RA7943). Spectra were obtained with the polarizing FT Spectrometer using conventional technique. Incident waves were polarized in the plane of incidence (TE polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, and 45°.

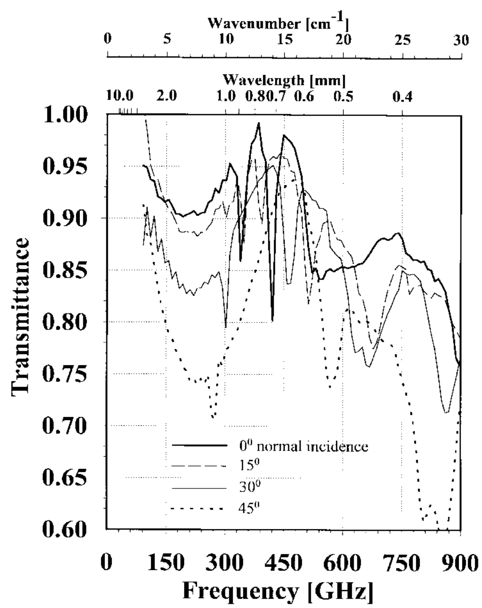

Fig. 3. Transmittance spectra for the heavy-duty radome membrane (RA7943). Spectra were obtained with the polarizing FT Spectrometer using conventional technique. Incident waves were polarized perpendicular to the plane of incidence (TM polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, 45°.

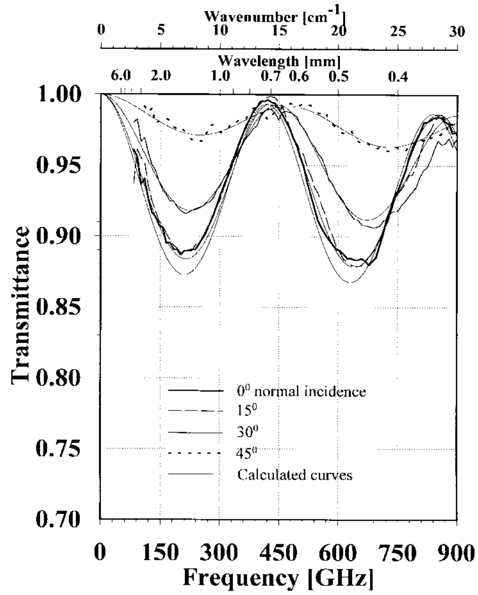

Fig. 4. Transmittance spectra for the radome membrane RA7947 w/m. This membrane is made from thinner threads than in the case of previous specimen (RA7943) threads and one side is covered with relatively thick laminate. Spectra were obtained with the polarizing FT Spectrometer using conventional technique. Incident waves were polarized in the plane of incidence (TE polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, and 45°. Thin solid lines represent results of simulation of transmittance for the plane parallel layer of the dielectric with dielectric constant $\varepsilon' = 2.09$, loss tangent $\tan\delta = 0.002$, and thickness $d = 0.0247$ cm.

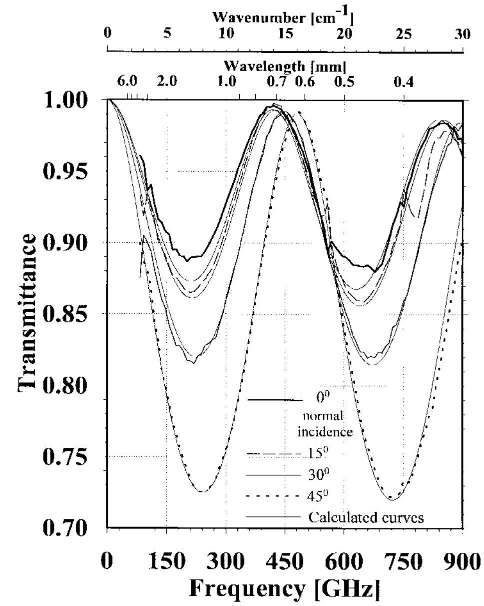

Fig. 5. Transmittance spectra for the radome membrane RA7947 w/m. Incident waves were polarized perpendicular to the plane of incidence (TM polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, and 45°. Thin solid lines represent results of simulation of transmittance for the plane parallel layer of the dielectric with dielectric constant $\varepsilon' = 2.09$, loss tangent $\tan\delta = 0.002$, and thickness $d = 0.0247$ cm.

Transmittance spectra of the specimen with lamination on one side for the incident wave polarized in the plane of incidence is shown in Fig. 4. The spectra is smooth even over 600 GHz (20 cm^{-1}). The smooth transmittance spectra (with obviously low absorption of the material over the wavenumber range of 1–30 cm^{-1} and 30–900 GHz) makes it possible to describe electromagnetic properties of the specimen with a simple model of a plane parallel slab. The transmittance for the normal incidence, and the transmittance for the broad range of angles of incidence for two polarization fit in the experimental data. The transmittance of the dielectric layer was simulated using a well-known formula [6] for transmission of a dielectric layer. The dielectric constant (the real part), loss tangent, and thickness of the layer have been used as variables for the fitting. It is unusual to use the thickness as a variable, but in this case the specimen has a complicated structure that consists of the following three variables:

1) Teflon threads;
2) laminate;
3) air.

A best fit to the complete set of experimental data over the entire frequency range was achieved with the following specifications of the dielectric layer: the dielectric constant of approximately 2.09, the loss tangent value of approximately 0.002 rad, and the thickness of approximately 247 μm. The results of this simulation are shown in Figs. 4 and 5, denoted by thin lines. The agreement between the measured and the simulated data is excellent, with the exception of the level of minima of transmittance for 0° and 15°. However, this disagreement does not exceed 3%. The frequency shift of maxima and minima with a changing angle of incidence is the same for both sets of data. The loss tangent value in the simulation was kept constant over the entire frequency range.

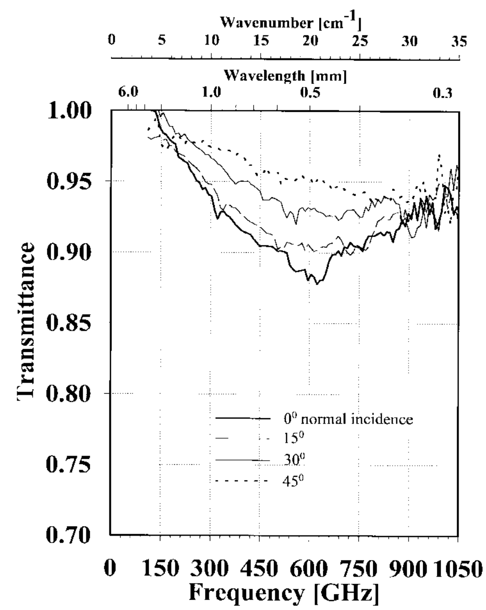

Fig. 6. Transmittance spectra for the radome membrane RA7947. Spectra were obtained with the polarizing FT Spectrometer using conventional technique. Incident waves were polarized in the plane of incidence (TE polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, and 45°.

Figs. 6 and 7 present transmittance spectra of the specimen with a very thin (compared to the thickness of the threads) laminate for different angles and for two polariza-

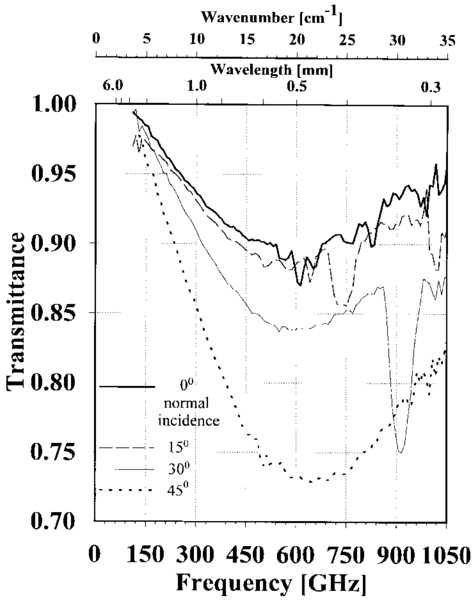

Fig. 7. Transmittance spectra for the radome membrane RA7947. Spectra were obtained with the polarizing FTS using conventional technique. Incident waves were polarized perpendicular to the plane of incidence (TM polarization). Data for the following angles of incidence are shown: 0° (normal incidence), 15°, 30°, and 45°.

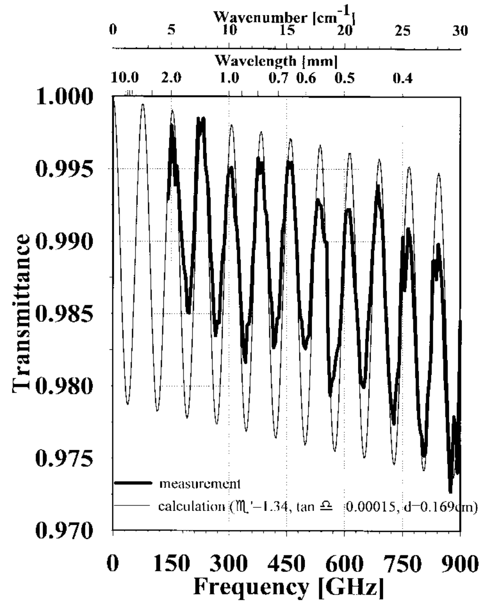

Fig. 8. Transmittance spectra for the prototype nonwoven (no product designation) Gore-Tex membrane manufactured by W. L. Gore and Associates, Inc. Spectra were obtained with the polarizing FT Spectrometer (with conventional FTS technique). The thick solid line represent measured data for the normal incidence, and the thin solid line is the result of the simulation for the dielectric layer with thickness 0.169 cm, dielectric constant $\varepsilon' = 1.34$, and loss tangent $(\tan\delta) = 0.000\,15$ rad.

tions (TE and TM modes) of the incident waves. Spectra were measured over the wavenumber range of 90–1050 GHz (3–35 cm^{-1}). One can see that spectra are smooth for wavenumbers up to 540 GHz (18 cm^{-1}) and become less smooth in the 540–1050-GHz band (18–35 wavenumber per centimeter). The scattering increases the insertion loss for frequencies over 540 GHz (18 cm^{-1}). These transmittance spectra were modeled with the transmission of a single plane parallel dielectric layer. However, it was not possible to achieve the reasonable agreement for all incident angles and for all frequencies with a reasonable precision at the same time.

In our data, one can see peaks of the insertion loss between 600–900 GHz (20 and 30 cm^{-1}) for both polarizations of the incident wave. For the normal incidence, the peak occurs at 600 GHz (20 cm^{-1}) and is very weak. At an angle of incidence of 15°, this peak becomes broader and occurs around 750 GHz (25 cm^{-1}). At the angle of incidence of 30°, this peak becomes strongest and moves to 900 GHz (30 cm^{-1}). Most likely, the same peak can be observed at 45° incident angle, but beyond the range of this measurement. The frequency locations of these peaks are the same for both polarizations. These peaks can originate from the wave scattering. At high frequencies the diffraction on the threads is capable of producing strong sidelobes which extract some power from the main beam.

W. L. Gore and Associates, Inc. developed a nonwoven material based on Teflon. With a special treatment, the company produces microporous material. One can say that this new material consists of microscopic air bubbles with Teflon between them. The material became leather-like, soft, and strong in its microporous treatment. The study of dielectric properties of Gore-Tex nonwoven microporous material is important from two points of view, in that: 1) it can be suitable as a radome membrane all by itself and 2) woven-membrane threads can be made of pure microporous material.

The transmittance spectrum of the Gore-Tex nonwoven microporous material is presented in Fig. 8. It shows remarkably low absorption characteristics and exceptionally low refractive index values of the material in this spectral region. The thickness of the sample used in this measurement was 1.69 mm. We have made some calculation to predict the transmission behavior of the nonwoven material. Simulated (calculated) results for the specimen are shown with the thin solid line. The best fit to the experimental data was achieved with dielectric constant value of 1.39 and loss tangent value of 0.000 15. The direct measurements of dielectric properties with dispersive FT spectrometric technique (when the specimen is placed in one of the active mirror arms of the interferometer) did not produce acceptable absorption data for this nonwoven specimen at this time because the thickness of the available specimen was only 1.69 mm, its refractive index value is very low (refractive index $n = 1.157$), and it has a very low absorption. It is necessary to stack together many layers of such specimen to form a thick layer so that the overall pure transmission loss through the specimen is large enough compared to the pure reflection loss from the front and rear surface of the stack. The method provides reliable data in a direct dielectric measurement utilizing dispersive FTS. The gap between layers is much smaller than the smallest wavelength (300 μm) in the range; waves then travel through the stack without suffering any reflection from interfaces. For the interferometer measurement, this stacked structure will be as good as a thick solid sample. The measurement of an angular dependency of the transmittance spectrum could give a better precision of fitted data, but available nonwoven specimens did not have enough surface area. This material by itself can serve as a very good radome membrane. The low-loss tangent value of nonwoven membrane will allow one to significantly increase the thickness of the walls if one desires to improve the mechanical strength further. The electromagnetic performance would not degrade too much even with two or three times the presently available thickness.

IV. CONCLUSION

In this paper and for the first time, accurate transmittance data over extended frequencies in the millimeter- and submillimeter-wave range (1–33 cm^{-1}, 30–1000 GHz) are presented for a variety of new Gore-Tex woven and nonwoven radome membranes. The transmittance of woven radome membranes has been studied for different incidence angles of the incident wave over frequencies from about 40 to 1050 GHz for both polarizations (TE and TM modes). It has been shown that the transmission of some woven membranes with a thick laminate and thin threads of the fabric (Teflon-based material) can be successfully modeled over the frequency range of 0–1000 GHz (0–33 wavenumber cm^{-1}) with a simple model that substitutes the entire woven membrane with a dielectric plane parallel layer. The combination of thicker laminate and thin threads of the fabric essentially makes the entire woven membrane (with laminate) to posses characteristics equivalent to pure laminate only electromagnetic behavior. However, the thinner threads would provide enough mechanical strength to the combination. The description of electromagnetic properties of woven membranes with thicker Teflon threads and/or with thin laminate would require a more sophisticated model, especially at higher frequencies. Above 600 GHz, woven membranes show narrow intense bands in their transmittance spectra when measured at different angle of incidence. The locations of these bands move in frequency with an increasing angle of incidence, which leads us to conclude that this phenomena is due to the electromagnetic-wave scattering in the woven structure of the membrane. This effect in case of membranes with thinner threads and thick laminate is smoothed and there is no scattering observed.

The study of the nonwoven Teflon-based Gore-Tex (microporous) material showed its excellent electromagnetic performance as a radome membrane material for radio telescopes applications in the frequency range of 0–1000 GHz. It is also possible that it can be successfully used for frequencies beyond 1000 GHz. This material also possesses satisfactory mechanical properties. We consider this nonwoven Gore-Tex membrane to be the best commercially available material for radome membrane applications. The nonwoven membrane has a very low-loss tangent ($\tan \delta$) value and its refractive index value is also very low (1.157).

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