Presentation of Findings

Wire Insert TE_{101} Rectangular Cavity Resonator

July 2026

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1.1 Experiment Introduction

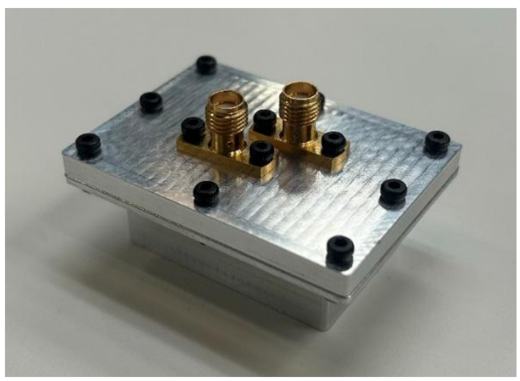

Figure 1: Microwave Cavity Resonator

I designed and fabricated a rectangular microwave cavity resonator to resonate at around 10.5GHz to investigate its effects on dielectric materials used in RF cable construction. The primary objective of this experiment was to determine if the microwave cavity resonator can correctly determine the dielectric constant of ePTFE and extruded FEP.

The cavity was designed with two coupling probes (SMA connectors) connected to a vector network analyzer (VNA). A sample wire could be inserted lengthwise through holes in the cavity walls, allowing data to be collected for different materials. The resulting S-parameter measurements from the VNA were used to identify the cavity's resonant frequencies and evaluate how each sample affected its RF response.

1.2 Cavity Geometry and SMA Probe Placement

An RF coaxial cable carries electrical energy primarily in a transverse electromagnetic mode, meaning that the electric field points radially outward from the center conductor. The goal is to simulate the transverse electric mode by making the electric field of the cavity resonator point perpendicular to the axis of the wire. To achieve this, I designed it to resonate in a TE_{101}cavity mode. Mechanically, this means that the cavity would be rectangular with the SMA probes positioned on top of the cavity.

The most useful frequency range for Glenair was 10GHz-18GHz. I chose around 10GHz because I wanted to maximize the size of the wavelength of the standing waves in the cavity. The 101 mode describes the shape of the standing electromagnetic field in the cavity. The 101 indicates one half wave in the a-axis, one half wave in the d-axis, and uniformity along the b-axis.

The cavity's lengthwise dimension is the a-axis, the depth dimension is the d-axis, and the height dimension is the b-axis. a = 30mm, d = 16.20mm, and b = 12mm.

The following equation gives the resonant frequency for rectangular dimensions:

$$f_{101} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2}$$

$$f_{101} = \frac{c}{2}\sqrt{\left(\frac{1}{0.030m}\right)^2 + \left(\frac{0}{0.012m}\right)^2 + \left(\frac{1}{0.0162m}\right)^2} = 10.523GHz$$

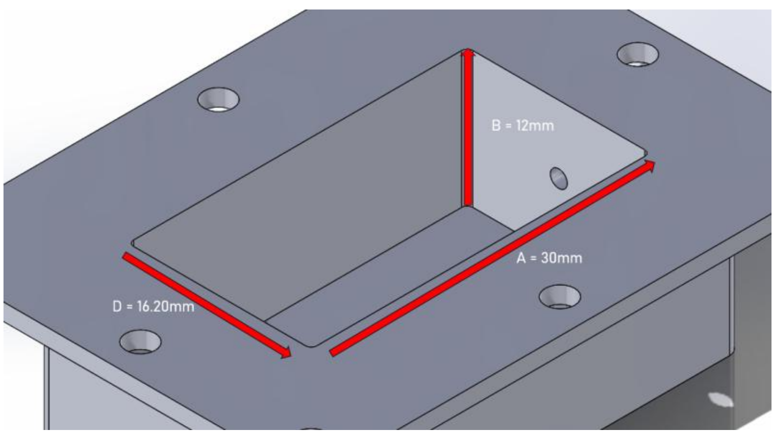

Figure 2: Cavity Dimensions

To maximize the electric field based on the dimensions of the cavity, looking from the top view, it would've been to place the probes at the positions (a/2, d/4) and (a/2, 3d/4). Unfortunately, the coupling nut needed more space for the VNA to connect to the SMA connector, so the d-axis placement was kept the same, but the a-axis (lengthwise) probe placement was changed to 3a/8 and 5a/8 on top of the cavity. The final probe placement on top of the cavity was (3a/8, d/4) and (5a/8, d/4). Since a=30mm and d=16.20mm, the probe placements were 11.25mm from each d-axis wall and 4.05mm from each a-axis wall.

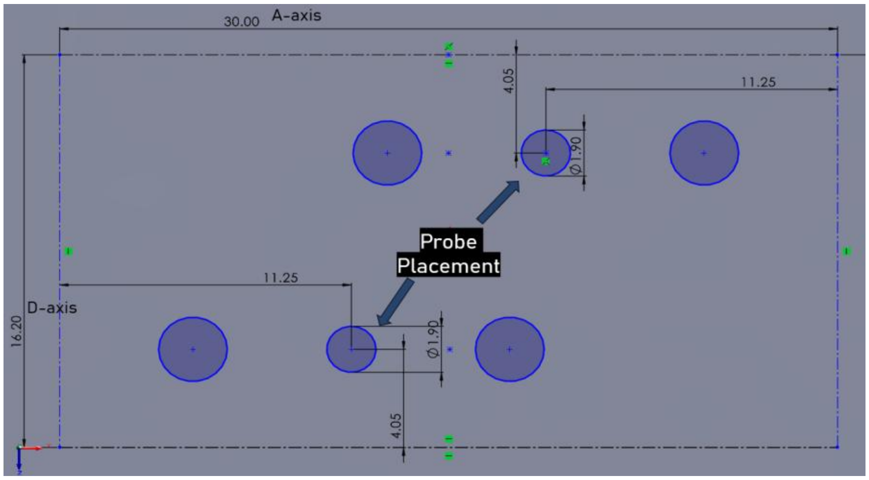

Figure 3: Cavity Top View, Probe Placement

The electric field's magnitude is only a fraction of what its maximum would've been if the probes were able to be positioned at (a/2, d/4) and (a/2, 3d/4). The electric field in the cavity is now only 65% of its maximum magnitude according to:

$$E_y = E_o\left[\sin\left(\frac{3\pi}{8}\right)\sin\left(\frac{\pi}{4}\right)\right] \approx E_o[0.65] \approx 65\%\ of\ E_o$$

The dimensions of the SMA connector can be found in Figure 4.

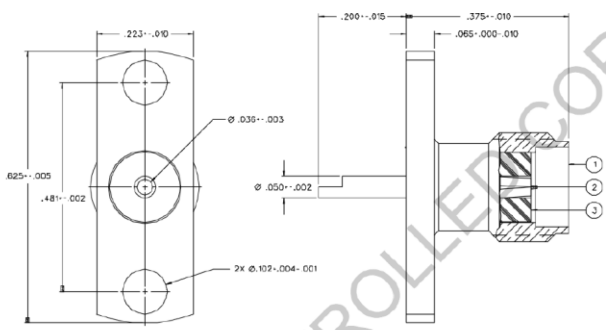

Figure 4: SMA Connector Dimensions

The cavity resonator has 4mm thick walls, a 4mm thick lid, and a 3mm thick bottom wall or cavity floor. The lid and cavity piece are mechanically held together by M2 screws and nuts. The SMA connectors are also mounted onto the cavity lid piece using M2 screws and nuts.

I took the SolidWorks design to ANSYS and simulated the electric field in the cavity.

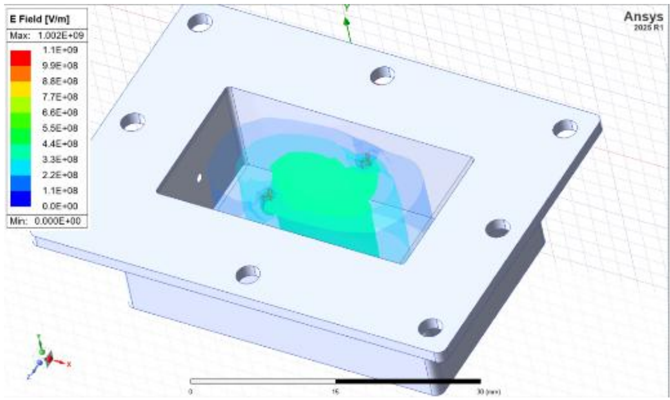

Figure 5: ANSYS E-Field Simulation

ANSYS returned the most prominent mode as having a resonant frequency of 10.56GHz. Second, 13.53 GHz; third 13.84 GHz, and so on.

re(Mode(1)) Setup1 : LastAdaptive	re(Mode(2)) Setup1 : LastAdaptive	re(Mode(3)) Setup1 : LastAdaptive
10560676685.118099	13532214774.235001	13840626938.680300

Table 1: ANSYS Simulated Resonant Frequencies

1.3 VNA Interpretation

The VNA measured the cavity's S-parameters. The two primary measurements in this experiment were S11 and S21.

S11 represents the portion of the signal applied at Port 1 that is reflected back toward Port 1. An S11 value near 0 dB indicates that most of the signal is being reflected back to where it came from. A downward dip in S11 indicates that less energy is being reflected at that frequency, which can occur when the cavity is excited at a resonant frequency, because instead of reflecting back, the energy would be transmitting in between ports. An S11 dip doesn't necessarily prove that the energy reached Port 2 because energy may also be dissipated through conductor losses, dielectric losses, radiation leakage, or imperfect connections. An example of S11 not proving energy reached Port 2 is showed in section 2.1.

S21 represents the signal transmitted from Port 1 through the cavity to Port 2. Because S21 is displayed in dB, a higher (or less negative) value represents greater transmission. A peak in S21 therefore indicates a frequency at which the cavity couples energy more effectively between its two ports.

A cavity resonance is supported when an S21 transmission peak occurs at approximately the same frequency as an S11 reflection dip. The S21 peak shows increased transmission through the cavity, while the S11 dip shows reduced reflection at Port 1. Resonant frequencies can then be compared between the empty cavity and the cavity containing a sample to determine how the inserted material changes the cavity response.

At around 18GHz and above the cavity resonator data is not useful due to the SMA connectors having a maximum rated frequency of 18GHz.

1.4 Test Setup

Two of the samples (ePTFE and FEP) that were inserted through the 2mm diameter hole had a 42 thou outer diameter (0.042”) with an inner conductor of 0.020”. The 42 thou ePTFE sample didn’t seem very reliable, so I also used an 80 thou ePTFE sample.

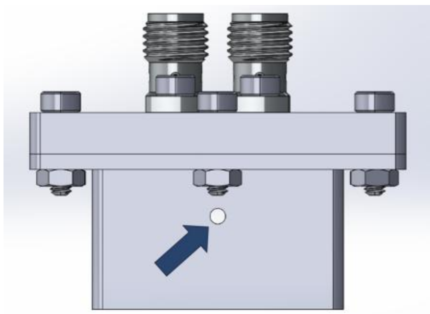

Figure 7: Hole in Cavity

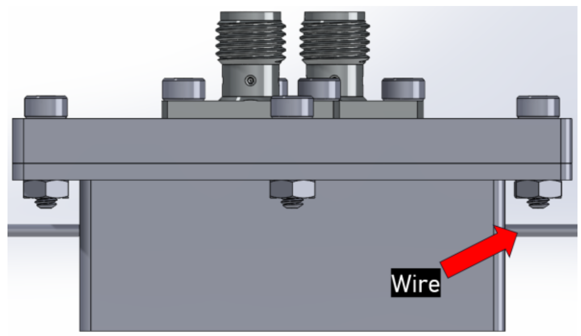

Figure 8: Wire going through cavity lengthwise

Ports 1 and 2 were calibrated before collecting data. Two terminated Glenair 962-032-160 cables were connected to Ports 1 and 2 of the VNA as well as the SMA connectors on the cavity resonator.

Figure 9: Terminated 962-032-160 cables

Figure 10: Test Setup

The VNA used was an Anritsu MS46524B. The microwave cavity resonator was machined by Protolabs using 6061 Aluminum. The SMA connectors used were Cinch Connectivity Solutions 50 Ohm 2-hole flange mount jack receptacles (P/N 142-0701-621). The SMA connectors were rated at a maximum frequency of 18GHz.

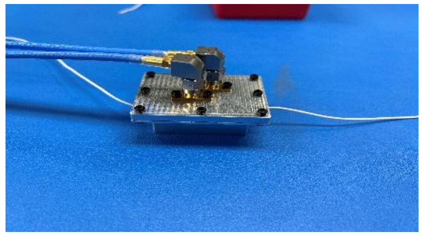

Figure 11: Terminated 962-032-160 connected to receptacles

The data from the VNA was exported as s2p files. I developed a python program to parse the s2p files and plot the data points. The program contains a feature to export the plots as well as overlay different types of data points such as S11 and S21 dB or wave angle data to help with the analysis.

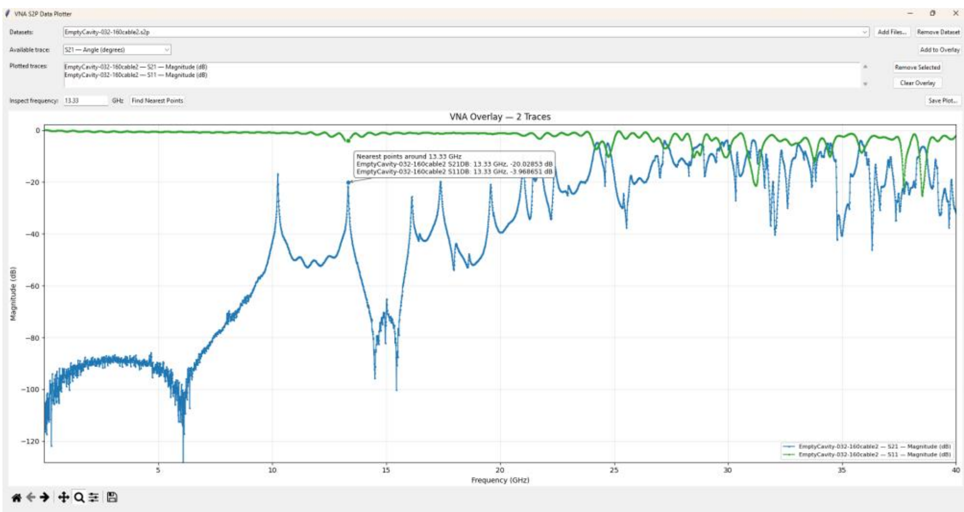

Figure 12: VNA Data Plotter Python Program

2.1 VNA Data, Plots, and Analysis

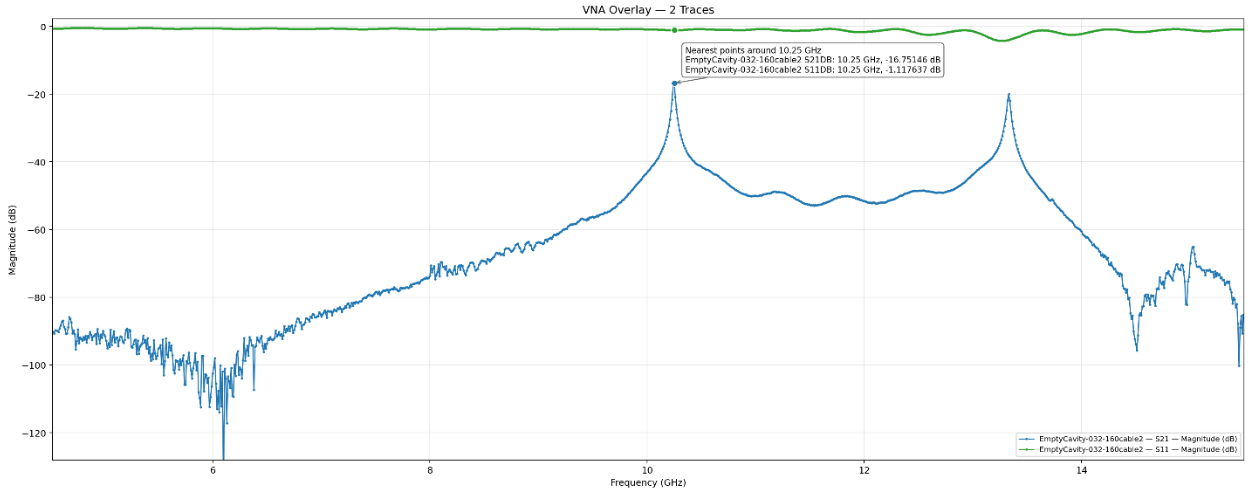

Figure 13: Empty Cavity 10.25 GHz Resonance

A spike in the S21 data indicates less loss, indicating signs of electromagnetic transmission between the ports. In Figure 13's empty cavity data, we see a sharp spike at 10.25 GHz, which is the primary mode's resonant frequency for the cavity resonator. There's a S21 loss of -16.75 dB and S11 loss of -1.12 dB. The power transmitted was about 2.113% and the power reflected was about 77.31% with a power loss of about 20.577%. According to the values generated from the electrical simulation in Table 1, the primary mode's theoretical resonant frequency was about 10.56 GHz. This means the experimental resonant frequency for the empty cavity had an error percentage of 2.926%.

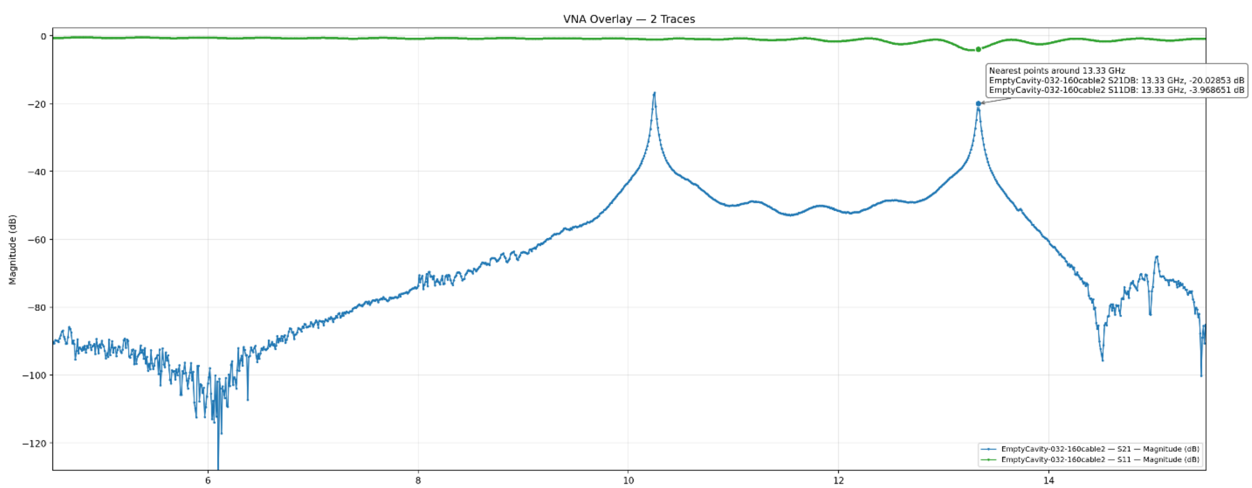

Figure 14: Empty Cavity 13.33Ghz Resonance

Based on Figure 14, we see another spike at 13.33GHz which indicates the frequency of another mode. We see here that unlike at 10.25GHz, there's a larger dip in the S11. At 10.25GHz, the S11 value is -1.12 dB, but the S11 value at 13.33GHz is -3.97 dB. The power transmitted at 13.33GHz was 0.9936%. The power reflected was 40.099% and power lost was 58.907%.

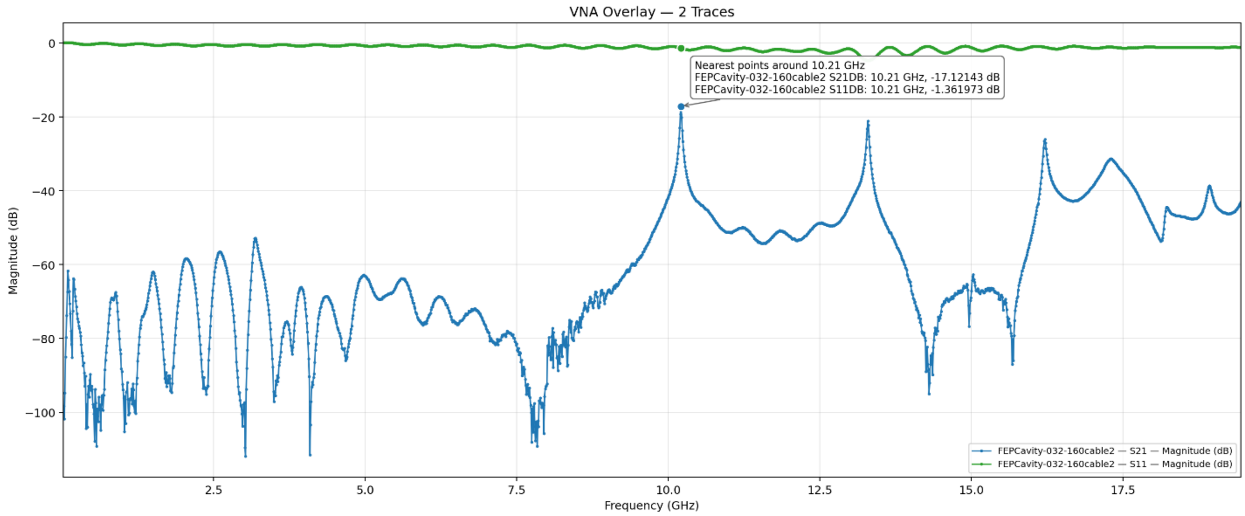

Figure 15: FEP Sample in Cavity

In Figure 15, the 42 thou FEP sample was inserted into the cavity. The resonant frequency was 10.21 GHz, the S21 was -17.12 dB, and the S11 was -1.36 dB. The power transmitted was about 1.941%, power reflected was 73.113%, and power lost was 24.945%.

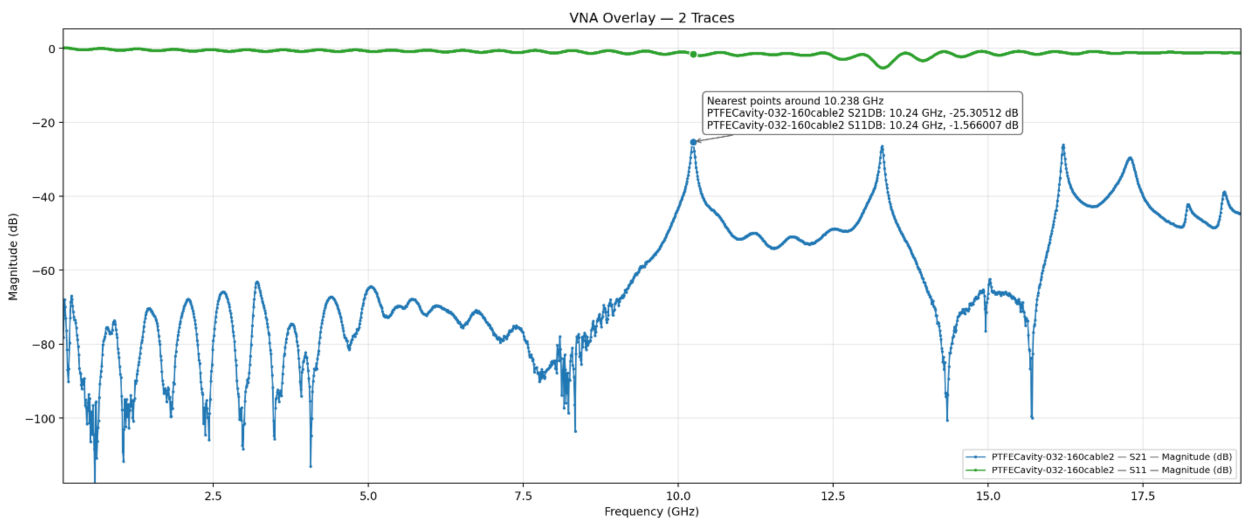

Figure 16: 42 thou PTFE Sample in Cavity

In Figure 16, we see a resonant frequency of 10.238GHz. The S11 is -1.56 dB and the S21 is -25.31 dB. The power transmitted was 0.294%, power reflected was 69.823%, and power lost was 29.882%. Table 2 contains the experimentally acquired values.

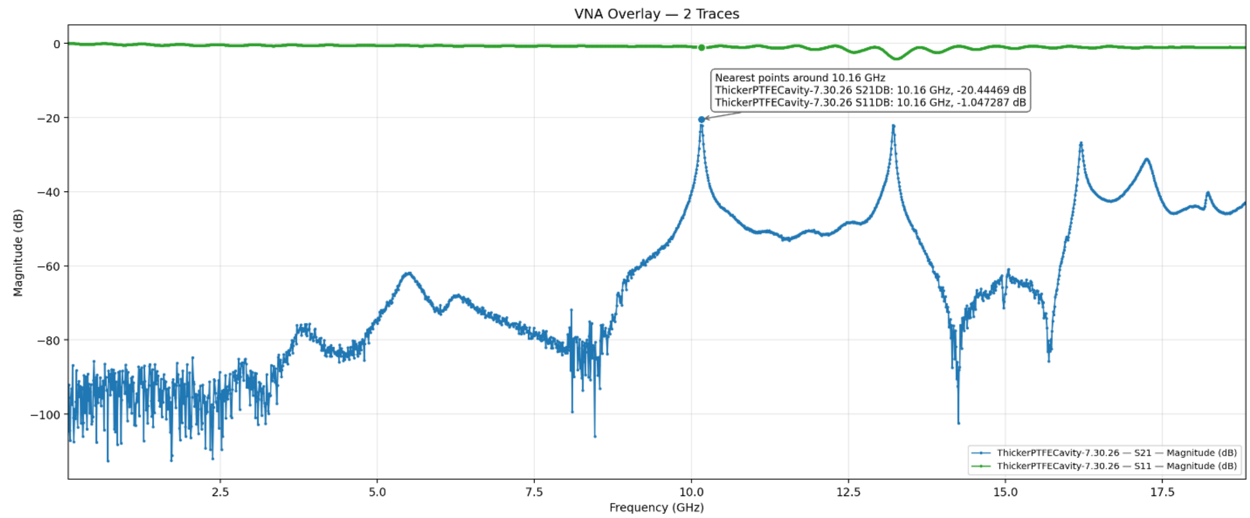

Figure 17: 80 thou PTFE sample in Cavity

I wasn't "convinced" by the ePTFE data, it seemed as though the dielectric constant would've been far too small and an experimental cause for this would be the fact that the sample takes up too small of a portion of the cavity's volume around the center. I decided to use an 80 thou ePTFE sample taken from 962-032-130 cable. In Figure 17, we see a resonant frequency of 10.16 GHz, S21 loss of -20.44 dB and an S11 loss of -1.05 dB. The power transmitted was 0.903%, power reflected was 78.573%, and power loss of 20.525%.

Type	Frequency (GHz)	S21 (dB)	S11 (dB)	Power Transmitted (%)	Power Reflected (%)	Power Lost (%)	ε
Empty Cavity	10.25 GHz	-16.75 dB	-1.12 dB	2.113%	77.31%	20.577%	N/A
FEP Sample	10.21 GHz	-17.12 dB	-1.36 dB	1.941%	73.113%	24.945%	2.10
42 thou ePTFE Sample	10.238GHz	-25.31 dB	-1.56 dB	0.294%	69.823%	29.882%	1.33
80 thou ePTFE Sample	10.16 GHz	-22.44 dB	-1.05 dB	0.903%	78.573%	20.525%	1.60

Table 2: Experimental Acquired Data

2.2 Estimated Dielectric Constant Calculations

The sample wires contain 0.020" of conductor and 0.022" of dielectric material. Since both the conductor and the dielectric are cylindrical, their volume ratio is based on diameter squared:

$$d = (0.020in)\left(25.4\frac{mm}{in}\right) = 0.508mm$$

$$\frac{V_d}{V_{wire}} = \frac{D^2 - d^2}{D^2} = \frac{(1.06)^2 - (0.508)^2}{(1.06)^2} = 0.7703$$

Approximately 77.03% of the wire volume is dielectric. The dielectric-to-cavity volume fraction is:

$$\frac{V_d}{V_c} = (0.000459708)(0.7703) = 0.003542$$

$$\eta_E = 2\frac{V_d}{V_c} = 2(0.003542) = 0.007084$$

η_E is the fraction of the cavity's electric field energy occupying the dielectric section. According to cavity perturbation theory:

$$\varepsilon' = 1 - \frac{2}{\eta_E}\left(\frac{f_s - f_{empty\ cavity}}{f_{empty\ cavity}}\right)$$

The FEP frequency shift is:

$$\Delta f_{FEP} = 10.210 - 10.250 = -0.040\ GHz$$

Then we substitute this into the cavity perturbation equation, we can now calculate the estimated permittivity:

$$\varepsilon'_{FEP} = 1 - \frac{2}{0.007084}\left(\frac{-0.040}{10.250}\right) \approx 2.10$$

The ePTFE frequency shift is:

$$\Delta f_{PTFE} = 10.238 - 10.250 = -0.012GHz$$

Substituting into the cavity perturbation theory equation:

$$\varepsilon'_{PTFE,42thou} = 1 - \frac{2}{0.007084}\left(\frac{-0.012}{10.250}\right) \approx 1.33$$

The dielectric constant of the ePTFE 80 thou sample with 0.029" conductor is:

$$\varepsilon'_{PTFE,80thou} = 1 - \frac{2}{0.0289793}\left(\frac{-0.089223768}{10.250}\right) \approx 1.600757$$

The relative dielectric constant of 1.6 in the 80 thou ePTFE sample is close to the dielectric constant calculated from the official Glenair test report for the 962-032-130 cable, which is the cable that the sample was extracted from. The cable has a V_p of $0.7857c$ and therefore a relative dielectric constant of:

$$\varepsilon' = \frac{1}{0.7857^2} = 1.619893$$

This cavity resonator's estimated error percentage was about 1.18%.

2.3 Conclusion

The rectangular TE_{101} cavity resonator was successfully designed, manufactured, and tested for evaluating dielectric materials used in RF-cable construction. The fabricated cavity produced a clear transmission resonance near 10.25 GHz, closely matching the intended operating frequency. Introducing the FEP- and PTFE-insulated conductors shifted the resonance to approximately 10.210 GHz, 10.16 GHz, and 10.238 GHz, respectively. These shifts demonstrate that the cavity can detect changes in the dielectric material surrounding a conductor.

Using cavity perturbation theory and an analytically estimated electric-energy filling factor, the effective relative permittivity was calculated to be approximately 2.10 for the FEP insulation, 1.33 for the 42 thou stretched, tape-wrapped ePTFE insulation, and 1.60 for the 80 thou stretched, tape-wrapped ePTFE insulation. The FEP and 80 thou ePTFE results agree with Glenair tested values, while the lower ePTFE value may be explained by the air gaps between the outer diameter and the 2mm sample insert holes.

Overall, the experiment validated the cavity resonator as a proof-of-concept tool for detecting differences in RF-cable dielectric construction. However, the analytical calculation does not fully account for the metal conductor, coupling probes, sample holes, and field distortion. Future testing should include a bare-conductor reference and an 80 thou FEP sample.