Radio Frequency Based Sensors design: Principles and Applications

Project

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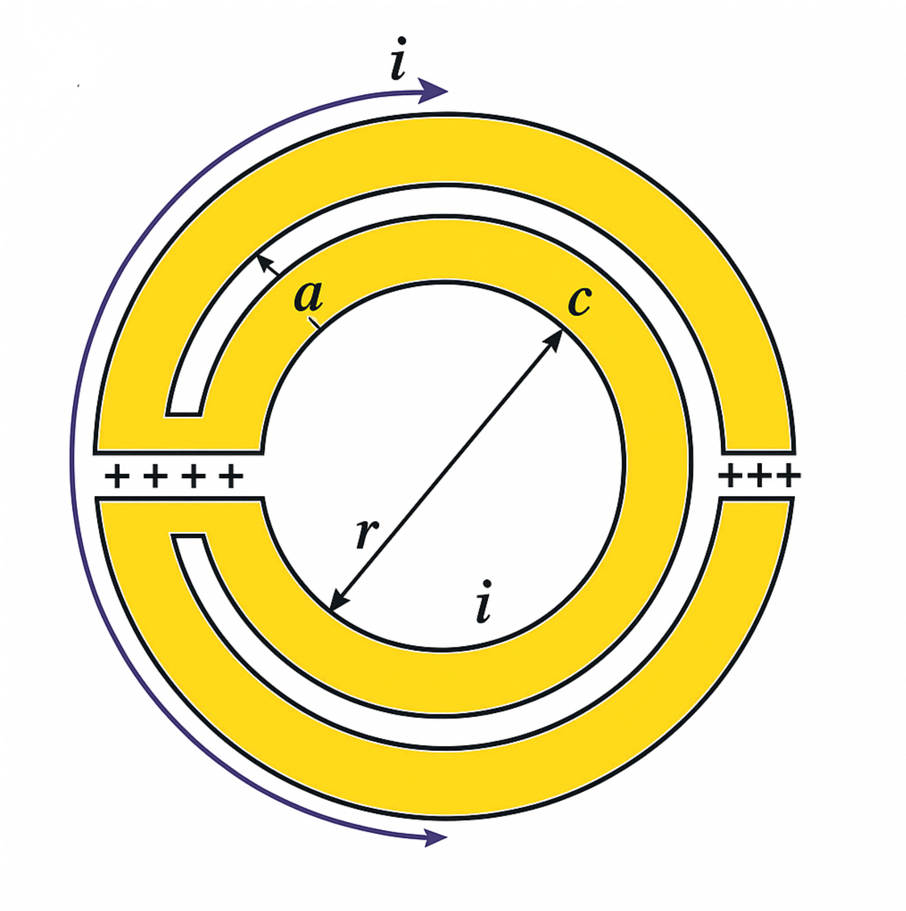
Design and Analysis of Split Ring Resonator Structures



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Abstract

Split Ring Resonators (SRR) are widely used in metamaterial and microwave engineering due to their compact size and strong negative permittivity characteristics.This report presents the design and analysis of split ring resonators (SRRs) for radio frequency applications using full-wave electromagnetic simulations. The study investigates both square and circular SRR geometries to understand their electromagnetic behaviour and resonance characteristics. The hypothesis is that by modifying the resonator geometry, number of concentric rings, and structural parameters such as the gap and split size, the resonant frequency can be effectively tuned to desired specifications. The methodology involves systematically modelling and simulating different SRR configurations in HFSS, analysing their S-parameter responses, and iteratively optimizing key design parameters. Through this approach, the project aims to demonstrate the impact of structural variations on the resonance behaviour of SRRs and establish a design guideline for achieving efficient and compact resonator structures suitable for sensing and filtering applications in the radio frequency domain.

1 Objective

This project focuses on the design and simulation of a **Split Ring Resonator (SRR)** intended to operate as a **notch filter** with a target resonant frequency of **2.5 GHz**. The aim is to effectively attenuate signals around the resonant frequency while allowing others to pass through with minimal loss. The design emphasizes compactness, high sensitivity, and strong filtering characteristics.

Table 1: Design Specifications: SRR Based Notch Filter

Parameter	**Requirement**
Resonator Type	Split Ring Resonator (SRR)
Operating Frequency	< 6 GHz
Resonant Frequency	2.5 GHz
S_{11} (Input Reflection)	> -1 dB
S_{21} (Output Reflection)	< -10 dB at resonance (Notch filter behavior)
Sensitivity	$> 10\%$
Size	As compact as possible

A **Split Ring Resonator** (SRR) is a sub-wavelength metallic structure designed to produce strong magnetic resonance in response to electromagnetic fields. It is one of the fundamental building blocks of metamaterials, which can exhibit properties not found in natural materials.

Structure of Split Ring Resonator (SRR):

- It is composed of two concentric metallic rings, each with a small gap (split) on opposite sides.
- It is typically placed on a dielectric substrate.
- The splits in the rings are essential for creating a resonant LC circuit.

Working Principle:

When an external magnetic field (usually perpendicular to the plane of the rings) interacts with the Split Ring Resonator , it induces circulating currents in the rings. These currents create a magnetic dipole, leading to resonance at a particular frequency. The structure behaves like a resonant LC circuit, where the Rings provide Inductance and the Gaps provide Capacitance.

At resonance, the Split Ring Resonator exhibits negative effective permeability $\mu < 0$.

1.1 Geometric Parameters of Square Split Ring Resonator

The geometric parameters that define an Split Ring Resonator are as follows:

- l_{in}: Length of Inner Metallic ring .
- l_{out}: Length of Outer Metallic ring .
- W: Width of the Metallic ring trace.
- S: Spacing between the inner and outer rings.
- D: Width of the split (gap) in each ring.
- t: Thickness of the metal layer.
- A: Equilibrium Constant
- ϵ_r: Relative permittivity of the dielectric substrate.

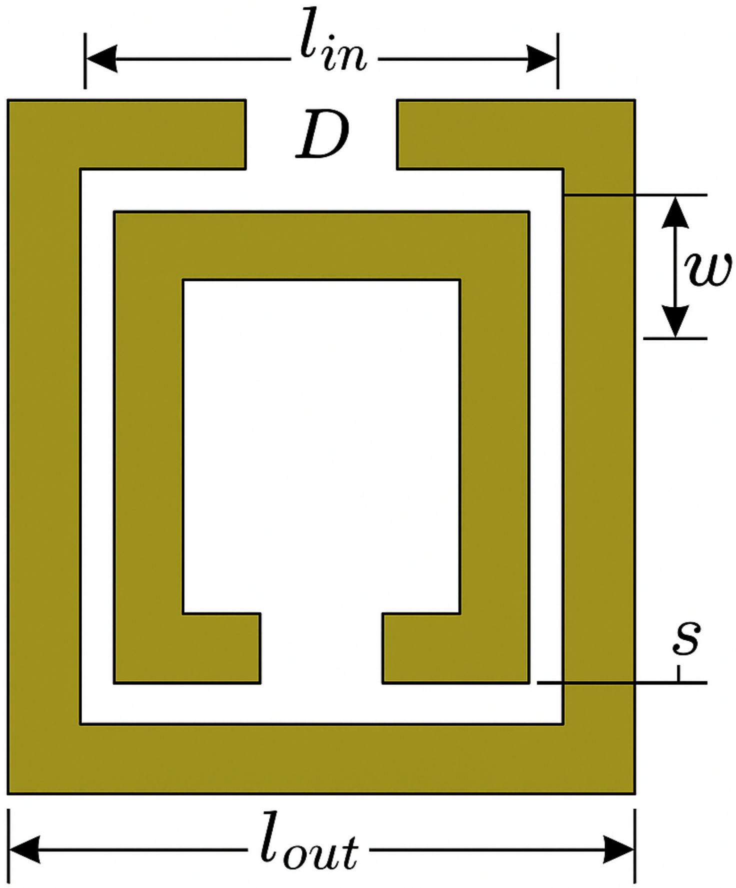

Figure 1: Circuit Diagram

1.2 Geometric Parameters of Circular Split Ring Resonator

The geometric parameters that define an Split Ring Resonator are as follows:

- r_o: Radius of Inner Metallic ring .
- r_{ext}: Radius of Outer Metallic ring .
- C: Width of the Metallic rings.
- D: Spacing between the inner and outer rings.
- g: Width of the split (gap) in each ring.

- t: Thickness of the metal layer.
- A: Equilibrium Constant
- ϵ_r: Relative permittivity of the dielectric substrate.

The SRR is designed so that the splits in the rings are diametrically opposite, maximizing capacitive coupling and allowing a strong resonant response to an incident magnetic field perpendicular to the plane of the rings.

2 Designing of Split Ring Resonator

2.1 Square Split Ring Resonator

Split Ring Resonator behaves like a resonant LC circuit , where each ring resembles a solenoid that can be represented by an Inductance L_m and the space between the two rings can be represented by a Capacitor C_m .

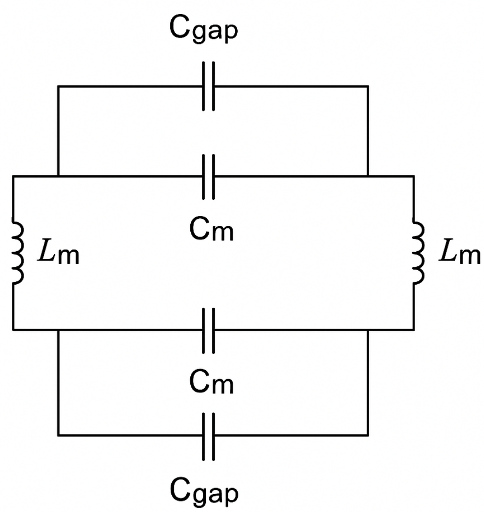

Figure 2: Equivalent Circuit

The Inductance L_m of each ring can be obtained as

$$L_m = \frac{\mu_o S}{W}[l_{out} + l_{in}]$$

The Capacitance C_{gap} of the slot ring is determined as

$$C_{gap} = \frac{\epsilon_o \epsilon_r t}{D}$$

The Capacitance C_m created between the two rings may be expressed as

$$C_m = \frac{A\epsilon_o \epsilon_r W(2l_{out} + 2l_{in} - D)}{2S}$$

The Resonant frequency f_o can be determined based on geometric parameters of the Split Ring Resonator as

$$f_o = \frac{1}{2\pi\sqrt{L_m(C_m + C_{gap})}}$$

$$f_o \approx \frac{1}{2\pi\sqrt{L_m C_m}}$$

2.1.1 Finding Values of Parameters

We want to work at an operating frequency equal to 2.5GHz with a dielectric substrate such as FR04-epoxy having relative permittivity $\epsilon_r = 4.4$.
Considering Inductance L_m as 60 nH . Then mutual capacitance C_m created between the two rings obtained as

$$C_m = \frac{1}{4\pi^2 L_m^2 f_o^2} \approx 75fF$$

For simple calculations , the value of S is considered as 1mm and W is also considered as 1mm .
From Equation of Inductance we get

$$l_{out} + l_{in} = 47.77mm$$

From the Figure , we can determine the expression of length of the outer ring as

$$l_{out} = l_{in} + 2S + 2W$$

From these two equations , we get $l_{in} = 21.885mm$ and $l_{out} = 25.885mm$.
Finally we get D equal to 1.14mm .
Parameters decided :

- l_{in}: 21.885 mm

- l_{out}: 25.885 mm
- W: 1 mm
- S: 1 mm
- D: 1.14 mm
- ϵ_r: 4.4
- L_m : 60 nH
- C_m : 75 fF

2.2 Circular Split Ring Resonator

- r_{ext}: 4.65mm
- C: 0.35mm
- D: 0.3mm
- g : 0.7mm
- t : 2.65 mm

3 Design Procedure

The simulation of the Split Ring Resonator sensor is performed using ANSYS HFSS software .

3.1 Square Split Ring Oscillator

Step-1 :
We made a FR04 Substrate whose permittivity is $\epsilon_r = 4.4$. Dimensions of the Substrate is $30\,\text{mm} \times 30\,\text{mm} \times 0.5\,\text{mm}$
Step-2 :
Procedure to Design Split Ring :

- If we are required to construct a Split Ring of Length L. Consider a Copper strip of dimensions L×L.

- Then also make a another copper strip of dimensions L-2W×L-2W.
- Subtract these two copper strips to obtain the Ring of Width W .
- Now build a copper strip of Dimensions D×W .
- Subtract this strip from Ring to produce a split ring of length L

Build two Split rings of length l_{out} and l_{in} . Note that slits in the two rings mus be opposite in direction . The Gap between the split rings must be S .
Step-3 :
Add a Copper Microstrip on the bottom of the substrate.

3.1.1 SRR with 2 rings

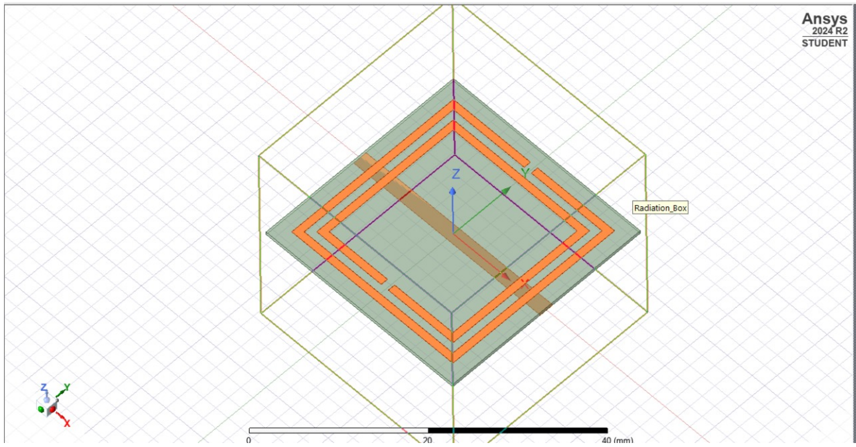

Figure 3: Square SRR with 2 Rings

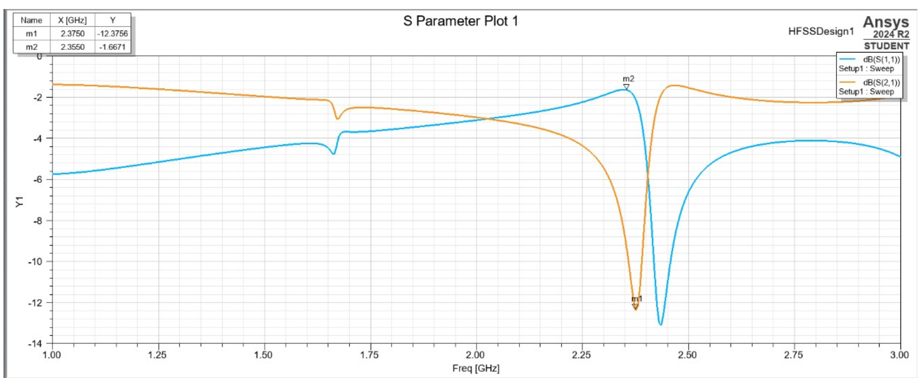

Figure 4: S_{11} and S_{21} Plots for Square SRR with 2 Rings

Calculated S_{11}, S_{21} for SRR with 2 Rings

- S_{11}= -1.6671 dB
- S_{21}= -12.3756 dB
- f_o= 2.3750 dB

3.2 Circular Split Ring Resonator

Step - 1 :
Build a ground plate of dimensions 35 mm × 25 mm
Step - 2 :
We made a FR04 Substrate whose permittivity is $\epsilon_r = 4.4$. Dimensions of the Substrate is 35 mm × 25 mm × 1.6 mm
Step - 3 :
Procedure to Design a Split Ring :

- If we are required to construct a Split Ring of radius r . Construct a Copper Cylinder of radius r and thickness t.
- Then also construct a another Copper Cylinder of radius r-C and thickness t.
- Subtract these two Copper Cylinders to obtain the Ring of Width C.
- Now build a Copper box of Dimensions g×C×t .
- Subtract this strip from Ring to produce a split ring of split width g .

Build required number of Split Rings with adjacent rings has width of D difference .
Step-3 :
Add a Copper Microstrip on the substrate on either sides of Outer Split ring .

3.2.1 SRR with 2 rings

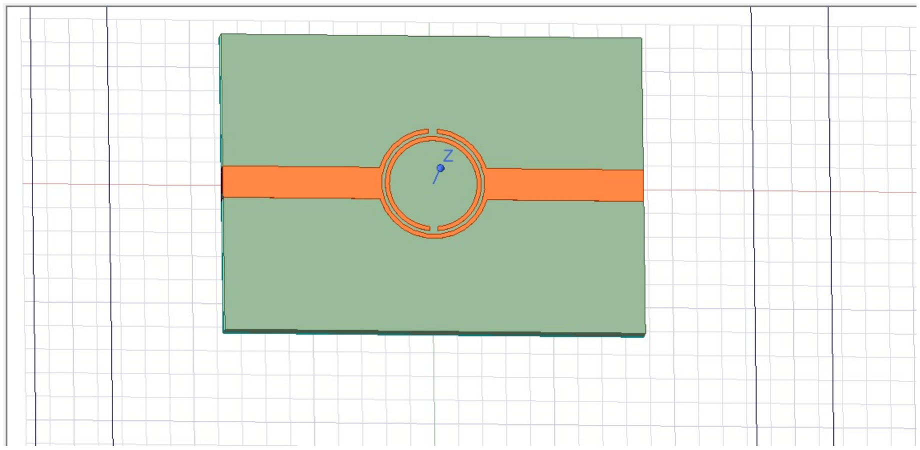

Figure 5: SRR with 2 Rings

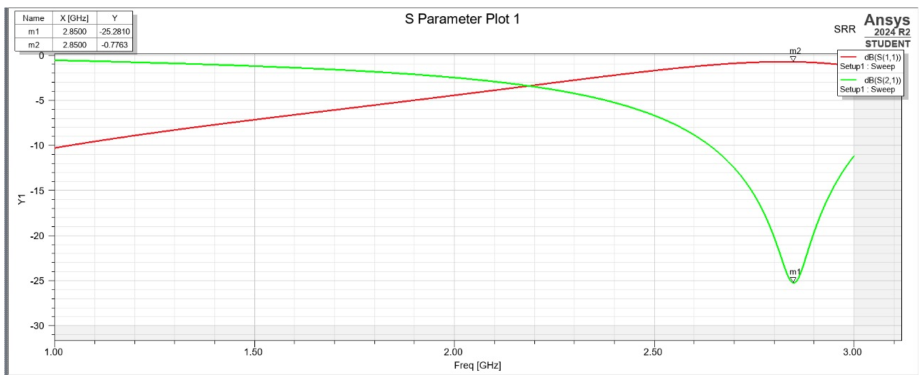

Figure 6: S_{11} and S_{21} Plots for SRR with 2 Rings

Calculated S_{11}, S_{21} for SRR with 2 Rings

- S_{11}= -25.2810 **dB**
- S_{21}= -0.7763 **dB**

3.2.2 SRR with 3 rings

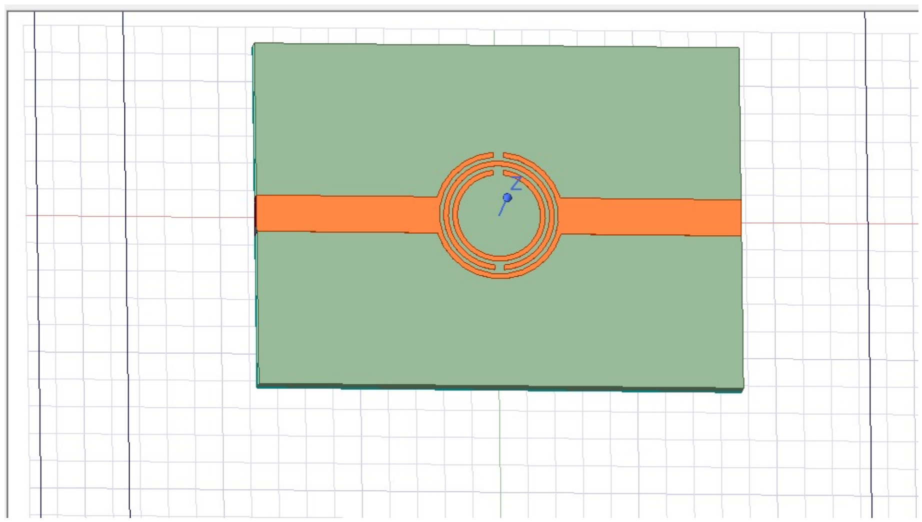

Figure 7: SRR with 3 Rings

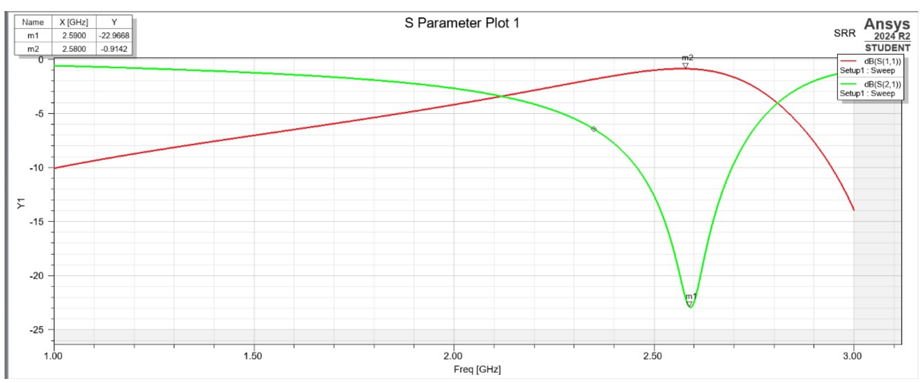

Figure 8: S_{11} and S_{21} Plots for SRR with 3 Rings

Calculated S_{11}, S_{21} for SRR with 3 Rings

- S_{11}= -22.9668 **dB**
- S_{21}= -0.9142 **dB**

3.2.3 SRR with 4 rings

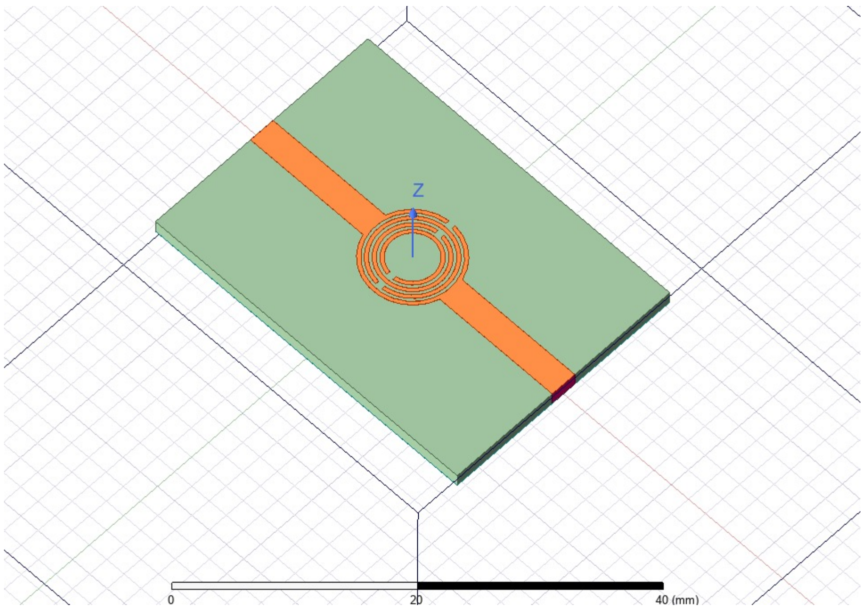

Figure 9: SRR with 4 Rings

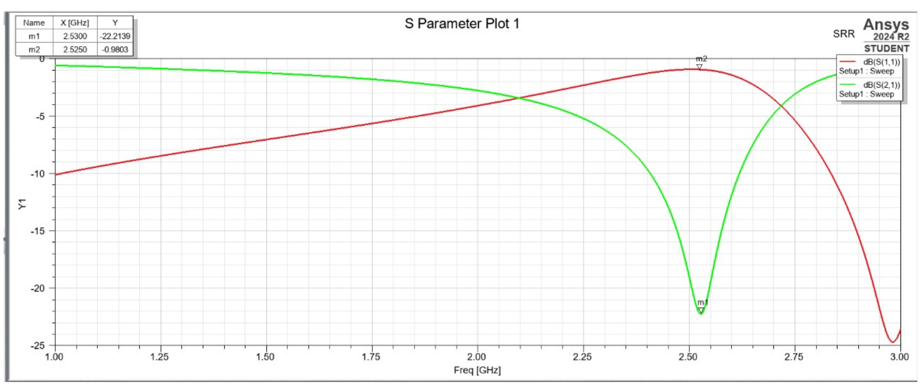

Figure 10: S_{11} and S_{21} Plots for SRR with 4 Rings

Calculated S_{11}, S_{21} for SRR with 4 Rings

- S_{11}= -22.2139 **dB**
- S_{21}= -0.9803 **dB**

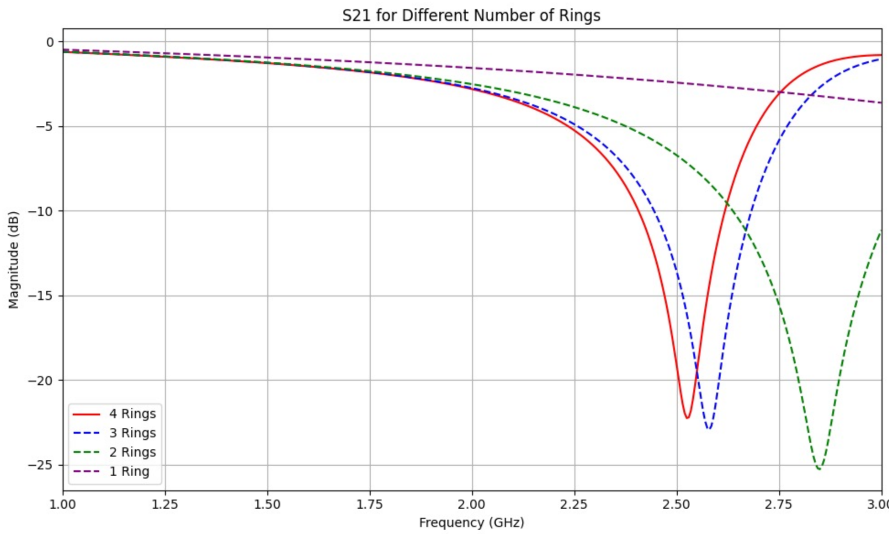

Figure 11: Comparison of S21(dB)

Table 2: S-Parameters and Resonance Frequency for SRRs with 2, 3, and 4 Rings

SRR Configuration	S_{11}	S_{21}	**Resonance Frequency (GHz)**
2 Rings	-25.2810	-0.7763	2.85
3 Rings	-22.9668	-0.9142	2.59
4 Rings	-22.2139	-0.9803	2.53

Initially, a square split ring resonator (SRR) structure was simulated using HFSS, yielding a resonant frequency of 2.375 GHz. To explore performance enhancements, the geometry was changed to a circular SRR. With two concentric rings, the structure exhibited a resonant frequency of 2.85 GHz. Upon adding a third ring, the resonant frequency decreased to 2.59 GHz, and further addition of a fourth ring reduced it to 2.53 GHz. This trend illustrates that increasing the number of rings enhances electromagnetic coupling, leading to a shift in resonance. To precisely tune the frequency, the gaps between the rings and the split dimensions were systematically adjusted. After optimization, the structure achieved a final resonant frequency of 2.53 GHz. The reflection coefficient (S_{11}) was observed to be -22.2139 dB, indicating excellent impedance matching, and the transmission coefficient (S_{21}) was -0.9803 dB, demonstrating minimal signal loss across the resonator. These results confirm the effectiveness of design modifications in achieving the desired frequency response.

4 Sensitivity

Sensitivity (**S**) is defined as the change in resonant frequency per unit change in its surrounding environment or structural parameters .

$$S = \frac{\Delta f_r}{\Delta X}$$

where :

- $\Delta f_r = f_{unloaded} - f_{loaded}$
- ΔX = Change in the quantity being measured .

Factors affecting Sensitivity :

- Geometry of the Split Ring Resonator (Length , Width , Gap size and Line width)
- Material properties
- Placement of analyte

Typically we measure Sensitivity as the change in resonant frequency per unit change in the dielectric constant The **gap region** in the Split ring resonator is highly sensitive to dielectric changes because it is where the electric field is Strongest . Increasing the Quality factor enhances sensitivity but can reduce bandwidth .

4.1 Sensitivity Calculations

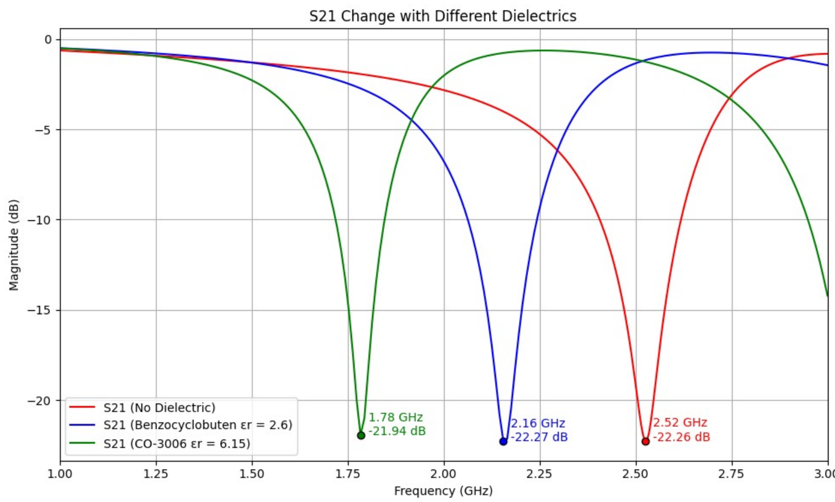

Figure 12: Frequency Shift Due For Different ϵ_r

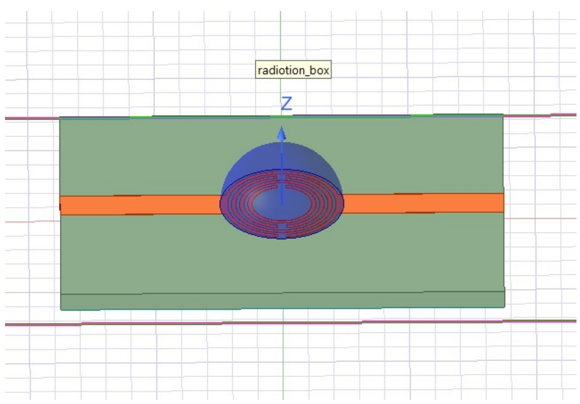

Figure 13: Dielectric on Split Ring Resonator

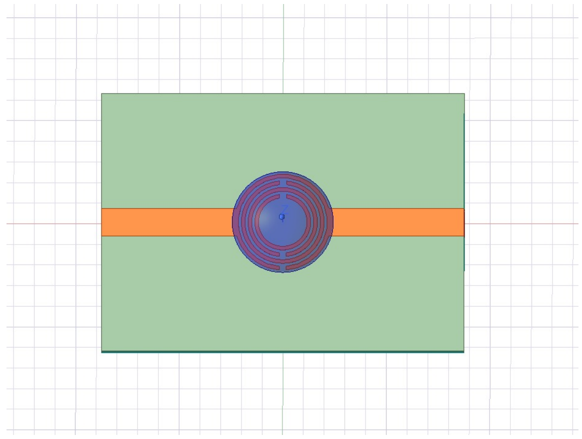

Figure 14: Dielectric on Split Ring Resonator

We found sensitivity of the sensor for two different dielectrics:

- Benzocyclobuten (ϵ_r= 2.6)
- CO-3006 (ϵ_r= 6.15)

4.1.1 Sensitivity Calculation with Benzocyclobuten

Benzocyclobuten has Relative permittivity ϵ_r of 2.6
The change in measuring parameter is

$$\Delta X = 2.6 - 1$$

$$\Delta X = 1.6$$

From above graph , The new Resonant frequency is 2.16 GHz .
The shift in Resonant frequency is

$$\Delta f = 2.52\ GHz - 2.16\ GHz$$

$$\Delta f = 0.36\ GHz$$

Now Sensitivity to addition of Benzocyclobuten Dielectric is

$$S = \frac{\Delta f_r}{\Delta X}$$

$$S = \frac{0.36\ GHz}{1.6}$$

$$S = 0.225 \frac{GHz}{\epsilon_r}$$

Sensitivity is of **22.5%** for **Benzocyclobuten**

4.1.2 Sensitivity Calculation with CO-3006

CO-3006 has Relative permittivity ϵ_r of 6.15
The change in measuring parameter is

$$\Delta X = 6.15 - 1$$

$$\Delta X = 5.15$$

From above graph , The new Resonant frequency is 1.78 GHz .
The shift in Resonant frequency is

$$\Delta f = 2.52\ GHz - 1.78\ GHz$$

$$\Delta f = 0.74\ GHz$$

Now Sensitivity to addition of CO-3006 Dielectric is

$$S = \frac{\Delta f_r}{\Delta X}$$

$$S = \frac{0.74\ GHz}{5.15}$$

$$S = 0.147 \frac{GHz}{\epsilon_r}$$

Sensitivity is of **14.7%** for **CO-3006**

Table 3: Sensitivity Calculation

Dielectric(ϵ_r)	Δf	ΔX	Sensitivity	Sensitivity(%)
Benzocyclobuten(2.6)	0.36 GHz	1.6	0.225	22.5%
CO-3006(2.6)	0.74 GHz	5.15	0.147	14.7%

5 Quality Factor

The **Q-factor** or **Quality factor** of a resonator is a dimensionless parameters that describes how sharp or selective the resonance is . It reflects how efficiently a resonator store energy versus how quickly it loses energy .

$$S = \frac{f_r}{\Delta f}$$

where :

- f_r is Resonant frequency
- Δf = Bandwidth
- A High Q-factor means narrow bandwidth and low energy loss . It is ideal for applications requiring high sensitivity or selectivity.
- A Low Q-factor means broad bandwidth and high energy loss . It is useful in wideband systems but with less precision.

The bandwidth Δf is often measured using the **Full Width at Half Maximum (FWHM)** method. This refers to the width of the resonance curve at the point where the response falls to half of its maximum value. In other words, FWHM is the frequency difference between the two points on the curve where the amplitude drops to 70.7% (or power to 50%) of the peak value.
Thus, the quality factor Q can also be interpreted as:

$$Q = \frac{f_\mathrm{r}}{\Delta f}$$

where f_r is the resonant frequency and Δf is the FWHM.

5.1 Q-factor Calculations

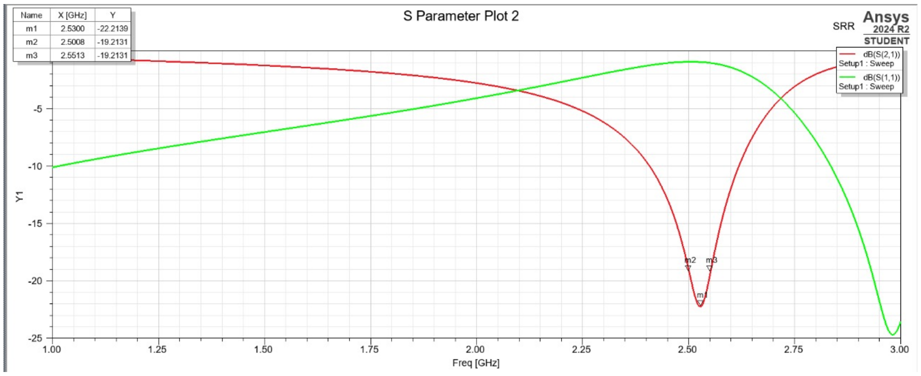

Figure 15: Quality factor calculation

The S11(dB) value at Resonant frequency is -22.2139dB . For Calculating we need points where the S11(dB) value is -19.2139dB .

Table 4: Bandwidth Calculation

S11 (dB)	Frequency (GHz)
-19.2139	2.5008
-19.2139	2.5513

The 3-dB Bandwidth is $\Delta f = 2.5513 - 2.5008 = 0.0505GHz$
The Quality-factor is

$$Q = \frac{f_{\mathrm{r}}}{\Delta f} = \frac{2.5300GHz}{0.0505GHz}$$

$$Q = 50.09$$

Table 5: Design Specifications: SRR Based Notch Filter

Parameter	**Requirement**	**Checklist**
Resonator Type	Split Ring Resonator (SRR)	✓
Operating Frequency	< 6 GHz	✓
Resonant Frequency	2.5 GHz	✓
S_{11} (Input Reflection)	> -1 dB	✓
S_{21} (Output Reflection)	< -10 dB at resonance (Notch filter behavior)	✓
Sensitivity	$> 10\%$	✓
Size	As compact as possible	✓

6 Radiation Plots

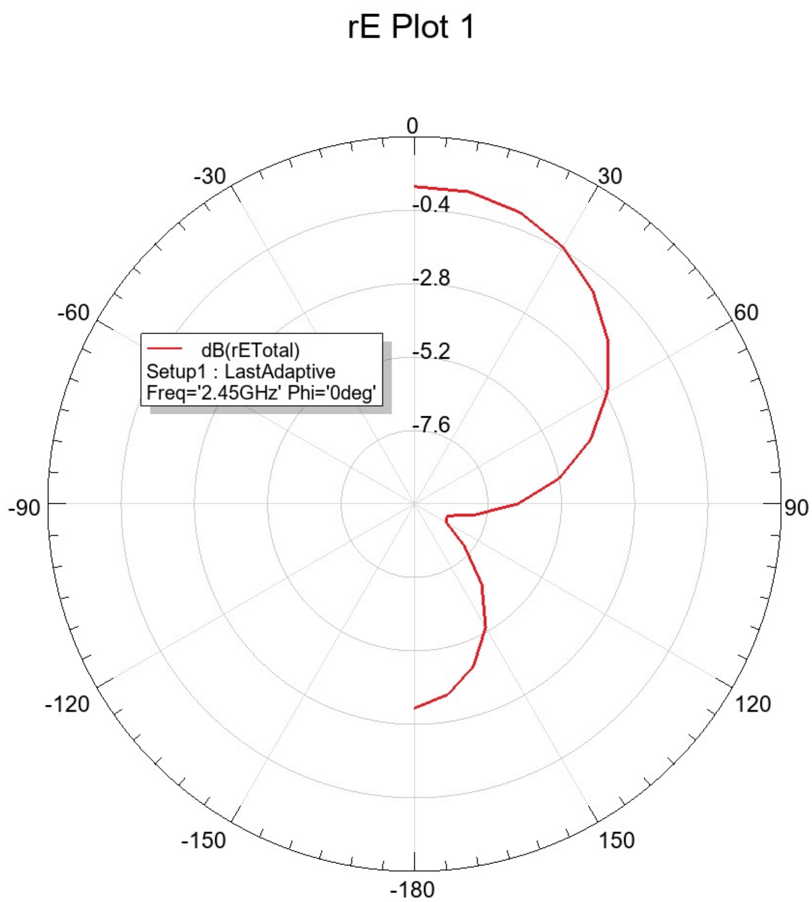

Figure 16: rE Radiotion Plot

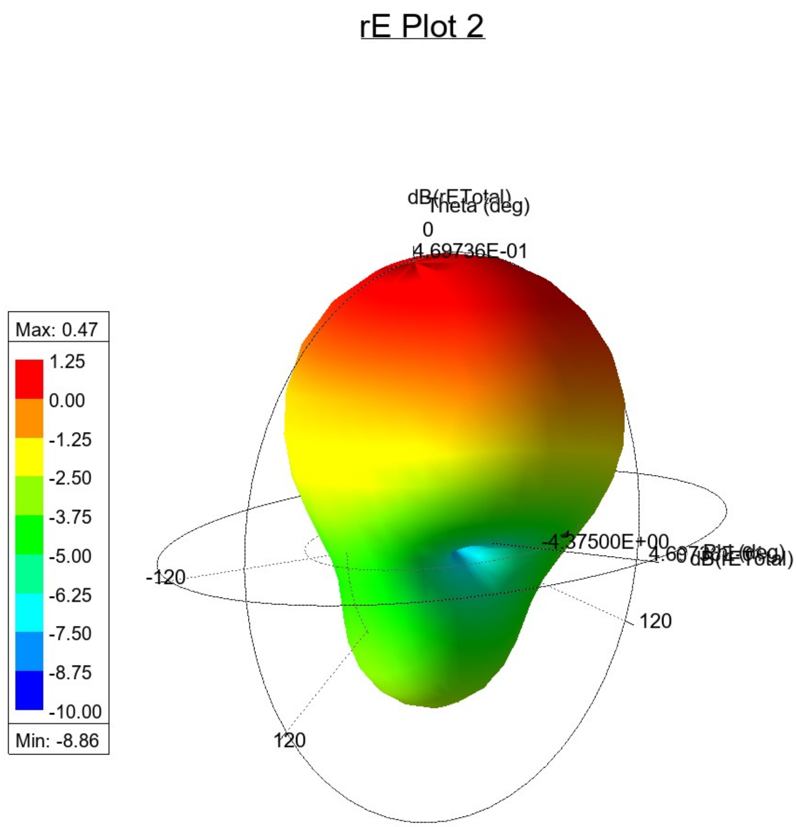

Figure 17: rE 3D Polar Plot

7 Conclusion

This project successfully demonstrated the design, simulation, and performance analysis of Split Ring Resonators (SRRs) for radio frequency sensing applications. Starting with a square SRR targeting a resonant frequency of 2.5 GHz, we developed models in HFSS and validated the behavior through S-parameter analysis. The square SRR with two rings yielded a resonant frequency of 2.375 GHz, S_{11} of -1.6671 dB, and S_{21} of -12.3756 dB, indicating moderate performance but room for improvement in sensitivity and filtering capability.
To enhance performance, we transitioned to circular SRR geometries. By incrementally increasing the number of concentric rings from two to four, we observed a notable shift in resonant frequency and improved electromagnetic coupling. The circular SRR with four rings achieved a final resonant frequency of 2.53 GHz with

an S_{11} of -22.2139 dB and an S_{21} of -0.9803 dB, demonstrating excellent impedance matching and minimal signal loss.

Sensitivity analysis further validated the sensor's responsiveness to environmental changes. With Benzocyclobuten ($\epsilon_r = 2.6$), the frequency shift was 0.36 GHz, yielding a sensitivity of 22.5%. Similarly, with CO-3006 ($\epsilon_r = 6.15$), the shift was 0.74 GHz, resulting in a sensitivity of 14.7%. These results highlight the SRR's effectiveness in detecting variations in dielectric permittivity, a critical parameter for RF sensing applications.

Moreover, the calculated quality factor (Q) of 50.09 for the optimized circular SRR reflects high selectivity and low energy loss, further confirming the suitability of our design for precise sensing and filtering tasks.

In summary, through systematic design evolution, parameter tuning, and simulation based validation, we achieved a compact, high sensitivity RF resonator structure. The study establishes a scalable framework for developing efficient SRR based sensors for applications in wireless communication, material characterization and environmental monitoring.

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