SPECTROSCOPIC MEASUREMENTS OF OPTICAL COMPONENTS AROUND 1 TERAHERTZ

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ABSTRACT

Recent advances in submillimeter SIS receivers necessitate the use of very-low-loss components in order to achieve their theoretical performance. Additionally, as HEB and thermal bolometer instruments become more sensitive, better infrared blocking filters are needed. Often these optical elements will be cooled to 4K, where their properties are less well measured. We present measurements of the effectiveness of dielectric antireflection coatings on quartz at 4K over the frequency range 0.3 to 1.6 THz. Absorption coefficients for materials used as infrared blocks are presented. Studies of the transmission of other optical components are discussed.

1. INTRODUCTION

In the design of optical systems for submillimeter wavelengths there is a variety of materials available with properties suitable for windows, filters, infrared blocks, and lenses. Advanced SIS receivers are achieving nearly quantum-limited performance: at 492GHz, Kooi et. al.[1] measured a receiver total noise temperature of 74K, of which 52K stems from optical losses. Modern bolometric instruments such as SHARC[2] have a total optical efficiency of only $\sim 30\%$, far from ideal. Clearly, choosing materials with the optimum dielectric constants, lowest loss, and best cryogenic performance is critical.

With this in mind, we have characterized optical elements using a Fourier Transform Spectrometer (FTS). The instrument was initially developed to test the response of SIS junctions[3], and consists of a Michelson interferometer with a movable mirror on a 2 meter translation stage as shown in figure 1. A glowing coil is used as a source, with an optical chopper modulating the beam between the source and a 77K blackbody at roughly 150 Hz. The source illuminates an off-axis paraboloid with an effective $f/2.5$ beam, where it is collimated in a 10" diameter beam. A Mylar beamsplitter separates and recombines the two beams, which are focused onto a detector. The entire optics setup is contained in an acrylic dry box which is purged using nitrogen gas to a relative humidity of $< 2\%$, reducing the contribution from the strong absorption features of water in the submillimeter. The moving stage is actively controlled to keep the two beams coincident over the long path length. A Macintosh computer running LabVIEW is used both to control the FTS and to collect and reduce the data.

The instrument used in this work was a 2K bolometer with a Winston cone providing a $f/4$ beam looking into the FTS. Also at 2K is a filter wheel with spaces for several materials under examination. An off-axis paraboloid (not shown in figure 1) is used to collimate the FTS beam into the dewar, providing an image of the collimated portion of the FTS inside the dewar at the position of the samples in the filter wheel. Because of the collimation, variations in the beam as a result of increasing optical path in the samples is not a problem. In addition to the samples, there is a clear aperture which

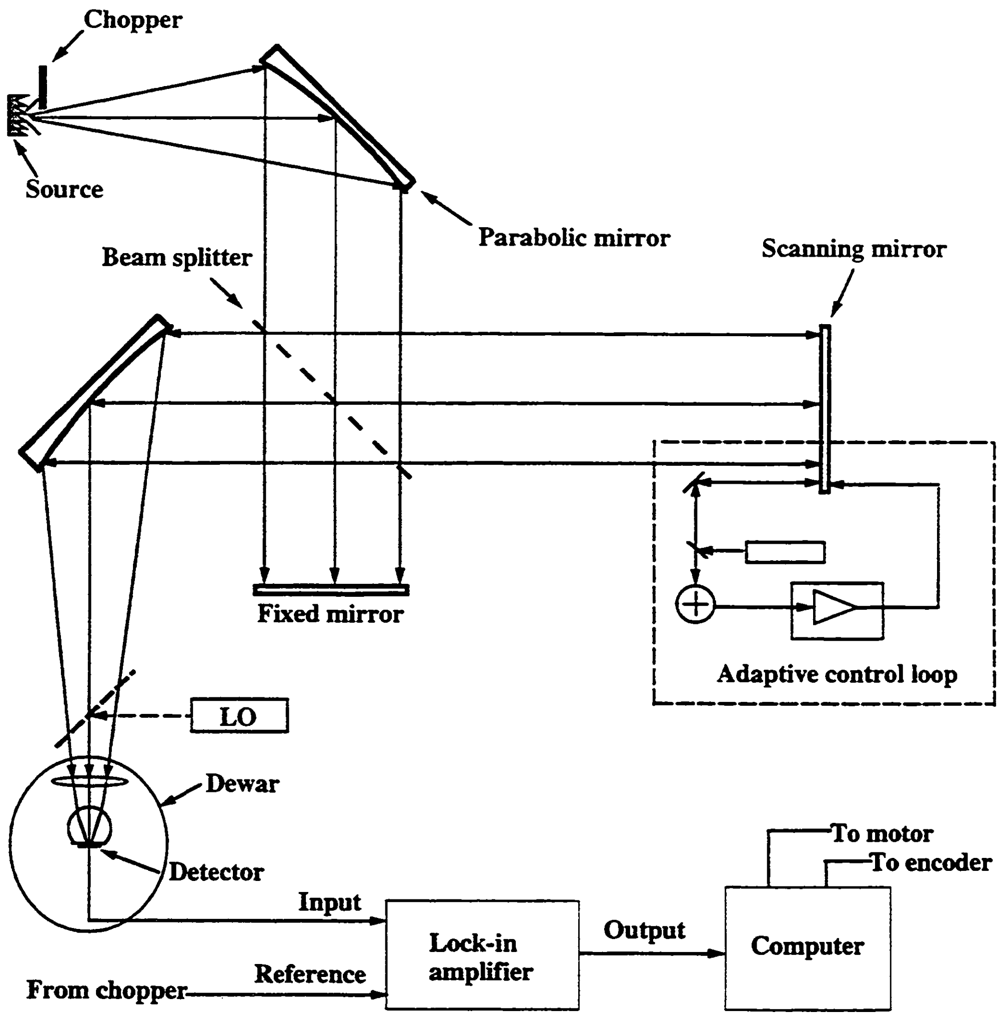

Fig. 1.— Block diagram of the FTS with a heterodyne receiver in place; the results presented in this paper used a bolometer, hence there was no LO.

permits the use of ratios to remove instrumental sensitivity and yield the calibrated transmission of the sample.

2. GERMANIUM

The spectral resolution of a grating spectrometer is linearly dependent on the optical path length (depth) of the grating. If the grating is immersed in a material of medium n, the grating depth increases by this factor. Hence, for a given spectral resolution, the grating volume can be reduced by a factor of n^3. We have designed an immersion grating spectrometer[4] in which the grating will be immersed in germanium since its index of nearly 4 is among the highest available. The desired resolution of ~ 1500, chosen to minimally exceed the width of extragalactic line emission, requires a grating almost 10cm in length. In order to be feasible, the absorption coefficient must be very small.

Several samples of germanium between 2 and 17mm thickness were measured in the FTS, and the absorption coefficient estimated for every possible pair. The refractive index at 2K is found to be $n = 3.90 \pm 0.01$. No absorption could be detected, allowing us to place a limit on the absorption coefficient at all frequencies below 1500GHz of $\alpha \leq 0.01$ cm^{-1}. Assuming the absorption goes as ν^2, the absorption coefficient at ~750 GHz is $\alpha \leq 0.003$. Thus the absorption in our germanium slab will be $\lesssim 5\%$.

3. FLUOROGOLD

Fluorogold, a form of glass-filled Teflon, is a material which has been measured at liquid helium temperatures in the past[5]. It is often used as an infrared blocking filter, but its absorption coefficient must be known precisely to yield the best transmission in the submillimeter band of interest.

Using three samples of Fluorogold at 2K, cut from sheets of thicknesses 0.79, 1.6 and 2.2mm, we measured the transmission of each with respect to an open port. The samples were also ratioed with each other to remove any error in the absorption coefficient induced by surface reflections. An excellent agreement was found between the samples, as is illustrated in figure 2. An approximate expression for the absorption coefficient of Fluorogold over the 300-1400 GHz range is $\alpha = 6\nu^4$ cm^{-1}, where the frequency ν is in THz. This value is close to the previous measurements of Halpern et. al.[5], $\alpha = 9\nu^{3.6}$ cm^{-1} at 4.8K over the 60-900 GHz range. As they suggest, the difference probably derives from differences in the manufacture of sheets versus disks cut from rods.

4. ZITEX

Zitex has recently enjoyed a surge of popularity as an inexpensive, low-loss infrared-blocking filter. Zitex[6] is a sintered Teflon material with voids of 1-50μm and a filling factor of ~ 50%. Several different varieties are available, divided into two categories by manufacturing process: Zitex A is designed to reproduce filter paper, and so has many

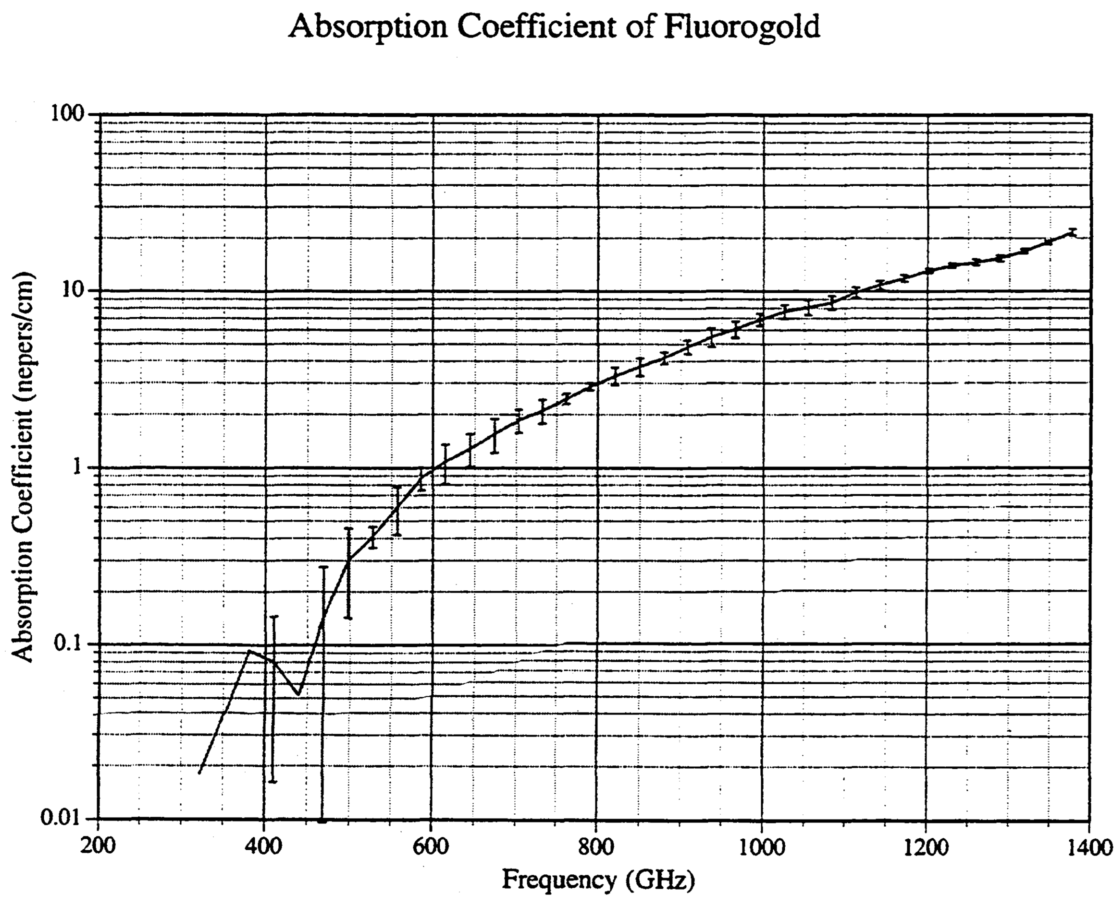

Fig. 2.— Absorption coefficient of Fluorogold sheets at 2K.

narrow linear paths through it and is a rough but soft sheet; Zitex G is made of sintered Teflon spheres of small sizes, resulting in a denser, smoother material. The grades of Zitex of each class differ primarily in the size of the voids in the Teflon; this affects the IR to Mid-IR scattering characteristics. A study of this material has been undertaken to understand its transmission properties from 1μm to 1mm wavelengths[7].

Whereas Zitex is typically available in thicknesses of 0.10mm (0.004") to 0.38mm (0.015"), we have measured a sample of Zitex G-125 3.53mm (0.139") thick. Being this thick, it is possible to measure both the loss, as shown in figure 3, and the refractive index, which is $n = 1.20 \pm 0.07$. Despite the scatter in the data, a power law fit to the data (excluding the absorption band at 1400 GHz) of $\alpha \simeq 0.25\nu^{3.1}$ cm^{-1} with ν in THz is quite good. This fit and the absorption band agree well with the results of Kawamura et. al.[8] in Teflon. Since this implies the submillimeter loss is from the bulk Teflon rather than the scattering in the near-infrared, extrapolation to other thicknesses at frequencies below $\sim$ 2 THz should be valid.

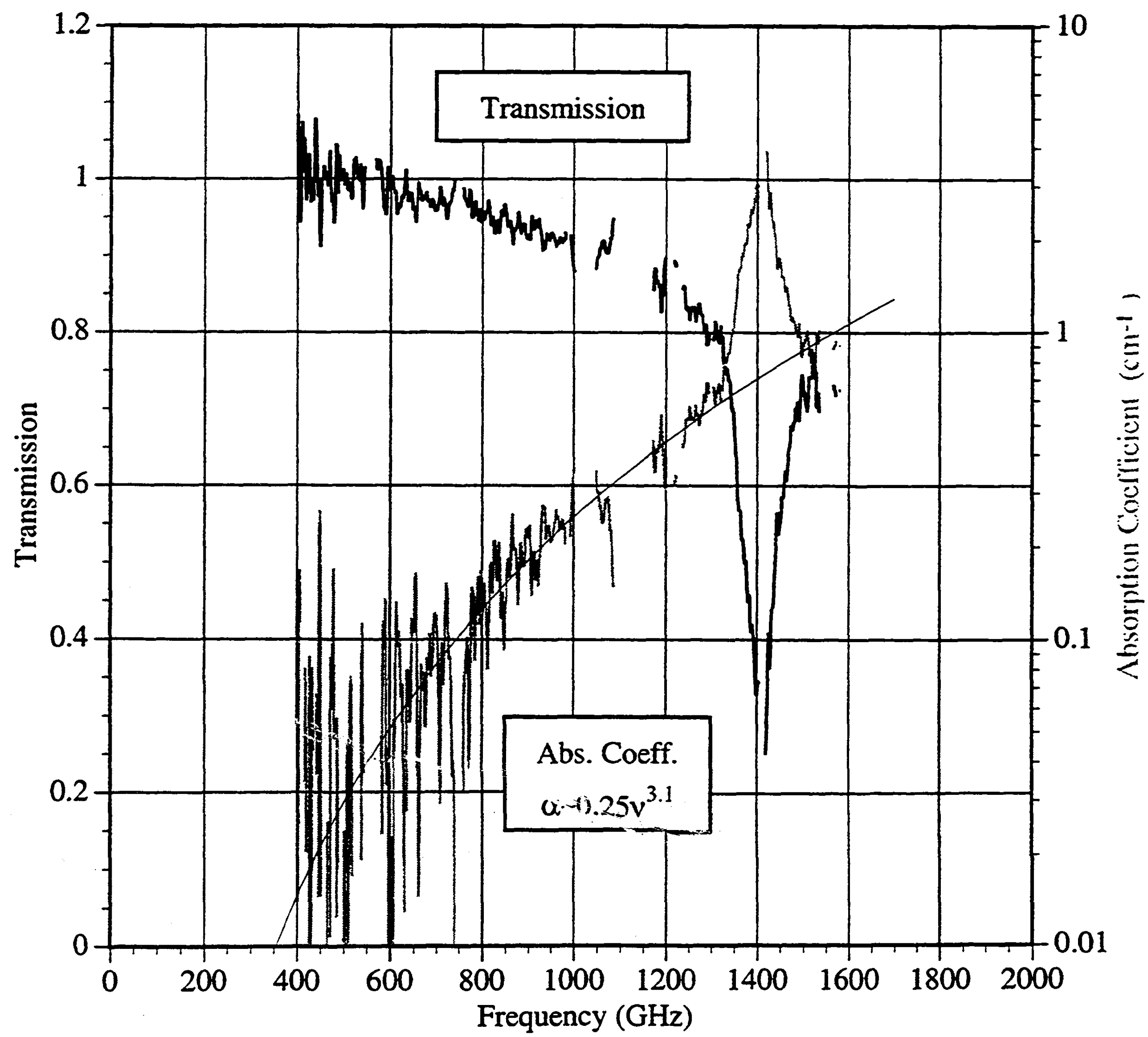

Fig. 3.— Transmission and absorption of Zitex at 2K.

5. QUARTZ WINDOWS

Quartz is a useful material both for vacuum windows and for infrared-blocking filters, because of its high transparency in the submillimeter and its relatively poor transmission in the infrared. However, its refractive index is high enough to cause substantial ($\sim$ 20%) reflection losses; for this reason, it is worthwhile to antireflection coat the quartz substrate with a layer of a material with index $n \sim 1.4$ such as Teflon. We have measured the transmission of numerous windows and infrared blocks with Teflon antireflection coatings of various manufacturers (e.g. Francis Lord Optics). Figure 4 is one such measurement: a 230 GHz antireflection coated window (heavy curve) compared with the theoretical design curve (light). The difference between the two most likely results from the generally poor uniformity of the thickness of the Teflon coatings, each roughly 0.2mm (0.008") thick but visible quite rough. Even so, the loss around 230 GHz is decreased by a factor of ~ 5, a substantial improvement.

6. QUARTZ LENSES

As quasioptical receivers become more common, the use of quartz lenses has increased. We have measured the improvement in transmission of a quartz lens when antireflection coated with Teflon. Using two lenses designed for CHAMP, the 16-element 492 GHz SIS array of the MPIfR[9], we ratioed the transmission of one with a coating and one without. Figure 5 shows the data (heavy curve) over the complete region while a calculated model (light curve) is plotted only for $\nu < 1000$ GHz to enable a clearer view of the measure transmission. Since an accurate calculation of the antireflection coating of a nonplanar surface is difficult, we have merely made an estimate of the ratio assuming a planar geometry; the two agree well in shape. This again shows the improvement found with a dielectric antireflection coating, improving the transmission by $\sim$ 20% at the design frequency.

7. METAL MESH FILTERS

Resonant metal mesh filters have been used as optical filters for some time[10]. We evaluated the transmission of several bandpass and long wavelength-pass filters, commercially available from Cochise Instruments[11], in figure 6. These are fabricated by depositing copper layers onto very thin mylar sheets which are stacked to improve rejection of out-of-band signal. In order to determine their effectiveness as blocking filters, we have measured the average attenuation of the signal in the out-of-band regions below 1 THz. The long wavelength-pass filters' out-of-band transmission is everywhere $\lesssim 0.001$ while the bandpass filters are typically ~ 0.002 with some variation as a function of frequency.

8. DOUBLE FABRY-PEROT FILTER

We have developed a double Fabry-Perot filter constructed from two precise silicon disks with a thin air gap between them[12]. The filter was designed to have transmission peaks approximately every 115GHz, the fundamental rotational transition of CO. Doubling the Fabry-Perot increases the width of the transmissive region of the spectrum while increasing the rejection of the reflective region. When used with a Fourier transform spectrometer, this filter will transmit only the wavelengths of interest while reducing the loading on the detector.

In order to characterize this filter before use at the Caltech Submillimeter Observatory, we performed careful measurements of the silicon disks. A computer model of a double Fabry-Perot was used to determine the optimum optical depth of each silicon disk, the product of its index and thickness. The thickness was measured interferometrically in the near-infrared, while we measured the index in the Terahertz region at 2K to be $n = 3.385 \pm 0.01$, somewhat lower than the room temperature value. After completion, the filter transmission was measured (figure 7); the data is shown by the solid line

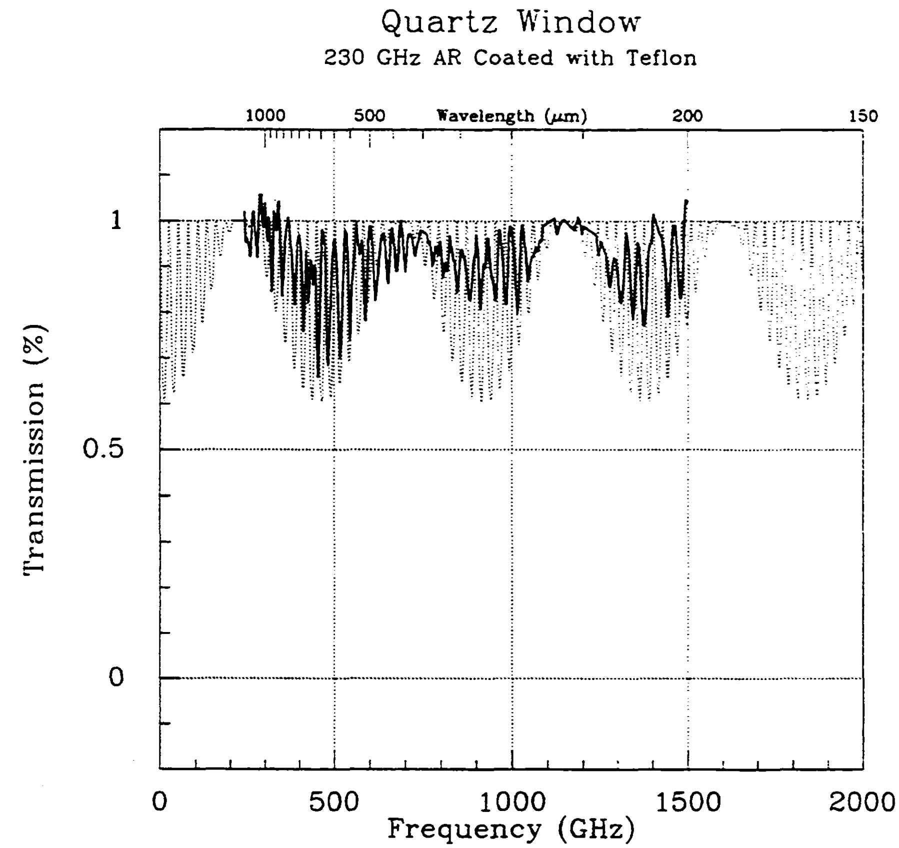

Fig. 4.— Transmission of an antireflection coated quartz window designed for the 230 GHz region.

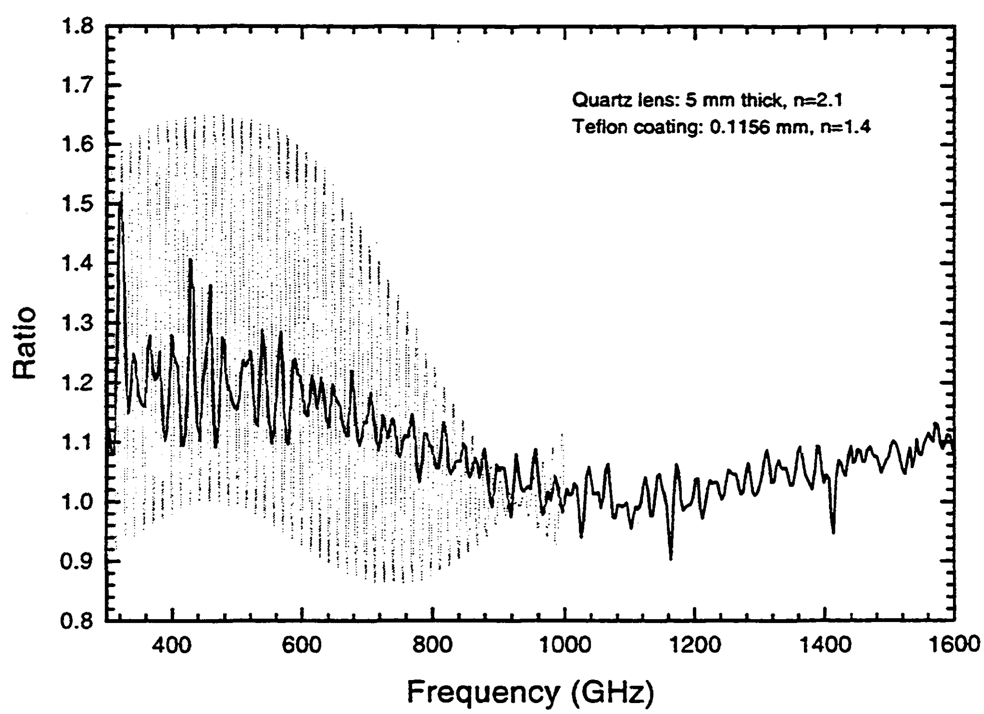

Fig. 5.— Transmission ratio of an antireflection coated quartz lens and an uncoated lens.

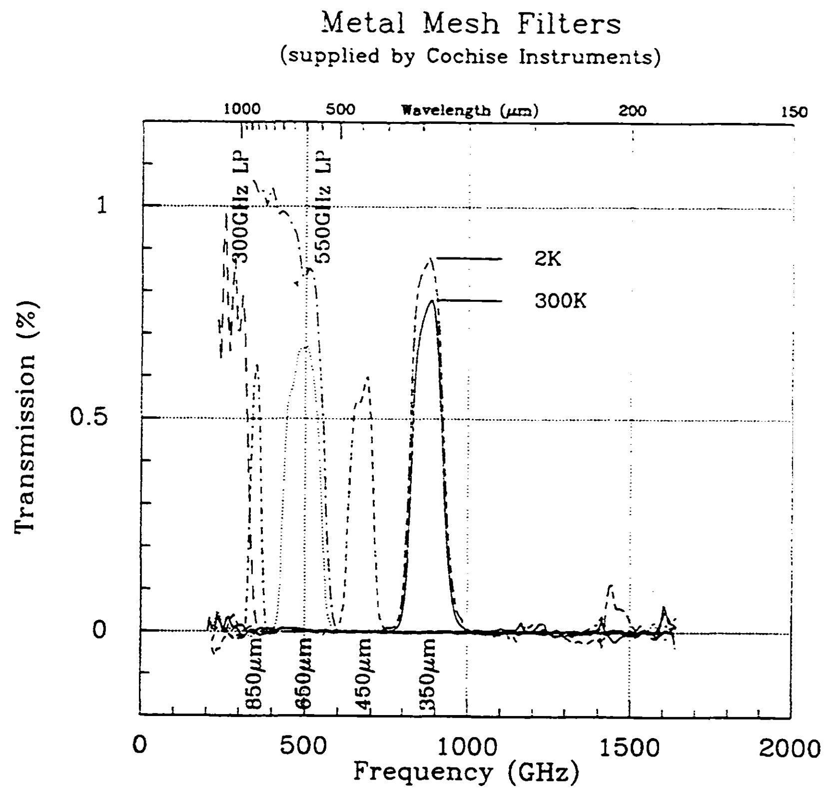

Fig. 6.— Transmission of resonant metal mesh bandpass and lowpass filters. All measurements but one are at 300K; the 350μm filter was also tested at 2K.

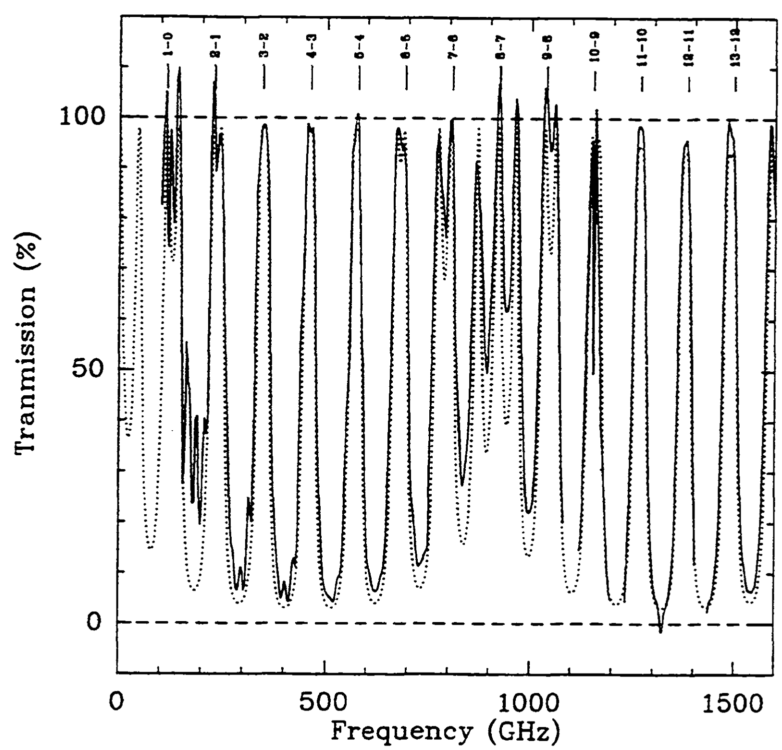

Fig. 7.— Double Fabry-Perot filter with CO transitions marked above the transmission curve.

while the theoretical spectral transmission is shown as a dotted line. The transmission in the bands of interest is > 90% while the rejection is around 10%. This filter is being used at the CSO to detect all available rotational transitions of CO in nearby galaxies.

9. RESTSTRAHLEN FILTER

Transmission filters made from polyethylene sheets loaded with varieties of powdered crystals have been fabricated for decades[13]. Each crystal scatters strongly in its reststrahlen band (in the 10-100μm range), so that combinations produce a broad region of near-zero transmission. Coupled with a small amount of carbon, these become good long-wavelength filters. However, the width of each crystal's scattering region increases with increasing temperature, so that the properties of this kind of filter changes drastically with temperature. We tested at 2K and 300K a commercially-available filter[14] with a nominal cutoff at 1650 GHz. The transmission from 300 to 1650 GHz is shown in figure 8. While our coverage does not provide any information about the rejection of higher frequencies, we do see a substantial decrease in transmission when the filter is warm compared to the relatively good cold transmission. Unfortunately, while the cutoff is sharp around 1600 GHz, the transmission at frequencies near 1 THz is far from ideal.

10. AEROGEL AND LIQUID NITROGEN

Aerogel is well-known as the least dense solid. Being made of an exceptionally low-density glass matrix, it might be useful as a scattering filter in the far-infrared and therefore its absorption coefficient might be a steep function of frequency. However, the absorption coefficient as shown in figure 9 goes as $\nu^{1.7}$ and is therefore unsuitable as a low-pass filter.

Liquid nitrogen is used by most experimenters as a cold load; often, fixed setups use a dewar flask of cryogen with a piece of eccosorb floating or submerged in it. We had wondered what would take place if the eccosorb were fully submerged: would the radiation penetrate into the liquid at all? The absorption coefficient (figure 9) is high enough that near 1 THz, a depth of a few centimeters is sufficient to attenuate the beam; therefore, eccosorb is not needed provided that surface reflection does not terminate at a different temperature.

11. CONCLUSION

We have measured the optical properties of a variety of materials and components useful in the submillimeter range using an FTS. Knowledge of these properties should be useful in the design of low-noise, high-efficiency instruments in the Terahertz region.

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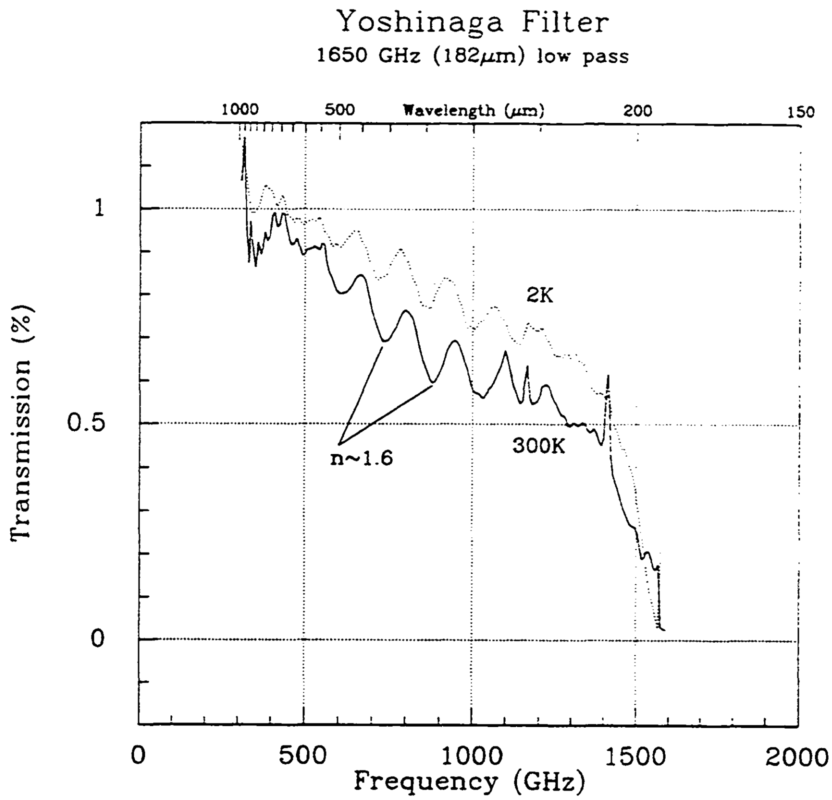

Fig. 8.— Transmission of a Yoshinaga-type reststrahlen crystal lowpass filter at 300K and 2K.

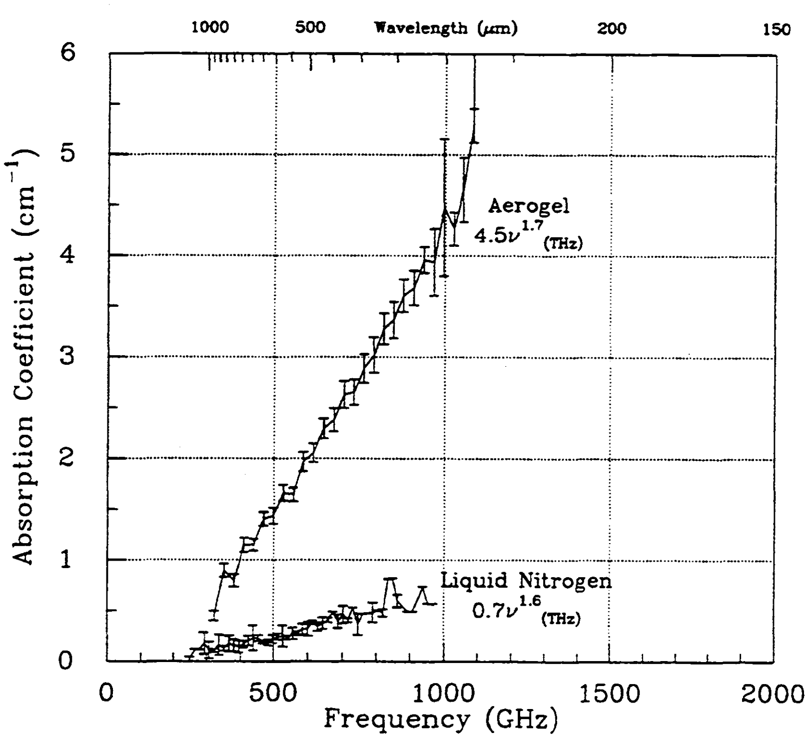

Fig. 9.— Absorption coefficient of aerogel and liquid nitrogen.