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**An electromagnetic window for
mm-wave receivers**

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Introduction

In the top of the metallic enclosure that will be used to protect the Q band (40-50 GHz) cryogenic receiver from environmental exposure on the surface of the VLA antennas, there is needed an electromagnetic window (EM-window) in order to cover the front-end while allowing the passage of energy towards the feed with a minimum of transmission loss. A single dielectric layer could be used as the required window, in a similar manner as they are used for radomes construction (see figure 1).

Dielectric materials for this purpose, should satisfy electromagnetic requirements as could be limits on transmission loss, reflection levels, etc. over the 40-50 GHz band. Also, they have to satisfy the size and load requirements under all conditions with an adequate safety factor.

For wideband transmission design, the single layer dielectric has maximum transmission when the thickness is very small compared to the wavelength or when the reflections cancel at the half-wavelength (in the dielectric) thickness, and at multiples thereof. Further, the lower the dielectric constant, the lower is the reflection; and the lower the absorption loss, the greater is the transmission.

Electromagnetic window design

In order to have a reflectionless dielectric sheet, the normalized input impedance at the EM-window - air interface must reduce to unity and under these conditions the sheet should look like a continuation of free space for the incident wave, and no reflections take place.

In the case of a single dielectric layer for adequate strength at high frequencies, the optimum thickness for the EM-window is given by [1]:

$$d := \frac{n \cdot \lambda}{2 \cdot \sqrt{\epsilon_r - (\sin \theta)^2}} \quad n=0,1,2,3...$$

where n is an integer multiple of half-wavelength, E_r is the relative dielectric constant and q is the angle of incidence. This equation strictly holds for lossless dielectrics, but is also a good approximation for the normal low-loss materials used for radomes and other EM-windows.

For $n=1$ and $q = 0^\circ$, the thickness is equal to a half-wavelength measured in the dielectric sheet for that particular angle of normal incidence. In this case we have:

$$d := \frac{\lambda}{2 \cdot \sqrt{E_r}}$$

For example, if we are going to use TEFLON as the dielectric material for the EM-window, we will have $E_r = 2.06$ at the mid-band frequency of 45 GHz, and then:

$$d := \frac{c}{2 \cdot f \cdot \sqrt{E_r}} = 2.3224 \text{ mm}$$

so, for one half-wavelength the thickness of the Teflon EM-window is $d = 2.3224 \text{ mm}$ ($=0.09146 \text{ in}$).

EM-window Analysis and Tolerances

To obtain the performance characteristics for this EM-window over the 40-50 GHz range, the formulas given by Cady [2] has been used to determine the behavior of the passage of electromagnetic waves through a flat panel of dielectric material and at normal incidence. By using these formulas, the amplitudes of the transmitted and reflected waves, as well as the absorbed energy were obtained.

The graph shown in figure 2 corresponds to three types of dielectric materials that could be used as EM-windows. The characteristics of the materials shown are as follows: a) a typical ESSCOLAM radome membrane with $E_r = 2.8$, $\tan d = 0.010$ and thickness $d = 1.992 \text{ mm}$; b) Gore-Tex woven fabric laminated with a very thin layer of pure teflon with $E_r = 1.55$, $\tan d = 0.010$ and thickness $= 2.6774$. Those curves are compared with the values obtained for TEFLON with $E_r = 2.06$, $\tan d = 0.010$, thickness $= 2.322 \text{ mm}$. The thickness in each case corresponds to one half-wavelength at 45 GHz. It can be seen that as lower the dielectric constant, the lower is the insertion loss involved in the transmission process.

In figure 3, the curves show results for TEFLON with characteristics that are more suitable for millimeter wave applications. In this case, the dielectric constant is again $E_r = 2.06$, the thickness $d=2.322 \text{ mm}$ (0.0914 in.) and the values used for loss tangent are 0.0002 and

0.0004. As shown in the graph, the highest values for the insertion loss are at the extremes of the frequency band of interest and the lowest insertion loss is found at midband, as expected.

As can be seen in figure 3, the insertion loss value introduced by the EM-window is relatively low at midband frequency, being greater at the extremes of the passband. As this window will be at the input of the receiver and at an ambient temperature of 300 K, its contribution to the overall system noise temperature could be in the 2-5 K range across the 40-50 GHz band.

It should be noticed that in practice, the bandwidth achievable may be further reduced by changes in dielectric constant due to tolerance manufacturing and temperature variations, and also by variations in the thickness of the dielectric material. For example by using the tolerance formulas given in [3], if a transmission loss of 10 % is permissible, then the specified value of dielectric constant ($\epsilon_r = 2.06$) has a tolerance of $\Delta\epsilon_r = 0.561$ (27.241%) and the thickness tolerance is $\Delta d = 0.220$ mm (9.49 %) at midband frequency, as illustrated in figure 4 that also shows tolerances for 5%, 10% and 20% transmission loss. Other results on tolerance analysis are available in the appendix.

Conclusions

The results shown are useful to determine that the dielectric material to be used for this EM-window, must have a very low dielectric constant (~ 2) and an associated very low loss tangent (0.0002-0.0004). Some materials that satisfy these requirements are the PTFE-based Duroid 5880 [4], and the Gore-tex laminated [5].

REFERENCES

- [1] Cary, J.R.H., "Radomes", chap. 14 in The Handbook of Antenna Design, vol 2, Rudge, A.W., Milne, K., Olver, A.D. and Knight, P., (Eds.), Peter Peregrinus Ltd.
- [2] Cady, W., Karelitz, M., and Turner, L.: 'Radar scanners and radomes', MIT Radiation Laboratory Series Vol. 26, Mc Graw-Hill, New York, 1948.
- [3] Tice, T.E. 'Techniques for airborne radome design', Vol. 1, Chapter 2, Sec. C, Mc Graw-Hill Book Co., dec 1966.
- [4] Duroid 5880, Rogers Corporation, Data Sheet R/T Duroid.
- [5] Rhoades, L.E. and Eisenberger, J. "Large Millimeter-Wave Antenna Systems", MSN, Vol. 18, No. 12, dec. 1988

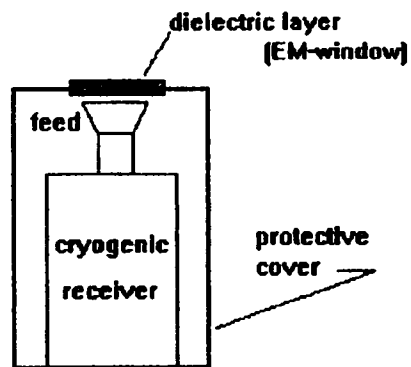


Figure 1. Electromagnetic window for the Q band receiver

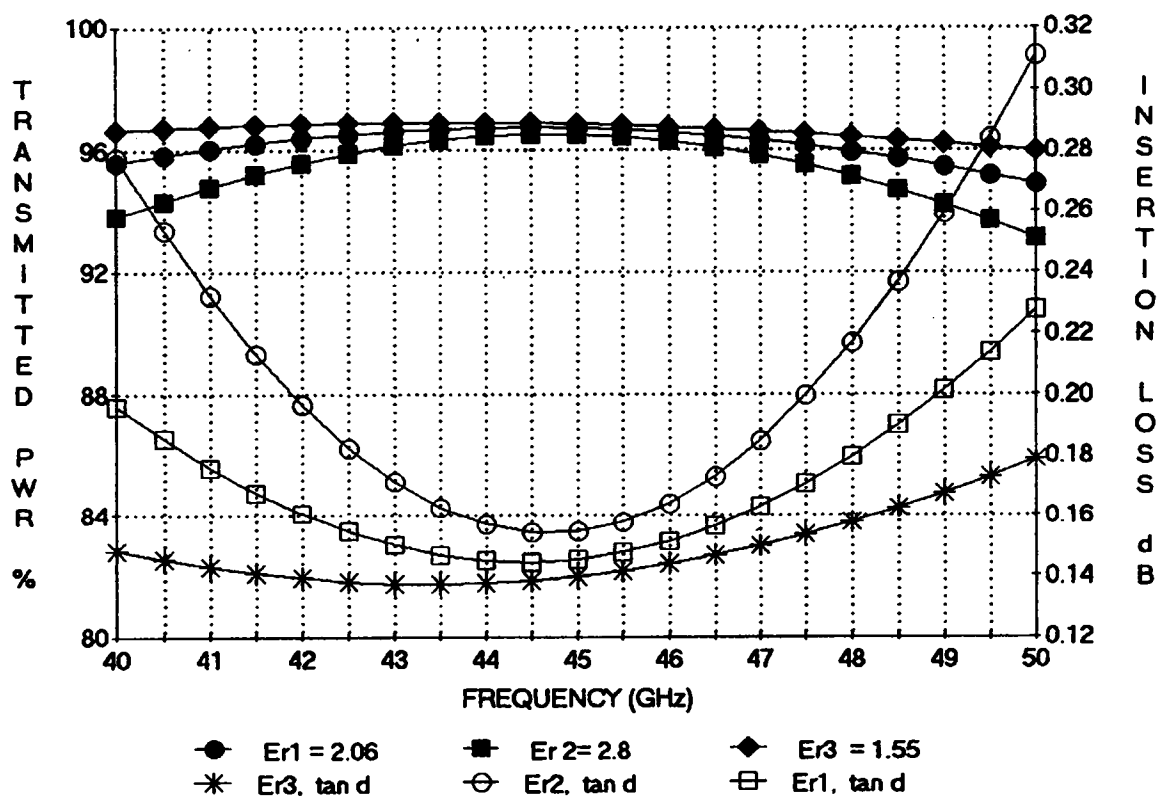


FIGURE 2. TRANSMITTED POWER AND INSERTION LOSS

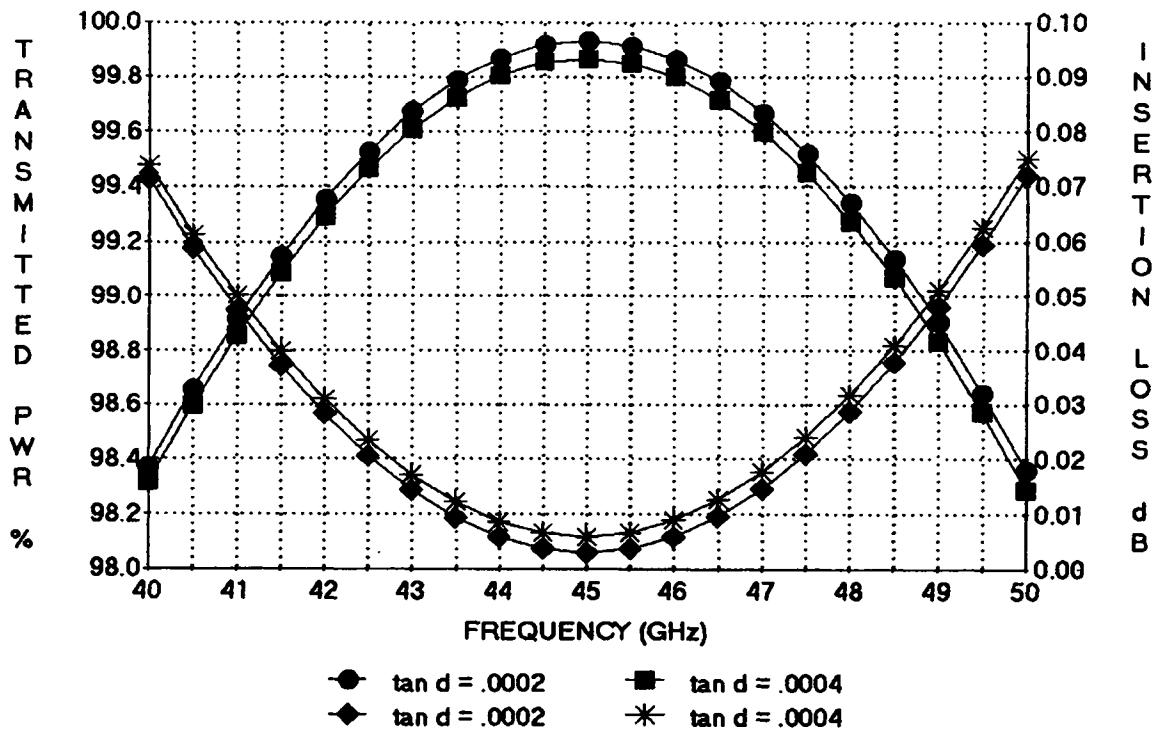


FIGURE 3. TRANSMITTED POWER AND INSERTION LOSS FOR TEFLON

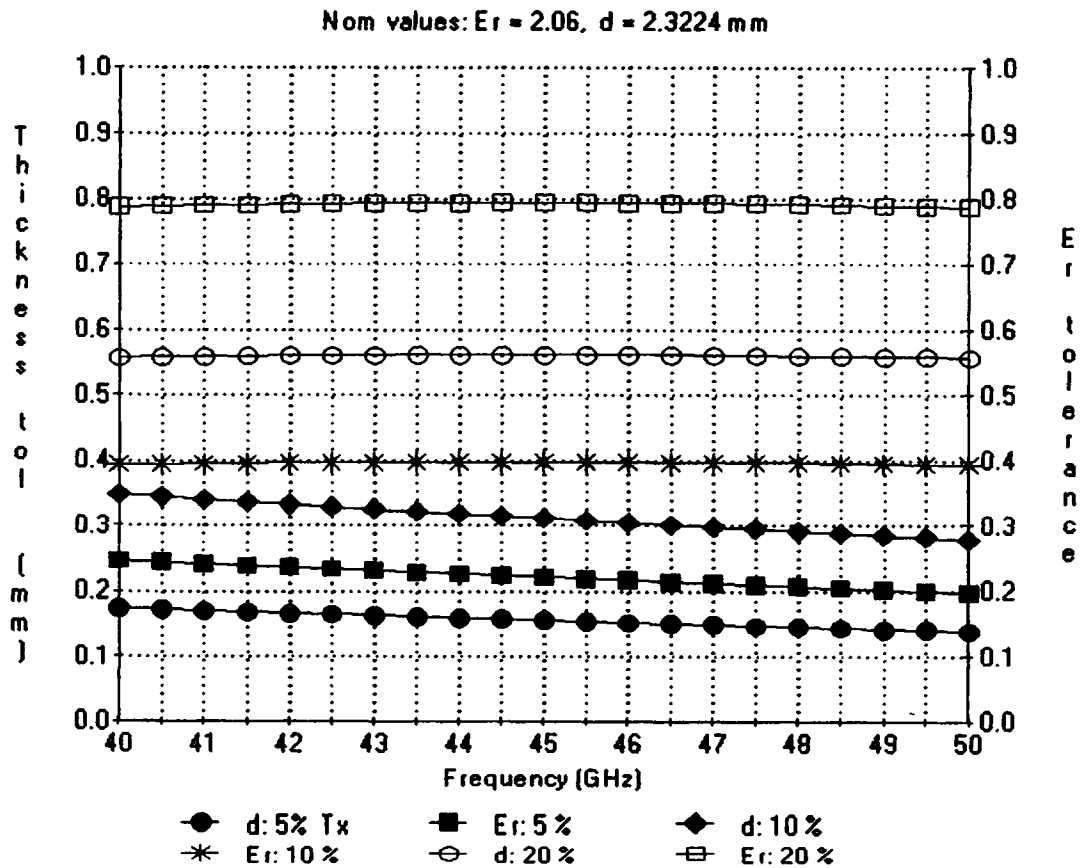


FIGURE 4. TOLERANCES FOR ϵ_r AND THICKNESS (d)

APPENDIX

TOLERANCE ANALYSIS FOR ELECTROMAGNETIC WINDOWS

REM Program to calculate transmission parameters for single
 REM layer dielectric windows. Normal incidence only.
 REM It uses the equations from CADY et al. 'Radar scanners and radomes'.
 REM For Tolerance Analysis the equations from TICE, T.E. 'Techniques
 REM for airborne radome design', vol I. are used.
 REM Last modified: Arturo Velazquez (CICESE/UNAM) 12/09/93
 REM NRAO/AOC. Socorro, NM.

```

    DIM tx(100)
1      pi = 4# * ATN(1#)
INPUT " enter Er & tan d : "; er, tand
INPUT " enter freq. (1) or d/l (0) "; in
IF (in = 0) GOTO 20
INPUT " enter freqs.(GHz) fmin, fmax, fstep: "; fmin, fmax, fstep
INPUT " enter thickness (1) or calculate 1-half-wavelength (0)?"; ithick
IF (ithick = 0) GOTO 50
INPUT " enter thickness value (mm) : "; thick
50 IF (ithick = 0) THEN thick = 300# / (fmax + fmin) / SQR(er)
    first = thick * fmin * SQR(er) / 300#
    alast = thick * fmax * SQR(er) / 300#
    Sstep = thick * fstep * SQR(er) / 300#
    GOTO 30
20 INPUT " enter d/lambda d/min, d/max, d/step: "; d/min, d/max, d/step
    first = d/min
    alast = d/max
    Sstep = d/step
30 IF in = 0 THEN PRINT " Er Tan d"
    IF (in = 0) THEN PRINT USING " ##.## #.#####"; er, tand
    IF in = 1 THEN PRINT " Er Tan d thick"
    IF in = 1 THEN PRINT USING " ##.## #.##### ##.###"; er, tand, thick
    num = INT((alast - first) / Sstep + .5) + 1
    dls = first
    IF (in = 1) THEN freq = fmin
    ene = SQR(er * .5# * (SQR(1# + tand * tand) + 1#))
    aka = SQR((SQR(1# + tand * tand) - 1#) / (SQR(1# + tand * tand) + 1#))
    r = (ene - 1#) / (ene + 1#)
    IF (in = 0) THEN PRINT " d/lambda tx% ref% diss% total% LL."
    IF (in = 1) THEN PRINT "freq d/lambda tx% ref% diss% total% LL."
    FOR i = 1 TO num
        fi = 2# * pi * ene * dls / SQR(er)
        a = EXP(-2# * pi * ene * aka * dls / SQR(er))
        tnum = (a ^ 2 * (1# - r * r) ^ 2)
        rnum = r * r * ((1# - a * a) ^ 2 + 4# * a * a * (SIN(fi)) ^ 2)
        tden = (1# - a * a * r * r) ^ 2 + 4# * a * a * r * r * (SIN(fi)) ^ 2
        trans = tnum / tden * 100#
        tx(i) = trans / 100#
        refle = rnum / tden * 100#
        disip = 100# - refle - trans
  
```



```

        yloss = -10# * LOG(trans / 100#) / LOG(10!)
        sum = disip + trans + refle
    IF (in = 0) THEN PRINT USING "  ###.### ###.### ###.### ###.### ###.###"; dls; trans;
refle; disip; sum; yloss
    IF (in = 1) THEN PRINT USING "###.### ###.### ###.### ###.### ###.### ###.###"; freq;
dls; trans; refle; disip; sum; yloss
        dls = dls + Sstep
        IF (in = 1) THEN freq = freq + fstep
NEXT i
    INPUT " OK tolerance analysis (1) or NOT (0):"; it
    IF (it = 0) GOTO 36
83 PRINT " Tolerances in Er and Thickness (1) or"
    INPUT " Tolerance in transmission loss (0) "; iw
    IF (iw = 0) GOTO 41
    INPUT " Maximum permissible Transmission Loss (%): "; rtole
    rtol = rtole / 100#
    IF (in = 1) THEN freq = fmin
    dls = first
    IF (dls <= .0001#) THEN dls = .001#
    ftol = (fmax + fmin) / 2#
    IF (in = 1) GOTO 149
    INPUT " give midband frequency for analysis: "; ftol
    thick = 150# / ftol / SQR(er)
149 PRINT USING " Permissible Tx. Loss ###.### % @ ###.### GHz: "; rtole; ftol
    PRINT USING " Nominal Thickness: ###.### mm Nominal Er: ###.### "; thick; er
    IF (in = 1) THEN PRINT " Freq d/lambda d tol(mm) d tol % Er tol Er tol %"
    IF (in = 0) THEN PRINT "d/lambda d tol(mm) d tol % Er tol Er tol %"
    FOR i = 1 TO num
        dtol = thick / dls * (SQR(rtol * tx(i)) / (2# * pi * (er - 1#)))
        ertol = 2# * ((SQR(er)) ^ 3 * SQR(rtol * tx(i)) / (pi * (er - 1#)))
        dtolp = dtol / thick * 100#
        ertolp = ertol / er * 100#
        IF (in = 1) THEN PRINT USING "###.### ###.### ###.### ###.### ###.### ###.###";
freq; dls; dtol; dtolp; ertol; ertolp
        IF (in = 0) THEN PRINT USING "###.### ###.### ###.### ###.### ###.###"; dls; dtol;
dtolp; ertol; ertolp
        dls = dls + Sstep
        IF (in = 1) THEN freq = freq + fstep
    NEXT i
43 INPUT " More tolerance analysis (1) or NOT (0): "; ia
    IF (ia = 1) THEN GOTO 83
    GOTO 36
41 INPUT " % Er variation = ? ... % Thick variation = "; ertol, dtol
    ervar = ertol * er / 100#
    dvar = dtol * thick / 100#
    dls = first
    IF (dls <= .0001#) THEN dls = .001#
    IF (in = 1) THEN freq = fmin

```

```

PRINT USING " Er variation: ###.## % (###.###) Thick variation: ###.## % (###.### mm)"; ertol;
ervar; dtol; dvar
IF (in = 1) THEN PRINT " Freq  d/lambda  Tx Loss (%)"
IF (in = 0) THEN PRINT " d/lambda  Tx Loss"
ertol = ertol / 100#
dtol = dtol / 100#
FOR i = 1 TO num
    tol = pi * pi * ((er - 1#) ^ 2) * (dtol * dls + ertol * er / (4# * (SQR(er)) ^ 3)) ^ 2
    ttol = tol * 100#
    IF (in = 1) THEN PRINT USING "###.##  ##.###  ##.###"; freq; dls; ttol
    IF (in = 0) THEN PRINT USING "  ##.###  ##.###"; dls; ttol
    dls = dls + Sstep
    IF (in = 1) THEN freq = freq + fstep
NEXT i
57 INPUT " More tolerance analysis (1) or NOT (0): "; ia
    IF (ia = 1) THEN GOTO 83
36 INPUT " More runs (1) or Not (0): "; ir
    IF (ir = 1) GOTO 1
END
REM C zia<31>% date
REM C Thu Dec 09 09:40:32 MST 1993

```

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

Freq(GHz)	d/ λ	transm.%	refle%	dissip%	total %	I.L.(dB)
30.00	0.3333	90.648	9.271	0.081	100.000	0.426
31.00	0.3444	91.354	8.562	0.084	100.000	0.393
32.00	0.3556	92.113	7.800	0.088	100.000	0.357
33.00	0.3667	92.912	6.997	0.091	100.000	0.319
34.00	0.3778	93.737	6.168	0.095	100.000	0.281
35.00	0.3889	94.573	5.328	0.099	100.000	0.242
36.00	0.4000	95.403	4.495	0.102	100.000	0.204
37.00	0.4111	96.210	3.684	0.106	100.000	0.168
38.00	0.4222	96.976	2.915	0.110	100.000	0.133
39.00	0.4333	97.683	2.204	0.113	100.000	0.102
40.00	0.4444	98.315	1.568	0.117	100.000	0.074
41.00	0.4556	98.855	1.024	0.121	100.000	0.050
42.00	0.4667	99.291	0.585	0.124	100.000	0.031
43.00	0.4778	99.609	0.263	0.128	100.000	0.017
44.00	0.4889	99.803	0.066	0.131	100.000	0.009
45.00	0.5000	99.866	0.000	0.134	100.000	0.006
46.00	0.5111	99.797	0.066	0.137	100.000	0.009
47.00	0.5222	99.598	0.263	0.139	100.000	0.018
48.00	0.5333	99.273	0.585	0.142	100.000	0.032
49.00	0.5444	98.832	1.024	0.144	100.000	0.051
50.00	0.5556	98.286	1.568	0.146	100.000	0.075
51.00	0.5667	97.649	2.203	0.148	100.000	0.103
52.00	0.5778	96.937	2.913	0.150	100.000	0.135
53.00	0.5889	96.166	3.682	0.152	100.000	0.170
54.00	0.6000	95.354	4.492	0.153	100.000	0.207
55.00	0.6111	94.520	5.325	0.155	100.000	0.245
56.00	0.6222	93.680	6.164	0.156	100.000	0.284
57.00	0.6333	92.850	6.992	0.158	100.000	0.322
58.00	0.6444	92.047	7.794	0.159	100.000	0.360
59.00	0.6556	91.284	8.555	0.160	100.000	0.396
60.00	0.6667	90.575	9.263	0.162	100.000	0.430

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

Permissible Transmission Loss: 5.00 %

Freq	d/ λ	Δd (mm)	Δd %	$\Delta \epsilon_r$	$\Delta \epsilon_r$ %
30.00	0.333	0.223	9.590	0.378	18.352
31.00	0.344	0.216	9.316	0.380	18.423
32.00	0.356	0.210	9.063	0.381	18.499
33.00	0.367	0.205	8.826	0.383	18.579
34.00	0.378	0.200	8.604	0.384	18.662
35.00	0.389	0.195	8.396	0.386	18.745
36.00	0.400	0.190	8.198	0.388	18.827
37.00	0.411	0.186	8.010	0.389	18.906
38.00	0.422	0.182	7.831	0.391	18.981
39.00	0.433	0.178	7.657	0.392	19.050
40.00	0.444	0.174	7.490	0.394	19.112
41.00	0.456	0.170	7.328	0.395	19.164
42.00	0.467	0.166	7.169	0.396	19.206
43.00	0.478	0.163	7.013	0.396	19.237
44.00	0.489	0.159	6.861	0.397	19.256
45.00	0.500	0.156	6.710	0.397	19.262
46.00	0.511	0.152	6.562	0.397	19.255
47.00	0.522	0.149	6.416	0.396	19.236
48.00	0.533	0.146	6.272	0.396	19.205
49.00	0.544	0.142	6.130	0.395	19.162
50.00	0.556	0.139	5.991	0.394	19.109
51.00	0.567	0.136	5.855	0.392	19.047
52.00	0.578	0.133	5.721	0.391	18.977
53.00	0.589	0.130	5.591	0.389	18.902
54.00	0.600	0.127	5.464	0.388	18.822
55.00	0.611	0.124	5.341	0.386	18.739
56.00	0.622	0.121	5.222	0.384	18.656
57.00	0.633	0.119	5.108	0.383	18.573
58.00	0.644	0.116	4.998	0.381	18.493
59.00	0.656	0.114	4.893	0.379	18.416
60.00	0.667	0.111	4.793	0.378	18.344

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

Permissible transmission loss 10.00 %

Freq	d/ λ	Δd (mm)	Δd %	$\Delta \epsilon_r$	$\Delta \epsilon_r$ %
30.00	0.333	0.315	13.562	0.535	25.953
31.00	0.344	0.306	13.175	0.537	26.054
32.00	0.356	0.298	12.816	0.539	26.162
33.00	0.367	0.290	12.482	0.541	26.275
34.00	0.378	0.283	12.168	0.544	26.391
35.00	0.389	0.276	11.873	0.546	26.509
36.00	0.400	0.269	11.594	0.548	26.625
37.00	0.411	0.263	11.328	0.551	26.737
38.00	0.422	0.257	11.074	0.553	26.844
39.00	0.433	0.252	10.829	0.555	26.941
40.00	0.444	0.246	10.593	0.557	27.028
41.00	0.456	0.241	10.363	0.558	27.102
42.00	0.467	0.235	10.138	0.560	27.162
43.00	0.478	0.230	9.918	0.560	27.206
44.00	0.489	0.225	9.702	0.561	27.232
45.00	0.500	0.220	9.490	0.561	27.241
46.00	0.511	0.216	9.280	0.561	27.231
47.00	0.522	0.211	9.074	0.560	27.204
48.00	0.533	0.206	8.870	0.559	27.160
49.00	0.544	0.201	8.670	0.558	27.099
50.00	0.556	0.197	8.473	0.557	27.024
51.00	0.567	0.192	8.280	0.555	26.937
52.00	0.578	0.188	8.091	0.553	26.838
53.00	0.589	0.184	7.907	0.551	26.731
54.00	0.600	0.179	7.727	0.548	26.618
55.00	0.611	0.175	7.554	0.546	26.501
56.00	0.622	0.172	7.386	0.543	26.383
57.00	0.633	0.168	7.224	0.541	26.266
58.00	0.644	0.164	7.069	0.539	26.152
59.00	0.656	0.161	6.920	0.537	26.044
60.00	0.667	0.157	6.778	0.534	25.943

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

Permissible transmission loss 15.00 %

Freq	d/ λ	Δd (mm)	Δd %	$\Delta \epsilon_r$	$\Delta \epsilon_r$ %
30.00	0.333	0.386	16.610	0.655	31.786
31.00	0.344	0.375	16.136	0.657	31.909
32.00	0.356	0.365	15.697	0.660	32.042
33.00	0.367	0.355	15.287	0.663	32.180
34.00	0.378	0.346	14.903	0.666	32.323
35.00	0.389	0.338	14.542	0.669	32.467
36.00	0.400	0.330	14.200	0.672	32.609
37.00	0.411	0.322	13.874	0.675	32.746
38.00	0.422	0.315	13.563	0.677	32.876
39.00	0.433	0.308	13.263	0.680	32.996
40.00	0.444	0.301	12.973	0.682	33.103
41.00	0.456	0.295	12.692	0.684	33.194
42.00	0.467	0.288	12.417	0.685	33.267
43.00	0.478	0.282	12.147	0.686	33.320
44.00	0.489	0.276	11.883	0.687	33.352
45.00	0.500	0.270	11.622	0.687	33.363
46.00	0.511	0.264	11.366	0.687	33.351
47.00	0.522	0.258	11.113	0.686	33.318
48.00	0.533	0.252	10.864	0.685	33.264
49.00	0.544	0.247	10.618	0.684	33.190
50.00	0.556	0.241	10.377	0.682	33.098
51.00	0.567	0.236	10.141	0.680	32.990
52.00	0.578	0.230	9.909	0.677	32.870
53.00	0.589	0.225	9.684	0.674	32.739
54.00	0.600	0.220	9.464	0.672	32.600
55.00	0.611	0.215	9.251	0.669	32.457
56.00	0.622	0.210	9.046	0.666	32.313
57.00	0.633	0.205	8.847	0.663	32.170
58.00	0.644	0.201	8.657	0.660	32.030
59.00	0.656	0.197	8.475	0.657	31.897
60.00	0.667	0.193	8.301	0.655	31.773

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

$\Delta\epsilon_r : 10.000 \% (0.206)$

$\Delta d : 15.000 \% (0.348 \text{ mm})$

Freq	d/ λ	Tx loss (%)
30.00	0.333	5.040
31.00	0.344	5.293
32.00	0.356	5.551
33.00	0.367	5.816
34.00	0.378	6.087
35.00	0.389	6.363
36.00	0.400	6.647
37.00	0.411	6.936
38.00	0.422	7.231
39.00	0.433	7.533
40.00	0.444	7.841
41.00	0.456	8.154
42.00	0.467	8.475
43.00	0.478	8.801
44.00	0.489	9.133
45.00	0.500	9.472
46.00	0.511	9.816
47.00	0.522	10.167
48.00	0.533	10.524
49.00	0.544	10.887
50.00	0.556	11.257
51.00	0.567	11.632
52.00	0.578	12.014
53.00	0.589	12.402
54.00	0.600	12.796
55.00	0.611	13.196
56.00	0.622	13.602
57.00	0.633	14.015
58.00	0.644	14.433
59.00	0.656	14.858
60.00	0.667	15.289

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

$\Delta\epsilon_r : 15.000 \% (0.309)$

$\Delta d : 15.000 \% (0.348 \text{ mm})$

Freq	d/ λ	Tx loss (%)
30.00	0.333	6.427
31.00	0.344	6.711
32.00	0.356	7.002
33.00	0.367	7.299
34.00	0.378	7.602
35.00	0.389	7.911
36.00	0.400	8.226
37.00	0.411	8.548
38.00	0.422	8.875
39.00	0.433	9.209
40.00	0.444	9.549
41.00	0.456	9.895
42.00	0.467	10.247
43.00	0.478	10.606
44.00	0.489	10.970
45.00	0.500	11.341
46.00	0.511	11.718
47.00	0.522	12.101
48.00	0.533	12.490
49.00	0.544	12.886
50.00	0.556	13.287
51.00	0.567	13.695
52.00	0.578	14.109
53.00	0.589	14.529
54.00	0.600	14.955
55.00	0.611	15.387
56.00	0.622	15.826
57.00	0.633	16.270
58.00	0.644	16.721
59.00	0.656	17.178
60.00	0.667	17.641

ELECTROMAGNETIC WINDOW TOLERANCE ANALYSIS

@45.00 GHz: $\epsilon_r = 2.06$, $\tan \delta = 0.0004$, thickness (d) = 2.3224 mm

$\Delta\epsilon_r : 20.000 \% (0.412)$

$\Delta d : 15.000 \% (0.348 \text{ mm})$

Freq	d/ λ	Tx loss (%)
30.00	0.333	7.981
31.00	0.344	8.298
32.00	0.356	8.621
33.00	0.367	8.950
34.00	0.378	9.285
35.00	0.389	9.626
36.00	0.400	9.974
37.00	0.411	10.328
38.00	0.422	10.687
39.00	0.433	11.053
40.00	0.444	11.425
41.00	0.456	11.804
42.00	0.467	12.188
43.00	0.478	12.579
44.00	0.489	12.976
45.00	0.500	13.378
46.00	0.511	13.788
47.00	0.522	14.203
48.00	0.533	14.624
49.00	0.544	15.052
50.00	0.556	15.486
51.00	0.567	15.925
52.00	0.578	16.371
53.00	0.589	16.824
54.00	0.600	17.282
55.00	0.611	17.747
56.00	0.622	18.217
57.00	0.633	18.694
58.00	0.644	19.177
59.00	0.656	19.666
60.00	0.667	20.162