ALMA MEMO NO. 397

Proposed Quartz Vacuum Window Designs for ALMA Bands 3 – 10

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Abstract

This memo describes the design of Z-cut crystal quartz vacuum windows with plastic antireflection layers for ALMA Bands 3 through 10. The windows can be made using readily available materials and proven construction techniques. Model calculations for each of the bands are presented showing the expected reflection loss and total insertion loss.

Introduction

Low loss vacuum windows utilizing Z-cut crystal quartz, coated with antireflection layers, have been proposed for use in ALMA Bands 3 through 10. NRAO has been using large diameter 3-layer PTFE/Z-Quartz/PTFE windows on the VLBA 3-mm receivers for several years and, more recently, 5-layer windows have been made for the ALMA Band 6 evaluation receiver. Construction of these multilayer windows has been described in detail in ALMA Memo 377 [1]. Discussed below are proposed designs for realizable vacuum windows using readily available materials for ALMA Bands 3-10. Bands 1 and 2 are expected to use plastic lenses as vacuum windows and are not considered here.

Design Procedure

ALMA Memo 362 [2], Table VIII, lists the window sizes required for the ALMA receivers. Memo 362 has several discrepancies between the figures showing the optical layouts which specify the clear apertures, and Table VIII. For Band 6, the clear aperture derived from Table VIII (60 mm) is greater than that specified in Figure 4 (44 mm). For Band 9, the clear aperture derived from Table VIII (18 mm) is much less than that shown in Figure 7 (26 mm). (Note the clear aperture for Band 3 is only specified in the table.) The values in Table VIII have been used as a basis for the thermal loading calculations, and this report uses the same values for the window designs.

Figure 1 shows the dimensions relevant to the mechanical design of a vacuum window. The diameter, $\mathbf{D_Q}$, of the quartz disk required for a vacuum window depends on the required clear aperture, **CA,** and the O-ring size. In Britain and the United States, O-rings are generally specified in English measure and only a few sizes of metric O-rings are available as standard off-the-shelf components. Only standard English size O-rings, of thickness $\mathbf{t_r}$ = 0.070" (1.8 mm), selected from the Parker catalog [3], were used in these designs. According to Parker, it is permissible to stretch O-rings by as much as 5%, and that is taken into account in the selection of O-rings. The minimum wall thickness, $\mathbf{t_w}$, between the clear aperture and the O-ring groove was set at 1.6 mm (1/16"). The width of the O-ring groove in this application is 0.087" (2.2 mm) to allow for O-ring compression.

The thickness of quartz required to support a pressure of 1 atmosphere, with a (pressure) safety factor of 4, is 0.059 times the diameter of the unsupported part of the quartz [1]. The conservative assumption was made that the quartz is supported at the diameter, $\mathbf{D_R}$, of the O-ring, and that its rim is unconstrained (not rigidly clamped). Table 1 summarizes the required quartz dimensions and O-ring sizes, allowing a 1.6 mm (1/16") clear radius outside the O-ring groove.

MMICAD [4] was used to optimize the thickness of the quartz and antireflection layers with the goal of keeping the total insertion loss less than 0.1 dB and the overall reflection loss greater than 20 dB across the band. To provide a conservative estimate of the RF loss at all frequencies, the model considers losses in all the materials [1], including 0.0002" of epoxy between each of the bonded surfaces. Note that only available thicknesses of Zitex were used because of the difficulty of machining that material.

At higher frequencies, the glue layer between the quartz and the plastic becomes a significant fraction of the thickness of the antireflection layer. In practice, however, the dielectric constant of the glue is similar to that of PTFE or HDPE and so the two layers are treated as one in determining the thickness to which the PTFE or HDPE is machined. In the 5-layer window, the behavior of the second glue layer is harder to predict as it is partially absorbed into the Zitex. Consequently, no correction was made to the HDPE thickness for the second glue layer. However, the second glue layer is included in the model to improve the accuracy of the loss calculations.

Window Performance

Table 2 summarizes the results of the MMICAD optimization. For each band, the thicknesses of the quartz and antireflection layers are given in mils (Table 2a) and mm (Table 2b). Note that in almost every case, the quartz thickness has been optimized by *increasing* it over the minimum allowed value for the given clear aperture. This would allow the window diameters to be increased slightly, if necessary. The final column indicates the maximum possible clear aperture, allowing for the O-ring thickness and a supporting wall. The details of the individual bands are discussed below.

Figures 2-10 show the results of the MMICAD simulation for each of the multilayer windows. In all figures, red curves indicate reflection loss, plotted on the left axis, while the green curves show the total insertion loss, plotted on the right, as a function of frequency. Triangular markers indicate the ALMA band edges as summarized in Table 2.

Band 3 (Figure 2) is covered effectively by a 5-layer window with < 0.05 dB insertion loss and > 20 dB reflection loss at the 89 and 116 GHz band edges. A recent proposal extends the coverage of this band down to 84 GHz [5]. The band is still effectively covered with a slightly modified design and some increased reflection loss at the band edges, shown in Figure 3. Note that the insertion loss remains within the 0.1 dB goal across most of the band.

Band 4 (Figure 4) is well behaved and falls well within specification across the band. Like the Band 3 design, this window is expected to be made using Zitex G-110, with a measured thickness of 0.0097" (0.246 mm).

Band 5 (Figure 5) utilizes Zitex G-104 for the outer layers. This material has a measured thickness of 0.00445" (0.113 mm), though note that in practice the material thickness may be sample dependent. The insertion loss is within specification and there is only a slight deterioration due to reflection loss at the band edges.

The Band 6 window (Figure 6) is similar to that for Band 5.

Band 7 (Figure 7a) has a relatively wide fractional bandwidth of 29%, so its insertion loss increases to 0.14 dB at the band edges. Note, however, that this window was designed using the actual measured thickness of 0.00445" (0.113 mm) for the Zitex G-104. Slightly better performance could be achieved if the Zitex thickness were held to its nominal 0.0040" (0.102 mm) value, and an Idealized calculation is shown in Figure 7b.

At higher frequencies, the increased loss of the second antireflection layer and the glue necessary to apply it tend to counter the effect of the increased bandwidth provided by the 5-layer window. Bands 8 – 10 are best covered with 3-layer windows utilizing PTFE for the single antireflection coating.

Performance of a 3-layer design for Band 8 is shown in Figure 8. Note that for this band, the quartz thickness is at the minimum safe value. Though the design meets the 0.1 dB insertion loss and > 20 dB reflection loss specification, performance could be improved at the band edges by making the quartz thinner.

For Bands 9 and 10, higher insertion loss due to absorption in the materials is more substantial, though it remains less than 0.2 dB across the band, and the reflection loss is > 20 dB as shown in Figs. 9 and 10.

Discussion

The window designs presented here were all calculated assuming normal incidence. It is expected that the windows will be tilted at a small angle to reduce interference from window reflections. A proper calculation of the effects of tilting the beam on the window is beyond the scope of this memo. To verify that no significant problems occur when the window is tilted, a simplistic calculation was performed by considering changes in the effective thickness of the materials seen by a refracted beam traversing the window. Tilt angles up to 15 degrees were considered, corresponding to the angle at the outer edges of a (geometric) F:2 light cone. The changes in window performance were found to be negligible. The result is expected because the large dielectric constant of the quartz ensures that the beam remains nearly normal to the surface within the disk. A more thorough calculation should consider the relative phase changes of the portions of the light cone as they cross the window. However, the estimated tilt effects were found to be too small to pursue further.

References

[1] Daniel Koller, A. R. Kerr, G. A. Ediss, and D. Boyd, “Design and Fabrication of Quartz Vacuum Windows With Matching Layers for Millimeter-Wave Receivers,” ALMA Memo 377, June 2001. Available on-line at http://www.alma.nrao.edu/memos/

[2] J. W. Lamb, A. Baryshev, M. C. Carter, L. R. D’Addario, B. N. Ellison, W. Grammer, B. Lazareff, Y. Sekimoto, C. Y. Tham, “ALMA Receiver Optics Design,” ALMA Memo 362, April 2001. Available on-line at http://www.alma.nrao.edu/memos/

[3] Parker Hannifin Corporation, O-ring Division, 2360 Palumbo Drive, Lexington , KY 45012. http://www.parker.com/O-ring.

[4] MMICAD is a microwave circuit analysis and optimization program available from Optotek, Ltd., 62 Steacie Drive, Kanata, Ontario, Canada K2K 2A9. http://www.optotek.com/

[5] ALMA Project Book, Engineering Specifications, Ch. 2. http://www.alma.nrao.edu/projectbk/construction/chap2/chap2.2/chap2.2.pdf, Nov. 6, 2001.

Tables and Figures

Table 1a. O-ring and window diameter selection process, in English units

Band	Area (in.^{2})	Clear Aperture (in.) CA	O-ring (Parker #)	Nominal O-ring ID (in.)	% stretch in length	Effective Dia. (in.) D_R	Quartz Dia. (in.) D_Q	Minimum Quartz thickness (in.) t_Q
3	3.82	2.205	2-035	2.239	4.1	2.400	2.750	0.141
3a	3.82	2.205	2-035	2.239	4.1	2.400	2.750	0.141
4	3.82	2.205	2-035	2.239	4.1	2.400	2.750	0.141
5	4.38	2.362	2-037	2.489	-	2.557	3.000	0.150
6	4.38	2.362	2-037	2.489	-	2.557	3.000	0.150
7	1.49	1.378	2-029	1.489	0.9	1.573	2.000	0.092
7a	1.49	1.378	2-029	1.489	0.9	1.573	2.000	0.092
8	0.95	1.103	2-026	1.239	-	1.298	1.625	0.076
9	0.39	0.708	2-019	0.801	4.0	0.903	1.250	0.053
10	0.27	0.591	2-018	0.739	-	0.786	1.125	0.046

Table 1b. O-ring and window diameter selection process, in metric units

Band	Area (mm^2)	Clear Aperture (mm) CA	O-ring (Parker #)	Nominal O-ring ID (mm)	% stretch in length	Effective Diam. (mm) D_R	Quartz Diam. (mm) D_Q	Minimum Quartz thickness (mm) t_Q
3	2463	56.0	2-035	56.9	4.1	60.95	69.9	3.58
3a	2463	56.0	2-035	56.9	4.1	60.95	69.9	3.58
4	2463	56.0	2-035	56.9	4.1	60.95	69.9	3.58
5	2827	60.0	2-037	63.2	-	64.95	76.2	3.82
6	2827	60.0	2-037	63.2	-	64.95	76.2	3.82
7	962	35.0	2-029	37.8	0.9	39.95	50.8	2.35
7a	962	35.0	2-029	37.8	0.9	39.95	50.8	2.35
8	616	28.0	2-026	31.5	-	32.96	41.3	1.94
9	254	18.0	2-019	20.3	4.0	22.94	31.8	1.35
10	177	15.0	2-018	18.8	-	19.97	28.6	1.17

Table 1. Physical dimensions used in the mechanical design. Clear Aperture, **CA**, is derived from ALMA Memo 362, Table VIII. The "Effective Diameter," $\mathbf{D_R}$, is the effective size of the quartz disk under vacuum, and is used to calculate the minimum quartz thickness required, $\mathbf{t_Q}$, for a safety factor of 4. "Quartz Diameter," $\mathbf{D_Q}$, is the suggested diameter of the quartz blank, allowing for a minimum 1/16" (1.6 mm) clearance outside the O-ring groove.

Table 2a. Window layer thicknesses, in English units						
Band	Frequency (GHz)	Bandwidth (%)	Material Thicknesses (mils)			Maximum Safe Clear Aperture (in.)
			Quartz	HDPE	Zitex	
3	89 - 116	26	231.7	15.3	9.7	3.75
3a	84 - 116	31	236.2	15.8	9.7	3.83
4	125 - 163	26	212.4	9.7	9.7	3.42
5	163 - 211	26	209.0	8.5	4.45	3.36
6	211 - 275	26	201.0	6.0	4.45	3.23
7	275 - 370	29	103.6	4.0	4.45	1.57
7a	275 - 370	29	103.1	4.2	4.0	1.56
			Quartz	PTFE		
8	385 - 500	26	76.0	4.5		1.10
9	602 - 720	18	76.2	2.9		1.10
10	787 - 950	19	61.0	2.2		0.84

Table 2b. Window layer thicknesses, in metric units						
Band	Frequency (GHz)	Bandwidth (%)	Material Thicknesses (mm)			Maximum Safe Clear Aperture (mm)
			Quartz	HDPE	Zitex	
3	89 - 116	26	5.885	0.389	0.246	95
3a	84 - 116	31	5.999	0.401	0.246	97
4	125 - 163	26	5.395	0.246	0.246	87
5	163 - 211	26	5.309	0.216	0.113	85
6	211 - 275	26	5.105	0.152	0.113	82
7	275 - 370	29	2.631	0.102	0.113	40
7a	275 - 370	29	2.619	0.107	0.102	40
			Quartz	PTFE		
8	385 - 500	26	1.930	0.114		28
9	602 - 720	18	1.935	0.074		28
10	787 - 950	19	1.549	0.056		21

Table 2. Thickness of the materials used in the 3- and 5-layer windows, as a function of band. The quartz thickness in each design allows a “Maximum Clear Aperture” which is larger than the specifications in Table VIII of ALMA Memo 362 for all bands except Band 8. 5-layer (Zitex / HDPE / Quartz / HDPE / Zitex) windows are used for Bands 3-7, while 3-layer (PTFE / Quartz / PTFE) windows serve Bands 8-10.

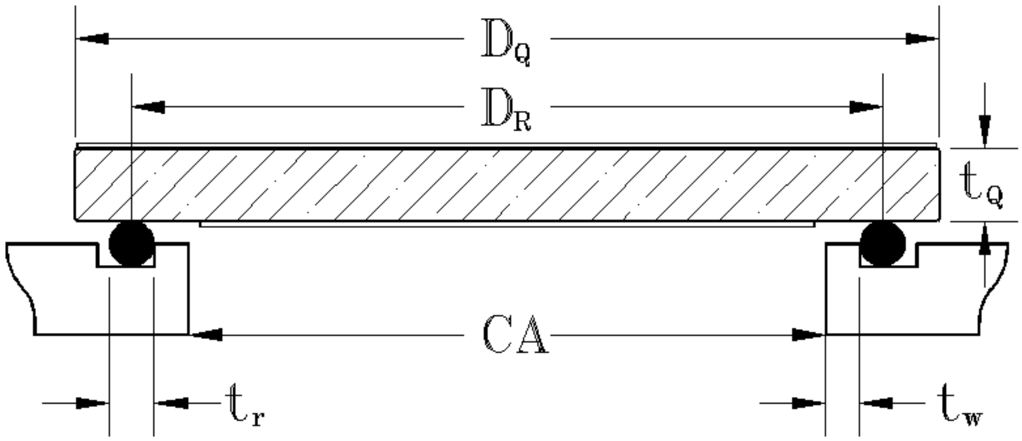

Figure 1. Definition of the various dimensions discussed in the text. $\mathbf{t_w}$ is the wall thickness. $\mathbf{t_r}$ is the O-ring thickness. **CA** is the clear aperture, $\mathbf{D_R}$ the effective window diameter and $\mathbf{D_Q}$ the overall diameter of the quartz disk. $\mathbf{t_Q}$ is the thickness of the quartz disk determined for $\mathbf{D_R}$ with a safety factor of 4.

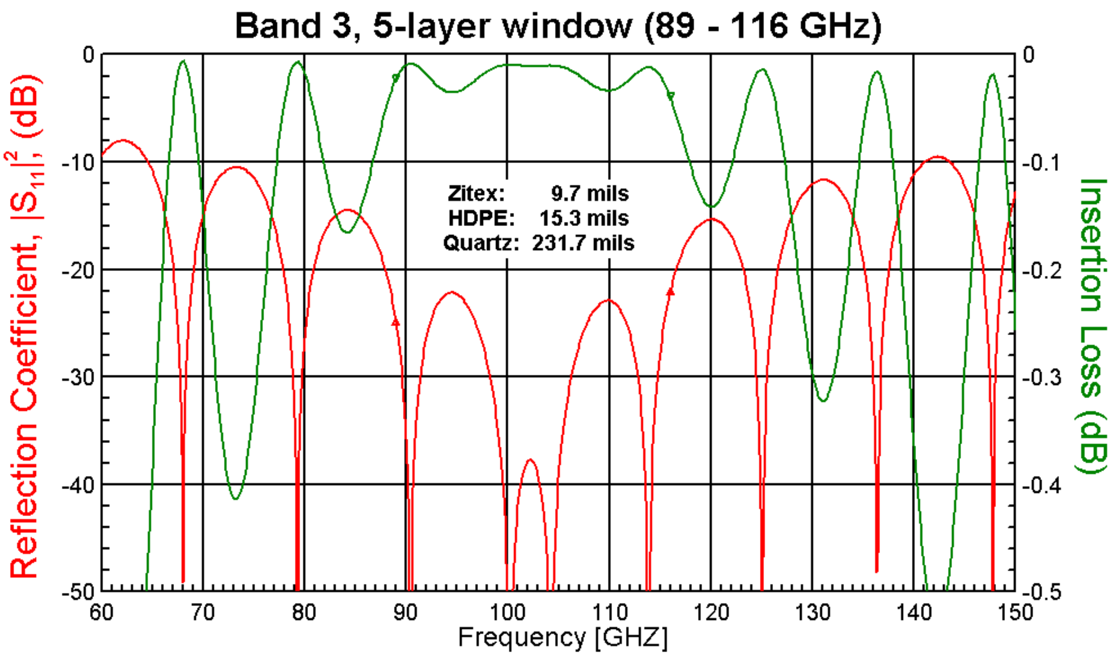

Figure 2. A five-layer window for 89 – 116 GHz as Band 3 was originally proposed. Material thicknesses are given in the figure, excluding the glue. 0.2 mils of glue is assumed to lie between the quartz and HDPE and the HDPE and Zitex layers. Performance is well within the specifications given in the text.

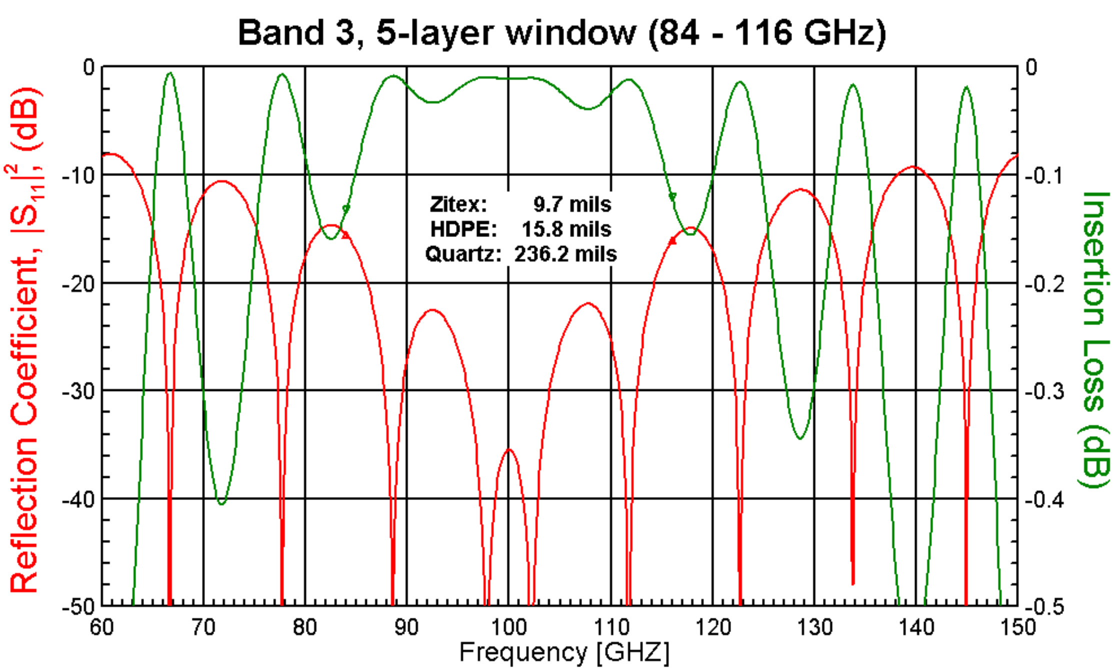

Figure 3. 5-layer window for Band 3, as recently proposed, extending the coverage down to 84 GHz. Some sacrifices must be made at the band edges to accommodate the increased bandwidth.

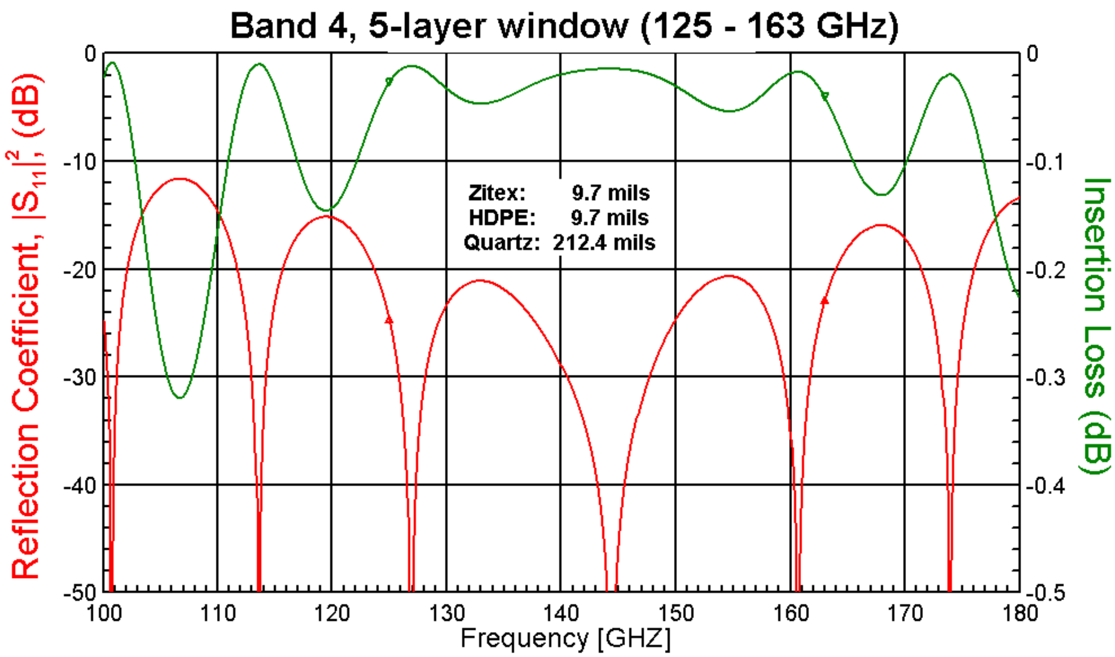

Figure 4. Band 4 window.

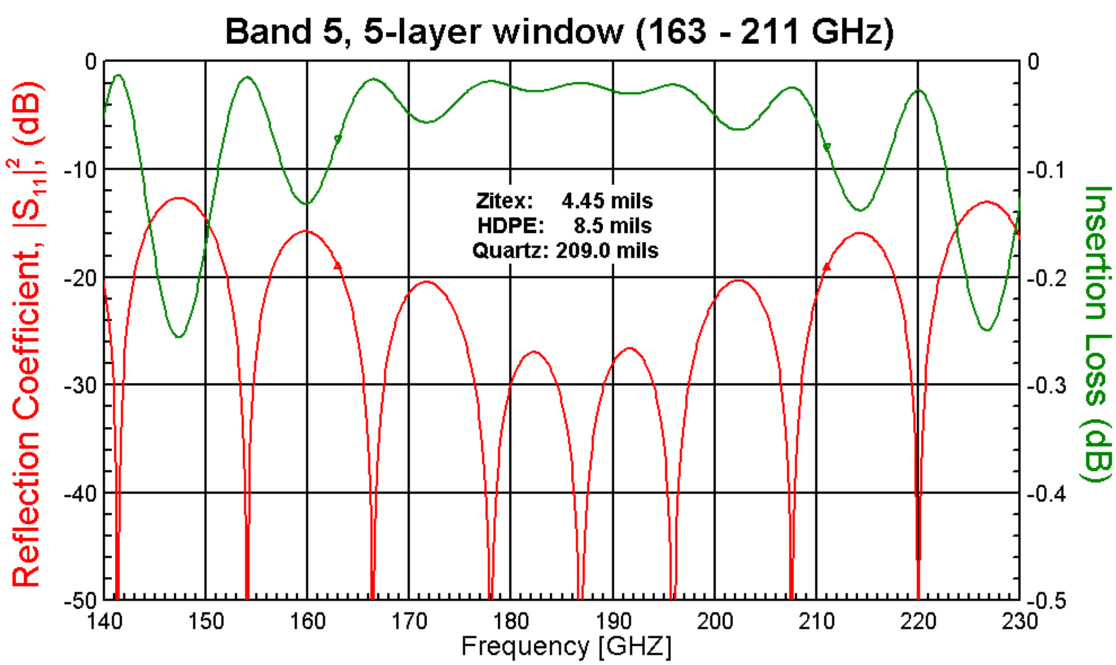

Figure 5. Band 5 window.

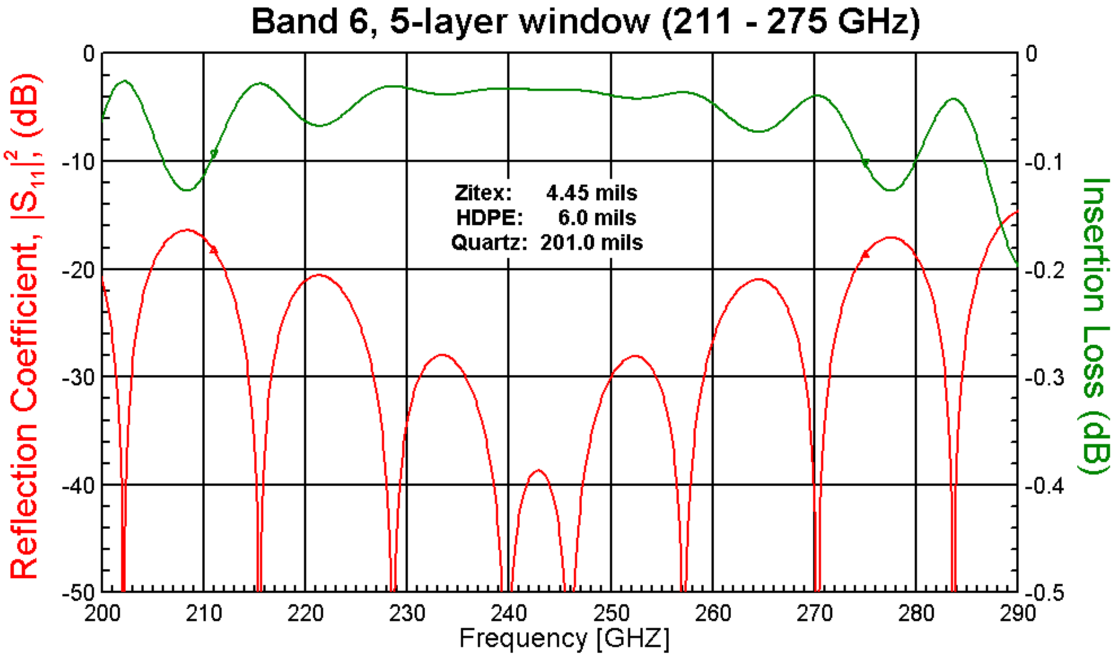

Figure 6. Band 6 window.

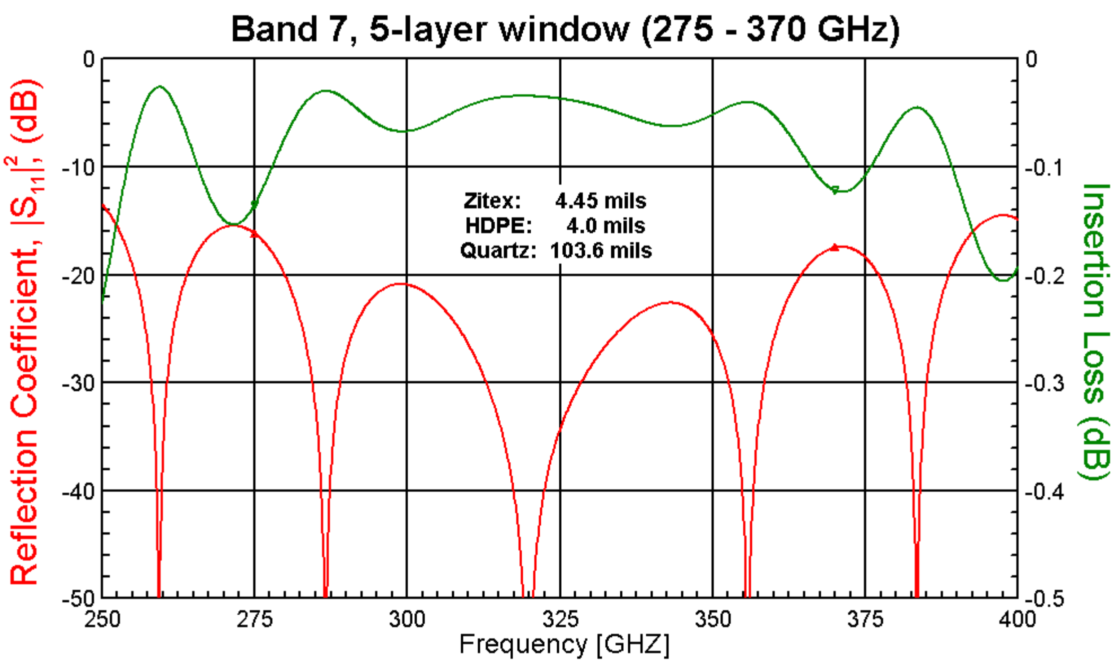

Figure 7. Band 7 window for 275 – 370 GHz. The performance of the design near the band edges is limited by the choice of available materials. The actual measured thickness of Zitex G-104 is 4.45 mils, not 4.0 mils as expected.

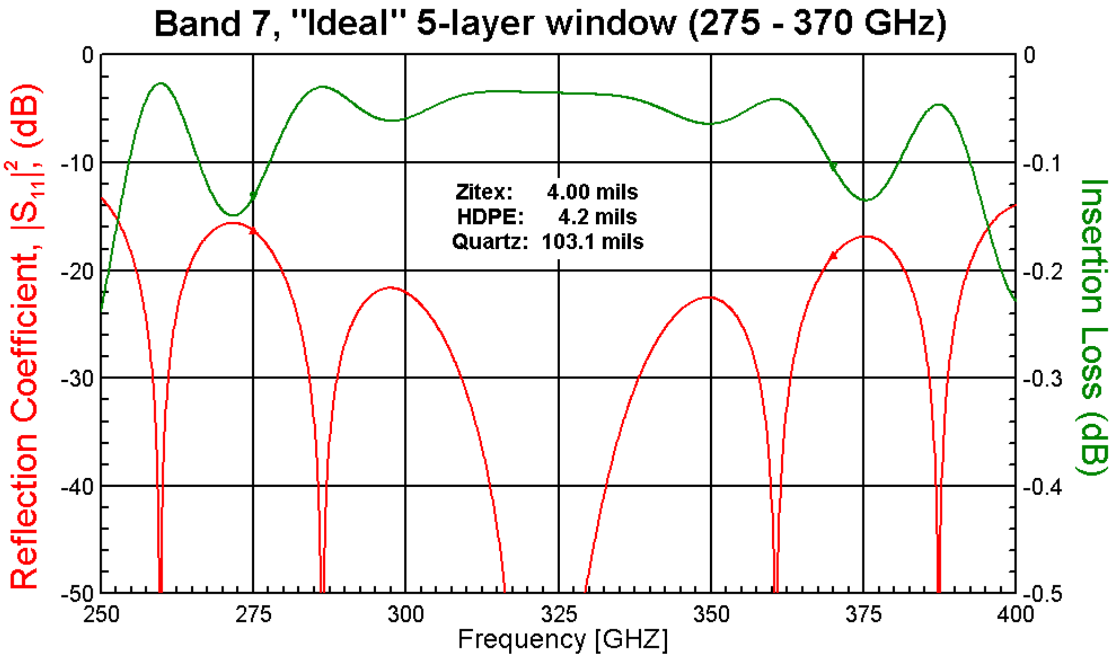

Figure 7A. A better design for Band 7, with improved performance at the band edges, assumes that Zitex G-104 can be obtained in 4.0 mil thickness.

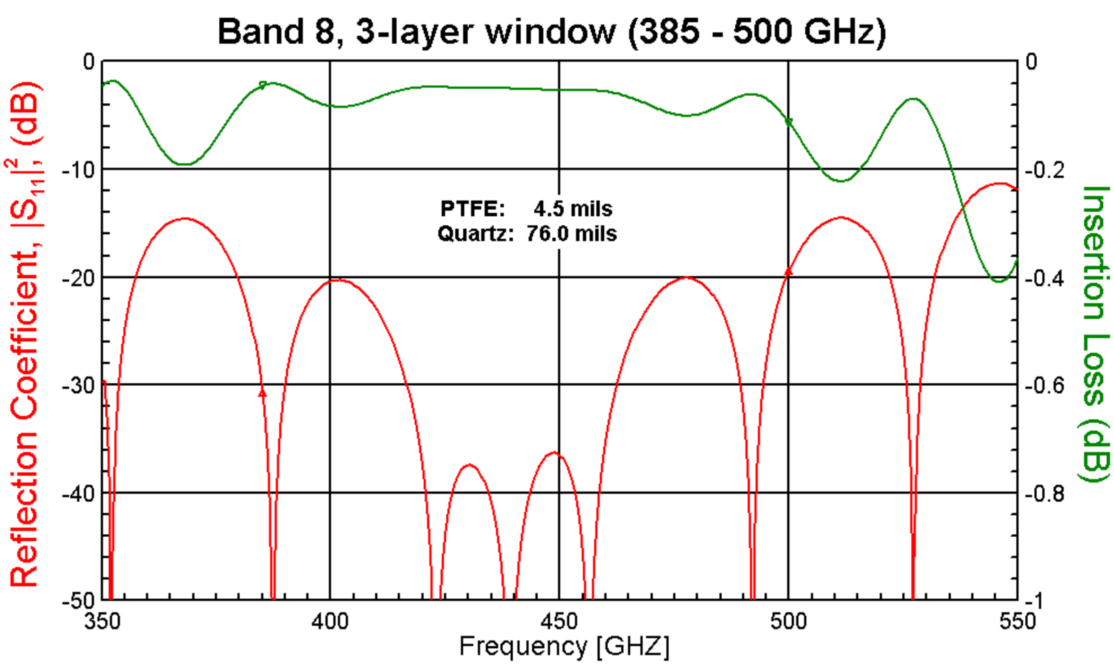

Figure 8. For Band 8 and above, a 3-layer PTFE/Z-quartz/PTFE window performs better than the 5-layer windows used at lower frequencies.

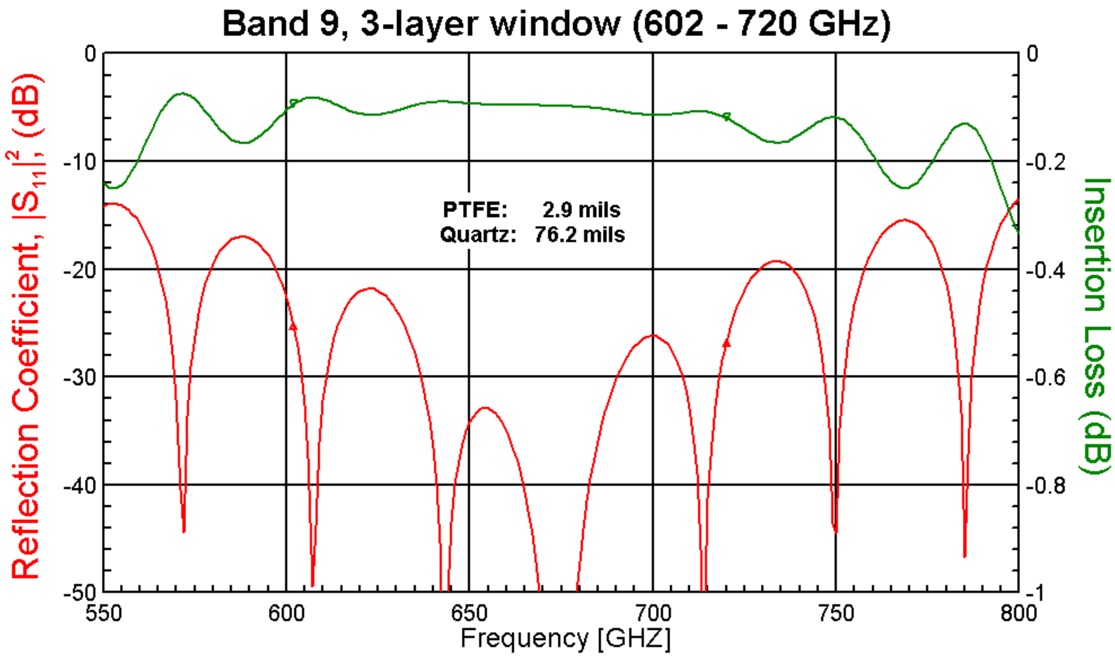

Figure 9. Band 9 window. At higher frequencies, the reflection losses can still be held to > 20 dB, but total insertion loss begins to increase to approximately 0.1 dB across the band due to absorption losses in the materials.

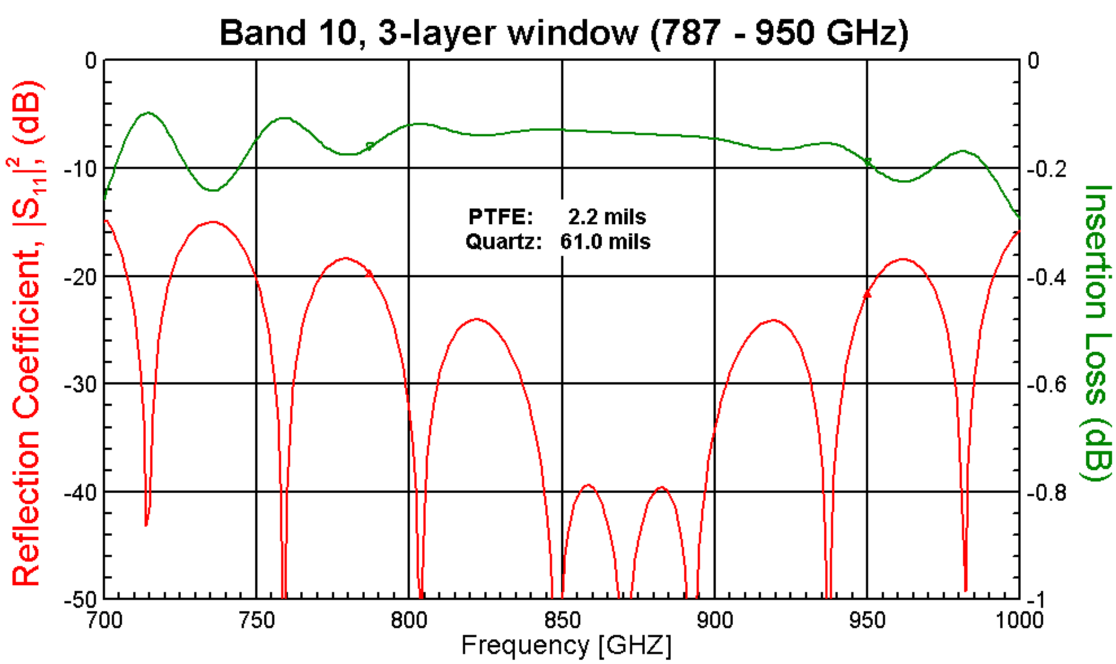

Figure 10. Band 10 window. Insertion loss remains < 0.2 dB across the band.