ASD Scorpius

Project Update

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National Nuclear Security Administration

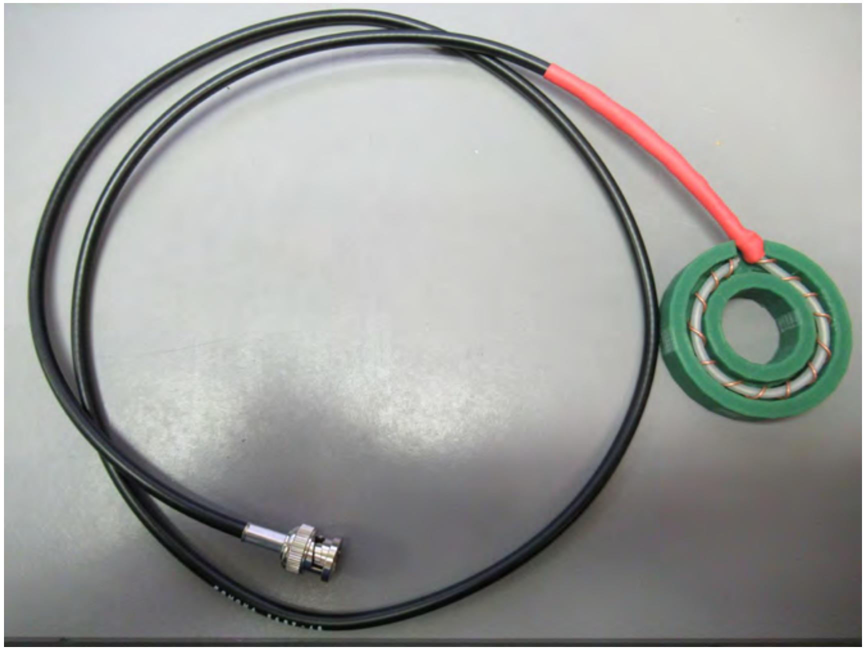
Los Alamos National Laboratory

Lawrence Livermore National Laboratory

Sandia National Laboratories

Nevada National Security Site

Custom Made Rogowski Coil



- Custom Rogowski made with RG-58 cable
- N=14 turns
- R=0.75 in
- R=0.098 in
- LCR meter measured ~250-260 nH (series inductance)
- Calculated self-inductance was ~20.5 nH

$$L_r := \mu_0 \cdot N^2 \cdot \left(R - \sqrt{R^2 - r^2}\right) = 20.489\ nH$$

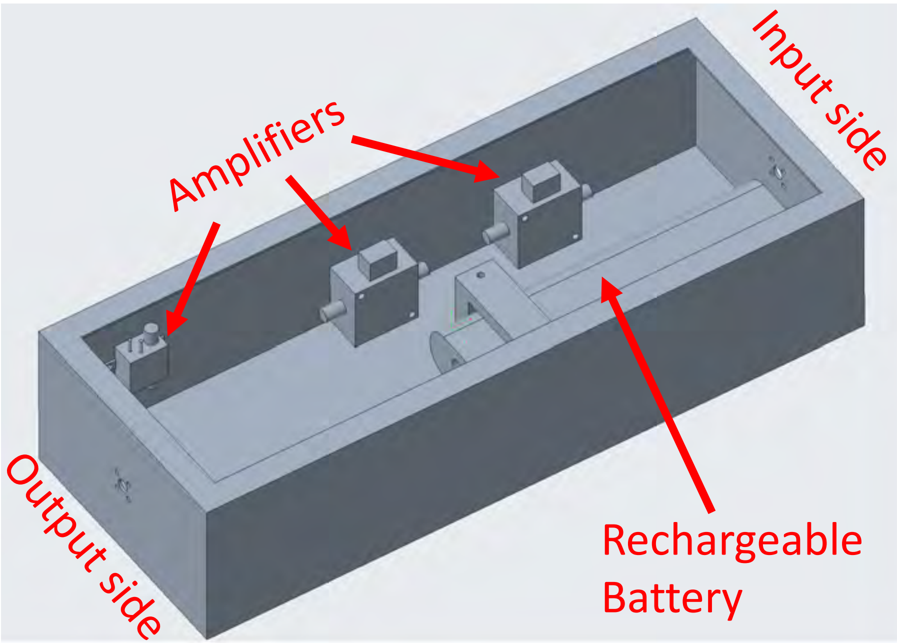
- L/R rise time is 5.2 ns (L=260 nH, R=50 Ω)
- Pulse rise time 10-15 ns, it will be able to measure the signal worst case scenario
- Induced voltage on the coil

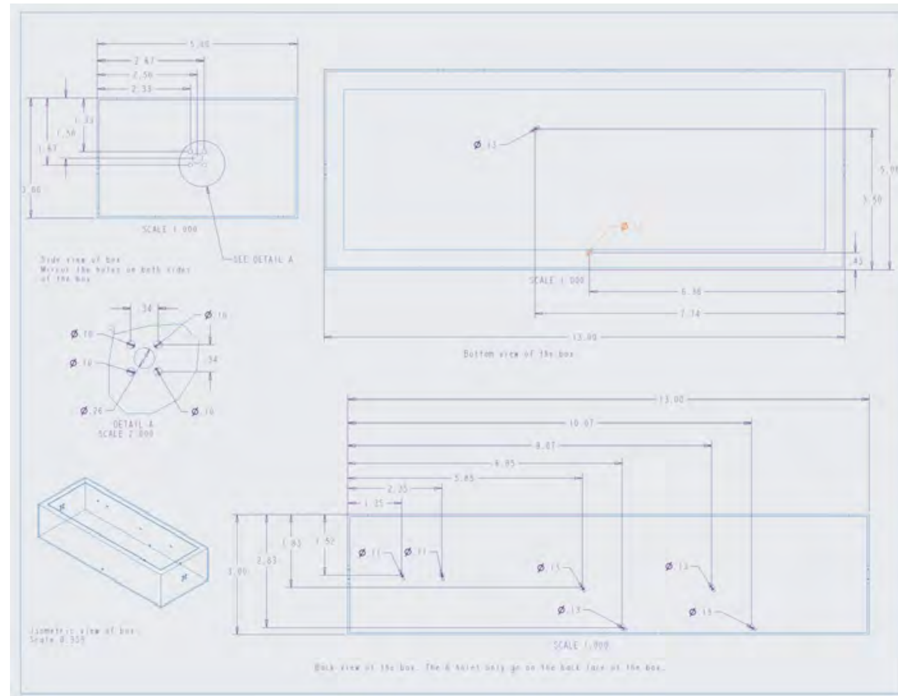
$$V_r := \frac{N \cdot \mu_0 \cdot r^2}{2 \cdot R} \cdot i_{dt} = 14.619\ mV$$

$$i_{dt} := \frac{0.1\ A}{10\ ns}$$

Current pulse rise time

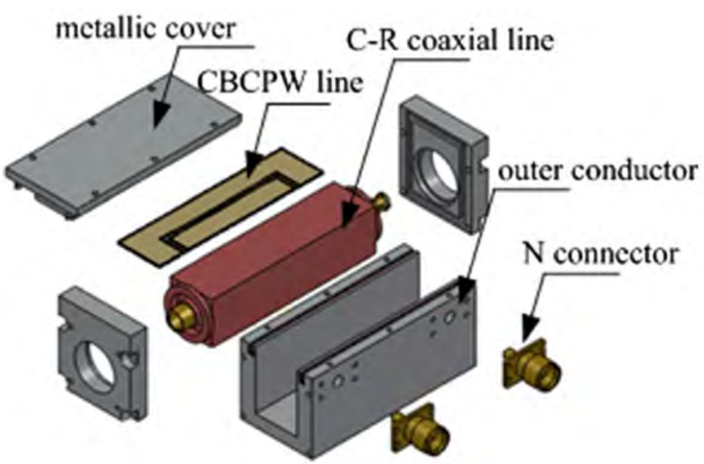
Amplification Box Assembly



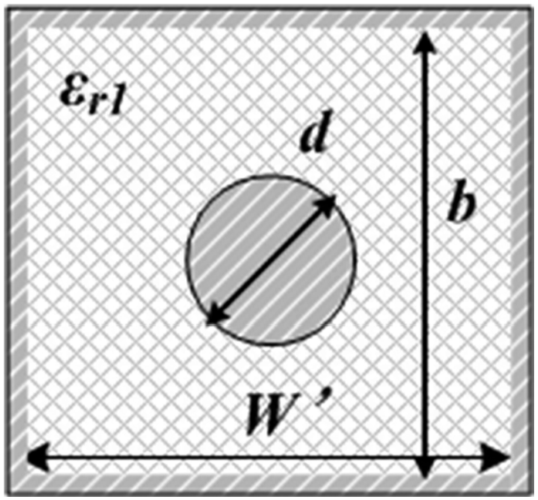


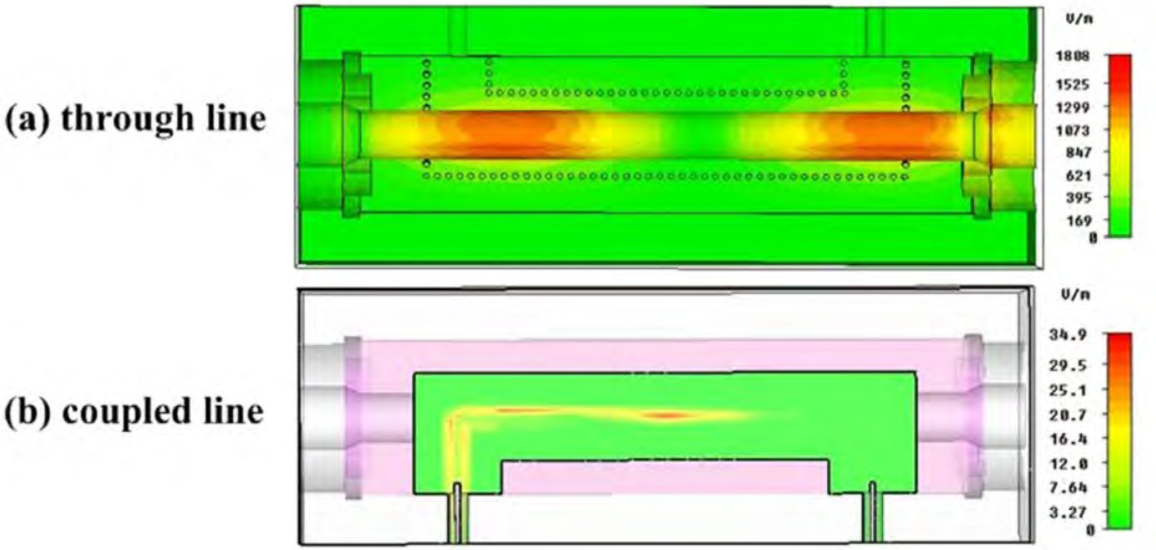
- I modeled the amplification box and components in Creo to figure out the placement of the components
- The box is currently getting mounting holes made by a machinist
- Following this, I will start assembling the box

Recall Coaxial to Coplanar Waveguide Directional Coupler



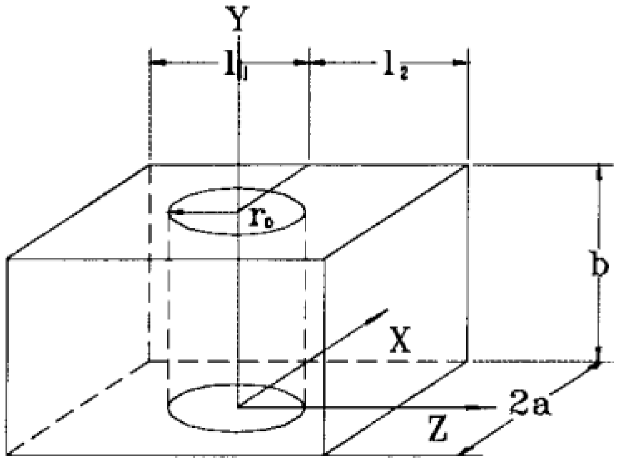
- Directional coupler (CPW) that couples signal from C-R coax line
- This design can be scaled up for use in an embedded diagnostic for Scorpius
- The first step is to start with the design of the C-R coaxial line

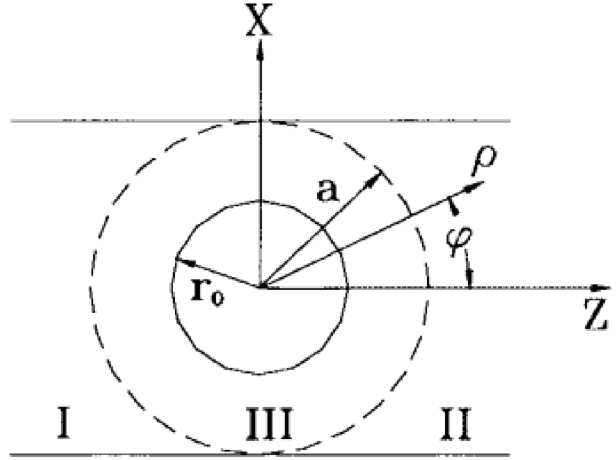




X. Cui, X. Wu, Z. Xiong, et al. "Design and development of compact coaxial to coplanar waveguide directional coupler for HPM measurement," in Rev. Sci. Instrum., vol. 88, 124702, November 2017, https://doi.org/10.1063/1.5001978.

TEM-Mode Based Analysis





- TEM-mode based analysis carried out to find analytical expressions for the characteristic impedance and attenuation coefficient
- Derived from eigensolution of the structure of a rectangular waveguide cavity with a full height conducting post
- After some deriving, the equation for impedance can be found as:

$$Z = \frac{V}{I} = \frac{\int_{r_0}^{a} E_\rho^{III}(\phi = \pi/2)\, d\rho}{\oint H_\phi^{III}(\rho = \rho_0)\rho_0\, d\phi} \qquad r_0 \le \rho_0 \le a$$

$$\oint H_\phi^{III} \rho_0\, d\phi = \left[C_{01}^{e} J'\left(\eta_1^{e}\rho_0\right) + D_{01}^{e} Y_0'\left(\eta_1^{e}\rho_0\right)\right]\frac{k_0^2}{\eta_1^2} 2\pi \cos\left(\frac{\pi}{b} y_0\right)\rho_0$$

$$\int_{r_0}^{a} E_\rho^{III}(\phi = \pi/2)\, d\rho = \sum_{n=0}^{N}\left(V_n^e + V_n^h\right)$$

Haiyin Wang, Ke-Li Wu and J. Litva, "A modal analysis of TEM mode in circular-rectangular coaxial waveguides," in IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 3, pp. 356-359, March 1999, doi: 10.1109/22.750240.

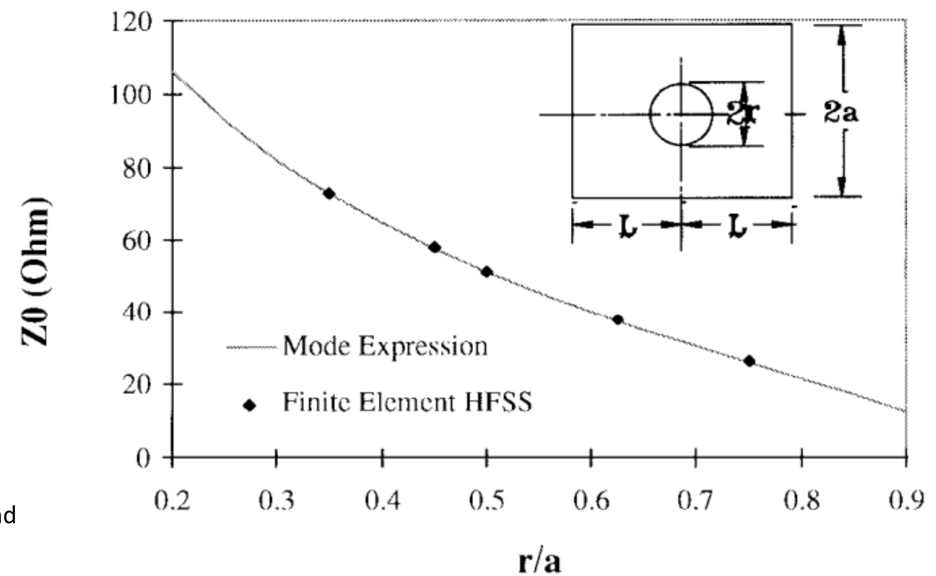
TEM-Mode Based Analysis Cont.

$$V_n^e = \left\{C_{n1}^e\left[J_n\left(\eta_1^e a\right) - J_n\left(\eta_1^e r_0\right)\right] + D_{n1}^e\left[Y_n\left(\eta_1^e a\right) - Y_n\left(\eta_1^e r_0\right)\right]\right\}\begin{Bmatrix}\sin(n\phi)\\ \cos(n\phi)\end{Bmatrix}\frac{(-\pi)}{b\eta_1^{e2}}\sin\left(\frac{\pi}{b}y_0\right)$$

$$V_n^h = C_{n1}^h\begin{cases} J_n\left(\eta_1^h a\right) - J_n\left(\eta_1^h r_0\right) - 2\sum_{k=1}^{n/2}\left[J_{2k}\left(\eta_1^h a\right) - J_{2k}\left(\eta_1^h r_0\right)\right] - J_0\left(\eta_1^h a\right) + J_0\left(\eta_1^h r_0\right) \\ \qquad n = 0, 2, 4, \cdots \\ J_n\left(\eta_1^h a\right) - J_n\left(\eta_1^h r_0\right) - 2\sum_{k=0}^{(n-1)/2}\left[J_{2k}\left(\eta_1^h a\right) - J_{2k}\left(\eta_1^h r_0\right)\right] + \int_{r_0}^{a} J_0\left(\eta_1^h r\right)\eta_1^h\, dr \\ \qquad n = 1, 3, 5, \cdots \end{cases}\begin{Bmatrix}\sin(n\phi)\\ \cos(n\phi)\end{Bmatrix}\frac{1}{\eta_1^{h2}}\sin\left(\frac{\pi}{b}y_0\right)$$

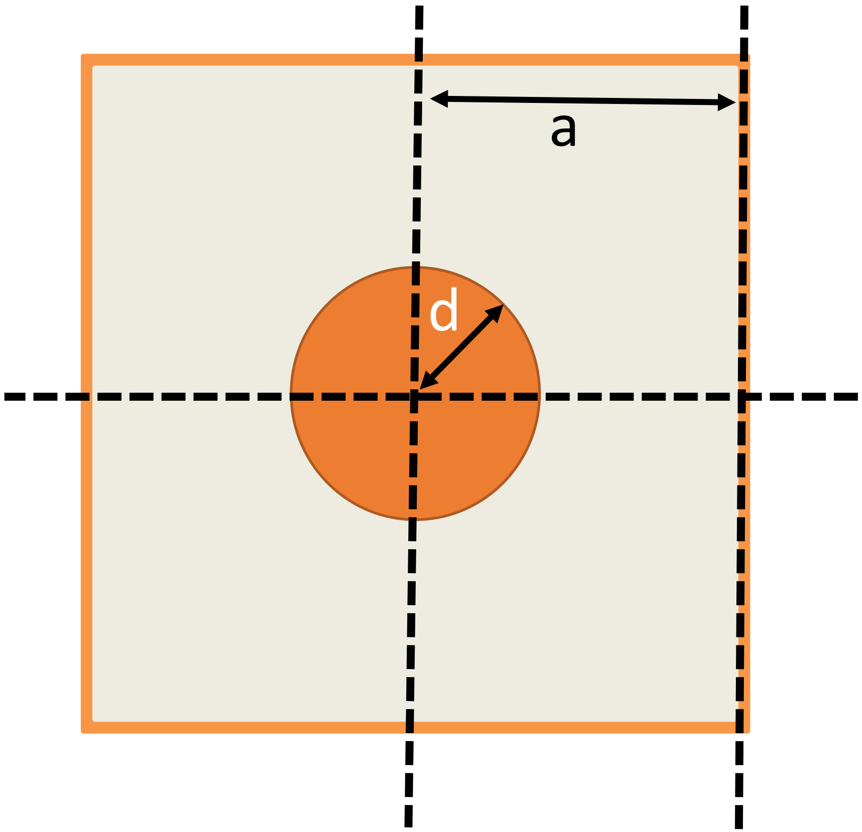
$$+ D_{n1}^h\begin{cases} Y_n\left(\eta_1^h a\right) - Y_n\left(\eta_1^h r_0\right) - 2\sum_{k=1}^{n/2}\left[Y_{2k}\left(\eta_1^h a\right) - Y_{2k}\left(\eta_1^h r_0\right)\right] - Y_0\left(\eta_1^h a\right) + Y_0\left(\eta_1^h r_0\right) \\ \qquad n = 0, 2, 4, \cdots \\ Y_n\left(\eta_1^h a\right) - Y_n\left(\eta_1^h r_0\right) - 2\sum_{k=0}^{(n-1)/2}\left[Y_{2k}\left(\eta_1^h a\right) - Y_{2k}\left(\eta_1^h r_0\right)\right] + \int_{r_0}^{a} Y_0\left(\eta_1^h r\right)\eta_1^h\, dr \\ \qquad n = 1, 3, 5, \cdots \end{cases}\begin{Bmatrix}\sin(n\phi)\\ \cos(n\phi)\end{Bmatrix}\frac{1}{\eta_1^{h2}}\sin\left(\frac{\pi}{b}y_0\right)$$

- The expression is complicated, but shows good results with simulation results from HFSS
- It would be more ideal to find a simpler expression to calculate the characteristic impedance



Haiyin Wang, Ke-Li Wu and J. Litva, "A modal analysis of TEM mode in circular-rectangular coaxial waveguides," in IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 3, pp. 356-359, March 1999, doi: 10.1109/22.750240.

Simplified Expression for Impedance of Square-Circular Coax



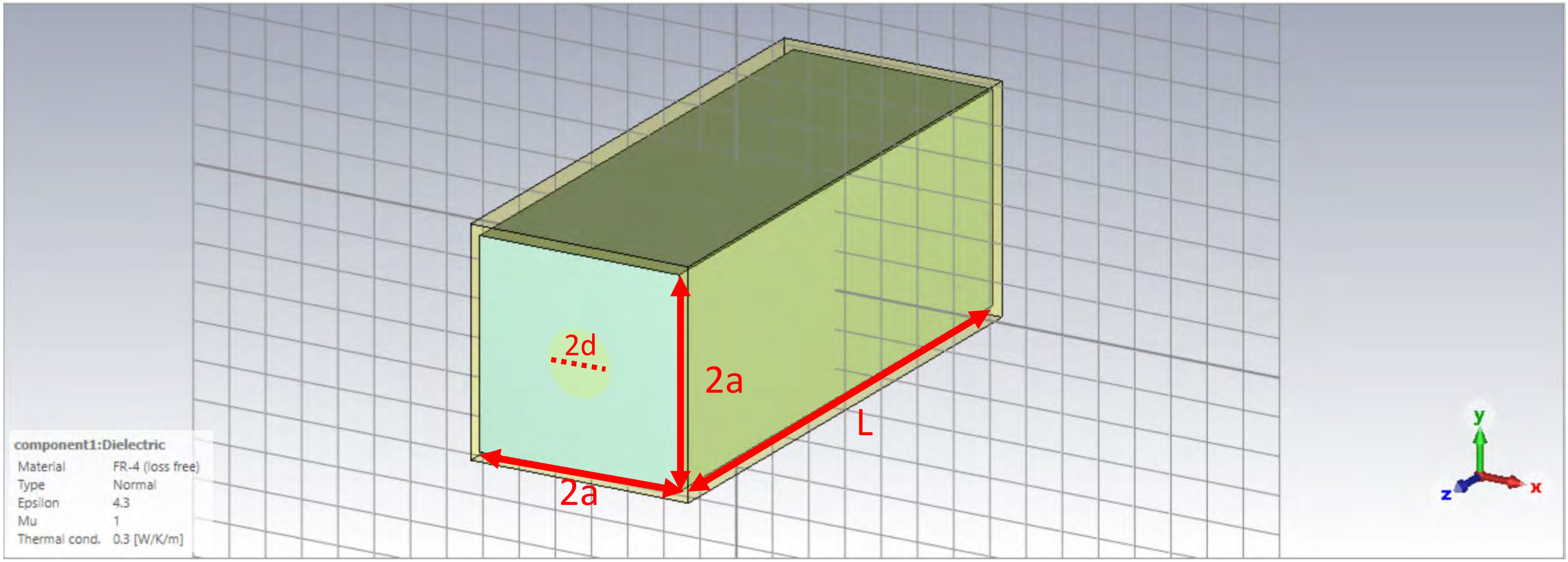
- Frankel gives the following equation for the characteristic impedance of square-circular coax

$$Z_0 = 138 \log_{10}\left(1.079 \cdot {}^{a}/_{d}\right) \; [\Omega]$$

- The equation assumes vacuum, as there is no term for the relative permittivity
- To validate the equation, I simulate a square-circular geometry in CST and calculate the impedance
  - a = 14 mm
  - d = 4.5 mm
  - Outer conductor is grounded

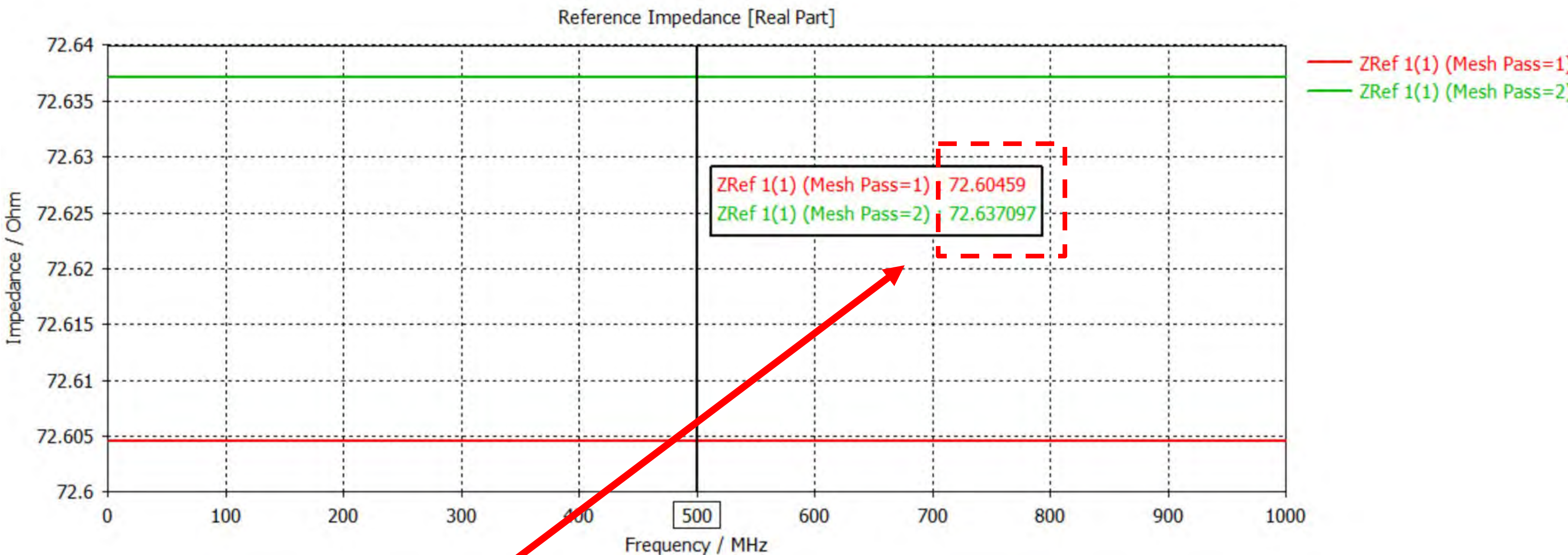
S. Frankel, "Characteristic Impedance of Parallel Wires in Rectangular Troughs," in Proceedings of the IRE, vol. 30, no. 4, pp. 182-190, April 1942, doi: 10.1109/JRPROC.1942.234653.

Simulation Geometry



d=4.5 mm
a=14 mm
L=50 mm
Dielectric media is alternated between vacuum, Teflon, and FR-4

Vacuum



$$138 \cdot \log\left(1.079 \cdot \frac{14}{4.5}\right) \cdot \Omega = 72.579\ \Omega$$

The equation is pretty spot on with the simulation results, next is to validate the modified equation to account for relative permittivity.

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} \log_{10}\left(1.079 \cdot {}^{a}/_{d}\right)\ [\Omega]$$

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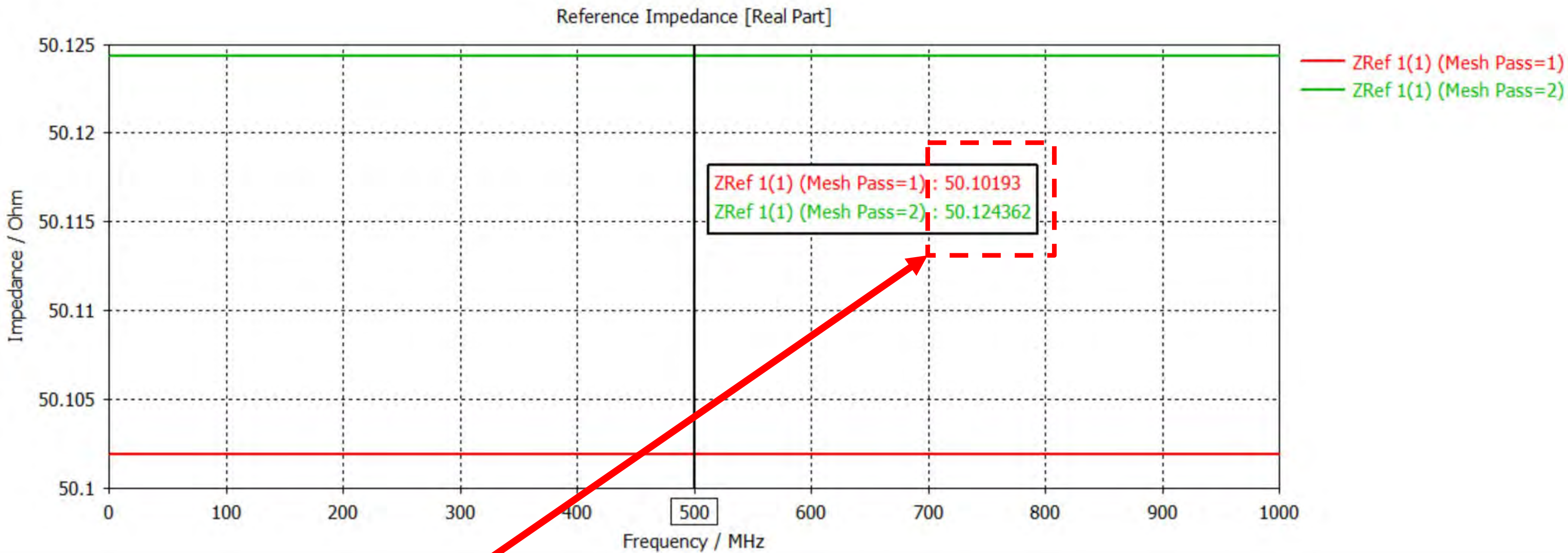
NNSA National Nuclear Security Administration

PTFE

I used the dimensions and dielectric reported by X. Cui et. al for their C-R coax (50 Ω with PTFE [ε_r = 2.1]) to verify the equation

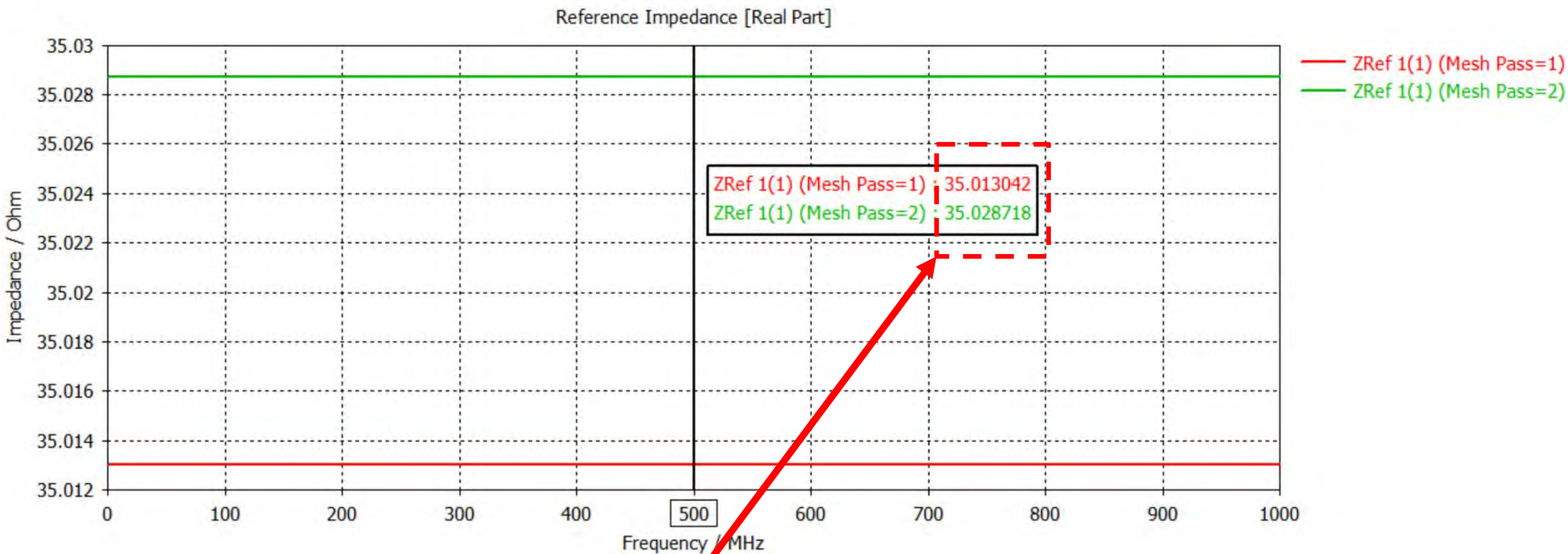


$$\frac{138}{\sqrt{2.1}} \cdot \log\left(1.079 \cdot \frac{14}{4.5}\right) \cdot \Omega = 50.084\ \Omega$$

Good agreement shown here

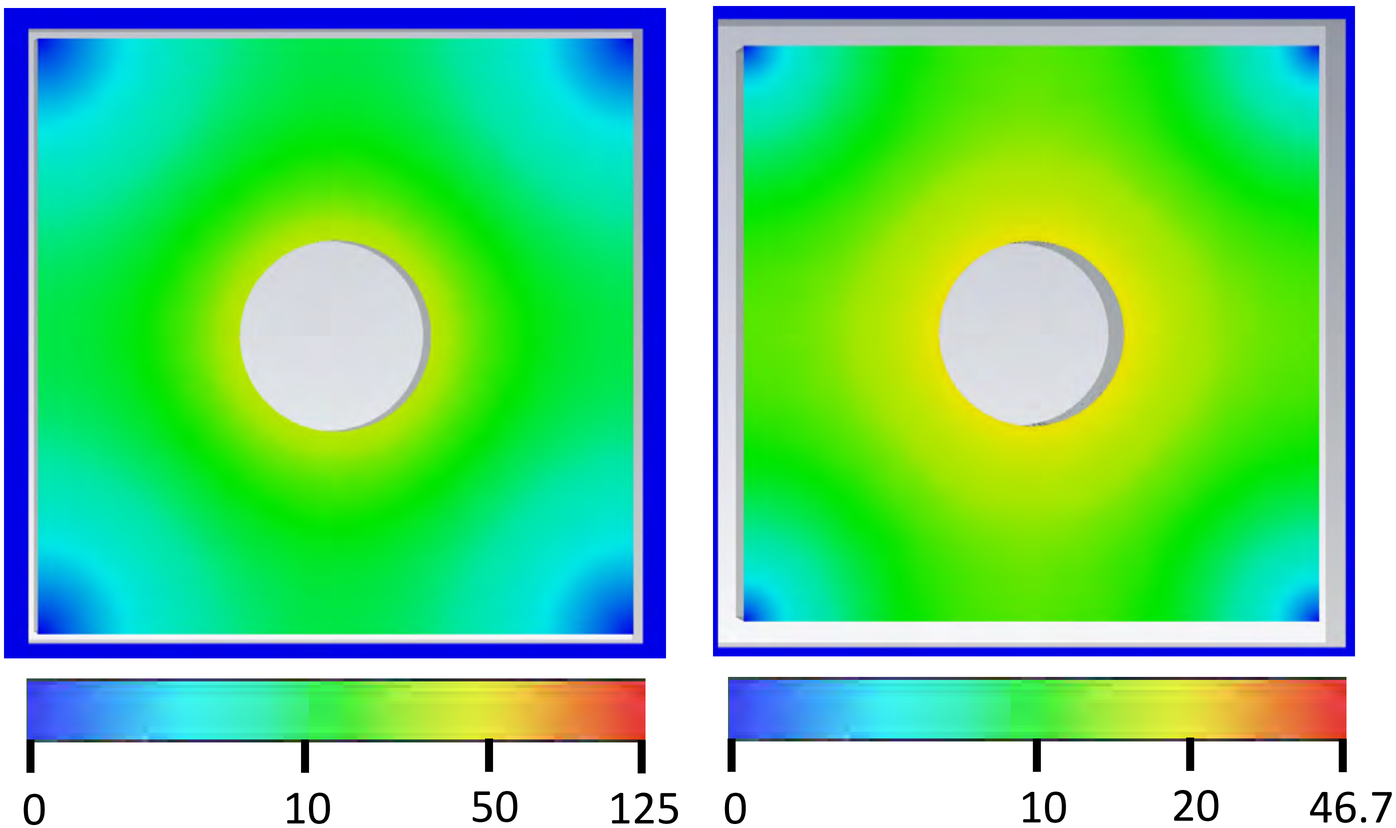
FR-4

One last sanity check (using FR-4 as the dielectric)



$$\frac{138}{\sqrt{4.3}} \cdot \log\left(1.079 \cdot \frac{14}{4.5}\right) \cdot \Omega = 35.001\ \Omega$$

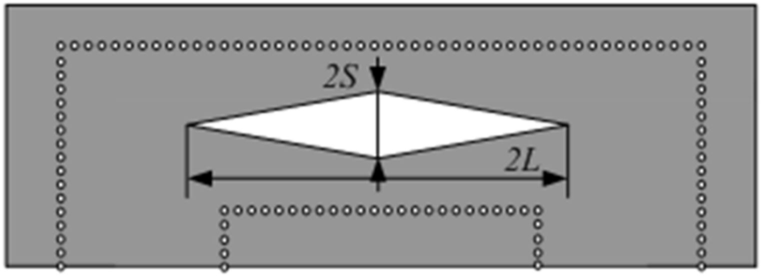
Brief Field Simulation

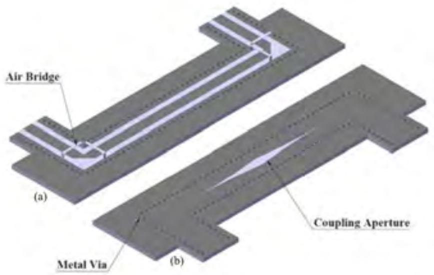


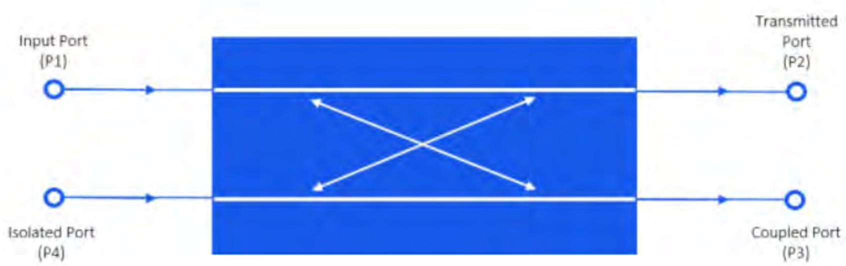
- Original geometry and scaled up geometry (3x)
- 25 kV on the inner conductor
- PTFE insulator inside the C-R coax
- Peak field ~ 46.7 kV/cm right at the surface of the inner conductor
- PTFE dielectric strength ~1 kV/mil -> ~393 kV/cm
- Volume breakdown should not occur

Diamond Aperture

- Diamond apertures have been implemented for this particular directional coupler geometry due to wide bandwidth performance and compactness
- Multihole apertures have great bandwidth performance and directivity, but are limited when it comes to miniaturization (especially in low frequency).





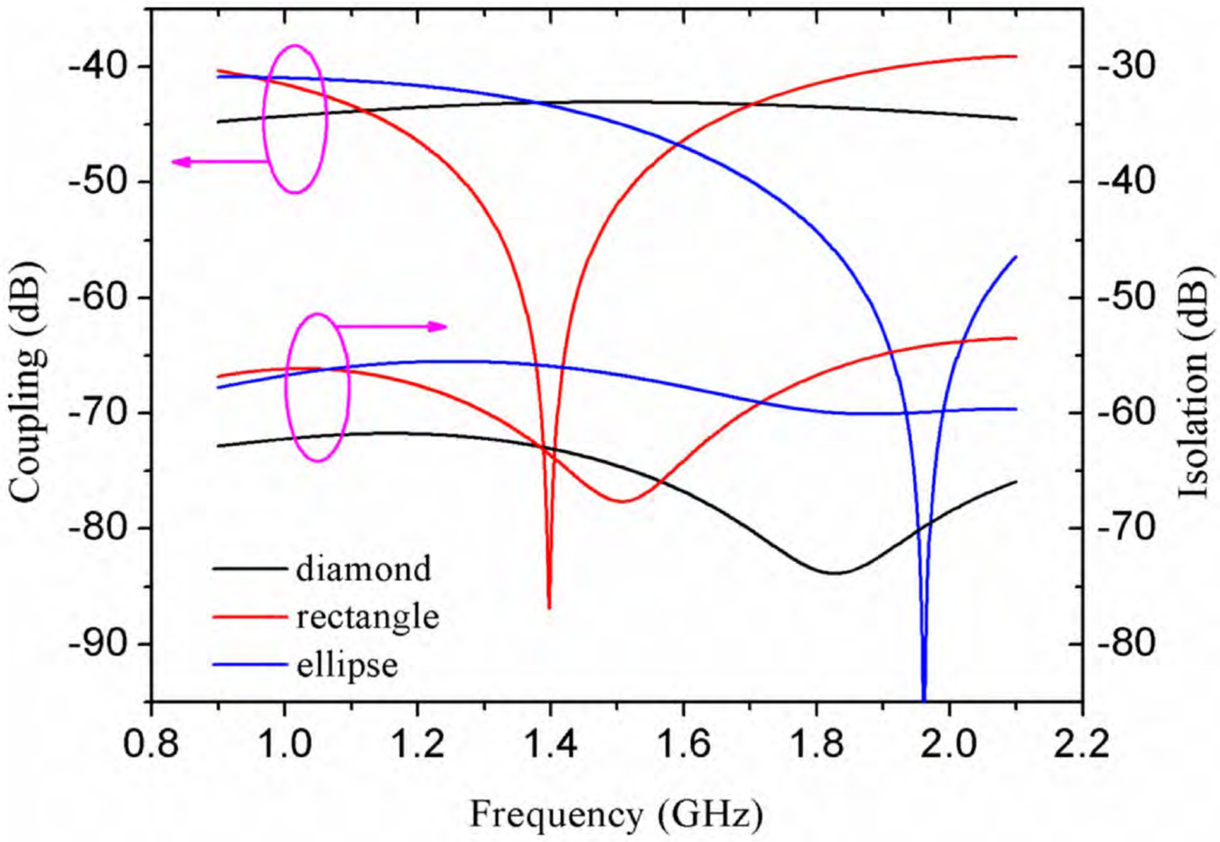


Directivity

- Measure of the coupler's ability to separate the forward and reverse waves
  - 10 log (P3/P4)
- Larger directivity is desirable (20 dB)

- X. Cui, X. Wu, Z. Xiong, et al. "Design and development of compact coaxial to coplanar waveguide directional coupler for HPM measurement," in Rev. Sci. Instrum., vol. 88, 124702, November 2017, https://doi.org/10.1063/1.5001978.
- H. Mirzaei, A. Nasr-Azadani, R. Safian and H. M. Sadeghi, "A novel broadband high power coaxial-to-CPW directional coupler," 2009 European Microwave Conference (EuMC), Rome, Italy, 2009, pp. 1152-1155, doi: 10.23919/EUMC.2009.5296105.

Comparison of Different Apertures From Literature



- Simulation of coupling and isolation for different apertures by Cui
  - Top set of curves is the coupling
  - Bottom set of curves is the isolation
- **Isolation** – forward power delivered to the isolated port (P1/P4)
- The coupling for the diamond aperture shows very good flatness over their desired frequency range (~1.7 dB)

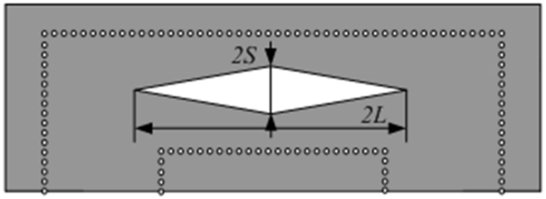
- I plan to carry out a similar simulation to sweep the directivity, isolation, coupling of the directional coupler for different aperture shapes

X. Cui, X. Wu, Z. Xiong, et al. "Design and development of compact coaxial to coplanar waveguide directional coupler for HPM measurement," in Rev. Sci. Instrum., vol. 88, 124702, November 2017, https://doi.org/10.1063/1.5001978.

Directivity of C-R Coax Directional Coupler

$$D = \frac{A_2^-}{A_2^+} = 20\log\left\{\left|\frac{a}{b}\cdot\left(\frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}}\cdot\frac{\sin\left(\pi\left(\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}\right)l_\lambda\right)}{\sin\left(\pi\left(\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}\right)l_\lambda\right)}\right)^2\right|\right\}$$

$$a = \sqrt{\varepsilon_1\varepsilon_2} + \frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2} \qquad b = \left|-\sqrt{\varepsilon_1\varepsilon_2} + \frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right| \qquad l_\lambda = \frac{L}{\lambda}$$



- A_2^- is the reverse coupling, A_2^+ is the forward coupling
- ε_1, ε_2 are the relative permittivities of the C-R coax and directional coupler, respectively
- L is the half length of the aperture, and λ is the wavelength
- Note that this derived equation for directivity by Cui et al. is inverted, so smaller directivity is better in this case

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Directivity Calculation

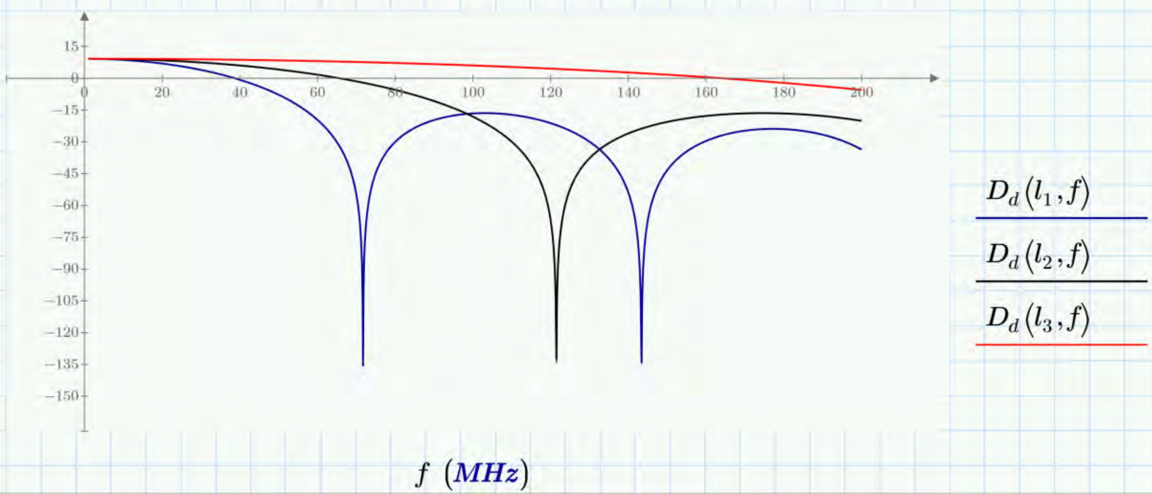
$$f := 1\ MHz, 1.1\ MHz .. 200\ MHz$$

$$\lambda(f) := \frac{c}{f} \qquad l_1 := 50\ in \qquad l_2 := \frac{c}{100\ MHz} \cdot 0.25 = 29.507\ in \qquad l_3 := \frac{c}{100\ MHz} \cdot 0.1 = 11.803\ in$$

$$l_\lambda(l,f) := \frac{l}{\lambda(f)} \qquad \varepsilon_1 := 2.1 \qquad \varepsilon_2 := 3.4$$

$$a := \sqrt{\varepsilon_1 \cdot \varepsilon_2} + \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 + \varepsilon_2} = 3.97 \qquad b := \left| -\sqrt{\varepsilon_1 \cdot \varepsilon_2} + \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right| = 1.374$$

$$D_d(l,f) := 20\ \log\left(\left| \left(\left(\frac{a}{b}\right) \cdot \left(\frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \cdot \frac{\sin\left(\pi \cdot \left(\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}\right) \cdot l_\lambda(l,f)\right)}{\sin\left(\pi \cdot \left(\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}\right) \cdot l_\lambda(l,f)\right)} \right) \right)^2 \right| \right)$$



- ε_2 permittivity of RG 4350
- Center frequency of 100 MHz
- Lengths are varied from 1/10λ, 0.25λ, and 50 in (extreme case)
- The directivity [dB] gets worse as the length decrease
- The dimensions are not physically feasible for an embedded cable diagnostic

Future Work

- Carry out experiment of rapid prototype diagnostic
- Simulation of different apertures (directivity, isolation, coupling) for relevant frequency range
- PPC 2023