**Measurement of the Permeability (μ) & Permittivity (ε) of Aluminum doped Yttrium-Iron Garnets from 100Hz to 1GHz**

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**Abstract**

Measurement of the Permeability (μ) and the Permittivity (ε) of Aluminum doped Yttrium-Iron Garnets from 100Hz 10 1GHz. ADAM W.S. LOWERY (Lincoln University, PA 19352) DAVE WILDMAN (Fermi National Accelerator Laboratory, Batavia, IL 60510).

Microwave circulators are important for the RFQ (radio frequency quadripole), that will be installed in the High Intensity Neutrino Source (HINS) linac front end at the Meson Detector building at Fermilab, in order to prevent energy reflections back at the phase shifters. They are composed of magnetized ferrite materials, i.e. garnets, which in collaboration with a permanent magnet produce the magnetic flux through the waveguide. Thus it is important to find and understand the properties of these garnets, two of which are the permittivity and permeability. This paper describes measurements of the permittivity (ε) and the permeability (μ) of Aluminum doped Yttrium-Iron Garnets at frequencies between 100Hz and 1GHz.The permittivity and permeability were found using a series of stripline circuits with the garnets so measurements on its different components such as the capacitance, inductance, phase, and the time delay through the stripline could be taken. Finding these quantities required the use of equipment like a Network Analyzer, a LCR Meter, and a Vector Impedance Meter.

**Introduction**

 At Fermilab, several unsolved questions are being asked everyday in hopes that an answer will soon come. This particular question came about from the unfortunate event of a Russian microwave circulator having an electrical malfunction.

***Figure. 1***

This microwave circulator was said to operate at 500kW but instead malfunctioned around 300kW, failing to operate at its specified parameters. A microwave circulator is a three-port, passive RF or microwave device made of magnets and ferrite material which is used to control the direction of signal flow in a RF or microwave circuit(DitomInc). This device is necessary for the RFQ (radio frequency quadripole), that will be installed in the High Intensity Neutrino Source (HINS) linac front end at the Meson Detector Building at Fermilab. But it’s not enough to just be familiar with the circulator, you must also be aware of the different components that make up the device, such as the ferrites.

The ferrites in this case are Aluminum doped Yttrium-Iron garnets. You must know the components of the ferrite and to what effect they play in the circulator. Two important components are the permittivity (ε) and the permeability (μ) of the garnet, which can be functions of the applied magnetic field.

**Materials and Methods**

***Materials***

**Aluminum doped Yttrium-Iron Garnets:** The **Aluminum doped Yttrium-Iron garnet** was the ferrite of choice for creating the stripline circuits. Each of the toroid-shaped garnets used were nine inches in diameter with an inner diameter of three inches and had a thickness of half an inch. The saturation magnetization of the garnets is 4πMs, ≈400.

**Copper (Cu):** **Copper** was used for the center conductor and the ground planes in the stripline circuits. Copper tape was also used to ensure that the plates and the center conductor maintained a good electrical connection. Copper was chosen because it has good electrical conductivity.

**Hewlett Packard LCR Meter, model #4263A:** The **LCR meter** is designed to measure the parameters of an impedance element with high accuracy and speed. The LCR meter provides measurements of inductance, capacitance, resistance, and dissipation factor over a range of frequencies. The LCR meter used in these experiments measured the impedance, inductance, and the capacitance at the frequencies of 100, 120, 1000, 10000, 100000 hertz.

**Hewlett Packard Network Analyzer, model #8753E:** A **network analyzer** is an instrument used to analyze the properties of electrical networks, especially those properties associated with the reflection and transmission of electrical signals known as scattering parameters (S-parameters). Network analyzers are used mostly at high frequencies (Wiki). The network analyzer in this experiment measured frequencies between 30 kHz and 6 GHz. While utilizing the network analyzer, the Smith Chart format was ideal for looking at and analyzing the impedance of different components of the stripline circuits.

* S- parameters are a parameter set that relates to the travelling waves that are scattered or reflected when an n-port network is inserted into a transmission line. S-parameters are important in microwave design because they are easier to measure and work with at high frequencies than other kinds of parameters (network analysers). In this situation we measured only two port networks, using S21 which measures transmitted power from port 1 to port 2, and S11 which measures reflected power.
* The Smith Chart is used to plot reflectance (S11). By using the Smith Chart we can see graphically how the impedance changes over a range of frequencies.

**Tektronix Digital Oscilloscope:** An **oscilloscope** is a type of electronic test equipment that allows signal voltages to be viewed, usually as a two-dimensional graph of one or more electrical potential differences plotted as a function of time or of some other voltage (Wiki). This device was used to determine the permittivity (ε).

**Hewlett Packard Vector Impedance Meter, model #4193A:** An instrument that not only determines the ratio between voltage and current, to give the magnitude of impedance, but also determines the phase difference between these quantities, to give the phase angle of impedance (answers). The **vector impedance meter** used was capable of operating at frequencies between 400 kHz and 110 MHz.

***Computer Software –***

* **Microsoft Excel** (full name **Microsoft Office Excel**) is a proprietary spreadsheet application written and distributed by Microsoft for. It features calculation, graphing tools, pivot tables and, except for Excel 2008 for Mac OS X, a macro programming language called VBA (Visual Basic for Applications) (Wiki). This program was important because it allowed me to plot the permittivity (ε) and permeability (μ) with respect to frequency.

***Methods***

***Solving for the center conductor of a stripline*** –

One method that could possibly be used in order to solve for the values of the permittivity and permeability of the garnets was to use them to create a stripline circuit. A stripline is a conductor sandwiched by dielectrics between a pair of ground planes. In between these dielectrics is a center conductor that is vital to its efficiency. Solving for the dimensions of the center conductor required that the proper equation to use, be researched in order to solve for the impedance. *Stripline Circuit Design* by Harlan Howe Jr. gives the expression that is ideal for my predicament.

**(Harlan’s Expression)**

***Figure. 2***



**(1)**

The above expression assumes that µ = 1, but our value for µ has µ ≠ 1. Take into account that the Impedance is proportional to the square root of permeability divided by the permittivity when the expression is rewritten,

 

t

b

εr

w

**(2)**

And,



**(3)**

After finding this expression, it was rewritten so that it could be solved for the width (w),

 

Simplifying,

Since the value for t is a small number compared to b, the difference between  is very small so for all extensive purposes I left the value as one, changing the equation to the following expression.



Then I proceeded to simplify the other values by using the theoretical answers the impedance, permittivity and permeability.

Z0 = 50 Ω µ = 4

ε= 14 b = 1in 

To continue, the previous equation for Cf was re-visited,



 (≈2) \* (≈.301) - (≈0) \* (≈0)

  .237

 .763 in

The value of the width was determined to be .763 in. With regards to the length of the center conductor, I needed to make sure it was long enough to expand into the cavity of the garnet. The length I decided on was 329/32 in.

**Length**

**.763 in**

**Copper Center Conductor**

**Width**

***Figure. 3***

**329/32 in**

***Creating the Stripline*** *–*

After procuring the necessary measurements for the center conductor, a piece of copper was cut to the exact specifications. This strip of copper would be used as the center conductor of the stripline circuit. From there, I obtained a pair of panel receptacles and some tinned copper wire. What I needed to do was, attach the copper strip to the wire and attach the wire to the panel receptacles. In order to carry out this task I enlisted the aid of a soldering iron. Carefully I soldered one end of the tinned copper wire to the panel receptacles and soldered the other end to the center conductor. This process was repeated for both receptacles only soldering them on different ends of the center conductor.

**(The sketch below is how the circuit should look up to this point)**

**Panel Receptacles**

**Tinned Copper wire**

**Copper Center Conductor**

***Figure. 4***

Once the previous structure was assembled, a garnet was placed at the top and bottom of the structure. These garnets work as the dielectric in the circuit. To complete the circuit I must now create a pair of ground planes.

(Courtesy of Wikipedia)

Cross-section diagram of stripline geometry. Central conductor (A) is sandwiched between ground planes (B and D). Structure is supported by [dielectric](http://en.wikipedia.org/wiki/Dielectric) (C).

The ground plates were cut from a sheet of copper. Care was taken to make sure the planes were long enough to fit across the garnets and wide enough to have good conductivity. The measurements I decided on for the ground planes were 213/32 inches wide by 411/32 inches long. Once the construction of the stripline circuits was finished, I began the test for the permittivity (ε) and the permeability (µ).

**(The completed stripline circuit)**

 

***Figure. 5***

***Measuring the Permeability (µ)*** –

To solve for the permeability of the stripline circuit the circuit was put through a series of test in which I would introduce a magnetic field and measure the phase difference and the change in voltage at the circuit underwent. To get a good series of measurements I continuously increased the distance between the stripline and the magnets, which would gradually decrease the magnetic field on the stripline. To do this aluminum beams were placed between the stripline and the magnet that was supplying the magnetic field. By continuing to place the beams between the two, the magnetic field became relatively insignificant.

In order to measure the time, phase difference and the change in voltage I used a Tektronix Digital Oscilloscope and the Hewlett Packard Network Analyzer. The network analyzer was used with the S21 parameter.

Once the data from the network analyzer was obtained I applied some fundamental physics in order to solve for the permeability of the stripline.

 , where “s” is the 3 in, the width of the garnet, and “t” is time. **(8)**

And,

 , where ε = 14 and µ0 and ε0 are the magnetic and electric constants. **(9)**

µ0 = 4π \* 10-7NA-2  ε0 ≈ 8.854 \* 10-11Fm-1

In order to solve for the permeability the equation was rewritten,

 





This was the result for one magnet,

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Height** | **Frequency** | **Phase** | **Phase ∆** | **Power (dB)** |  |  |
| 0 | 325MHz | 136.2 | 223.8 | -2.26 |  |  |
| 1 | 325MHz | 105.1 | 254.9 | -4.27 |  |  |
| 2 | 325MHz | 57.4 | 302.6 | -11.8 |  |  |
| 3 | 325MHz | 76.2 | 283.8 | -20.8 |  |  |
| 4 | 325MHz | 114 | 246 | -22.3 |  |  |
| 5 | 325MHz | 145.7 | 214.3 | -20.4 |  |  |
| 6 | 325MHz | 133.8 | 226.2 | -16.4 |  |  |
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I added an additional magnet to the top of the stripline to see how it might affect the power and phase difference of the stripline. By doing this I increased the magnetic force. To get a good series of data I uniformly increased the distance the magnets were from the stripline and monitored the results.

Here were the results,

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Height** | **Frequency** | **Phase** | **Phase ∆** | **Power (dB)** |  |  |  |
| 0 | 325MHz | 156.45 | 203.55 | -6.61 |  |  |  |
| 1 | 325MHz | 159.82 | 200.18 | -6.86 |  |  |  |
| 2 | 325MHz | 150.98 | 209.02 | -6.13 |  |  |  |
| 3 | 325MHz | 128.34 | 231.66 | -7.61 |  |  |  |
| 4 | 325MHz | 125.07 | 234.93 | -14.67 |  |  |  |
| 5 | 325MHz | 133.02 | 226.98 | -16.93 |  |  |  |
|  |  |  |  |  |  |  | ***Figure. 16*** |
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The results for the permeability turned out as the following,

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Trial | Frequency (MHz) | Power (dB) | Phase (°) | Phase ∆ (°) | Period (s) | Time (s) | Speed (m/s) | Mu (µ) |
| 1 | 1 | -0.0646 | 2.3948 | 2.3948 | 1.00E-06 | 6.65E-09 | 1.15E+07 | 48.91658 |
| 2 | 5 | -0.3407 | 12.025 | 12.025 | 2.00E-07 | 6.68E-09 | 1.14E+07 | 49.33416 |
| 3 | 10 | -1.3205 | 18.932 | 18.932 | 1.00E-07 | 5.26E-09 | 1.45E+07 | 30.57107 |
| 4 | 15 | -1.9021 | 22.785 | 22.785 | 6.67E-08 | 4.22E-09 | 1.81E+07 | 19.68037 |
| 5 | 20 | -2.3182 | 26.643 | 26.643 | 5.00E-08 | 3.7E-09 | 2.06E+07 | 15.13644 |
| 6 | 25 | -2.6712 | 29.734 | 29.734 | 4.00E-08 | 3.3E-09 | 2.31E+07 | 12.06547 |
| 7 | 30 | -2.8494 | 32.907 | 32.907 | 3.33E-08 | 3.05E-09 | 2.50E+07 | 10.26246 |
| 8 | 35 | -3.0181 | 36.911 | 36.911 | 2.86E-08 | 2.93E-09 | 2.60E+07 | 9.486219 |
| 9 | 40 | -3.2904 | 40.738 | 40.738 | 2.50E-08 | 2.83E-09 | 2.69E+07 | 8.84702 |
| 10 | 45 | -3.5266 | 43.721 | 43.721 | 2.22E-08 | 2.7E-09 | 2.82E+07 | 8.051425 |
| 11 | 50 | -3.6356 | 47.043 | 47.043 | 2.00E-08 | 2.61E-09 | 2.92E+07 | 7.550359 |
| 12 | 60 | -3.8916 | 55.469 | 55.469 | 1.67E-08 | 2.57E-09 | 2.97E+07 | 7.289803 |
| 13 | 70 | -4.4437 | 61.678 | 61.678 | 1.43E-08 | 2.45E-09 | 3.11E+07 | 6.621892 |
| 14 | 80 | -4.5046 | 68.943 | 68.943 | 1.25E-08 | 2.39E-09 | 3.18E+07 | 6.334582 |
| 15 | 90 | -5.08 | 77.416 | 77.416 | 1.11E-08 | 2.39E-09 | 3.19E+07 | 6.31094 |
| 16 | 100 | -5.575 | 83.563 | 83.563 | 1.00E-08 | 2.32E-09 | 3.28E+07 | 5.955876 |
| 17 | 200 | -11.09 | 143.15 | 143.15 | 5.00E-09 | 1.99E-09 | 3.83E+07 | 4.369586 |
| 18 | 300 | -16.362 | 177.56 | 177.56 | 3.33E-09 | 1.64E-09 | 4.63E+07 | 2.987895 |
| 19 | 400 | -21.485 | 147.79 | 212.21 | 2.50E-09 | 1.47E-09 | 5.17E+07 | 2.400653 |
| 20 | 500 | -25.787 | 134.08 | 225.92 | 2.00E-09 | 1.26E-09 | 6.07E+07 | 1.741354 |
| 21 | 600 | -28.088 | 125.55 | 234.45 | 1.67E-09 | 1.09E-09 | 7.02E+07 | 1.302314 |
| 22 | 700 | -28.929 | 116.83 | 243.17 | 1.43E-09 | 9.65E-10 | 7.90E+07 | 1.029299 |
| 23 | 800 | -29.158 | 106.25 | 253.75 | 1.25E-09 | 8.81E-10 | 8.65E+07 | 0.858123 |
| 24 | 900 | -28.938 | 99.209 | 260.791 | 1.11E-09 | 8.05E-10 | 9.47E+07 | 0.716173 |
| 25 | 1000 | -27.354 | 97.423 | 262.577 | 1.00E-09 | 7.29E-10 | 1.04E+08 | 0.588073 |
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| ***Figure. 18*** |  |  |
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As you can see from the graph as the frequency continued to raise the permeability of the stripline fell to almost zero. However, is not logically possible because in order for the permeability to fall below one, the signal would have to be going faster that the speed of light. This means that either the permittivity of the stripline is changing with frequency, at some point a mistake had been made, or there is some component about the stripline that we are not fully aware of.

Another way in which I went about finding the permeability of the garnets was by turning one of the garnets into a toroid. A toroid is an electronic device, typically a magnetic core, with wire wrapped around it in order to make an inductor. For this toroid, copper tape was used instead of the wire. The copper tape was wrapped around one garnet so there were six turns and wrapped around another garnet so there were seven turns. I would test by of these garnets in order to find the permeability. By using the LCR meter and the vector impedance meter I was able to measure the inductance and impedance of the toroid.

By using this equation I could solve for the inductance of the toroid while using the vector impedance meter.

 

**(10)**

Once the inductance was solved for, using this equation allowed me to find the permeability of the circuit.

, where “N” is the number of turns and µ0 is the permeability constant:

4π\*10-7.

**(Side and top view of the toroid)**

**a**

**b**

**H**

***Figure. 19***

**b = 4.5 in**

**a = 1.5 in**

**H ≈ .0127 m**

By rewriting the equation I could solve for the permeability,

 

**(11)**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Frequency (Hz) | (ω) | Impedance, Z (Ω) | Inductance (H) | Mu, μ |  |
| 100 | 628.3185307 | 2.42E-02 | 3.85E-05 | 382.7604861 | Bogus |
| 120 | 753.9822369 | 2.45E-02 | 3.24E-05 | 322.3954074 | Bogus |
| 1000 | 6283.185307 | 3.34E-02 | 5.31E-06 | 52.78581983 |  |
| 10000 | 62831.85307 | 2.17E-01 | 3.45E-06 | 34.29654211 |  |
| 100000 | 628318.5307 | 2.12E+00 | 3.37E-06 | 33.52912237 |  |
| 400000 | 2513274.123 | 8.42E+00 | 3.35E-06 | 33.30759914 |  |
| 1000000 | 6283185.307 | 2.11E+01 | 3.36E-06 | 33.38671458 |  |
| 5000000 | 31415926.54 | 1.35E+02 | 4.29E-06 | 42.69069002 |  |
| 10000000 | 62831853.07 | 2.96E+02 | 4.71E-06 | 46.83633894 |  |
| 20000000 | 125663706.1 | 3.36E+02 | 2.67E-06 | 26.58278696 |  |
| 30000000 | 188495559.2 | 2.65E+02 | 1.41E-06 | 13.97706061 |  |
| 40000000 | 251327412.3 | 2.20E+02 | 8.75E-07 | 8.702698113 |  |
| 50000000 | 314159265.4 | 1.61E+02 | 5.12E-07 | 5.095034168 |  |
| 60000000 | 376991118.4 | 1.32E+02 | 3.49E-07 | 3.467893339 |  |
| 70000000 | 439822971.5 | 1.00E+02 | 2.28E-07 | 2.267222392 |  |
| 80000000 | 502654824.6 | 7.96E+01 | 1.58E-07 | 1.574397204 |  |
| 90000000 | 565486677.6 | 6.81E+01 | 1.20E-07 | 1.197280286 |  |
| 100000000 | 628318530.7 | 6.09E+01 | 9.69E-08 | 0.963626027 |  |
| 110000000 | 691150383.8 | 5.12E+01 | 7.41E-08 | 0.736492799 |  |
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***Figure. 20***

As you can see from the following results, the value of the 6 loop toroid fell below one as the frequency continued to increase. Also keep in mind that the values at the frequencies 100 & 120 Hz was considered bogus. I registered them as bogus because the values should have not reached this high and also around those frequencies the toroid was out of phase. When the values for the permeability started to fall the toroid started looking like a capacitor due to the phase change.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Frequency (Hz) | (ω) | Impedence, Z (Ω) | Inductance (H) | Mu, μ |  |
| 100 | 628.3185 | 2.68E-02 | 4.27E-05 | 311.7859 | Bogus |
| 120 | 753.9822 | 2.71E-02 | 3.59E-05 | 262.5341 | Bogus |
| 1000 | 6283.185 | 4.02E-02 | 6.39E-06 | 46.67488 |  |
| 10000 | 62831.85 | 2.87E-01 | 4.56E-06 | 33.30598 |  |
| 100000 | 628318.5 | 2.82E+00 | 4.49E-06 | 32.78285 |  |
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***Figure. 21***

For the 7 loop toroid I was unable to measure the impedence of the toroid with the network analyzer so I only took measurements with the LCR meter. Once again my values at 100 & 120 Hz were ridiculous, so they were not taken into account. ***Measuring the Permittivity (ε)*** –

Solving for the permittivity required knowledge of the capacitance, inductance, and the impedance of the circuit. Also, solving for the permittivity required the use of the vector impedance meter and the LCR meter.

To find the necessary quantities, a LCR meter was used in order to find the capacitance of the stripline at lower frequencies. I also took note of the dimensions of the center conductor and used the measurements to solve for the area. I used the equation for the capacitance of a parallel plate capacitor to solve for the permittivity of the stripline.

**(Capacitance for a parallel plate capacitor)**

Since the stripline is composed of two capacitors expression 5 must be doubled.

 

**(4)**

d = .50 in ≈.0127 m

A = .00189 m² ε0 ≈ 8.854 \* 10-11Fm-1

Once I solved for the permittivity with the LCR meter, I repeated the process with the network analyzer. By using the network analyzer, it became possible to measure the values of the capacitance at higher frequencies. Also, in order to effectively solve for the permittivity using the S11 parameter was required. To begin the process I needed to find out the values of the capacitance and inductance at the resonant frequency. By using the short, a calibration tool, and a circuit, which represents the portion of the center conductor that is not being sandwiched between the garnets, the values of these to quantities was found to be 8.9nH for inductance and 4.0pF for the capacitance.

**(Circuit Design & Equations)**

“w/o short” “with short”

**R**

**L**

**L**

**C**

**Z**

**R**

**L**

**C**

**Z**

 

***Figure. 6***

**(6)**

**(5)**

After finding the resonant values for the stripline I preceded to measure the impedance at frequencies ranging between 1MHz and 1GHz. By altering the equation for the circuit to allow solving for the capacitance was possible. I found out that as the frequency increased the capacitance of the stripline decreased and the circuit started to look like an inductor. In other words, at low frequencies the capacitance looked like an open and the inductance looked like a short and vice-versa for higher frequencies.

**(The stripline circuit equation)**

  

Once the expression was rewritten so that I could solve find the capacitance, solving for the permittivity required revisiting equation 5. “R” in this expression is negligible.

Here were the results,

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency (Hz) | (ω) | Z, Impedance (Ω) | Capacitance (F) | ε, Epsilon |
| 1000000 | 6283185 | -2774.1 | 5.33706E-11 | 20.2510044 |
| 5000000 | 31415927 | -755.25 | 3.81307E-11 | 14.4683618 |
| 10000000 | 62831853 | -372.45 | 3.86678E-11 | 14.6721734 |
| 15000000 | 94247780 | -245.03 | 3.91544E-11 | 14.8568106 |
| 20000000 | 1.26E+08 | -180.61 | 3.97892E-11 | 15.0976781 |
| 25000000 | 1.57E+08 | -141 | 4.07071E-11 | 15.4459442 |
| 30000000 | 1.88E+08 | -114.18 | 4.17904E-11 | 15.8569993 |
| 35000000 | 2.2E+08 | -94.996 | 4.29018E-11 | 16.2787308 |
| 40000000 | 2.51E+08 | -80.191 | 4.4271E-11 | 16.7982492 |
| 45000000 | 2.83E+08 | -68.68 | 4.56763E-11 | 17.3314861 |
| 50000000 | 3.14E+08 | -59.336 | 4.72312E-11 | 17.9214751 |
| 55000000 | 3.46E+08 | -51.678 | 4.885E-11 | 18.5356907 |
| 60000000 | 3.77E+08 | -45.232 | 5.05942E-11 | 19.1975449 |
| 65000000 | 4.08E+08 | -39.672 | 5.25393E-11 | 19.9355824 |
| 70000000 | 4.4E+08 | -34.965 | 5.44793E-11 | 20.6717024 |
| 75000000 | 4.71E+08 | -30.781 | 5.66737E-11 | 21.5043614 |
| 80000000 | 5.03E+08 | -27.194 | 5.88224E-11 | 22.3196537 |
| 85000000 | 5.34E+08 | -24.059 | 6.09867E-11 | 23.1408654 |
| 90000000 | 5.65E+08 | -21.318 | 6.31094E-11 | 23.9463105 |
| 95000000 | 5.97E+08 | -18.945 | 6.5064E-11 | 24.6879671 |
| 100000000 | 6.28E+08 | -16.946 | 6.66162E-11 | 25.2769226 |
| 200000000 | 1.26E+09 | -17.352 | 2.38866E-11 | 9.06357293 |
| 300000000 | 1.88E+09 | -13.74 | 1.33848E-11 | 5.07874736 |
| 400000000 | 2.51E+09 | -6.459 | 9.80253E-12 | 3.71948354 |
| 500000000 | 3.14E+09 | 0.4766 | 7.58182E-12 | 2.87685676 |
| 600000000 | 3.77E+09 | 8.3711 | 6.53402E-12 | 2.47927605 |
| 700000000 | 4.4E+09 | 17.029 | 6.28088E-12 | 2.38322589 |
| 800000000 | 5.03E+09 | 26.343 | 6.81611E-12 | 2.58631263 |
| 900000000 | 5.65E+09 | 37.064 | 9.33192E-12 | 3.5409174 |
| 1000000000 | 6.28E+09 | 50.352 | 2.45821E-11 | 9.3274527 |
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|  |  |  |  |  |
|  |  | Distance = .0127 m |  |
|  |  | Area = .00189m² |  |  |
|  |  | Induction = 8.9\*10^-9 H |  |
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|  |  | ***Figure. 7*** |  |  |

Another venture that took place to measure the permittivity of the garnet was covering both sides of a garnet with copper tape. This process turned the garnet into a capacitor for which you could determine its permittivity. To determine the permittivity, I had to use the vector impedance meter, which measures the impedance and phase of the garnet at high frequencies and the LCR meter, which displayed the capacitance for lower frequencies. This process was done twice with two different garnets, one 9 inches in diameter and the other 3 inches in diameter.

The impedance of the capacitor is equal to:

**Capacitor with copper tape**

 

**(7)**

***Figure. 8***

The permittivity of the 3-inch capacitor,

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency (HZ) | (ω) | Impedance, Z (Ω) | Capacitance (F) | Epsilon (ε) |
| 400000 | 2513274.123 | 8.03E+03 | 4.96E-11 | 16.04371993 |
| 1000000 | 6283185.307 | 3.29E+03 | 4.84E-11 | 15.66335211 |
| 5000000 | 31415926.54 | 6.56E+02 | 4.85E-11 | 15.71110623 |
| 10000000 | 62831853.07 | 3.26E+02 | 4.88E-11 | 15.80749338 |
| 20000000 | 125663706.1 | 1.60E+02 | 4.97E-11 | 16.08377916 |
| 30000000 | 188495559.2 | 1.01E+02 | 5.25E-11 | 16.99057976 |
| 40000000 | 251327412.3 | 7.53E+01 | 5.28E-11 | 17.10903998 |
| 50000000 | 314159265.4 | 5.72E+01 | 5.56E-11 | 18.01833162 |
| 75000000 | 471238898 | 2.98E+01 | 7.12E-11 | 23.05701496 |
| 100000000 | 628318530.7 | 1.74E+01 | 9.17E-11 | 29.70168785 |
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|  |  | ***Figure. 9*** |  |  |
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|  | Area = 4.43 \*10^-3 m² |  |  |  |
|  | Distance = .0127 m |  |  |  |
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As you can see, the values from this plot are not that much different from the previous graph. Both of the graphs are approaching a steep incline around 100MHz. The reason why this is happening is because at high frequencies the phase starts to decrease.

Here are the results for the 9 inch garnet,

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency (Hz) | (ω) | Impedance, Z (Ω) | Capacitance (F) | Epsilon (ε) |
| 100 | 628.3185307 | LCR | 3.49E-10 | 13.71503012 |
| 120 | 753.9822369 | LCR | 3.50E-10 | 13.74450368 |
| 1000 | 6283.185307 | LCR | 3.44E-10 | 13.52934669 |
| 10000 | 62831.85307 | LCR | 3.42E-10 | 13.44957159 |
| 100000 | 628318.5307 | LCR | 3.41E-10 | 13.3878736 |
| 400000 | 2513274.123 | 1.08E+03 | 3.68E-10 | 14.46457858 |
| 1000000 | 6283185.307 | 4.36E+02 | 3.65E-10 | 14.34514628 |
| 5000000 | 31415926.54 | 84 | 3.79E-10 | 14.89162804 |
| 10000000 | 62831853.07 | 38.4 | 4.14E-10 | 16.28771817 |
| 20000000 | 125663706.1 | 12.18 | 6.53E-10 | 25.67522077 |
| 30000000 | 188495559.2 | 5.3 | 1.00E-09 | 39.33637597 |
| 40000000 | 251327412.3 | 11.56 | 3.44E-10 | 13.52613274 |
| 50000000 | 314159265.4 | 19.43 | 1.64E-10 | 6.437965804 |
| 60000000 | 376991118.4 | 27.7 | 9.58E-11 | 3.763227304 |
| 70000000 | 439822971.5 | 35.9 | 6.33E-11 | 2.488851484 |
| 80000000 | 502654824.6 | 41.1 | 4.84E-11 | 1.902215261 |
| 90000000 | 565486677.6 | 39.1 | 4.52E-11 | 1.777346911 |
| 100000000 | 628318530.7 | 32.9 | 4.84E-11 | 1.901058899 |
| 110000000 | 691150383.8 | 20.3 | 7.13E-11 | 2.800933175 |
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|  | Area = 3.65\*10^ -2 m² |  | ***Figure. 10*** |  |
|  | Distance = .0127 m |  |  |  |
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With this plot you can see a few discrepancies that the others didn’t have. This is due to the fact that around 20 MHz and 30 MHz the garnet looks more real than capacitive due to the phase changing. And after 30 MHz the capacitor looks more like an inductor than a capacitor due also to the phase changing. So you cannot fully believe the data after 10MHz.

In an attempt to find the permittivity of the garnets, I created another stripline circuit. However, for this stripline, only one panel receptacle was attached to the center conductor and the size of the center conductor decreased to 1/10th its original area. By using the network analyzer, I was able to find the capacitance and the total impedance of the circuit. After subtracting out the inductive load from the impedance finding the capacitive load of the circuit became possible. Using equation 4 allowed me to solve for the true capacitance. Once the true capacitance was found, equation 7 allowed me to find the permittivity at various frequencies.

Displayed below are the results from this experiment,

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Frequency (Hz) | (ω) | NA, Capacitance (F) | X,total | Xl |  Xc | Capacitance (F) | Epsilon (ε) |
| 1000000 | 6283185.307 | 3.8883E-12 | -40931.75503 | 0.026012387 | 40931.78104 | 3.8883E-12 | 14.754751 |
| 5000000 | 31415926.54 | 3.7387E-12 | -8513.918907 | 0.130061936 | Frequency (Hz) | 3.73864E-12 | 14.186863 |
| 10000000 | 62831853.07 | 3.8868E-12 | -4094.755148 | 0.260123872 | 4095.015272 | 3.88655E-12 | 14.748132 |
| 20000000 | 125663706.1 | 3.8401E-12 | -2072.276023 | 0.520247743 | 2072.79627 | 3.83914E-12 | 14.568201 |
| 30000000 | 188495559.2 | 3.8736E-12 | -1369.569592 | 0.780371615 | 1370.349963 | 3.87139E-12 | 14.690609 |
| 40000000 | 251327412.3 | 3.8562E-12 | -1031.812037 | 1.040495487 | 1032.852533 | 3.85232E-12 | 14.618211 |
| 50000000 | 314159265.4 | 3.8535E-12 | -826.0279906 | 1.300619359 | 827.32861 | 3.84744E-12 | 14.599719 |
| 60000000 | 376991118.4 | 3.8819E-12 | -683.3206381 | 1.56074323 | 684.8813813 | 3.87305E-12 | 14.696906 |
| 70000000 | 439822971.5 | 3.8797E-12 | -586.0355296 | 1.820867102 | 587.8563967 | 3.86768E-12 | 14.676525 |
| 80000000 | 502654824.6 | 3.9163E-12 | -507.9888641 | 2.080990974 | 510.0698551 | 3.90032E-12 | 14.800381 |
| 90000000 | 565486677.6 | 3.9384E-12 | -449.0118466 | 2.341114845 | 451.3529614 | 3.91797E-12 | 14.867356 |
| 100000000 | 628318530.7 | 3.9485E-12 | -403.0769738 | 2.601238717 | 405.6782125 | 3.92318E-12 | 14.887126 |
| 200000000 | 1256637061 | 4.1147E-12 | -193.3979915 | 5.202477434 | 198.6004689 | 4.00691E-12 | 15.204855 |
| 300000000 | 1884955592 | 4.2359E-12 | -125.2429181 | 7.803716152 | 133.0466343 | 3.98745E-12 | 15.130992 |
| 400000000 | 2513274123 | 4.3071E-12 | -92.37941021 | 10.40495487 | 102.7843651 | 3.87109E-12 | 14.689448 |
| 500000000 | 3141592654 | 4.2924E-12 | -74.15662245 | 13.00619359 | 87.16281603 | 3.6519E-12 | 13.857704 |
| 600000000 | 3769911184 | 4.3577E-12 | -60.87115646 | 15.6074323 | 76.47858876 | 3.4684E-12 | 13.16138 |
| 700000000 | 4398229715 | 4.5833E-12 | -49.60709629 | 18.20867102 | 67.81576731 | 3.35267E-12 | 12.722247 |
| 800000000 | 5026548246 | 5.0219E-12 | -39.6152211 | 20.80990974 | 60.42513084 | 3.2924E-12 | 12.493524 |
| 900000000 | 5654866776 | 5.7763E-12 | -30.61455009 | 23.41114845 | 54.02569854 | 3.27324E-12 | 12.420802 |
| 1000000000 | 6283185307 | 7.1678E-12 | -22.20415512 | 26.01238717 | 48.21654229 | 3.30084E-12 | 12.52554 |
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|  |  |  | ***Figure. 11*** |  |  |  |  |
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**Conclusion**

***Figure. 13***

***Figure. 12***

In this experiment I set out to measure the permittivity (ε) and the permeability (μ) of Aluminum doped Yttrium-Iron garnets. My values for the permittivity of the garnets were around 14. This is relatively consistent with the predetermined values of the permittivity that were measured prior to my coming to Fermilab. For the permeability of the garnets, I found values that were between 30 & 49. In this experiment I did experience a few set back. I noticed that the values for the permeability constantly fell below zero. In order to solve this problem I know further analyization wil be necessary. Overall, I would say this experiment was successful.

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