Multiple Complementary Split-Ring Resonator

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***Abstract*—This paper presents a comprehensive simulation study of a microwave sensor based on multiple complementary split-ring resonator (MCSRR) for dielectric characterization of liquids. Using ANSYS HFSS software, we analyze the performance of an MCSRR design on FR-4 substrate in the high electric field region to simulate effect of test samples on resonant frequency. The sensor is designed to operate at a resonant frequency of 2.5GHz for an empty air filled hole, with shifted resonant peaks used for dielectric characterization of different test samples.**

***Index Terms*—Multiple complementary split ring resonator (MCSRR), microwave sensor, dielectric characterization, electromagnetic simulation, HFSS**

I. Introduction

The dielectric properties of liquids are crucial in various applications, including food quality assessment, chemical analysis, and biomedical diagnostics. Traditional methods for measuring dielectric properties often involve complex and expensive equipment. In contrast, microwave sensors based on split-ring resonators (SRRs) offer a cost-effective and efficient alternative for dielectric characterization. The complementary split-ring resonator (CSRR) are dual structures of SRR.

A. Why MCSRR over SRR?

CSRRs primarily couple to electric fields rather than magnetic fields (as in SRRs), making them more sensitive to changes in the dielectric properties of materials, which is crucial for liquid characterization. This fundamental difference stems from their structural design:

Traditional SRRs consist of metallic rings with gaps printed on a dielectric substrate. These structures act as LC resonant circuits where the ring forms an inductance and the gap between split creates a capacitance. When excited by an electromagnetic wave, SRRs couple strongly to the magnetic field component perpendicular to the ring plane, creating circulating currents in the rings.

In contrast, CSRRs are created by etching ring-shaped slots in a metallic ground plane—essentially the "negative" or complementary structure of SRRs. According to Babinet's principle in electromagnetics, this complementary geometry reverses the response characteristics: S_{21} and S_{11} parameters of the CSRR and SRR are inverted.

By carefully choosing the dimension of Microstrip line in CSRRs, we can improve the capacitance between the resonator and the microstrip line, which increases the quality factor and ensures purer resonance at the desired frequency.

II. Resonant Frequency & Quality factor

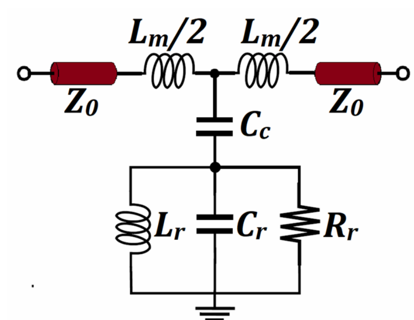


Fig. 1

In this lumped MCSRR model, the top line models the microstrip transmission line, C_c models the dielectric capacitance between ground plate and microstrip, and the L_r, C_r, R_r correspond to the inductance, capacitance and resistance offered by the resonator. Given these parameters we can calculate the resonant frequency and quality factor as follows:

$$f_r = \frac{1}{2\pi\sqrt{L_r(C_r + C_c)}} \tag{1}$$

$$Q = R_r\sqrt{\frac{(C_r + C_c)}{L_r}} \tag{2}$$

We can influence the values of the lumped quantities by understanding the purpose of the utilised geometry. The splits used in the etched rings attach the central plate to the inner metallic rings in the resonator, which provides a path for current flow. Since the flow of current is associated with a magnetic field. this can be viewed as affecting L_r (the inductive behaviour of the resonator). Increasing the size of the splits allows a larger current to flow, and this reduces inductance.

On the other hand, the capacitance C_r is contributed to by the width of the etched out rings - between metallic rings, a capacitance is formed, thus, the overall capacitance of the structure will decrease for larger etched widths and increase for smaller widths.

As we will see in the design procedure, these insights influence the geometric alterations made to suit the specifications.

III. MCSRR Design Parameters

The following dimensions are taken from reference [1] and are used to design the MCSRR microwave sensor. The design is shown in Fig. 2.

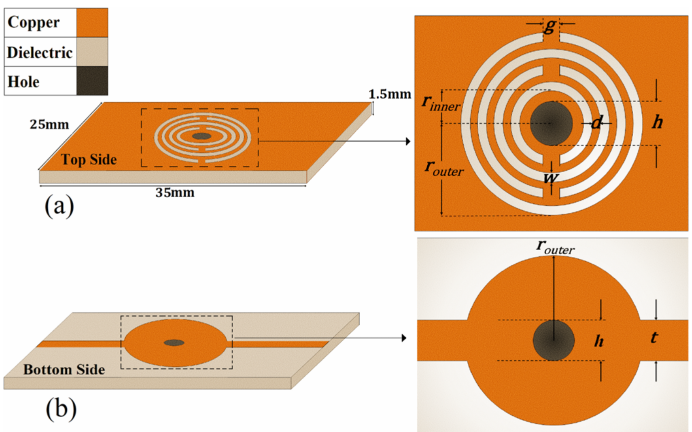


Fig. 2: Design of proposed microwave sensor along with different dimension parameters. (a) MCSRR on top side where the dimensions are: r_{outer}=4.65mm, r_{inner}=2.35mm, g=0.7mm, d=0.3mm, w=0.35mm, h=1.5mm (b) Microstrip line on bottom side where t=2.65mm

Our sensor design uses FR-4 substrate with a dielectric constant of 4.4 and design parameters as follows:

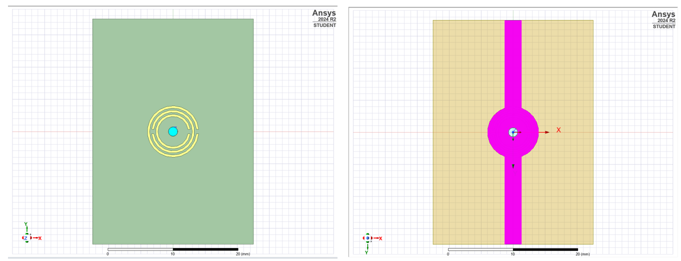
- r_{inner}: Inner radius of the MCSRR (2.35mm)
- g: Gap width between the rings (0.7mm)
- d: Distance between the rings (0.3mm)
- w: Width of the etched ring (0.35mm)
- t: Width of the microstrip line (2.65mm)
- h: Height of the substrate (1.5mm)
- l: Length of the sensor (35mm)
- b: Width of the sensor (25mm)

Instead of assigning the ground planes and microstrip to be perfect conductors, we used 35 micrometer thick copper sheets. The etching was created in the ground plane by subtracting the relevant 3D structures.

We are tasked with designing the MCSRR is designed to operate at a resonant frequency of 2.5GHz. For effecitvely picking up the resonance frequency, we declared a radiation boundary with its faces at a distance of $\lambda/4$ from the designed geometry, where λ = 12.25cm.

IV. Design Procedure

The simulation of the MCSRR microwave sensor is performed using ANSYS HFSS software. The sensor is modeled as a 3D structure as depicted in the figure. The top and bottom views of the following sensor designs are similar to what is given below:



MCSRR structure Top view   Bottom view (microstrip line)

Fig. 3: Top and bottom views of the MCSRR sensor design

A. Single Ring Complementary Structure without split

First we add just a single ring to our complementary ring and simulate. To understand the significance of the split in the rings, we complete the rings and simulate. Doing so will eliminate the inductance making the circuit have a very large resonant frequency. As explained earlier, the split in CSRR contributes to the inductance of the device. This is because the current is reduced when the ends are shorted, leading to reduced inductance and consequently making the resonant frequency large. Following is the HFSS design of the same.

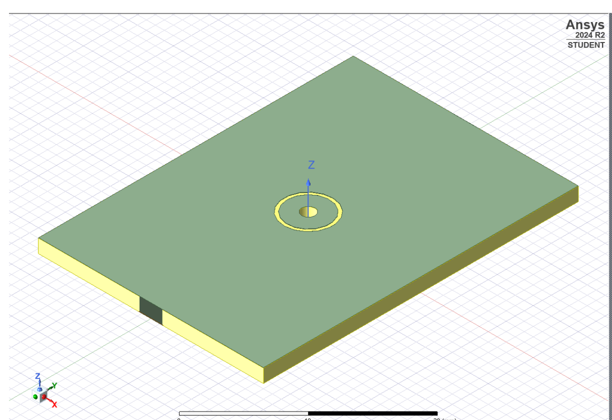


Fig. 4: HFSS Design of Single ring without split

Following is the S_{21} and S_{11} plot over the range of 8 GHz. We see that there is no notch in the plot which is the indication of resonance.

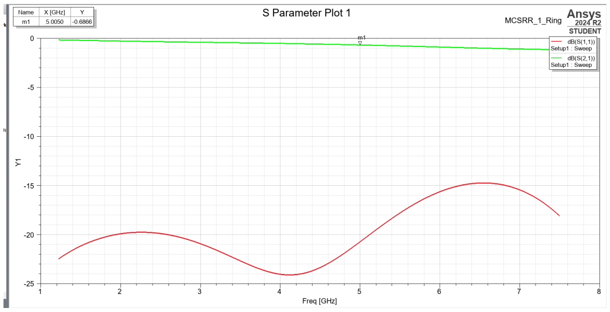


Fig. 5: Single Ring without split S-parameters Plot

B. Single Ring Complementary Structure with split

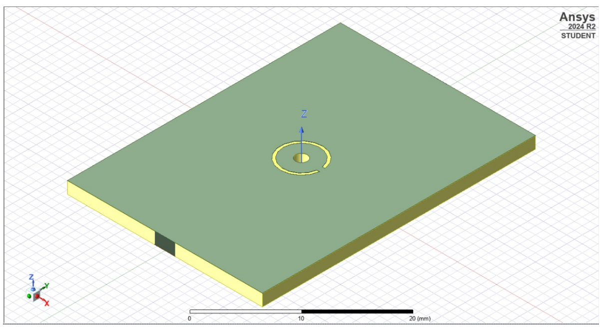


Fig. 6: HFSS Design of Single ring with split

Now that we have understood the significance of the split in the rings, we add a split, **0.7 mm** wide and simulate the same. The split provides non-zero inductance thus resonating the device at frequency given by (1). The following is the HFSS design of the same.

Following is the S_{21} and S_{11} plot over the range of 8GHz. We clearly see a notch of S_{21} at **5.275 GHz** with a magnitude of **-14.79 dB**. The S_{11} at the same frequency has a magnitude of **-2.39 dB**.

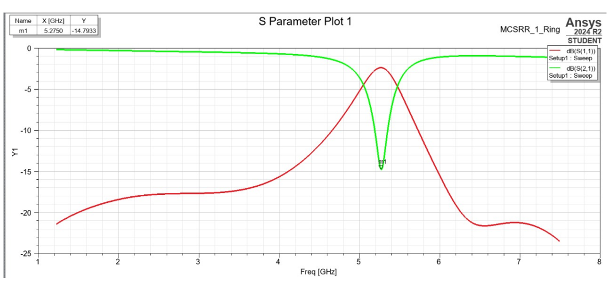


Fig. 7: Single Ring with split S-parameters Plot

C. MCSRR with 2 rings

Now, we add another ring and simulate the same. Adding an additional ring increases both the capacitance and inductance, hence reducing the resonant frequency as given by (1). This happens at two different levels. First adding them increase the total capacitance and inductance, as their individual C, L ones add up in the effective C, L. Moreover, because of multiple rings, we now have cross-coupling between the first and the second ring. The following is the HFSS design for dual ring structure.

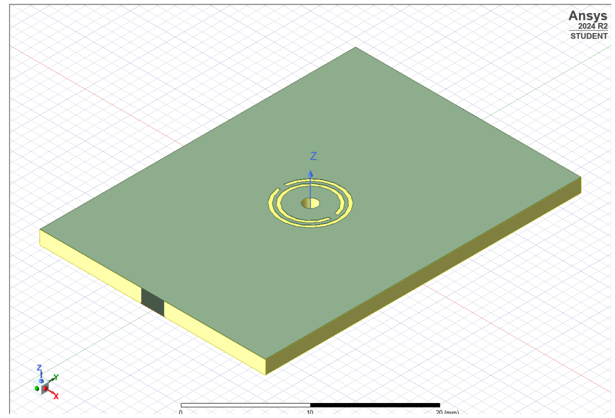


Fig. 8: HFSS Design of Dual ring

The following is the S-parameters plot. We clearly see a notch as **3.385 GHz** with S_{21} = **-16.59 dB** and S_{11} = **-2.09 dB**. This resonant frequency is around 1.89 GHz lesser compared to the single ring structure.

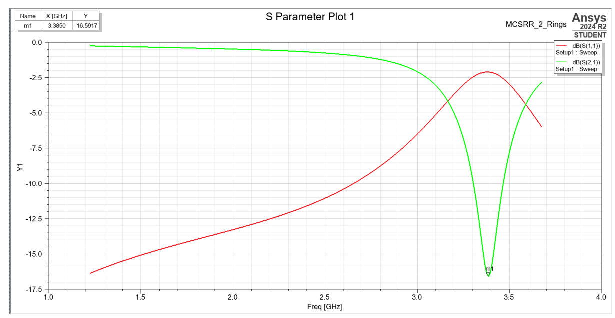


Fig. 9: Dual Ring with split S-parameters Plot

D. MCSRR with 3 Rings (FINAL DESIGN)

Now we add another ring and simulate the same. Similar to the case of 2 rings, the three ring structure further increase both the equivalent capacitance and inductance as explained above.

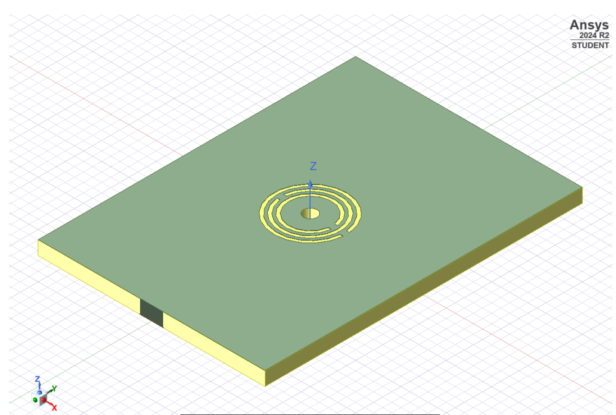


Fig. 10: HFSS Design of Triple Ring

Following is the S-parameters plot for the three ring structure. We clearly see a notch as **2.505 GHz** with S_{21} = **-21.57 dB** and S_{11} = **-1.1 dB**. This resonant frequency is around 2.77 GHz lesser compared to the single ring structure.

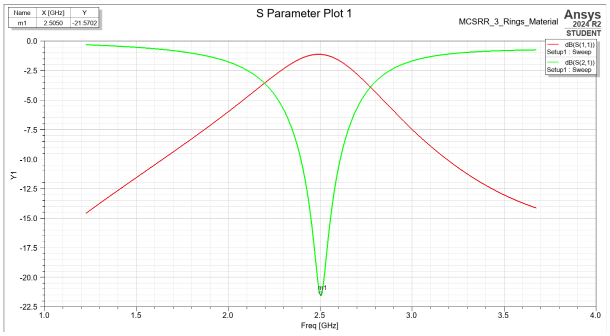


Fig. 11: Triple Ring S-parameters Plot with **air**

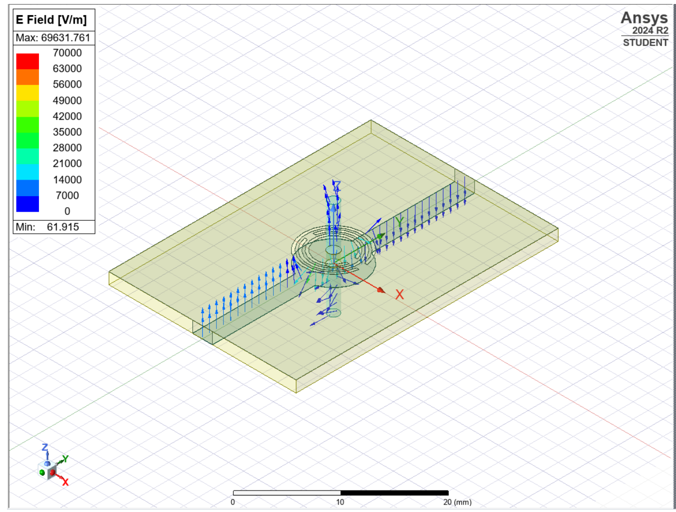


Fig. 12: Time varying vertical electrical field due to excitation

With the initial dimensions, we achieved a resonant frequency of 2.425 GHz. In order to achieve resonance at 2.5GHz, we increased the split size - 'g' to **1.57 its current size** i.e., 1.1 mm. We calculate the **-3dB bandwidth** of the notch to be nearly **650 MHz**. The **Q-factor comes out to be 3.84**. Since increasing the split gap decreases the inductance corresponding to the split this increases the frequency and provides the desired 2.5 GHz. In order to increase frequency, capacitance can also be reduced, however, this would degrade the Quality factor (sharpness at resonance) as given by (2) .

Another observation is that with increase in rings, the S_{21} magnitude at the resonant frequency reduces and that of S_{11} increases. Thus with additional rings, the sensor is behaving better in the sense that reflection is increased and transmission is reduced. This is exactly opposite to the case of SRRs where it is desired to reduce reflections and maximize transmission. Thus this structure with three rings can be used to characterize the relative permittivity of various material(In the plots given so far, the hole was filled with air).

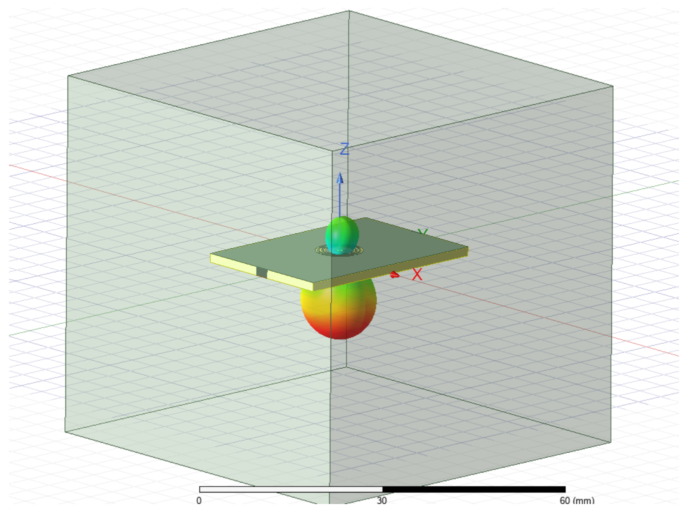


Fig. 13: Electric Field Heatmap Visualized on the device

E. Dielectric Characterization

As Discussed in the above subsection, we can make use of the this device for the dielectric characterization of different materials. For this, in the HFSS, we add a cylinder in the center hole and vary its material. We know that CSRR is mainly influenced by the Electric field unlike SRR where Magnetic field is prominent. As will be seen in the Electric field plots, it is mostly concentrated in the hole region, providing us a very suitable place to place our material and observe the change in the resonant frequency.

Since air has a relative permittivity of 1, any material with $\epsilon_r > 1$ increases the strength of electric field and hence the equivalent capacitance of the device. The results in a lower resonant frequency as given by (2).

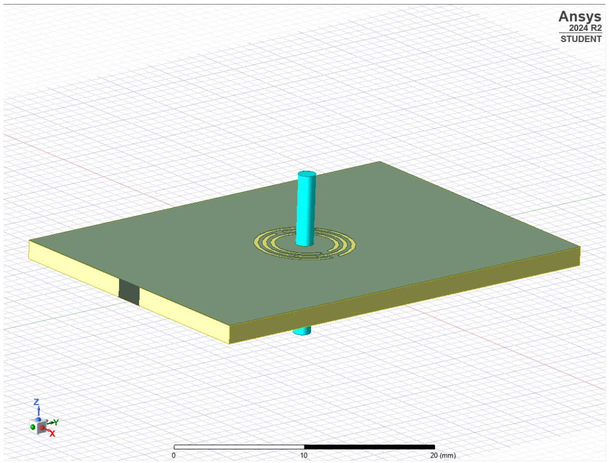


Fig. 14: HFSS Design of triple ring with material

The following is the S-parameter plot for **Diamond** as the material under test. Diamond has $\epsilon_r = 16.5$. Corresponding to this, we get the resonant frequency = **2.345 GHz** with $S_{21} = -22.17dB$ and $S_{11} = -1dB$. This reduction in resonant frequency was expected as discussed above.

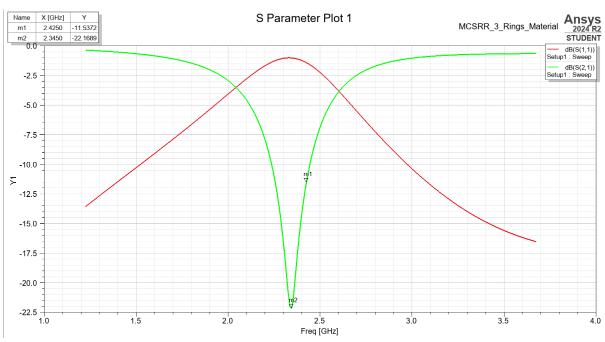


Fig. 15: Triple Ring S-parameters Plot with **diamond**

The following is the S-parameter plot for **Distilled Water** as the material under test. Distilled Water has $\epsilon_r = 81$. Corresponding to this, we get the resonant frequency = **2.245 GHz** with $S_{21} = -23.09dB$ and $S_{11} = -1dB$. Thus we see that water having higher ϵ_r than diamond shift the frequency to a smaller value. This observation is in general true, and the resonant frequency with the material is inversely proportional to its ϵ_r.

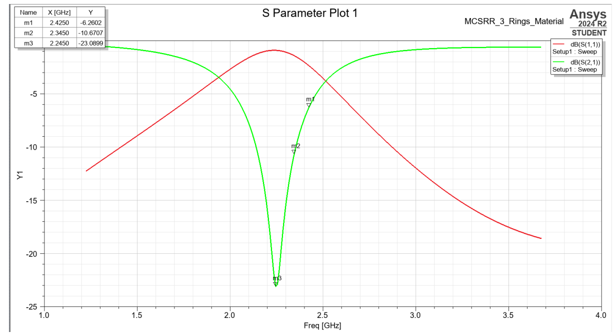


Fig. 16: Triple Ring S-parameters Plot with **water**

We can use these plots to check the variation of sensitivity for different dielectric materials using the below relation:

$$S = \frac{f_{empty} - f_{sample}}{f_{empty}(\epsilon_r - 1)} \cdot 100 \quad (3)$$

Using $f_{empty} = 2.505GHz, f_{diamond} = 2.345GHz, \epsilon_r = 16.5$:

$$S = \frac{2.505 - 2.345}{2.505(16.5 - 1)} \cdot 100 = 0.412 \quad (4)$$

Using $f_{empty} = 2.505GHz, f_{water} = 2.245GHz, \epsilon_r = 81$:

$$S = \frac{2.505 - 2.245}{2.505(81 - 1)} \cdot 100 = 0.130 \quad (5)$$

We observe some degree of non-linearity over a range of hundreds of MHz.

F. MCSRR with 4 Rings

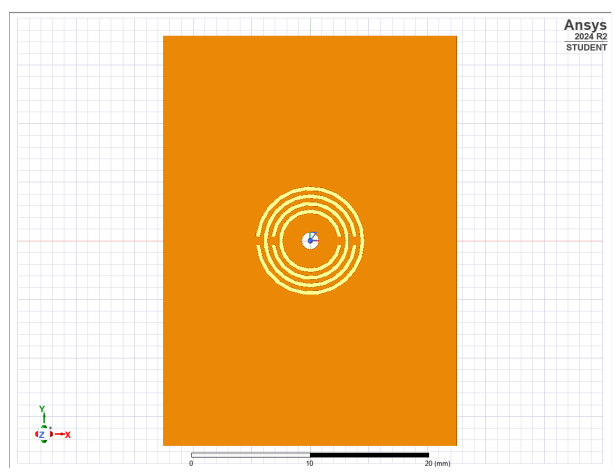


Fig. 17: HFSS Design of Quadruple Ring

Now, to further verify out hypothesis, we design MCSRR with 4 rings too. Above is the HFSS design for the same. With this addition of another ring, the capacitance and inductance is further increased leading to a much lower resonant frequency.

Following is the S-parameter plot for the four rings structure. As expected the resonant frequency has gone down, and is **1.905 GHz** with $S_{21} = -21.5dB$ and S_{11} = -1 dB. We can also conclusively say that after adding three rings, adding additional rings or changing the material doesn't further affect or change the s parameters. Only the resonant frequency changes. This is because of a adding enough (3 here), the EM field saturate because rings very far away from the centre are weakly coupled with each other. This is also consistent with the fact that the EM field is concentrated mainly in the centre.

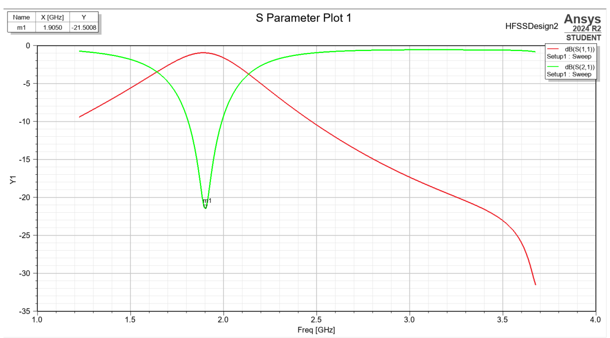


Fig. 18: Quadruple Ring with split S-parameters Plot

V. Radiation Patterns

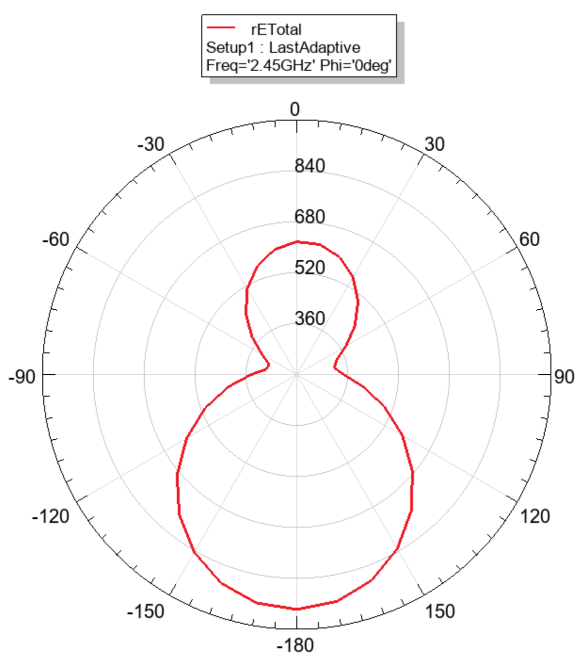


Fig. 19: Radiation Pattern for Electric Field

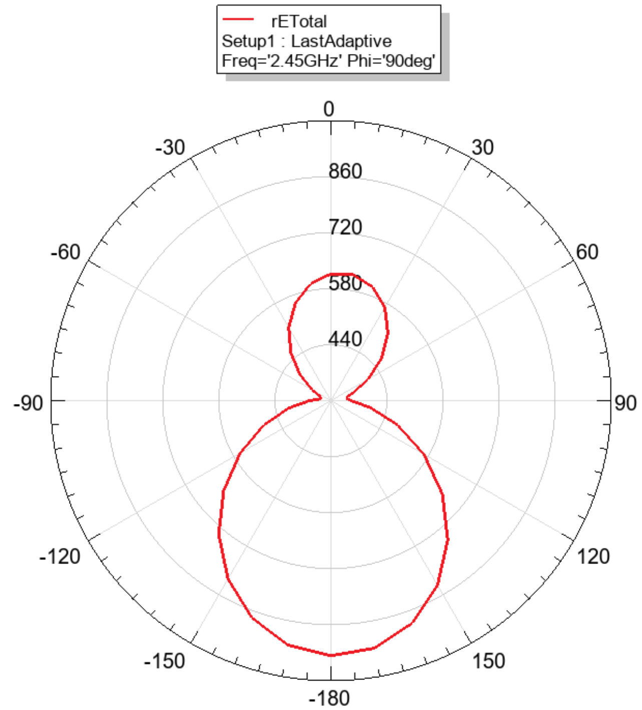


Fig. 20: Radiation Pattern for Magnetic Field

VI. Conclusion

In this project, we have simulated an MCSRR structure that resonantes at 2.5GHz with the S_{11} value being above -3dB and S_{21} value being less than -20dB at the resonance frequency. We also obtained a 40% sensitivity for diamond dielectric ($\approx$ 150MHz frequency shift) and 13% sensitivity for distilled water sample ($\approx$ 250MHz frequency shift), which satisfies the project constraints for our design.

References

[1] A. Javed, A. Arif, M. Zubair, M. Q. Mehmood, and K. Riaz, "A Low-Cost Multiple Complementary Split-Ring Resonator Based Microwave Sensor for Contactless Dielectric Characterization of Liquids," *IEEE Sensors Journal*, vol. 21, no. 16, pp. 17740-17747, Aug. 2021.

[2] Dr. HariPrasad Naik Bhattu, "WMICROSTRIP PATCH ANTENNA DESIGN WITH HFSS." YouTube, Jan. 24, 2021. [Online]. Available: https://www.youtube.com/watch?v=vHUbV_7f_dE