Additive Manufactured Compact Microwave Absorber

Greg P. Le Sage, Muhammad Shumail

16 FEB 2024

U.S. DEPARTMENT OF ENERGY
Office of Science

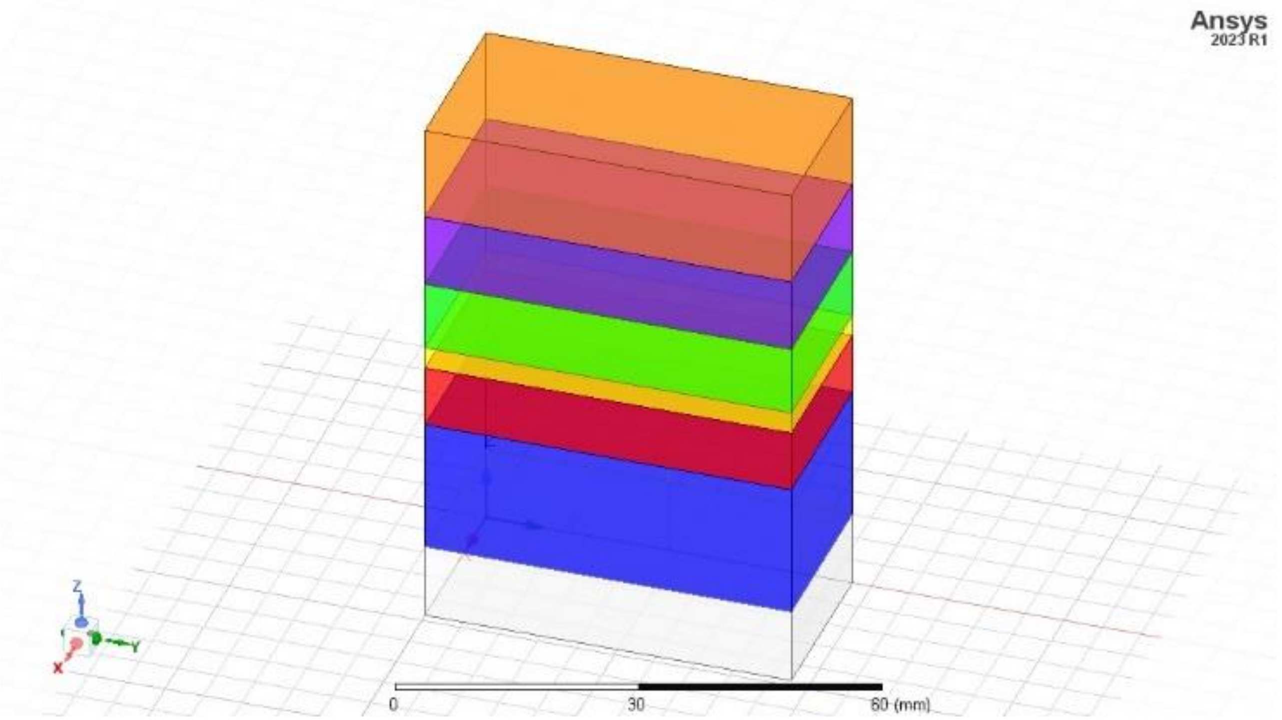
SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

- We designed a 3D printed microwave absorber at C band: 3.95 – 5.85 GHz
- The absorber is composed of 5-6 3D printed “pucks” of three different materials with varying “fill factor,” which is the percentage of plastic.
- The attenuator was optimized both for a single frequency and for broadband operation. HFSS was used and later complimented by analytic solution in MATLAB.
- Single frequency operation at 4.93 GHz was -73 dB with an absorber length of 2.44 inches.
- A commercial broadband load (a triangular taper) has length 13 inches. It has loss of 40 dB across the band.
- The materials that were used were carbon loaded PLA (Proto Pasta), a second carbon loaded PLA (Sunlu) – which has lower loss, and regular PLA plastic.
- HFSS optimized fill factors and puck lengths with a goal of minimal S_{11} at a design frequency at mid band: 4.9 GHz.

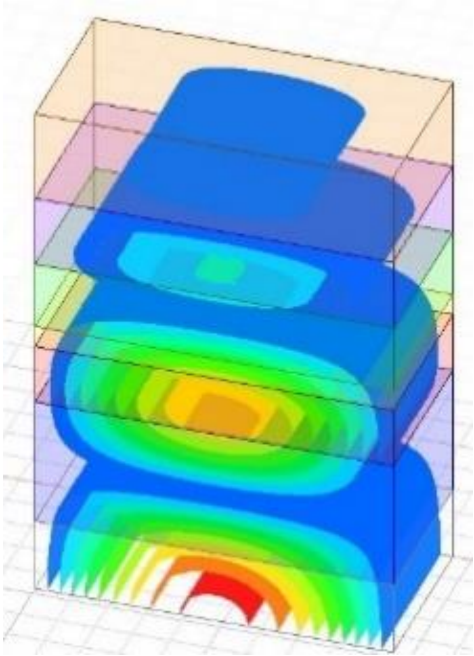
Absorber Model

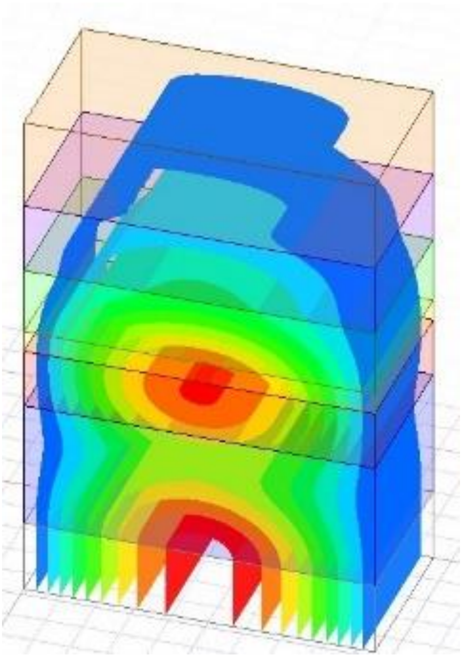
- The HFSS model includes six pucks (later 5) in a WR-187 waveguide terminated with a shorting plane.
- The loss tangent and dielectric constant increase from the input side to the short.
- The first two layers are plain PLA. The second one or two are SUNLU carbon loaded PLA and the last two are Proto Pasta carbon loaded PLA.



HFSS Model

- HFSS is parameterized with the bulk dielectric values and calculates ε_r and tan δ for each puck.
- The 3D EM model provides the value of S_{11} as a function of frequency.
- I am using project variables for material parameters and design properties for puck lengths.
- The code can vary the fill factors and lengths of all five or six pucks.
- The HFSS code optimizes minimum S_{11} at a particular frequency.





Theory

- With the bulk dielectric constant and loss tangent known, ε_r and tan δ can be determined as a function of the fill factor.
- Practically speaking, fill factor can't be less than about 20%
- The formulas make physical sense. Physical features are small compared to a wavelength, so a 3D printed object acts like bulk material.

$$\varepsilon_{custom} = ff * \varepsilon_{bulk} + (1 - ff) * \varepsilon_{hole} = \varepsilon' - j\varepsilon''$$

$$tan\delta_{custom} = ff * tan\delta_{bulk}\left(\frac{\varepsilon_{r,bulk}}{\varepsilon_{r,custom}}\right) + (1 - ff) * tan\delta_{hole} * \left(\frac{\varepsilon_{r,hole}}{\varepsilon_{r,custom}}\right)$$

$$\varepsilon_{custom} = ff * \varepsilon_{bulk} + (1 - ff)$$

$$\tan\delta_{custom} = ff * tan\delta_{bulk}\left(\frac{\varepsilon_{r,bulk}}{\varepsilon_{r,custom}}\right)$$

Assuming $\varepsilon_{r,hole} = 1$, and tan $\delta_{hole} = 0$

Difficulty

SLAC

- There are many ways to measure dielectric properties. These include cavity perturbation, coaxial probing, resonant cavity measurement, transmission methods, and more.
- For this project, I have used all the techniques I know. Some work well for low loss materials but don’t work at all for high loss materials.
- If you read published literature on the materials we are using, you can find a factor of two difference in accepted results for ε_r and tan δ. Someone is wrong.
- The problem is that you make a measurement, and you get a number. It’s hard to know if the result is right or not.
- Not knowing the true bulk parameters make optimization useless.
- This is why I was unsuccessful for a long time.

Solution

- Muhammad Shumail became involved in this project and changed everything.
- He has developed a waveguide measurement technique which is obviously accurate for both low loss and high loss materials, as proven by the fact that using his numbers leads to designs that work!
- The results agree with cavity perturbation and resonant cavity measurement methods for plain PLA (low loss). There I can rely on these other techniques, which also agree with each other.
- To estimate relative permittivity and loss-tangent he uses two methods: S Parameter based, and Two-Reflection based.
- We plan to publish this new technique in a separate paper.
- Shumail also solved the problem analytically using MATLAB.
- I added an optimizer to his code. It solves the problem in seconds!

S-parameters Method

$$\gamma_a = i2\pi\left(\frac{1}{{\lambda_0}^2} - \frac{1}{4a^2}\right)^{1/2}.$$

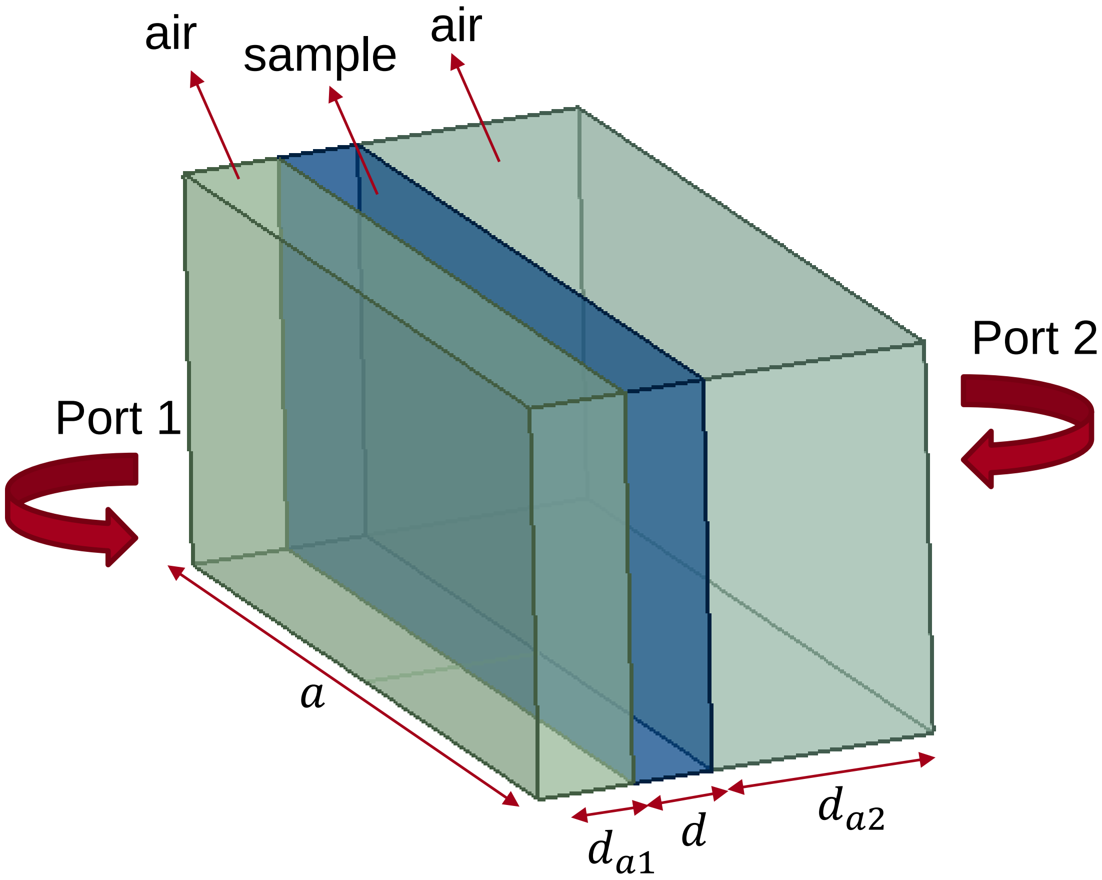
$$\Delta S = S_{11}S_{22} - S_{12}S_{21}.$$

$$K = \frac{1 + \Delta S\, e^{2\gamma_a d_a}}{\left((1 - \Delta S\, e^{2\gamma_a d_a})^2 - 4S_{21}^2 e^{2\gamma_a d_a}\right)^{1/2}}.$$

$$\gamma = \alpha + i\beta = \gamma_a\left(K + \sqrt{K^2 - 1}\right).$$

$$\epsilon_r = \frac{\left(\frac{\pi}{a}\right)^2 - \mathrm{Re}[\gamma^2]}{\left(\frac{2\pi}{\lambda_0}\right)^2}.$$

$$\tan\delta = \frac{\mathrm{Im}[\gamma^2]}{\left(\frac{2\pi}{\lambda_0}\right)^2 \epsilon_r}.$$



γ_a: propagation constant in air
λ_0: free space wavelength
a: guide width
d_a: total length of guide on each side of the sample (air length)

$$d_a = d_{a1} + d_{a2}$$

Single measurement of two ports does not depend on sample location in waveguide

Two Reflection Method

$$\gamma = j\beta_a\left(-\frac{j}{\sin\beta_a d_a\,(1+\Gamma_1)}\left((1-\Gamma_1)\cos\beta_a d_a-\left(e^{-j\beta_a d_a}+e^{j\beta_a d_a}\Gamma_1\right)\frac{1-\Gamma_2 e^{j2\beta_a d_a}}{1+\Gamma_2 e^{j2\beta_a d_a}}\right)\right)^{1/2}$$

$$\epsilon_r = \frac{\left(\frac{\pi}{a}\right)^2-\mathrm{Re}[\gamma^2]}{\left(\frac{2\pi}{\lambda_0}\right)^2}.$$

$$\tan\delta = \frac{\mathrm{Im}[\gamma^2]}{\left(\frac{2\pi}{\lambda_0}\right)^2\epsilon_r}.$$

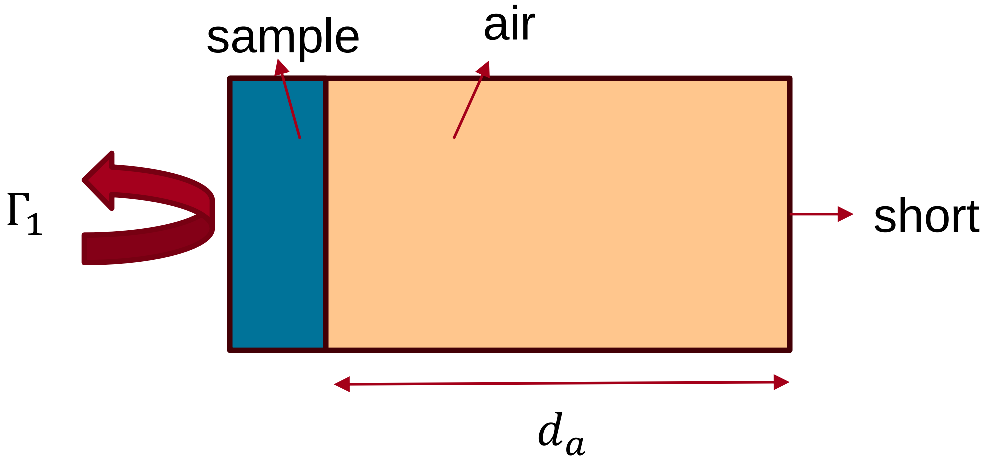
λ_0: free space wavelength

a: guide width

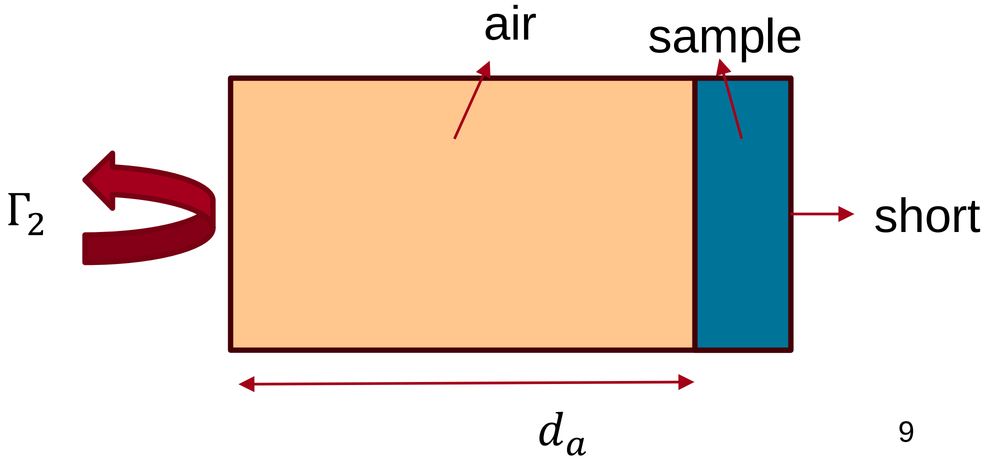
β_a: $2\pi/$guide-wavelength-in-air

- Two one port measurements
- Does not depend on sample thickness

First reflection measurement



Second reflection measurement



This method can also be used to estimate the electrical length of a sample

- This technique also determines the electrical length of the sample using the following equations.

$$\frac{S_{11}}{S_{22}} = e^{-2\gamma_a(d-d_s)}$$

$$d_s = d + \frac{Arg\left(\frac{S_{11}}{S_{22}}\right)+n\cdot 2\pi}{2\beta}$$

- Where d is the waveguide length and d_s is the sample length. The argument of S_{11}/S_{22} is the angular component of the complex value. One adds $n2\pi$ as appropriate to find a physical length.

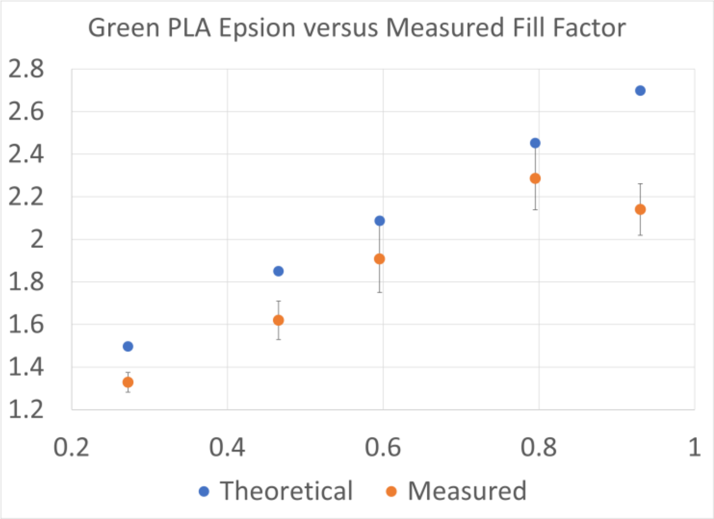
Analytic Solution in MATLAB

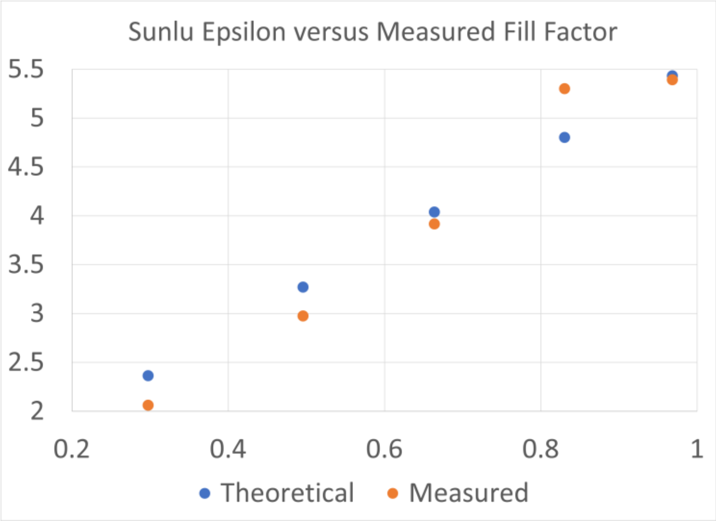
```
gamma = ( (pi/a)^2 - (2*pi/lambda0)^2 * epsilon.*(1 - 1i*tandelta) ).^(1/2); %(cm^-1)
Zg= eta0*2*pi*1i./(lambda0*gamma); %Ohm
T11=(gamma(1:N-1)+gamma(2:N));
T22=T11;
T12=(gamma(1:N-1)-gamma(2:N));
T21=T12;
Td=2*(gamma(1:N-1).*gamma(2:N)).^(1/2);
Tinterface=reshape([T11./Td; T12./Td; T21./Td; T22./Td],[2,2,N-1]);
Tsection=reshape([exp(gamma.*d); 0*d; 0*d; exp(-gamma.*d)],[2,2,N]);

Tfull = Tsection(:,:,1);
for i = 1:N-1
Tfull=Tfull*Tinterface(:,:,i)*Tsection(:,:,i+1);
end

S21=1/Tfull(1,1);
S11=Tfull(2,1)/Tfull(1,1);
S22=-Tfull(1,2)/Tfull(1,1);
DeltaS=-Tfull(2,2)/Tfull(1,1);
S12=(S11*S22-DeltaS)/S21;
Sfull=[S11 S12; S21 S22];
Gamma = (S11+DeltaS)/(1+S22);%reflection when far end is shorted


S11dB(loop)=20*log10(abs(Gamma));

end
```

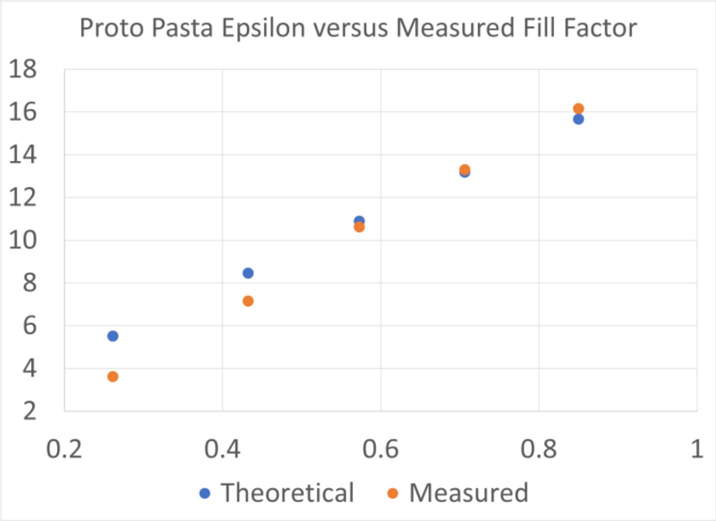
- The puck stack is physically modeled inside of a waveguide.
- The value of S_{11} is calculated as a function of frequency.
- A loop can solve the whole bandwidth.
- An optimizer was wrapped around the analytical solution developed in Mathematica and ported to MATLAB.
- The initial optimizer solved a single frequency.
- Additional code solved ten frequency points. The sum was sent to the optimizer with the lowest point dropped. That prevented a single point solution.
- This provided broadband optimization.

Compare theory, simulation, and measurement

- I 3D printed a series of pucks with 20%, 40%, 60%, 80%, and 100% fill factor for all three materials.
- I used puck weight and volume to determine the measured fill factor, which varies from the value put in to the 3D printer.
- Note that print temperature also has a significant impact on density.
- I simulated all of this using HFSS and MATLAB to compare to theory and measurement.

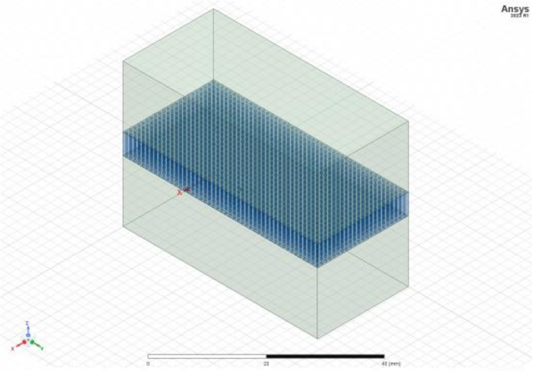
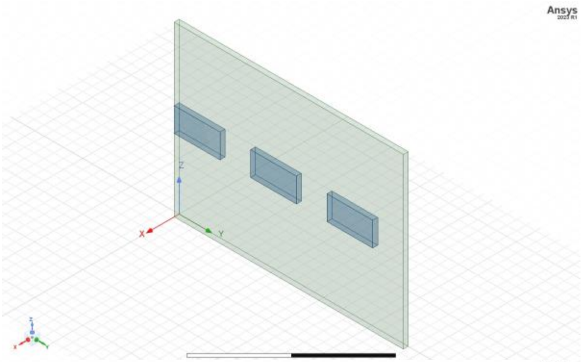
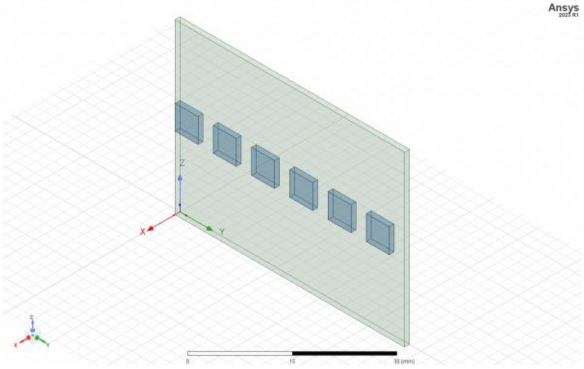
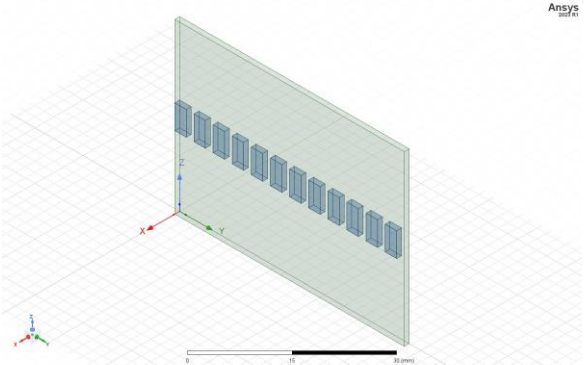
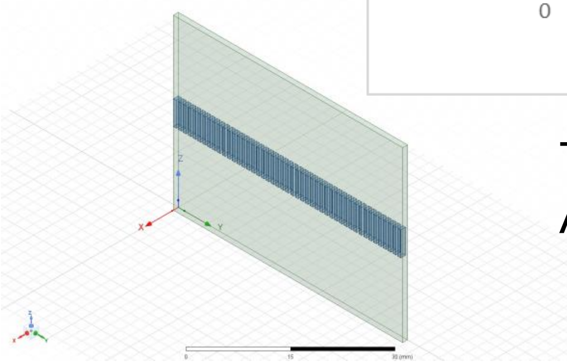


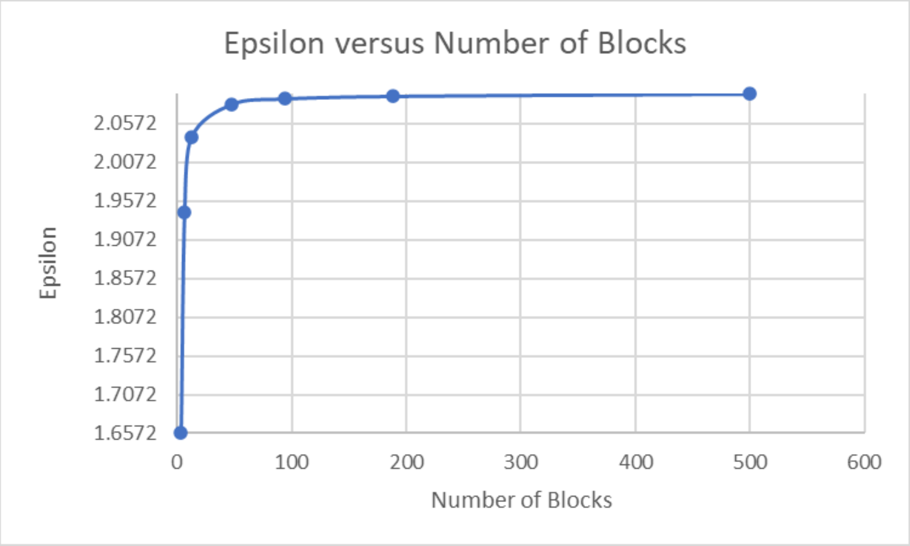




Simulate partially filled dielectric pucks HFSS and MATLAB

- Simulating a solid puck with epsilon and tan δ set by theoretical formulas simply resulted in expected values with MATLAB – not interesting: Input = Output
- A full-size puck with round holes took much too long to simulate and crashed the cluster.
- TE_{10} allows arbitrary waveguide height and rectangular holes simulated quickly. Set waveguide height = 2 mm.
- Try progressive numbers of holes to see when the value converges to the theoretical expectation.
- Tiny gaps (λ/300) change the reported value of epsilon.



The lesson is that pucks must
Always be measured.

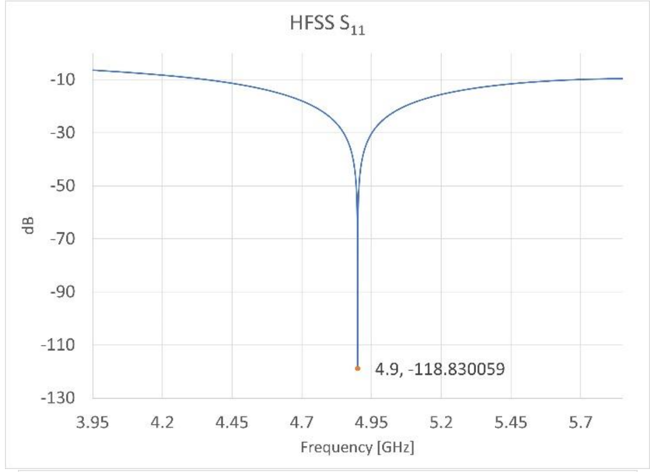
Single frequency solution – a big success

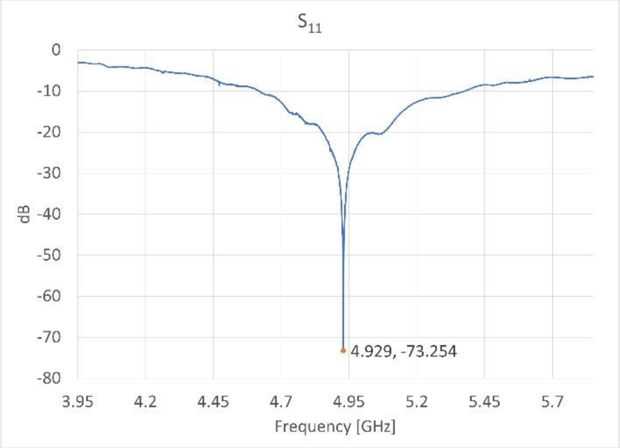
- The absorber optimized for a single frequency worked exceptionally well.
- Theory showed S_{11} = -119 dB. Measurement showed -73 dB with a small shift in frequency.

Block	Actual/Design Length	Calc/Design Fill Factor
1	16.78/16.851	68.97/68.270
2	8.27/8.186	40.13/38.942
3	3.90/3.888	47.36/47.067
4	4.22/4.197	51.77/50.834
5	14.48/14.490	59.171/60.566
6	14.40/14.369	35.94/35.849

Block	Design ε	Measured ε	Design tan δ	Measured tan δ
1	2.246	2.1	0.007	0.005
2	1.711	1.6	0.005	0.005
3	3.154	3.2	0.011	0.012
4	3.327	3.4	0.011	0.012
5	11.444	11	1.166	1.3
6	7.182	5	1.100	1.5

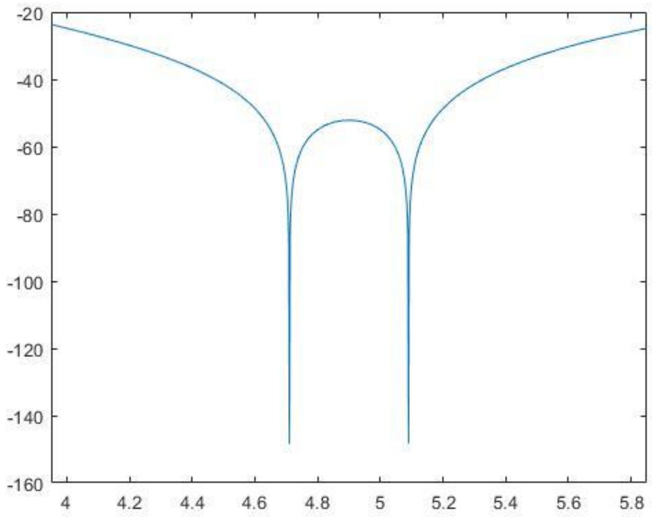
Commercial Load with pucks

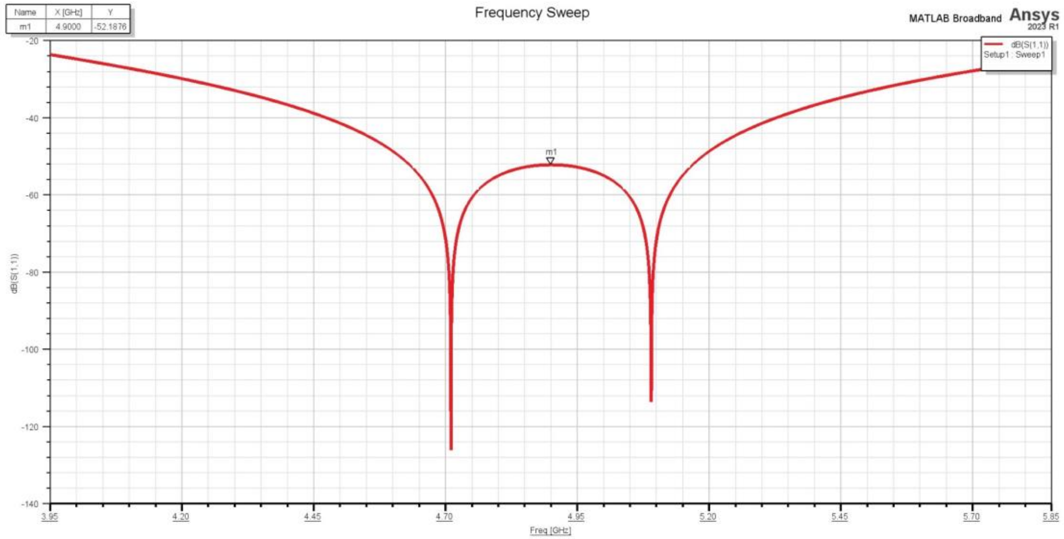




Broadband solution

- The broadband solution is too slow using HFSS. The single frequency solution takes days, so a broadband solution will take much longer.
- The MATLAB code optimizes a single frequency in a few seconds.
- I looped MATLAB to solve ten frequencies in the band, added the result, dropped the lowest result. I optimized the result based on the sum.
- The MATLAB code provides a new design for the pucks.
- Putting the design values in to HFSS gives a very similar result.

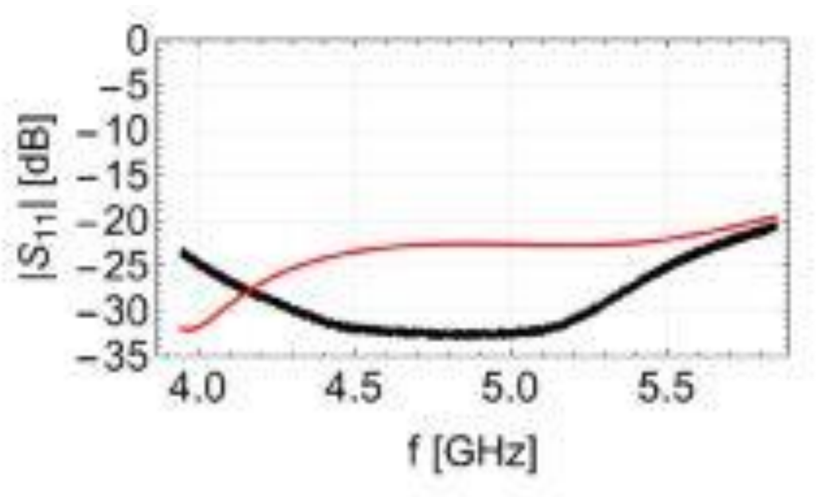




Broadband construction

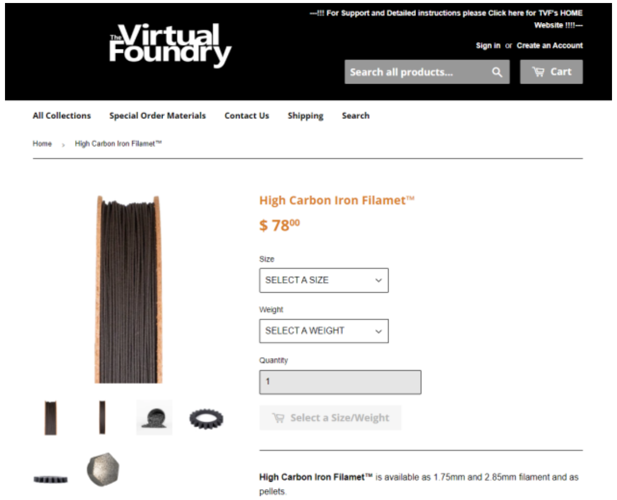
- A broadband load was built.

#	Name	length (mm)	Epsilon_r	Tan(delta)
5	Proto Pasta	23.83 +/- 0.02	9.8 +/- 0.3	1.65 +/- 0.01
4	Proto Pasta	7.15 +/- 0.04	4.5 +/- 0.2	2.00 +/- 0.05
3	Sunlu	3.72 +/- 0.04	5.52 +/- 0.02	0.008 +/- 0.002
2	Green PLA	6.36 +/- 0.03	2.046 +/- 0.005	0.010 +/- 0.001
1	Green PLA	14.2 +/- 0.1	1.237 +/- 0.002	0.003 +/- 0.002



The future

- I want to transition to 3D printing metal loaded ceramics.
- Structures can be sintered so that they are solid and contain no plastic.
- These structures could tolerate high power and be vacuum compatible.
- I want to create high power, UHV loads appropriate for use at SLAC.
- I am talking to The Virtual Foundry. I can 3D print their materials and send them to be sintered. We will measure the ε_r and tan δ.
- Some customers 3D print Silicon Carbide and sinter in a microwave oven.
- I want to create a load with ceramics.
- I want to apply for SLAC LDRD.



SLAC Requirements

- The Klystron lab uses water loads.
- High pressure water behind a thin ceramic is a risk.
- Only dry loads are used on the linac