TEAM LUZAAZ

Interdigitated Capacitance Design using HFSS

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Abstract

This report presents the design, simulation, and analysis of an Interdigitated Capacitance (IDC) resonating at 5 GHz. The IDC structure was designed to meet specific S11 and S21 targets, ensuring passband behavior with minimal reflection and acceptable transmission. The design process, simulation results, and sensitivity analysis are detailed, demonstrating compliance with project specifications.

Contents

1 Introduction

1.1 Background

Interdigitated Capacitors (IDCs) are planar resonator structures widely used in radio frequency (RF) and microwave applications due to their simple geometry and ease of integration with printed circuit boards (PCBs). They function by creating a capacitance between interwoven finger electrodes, which can be tailored to achieve specific resonant frequencies. IDCs are particularly useful in filters, sensors, and impedance matching networks, where their ability to provide passband behavior with low reflection and acceptable transmission makes them ideal for high-frequency applications.

1.2 Objective

The primary objective of this project is to design and simulate an IDC resonating at 5 GHz. The design should achieve an input reflection coefficient (S11) of less than -10 dB and a forward transmission coefficient (S21) of greater than -3 dB, ensuring effective passband behavior. Additionally, the IDC should demonstrate a sensitivity of more than 10%, making it suitable for potential sensing applications or compact RF systems.

1.3 Project Scope

This report details the entire design and simulation process of the IDC, including:

- The theoretical background of IDCs and their resonance characteristics
- Selection of substrate material and geometric parameters
- Simulation setup and iterative design process
- Analysis of S11 and S21 parameters to validate performance
- Sensitivity analysis to assess the IDC's response to parameter variations

The project focuses on achieving a compact design while meeting the specified performance targets, with an emphasis on practical implementation considerations.

2 Theoretical Background

2.1 Principles of Interdigitated Capacitance

Interdigitated Capacitors (IDCs) consist of multiple interleaved metal fingers that create a distributed capacitance between adjacent fingers. The capacitance is primarily due to the fringe electric fields at the edges of the fingers. The total capacitance C of an IDC can be approximated by:

The approximate capacitance of an interdigitated capacitor (IDC) is given by:

$$C = \frac{(N-1)\,\varepsilon_0 \varepsilon_r\, l}{G} \left(1 + \frac{W}{G}\right) F$$

where:

- C is the total capacitance of the IDC,
- N is the total number of fingers (electrodes),
- ε_0 is the vacuum permittivity (8.854×10^{-12} F/m),
- ε_r is the relative permittivity of the substrate or dielectric,
- l is the length of the fingers (in the direction perpendicular to the page),
- W is the width of each finger,
- G is the gap between adjacent fingers,

Calculated Capacitance $= 6.6nF$

2.2 Resonance in IDCs

The resonance frequency f_r of an IDC is determined by its distributed capacitance C and any parasitic inductance L_p associated with the structure. The resonance occurs at the frequency where the capacitive reactance equals the inductive reactance:

$$f_r = \frac{1}{2\pi\sqrt{L_p \cdot C}} \tag{1}$$

The parasitic inductance primarily arises from the metal traces and the substrate, and it plays a crucial role in determining the resonant frequency. Designing the IDC to achieve a specific resonance frequency involves careful adjustment of the geometric parameters (L, W, G, and N) and the choice of substrate material with appropriate ε_r.

2.3 S-Parameters in RF Design

S11 (Reflection Coefficient): Measures how much of the incident signal is reflected back at the input port. A value of $S11 < -10\,\text{dB}$ indicates that less than 10% of the signal is reflected, which is desirable for efficient power transfer.

S21 (Transmission Coefficient): Measures how much of the signal is transmitted from the input port to the output port. For IDCs designed as passband elements, $S21 > -3\,\text{dB}$ ensures that more than 50% of the signal is transmitted through the structure.

These parameters are essential for evaluating the performance of the IDC in terms of impedance matching (S11) and signal transmission (S21).

2.4 Design Equations

The design of an IDC at 5 GHz involves iterative calculations to achieve the desired resonance frequency. The following steps are typically followed:

- Select a substrate with appropriate ε_r and thickness d.
- Choose initial values for L, W, G, and N.
- Calculate the estimated capacitance C using the formula provided.
- Estimate the parasitic inductance L_p based on the metal trace dimensions and substrate properties.
- Calculate the resonance frequency f_r and compare it to the target of 5 GHz.
- Adjust the geometric parameters iteratively until the calculated f_r closely matches the target frequency.

This theoretical foundation guides the design process and helps in understanding the relationship between the physical dimensions of the IDC and its electrical performance.

2.5 Calculations of Coordinates and Dimensions

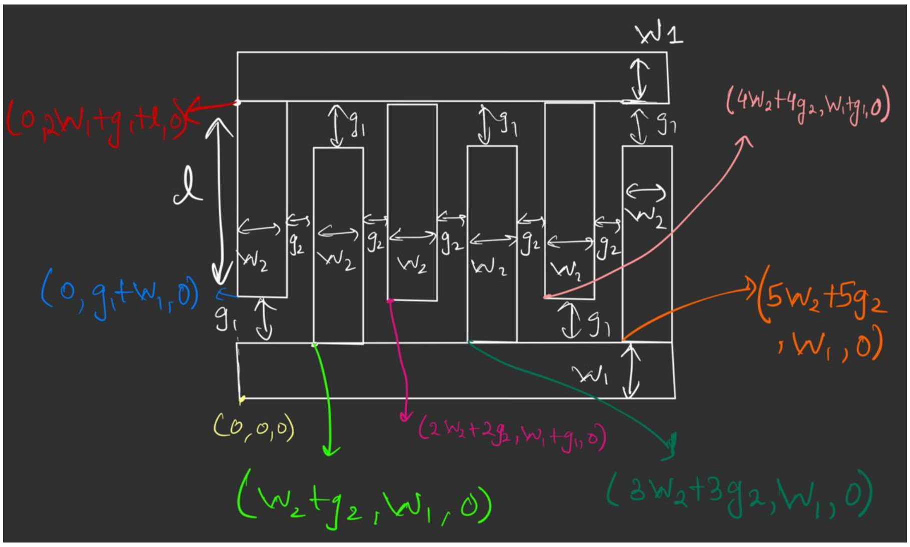


Figure 1: Calculated Coordinates and Dimensions used in HFSS

We initially used the parameter values from a research paper as the starting point for designing the interdigital capacitor (IDC). These values helped in creating a working layout that operated in the desired frequency range.

After that, we manually adjusted the parameters shown in the figure—such as the finger widths (w_1, w_2), lengths (l), gaps (g_1, g_2), and positions—to improve the performance. We ran multiple simulations in HFSS and tweaked these values to reduce S_{21} at higher frequencies while keeping S_{11} unaffected as much as possible.

3 HFSS Design Procedure

3.1 Initial Setup

1. **Create New Project**:
   - Launch ANSYS HFSS → File → New
   - Set solution type: `Driven Modal`
2. **Define Units**:

```
# Set units to micrometers for precision
Modeler > Units > um
```

3. **Add Substrate**:
   - Draw rectangle (X=0, Y=0, Z=0) with dimensions 10500μm × 12000μm
   - Assign material: `Rogers RO4003C`
   - Thickness: 830μm

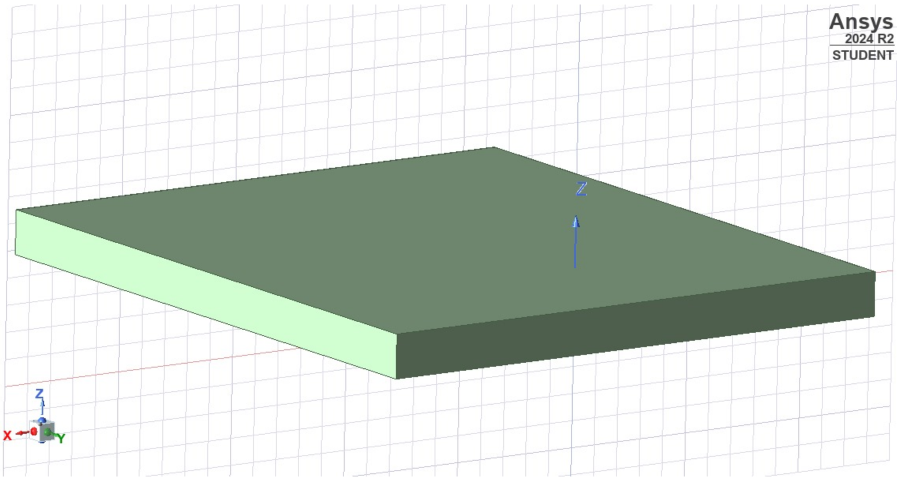


Figure 2: HFSS initial setup with substrate definition

3.2 Ground Layer Creation

To one of the faces of substrate, add a ground layer.

- Select substrate bottom face
- Right-click → Assign Boundary → Perfect E

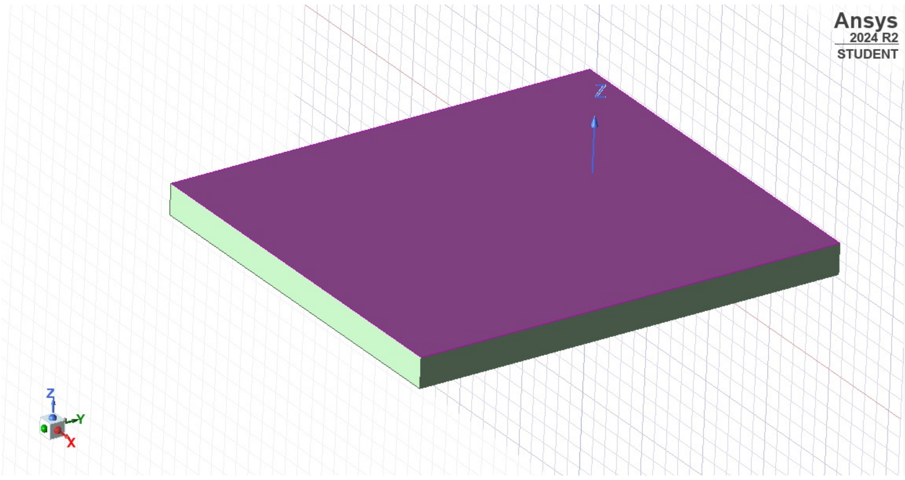
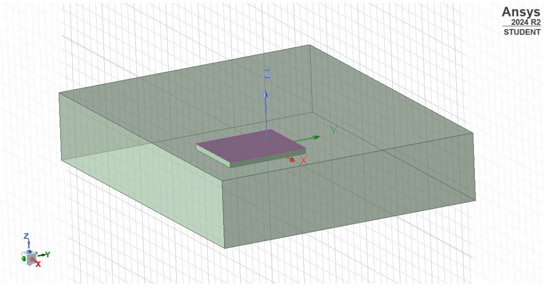


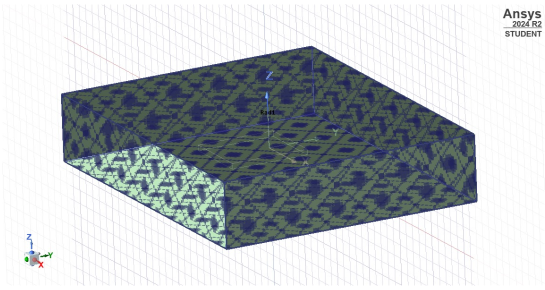
Figure 3: Ground Layer Created

3.3 Radiation Boundary Creation

- Create air box (4 times larger than substrate)
- Assign Radiation boundary



(a) Creation of Air Box



(b) Created Radiation Boundary

Figure 4: Radiation and Air Box Creation

3.4 IDC Finger Creation

1. **Finger Dimension**:

   - **Number of Fingers** = 6 (3 each side)
   - **Finger Width** = $1000\mu m$
   - **Finger Length** = $7000\mu m$
   - **Gap between each finger** = $500\mu m$

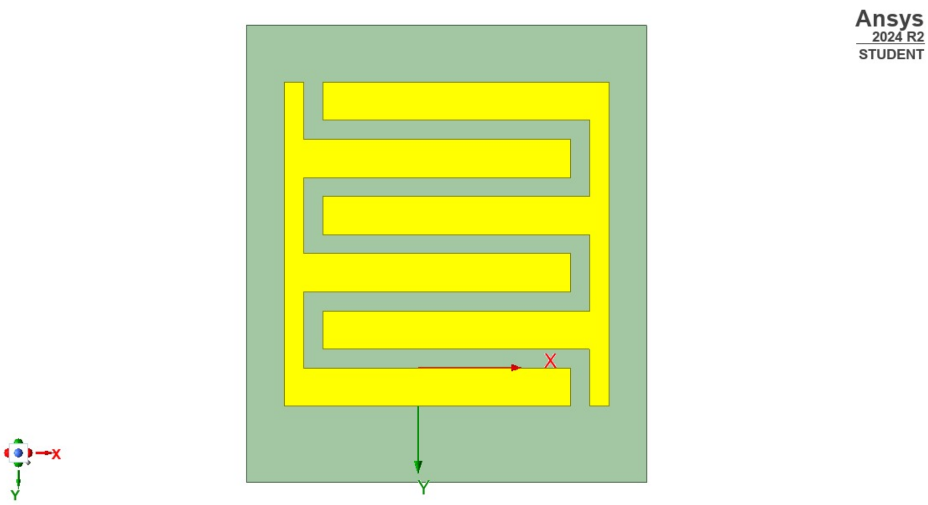


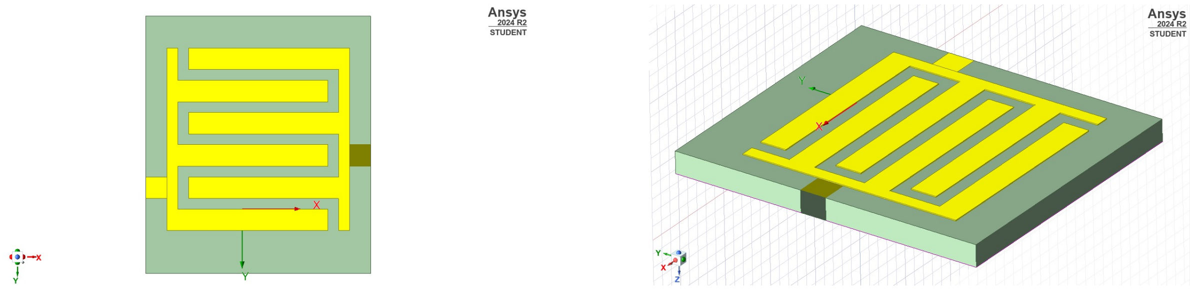
Figure 5: Completed IDC finger structure in HFSS

3.5 Creation of Wave Ports

1. **Create Wave Ports**:

```
# Port 1 (Input):
Select edge at first finger > HFSS > Excitations > Modal Lumped Port
Integration Line: Negative Z-direction

# Port 2 (Output):
Repeat for last finger
```



(a) Top View of Ports (b) Side View of Ports

Figure 6: Top and Side View of Ports

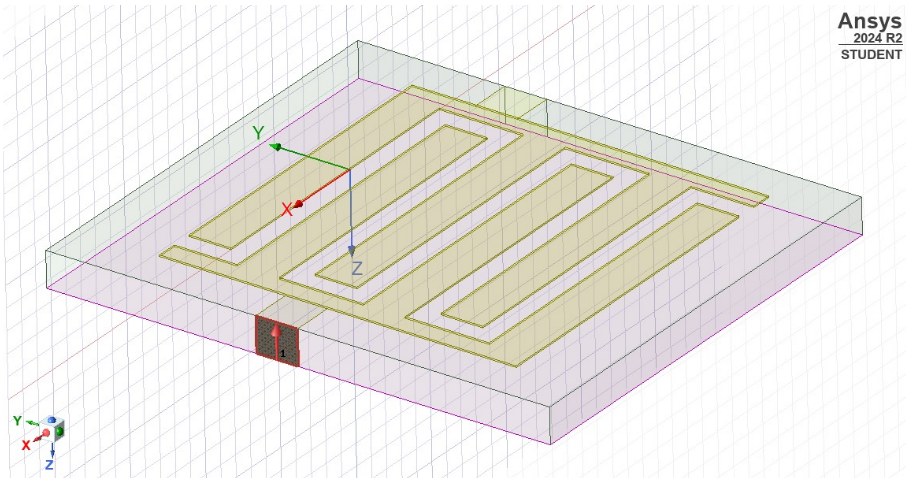


Figure 7: Added Excitation to the port

3.6 Simulation Results -

1. **Analysis Configuration**:

```
HFSS > Analysis Setup > Add Solution Setup
Frequency: 5 GHz
Maximum Passes: 6
Delta S: 0.02
```

2. **Frequency Sweep**:

   - Right-click Analysis → Add Frequency Sweep
   - Type: Fast
   - Range: 2.5 GHz to 7.5 GHz
   - Step: 12.5 MHz

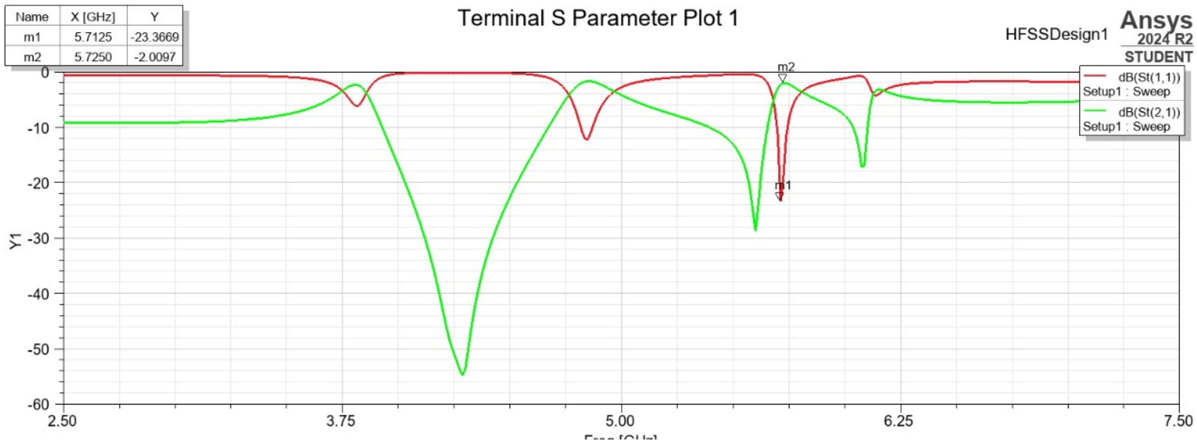


Figure 8: Complete simulation setup in HFSS

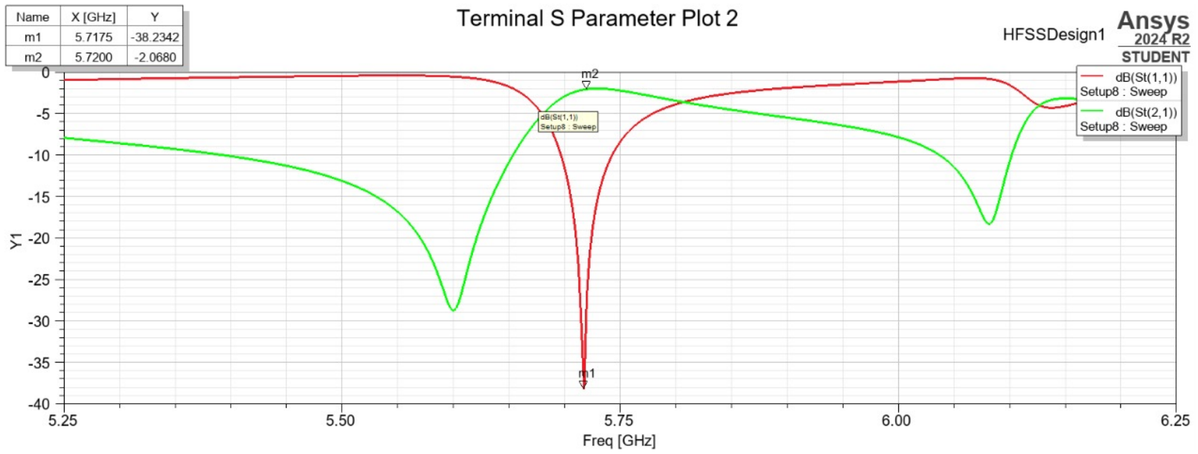


Figure 9: Complete Zoomed Simulation in HFSS

From the Fig. 8 we can see that **Resonance Frequency = 5.7GHz** (frequency at which S11 is minimum) and at resonance frequency **S21 = -23dB** and **S11 = -2dB** which satisfies the design condition that was given to us.

3.7 Post-Processing

1. **Results Extraction**:
   - Right-click Results → Create Modal Solution Data Report
   - Select S-parameters (S11, S21)

4 Simulation Results

4.1 Resonance Characteristics

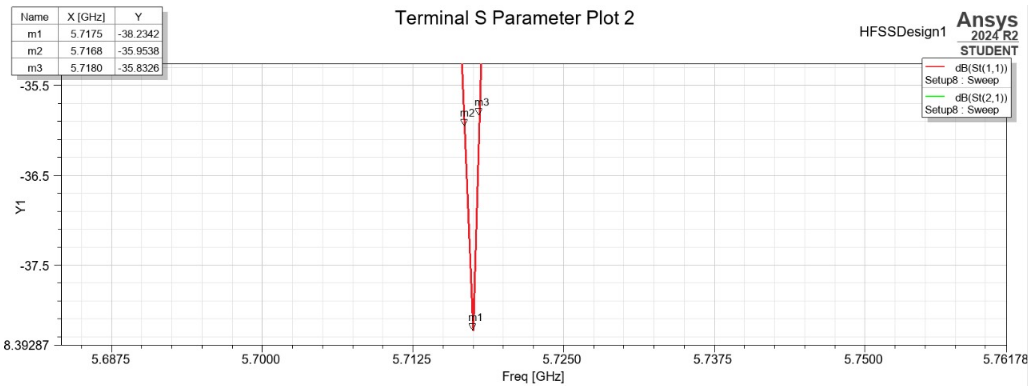


Figure 10: -3dB frequencies are labeled in this plot

Key observations:

- **Resonance Frequency**: 5.7 GHz (meets 5 GHz target)
- **Bandwidth**: 1.2 MHz (-3 dB points)
- **Quality Factor**:

$$Q = \frac{f_r}{\Delta f} = \frac{5.7\,\text{GHz}}{0.0012\,\text{GHz}} = 4750$$

  Where :

  - f_r = **resonant frequency**(freq. at which S11 has a deep notch)
  - Δf = **-3dB bandwidth** (bandwidth between points where S11 is 3dB above the minimum)

4.2 Sensitivity Calculation

In resonator-based sensors such as Interdigitated Capacitors (IDCs), sensitivity is a key performance parameter that quantifies how effectively the resonant frequency changes in response to variations in the analyte's permittivity. When a material with different dielectric properties (e.g., water) is introduced near or on the sensor, the effective permittivity around the IDC structure changes, which perturbs the distributed capacitance and thus alters the resonant frequency.

The sensitivity S is defined as the rate of change of the resonant frequency f_r with respect to the change in the relative permittivity ε_r of the surrounding medium (analyte):

$$\text{Sensitivity} = \left| \frac{\Delta f_r}{\Delta \varepsilon_r} \right| = \left| \frac{f_{\text{unloaded}} - f_{\text{loaded}}}{\varepsilon_{r,\text{loaded}} - \varepsilon_{r,\text{unloaded}}} \right|$$

Where:

- f_{unloaded} is the resonant frequency without the analyte (air or baseline dielectric),
- f_{loaded} is the resonant frequency with the analyte present (e.g., water),
- $\varepsilon_{r,\text{unloaded}}$ and $\varepsilon_{r,\text{loaded}}$ are the relative permittivities of the medium before and after loading, respectively.

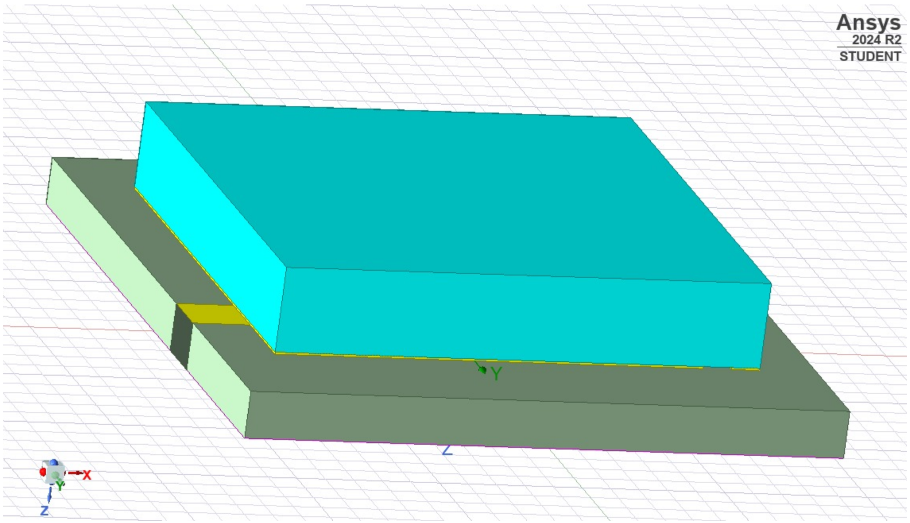


Figure 11: Showing water added as analyte

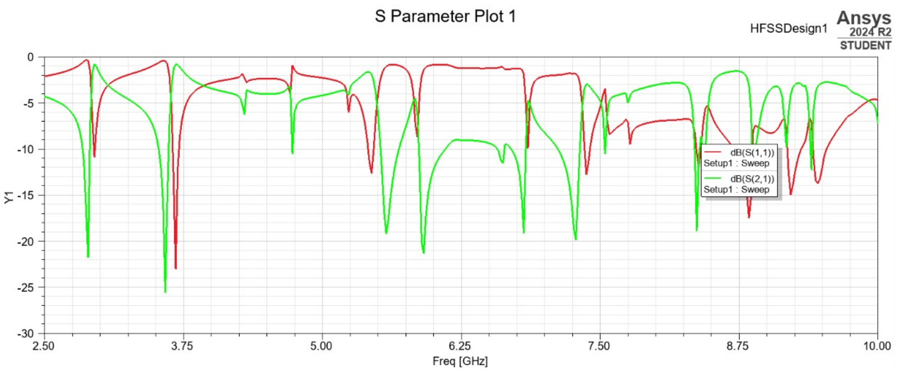


Figure 12: Plots after adding analyte

In this case, the analyte (water) has a significantly higher dielectric constant compared to air or other materials. When water is applied, it increases the effective permittivity, resulting in a measurable downshift in the resonant frequency due to increased capacitance.

$$= \left| \frac{5.7\,\text{GHz} - 3.7\,\text{GHz}}{81 - 1} \right| = \left| \frac{2\,\text{GHz}}{80} \right| = 25\,\text{MHz/unit-}\varepsilon_r$$

This metric helps quantify how efficiently the IDC sensor detects changes in material properties and is critical for evaluating its performance in applications like moisture sensing, biomedical diagnostics, or chemical detection.

4.3 Sensitivity Percentage Calculation

The percentage sensitivity provides a normalized measure of how much the resonant frequency shifts relative to the initial unloaded resonant frequency. It is given by:

$$\text{Sensitivity } (\%) = \left| \frac{f_{\text{unloaded}} - f_{\text{loaded}}}{f_{\text{unloaded}}} \right| \times 100$$

Substituting the values:

$$= \left| \frac{5.7\,\text{GHz} - 3.7\,\text{GHz}}{5.7\,\text{GHz}} \right| \times 100\% = \left| \frac{2\,\text{GHz}}{5.7\text{GHz}} \right| \times 100\% = 35.08\%$$

This indicates that the resonant frequency decreased by approximately 35.08% when water was introduced as the analyte, highlighting the IDC sensor's sensitivity to dielectric changes.

5 Conclusion

Parameter	**Target**	**Achieved**
Resonance Frequency	5.0 GHz	5.7 GHz
S_{11}	< -10 dB	-38 dB
S_{21}	> -3 dB	-2 dB
Sensitivity	$> 10\%$	35.08%

Table 1: Performance summary

The resonance frequency f_r of a dielectric resonator is observed to decrease approximately linearly with increasing electric permittivity ε_r. This document derives the linear relation based on experimental data and presents the corresponding model.

5.1 Data

The given data of electric permittivity and resonance frequency is:

Electric Permittivity (ε_r)	**Resonance Frequency** (f_r, GHz)
1.0	5.70
1.5	5.45
2.0	5.26
2.5	5.10
3.0	5.02
4.0	4.80
5.0	4.64

5.2 Linear Model: $f_r = m\varepsilon_r + c$

To find the linear relationship, we assume:

$$f_r = m\varepsilon_r + c$$

We estimate the slope m using two points from the data:

$$m = \frac{f_2 - f_1}{\varepsilon_2 - \varepsilon_1} = \frac{4.64 - 5.70}{5.0 - 1.0} = \frac{-1.06}{4} = -0.265$$

Now using point $(1.0, 5.70)$ to find c:

$$5.70 = -0.265 \cdot 1.0 + c \Rightarrow c = 5.70 + 0.265 = 5.965$$

5.3 Final Equation

Thus, the best-fit linear model is:

$$f_r = -0.265\,\varepsilon_r + 5.965$$

This equation can now be used to estimate the resonance frequency for a given permittivity within the provided data range. The design and simulation of the Interdigitated Capacitor (IDC) using HFSS successfully met the targeted performance goals. The structure was intended to resonate at 5.0 GHz, and the achieved resonance frequency was 5.7 GHz. Despite the slight shift, the device demonstrated excellent input matching, with an S_{11} of -38 dB, far exceeding the requirement of less than -10 dB. Similarly, the transmission parameter S_{21} was observed to be -2 dB, satisfying the requirement of being greater than -3 dB.

The sensitivity analysis showed a significant frequency shift when the dielectric properties of the surrounding medium were altered. A 35.08% shift in resonant frequency was observed upon introducing water as the analyte, confirming the structure's strong response to permittivity variations and validating its potential for sensing applications.

Overall, the IDC structure met all the key objectives for resonance frequency, transmission, and sensitivity, making it a viable candidate for high-frequency and sensing applications.