ARDB, Technical Note # 139 September 1, 1997

Analysis of an Air Gap Effect in W-Band Muffin-Tin WBAND-000

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This paper is part of a group of papers about the first SLAC W-Band structure WBAND-000.

Abstract

This Paper presents an analysis of an air gap inside the sandwich structure between mechanical supports and cavity plate of W-Band structure WBAND-000. Further more it contains a comparison for S_{11} and S_{12} measurements between analytical and numerical results. It is an attempt to understand anomalous high losses as seen in recent results of measurements and a flipping effect of S_{11} and S_{12} charts.

I. Introduction

The motivation for this note is the need to understand anomalous loss seen in recent results of bench measurements on the 7-cell W-Band muffin tin structure. First a review of [1] is given and the perfect theoretical solution for S_{11} and S_{12} parameters is compared with measurement data.

To understand the discrepancies between measurements and theoretical results, a numerical model was created and calculated. All numerical simulations are done with our improved code GdfidL [2], which is freely available and faster than MAFIA.

The GdfidL results will be compared to the results of [1]. An attempt to explain the discrepancies was to assume a bad contact between the different plates, because the real structure is built like a sandwich. So a simulation of a bad contact, a so called air gap was done. These results will be compared too. It is shown that an air gap does cause a flipping effect of S_{11} and S_{12} chart, but does not make a backward structure from a designed forward structure. What happens is that we get an increased bandwidth, that means an increased coupling and further an increased group velocity as well as high losses caused through high field density in the gaps.

II. Comparison of theoretical results with measurements

In [1] a detailed comparison was done. Let us review the results. For theoretical calculation we use the S-Matrix elements [1]:

$$S_{11}(\Omega)+1=\frac{A+B}{\tilde{V}_F(\Omega)}=2j\frac{\omega_1\Omega}{Q_{e1}}\frac{1}{\Xi}\left(\left[\Delta_N-\tfrac{1}{2}\omega_N^2\kappa_N e^{-\gamma}\right]e^{(N-1)\gamma}-\left[\Delta_N-\tfrac{1}{2}\omega_N^2\kappa_N e^{\gamma}\right]e^{-(N-1)\gamma}\right), \tag{1}$$

$$S_{12}(\Omega)=\frac{Ae^{-(N-1)\gamma}+Be^{(N-1)\gamma}}{\tilde{V}_F(\Omega)}=2j\frac{\omega_1\Omega}{Q_{e1}}\frac{1}{\Xi}\left(\left[\Delta_N-\tfrac{1}{2}\omega_N^2\kappa_N e^{-\gamma}\right]-\left[\Delta_N-\tfrac{1}{2}\omega_N^2\kappa_N e^{\gamma}\right]\right). \tag{2}$$

We apply these formulas to the 7-cell W-Band structure WBAND-000. For calculations the FORTRAN code NMAT is used [1]. The structure was intended to be a 0.09 c, 7-cell 2 pi/3 mode, constant-impedance structure. We choose $Q_W = 2200$ as a reasonable guess. This corresponds to the inputs of the structure parameters for NMAT listed in table 1.

TABLE 1. “Ideal” parameter set : 0.09 c, 7-cell 2pi/3 mode, $Q_W = 2200$

iphase=2,	constant phase-advance per interior cell
bphase=120.	phase advance is 120°
qw0=2200.	wall Q is 2200
qem=0.	let NMAT select external Q’s for cells
idetune=0	let NMAT detune coupler cells for match
ncell=7,	a 7-cell structure
xcell=0.1093	cell length (cm) for synchronism at 120°
ibeta=2	constant impedance structure
beta0=0.09	0.09c group velocity
freq0=91.392e9	designed for 91.3892 GHz

Results for the calculation are shown in figures 1-2. The result of the tridiagonal matrix solver is overlaid with the analytic result. Also shown are results of measurements done by P.J. Chou and R. Siemann [3],[4],[5]. The result disagrees with measurements. Now let us attempt to fit the results. This means we modify the input parameter for NMAT, until the shape of S_{11} and S_{12} becomes approximately the shape of the measured data. After tweaking parameters, the results for the best eye ball fit which seems to provide a fair fit to measurement looks like that in figures 3-4. The changed parameters from table 1 are given in table 2 .

TABLE 2. “Best Eyeball Fit” parameter set : -0.05 c, 7-cell 2pi/3 mode, Qw=500

qw0=500.	wall Q is 2200
beta0=-0.05 c	backward wave
freq0=90.892e9	structure is detuned to operate at design - 0.5 GHz

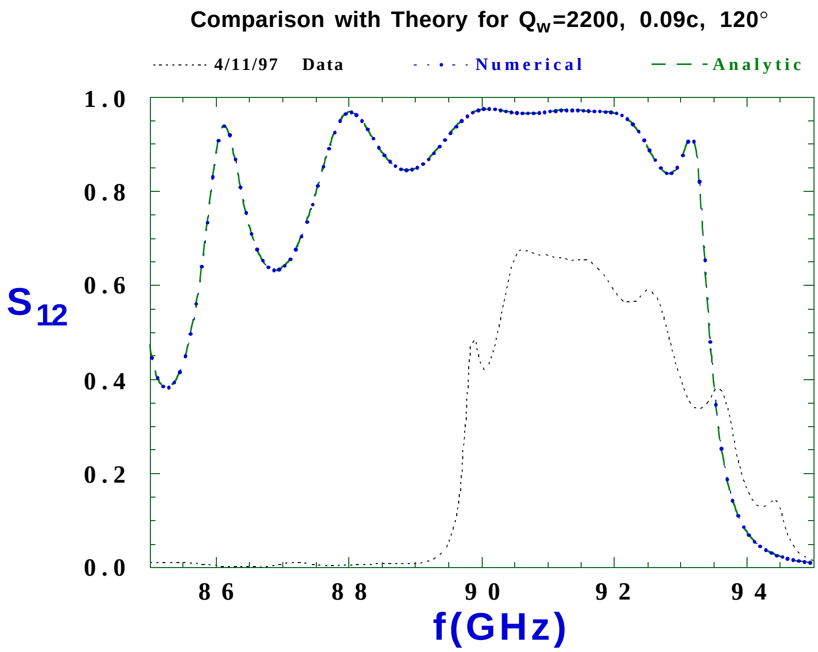


FIGURE 1. Overlay of the S_{12} component of the S-matrix for a 7-cell structure with results of measurements.

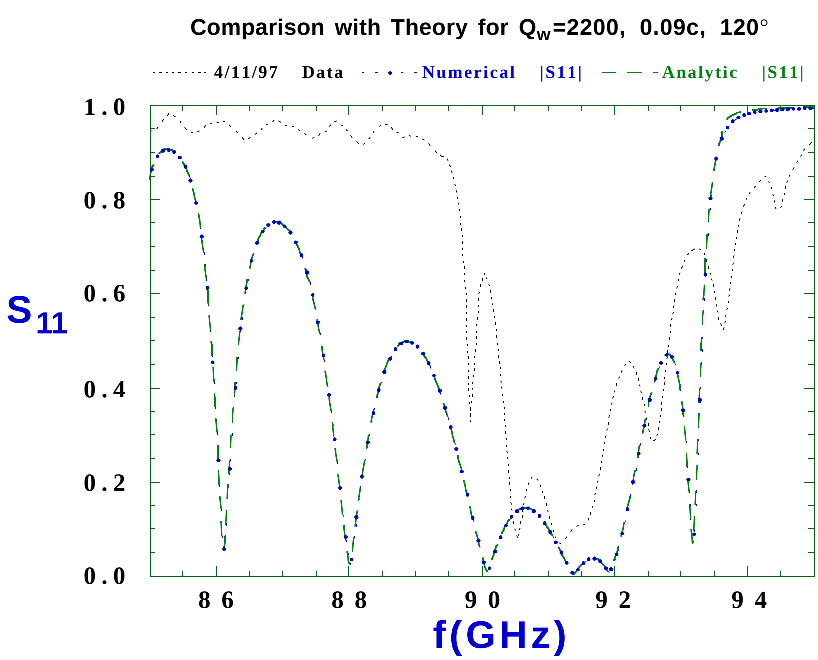


FIGURE 2. Overlay of the S_{12} component of the S-matrix for a 7-cell structure with results of measurements.

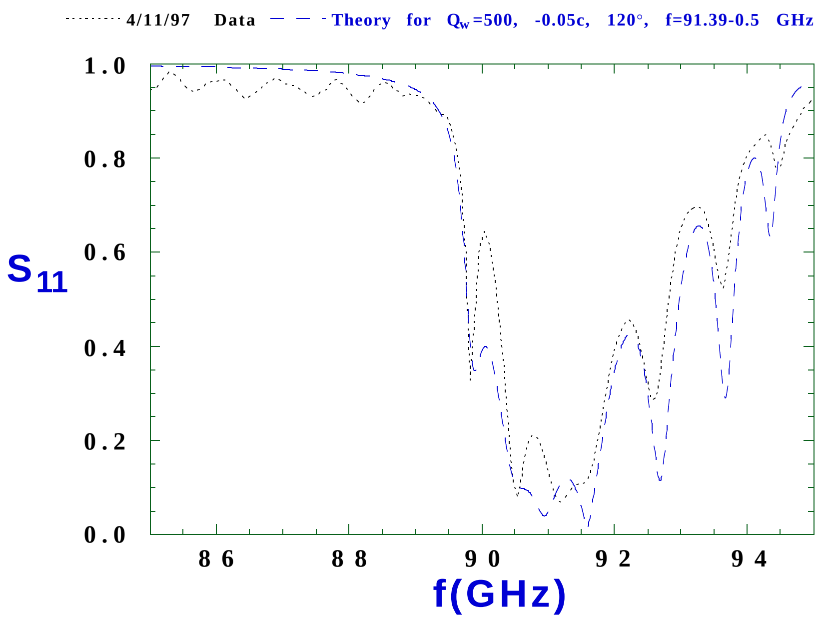


FIGURE 3. Overlay of the S_{11} component of the best eye ball fit, to adjust the results of the S-matrix for a 7-cell structure with results of measurements.

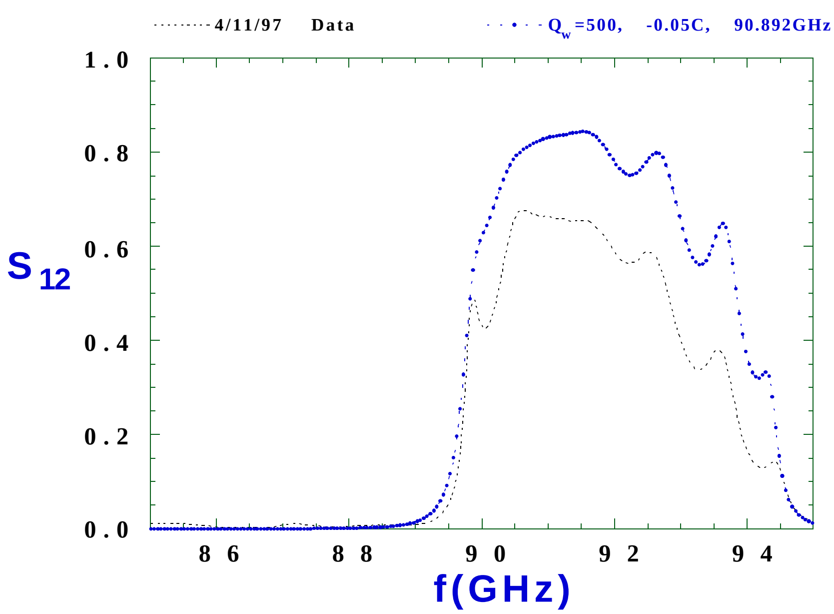


FIGURE 4. Overlay of the S_{12} component of the best eye ball fit, to adjust the results of the S-matrix for a 7-cell structure with results of measurements.

The best fit to the results is seen in figure 3, and corresponds to a low $Q_w = 500$, a backward wave circuit (- 0.05 c), and a structure tuned to operate at the 91.39 GHz - 0.5 GHz, off by 0.5 GHz in tune. The S_{12} corresponding to this circuit is depicted in figure 4 and while qualitatively similar to the 4/11/97 data, it does not exhibit enough loss (-1.7 dB insertion loss, not -3 dB). This could likely be fixed by adjusting the wall Q to a still lower value. The question now is how can we explain the discrepancies. We need to figure out two facts. First, why does this structure look like a backward structure and second why do we have so many losses? One point we discussed was the possibility of a bad contact between the different sheets. The structure is built like a sandwich, in the middle the cavities, below and above the mechanical support and tightened by four screws. Maybe the pressure is not enough or we got no real parallel plane surfaces. That would mean we get air gaps between the layers, as seen in figure 5.

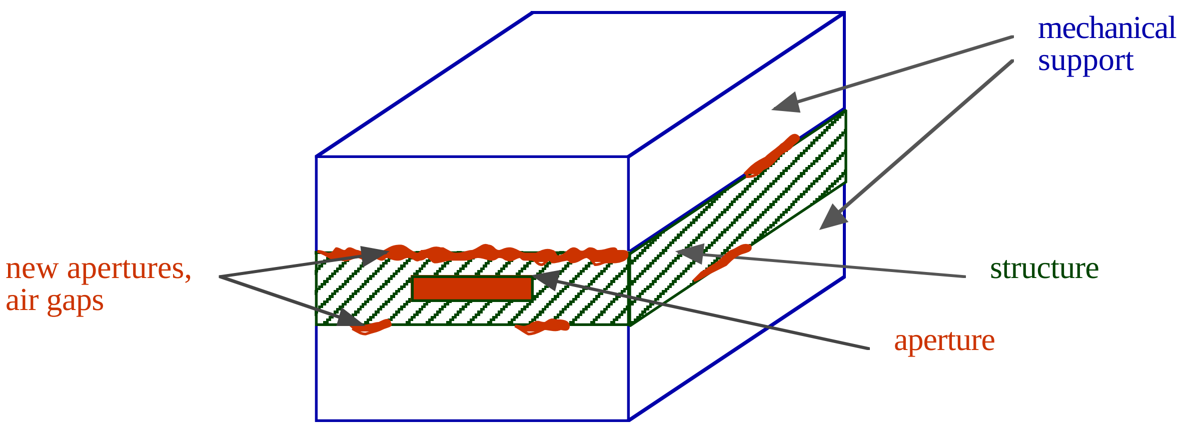


FIGURE 5. Sandwich technique of the structure and new apertures, caused by bad surfaces or bad contact.

What does this mean physically? We have two kinds of coupling between the cavities: electric and magnetic coupling. The magnetic fields are tangential to the surfaces of cavities. If we have an air gap under each iris, two new apertures are present in an area where the magnetic field is very strong, increases the magnetic coupling dramatically. If that so is, electric and magnetic coupling are fighting each other. If the magnetic coupling is stronger so we will get a backward structure. See figure 6.
If we consider Bethes theorem of hole coupling, it is questionable that we really get so much magnetic coupling in the gap! We need to prove it.

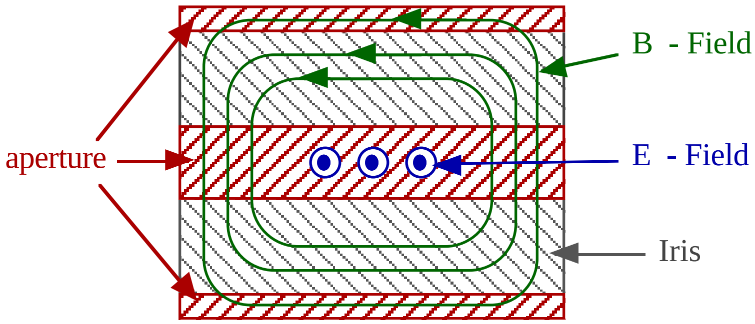


FIGURE 6. Fields in the middle of a cavity.

III. Simulation of an air gap

Now let’s figure out what’s going on, when we apply these theoretical ideas to a structure. To demonstrate this, a very good matched structure was taken. See figure 7. Under each iris an air gap of 0.01 mm was simulated as shown as a zoom in figure 8.

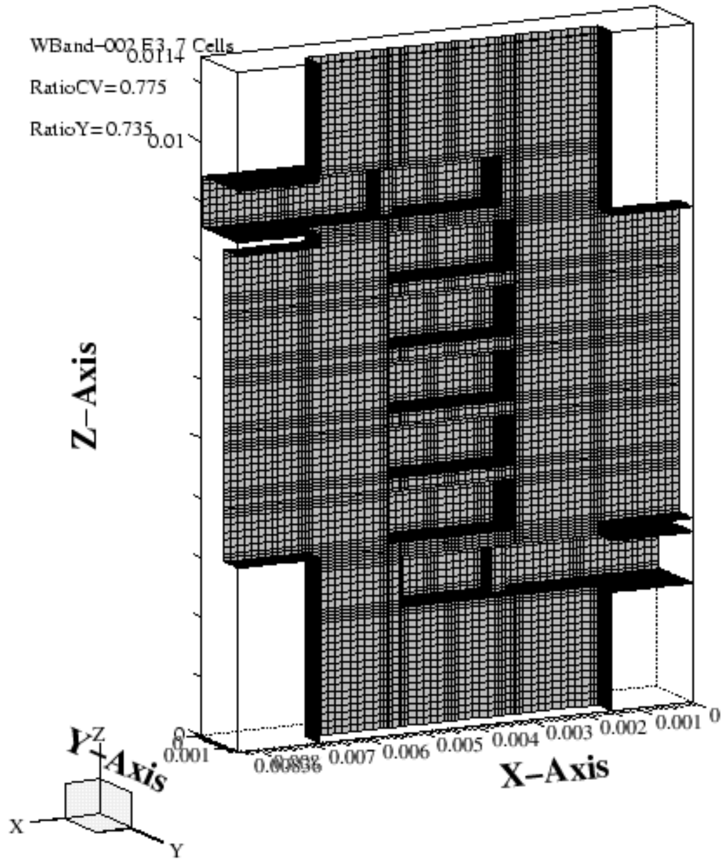


FIGURE 7. GdfidL model of a very well matched 7 cell structure.

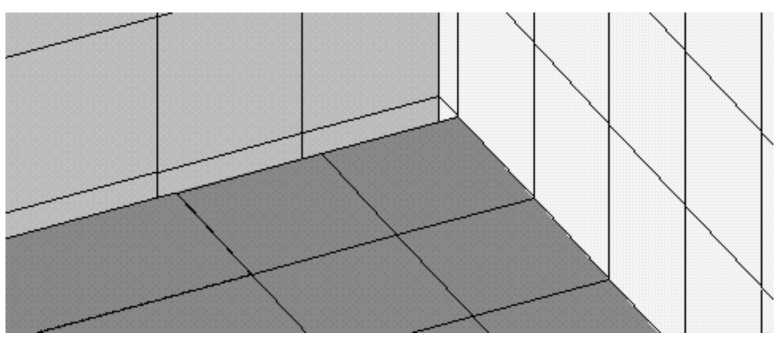


FIGURE 8. Simulated air gaps below each iris, zoom of figure 7.

In figures 9-10 the results of the numerical calculation are shown. As you can see the air gap caused an increasing of the bandwidth, that means a higher coupling and flipping effect of the charts. This means actually we indeed get a backward structure. Is this really so? If yes, the theoretical thoughts of chapter II are confirmed numerically. To prove this we need to do a further analysis. For this we calculate a dispersion chart. For this we compute two half cells with an air gap and a phase shift of 10 degree from 0 to 180 degree. If we get a negative group velocity we are right.

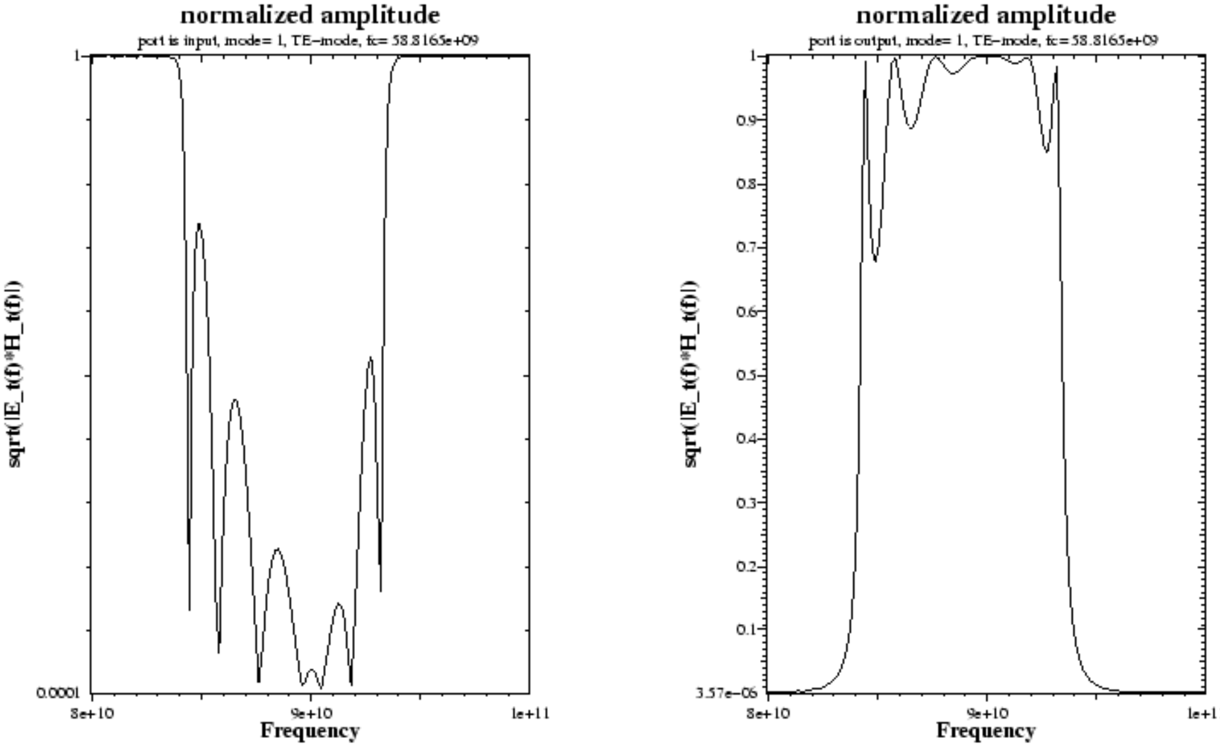


FIGURE 9. S_{11} and S_{12} computed with GdfidL with no air gap.

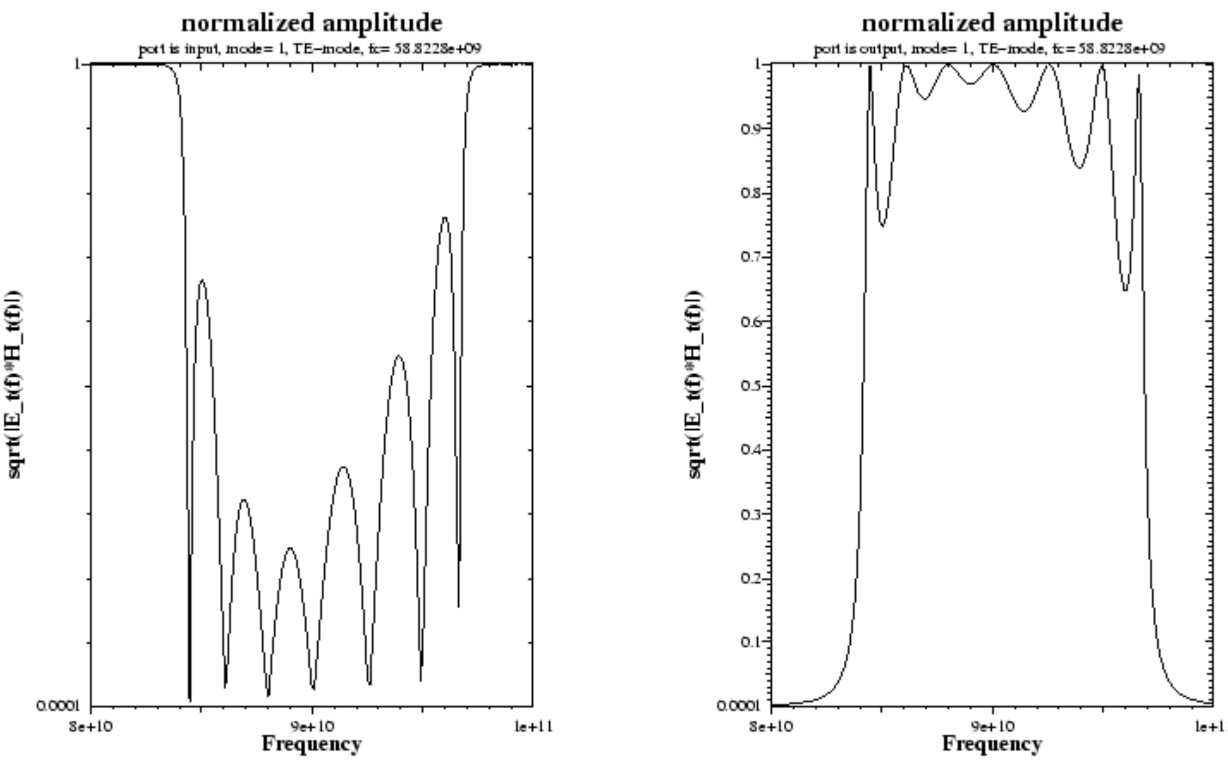


FIGURE 10. S_{11} and S_{12} computed with GdfidL with an air gap of 0.01 mm.

Figure 11 shows the electric field of the Pi Mode in the air gap. The geometry there is two half cavities with an iris in the middle. The size of the arrows indicates the strength of the field. As you can see, we get a very strong field under the iris. This high field causes losses, but it is questionable that these losses are responsible for the discrepancy shown in figure 1. However, an air gap caused something.

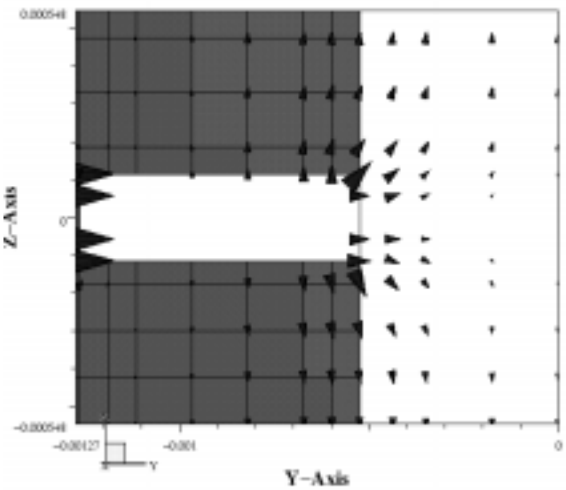


FIGURE 11. Field plot of cross section iris/two half cavities.

In figures 12-14 the dispersion chart of the structure WBAND-002 are shown. Figure 12 shows the results when no air gap is simulated. It is the ideal case and the reference for figures 13-14.
We get a bandwidth of 9.3 GHz, a positive group velocity and the function $v_{ph} = c_0$ has a crossing point at a phase shift of 2 pi/3 which is the designed and aimed frequency of 91.392 GHz.

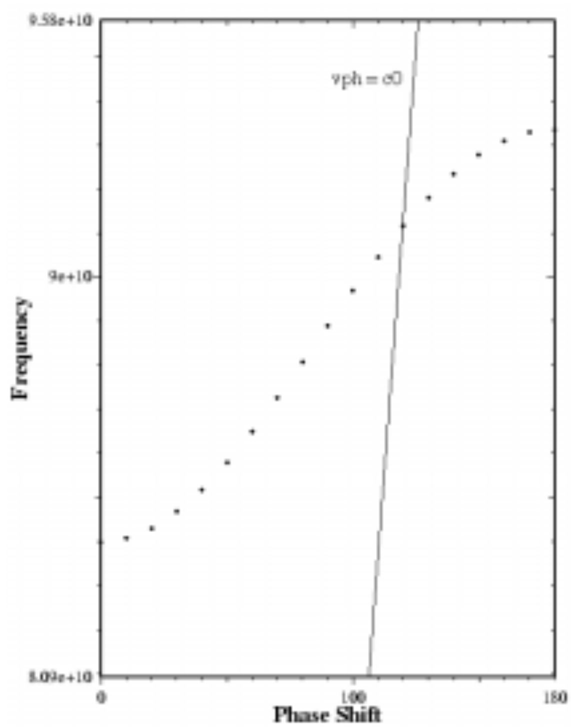
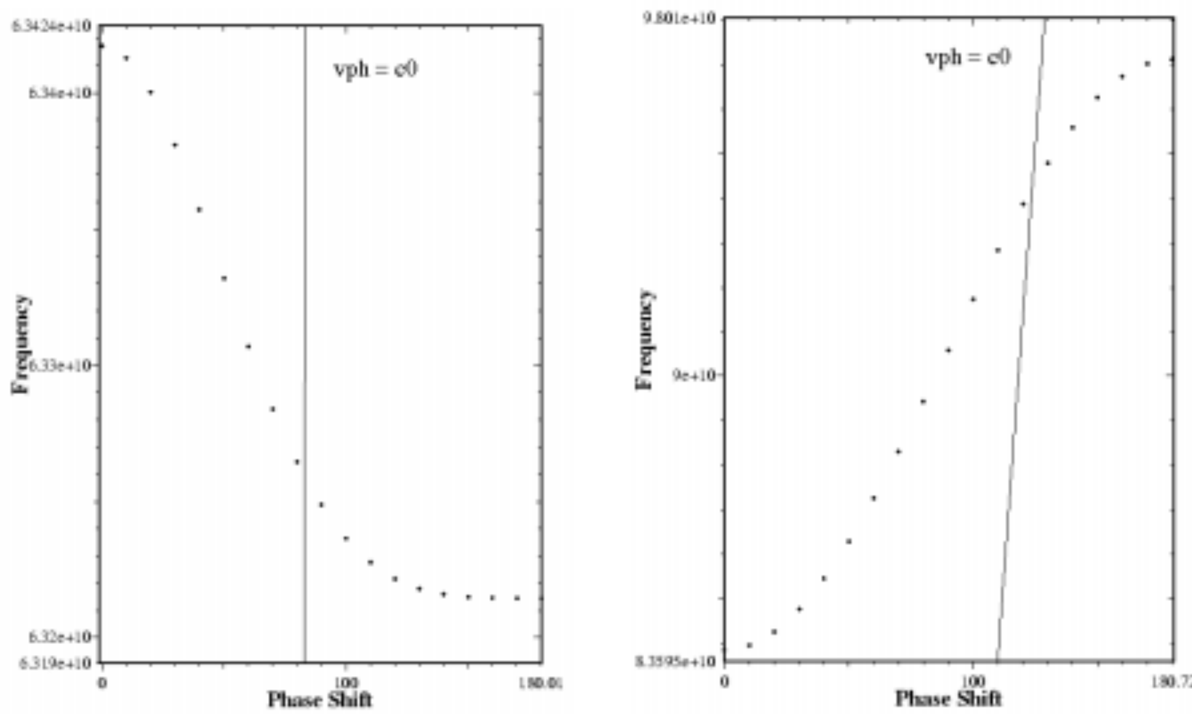


FIGURE 12. Dispersion chart of structure WBAND-002 with no air gap.

In figures 13-14 the same dispersion charts are presented for a structure with an air gap of 0.01 mm. Figure 13 shows the lowest band which is excited through the air gap. It has a bandwidth of 200 MHz and is a typical backward structure dispersion chart. The aimed frequency of 91.392 GHz is not within the band. Figure 14 presents the second band. It has a bandwidth of 13.5 GHz, this means an increasing of 50 % compared to no air gap. The air gap makes the structure faster. The structure is detuned with a 2 pi/3 mode at 94.3 GHz and has a typical forward structure dispersion chart.



FIGURES 13-14. Dispersion chart of structure WBAND-002 with an air gap of 0.01 mm.

After we did this numerical simulation, it is proved that the air gap doesn‘t cause a change from a forward to a backward structure. There is a new mode band excited from the gap which is indeed a band of a backward structure, but frequency range is too low and doesn‘t include the operating frequency.

After we saw the charts of the S parameter it was obvious to say that the air gap causes a flipping effect and a backward structure. After a dispersion chart calculation we can not confirm this. The flipping effect of the S_{11} and S_{12} charts is simply caused through a detuned structure.

This model was chosen to demonstrate the air gap effect, because not a lot of grid cells were necessary. The next step is to apply these results to the measured structure WBAND-000.

IV. Comparison of numerical results with measurements

After we saw in figure 1 how bad the measurements compare to the analytical solution, let us see what happens if we compare this with numerically determined results. A simulation was done with GdfidL [2]. The model of the W-Band structure is shown in figure 15. You see only one half, because a major symmetry is used. The used step size for the FDM mesh you see is not the used density. Calculations are done with a step size of 40 micrometers by applying an inhomogeneous mesh. The picture you can see is made with a step size of 0.1 mm. All important run time parameters for GdfidL are given in table 3 (RTFM for the meanings).

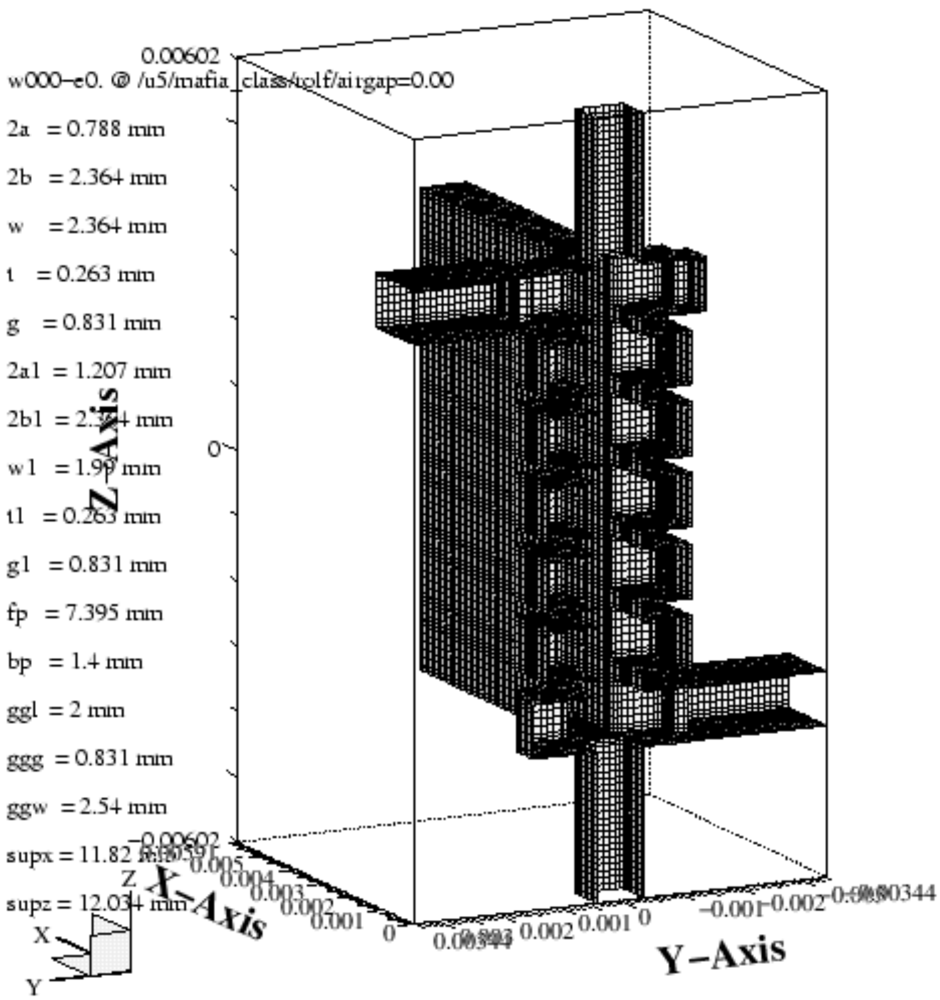


FIGURE 15. FDM model of WBAND-000 for GdfidL input.

```
define( NSOL,  eval(    30       ))   define( FUP,      eval(   3*FREQ    ))
define( NDZ,   eval(    1000     ))   define( AMPTRESH, eval(   1.0e-4    ))
define( TMIN,  eval( 500*PERIOD  ))   define( TMAX,     eval( 6000*PERIOD ))
define( TSF,   eval( 100*PERIOD  ))   define( TSL,      eval( 112*PERIOD  ))
define( TSD,   eval( 0.25*PERIOD ))
```

TABLE 3. GdfidL run time parameter.

Figures 16-17 show the result of the numerical simulation compared with the result of a own measurement [6]. As you can see the structure is not matched very well. It seems to be a backward structure without considering any effect. If we simulate an air gap here, we will get very bad results because of the bad match, but it is not necessary to do this, the results of chapter III are fine for our discussion.

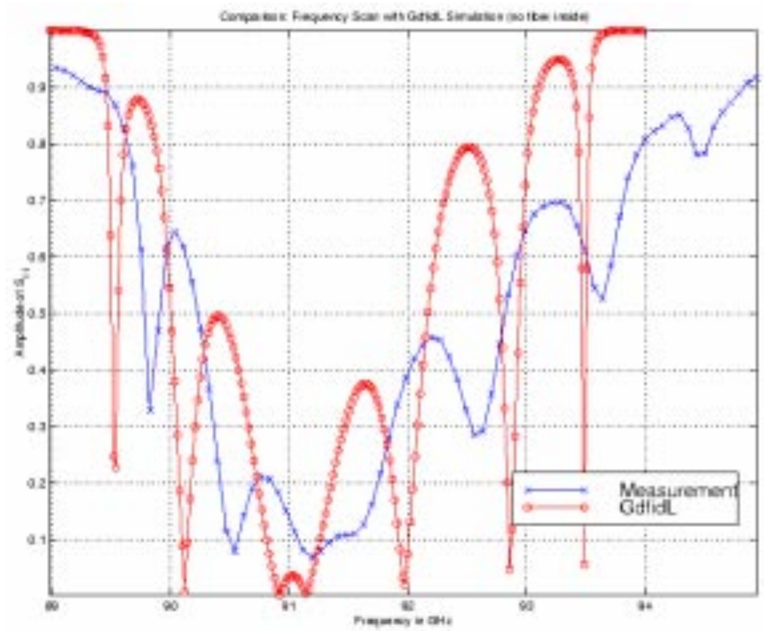


FIGURE 16. Overlay of the S_{11} component of the GdfidL simulation with results of measurements.

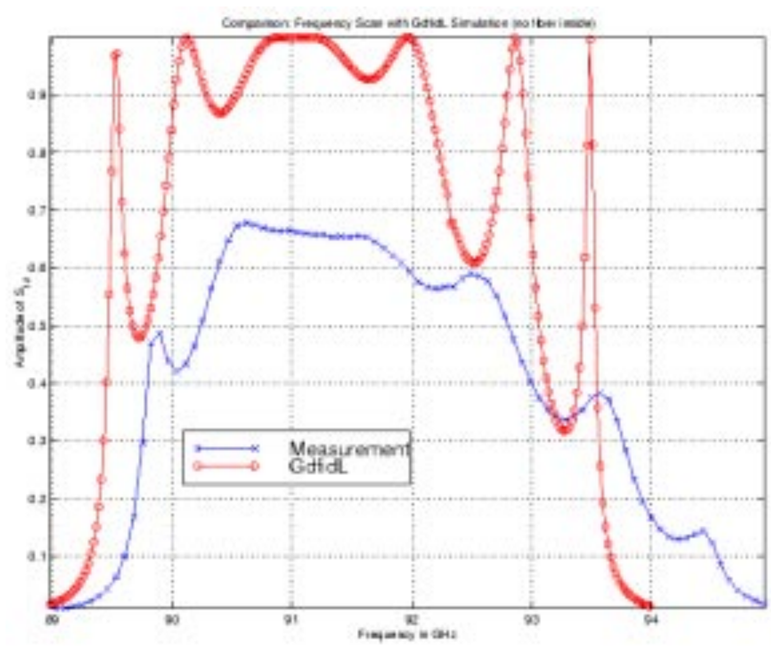


FIGURE 17. Overlay of the S_{12} component of the GdfidL simulation with results of measurements.

V. Conclusion

We saw some discrepancies between a perfect theoretical solution and measured data. Therefore an analysis of an air gap was done to determine the reasons for this.

First we used the program NMAT and compared the results with measured data. That what we got in chapter I was, that the measured structure has to be backward structure.

Second we did a numerical simulation of an air gap. It was shown that the air gap caused a flipping of the S parameter charts and it was obvious to say, that if an air gap is assumed for a well matched forward structure and we get a backward structure as shown in chapter I, that the air gap caused a flipping effect and a backward structure. The reason for this could be increased magnetic coupling in areas where the magnetic field is very strong, unfortunately the air gap area.

However, a calculation of the dispersion chart showed that we were wrong. The air gap doesn‘t cause a change from a forward to a backward structure. After a dispersion chart calculation we can not confirm this. The flipping effect of the S_{11} and S_{12} charts is simply caused through a detuned structure.

Otherwise it was shown that the WBAND-000 structure is not the same as we thought. Comparing the charts of the numerical GdfidL simulation with measured data, we saw that the discrepancies are not as big as they were when compared with the perfect solution in chapter I. The structure is not matched very well, therefore it is not necessary to consider an air gap effect to explain differences. Further we have losses in reality which were not considered in numerical calculation and losses in air gaps caused through strong fields. Maybe this is the answer for the anomalous losses as seen in figure 17. In point of losses a further detailed analysis is necessary.

The conclusion is, that the flipping effect of the S parameter charts is determined because the structure is matched like a backward structure, no air gap effect causes this. But an air gap effect may cause such a flipping of charts, but the reason is not a change to a backward structure, it is simply a detuned structure.

We need to apply a technology which avoids such bad contacts. One possibility is the application of diffusion bonding in further W-Band structures.

VI. References

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[2] W. Bruns, “GdfidL: A finite difference program for arbitrarily small perturbations in rectangular geometries”, IEEE Trans. Magn. Vol. 32, No. 3 May 1996.

[3] R. Siemann, “CALIBRATION OF W-BAND MEASUREMENT APPARATUS AND RESULTS FOR FIRST STRUCTURE”, Tech. Note 45, ARDB, SLAC, Stanford.

[4] P.J. Chou, G.B. Bowden, M.R. Copeland, H. Henke, A. Menegat, D.P. Pritzkau, R.H. Siemann, “DESIGN AND FABRICATION OF A TRAVELING-WAVE MUFFIN-TIN ACCELERATING STRUCTURE AT 90 GHZ”, PAC97, Paper 5B011, SLAC-PUB-7498.

[5] P.J. Chou, G.B. Bowden, M.R. Copeland, H. Henke, A. Menegat, D.P. Pritzkau, R.H. Siemann, “RF MEASUREMENT OF A TRAVELING-WAVE MUFFIN-TIN ACCELERATING STRUCTURE AT 90 GHZ” PAC97, Paper, SLAC-PUB-7499.

[6] R. Merte, “Bead Pull Measurement and Sensitiveness Analysis of a W-Band Muffin Tin”, Tech. Note 159, ARDB, SLAC, Stanford.