A CIRCULAR WAVEGUIDE SIS RECEIVER
FOR 600-720 GHz

P. A. Jaminet[1], J. A. Stern[2], H. G. LeDuc[2],
C.-Y. E. Tong[1], S. Shepard[3], J. Kawamura[1], X. Zhang[1]

ABSTRACT

We have designed a 600-720 GHz SIS receiver which uses a novel fixed-tuned, circular waveguide mixer block mount. We describe the design, and discuss its advantages and disadvantages compared to more conventional rectangular-waveguide mounts. Also, we describe a new technique for making durable anti-reflection coatings for quartz optical elements, including lenses.

Introduction

SIS receivers using rectangular waveguide mixer mounts have provided very impressive performance through the Niobium gap frequency, slightly above 700 GHz [5, 6, 7, 8]. However, at very high frequencies there may be grounds for considering circular waveguide mounts as a competing technology.

Circular waveguides have intrinsically lower loss than rectangular waveguides, and can be matched to corrugated feed horns with slightly shorter transition sections, so that waveguide losses will be slightly lower. Also, non-contacting backshorts can be made more effectively in circular waveguide than rectangular waveguide: the best rectangular waveguide backshorts at high frequencies use circular sections to produce a reflective filter [4], just as non-contacting backshorts in circular waveguide do, but the range of impedances in the filter sections is more restricted. Against this must count a few deficiencies of circular waveguide mounts. First, because of the increased density of modes in circular waveguide, the receiver bandwidth is somewhat reduced; tunerless designs have achieved 40% bandwidth in rectangular waveguide [1], whereas the design we will describe here achieves roughly 25% bandwidth. This need not be a crippling consideration at high frequencies, as the atmospheric windows above 500 GHz are less than 20% wide. Second, circular waveguides have no intrinsic polarization selectivity. Therefore, much more than rectangular waveguide mounts, they are vulnerable to losing power into a cross-polar component which does not couple to the receiver

[1]Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138.

[2]Jet Propulsion Laboratory, Center for Space Microelectronics Technology, Pasadena, CA 91109.

[3]Harvard University, Division of Applied Sciences, McKay Laboratory, Cambridge, MA 02138.

optics.

As the waveguide and backshort losses tend to rise rapidly with frequency, while the polarization losses probably do not rise so rapidly with frequency, at sufficiently high frequencies circular waveguide mounts may be competitive with (or superior to) rectangular waveguide mounts. At frequencies above the Niobium energy gap, the improved backshort performance may make it possible to tune close to the edge of the Smith chart, and thereby match to untuned junctions. Furthermore, to our knowledge, before this work there was no existing circular waveguide mixer mount design which is known to be capable of giving performance comparable to that of rectangular waveguide mounts. Thus, we thought it both interesting and worthwhile to investigate circular waveguide designs.

Design of the RF Block

Because this design was intended to operate at short wavelengths ($\lambda < 500$ μm), where junction chips can become fragile, some attention was given to developing a design which makes the junction chips mechanically robust. This requires, first, a small aspect ratio between the long and small dimensions; as well as minimizing the length of the chip, this leads to the use of a chip with a nearly square cross-section.

Additionally, because very fine dicing tolerances are difficult to meet, a design was sought in which the width of the substrate was not critical. These conditions, for thick substrates and loose constraints on the substrate width, led us away from suspended stripline designs, and to a "microstrip-in-a-box" configuration.

Figure 1 presents the design of the IF transmission line (RF block) in our 600-720 GHz mixer block. With the parameters shown, the effective dielectric constant is about 1.44 at the IF. At the time the RF filter structure was designed, we were considering both the use of thicker substrates and a smaller airgap, and using some dielectric to fill in the airgap. For this reason the filter section lengths are optimized for a somewhat higher effective dielectric constant. As a result the filter sections (shown in Figure 3) are shorter than optimal for blocking the 600-720 GHz TEM mode transmission down the line. However, these filter lengths should still work adequately well.

Scale Model Tests

We performed scale model tests on a 2.0 inch diameter circular waveguide mount. For this waveguide diameter, cutoff of the desired TE_{11} mode is at 3.46 GHz, cutoff of the TM_{01} mode is at 4.52 GHz, and the onset of higher order modes begins at 5.74 GHz. The TM_{01} mode has radial electric fields with a null in the electric field at the center of the waveguide; thus symmetric designs, which place the antenna feed point at the center of the guide, do not couple

to this mode. This arrangement makes possible moderately wideband circular waveguide mixers.

Figure 2 is a Smith chart showing the best results we obtained from a scale model. For a fixed-tuned mount matching to a detector impedance of 40 Ω, performance is reasonably good from 3.88 GHz to 5.46 GHz, a bandwidth of 40%. However, it is best from about 4.2 to 5.3 GHz; in this range the reflection coefficient from a 40 Ω detector is less than 5%. This corresponds to a bandwidth of 25%, slightly wider than the high-frequency atmospheric windows. Using this band would lead to a scaling factor of 140 for the 600-720 GHz window. However, we chose a slightly larger scaling factor, as the lower end of the 3.88-5.46 GHz frequency band was less sensitive to parameter changes in the substrate, antenna pattern, RF block, and backshort position. For instance, for the same scale model test shown in Figure 2, a small change in backshort position produces a good fixed-tuned match from 4.0 to 4.9 GHz at 43 Ω.

600-720 GHz Receiver

A mixer block of design closely similar to the optimal scale model design was acquired from Custom Microwave [2]. There were a few slight deviations. The most significant occurs in the RF block.. The smallest available slitting saw for cutting the slot for the RF block was 0.004 inch wide (0.102 mm). The slitting saw blades could be ground down to the proper size; however, at the time of ordering the vendor was reluctant to do this and we chose instead to receive a 0.102 mm wide slot and solder indium to the sides and bottom to reduce it to approximately the proper dimensions. This seems to have worked fairly well, at least in mechanical terms: by using a junction chip we have formed a rectangular slot of the appropriate size. The extra RF loss due to the indium walls of the slot actually improves the RF block.

The mixer block and junction chip layout of the 600-720 GHz mixer are shown in Figure 3. The waveguide is 0.326 mm in diameter; the RF block is 0.318 mm long. The design is not perfectly symmetric, as an indium press contact to ground is made just outside the waveguide wall on one side of the waveguide. However, this alteration did not seem to affect results in scale model tests, perhaps because the attenuation length in the RF block is relatively short (e-folding length less than 85 μm for non-TEM modes). This deviation from a symmetric design reduces the length of the junction chip, improving its mechanical strength, and also improves the thermal grounding of the junction. After passing through the RF block, the junction makes another indium press contact to an IF transmission line which is also a superconducting microstrip line. The substrate metallization faces the backshort.

AR-Coated Crystalline Quartz Lenses

Another novel feature of this receiver is its use of crystalline quartz lenses and windows AR-coated with a novel material, Teflon AF 1600 Fluoropolymer [3]. Teflon AF is a Teflon variant which is soluble in an inert solvent (we use Fluorinert FC-75, made by 3M and sold by DuPont). In solution, it can be spray- or drip-coated, and after baking (up to 300 C), it forms a strongly adhering film. We have cycled an AR-coated lens between nitrogen temperature and room temperature with no loss in adhesion. The coatings do not peel, even under scraping by a razor blade. However, they can be easily removed by overnight soaking in the solvent.

AR-coated quartz has some advantages over the competing technology of grooved plastic lenses. The anti-reflection grooves are difficult to machine at short wavelengths because the plastic deforms and does not cut cleanly. The plastics have a lower dielectric constant and consequently cannot reach focal lengths as short as quartz can. They have low thermal conductivity, and under radiative load are difficult to cool. The favorite material from a machinist's point of view, teflon, becomes lossy at high frequencies; while polyethylene, which has low loss, is more difficult to machine.

Crystalline quartz, on the other hand, has high thermal conductivity; lens surfaces can be polished to very high tolerances; and it has modest submillimeter loss even at room temperature and negligible loss at cryogenic temperatures. It is transparent to visible light, which is convenient. The loss due to birefringence in z-cut crystalline quartz is very small as long as all significant power lies in rays making an angle to the quartz optical axis of less than 10 degrees, which is easily achieved for typical receiver designs. (The loss due to birefringence goes as the fourth power of the angle to the optical axis.) Its liabilities, compared to plastic lenses, are the need to make an AR-coating, and the losses due to spherical aberration if (inexpensive) spherical surfaces are obtained from an optical lens maker. (Plastic lenses can very readily be machined to non-spherical surfaces.) The use of Teflon AF obviates the problem of AR-coating the quartz.

The calculated transmission through a 1.5 mm thick (two inch diameter) vacuum window AR-coated for 600-720 GHz is shown in Figure 4. It may be possible to reduce the thickness, which provides a somewhat conservative safety margin against rupture. Typical absorption losses are 3% at 660 GHz, while reflection losses are on the order of 1% within the band.

Reflectivity from a single AR-coated crystalline quartz surface was measured in a Fourier Transform Spectrometer. The reflectivity was nearly uniform at about 1.5 - 2% over a 40% band. Using indices of 1.38 for Teflon and 2.107 for z-cut crystalline quartz, one would expect a minimum reflectivity of 0.25% rising to 2% over a nearly 50% band from a perfect coating. We attribute the washing out of the resonance to nonuniformity in the Teflon film. When baked at 300

C, the Teflon film is a viscous fluid and can slowly flow to make a more uniform coating. However, if the substrate is not parallel to the ground, the Teflon also tends to flow toward the lower gravitational potential. To preserve the coating uniformity to within 10% (.008 mm) over a 2 inch aperture requires a flatness of 30 arcseconds, which is difficult to achieve. For this reason, it may be best to use relatively short bakes for very high-frequency coatings, in which case the coatings must be applied with a uniform spray-coating. An alternative we intend to investigate is using a lathe to machine down a thick coating to the proper thickness.

Conclusion

As we write, the receiver is very nearly complete and mixer measurements should begin shortly. Testing has been delayed by several problems typical when a new design, and receiver, are used for the first time. In addition to standard problems such as a backshort which froze up upon first cooldown, and the need to improve thermal conduction from the helium cold can to the mixer block, there were a few unexpected difficulties. A notable one was the poor mechanical robustness of the indium press contact on the IF transmission line in the mixer block. This superconducting line was made of niobium with a gold contact layer, and the gold was easily stripped from the niobium even by gentle nudges to the indium soldered to it. We are remaking the circuit with a niobium-aluminum-chrome-gold layering to improve the adhesion.

We expect to obtain mixing results within a few weeks. We expect that these will show that a circular waveguide mount can provide comparable performance to rectangular waveguide mounts, and can give us evidence of the utility of circular waveguide mounts at still higher frequencies.

References

[1] R. Blundell, C.-Y. E. Tong, D. C. Papa, R. L. Leombruno, X. Zhang, S. Paine, J. A. Stern, H. G. LeDuc, B. Bumble, *Fifth International Symposium on Space Terahertz Technology*, "A Wideband Fixed-Tuned SIS Receiver for 200 GHz Operation".

[2] Custom Microwave, Inc., 940 Boston Avenue, Longmont, CO 80501, USA.

[3] Du Pont Specialty Polymers, P. O. Box 80713, Wilmington, DE 19880.

[4] A. R. Kerr, *NRAO Electronics Division Internal Report*, No. 280, "An Adjustable Short-Circuit for Millimeter Wavelengths".

[5] J. W. Kooi, C. K. Walker, H. G. Leduc, P. L. Schaffer, T. R. Hunter, D. J. Benford, and T. G. Phillips, *International Journal of Infrared and Millimeter Waves*, **15**, 477 (1994).

[6] Morvan Salez, Pascal Febvre, William R. McGrath, Bruce Bumble, and Henry G. Leduc, *International Journal of Infrared and Millimeter Waves*, **15**, 349 (1994).

[7] K.-F. Schuster, A.I. Harris, and K.-H. Gundlach, *International Journal of Infrared and Millimeter Waves*, **14**, 1867 (1993).

[8] C.-Y. E. Tong, R. Blundell, D. C. Papa, J. W. Barrett, S. Paine, X. Zhang, J. A. Stern, and H. G. LeDuc, *Sixth International Symposium on Space Terahertz Technology*, "A Fixed Tuned Low Noise SIS Receiver for the 600 GHz Frequency Band".
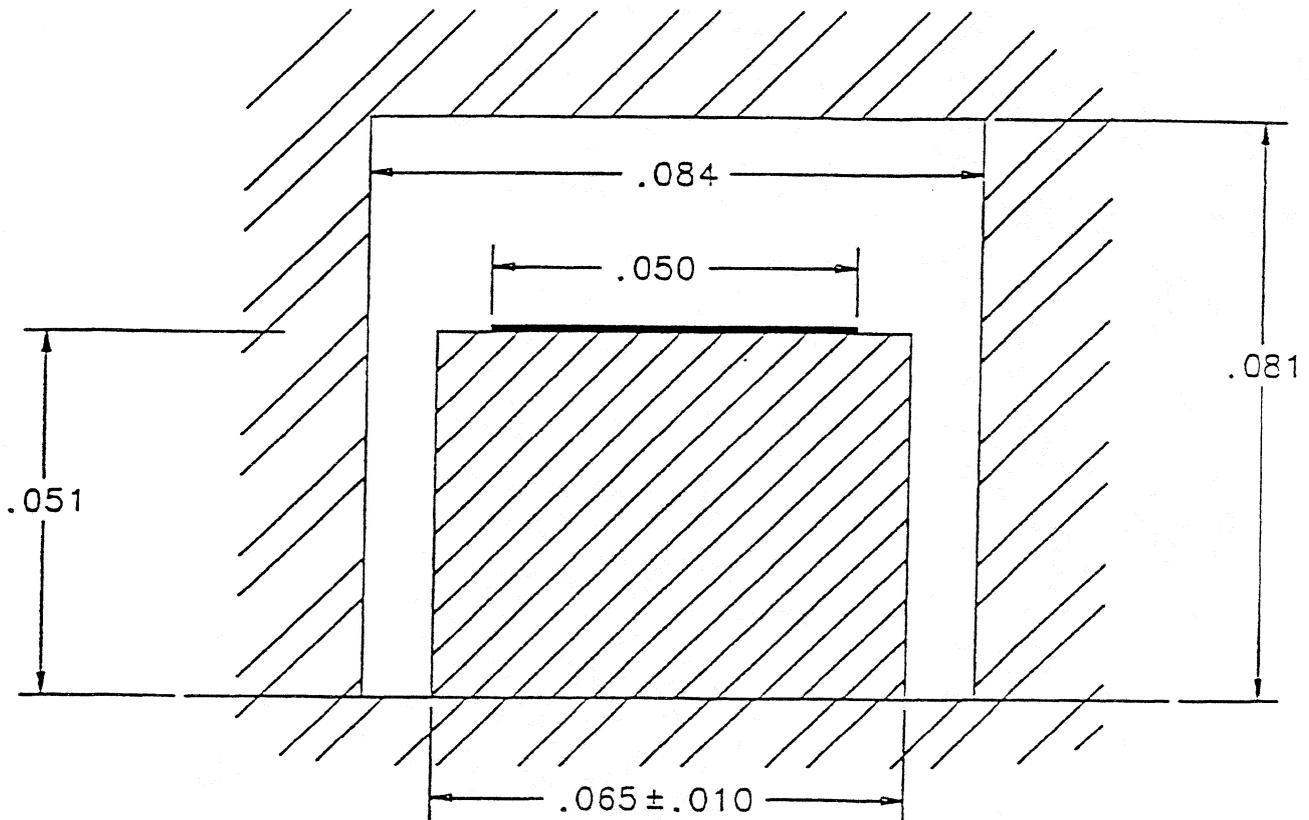
Figure 1: A cross-section of the RF block and IF transmission line used in the 600-720 GHz receiver. Dimensions are in millimeters. On a fused quartz substrate are filter sections alternately 2 μm and 50 μm wide. The cutoff frequency for non-TEM modes in this line is nearly 1.5 THz, well above the RF.

MARKER 1   MARKER 2
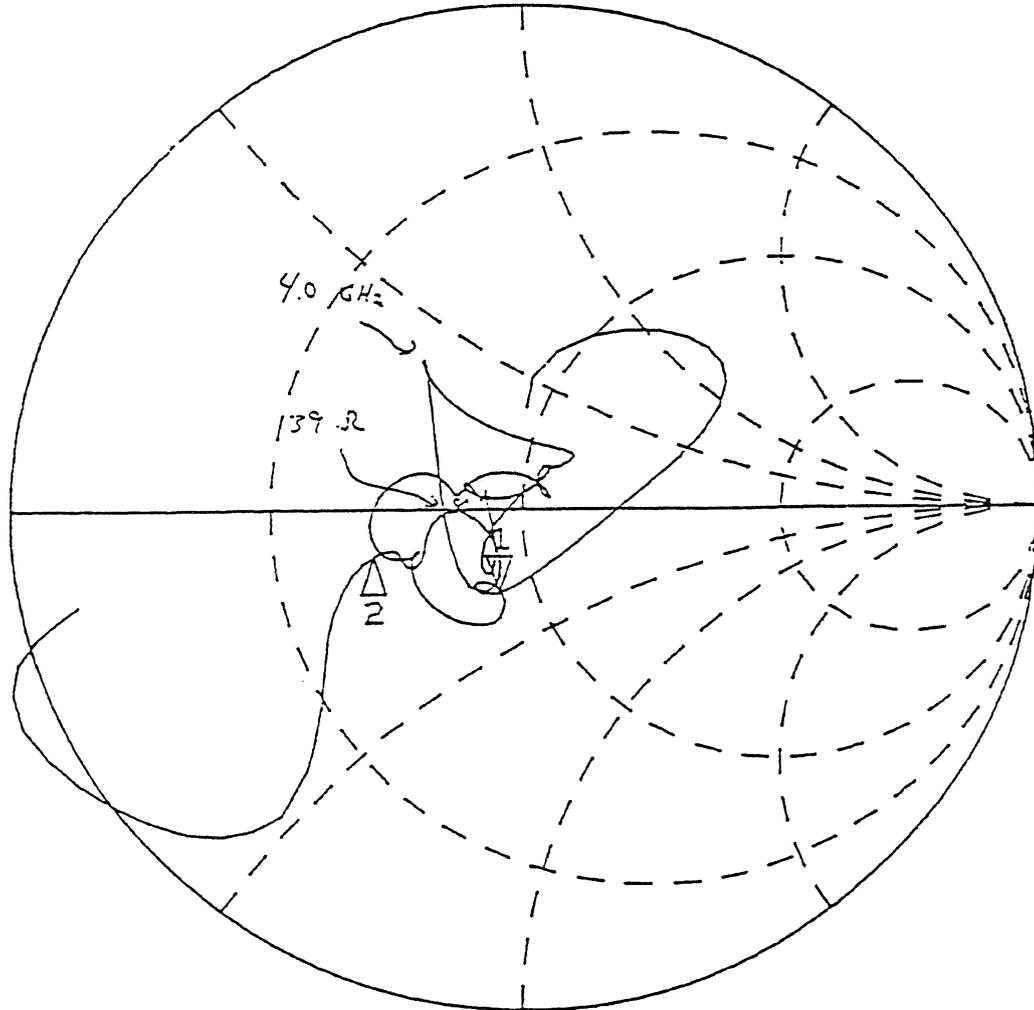
3.88 GHz   5.46 GHz

$43.3 - j\, 15.1\ \Omega$ $27 - j\, 5\ \Omega$

$4.2 - 5.3$ GHz $\times\ 140 = 588 - 742$ GHz

$R < 57\ to\ 40\ \Omega$

4.0 GHz

$139\ \Omega$

2

START   3.700000000 GHz

STOP   5.700000000 GHz

Figure 2: A Smith chart of the embedding impedance seen at the antenna feed point in the best scale model mixer mount. An impedance of 40 Ω makes a good match to the radiation over a nearly 40% bandwidth, and an excellent match over a 25% bandwidth.
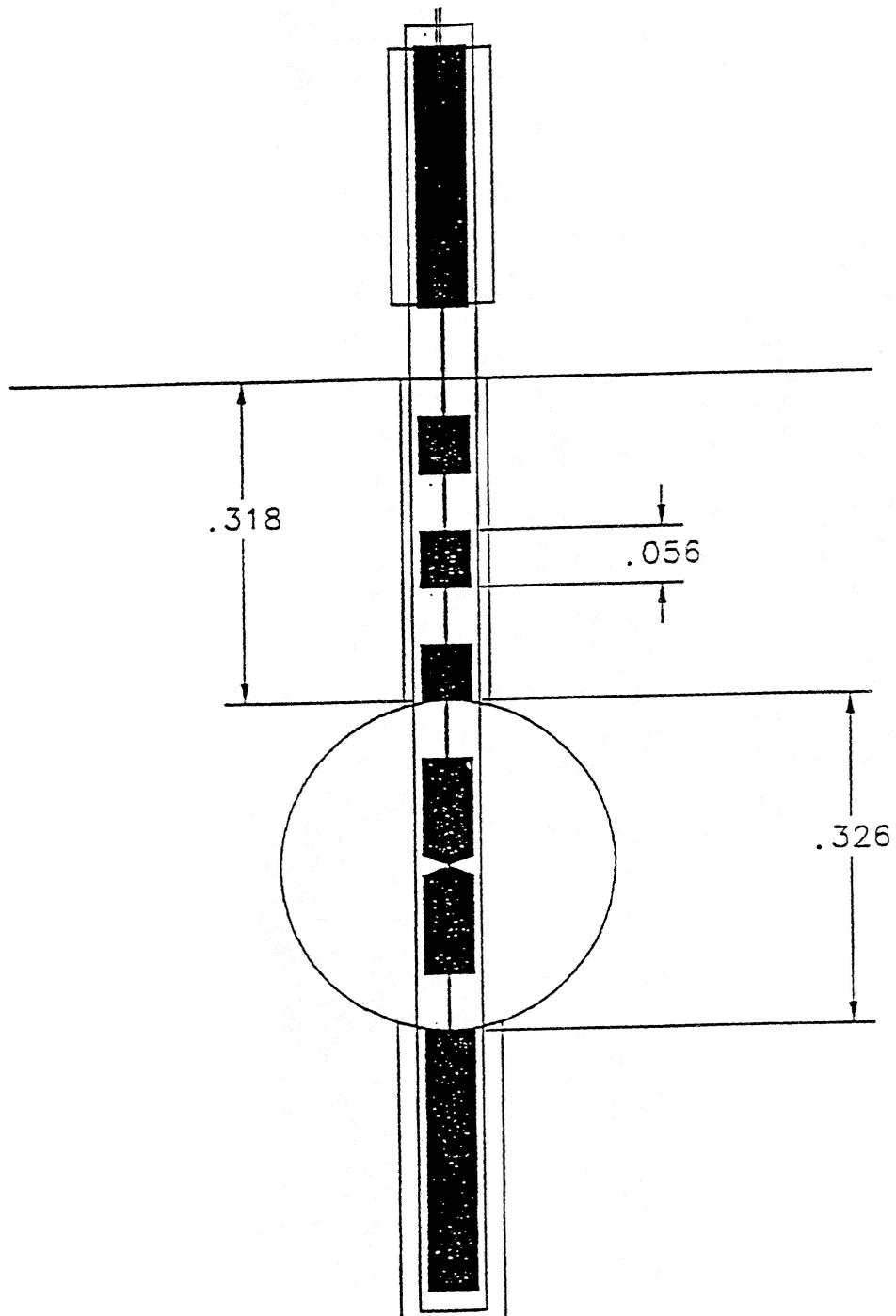
Figure 3: The layout of the 600-720 GHz mixer block and the junction chip metallization pattern. Dimensions are in millimeters. The junction chip makes indium press contacts at each end: at bottom, to ground; at top, to a superconducting microstrip IF transmission line.
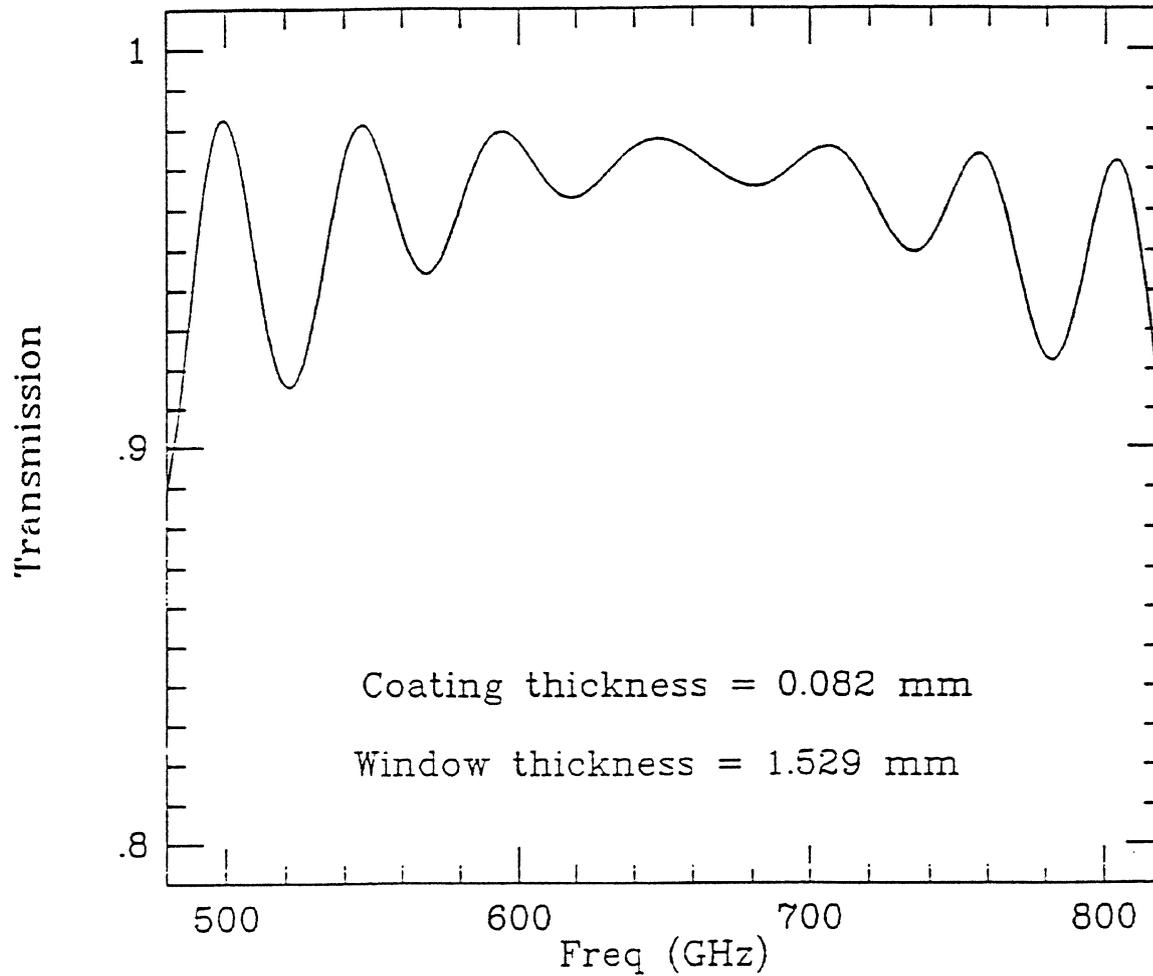
Figure 4: Calculated transmission through a 1.529 mm thick z-cut crystalline quartz vacuum window AR-coated with 0.082 mm layers of Teflon AF 1600 Fluoropolymer. Absorption losses are larger than reflection losses throughout the 600-720 GHz band.