Transmission Measurements of Infrared Filters for Low-Noise Terahertz Receiver Applications

D. Loudkov, C.-Y. E. Tong, D. P. Marrone, S. Ryabchun, S. N. Paine, and R. Blundell

Abstract — **Infrared (IR) filters are very important to the efficient operation of cryogenic receivers. Usually, such filters are mounted on the radiation shield of the cryostat to reduce the heat load to the 4 K stage. Insufficient filtering may cause the temperature of the mixing element in a receiver to be excessively warm, leading to degradation in sensitivity. These filters should be effective in blocking the room temperature IR radiation from outside the cryostat, yet should be transparent across the desired signal frequency band. In the Terahertz frequency range, which is close to the infrared, it is difficult to find an inexpensive low-loss material that can provide the required IR blocking capacity.**

We present transmission measurements, made using a Fourier Transform Spectrometer (FTS), of a number of potential infrared filters between 0.4 and 1.6 THz. The filters tested include the widely-used, Teflon-based, Zitex-A and Zitex-G films, alkali halide based infrared filter, and crystalline quartz coated with Parylene, and polyethylene films.

Index Terms—**Infrared filters, Zitex, LDPE, Crystalline quartz, Antireflection coating, Parylene.**

I. INTRODUCTION

HETERODYNE receivers for terahertz spectroscopy are showing noise performance close to the fundamental quantum noise limit [1, 2]. These low noise cryogenic receivers require infrared (IR) filters to reduce the thermal loading to the cryostat. Since terahertz mixers have generally higher conversion loss, any input losses introduced by the filter material will further increase the conversion loss of the front-end mixer and would cause substantial degradation to the receiver noise temperature. Therefore, it is important to find an inexpensive low-loss material that can provide the required IR blocking capability and yet transparent to terahertz radiation.

The double-side-band receiver noise temperatures of a 1.5 THz waveguide Hot Electron Bolometer (HEB) receiver are displayed for the cases when two different IR filters were used (Fig.1) [3]. With multi-layer Zitex (expanded Teflon) filter, we obtained higher noise temperature than a full-wave thick crystalline quartz slab. This demonstrates that the choice of low loss and IR filter is critical to the operation of terahertz receivers [4-7].

Transmission measurements were performed for various IR filters using a Fourier Transform Spectrometer (FTS). The samples were inserted in one arm of the Martin-Puplett interferometer which is placed in a vacuum chamber to eliminate the effects of atmospheric absorption [8]. Our set-up also allows us to cool the sample to perform measurements at cryogenic temperatures.

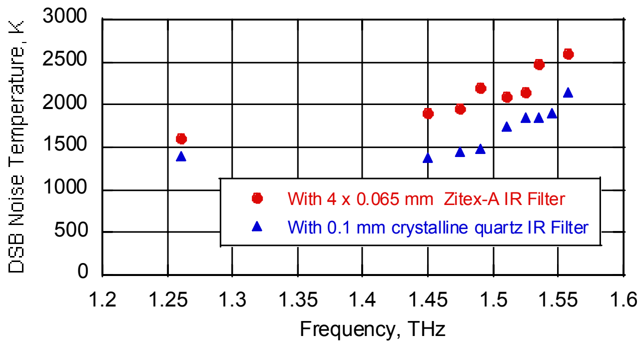

Fig. 1 Receiver noise temperature of a 1.5 THz HEB receiver using two different IR filters mounted on the 4.2 K cold plate [3]. Lower noise temperatures are obtained with the full-wave crystalline quartz filter, centered at around 1.45 THz, than the four layer Zitex-A filter.

II. DIELECTRIC FILM IR FILTERS

Infrared filters based on dielectric films, such as Teflon-based Zitex, are widely used in cryogenic terahertz receivers. We have tested two types of Zitex (type A and G). Zitex-A is a Teflon sheet perforated with pores that are generally bigger than 10 µm in diameter. Zitex-G is made of very fine sintered Teflon spheres, yielding pores that are generally smaller than 10 µm in diameter. Transmission measurements of 0.37 mm thick films are shown in Fig. 2. Clearly, the transmission Zitex- G film is substantially better above 0.6 THz.

Zitex films are useful as IR filters because the transmission of radiation in Teflon drops dramatically at frequencies above 5 THz [9]. However, since Zitex films are porous, a few layers are required to achieve reasonable IR blocking. This also leads

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to reduction in the signal transmission in the frequency band of interest. It is noted that if the transmission for a single layer is 95%, due to absorption loss, then the use of four layers will yield a transmission of 81%.

We have also made measurements on an IR filter made of polyethylene loaded with powdered alkali halide crystals [10]. Scattering of mid-IR radiation by powdered crystals is the basis of operation of this type of IR filter [11]. The sample is dark grey in color and its thickness is 0.42 mm. As shown in Fig. 3, the measured transmission coefficients do not show much dependence in temperature in the frequency range 0.4 – 1.6 THz. Based on these data, the estimated complex refractive index is n = 1.61 + i0.003. It should be noted that the sinusoidal frequency response of this filter may limit its applicability to wide-band low noise receivers at Terahertz frequencies. For narrow band operation, it is important to choose an appropriate thickness for the filter.

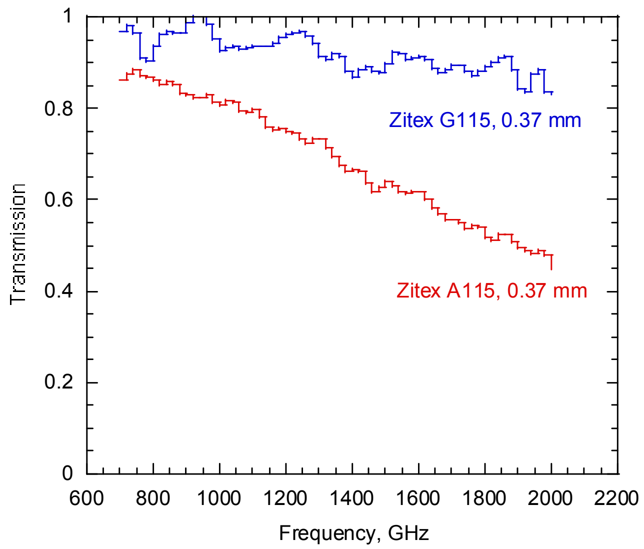

Fig. 2 Measured power transmission coefficients of Zitex-A115 and Zitex-G115 at 295 K.

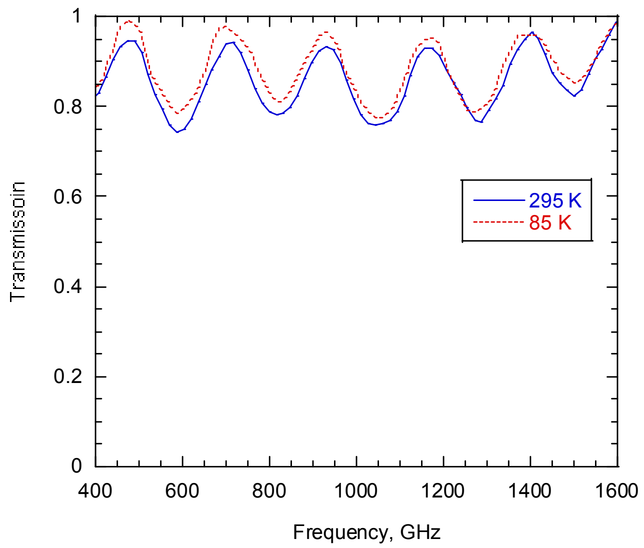

Fig. 3 Measured power transmission coefficient of the polyethylene loaded with alkali halide IR filter.

The measured transmission coefficient of a sheet of low density polyethylene (LDPE) film 0.47 mm thick at 295 K is shown in Fig. 4. The experimental data shows very good agreement with the theoretical complex index of n = 1.51 + i0.002. These results also agree with the reported properties of LDPE [6] and indicate the reliability of our measurements. LDPE is quite transparent to infrared radiation and it is not a candidate for a stand alone IR filter but as seen in the next section, it can be used as a matching layer for other materials.

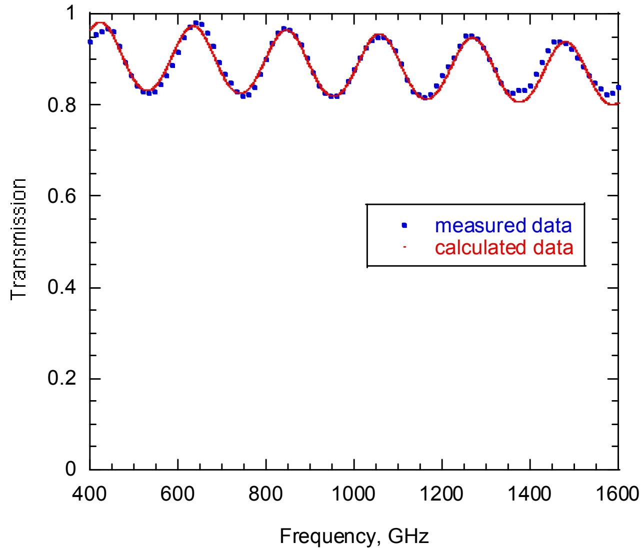

Fig. 4 Power transmission coefficient of a 0.47 mm thick LDPE sheet at 295 K.

III. Uncoated and Coated Crystalline Quartz

IR filters are usually placed inside a cryostat on the low temperature radiation shields for effective IR blocking. The filtering materials are therefore subjected to heating by either room temperature radiation or radiation originating from higher temperature stages. This may produce non-uniform temperature profile due to poor thermal conductivity. From this point of view, crystalline materials with much higher thermal conductivities, like quartz, are preferable.

Crystalline quartz is a very good IR filter candidate because it is essentially opaque to wavelengths around 10 µm, the peak of the black body radiation from ambient sources. As illustrated in Fig. 1, the use of a half-wave or full-wave slab of crystalline quartz allows for very good matching to the RF signal. However, such a thin piece of quartz (0.1 mm thick for a 1.5 THz full-wave plate) is very fragile. On the other hand, the use of a thick uncoated slab of crystalline quartz is not practical due to multiple internal reflections inside the quartz. The transmission coefficient of a 3.1 mm thick crystalline quartz slab is presented in Fig. 5. By fitting to the data, we obtained the complex index of n = 2.1 + i0.0006.

The standard ways of reducing reflection losses are surface grooving or application of an antireflection coating. The latter is chosen because it is fairly time consuming to mechanically create fine grooves. Two materials were tested as the coating layer: Parylene and LDPE. Silicon lenses coated by Parylene have been previously reported and show good improvement over uncoated lenses [12, 13]. Parylene coating was applied by vapor deposition in a vacuum chamber. This procedure is generally performed by a specialized coating company. In contrast, coating by LDPE can be done in any laboratory by baking a sandwich of LDPE and quartz under pressure for several hours. Since quartz and LDPE have significantly different thermal contraction coefficients, the LDPE matching layer tends to peel off the quartz disk when cooled to low temperatures. In order to limit the strain caused by differential contraction, we have scored the LDPE matching layer with a dicing saw to produce an array of square patches (5 x 5 mm). These grooves allow the LDPE coated quartz disk to withstand thermal cycling.

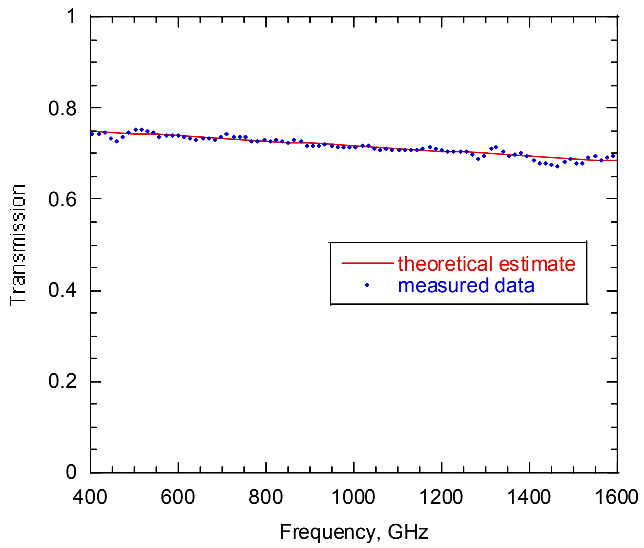

Fig. 5 Transmission coefficient of a 3.1 mm thick crystalline quartz slab.

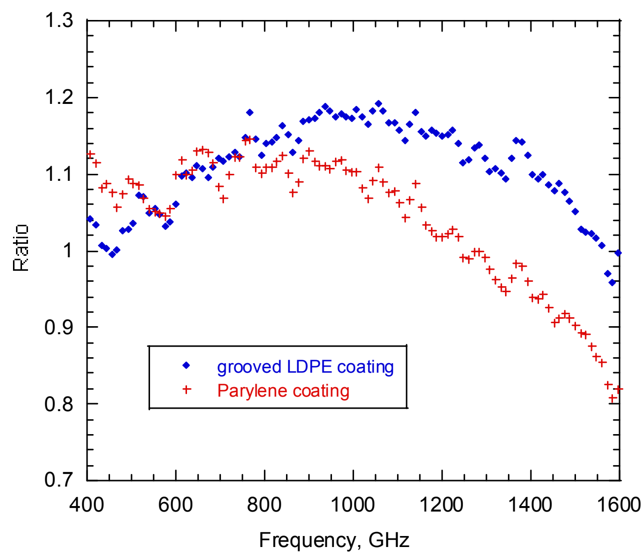

Fig. 6 Transmission ratio of an antireflection coated crystalline quartz window to an uncoated one. Two samples are presented with the Parylene coating and the grooved LDPE coating.

Using 3 mm thick crystalline quartz disks, we measured the transmission coefficients of crystalline quartz filters coated with Parylene and with LDPE. In Fig. 6, we plot the ratio of the measured transmission coefficients of the coated filter to uncoated one as a function of frequency. The two samples have slightly different center frequency of operation because of the thicknesses of the matching layer. The LDPE coating clearly provides better signal coupling. However, we have observed small variations in the optical properties of the LDPE films from different batches.

The transmission of the quartz window with grooved LDPE coating on both sides is presented in Fig. 7. The thickness of the coating was 0.13 mm and the thickness of the quartz disk was 2.9 mm. The complex refractive index was estimated by the fitting the calculated data to the measured data. The best correlation of the theoretical calculations and measured data was achieved for the refractive indices of $n = 1.5 + i\,0.002$ and $n = 2.1 + i0.0003$ for the polyethylene and quartz respectively. This corresponds to a loss tangent of 2.6×10^{-3} for LDPE. These losses are higher then that reported in [6], possibly due to the grooves and changes in the LDPE density during coating process.

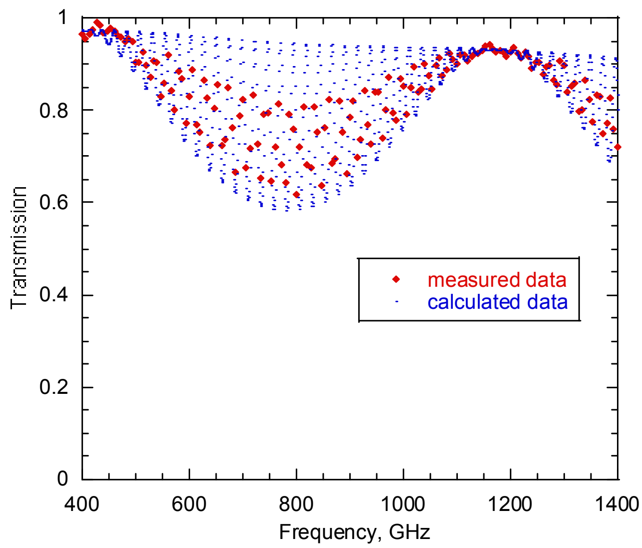

Fig. 7 Transmission of the crystalline quartz window coated with grooved LDPE film.

Calculated and measured transmissions of the quartz window with Parylene antireflection coating are shown in Fig. 8. The crystalline quartz slab was 3.1 mm thick and the Parylene film was 0.14 mm thick. The estimated refractive index of Parylene are $n = 1.62 + i\,0.025$ and $n = 2.1 + i0.0003$. This gives a loss tangent of 3×10^{-2}. Clearly, LDPE is a lower loss material in this frequency range.

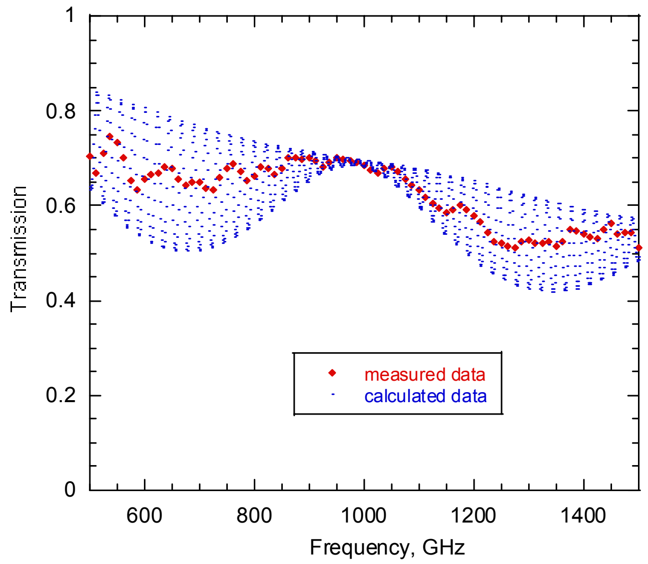

Fig. 8 Transmission of the crystalline quartz window coated with Parylene film.

IV. SUMMARY

We have conducted investigations based on FTS measurements of the optical properties of different materials. Investigations of Teflon based IR filters show that G-type Zitex has lower losses than Zitex-A above 0.6 THz.

The FTS transmission measurements also show that the performance of a crystalline quartz IR filter with grooved low density polyethylene coating is better than one with Parylene coating. The estimated loss tangent is 3×10^{-2} for Parylene and 2.6×10^{-3} for LDPE in covered frequency range. The calculated data shows good overlap with measured one.

The crystalline quartz IR filter with grooved LDPE antireflection coating may be a good alternative to the widely used multilayer Zitex filters. However variations in the refractive index of LDPE must be considered in the matching layer design.

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