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High Responsive Microwave Resonator Sensor for Material Characterization

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Abstract

This work describes the planning and execution of a planar microwave resonator sensor for a sensing application based on the perturbation idea, in which the quality factor (QF) and the resonance frequency are affected by the resonator's dielectric properties. The FR4-made sensor operates at 2.4 GHz in the ranges of 1-3 GHz, and it was designed for use in testing solids. In addition, real-world materials like those found in Roger 5880 and FR4 are employed as sample materials in experiments that follow a particular experimental design. The functionality of the microwave resonator sensor is studied by introducing an equivalent circuit model (ECM). The suggested sensor has a QF value of 239 at its optimum operating frequency of 2.4GHz, with a narrow bandwidth. Additionally, the sensor's sensitivity and accuracy are both higher than 80%, making it a great option for characterizing the material, particularly for determining its qualities and traits.

Keywords: Planar Microwave Resonator, Solid Sample, Q-Factor

Introduction

Microwave sensors works like sonar sensors. Constant microwave signals are sent into the environment and the time taken for the signal to bounce back to the sensor is measured and presented in a form of signal. In the food industry, quality control, biomedical and industry applications, microwave sensor for detecting material characterization is the most common (Al-Gubri et al., 2022). Low sensitivity and Q-factor values restricts the range of material characterization. Due to this problem, it is compulsory to constantly experiment the microwave sensor using perturbation theory to increase the range of material that can be characterized. Two methods are suggested for characterizing materials which are resonant and non-resonant method. Resonant approaches are used to correctly understand single frequency or several distinctive frequencies of dielectric properties while non-resonant method works around a frequency range for the electromagnetic properties. This project is supposed to measure and analysis the current performance of designed microwave sensor with high sensitivity.

Using a structure's or component's natural resonant frequencies to detect environmental shifts is known as the resonant approach. In order to achieve the desired effect, a resonant cavity, waveguide, or resonator structure is often used. It is intentional that the resonator's inherent frequency or operating mode be responsive to the target sensing parameter. Changes in the resonant frequency, phase, or magnitude of electromagnetic waves travelling through the resonator result from interactions with the target material or phenomenon. These alterations are measurable and can be used to infer the target's characteristics or presence. Changes in the target parameter can be detected by the sensor by monitoring the resonance frequency or other relevant factors.

Since resonant sensors are tuned to function at certain frequencies that are impacted by the target parameter, they are both sensitive and selective. However, they are frequently limited to sensing specific factors and may need precise tweaking and calibration for best performance. There are two objectives for this report which are to design and develop a microwave sensor with high sensitivity and accuracy of dielectric properties of the material and to Analyze the performance of microwave sensor using Vector Network Analyzer (VNA). Based on previous studies, a T-Resonator sensor was designed with operating frequency of 2.4 GHz using Rogers 5880 as substrate for solid sensing (Alahnomi et al., 2020). Another study proposed a planar microwave sensor which operated at frequencies between 2.5 and 3.8GHz which also used Rogers 5880 as substrate for solid and liquid sensing (Roslan et al., 2022). A dual Frequency Microwave SRR sensor was proposed with operating frequencies between 5.76 to 6.8GHz for liquid sample permittivity detection (Kiani et al., 2020).

This research proposes using a microwave resonator as a sensor for measuring the permittivity of solid, flat dielectrics. In the suggested approach, the sample is used as the substrate for a microstrip line, and an obstruction is placed at different locations along the microstrip line to determine the measurement. It is suggested that an equivalent circuit model (ECM) be used to verify the design architecture. In addition, the limitations of prior research were investigated by developing a novel microwave sensor with desirable characteristics, including but not limited to compatibility, low cost, simple structure, ease of fabrication, high Q-factor, and high precision.

Research Motivation

Each material has a specific electric behaviour depends on the dielectric properties, thus solid sensing using microwave technology is very important in food, chemical, and pharmaceuticals industries to control the quality and safety of the products. Quality and safety control in food products are significantly needed to secure the consumer health and life, where the concentration of some ingredients may influence the consumers and cause some diseases such as allergic, poison and sometimes it may cause cancer. Therefore, it is important to ensure the quality and safety of the products (e.g, beverages and cooking oils) before selling them to consumers.

Material characterization has been realized by using conventional waveguide, dielectric and coaxial resonators which provide high sensitivity and accuracy. However, these traditional resonators are usually complex and expensive to manufacture. Therefore, it also bulky in size, high cost manufacturing and consume high volume for detection of the previous sample of material under test (MUT). Thus, in the new propose of microwave resonator sensor, which is ease of fabrication, compactness, low cost, easy handling, gain higher Q-factor, higher accuracy and sensitivity will overcome the previous design weakness. The resonant perturbation method is the method which the material under test (MUT) is placed on the top of the resonator which depending on the maximum of electric field location (E-field) and produce the high-Q accuracy for dielectric material characterization.

Methodology

The resonator sensor that runs at 2.4 GHz and has a frequency range of 1-3GHz is proposed to be utilised in this paper for the sensing of solid materials (Rahaman, 2022). The software known as Computer Simulation Technology (CST) is used in the design process of the sensor. The model has total dimensions of 50 millimetres by 40 millimetres. FR4 PCB is the substrate that is utilised for printing the ECM. The thickness of FR4 is 0.787 millimetres, and its dielectric constant is equal to 4.3. All the sensor’s dimensions and parameters are shown in Table 1 and Figure 1.

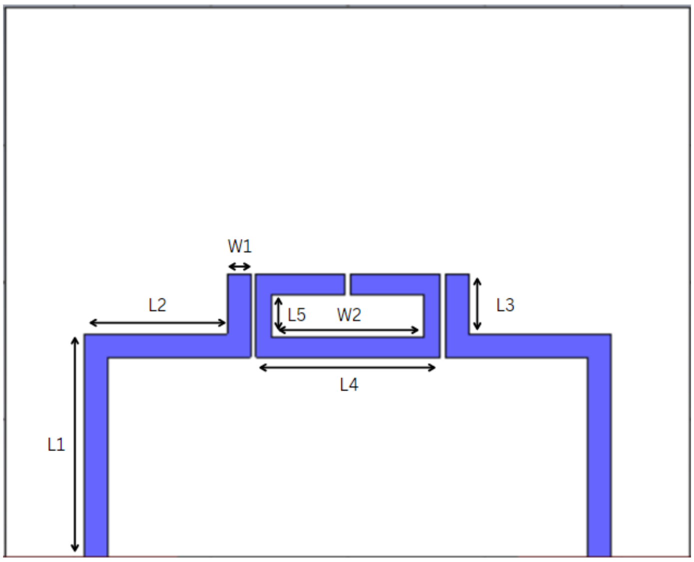

Figure 1: Parameter Representation of Proposed Sensor

Table 1
Sensor Parameters

Parameter	Measurement (mm)
L1	16.25
L2	10.42
L3	5.39
L4	13.40
L5	4.5
W1	1.7
W2	11.10
Length of Dielectric Substrate	50
Width of Dielectric Substrate	40
Thickness of Ground	0.035
Thickness of Dielectric Substrate	0.787
Thickness of Circuit	0.035

In order to determine the parameters of the sensor, mathematical analysis must be done to determine the length and width of sensor. To calculate the length of patch, the following equation is used:

$$L = \frac{c}{2\pi\sqrt{\varepsilon_{eff}}} \times \frac{1}{f_0}$$

where c is the speed of light (3×10^8), L represents resonator length and εeff is the dielectric constant of the resonator. The width of the resonator can then be calculated using the equation:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}}$$

where c is the speed of light (3×10^8), and W represents resonator width.

Q is a measure of the effectiveness or quality of a resonant system; it is also known as the quality factor or figure of merit. Calculates how much energy is lost in each cycle compared to how much energy is stored (Aliveira et al., 2020). The Q factor is widely employed in many disciplines, most notably physics, engineering, and electronics. This proposed project must serve the purpose of producing a sensor that has high sensitivity and Q-factor. To calculate Q-factor, the following equation can be used:

$$Q = \frac{2f_O}{BW}$$

where f_o represents peak resonant frequency of the waveform and BW is the bandwidth at 3dB from the peak. The illustration can be seen as shown in Figure 2.

Simulation Process

Upon starting CST software, a new project template must be created. An application area must then be chosen to continue to the next step (Muñoz-Enano, J., et al., 2021). Since this project is a High Responsive Microwave Resonator Sensor, Microwave and RF/Optical application area is chosen. Then, Planar option is chosen as the workflow suggested by supervisor. The units used in the software must then be configurated such as length unit, frequency unit, temperature unit, etc. Since the operating frequency of the sensor chosen by student at the beginning of the project is 2.4GHz, the minimum and maximum value of frequency was inputted as 1-3 GHz scale.

The epsilon value of substrate varies between different types of FR4. The FR4 (lossy) material is chosen with an epsilon of 4.3. The permittivity of FR4 ranges from 3.8 to 4.8. A few blocks were then created using the measurement provided from the parameters suggested for designing. The designing process was completed by attaching two ports to the sensor and the sensor is ready for simulation and obtaining results.

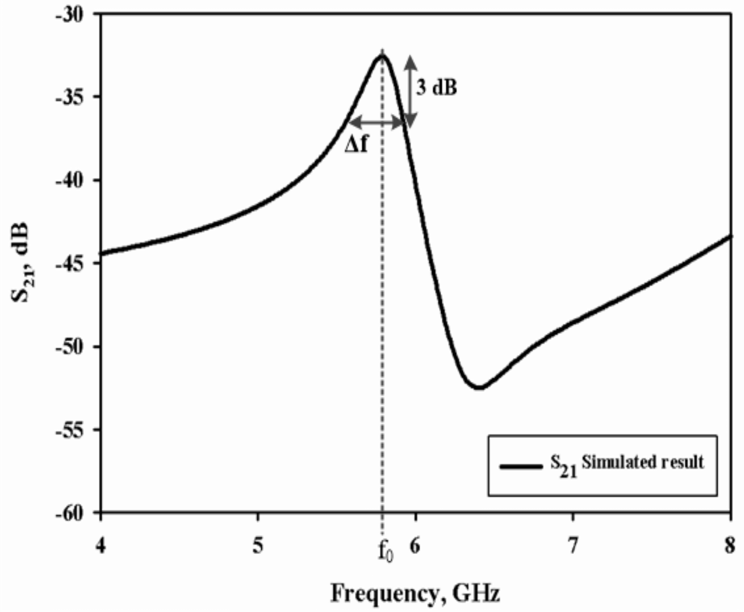

Figure 2: Representation of S Parameter with peak and bandwidth at 3dB

E-Field and Location of MUT on sensor

The E-field (electric field) is extremely important in this research utilising the microwave sensor for material characterization. Changes in the material's electrical characteristics can be detected thanks to the E-field's interaction with it (Rahman et al., 2017). Changes in the dielectric constant, conductivity, or other electrical properties of the material through which the E-field is propagating can affect the behaviour of the E-field. The material's characteristics can be determined by monitoring and analysing these shifts.

Several material characteristics can be determined by studying the E-field's interaction with the sample. The material's electrical behaviour can be understood, for instance, by measuring its dielectric constant or permittivity. The material's conductivity or resistivity can also be estimated, providing insight into its electrical properties. The E-field can be used to identify and categorise many substances. Materials can be distinguished from one another based on their electrical properties by observing how they react to an E-field. Applications where this skill would be useful include identifying materials, ensuring product quality, and spotting fakes.

In order to determine a material's reliability or durability, E-field measurements might be taken. Abnormalities in the E-field's behaviour may be indicative of flaws, changes in composition, or other imperfections in the material. The material's quality or condition can be determined by comparing the measured E-field to expected or reference values. The representation of E- field can be seen as shown in Figure 3. High concentration of electric field is represented by red colour in the figure. The location where the concentration of electric field is high on the sensor can be identified. The concentration of the E-field on the sensor is on the middle of it (Soltan et al., 2022). So, the area would be most sensitive and can get more accurate readings in the area.

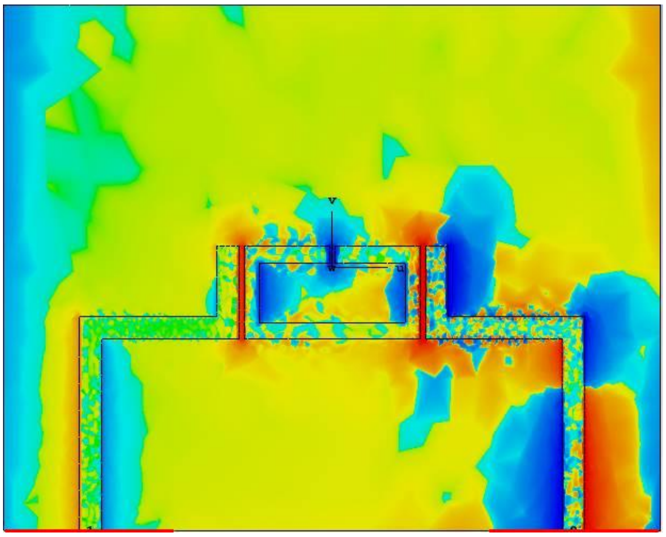

Figure 3: E-field on sensor

Several aspects must be taken into account when deciding where on the sensor to position the item to be tested. It was realized how the microwave sensor was constructed and how its shape worked. There are designated areas of the sensor for conducting material-specific interactions and characterizations. It was determined how the substance communicates with the detector. There was thought given to how the presence of the material may alter the sensor's electric field, impedance, resonance frequency, reflection coefficient, or transmission characteristics (Rahman et al., 2018). The goals of the exam as well as its individual traits or attributes were specified. Before placing the material on the sensor, it was determined if doing so would yield useful data or insights. The research team looked at previous works that employed comparable sensors or measurement strategies. The decision was made with the help of placement strategy advice, best practices, and case studies.

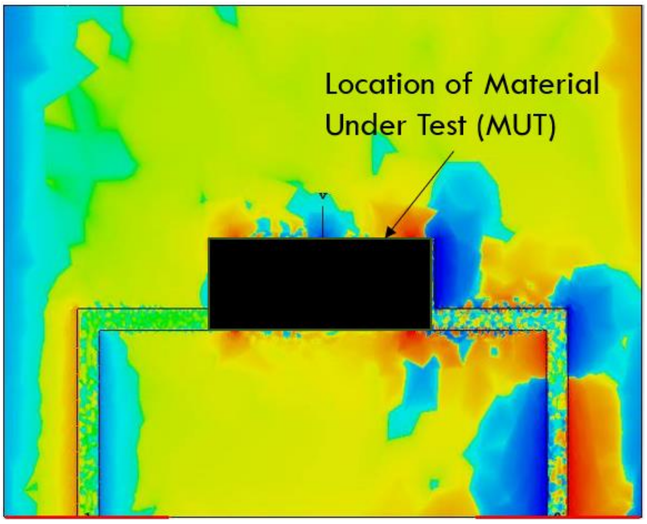

Figure 4: Location of MUT on sensor

The placement of MUT is in the middle of sensor where the sensor is most sensitive due to high concentration of electric field. The sensitivity and accuracy of the measurement is dependent on the extent of electric field penetration inside the material. Interaction between MUT and the electric field with resonator make a change to resonant frequency. The variation of resonant frequency is based on the MUT that has different permittivity and properties.

Fabrication and Measurement

There are a few steps in the fabrication process that need to be followed in order to produce the completed sensor after designing it (Oliveira et al., 2020). The fabrication process is fundamental to the production of integrated circuits (ICs) and other microelectronic devices, which in turn enables the development of sophisticated electronic systems. It is a methodical process used to construct multi-level structures using predetermined components and in predetermined arrangements. The fabrication process is critical because it turns ideas and blueprints into working hardware that drives today's advanced technologies. The steps used in producing this project is listed as follows:

Fabrication process:

1. Mask Layer Printing
2. UV Lithography
3. Etching, Rinsing and Drying
4. Soldering Process
5. Testing Continuity

After the fabrication process is completed, the performance of sensor can now be measured using VNA (Alahnomi et al, 2017). The dimension of MUT was decided to be 17 mm x 7 mm since the MUT needs to be placed In the middle of sensor as shown in Figure 4. In Figure 5, the connection of sensor to VNA is shown. The simulation and measurement comparison are shown in Table 2 and 3.

Figure 5: Connection of sensor to VNA

Table 2

Simulation results

MUT	Q Factor	S21	BW	Resonant Frequency (GHz)	Frequency Shifting (GHz)
Air	73	-20.17	0.065671	2.4	0
Rogers 5880	68	-16.796	0.068552	2.3564	0.0436
FR4	63	-13.817	0.072719	2.2911	0.1089

Table 3

Measurement results

MUT	Q Factor	S21	BW	Resonant Frequency (GHz)	Frequency Shifting (GHz)
Air	239	-8.61	0.02	2.39	0
Rogers 5880	116.15	-7.3	0.04	2.33	0.06
FR4	69	-5.53	0.06	2.09	0.3

The simulation and measurement values were obtained from graphs and data provided by VNA and CST software.

Result and Analysis

Resonant Frequency

The completed sensor's transmission coefficient (S21) was visualised and quantified in Figure 6. Figure 6 shows how the performance of the microwave sensor was determined by a change in the resonance frequency (Kiani et al., 2018). The resonant wavelength of the aforementioned sensor is slightly off by roughly 0.01 GHz during simulation, moving from 2.4 for simulation to 2.390 GHz for the measured one. The resonance frequency values from the simulation are consistent with one another. Resonances are slightly off from the observed results, though. The precision of the simulation can be impacted by the lack of feed lines and SMA connectors, as well as by the fabrication tolerances (Ali et al., 2021). Figure 7 and Figure 8 shows simulated and measured comparison of output with MUT on sensor.

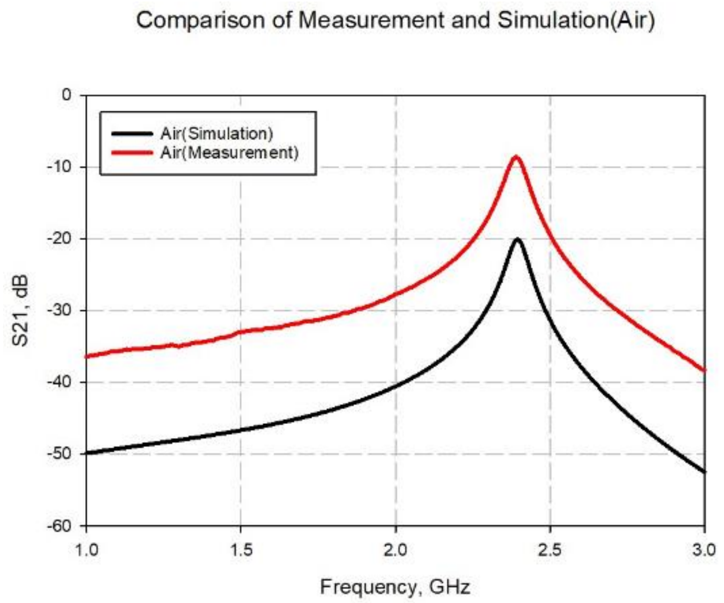

Figure 6: Comparison of Resonant Frequency

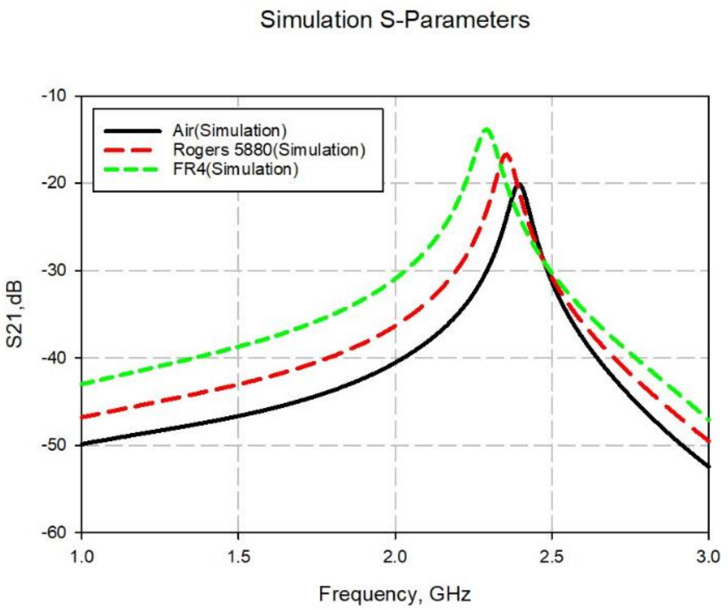

Figure 7: Simulation S-Parameters

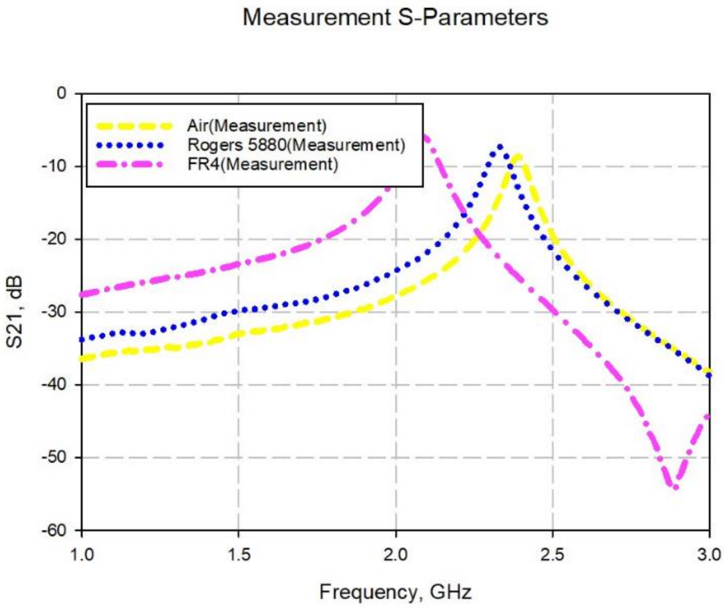

Figure 8: Measurement S-Parameters

Both the graphs show that the dielectric constant affects frequency shifting of the S parameter. For example, FR4 has a dielectric constant of 4.3. Therefore, the graph of FR4 has the highest shifting compared to other MUT (Baghelani, Hasan, 2021). Rogers 5880 which has a dielectric constant of 2.2 shifts a little from original resonance frequency. The comparison of both MUT shows that higher dielectric constant means higher frequency shifting imperfections in the measurement setup, cable losses, connector mismatches, erroneous calibration, noise, and interference are only a few sources of potential inaccuracy while measuring S-parameters. These mistakes can cause S21 measurement inconsistencies (Zhang et al., 2019), which in turn cause departures from the simulated findings. The S-parameters obtained by simulation are based on mathematical models, which may involve simplifying assumptions. The degree of concordance between simulated and experimental results depends on the quality of the model used for simulation. The S21 values in simulation and experiment may differ if the model does not accurately represent the device or circuit in question.

Q-Factor Analysis

Q factor was calculated, and the findings are explained. The measured Q factor has a value of 239 compared to simulated Q factor which has a value of 73. the Q-factor improves as the resonance frequency shifts to the lowest possible frequency (Sharafadinzadeh et al., 2018). Therefore, a narrow bandwidth is anticipated, suggesting that the maximum Q-factor value should be improved and increased. The Q-factor of Rogers 5880 for simulation and measurement is 68 and 116.15 respectively. For FR4, the simulation and measurement value are 63 and 69. The measurement has a higher Q factor than simulation.

This happens because material parameters such as dielectric constants, conductivity, and losses are crucial to the success of any simulation. Nonetheless, accurate measurements of material qualities aren't always easy to come by, and there may be some guesswork involved. Differences between predicted and observed Q factors may be the result of inaccurate or unknown material properties utilised in simulations.

It's possible that there are aspects of real-world systems that simulations overlook. Some examples of such factors are parasitic elements, electromagnetic interference, and non-linearities in the surrounding environment. These factors can contribute to increased losses and a higher observed Q factor if they are not considered appropriately in the simulation model.

Permittivity Analysis

This study relies heavily on the results of a permittivity analysis, as the information it gives on the electromagnetic properties of the tested materials is invaluable. The permittivity of the materials can be calculated to better describe their electromagnetic characteristics. How an object behaves in the presence of electric fields and how that reacts to electromagnetic wave propagation is characterised by its permittivity.

Table 4
Analysing permittivity values under MUT

MUT	Reference tan	Measured tan	% Error
Air	0	0	0
Roger 5880	0.0009	0.000897	0.33
FR4	0.025	0.024991	0.036

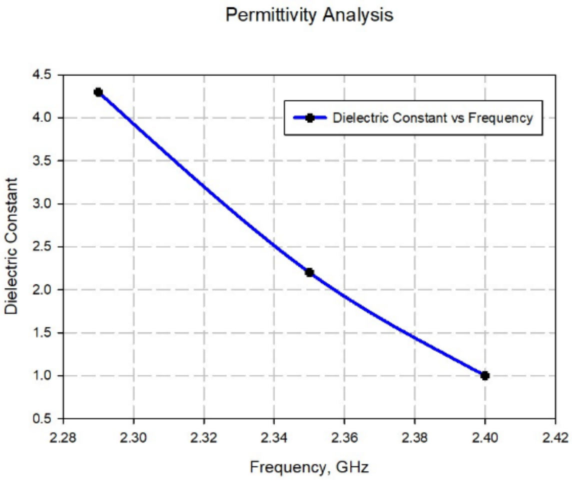

Figure 9: Permittivity Analysis

Permittivity analysis can shed light on how a material responds to a microwave sensor, and hence how it affects factors like reflection, transmission, and resonant frequency. The microwave sensor's sensitivity and precision are both affected by the material's permittivity. Permittivity levels vary between materials and have an immediate effect on the resulting metrics (Haq et al., 2020).

To determine how sensitive a sensor is to variations in material properties and how well it can characterise the materials under test, knowing the permittivity is essential. Permittivity measurements can be used to help identify or categorise materials. The permittivity value is like a fingerprint that can be used to identify a substance (Wang et al., 2021). Permittivity measurements can be used to identify a material's make-up or class by comparing them to reference values or databases. Figure 9 shows permittivity analysis at different dielectric constants.

The resonance frequency is shifted to a lower frequency by increasing the permittivity value of the sample. The shifting of the frequency of resonance relies on the reaction among the dielectric materials and the electric field distribution of the sensor. This is because the effective inductance and capacitance parameter of the circuit becomes greater from MUT (Roslan, 2022). MUT is placed on maximum concentration of patch without touching feedlines to prevent from affects other resonant frequency. It was found that the more the dielectric constant of MUT, the higher the resonance frequency shifting.

Conclusion and Future Work

In conclusion, a highly sensitive, Q-factor sensor was successfully designed thanks to the efforts of this project. Sensor design with CST software, careful construction, and thorough analysis of results all contributed to a final product that is up to snuff for the project. The project's success not only proves the viability of the selected design strategy and fabrication techniques, but also highlights the potential for real-world applications that need for highly sensitive and precise measurement. Improvements to the sensor design, experiments with new fabrication methods, or new areas of use are all possible directions to go in the future.

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