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 non-woven radome membranes with various diameter of threads of the fabric and thickness of the laminate has been studied as a continuous function of frequency over the range 30-1000 GHz by utilizing Fourier Transform Spectroscopy. These woven and non-woven radome membranes were manufactured by W. L. Gore and Associates and known as "Gore-Tex". It is for the first time the transmittance has been measured with various angles of incidence of the incident wave. Strong diffractive scattering has been found above the frequency with wavelength comparable with period of the fabrics (240 GHz for the standard Gore-Tex product). Gore-Tex woven membrane materials are suitable for radome applications up to 1000 GHz.

INTRODUCTION

Large microwave and millimeter - wave antenna systems have been used for more then twenty years by radioastronomers. These systems are normally enclosed in radomes. For radioastronomy applications it is desirable that radomes are usable over a broad frequency band. Nowadays the receiver technology has improved significantly at higher millimeter wave 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 metal-space frame structure. This structure consist of metal thin frames and dielectric membranes tightened over them. Metal-space frame design allows to use thin dielectric materials. The use of thin dielectric membranes is a great advantage. Fistly, 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 inert to most atmosphere chemicals and be durable that makes Teflon based materials very attractive. To make membranes thin and to have good mechanical strength at the same time in woven membrane materials are desired in radome design. W. L. Gore and Associates, Inc., developed a Teflon based material which is known as "Gore-Tex". The commonly known "Gore-Tex" material is a fabric, threads of which are made from Teflon and a plastic layer laminated on one side of the fabric. However, the periodical structure of these materials raises the concern about possible diffraction 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 deteriation 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 produce sufficient precision in such calculations because of the mismatch of reflection and transmission in the weave formation. Thus electromagnetic properties of these materials should be measured experimentally (directly) in order to use this data in radome design and to create an electromagnetic model for these materials. This paper presents experimental results obtained using the Fourier transform spectrometers (FTS). The Fourier Transform spectroscopy is the only technique which allows to perform such measurements over the entire required frequency band (as a continuous function of frequency) with sufficient precision [1 - 4]. We studied Teflon based woven membranes manufactured by W. L. Gore and Associates, Inc.

MEASUREMENT TECHNIQUES

Data presented in this paper was measured with a specially constructed Fourier Transform spectrometer. The Fourier transform spectrometry (FTS) is a well known 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 methods [1 - 4]. The FTS methods we developed are only techniques those provide continuous broad-band (over the entire frequency region) measurements of real and imaginary parts of dielectric permittivity, loss tangent and insertion loss with high precision. In this work the transmittance of membranes was studied as a function of angle

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of incidence. A pair of free standing wire grid polarizers was used for beam divison in our Fourier transform spectrometers. At the millimeter wave region the spectral energy loss due to the channel behavior of a myler beam splitter can be avoided in a polarizing interferometric configuration. The ray diagram of our polarizing Fourier tansform interferometer is shown in Figure 1. For transmission measurements the conventional Fourier transform interferometric technique was employed in which the specimen was placed in the detector arm of the interferometer in front of the detector, position A in the diagram in Figure 1. A specially designed sample holder was installed between the interferometer and the detector. This sample holder allows 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. A highly sensitive liquid helium cooled Indium Antimonide Rollin detector was used for detection of energy. This detector allows us to perform reliable measurements in the 1 - 34 cm^{-1} range (30 - 1,020 GHz). One wire grid polarizer 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 pass band filter allowing the interferometer to work from 30 GHz to 6,000 GHz (1 - 200 wavenumber per cm) in a single beam splitting operation. Additially 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.

RESULTS

We have studied three types of "Gore-Tex" specimens: the heavy duty radome laminate membrane (specimen NR7943), the radome membrane with thinner threads and relatively thicker laminate (NR7947 w/m) and the membrane with similar threads as NR7943 w/m but with no laminate layer (NR7947).

The heavy duty radome laminate membrane is woven with 210 ×410 μm threads with 100 μm spacing between them. One side of this membrane is covered with an additional membrane (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 equally thick layers composed of "Gore-Tex" membrane laminated to the woven "Gore-Tex" fiber fabric. Figure 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 15^0 incident angle, the thin solid line and dotted line represent spectra for 30^0 and 45^0 incident angles respectively. The overall trend of these curves agrees with the theoretical transmittance (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 11 and 14 wavenumbers per cm (330 and 420 GHz). These valleys in transmittance could be explained by absorption lines in 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.

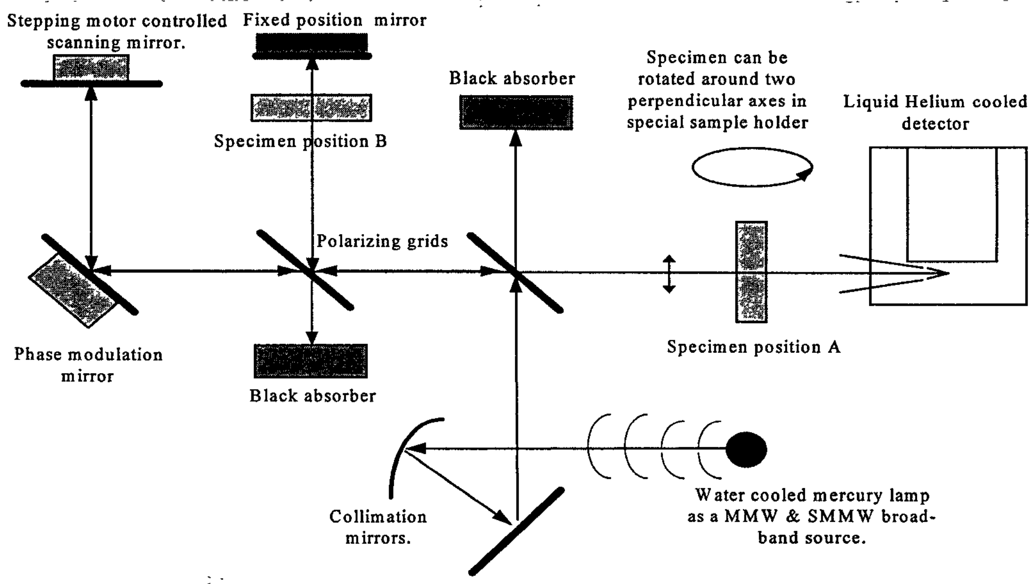

Figure 1. The ray diagram of the two beam interferometer (used for millimeter wave Fourier transform spectroscopy) shown in its polarization mode configuration. A pair of wire grid polarizes, polarizes the incident radiation, splits the beam, recombine beams and analyze, The specimen can be placed at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

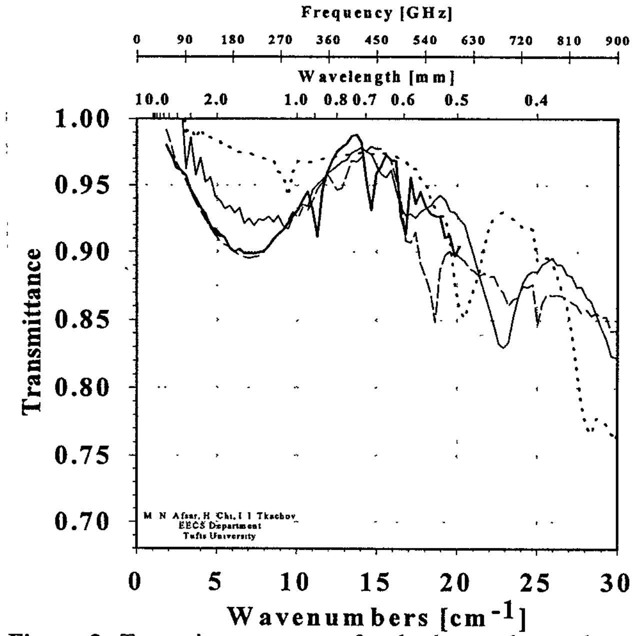

Figure 2. Transmittance spectra for the heavy duty radome membrane (NR7943). Spectra were obtained with the polarizing Fourier Transform Spectrometer with conventional technique. Incidend waves were polarized in the plane of incidence. Data for the following angles of incidence are shown :

———— 0^0 normal incidence	———— 30^0
------------ 15^0	.... 45^0

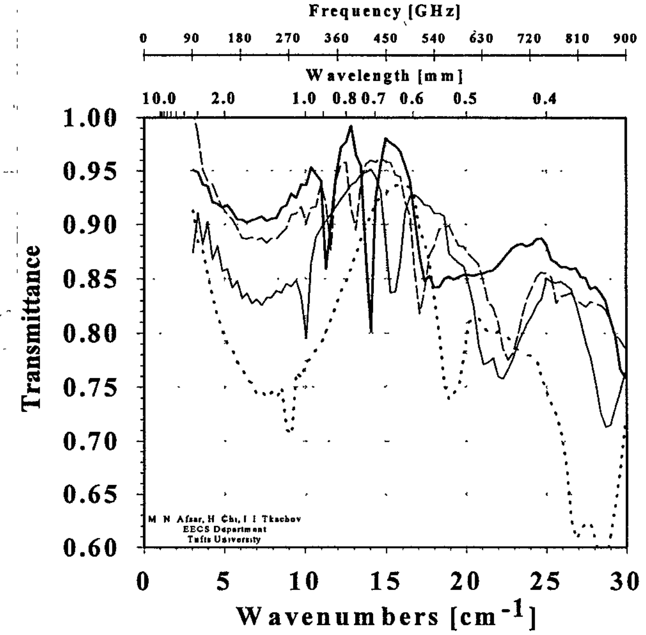

Figure 3. Transmittance spectra for the heavy duty radome membrane (NR7943). Spectra were obtained with the polarizing Fourier Transform Spectrometer with conventional technique. Incident waves were polarized perpendicular the plane of incidence. Data for the following angles of incidence are shown :

———— 0^0 normal incidence	———— 30^0
------------ 15^0	.... 45^0

Transmittance spectra for the "Gore-Tex" heavy duty radome laminate membrane (NR7943) for the incident wave perpendicular to the plane of incidence are presented in Figure 3. One can see unidentified peaks clearly in this Figure. These peaks also move away from each other with increasing angle of incidence. In Figures 2 and 3 one can see increasing absorption valleys above 600 GHz(20 cm^{-1}) for both polarizations. As mentioned earlier, this phenomenon could emerge from increasing scattering in this range. The period of the threads in the material is comparable with the radiation wavelength.

Two other specimens we studied have the same woven structure, but only one specimen has the lamination on one side (NR 7947 w/m). The woven fabric consists of Teflon based threads 130 μm in diameter. The distance between threads is not uniform and varies in the range of 90 - 254 μm with a typical average value of about 100 μm. The average thickness of the specimen without the laminate layer is 150 μm (NR 7947), and for the specimen with lamination is 270 μm (NR7947 w/m). The transmittance of the dielectric layer was simulated using well known formula [5] for transmission of a dielectric layer.

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

The transmittance spectrum of the "Gore-Tex" non-woven microporous material is presented in Figure 4. It shows the 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 1.686 mm. We have made some calculation to predict the transmission behavior of the non-woven 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 0.00015. The direct measurements of dielectric properties with dispersive Fourier transform 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 non-woven specimen 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

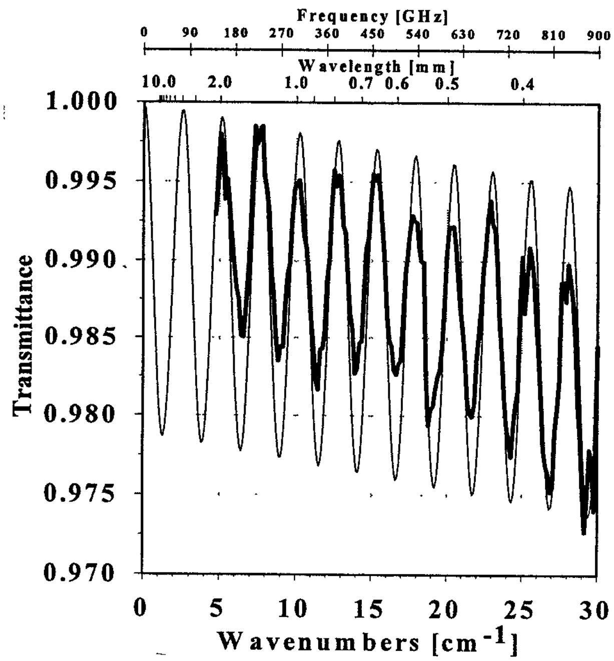

Figure 4. Transmittance spectra for the microporous non-woven Teflon manufactured by W.L.Gore and Associates, Inc., Spectra were obtained with the polarizing Fourier Transform Spectrometer (with conventional FTS technique). Thick solid line represent measured data for the normal incidence, and thin solid line is the result of the simulation for the dielectric layer with thickness 0.169cm, dielectric constant $\varepsilon' = 1.34$ and loss tangent ($\tan\delta$) = 0.00015 radians

method provides reliable data in a direct dielectric measurement utilizing dispersive Fourier transform spectroscopy. 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 non-woven 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 non-woven membrane will allow to increase the thickness of the walls significantly 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.

CONCLUSIONS

In this work it is for the first time accurate transmittance data over extended frequencies in the millimeter and submillimeter wave range (1 - 33cm^{-1}, 30 - 1000 GHz) are presented for different types of "Gore-Tex" woven and non-woven radome membranes. The transmittance of woven radome membranes has been studied for different incidence angles of the incident wave over frequencies from about 40 GHz to 1,050 GHz. It has been shown that the transmission of some woven membranes with a thick laminate and thin threads (Teflon based material) can be successfully modeled over the wavenumber range 0 - 33 cm^{-1} (0 - 1000 GHz in frequency) with a simple model that substitutes the entire woven membrane with a dielectric plane parallel layer. The combination of thicker laminate and thin threads essentially makes the entire woven membrane (with laminate) to posses characteristics equivalent to pure laminate only electromagnetic behavior. The thinner threads however 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 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 thiner threads and thick laminate is smoothed and there is no scattering was observed.

The study of the non-woven Teflon based Gore-Tex (micro-porous) material showed its excellent electromagnetic performance as a radome membrane material for radio telescopes applications in the range 0 - 1,000 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 non-woven Gore-Tex membrane to be the best commercially available material for radome membrane applications. The non-woven membrane has a very low loss tangent (tan δ) value and its refractive index value is very low(1.157).

REFERENCES

[1] M. N. Afsar, "Dielectric Measurements of Millimeter-Wave Materials", IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No-12, pp. 1598 - 1608, December 1984

[2] M. N. Afsar, "Precision Millimeter Wave Dielectric Measurements of Bire-fringent Crystalline Sapphire and Ceramic Alumina", IEEE Transactions on Instrumentation and Measurements, Vol. IM-36, No.-2, pp. 530- 536, June 1977

[3] M. N. Afsar, "Precision Millimeter Wave Measurements of Complex Refractive Index, Complex Dielectric Permittivity and Loss tangent of Common Polymers", IEEE Transactions on Instrumentation and Measurements, Vol. IM-36, No.-2, pp. 554 - 561, June 1977

[4] M. N. Afsar, Hua Chi, Igor Tkachov, "Milimeter and submillimeter wave transmission and dielectric properties of radome materials" in *Millimeter and Submillimeter Waves II*, Edit. Mohammed N. Afsar, SPIE Proceedings Vol.2558, 1995, pages 73 - 85

[5] G. .P. Tricoles, "Radome Electromagnetic Design", in *Antenna Handbook*, Van Nostrand Reinhold Company, Inc,. New-York, edit. Y.T. Lo and S.W. Lee, Chapter 31, 1988