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ALMA MEMO NO. 377

Design and Fabrication of Quartz Vacuum Windows with Matching Layers for Millimeter-Wave Receivers

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Abstract

Sensitive radio receivers operating at frequencies above approximately 100 GHz require the use of cryogenic detectors, often SIS mixers, cooled to liquid helium temperatures. A vacuum window is required to couple the radiant energy through the chamber walls to the detector element with as little loss as possible. While seemingly simple to make, the optimization of windows for high transparency and low leak rate is a non-trivial problem requiring the construction of multilayer dielectric structures.

The Atacama Large Millimeter Array (ALMA) telescope, to be built in Chile, will require over 600 vacuum windows covering ten frequency bands. In support of ALMA and its own in-house development needs, NRAO has developed a number of crystal quartz vacuum windows utilizing Zitex, Goretex, Teflon and other plastic antireflection coatings to improve the window's overall transmission within specific bands. The design, fabrication details and testing of some of these windows are discussed.

Introduction

For many years, NRAO has used plastic film vacuum windows on its millimeter-wave receivers [1]. The most recent version of this window has the plastic film vacuum barrier supported by a 0.125″ -thick sheet of open-cell expanded PTFE. Such windows offer very low absorption over a very wide frequency range, but are easily damaged and have a significant leak rate for air, water vapor, and helium. Cryogenic receivers using similar windows on the 12 Meter Telescope became noticeably less sensitive after one or two months of continuous operation, and required periodic warming up and evacuation to remove condensed air and water. The high permeability to helium precludes the use of a helium leak detector on receivers with such windows. For these reasons, plastic film vacuum windows are considered inappropriate for use on ALMA receivers.

To develop a more robust window with negligible air or helium leakage, we decided in 1996 to explore the use of crystal quartz with various antireflection layers to reduce the insertion loss within a desired frequency band. This report describes the design and construction of several crystal quartz multilayer windows. Some of these windows are now in use in VLBA receivers, and others are intended for use in receivers for testing the ALMA antennas and for production testing of SIS mixers for ALMA.

The Choice of Crystal Quartz

Crystaline quartz has very low loss at millimeter wavelengths and high physical strength [2-6]. The z-orientation was selected to minimize the effects of birefringence and so have minimal effect on the polarization of the incoming beam. With optically polished surfaces, a quartz window can be sealed to the cryostat using a standard O-ring. The minimum thickness of the quartz plate is determined by the desired clear aperture of the window and the safety factor, as described in Appendix 1. However, the relatively high dielectric constant, $\varepsilon_r = 4.45$ [2-6], causes large interference fringes to be generated so a quartz window requires matching layers to reduce the insertion loss. For narrow-band operation, a quarter-wave layer is needed with $\varepsilon_r = (\varepsilon_{r,\ quartz})^{0.5}$. To achieve wider bandwidth, multiple matching layers can be used if it is possible to find materials with the desired dielectric constant and low loss. The three- and five-layer windows described below use PTFE, high density polyethylene (HDPE), and expanded PTFE as matching layers.

Three-Layer PTFE/Z-Quartz/PTFE Window

The three-layer Teflon/z-Quartz/Teflon windows described here are currently in use on the VLBA receivers for the 80-96 GHz band. These windows consist of a z-cut crystal quartz plate, 0.2260″ thick. The minimum plate thickness was determined by the desired 3.5″ clear aperture as shown in Figure 7 of Appendix 1, and the thickness was *increased* slightly to optimize the performance as described below. Each face is covered with a Teflon layer 0.0220″ thick. Teflon, with a dielectric constant of 2.1 [7], is a nearly ideal antireflection layer. The construction is described in Appendix 2.

The goal was to keep the return loss of the window >20 dB and the absorption loss < 0.05 dB, for a total insertion loss < 0.1 dB, over the widest possible range within the WR-10 waveguide band (75-110 GHz), including the 80-96 GHz VLBA band. Note that a window at room temperature with an insertion loss of 0.1 dB adds approximately 7 K to the noise temperature of a low-noise receiver, assuming all power entering the receiver by reflection or scattering from the window originates at room temperature. The microwave circuit analysis program MMICAD [8] was used to simulate the window and optimize the thickness of Teflon and quartz for maximum transmission within the desired band. The resulting design allows machining errors of ±0.0002″ in the Teflon thickness without compromising the window specifications. A model calculation is shown in Figure 1.

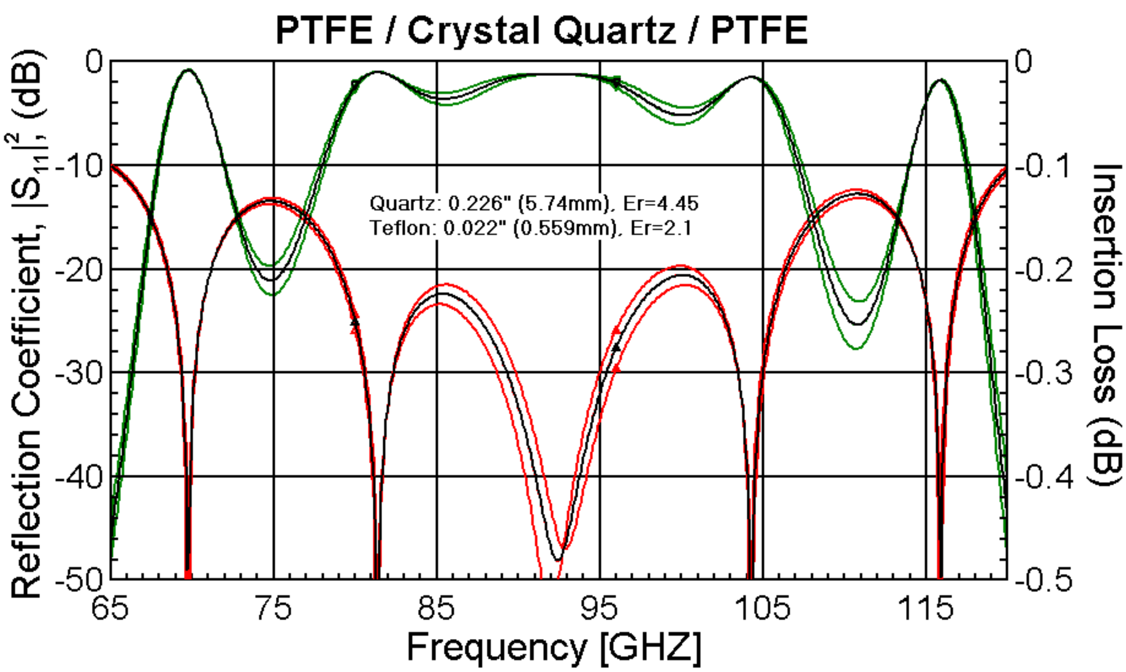

Figure 1. MMICAD model of a Teflon / quartz / Teflon window for the VLBA. Upper curve is insertion loss (right scale), and lower curve is reflection coefficient. Markers denote the edges of the 80-96 GHz VLBA band. Adjacent lines show the effect of changing the Teflon thickness by ±0.0002″, indicating the design tolerance to machining errors. Absorption of the glue is included.

The calculations in all of the figures shown here include the attenuation due to approximately 0.0002″ of EpoTek 301-2 epoxy used to bond the plastic to the quartz (see Appendix 4). Optical properties of the glue were measured on a Fourier Transform Infrared Spectrometer (FTS) from 300 GHz to approximately 1 THz and extrapolated to lower frequencies [9]. The dielectric constant of the epoxy is 2.8, and the attenuation is best fit by the expression

$$\alpha \text{ (dB / m)} = 2.10 f + 0.00571 f^2, \text{ …where f is the frequency in GHz.}$$

Measurements of the loss of a window with useful frequency resolution and amplitude accuracy are very difficult to obtain at millimeter wavelengths. Short of measuring the window one frequency at a time in front of a low-noise receiver, the best results have been obtained with a time-domain-gated vector network analyzer, as described in [10]. Results are shown in Figure 2 with the model calculation for comparison. Attenuation of the quartz and Teflon was taken from [2] and [7]. Within the ±0.1 dB accuracy of the measurements, the window performs as predicted. The quartz for this window was 0.22590″ thick, and the Teflon faces were 0.0220″ thick.

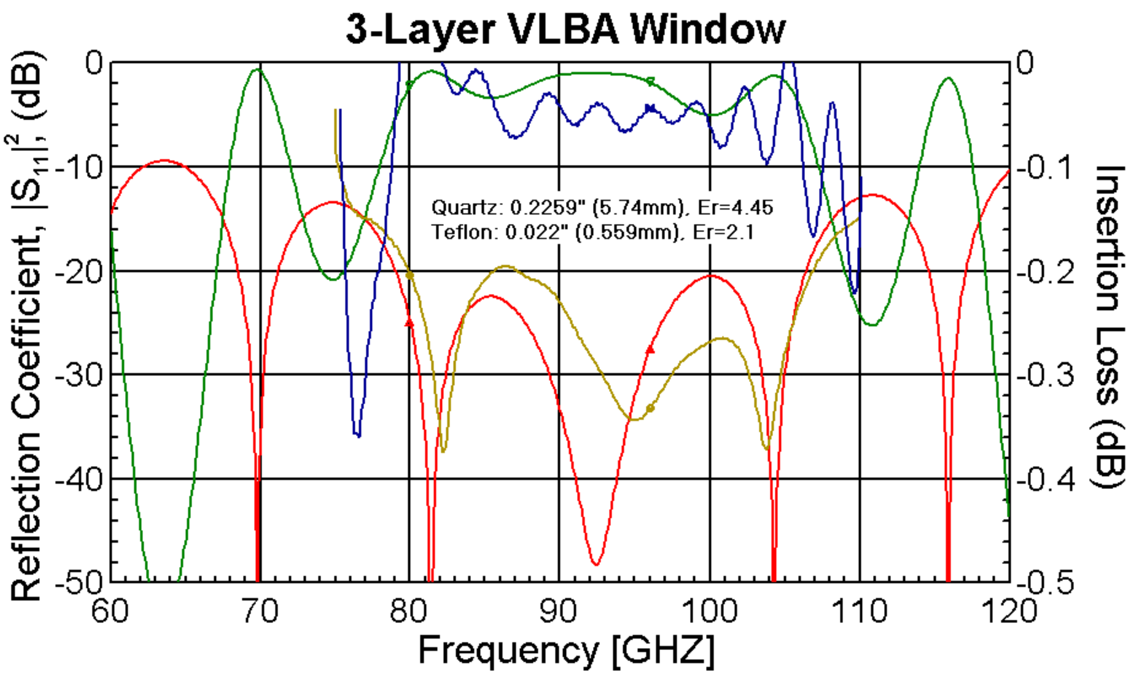

Figure 2. Predicted reflection coefficient and insertion loss of VLBA window "SN6," along with actual performance recorded on the HP 8510 network analyzer, as described in [10]. Blue and yellow curved represent the measured data.

The first three-layer windows had the Teflon AR layers completely covering both faces of the quartz. The vacuum seal was made by an O-ring in contact with the machined Teflon. Reports from the VLBA in February 2000 indicated that the windows had good vacuum integrity when delivered, but after six months to a year began to leak, sometimes significantly. Turned over in their frames, the windows again worked initially, but eventually began to leak again. It was determined that the leaks were due to the roughness of the machined Teflon surfaces; apparently vacuum grease would allow a good seal at first, but would gradually flow under pressure, opening small leaks. To remedy the problem, 0.55″ was removed from the diameter of the Teflon, leaving the quartz exposed in a 0.275″ ring at the edge of the window. The quartz produces a superior seal against the O-ring, as verified with a helium leak detector.

ALMA Evaluation Receiver

A three-layer window has recently been completed for 86-100 GHz to be used in the ALMA antenna test receiver. The window consists of a 0.226″ thick quartz plate, 3.75″ in diameter, faced with Teflon sheets, 0.023″ thick. The performance of this window, as measured on the HP 8510 network analyzer, is shown in Figure 3 and compared with the model calculations. Note that the bandwidth exceeds the requirements of the evaluation receiver, but not that of ALMA Band 3 (89-116 GHz[1]). In order to cover the ALMA bands, additional matching layers are required.

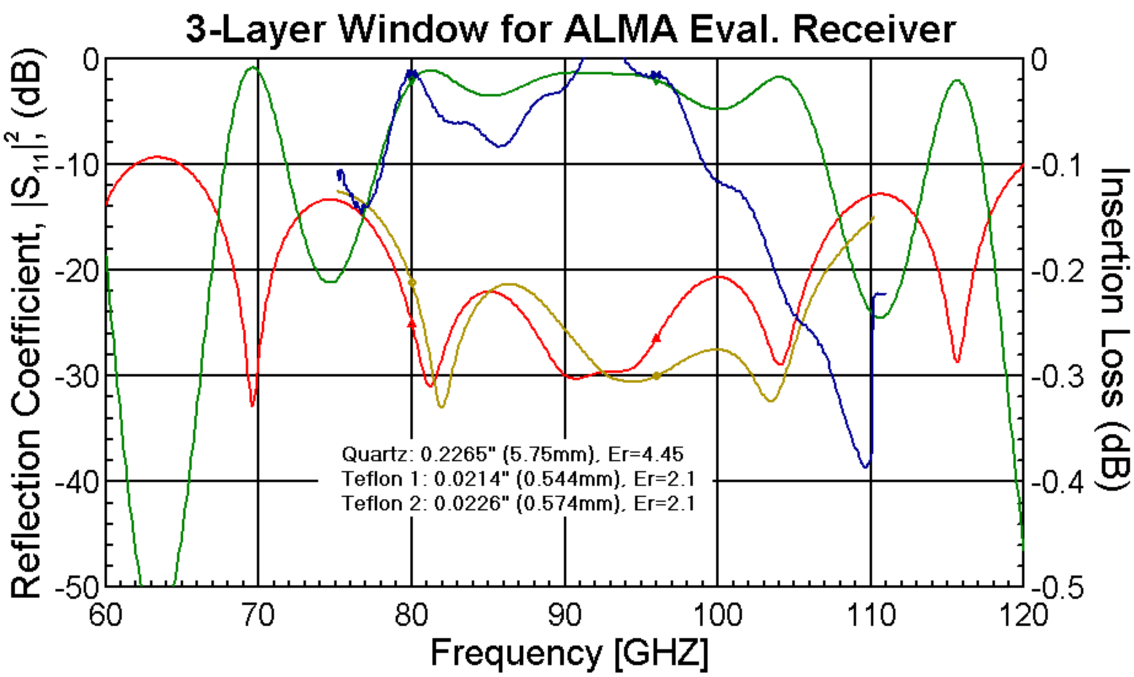

Figure 3. Simulated (green, red) and measured (blue, yellow) results for a three-layer Teflon / quartz / Teflon window for the ALMA evaluation receiver Band 3 (86-100 GHz). The quartz is 0.2265″ thick. Teflon AR layers are 0.0214″ and 0.0226″ thick, the latter having been made thicker to compensate for a thinner-than-desired layer 1.

Five-Layer Expanded PTFE/HDPE/Z-Quartz/HDPE/Expanded PTFE Window

For the relatively wide bandwidths of ALMA receivers, three-layer windows are insufficient to cover the full band and a five-layer design is required. The original five-layer designs at NRAO were for the proposed 4-beam 3-millimeter receiver for the 12 Meter Telescope, before it was decommissioned. These windows were to cover 86-116 GHz with <0.05 dB insertion loss and >20 dB return loss at the band edges. Few materials have suitable dielectric constant and low loss for antireflection layers; the best were high density polyethylene (HDPE) and Gore RA7957 Radome material[2], referred to here as “Goretex” [11,12]. Goretex is a pure expanded PTFE (X-PTFE) open-cell material made by a proprietary process. The slightly more complicated procedures for constructing a five-layer window are discussed in Appendix 3, and network analyzer data are compared with the model for an ALMA Band 3 window in Figure 4.

Discussion

As designs for new quartz vacuum windows progress towards higher frequencies, Goretex RA7957 becomes unsuitable as the outer layer for the five-layer windows as it is not available in thickness of less than 0.020″, precluding its use above approximately 200 GHz [12]. Fortunately, a similar expanded PTFE

[1] At the time of writing, there is a proposal pending to increase Band 3 to 84-116 GHz.

[2] There was considerable difficulty in obtaining Goretex in the appropriate thickness, and there is some question as to whether it will be available from the manufacturer in the future. See [12] for more details on this material.

material, known as Zitex-G, has been identified as a good candidate replacement [13]. Using methods similar to those described in [12], the dielectric constant of Zitex G has been found to be 1.45, slightly higher than that of Goretex. However, the material is much more mechanically robust than Goretex and is available in sheets as thin as 0.004″ and up, in increments of 0.002″. Using Zitex G-104 (0.004″ thick), a window has been designed for the ALMA evaluation receiver's 210-275 GHz band, and the model performance is shown in Figure 5.

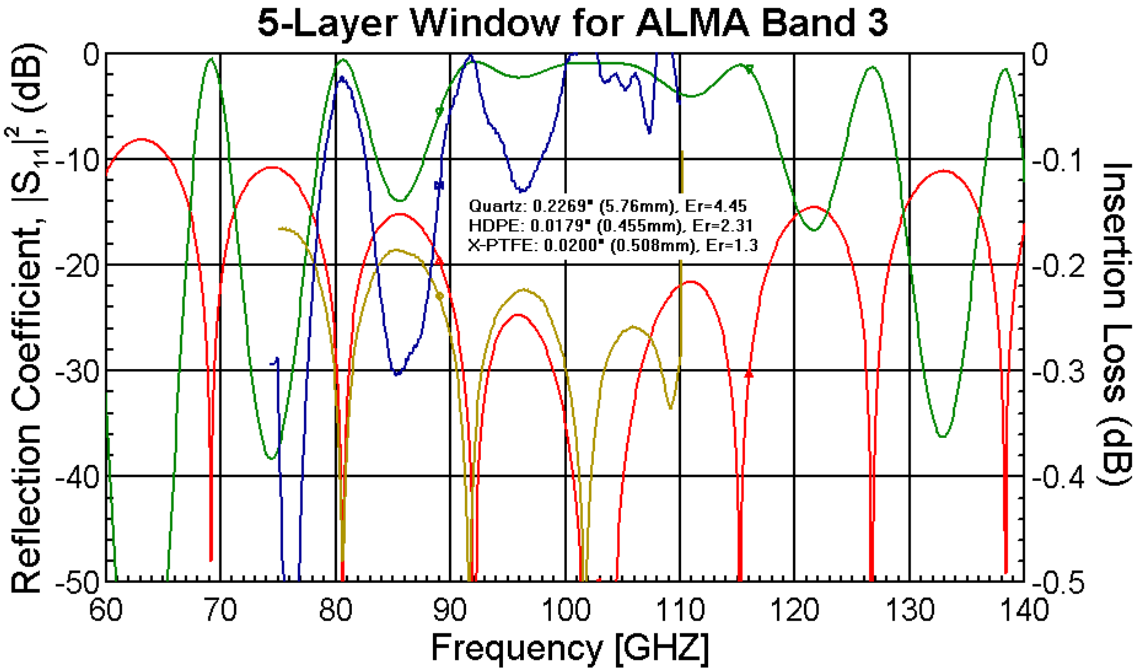

Figure 4. A five-layer window design for the ALMA 89-116 GHz band, utilizing Expanded PTFE / Polyethylene / Quartz / Polyethylene / Expanded PTFE. The expanded PTFE is Goretex RA7957, as described in the text. Thicknesses of layers are indicated in the figure.

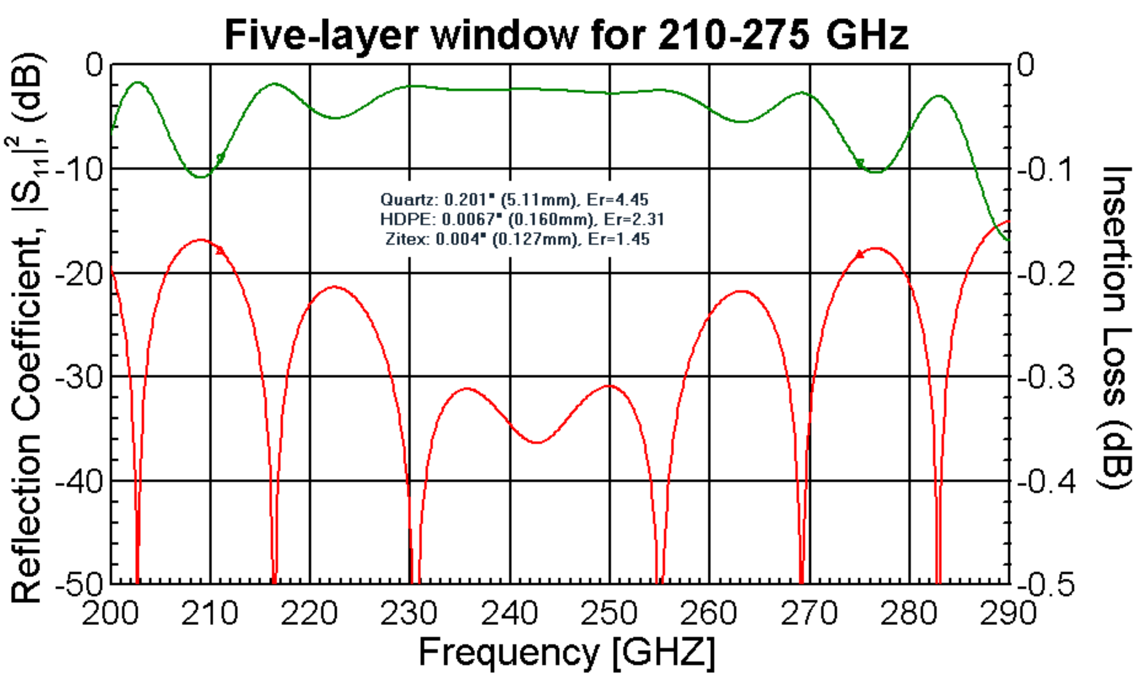

Figure 5. A five-layer window for the ALMA evaluation receiver's 210-275 GHz band, utilizing Zitex G-104 as the outer AR layers. Zitex G is an expanded PTFE material similar to RA7957, but available in thinner sheets.

At higher frequencies, wide bandwidth measurements of the window performance become increasingly difficult, and extending the network analyzer capabilities to each of the bands of interest becomes prohibitively expensive. A workable solution may be the use of a Fourier Transform Spectrometer (FTS) optimized for use at very long wavelengths. Figure 6 shows the MMICAD model calculations and

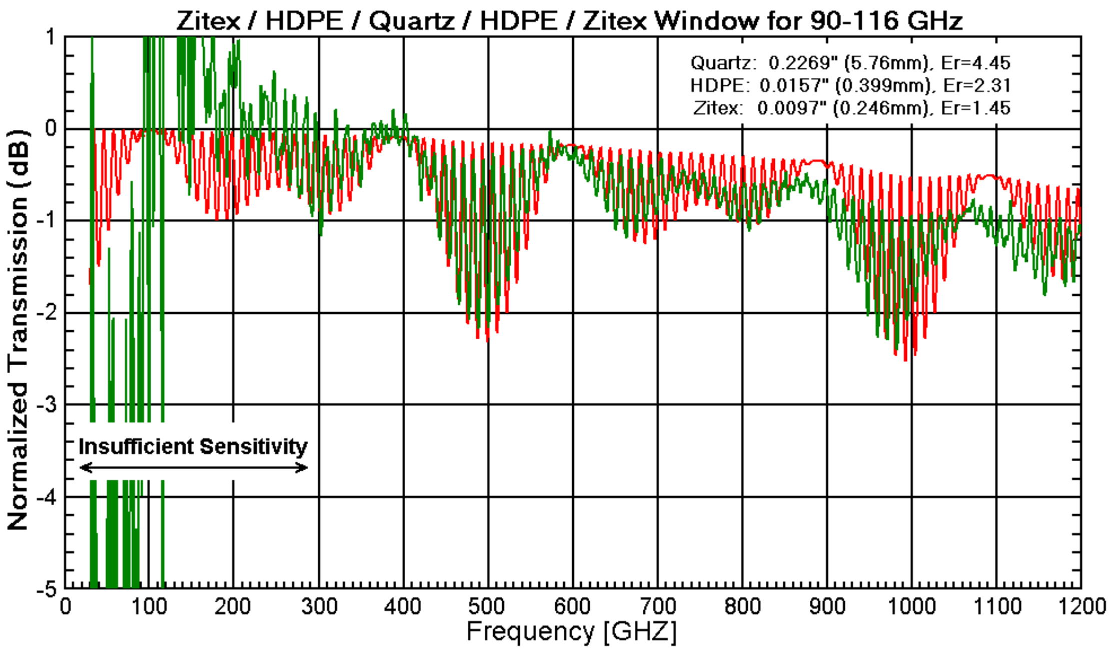

Figure 6. **Calculated (red) and measured (green) performance of a Zitex/HDPE/quartz/HDPE/Zitex window for the 90-116 GHz band. Due to lack of sensitivity, the long wavelength, high-resolution Fourier Transform Spectrometer was not capable of measuring in-band performance; however, it does confirm the very good agreement with the model.**

measured performance from 30-110 GHz of a five-layer window designed for the 90-116 GHz band. The instrument used was Science Tech STS-200 FTS, installed at the National Synchrotron Light Source at Brookhaven National Labs [14]. The instrument is, in theory, capable of $0.03 cm^{-1}$ (approximately 1 GHz) resolution with useable signal at frequencies above approximately 60 GHz. Numerous technical difficulties compromised the measurements of the window at low frequencies, but the second through fifth pass bands, centered around 385, 600, 890 and 1090 GHz, are clearly resolved. The data also show very good agreement between the modeled and actual window performance. An improved instrument is expected to function down to approximately 60 GHz, allowing verification of window designs at higher frequencies.

If a total insertion loss of 0.1 dB were allowed, it is expected that quartz vacuum windows could be designed up to at least Band 9 (600-720 GHz) using Zitex G in the five-layer configuration.

After we had completed most of this work, QMC Instruments [15] agreed to make multilayer quartz windows to specification. Tests of these windows were reported in [16]. The performance of the QMC windows was similar to that of our own 5-layer windows.

Appendix 1: Notes on Z-Quartz — Data, Calculations, Assumptions

The minimum thickness of the crystal quartz windows was chosen to withstand a pressure difference of 4 atmospheres, *i.e.*, with a safety factor of 4. Formulas for the stress in loaded circular plates with clamped and free rims are given in [17]. The tensile strength of z-cut crystal quartz was taken as 5400 PSI [18]. Figure 7 gives the minimum quartz thickness required to achieve a 4-atmospheres bursting pressure, as a function of the clear aperture, with clamped and free rims. Because the window clamping arrangement is always somewhat flexible, it is safest to assume a free rim and use the thicker quartz as required.

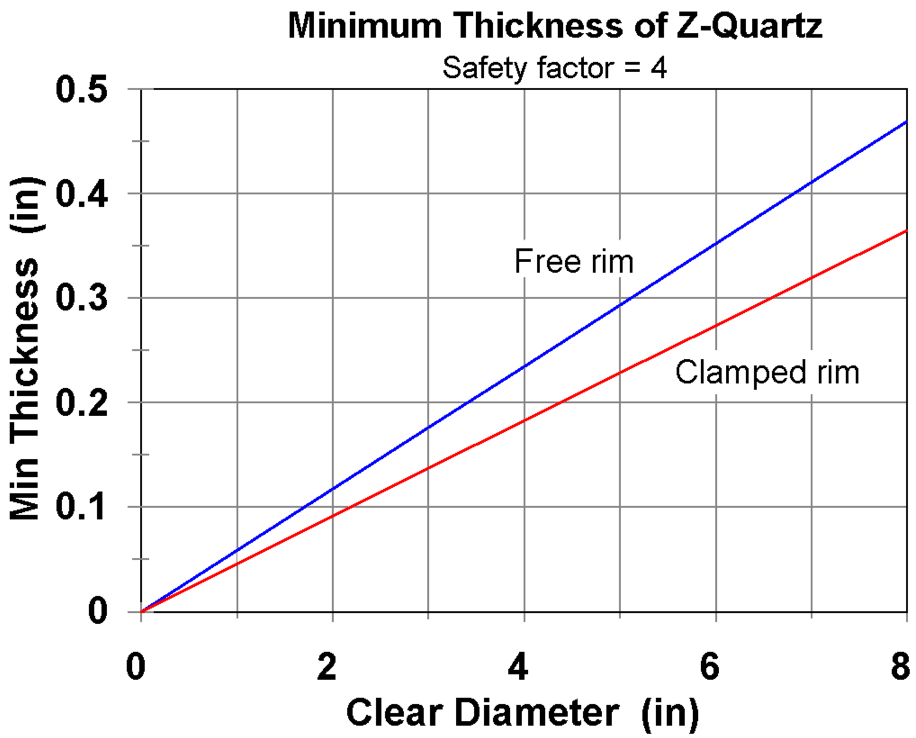

Figure 7. Minimum thickness of crystal quartz required to achieve a 4-atmospheres bursting pressure.

The quartz windows must have a diameter substantially larger than the clear aperture of the window to allow contact with a standard size O-ring. According to one supplier, quartz crystals larger than approximately 4.5″ diameter are very difficult to obtain. For the VLBA windows, having a diameter at the O-ring of approximately 4″, 0.225″ was chosen as the minimum thickness for the quartz, based on the figure above. The thickness was then *increased* using the MMICAD model as a guide to optimize the multilayer window.

Appendix 2: Construction of the Three-Layer PTFE / Z-Quartz / PTFE Window

Construction of the quartz vacuum windows might appear relatively straightforward, but there are many subtleties to the procedures that have been worked out over several years. For this reason, the complete procedure is described here in detail.

Preparing the Quartz:

Quartz blanks were obtained from Boston Piezo Optics (see Appendix 4). The blanks, as specified, vary in thickness by ± 0.0005″ and so must be measured accurately to make adjustments to the Teflon layer thickness as required by the model. Blanks are measured on a flat granite slab using an Ono-Sokki digital micrometer accurate to 50 microinches with a 0.125″ diameter flat foot. Calibration was checked using high precision gauge blocks.

After measuring, the quartz blanks are scrubbed on one side with a Kimwipe cloth soaked with hexane to remove fingerprints. If the quartz has not been handled with bare hands, this step can be omitted. The quartz is next scrubbed with acetone, using a Kimwipe, to remove more organics, then distilled water to remove the acetone, and isopropyl alcohol to dry the surface. After blowing the surface with clean nitrogen, blanks are baked for 1 hour at approximately 100 C in a vacuum oven at low pressure (approximately ½ atmosphere).

Preparing the Teflon:

Teflon sheets are obtained in pre-etched form (see Appendix 4). Discs are cut to approximately 1″ larger diameter than the quartz blank. The bonding surface, which should be brown and smooth, is cleaned and baked with the same procedure used for the quartz.

Preparing the Epoxy:

Epo-Tek 301-2 low-viscosity epoxy (Appendix 4) has been found to give the most consistent glue layer with the procedure described here. The layer is of uniform thickness, approximately 0.2 mils thick for the construction parameters given here, and free of bubbles and voids. As described in the epoxy instructions, mix 3.00 g of part A and 1.05 g of part B in a small container. Components are weighed to the nearest 10 mg on a digital balance, and part B is added by syringe to facilitate the operation. Approximately 2 g is needed for one surface, but the epoxy should not be mixed in quantities of less than approximately 4 g to insure accuracy in the mixture. The epoxy is stirred by hand for 5 minutes, and then vacuum degassed for approximately 1 hour. Pot life is well over 6 hours at room temperature so the epoxy can be left pumping longer if desired. Release the vacuum slowly to avoid trapping air in the degassed mixture.

Glueing PTFE to Quartz:

Glueing under pressure was found to be the best means of achieving a durable, bubble-free glue line. In order to reduce the curing time to approximately 12 hours, the press is heated to 65 C. Figure 8 shows a cross section of the various components of the press and window. An aluminum pressure distribution plate sits on the foot of the press. On top of that lies a piece of pressboard ceiling tile to serve as a thermal insulator. A thin film heater (McMaster Carr #35765K143) lies between the insulator and the bottom of the window jig.

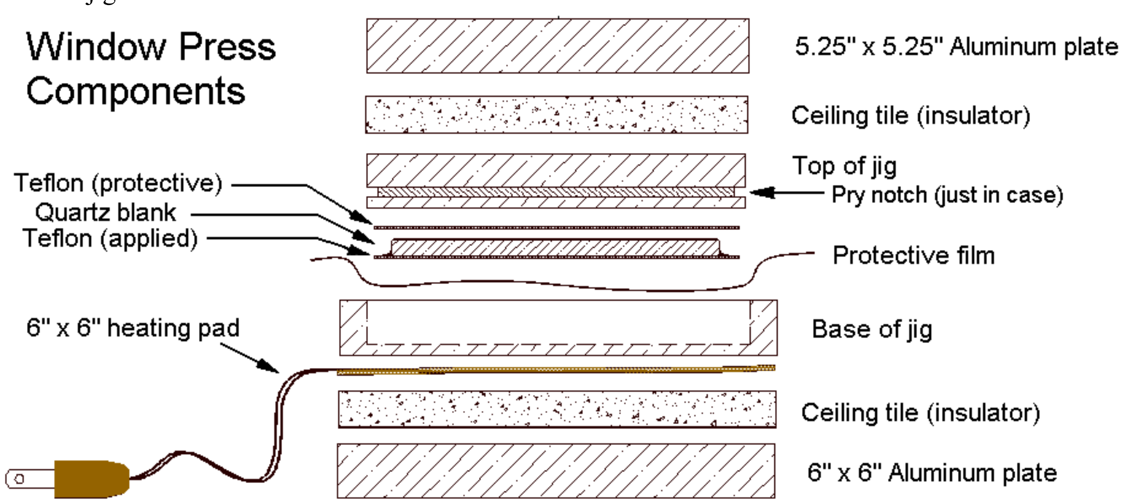

Figure 8. Components of the window press, in cross-section.

A wide piece of plastic film (Mylar or HR500 film) protects the jig bottom from epoxy overspill, and the inside of the jig is sprayed with a PTFE-based mold release agent. The Teflon sheet is placed glue-side up on top of the film and approximately 2 g of epoxy is poured out and allowed to spread to about half the window diameter. The quartz blank is laid gently on top of the epoxy and held centered while it settles. It can be pressed down to drive bubbles to the edge of the epoxy if desired, but this step is generally unnecessary, as the bubbles will be completely squeezed out under pressure. A spare piece of Teflon is placed on top of the quartz blank to protect the surface, and the press is closed with the top of the window jig, a piece of ceiling tile for thermal insulation, and the thicker aluminum pressure plate, in that order. A photograph of the assembled stack is shown in Figure 9.

Figure 9. **Photograph of the assembled window press. The Variac and heating pad are used to increase the temperature of the jig and so decrease the curing time of the epoxy. Note the thin film thermometer on the lower half of the jig.**

Pressure is applied to the air press from a regulator attached to a nitrogen cylinder and must be increased VERY SLOWLY to avoid smashing the piston into the jig and breaking the window. Pressure is raised slowly over the next 5-10 minutes to allow the glue to be squeezed out uniformly before reaching the final value of 30 PSI at the window surface. With a 4.5″-diameter quartz blank and the McMaster Carr #2373A14 press, the operating pressure corresponds to 35 PSI air at the 5" diameter piston. The air pressure must also work against the piston return spring.

The heater is turned on as soon as the press is assembled and remains on for 12 hours (typically overnight). A Variac was found to be an effective means of adjusting the temperature. For the 90 W heaters described in Appendix 4, a Variac setting of 32% typically stabilizes the jig temperature at 65 C within several hours. To aid in monitoring the temperature, a liquid-crystal self-adhesive thermometer strip is applied to the lower half of the jig. After at least 12 hours, the Variac is turned off and the jig allowed to cool for at least 2 hours before releasing the pressure.

Trimming and Machining the Teflon:

After removal from the press, excess Teflon is cut off with heavy-duty hand scissors as close to the window as the hardened epoxy will allow. The remaining epoxy must be ground off. It was found that sanding the epoxy off on a belt sander can compromise the bond layer, and can also cause chips at the edge of the quartz disk. Instead, a dedicated table router is used to grind the Teflon and epoxy away with a high-speed motion parallel to the window surfaces. A standard alumina grinding bit, with a ¼″ diameter shank, is mounted in place of the router bit. The router is additionally jigged to prevent grinding the quartz once all the excess epoxy is removed. The alumina grinding bits have little effect on the crystal quartz, but can cause small chips if the disk is forced.

Teflon can be machined on a lathe using a sharp high-speed steel tool. A vacuum chuck, custom made for a particular window diameter, is used to hold the window securely in place. A facing cut is first taken from the face of the chuck, and the digital gauges zeroed on that face. The quartz is wiped clean with acetone to remove grease and debris, and placed on the vacuum chuck for cutting. After the final cut, the window is removed from the chuck, and the edges of the Teflon are beveled with a razor blade. The window thickness as cut on the lathe is typically within ± 0.2 mils of the desired thickness. In the event that the Teflon is too thin, some compensation can be made by increasing the thickness of the Teflon on the opposing face, as determined by the model calculations (see, for example, Figure 3 above).

Finishing the Windows:

The second side of the window is completed just as the first side. The quartz must be cleaned to remove machine oil and fingerprints, and a new sheet of Teflon is glued on. As before, the Teflon to be applied is placed in the bottom of the jig to prevent epoxy from running onto the window, and a spare sheet of Teflon is placed on top to protect it. Additional care must be taken not to scratch the finished surface of the first side during pressing, grinding and machining.

After turning down the second surface, an annulus of Teflon is cut away around the perimeter to expose the quartz surface, which will contact the O-ring. This must be done slowly and carefully to avoid scoring the crystal. It is best to stop when most of the Teflon has been removed, exposing the brownish etched Teflon just above the epoxy. At this point, the epoxy can be scraped off manually with a razor blade. After a final degreasing and cleaning, the window is measured to confirm the total thickness and it is ready for testing (Figure 10).

Figure 10. **A nearly completed 4.5″ diameter, three-layer window for the VLBA. The outer surfaces are PTFE, which has not yet been trimmed for the O-ring seal.**

Appendix 3: Construction of a Five-Layer X-PTFE / HDPE / Z-Quartz / HDPE / X-PTFE Window

Construction of the five-layer windows proceeds in much the same fashion as the three-layer windows but differs significantly in the way the polyethylene and X-PTFE are handled. Like PTFE, polyethylene is extremely inert and its surface must be chemically activated to make bonds available for glueing. However, HDPE is not readily available in sheets with a pretreated surface, so it must be etched prior to use. The solution of choice is a chromic/sulfuric acid solution:

		Parts By Weight
H_2SO_4	(Sulfuric acid)	100
$Na_2Cr_2O_7 \bullet 2H_2O$	(Sodium Dichromate)	5
H_2O	(Water)	8

The solution should be mixed with care as it is an extremely strong oxidizer. When fresh, it is dark brown, and gradually becomes dark green upon exposure to air and in use – a practical indicator that it should be replaced. The solution will naturally etch through a polyethylene container and should be stored in safety-glass bottles. Note that in past decades Emerson and Cuming manufactured “Ecoprime PP” as a recommended treatment for polyethylene prior to bonding. Though the solution is no longer available, it appears to be very similar to the mixture above as deduced from the Material Safety Data Sheets.

The polyethylene sheets are cut from HDPE rod stock and turned on a vacuum chuck to approximately 20-mils thickness. They are then rubbed with an acetone-soaked Kimwipe to remove gross dirt and organics, then placed in the etching solution. The disks are etched for approximately 1 hour with intermittent stirring, then rinsed for 5 minutes under warm running water, and given a final rinse with distilled water. Baking is *not* recommended for the surface-treated polyethylene, nor is wiping the surface. Instead, the windows should be blown dry with clean nitrogen gas. If a bake is necessary to dry them, the temperature should be kept at approximately 50 C.

The polyethylene is applied to the quartz with Epo-Tek 301-2 epoxy, as the Teflon. Machining the polyethylene layers to the desired thickness is more complex, however. The trimmed window is first chucked in the lathe and the polyethylene turned down to be approximately 1-2 mils thicker than desired. Machining HDPE on the lathe leaves undesirable tool marks, a surface which is convex near the center, and other features greater than 1 mil in height. As a result, the plastic must be ground to the correct thickness on a surface grinder. The proper grinding wheel to use is designated #32A46-GVBEP (see Appendix 4), operated at 2850 RPM (1492 in/sec at the wheel surface). Feed rates are on the order of 10 inches/sec longitudinal, and 1 inch/minute transverse. Only 0.2-mils may be removed per pass or scoring will result.

To apply either Goretex or Zitex outer layers, a minimal glue transfer method is used to minimize the amount of glue available to soak into the porous materials. The polyethylene-covered window is given a 5-minute etch in the chromic/sulfuric acid mixture, rinsed, and baked 30 minutes at 50 C under a partial vacuum of approximately ½ atmosphere in a vacuum oven. Epo-Tek 301-2 epoxy is prepared in the usual manner, and about 2 drops of it are squeezed between a pair of 6″-diameter, 3/8″-thick aluminum disks for 1 minute at 40 PSI air pressure in the air press. The excess is wiped from around the disk edges, and the disks are pried apart. X-PTFE disks, pre-cut to match the diameter of the window, are pressed against the glue surface for 1 minute at 10 PSI air to transfer the epoxy. The X-PTFE disks are then placed on their respective quartz window faces. The window is sandwiched in the air press with Goretex sheets protecting the window faces, and the press is operated at 10 PSI air overnight with the heater set to approximately 65 C. At the time of publication, the glue transfer technique is still being refined. The technique described transfers approximately 0.0003" of glue to the X-PTFE surface as determined by weighing the disks before and after application of the epoxy.

To complete the window, the plastics are trimmed from the window to expose the quartz sealing surface, as for the three-layer window. The expanded PFTE will not cut off neatly with the turning tool on the lathe, so it must first be sliced with a razor blade and peeled off. The HDPE can then be turned down to the quartz with a standard tool to expose the O-ring contact surface. Final cleaning of the sealing surface is done by hand with a razor blade.

Appendix 4: Sources of Materials

Quartz: Obtained from Norman Benoit and Steve Wickstrom of Boston Piezo Optics, Medway, Massachussetts. In March of 2001, the facilities are expected to move to Bellingham, MA, (508) 966-4988.

Teflon: McMaster-Carr #8711K12. 12″ x 12″ x 1/32″-thick sheet, etched on one side. Also available in 0.015″ and 0.020″ thicknesses.

EpoTek 301-2 is available from Epoxy Technology, Inc., 14 Fortune Dr., Billerica, MA 01821-3972. 301-2 is a two-part, slow-curing optical epoxy.

Heating Pad: McMaster-Carr Model #35765K143. 6″ x 6″ semi-flexible rubberized heating pad, 2.5 Watt/square inch.

Press: Air Mite, Model # AP 19, Air Mite, Chicago, IL 60641. 2″-stroke, 5″-diameter cylinder, 120 PSI maximum pressure. Available as McMaster-Carr #2373A14.

Grinding wheel: Sears Craftsman. ½″ diameter x 1-½″ long with ¼″ shank. Aluminum oxide.

Router: Sears Craftsman router, Model #917506. 2-HP, variable speed, with work light and dust collection. 15,000 – 25,000 RPM, run at its fastest speed for removing epoxy. Cheaper models don't have the dust collection system which is essential.

Router table: Sears Craftsman router table, Model #925560. 13″ x 18″ with adjustable fence.

Grinding wheel: Norton Bonded Abrasives, Worcester, Massachussetts, (508) 795-5000. The applications engineer checked the records and recommended a 32A (Aluminum Oxide), 46 grit, G hardness, Vitrified (V) bonded wheel with a porous structure. The complete designation of the wheel is: 32A46-GVBEP. In a 10″ x 1″ x 3″ wheel, the 10-digit ID number is 6253160932. The wheel is available from Manhattan Supply Company (MSC) as part number 05986013.

Polyethylene: High-density polyethylene (HDPE) rod stock. Avoid sheet stock due to the possibility of polarization effects caused by the extrusion process. McMaster-Carr #8624K56, 5″ diameter.

Goretex: See [11].

Zitex: See [13]. Zitex G is available in thicknesses of 4, 6, 8, 10, 15 mils, and larger thicknesses up to 150 mils. A 5″-wide, 26-foot long roll of Zitex G110 (10 mils) is the minimum order available.

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