Optical properties of Zitex in the infrared to submillimeter

Dominic J. Benford, Michael C. Gaidis, and Jacob W. Kooi

The results of measurements of the refractive index and power attenuation coefficient of Zitex at 290, 77, and 4 K in the spectral region from 1 to 1000 μm are presented. Zitex is a porous Teflon sheet with a filling factor of ~50% and is manufactured in several varieties as a filter paper. Zitex is found to be an effective IR block, with thin (200-μm) sheets transmitting less than 1% in the 1–50-μm range while attenuating ≲10% at wavelengths longer than 200 μm. Some variation in the cutoff wavelength is seen, tending to be a shorter-wavelength cutoff for a smaller pore size. In addition, the thermal conductivity of Zitex at cryogenic temperatures has been measured and is found to be roughly one half that of bulk Teflon. Finally, its dielectric constant has been measured in the submillimeter as $n = 1.20$, resulting in extremely low dielectric reflection losses. As a result, Zitex is particularly useful as an IR blocking filter in low-noise heterodyne receivers; in the millimeter-wave range ($\lambda \gtrsim 850$ μm or $\nu \leq 350$ GHz) the attenuation of $\alpha \leq 0.01$ cm^{-1} for a 3.5-mm thickness filter of Zitex G125 would raise receiver noise temperatures by <1 K. © 2003 Optical Society of America

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1. Introduction

To reduce the loading on cold optical elements operating in the far IR, room-temperature IR radiation must be blocked efficiently while allowing the desired wavelengths to pass unattenuated.[1,2] Commonly used materials include blackened polyethylene and quartz. Unfortunately, the transmittance of blackened polyethylene is dependent on the size, concentration, and form of the carbon used to blacken it and varies substantially in its far-IR properties.[3] Quartz is a low-loss material when a suitable antireflection coating like Teflon is applied, but this is difficult and restricts the wavelengths over which it can be used as a highly transmissive element.[4] Teflon itself is a good IR block, but transmits power in the 5–10-μm range and longward of 50 μm, limiting its usefulness. Several more absorbing materials, such as Fluorogold and Fluorosint, have been used for low-frequency applications, but their slow spectral cutoff characteristics are not ideal for receivers operating near 1 THz.[4,5]

Zitex[6] is a sintered Teflon material with voids of size ranging from 1 to 60 μm and a filling factor of ~50%. Several different varieties are available, divided into two categories by the manufacturing process. Zitex A is designed to reproduce filter paper and so has many narrow linear paths through it and is a rough but soft sheet. It is available in 11 grades with effective pore sizes ranging from 3 to 45 μm and in thicknesses from 0.13 cm (0.005 in.) to 0.64 cm (0.025 in.). Zitex G is made of sintered Teflon spheres of small sizes, resulting in a denser, smoother material. Available in five grades, the pore sizes range from 1.5 to 5.5 μm and is available in standard thicknesses of 0.10 cm (0.004 in.) to 0.38 cm (0.015 in.), although larger thicknesses are available.

Zitex is similar in geometry to glass bead filters, in which dielectric spheres are embedded in a suspending material with a different index of refraction. A single sphere of radius a in a material of index n will scatter strongly for wavelengths $\lambda \lesssim \pi a(n - 1)$.[7] Thus, for Teflon [$n = 1.44$ (Ref. 8)], a sphere of radius of 10 μm produces a shadow for wavelengths shortward of 15 μm. At short wavelengths, then, a perfectly randomly scattering screen will redistribute the optical power in an incident beam equally in all directions, resulting in a large loss for well-collimated beams. In addition to sintered Teflon, is is also possible to use polystrene foam as a scattering medium. The loss and refractive index of some polystrene foams with larger effective scattering sizes (of the order of 100 μm) have been measured in the low

D. J. Benford (dominic.benford@gsfc.nasa.gov) is with NASA Goddard Space Flight Center, Code 685, Greenbelt, Maryland 20771. M. C. Gaidis is with IBM, ZIP 33F, Hopewell Junction, New York 12533. J. W. Kooi is with the California Institute of Technology, Mail Code 320-47, Pasadena, California 91125.

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Table 1. Measured Zitex samples

Grade	Pore Size (μm)	Thickness (mm)	Filling Factor[a]	Near-IR Data	Far-IR Data	Submillimeter Data
G104	5–6	0.10	0.45	X		
G106	4–5	0.16	0.50	X		
G108	3–4	0.20	0.55	X	X	
G110	1–2	0.25	0.60	X	X	
G115	1–2	0.41	0.60	X		
G125	~3	3.53	~0.5	X		X
A155	2–5	0.27	0.40	X		

[a]Relative density of Teflon.

terahertz frequency range,[9] yielding results similar to those presented here.

2. Measurements

Because of the large wavelength range involved, three Fourier-transform spectrometer (FTS) instruments were used to characterize Zitex. For the near to mid-IR (1–80 μm, 10,000–125 cm^{-1}) a commercially available Nicolet 60SX spectrometer[10] was used. The far-IR (50–200 μm, 200–50 cm^{-1}) measurements were made on a Bruker interferometer[11] at NASA's Jet Propulsion Laboratory. The submillimeter data (200–1000 μm, 50–10 cm^{-1}) were obtained on a FTS at Caltech.[12] The focal ratio of the spectrometers was roughly $f/4$. A perfectly scattering surface would yield a transmission of roughly 0.4% in this case. Table 1 lists the samples that we measured.

3. Teflon

So that we could characterize qualitatively the difference between bulk Teflon and Zitex sheets, we measured one thin (0.25-mm) and one thick (0.75-mm) sample of a plane-parallel Teflon sheet. Figure 1 shows the results of a measurement of the far-IR transmission of the thick sample near the cut-on region at 50–100 μm. The sample was measured at room temperature and liquid-nitrogen temperature, showing a slight improvement in the transmission when the sample is cold. Figure 2 shows the mid-IR transmission of the thinner sample, which highlights the fairly narrow regions near 10–20 μm where the absorption is large.

4. Zitex G104, G106, G108, G110, G115, and A155

The samples of G104 and G106 were measured in the near to mid-IR to derive a transmission and an effective attenuation coefficient, as shown in Fig. 3. The attenuation coefficient α for a sheet of thickness h is calculated from the transmission T as $-\ln(T)/h$. Because some wavelength-dependent fraction of the loss $(1 - T)$ is from scattering and some from absorption, the attenuation coefficient cannot be used to estimate the transmission of arbitrary thicknesses. It does, however, provide a useful means of comparison with other, more purely absorptive, materials.

Combining sets of data in the near through far-IR for samples of G108 and G110 allows us to build a more complete picture of the profile of the cut-on of Zitex near 100 μm, as shown in Fig. 4. Measurements of G115 and A155 are shown in Fig. 5. A marked shortening of the cut-on wavelength can be seen in the A155 sample, presumably as a result of its different structure. Although all the G-series sheets are quite smooth, comprised of approximately spher-

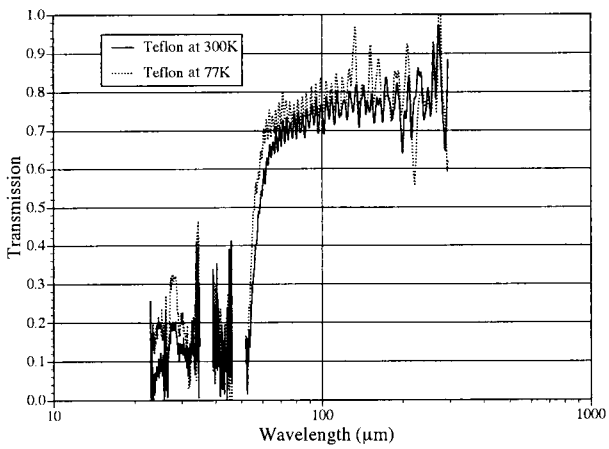

Fig. 1. Far-IR transmission of a 0.75-mm-thick sheet of Teflon at 300 and 77 K. Fabry–Perot fringes can be seen in the transmissive region longward of 60 μm.

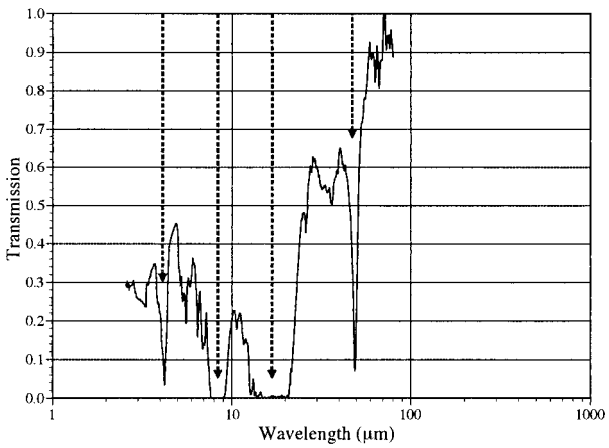

Fig. 2. Mid-IR transmission of a 0.25-mm-thick Teflon sheet, highlighting the regions of good absorption.

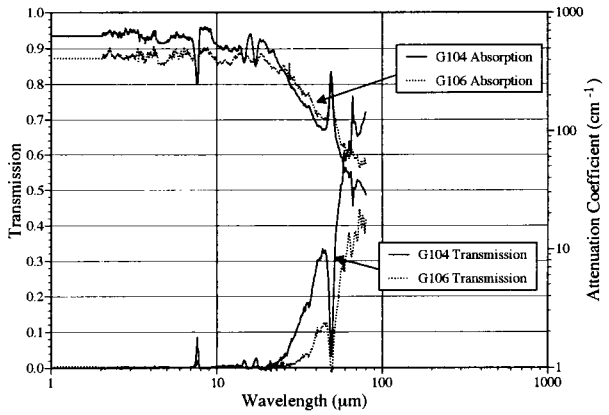

Fig. 3. Transmission and effective attenuation coefficient in nepers per centimeter of single sheets of Zitex G104 and G106 (pore sizes 5–6 and 4–5 μm, respectively).

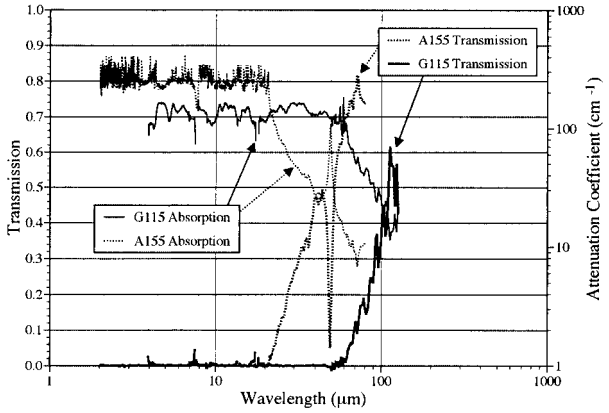

Fig. 5. Transmission and effective attenuation coefficient of Zitex G115 and A155 (pore sizes 1–2 and 2–5 μm, respectively) in the near to mid-IR.

ical particles, the A155 is rougher and consists of Teflon filaments.

5. Zitex G125

As the thickest of all the samples, the G125 sheet of Zitex was used for the longest wavelengths, covering 400–1600 GHz (188–750 μm). Even with a 3.5-mm-thick slab, the loss was small enough to be below detectability at longer wavelengths. The sample was cooled to 2 K to determine its suitability as a mid-IR blocking filter for helium-cooled cryostats. The transmission and effective attenuation coefficient are shown in Fig. 6. The attenuation, neglecting the absorption band, follows $\alpha = 0.25\ \nu_{\mathrm{THz}}^{3.1}$ Np/cm. The 1400-GHz (214-μm) absorption feature is known as an absorption band that is seen in cold Teflon.[8]

Combining the data on G125 near 1 THz with data at shorter wavelengths allows us to determine the transmission over the range of 20–1000 μm (300 GHz–15 THz), as shown in Fig. 7. The effective attenuation coefficient for this whole range (with the exception of the Teflon absorption band) is well fit by

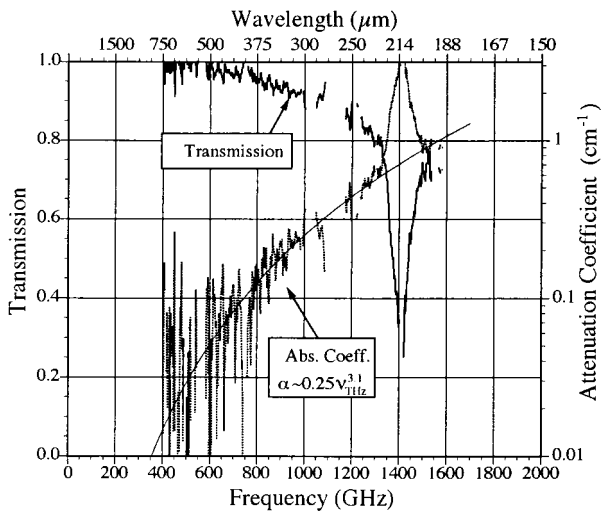

Fig. 6. Transmission and attenuation coefficient in nepers per centimeter of Zitex G125 between 400 and 1600 GHz (188 and 750 μm).

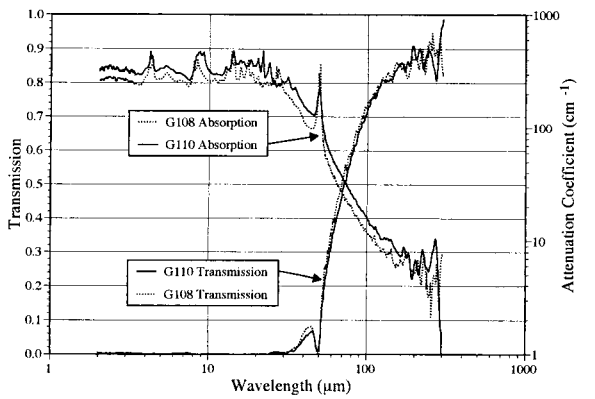

Fig. 4. Transmission and effective attenuation coefficient in nepers per centimeter of single sheets of Zitex G108 and G110 (pore sizes 3–4 and 1–2 μm, respectively) by use of near-, mid-, and far-IR data.

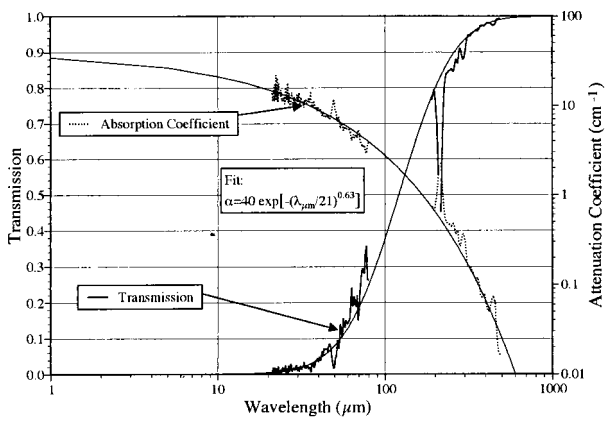

Fig. 7. Transmission and attenuation of Zitex G125 (pore size ~3 μm).

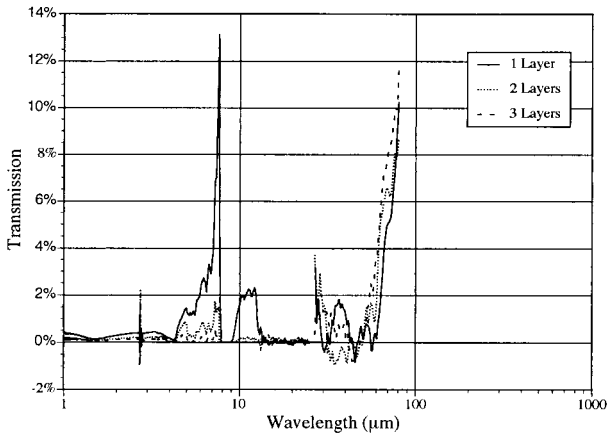

Fig. 8. Transmission of single, double, and triple layers of Zitex in close proximity. The transmission drops more slowly than for a pure absorbing medium, implying strong scattering.

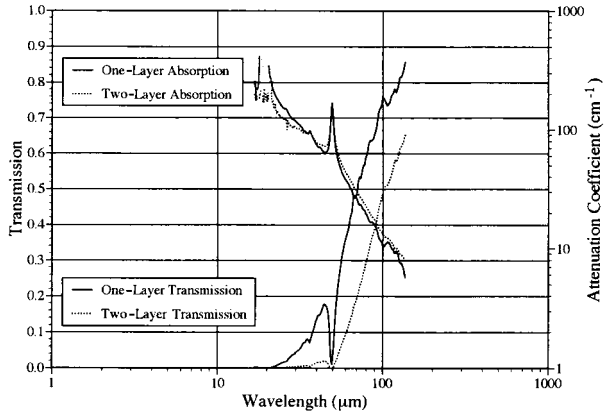

Fig. 9. Transmission of single and double layers of Zitex in an $f/4$ beam with 7-mm spacing. At mid-IR wavelengths, the Zitex acts as two scattering surfaces; at far-IR wavelengths, it acts like an absorber.

$\alpha = 40 \exp[-(\lambda_{\mu m}/21)^{0.63}]$ Np/cm. The transmission, neglecting the absorption band, follows $T = \exp(-145\lambda_{\mu m}^{-1.06})$ to within 20% over 20–1000 μm.

6. Multiple Layers

A helium-cooled receiver is likely to have several layers of IR blocking filtration in the optical path. As a result, it is natural in the case of a scattering material like Zitex to question its efficacy in a multilayer application. Layering single-, double-, and triple-ply sheets of Zitex in close proximity (limited only by the natural wavy contours of the thin sheets) yields the transmission measurements shown in Fig. 8. Because the transmission drops more slowly that for a pure absorbing medium (which would have $T_3 = T_1^3$ and $T_2 = T_1^2$) in the mid-IR, we can infer that scattering is the dominant loss mechanism and that multiple sheets are not substantially more effective than single sheets.

However, if we separate the layers slightly and look at longer wavelengths, the picture changes. Using Zitex A155 sheets spaced by roughly 7 mm, we find the transmission shown in Fig. 9. At mid-IR wavelengths, the Zitex still appears to be dominated by scattering because the effective attenuation coefficient of two layers is less than that for one layer. However, at far-IR wavelengths, the transmission appears to be increasingly determined by absorption alone, presumably in the bulk of the Teflon; the absorption is similar to that of Birch.[13]

7. Temperature Variation

In the case of many materials (e.g., quartz), the absorption of mid-IR radiation is known to vary as the temperature changes.[14] To determine if there was any effect of the temperature on the transmission of Zitex, we measured the transmission of samples of G110 at 300 and 77 K in the far IR near the cut-on region. No significant variation in the transmission was seen upon cooling (Fig. 10), which is to be expected for dielectric scattering.

8. Refractive Index

Measuring the refractive index of a material of low dielectric constant is difficult near 1 THz for a nondispersive FTS. Only the thick sample of G125 could be measured, which was done by determination of the fringe spacing in the 3.5-mm-thick slab. The fringe spacing, averaged between 13 and 45 cm^{-1} (200–800 μm or 400–1350 GHz), was 1.18 cm^{-1}. This yields a refractive index for Zitex of $n = 1.20 \pm 0.07$ at a temperature of 2 K. This can be compared with Teflon, which has $n = 1.44$ (Ref. 8); with a filling factor of ~50%, the expected refractive index is $n = 1.22$, exactly as measured. With such a low index, the dielectric reflection loss is <1%.

9. Thermal Conductivity

We measured the thermal conductance of a thick slab of Zitex in the direction along the sheet using an apparatus developed for the purpose of measuring lateral thermal conductance in sheets.[15] At cryogenic temperatures ($T \leq 150$ K), the conductivity of Zitex is found to be well fit by $K(T) = 0.01\, T^{0.58}$ W K^{-1}

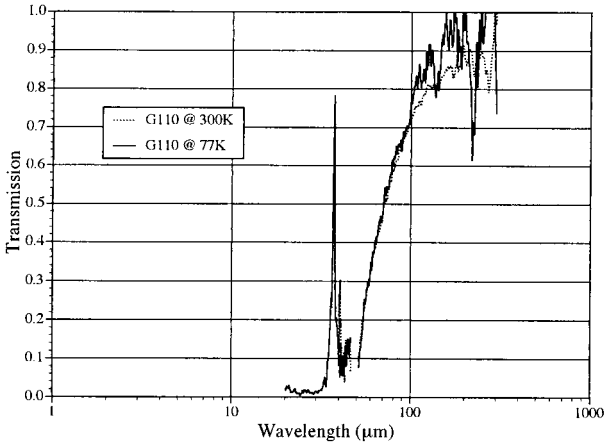

Fig. 10. Far-IR transmission of Zitex G110 at 300 and 77 K. No substantial variation can be seen.

m^{-1}. This value is half that of the bulk conductivity of Teflon,[16] indicating that the porous nature of Zitex does not substantially affect its thermal conductance beyond the geometric reduction. However, because Zitex sheets tend to be thin (~0.3 mm), a small amount of power absorbed in Zitex when used as a near-IR blocking filter would raise its temperature by a significant fraction. This suggests use of two layers for good blocking, whereas one Teflon layer might have been sufficient to handle the optical loading. However, because the loss in Zitex at long wavelengths is so low, this solution is likely to be more efficient than use of Teflon. Furthermore, because the predominant power attenuation is by scattering, the overall power absorbed in Zitex is relatively low.

10. Conclusions

We have measured the refractive index and power attenuation coefficient of Zitex at 290 and 77 K in the spectral region from 2 to 200 μm. We have also measured the transmission of the thickest variety, G125, at 4 K over 400–1600 GHz (188–750 μm). For all varieties of Zitex, the attenuation at wavelengths longer than ~100 μm is found to be extremely small, and with an index of refraction of $n = 1.2$, there is little reflection loss.

Zitex is an effective IR block when used to inhibit wavelengths shortward of 100 μm, having lower absorption and reflection losses than black polyethylene or quartz and better IR blocking characteristics than Teflon. Most of the loss at IR wavelengths is due to scattering, so the material—which has a low thermal conductivity—should not warm up when used as an IR block even with large filter sizes. Zitex is particularly beneficial for use in low-noise superconducting heterodyne receivers[17,18] where some amount of out-of-band transmission is acceptable provided that the in-band insertion loss is small. In the millimeter-wave range, $\lambda \geqslant 850$ μm or $\nu \leq 350$ GHz, the attenuation of $\alpha \leq 0.01$ cm^{-1} for the 3.5-mm-thick Zitex G125 is significantly superior to other commonly used materials.[5]

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