Spectroscopic Measurements of Optical Elements For Submillimeter Receivers

J. Kawamura, S. Paine, and D. C. Papa
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, Massachusetts 02138

Abstract

As submillimeter receivers improve in performance, more attention needs to be given to the design of lenses and windows, because input and coupling losses are responsible for an increasingly larger fraction of the total system noise. In order to optimize the designs, accurate measurements of optical and thermal contraction properties are needed. We discuss techniques of dispersive Fourier transform spectroscopy by which optical constants, thermal contraction coefficients, and surface reflectivities may be measured. Measurements of the optical constants of TPX, Teflon (PTFE), polyethylene, and Teflon-AF, a new material, are presented over the frequency range 0.3 to 2.5 THz. Thermal contraction properties for Teflon are presented. Reflection measurements are presented for a quartz window with a machined matching layer; properties of wire-meshes and wire-grids are also measured.

1. Introduction

Receiver noise temperatures for receivers under 800 GHz are rapidly nearing the noise limit predicted by the quantum theory of mixing. For example, in the 450 GHz SIS receiver developed by Tong et al. [1], the receiver noise temperature is 80 K (DSB). The input losses contribute 50 K to the total noise, the multiplied noise from the IF chain 12 K, and the mixer noise 18 K. The greatest opportunity for further improvements in the noise performance is thus in the receiver optics. The designs of windows, filters, diplexers and lenses may be improved by carefully characterizing each component. Furthermore, as development of higher-frequency receivers progresses, it is necessary to characterize new materials and components for their possible use.

As these new low-noise receivers come on-line at astronomical facilities, the effort will enlarge to improving the system noise rather than just the receiver noise. A receiver which gives good performance in the laboratory will not necessarily operate efficiently when it is coupled to a telescope. If there is a flaw in the lens design, for example, the receiver will not properly illuminate the telescope. For lenses operated at low temperature, careful attention must be given to thermal contractions and the change in optical properties of the lens material. Unfortunately, reliable design data is not always available. This is especially true for polymers, which have properties that vary depending on composition and manufacturing process. In the case of wire-grids or wire-meshes, theoretically modeling their behavior cannot provide the precision necessary in practice.

Our effort has been to characterize optical elements using a Fourier transform spectrometer (FTS). We use dispersive Fourier transform spectrometry to measure the complex refractive index and the thermal contraction of materials. Surface reflectivity is measured for an anti-reflection scheme; wire-grids and wire-meshes are directly characterized.

2. Experimental setup

The FTS is a Martin-Puplett interferometer, employing free-standing wire grids as polarizers. The polarizers are made from gold-plated tungsten wires, 25 µm in diameter and spaced 75 µm apart. The instrument's useful frequency range is from 300 GHz to 2.6 THz, with a minimum unapodized frequency resolution of 1 GHz. The radiation source is a thermal glower, and its power fall-off at low frequencies determines the lower end of the spectral coverage. The upper end of the frequency coverage is determined by the effectiveness of the wire-grid polarizer and the response of the silicon bolometer. The entire FTS is enclosed in a vacuum chamber to allow cryogenically-cooled samples to be tested and to eliminate atmospheric absorption. For component and materials measurements, the sample holder accommodates plane-parallel components with 23 mm diameter and thickness up to 10 mm. The sample holder is mounted on a continuous-flow liquid helium-cooled cold head, and the sample can be made to vary in temperature from 4 K to room-temperature. There are two identical apertures in the sample holder, and a bellows attachment quickly allows either aperture to intercept the beam.

3. Materials measurements

Material measurements are performed using dispersive Fourier transform spectroscopy (DFTS) [2]. A sample inserted into the optical path of one of the arms of the interferometer introduces a frequency-dependent complex factor, called the complex insertion loss, to the electric field of the beam in one of the arms. This factor is merely the product of all relevant Fresnel terms and propagation constants through the sample. By isolating the complex insertion loss, it is possible to solve for the optical constants.

Figures 1–4 present our materials measurements. The values for the sample thicknesses, which are necessary in the calculation of the complex refractive index, are determined interferometrically using the technique described in [3]. Figure 1 shows the room temperature complex refractive index spectrum for TPX, a semi-transparent plastic commonly used for millimeter-wave work. Figure 2 shows the measurements on high density polyethylene at room temperature. Figure 3 shows the refractive index spectrum of Teflon-AF, a new material [4]. The interesting property of this optically clear material is that it is available in soluble form, and may be used to coat high refractive index materials, particularly quartz, for excellent anti-reflection. However, Teflon-AF becomes rather lossy near 1 THz, which limits its use. The room temperature and 70 K measurements on a sample of Teflon are presented in Figure 4. One striking feature in the cold spectrum is the lossy bands above 1 THz. A useful result of our measurements is that they demonstrate a clear advantage in cooling Teflon windows or lenses under 900 GHz.

4. Birefringence and Anisotropic Thermal Contraction of Extruded Teflon

Teflon optics are frequently fabricated from sections of extruded rod stock. The

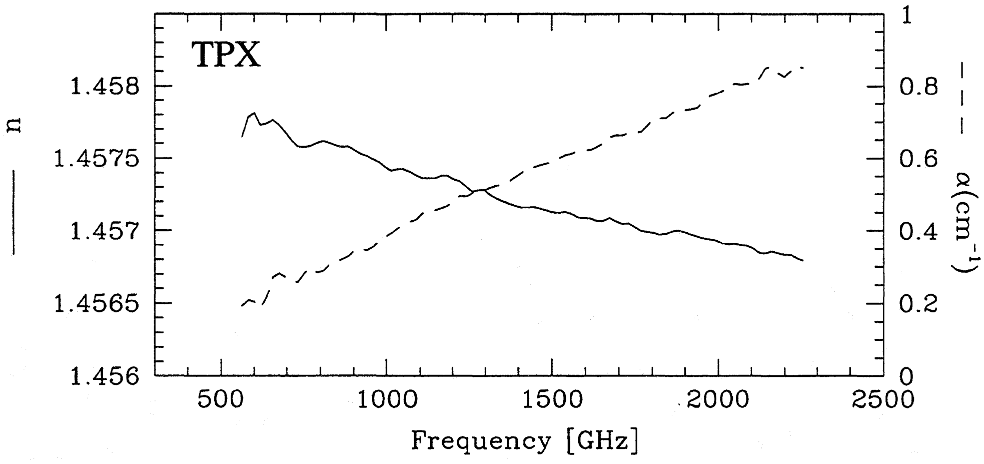

Figure 1. Refractive index and absorption coefficient for TPX at 295 K.

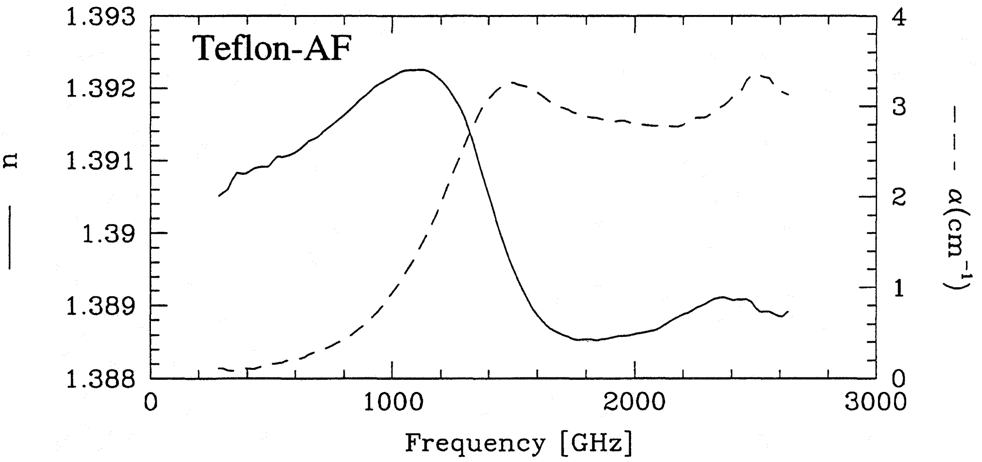

Figure 2. Refractive index and absorption coefficient for Teflon-AF at 295 K.

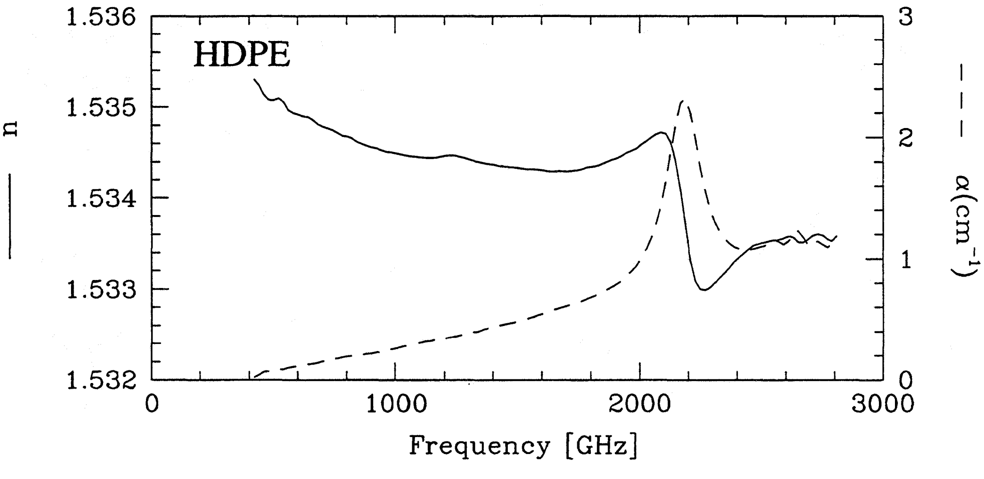

Figure 3. Refractive index and absorption coefficient for high-density polyethylene at 295 K.

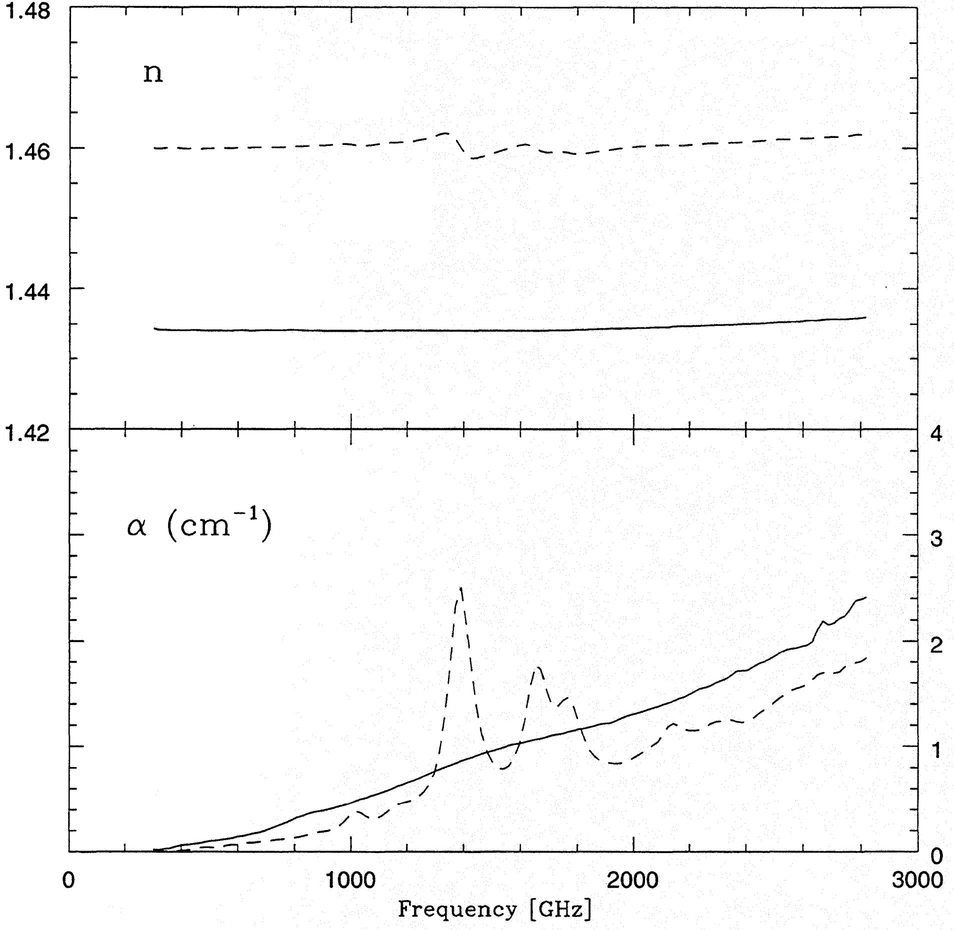

Figure 4. Refractive index and absorption coefficient for Teflon. The solid line is room temperature, and the dashed line is 70K.

extrusion process introduces an orientation in the material which gives rise to birefringence and anisotropic thermal contraction properties. Measurements were made on a sample of Teflon with polarization perpendicular and parallel to the extrusion axis. For the parallel polarization measurements a split sample consisting of two halves, one half rotated 90° with respect to the other, was used. Measurements thus yielded an average of the perpendicular- and parallel-axis properties. (The measurements in Figure 4 used a sample with the polarization perpendicular to the extrusion axis.)

Figure 5 shows the ordinary and extraordinary refractive indices at 70 K and room temperature, and the corresponding power absorption coefficients. The thicknesses are also determined in the measurements, thus it is possible to calculate the thermal contraction. For the sample with the polarization perpendicular to the extrusion axis, the thermal contraction between room temperature and 80 K was 2.63(4)%, and for the other sample, 0.8(1)%. For a lens, this means that the effect of thermal contraction is to increase the radii of curvature of the lens surfaces by about 1%. Nevertheless, the increase in refractive index dominates, resulting in a net 5% reduction in focal length on cooling.

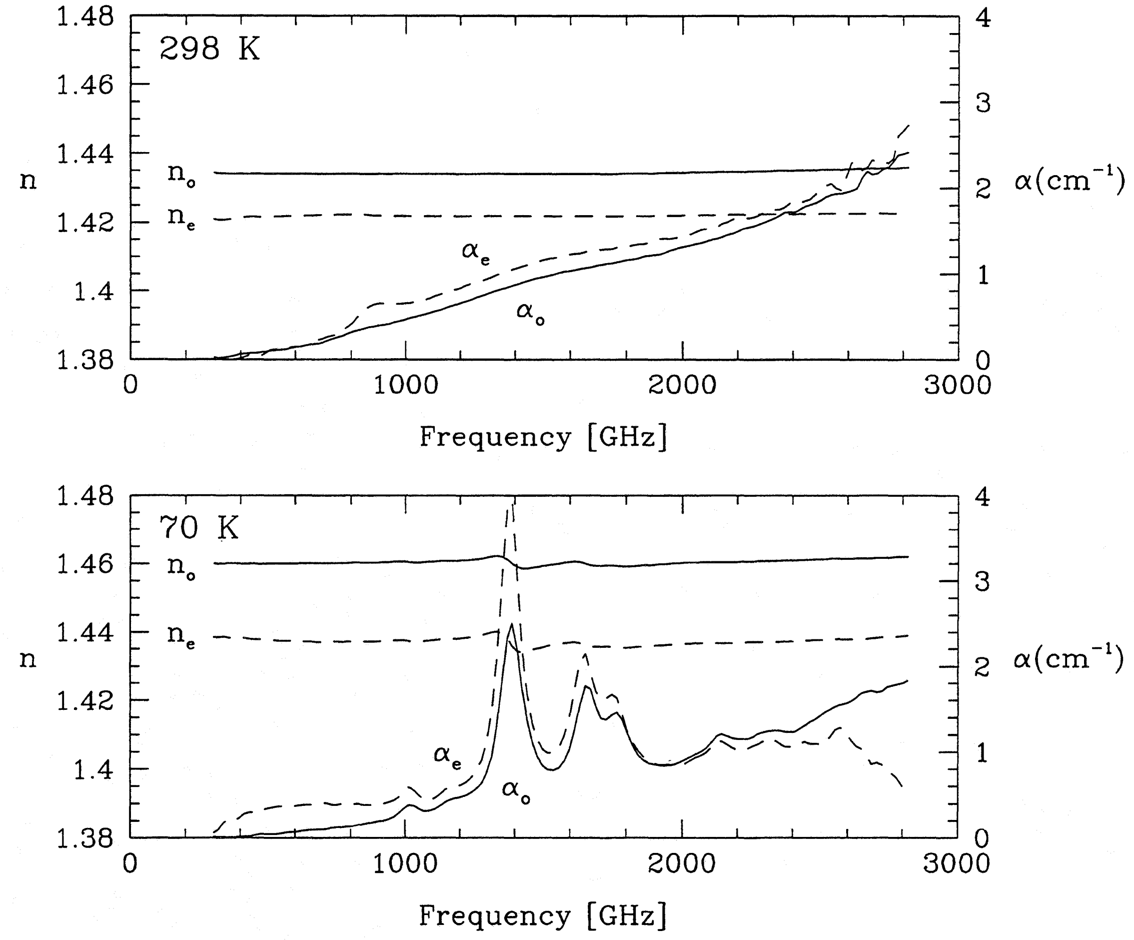

Figure 5. Refractive index and absorption coefficient for Teflon. The top panel shows measurements at room temperature, and the bottom panel, at 70 K. The extraordinary index is computed by assuming that the measurements on the split sample give an average of the o- and e- complex refractive indices. Therefore, the values are probably only approximate.

5. Reflectivity measurements

We are considering an anti-reflection scheme in which two orthogonal sets of grooves are machined into a quarter-wave plate with a dicing saw. This is analogous to grooves machined into lenses. To evaluate the technique, grooves were machined into a small sample of fused quartz. A dispersive measurement was used to measure the effectiveness the machined matching layer by measuring the Fresnel reflection coefficient over a large bandwidth. The groove width is determined by the width of the cut, and the pitch determines the effective refractive index of the matching layer. Figure 6 presents our measurement of the relative reflectivity of a piece of quartz with a machined matching layer. The solid line represents the measurement; the dashed line is the design.

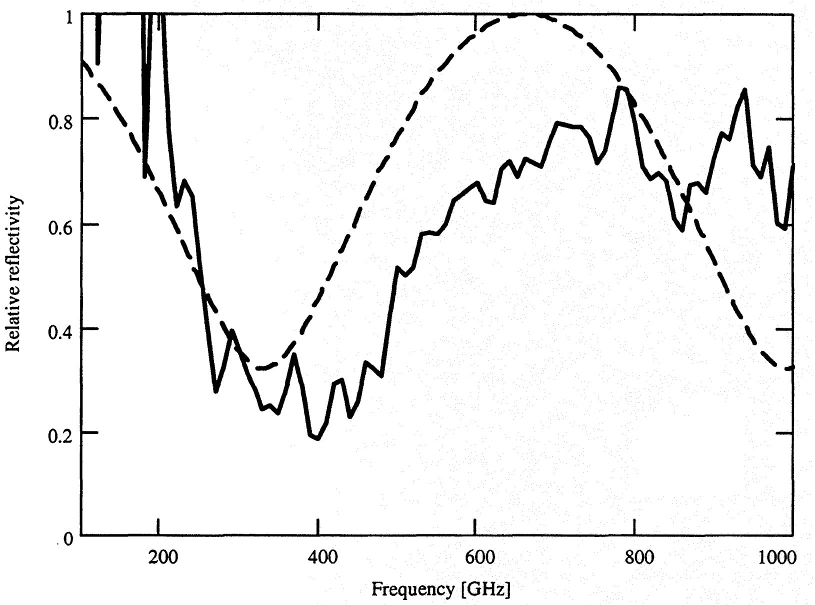

Figure 6. The surface reflectivity of a sample of fused quartz with machined matching layer. The vertical axis is measured relative to the reflectivity of quartz. The solid line is the FTS measurement, and the dashed line is calculated from the as-machined mechanical dimensions of the matching layer.

6. Measurements of a Wire-grid, Wire-meshes and a Fabry-Perot interferometer

The FTS has been used to directly measure the performance of wire-grids and wire-meshes. The wire-grid measurement is shown in Figure 7. The grid under test was made from gold-plated tungsten wires, 25 μm in diameter and 75 μm in pitch. Since the FTS itself is composed of wire-grids, the measurement of the grid has to be considered as a lower limit of its performance. (Because the FTS is a polarizing interferometer, this measurement was not dispersive.)

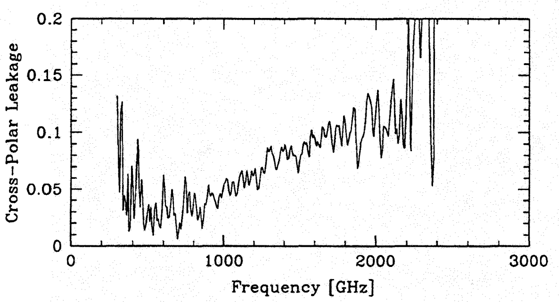

Figure 7. Performance of a wire-grid polarizer. The grid wire was 25 μm diameter and 75 μm pitch.

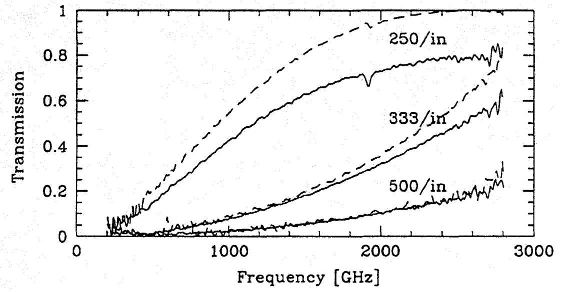

Figure 8. Performance of wire meshes of varying pitch. Solid lines are transmission measurements; dashed lines are (cos θ)^2.

A set of wire meshes [5] were also evaluated, and the measurements are shown in Figure 8. The meshes were mounted in a 25 mm holder and evaluated dispersively. The dispersive measurement allows the simultaneous determination of the transmission and phase shift introduced by the wire-mesh. For a lossless mesh, the transmission and phase shift are related by $T = (\cos\theta)^2$, where θ is the phase shift, and the figure shows reasonable agreement to this relation.

If two wire meshes are closely adjoined parallel to each other, the configuration is a Fabry-Perot cavity. The measurements are shown in Figure 9. It is possible to quantify the finesse from the measurements.

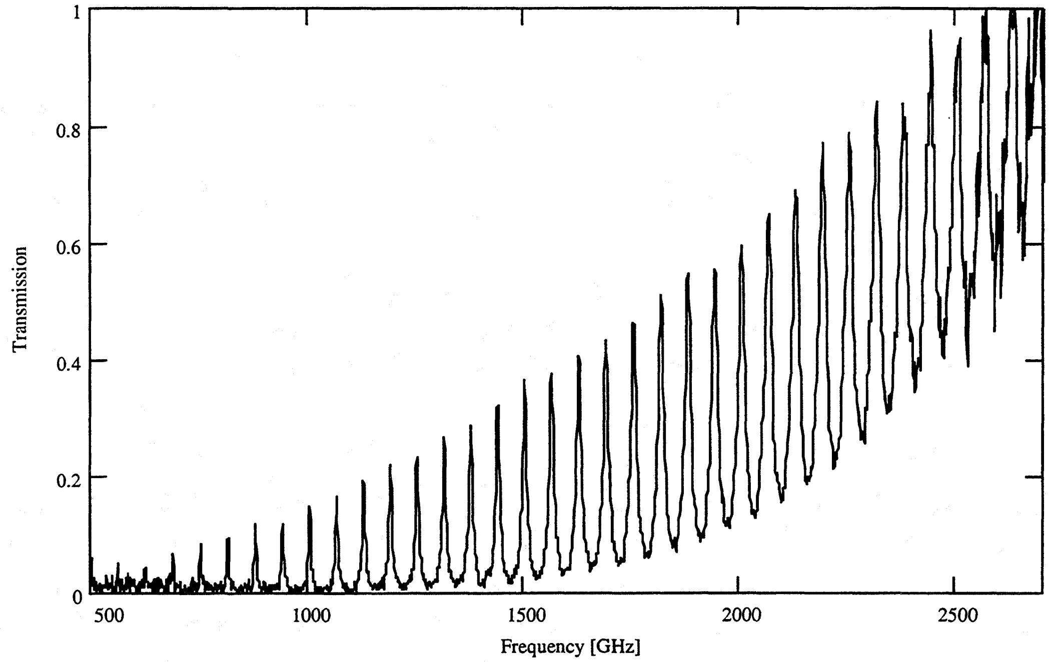

Figure 9. Transmission through a Fabry-Perot etalon.

7. Conclusion

We have used the FTS to characterize optical components and materials at submillimeter wavelengths. In addition to its importance as design data, the materials measurements reveal some interesting properties of Teflon.

8. References

[1] C.-Y. E. Tong, R. Blundell, B. Bumble, J. A. Stern, & H. G. LeDuc, *Appl. Phys. Lett.* **67** 1304 (1995)

[2] J. R. Birch & T. J. Parker, *Infrared and Millimeter Waves*, K. J. Button, ed., **2** (Instrumentation) New York: Academic Press (1979)

[3] S. Paine & J. Kawamura, in preparation (1996)

[4] Teflon-AF is available in solid form or as a solution from Du Pont Polymers, Wilmington, Delaware.

[5] Manufactured by Buck-Mears St. Paul, St. Paul, Minnesota