Design and Optimization of Periodic Structures for Electromagnetic Wave Manipulation

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Abstract

This research presents the design, simulation, and characterization of novel resonator structures based on the principles of coupling electric fields using periodic metamaterial-inspired configurations. These resonators are meticulously crafted to harness electromagnetic wave phenomena through the implementation of different periodic structures. It also tries to derive the relation of complementary split ring resonators with microstrip transmission line antenna. Design parameters of the micro-strip transmission line are also discussed in this study, where, effective permittivity, input impedance, height and width of microstrip transmission line were optimized. The periodic structures have different configurations keeping in mind the parameters like surface area, number of slit and loops. Five such structures were simulated which consist of Double Square, Double Circular, Square-Circular, Arrow, and Diamond shaped CSRR. It was observed that the structure with diamond shaped periodic structure is optimal for employing these devices as sensors because of highest quality factor (Q) of 181 and smallest full width at half maximum (FWHM) value of 0.02. These structures were then employed with a slit/gap to study the devices behavior for sensing a chemical moiety. Ethanol was sensed using these resonator structures and it was found that the CSRR with diamond shaped periodic structure showed sensitivity of about 189 MHz/μL of ethanol. The simulation results underscore the potential of these metamaterial-inspired resonators for applications in various fields of sensing including chemical sensing, biological sensing, physical sensing and many others. The achieved resonant frequencies and Q-factors signify promising advancements and optimization in the design of electromagnetic wave manipulation devices. This work contributes to the on-going exploration of metamaterial concepts in resonator engineering and offers insights into tailoring electromagnetic responses for specific applications.

Keywords

Sensors, resonator structure, explosive detection, machine learning, k-NN.

INTRODUCTION

In present time, utilization of sensors based on periodic structures is in huge demand. This is specifically because of their advantages in multi-parameter sensing with properties like high sensitivity, high quality factor, detection at very low concentrations, and very small recovery times. Researchers have demonstrated several types of periodic structures for achieving optimization of sensing parameters. Some of these structures work on the principle of antenna, when used as a sensing device (these devices are in general called as resonators). When the dimensions of these periodic structures are made very small, then they start showing the characteristics of a metamaterial. In other words, they start showing the properties like negative permittivity, negative permeability and also negative index of refraction in some cases. Sensors which utilize such properties are becoming increasingly popular as they have the benefits like label free detection, huge quality factor and sensitivity with real-time measurements. When we talk about utilizing a resonator structure (whose phenomena of operation is based on antenna) as a sensor device, there are several factors that must be optimized so as to achieve better performance in sensing. These factors include full width at half maximum (FWHM), resonant frequency or frequency of operation, overall dimension of the periodic structure, quality factor, and sensing efficiency or sensitivity.

There are several types of structure that researchers have demonstrated such as split ring resonators, double split ring resonators, complementary split ring resonators, double-faced split ring and complementary split ring resonators, cross-shaped resonators, and looped ring resonators [1]–[5]. All these structures have their own advantages when it comes to a specific type of application. The application where these different types of periodic structures are used for sensing varies from chemical sensing [6]–[8] to applications like biological sensing [9], [10], gas sensing [11], [12], alongwith physical sensing like position sensing [13], [14], crack detection [15], [16], and strain measurement [17].

Reported studies show that these metamaterials inspired sensors (antenna-based structures) shows changes in resonant frequency on the basis of interaction with external (moieties) changes or surrounding with electrical or magnetic field developed by transmission line present in sensor device.

In this work, we have used a simulation tool named COMSOL Multiphysics, version 5.6 for modeling of antenna with different periodic structures to be used as resonators. In this, we have used CAD Import Module, Design Module and RF Module for performing complete study. Although, there are multiple simulation tools using which researchers have performed simulation study like CST Microwave studio, HFSS, and others. But, there exist

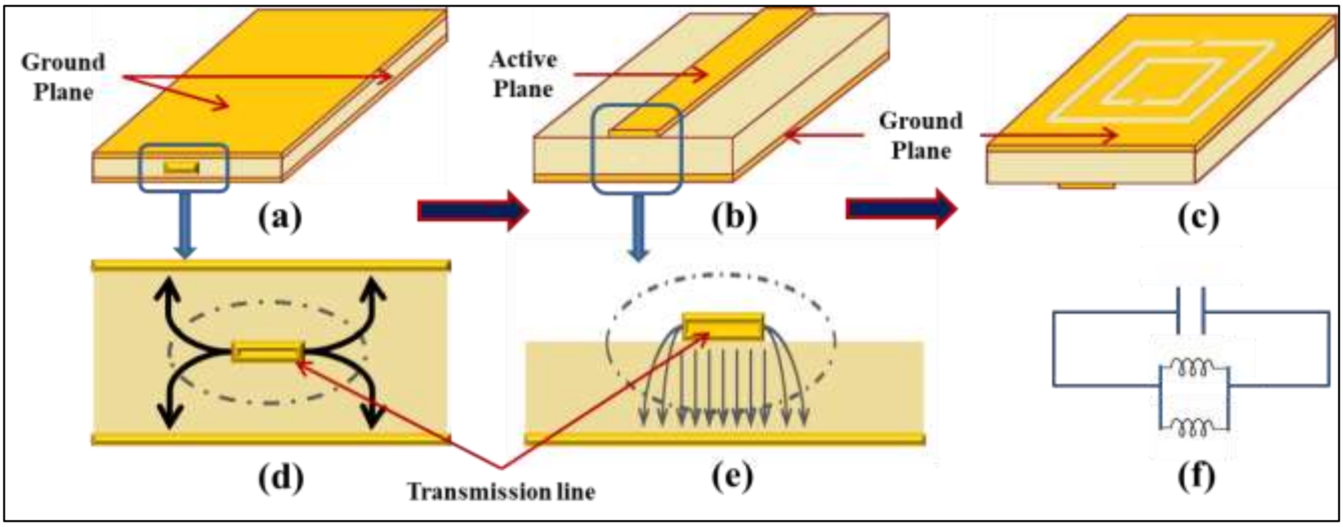

Figure 1: *(a) Stripline antenna structure with ground plane on both sides. (b) Microstrip line antenna with ground plane. (c) CSRR structure having periodic structure on ground plane. (d) Electromagnetic field distribution in stripline antenna. (e) Electromagnetic field distribution in microstrip line antenna (solid line- Electric field, dashed line- Magnetic field). (f) Electrical equivalent of a CSRR structure.*

no comparative study for sensing of ethanol using any of these software's for different types of periodic structures after optimization.

Table I: *Reported studies on resonator structures*

Ref.	Periodic structure	Resonant frequency	Frequency shift	Sensitivity
[18]	Hexagonal CSRR	8.28 GHz	920 MHz	11.11
[19]	Tilted metallic crosses	1.52 THz	200 GHz	13.157
[20]	CSRR	2.7 GHz	720 MHz	26.66
[21]	H-shaped resonator	9.38 GHz	520 MHz	5.54
[22]	CSRR	0.85 THz	70 GHz	8.235
[23]	A-G-MSRR/ C-G-MSRR	4.90 GHz/ 4.53 GHz	380 MHz/ 340 MHz	7.755/ 7.50
[24]	CSRR	2.54 GHz	170 MHz	
[25]	CSRR	2.65 GHz	285 MHz	10.7
[26]	Nested SRR	7.54 GHz	230 MHz	3.05
[27]	SRR	2.1 GHz	433 MHz	30.14

The benefit of using this simulation tool is that we can perform process simulation of the designed structure for sensing of different changes. Here, we have designed the periodic structures in such a way that the effective area of different periodic structure is almost equal. We have used five different types of periodic structures with complementary design on the ground plane for optimizing the sensor parameters. Further, we have simulated the structure in a way where we have introduced an engineered slit in between the periodic structure (ground plane) and the transmission line (active plane). In this engineered slit, we have introduced a chemical moiety (Ethanol) for observing the changes in resonant frequency, quality factor, and other factors.

THEORY, DESIGN AND SIMULATION

The basic operation of metamaterial inspired structures is based on the phenomena of antenna. This is because the transmission line used in these structures is very similar to that of a micro-strip transmission line used in a patch antenna. As we can understand from Figure 1(a) in case of a stripline antenna, the transmission line is surrounded by same dielectric material from all the sides. This type of sandwich structure results in a transverse electromagnetic (TEM) mode of propagation as there exists no mismatch of velocity of propagation along both the sides of micro-strip transmission line. Now, if we observe the micro-strip line in Figure 1(b), we can see that one side of the transmission line is high dielectric material while other side is air with low dielectric value. Because of this difference in dielectric, there is a mismatch in the velocity of propagation at the interface of dielectric material and air. This results in a quasi-TEM mode of propagation, where most of the electric field line gets located along the dielectric material and very small radiation happens in the direction of air medium. This operation is nearly opposite to that of a micro-strip patch antenna where radiation is direction opposite to that of dielectric material.

The magnetic field lines generated by these transmission lines are in-plane of the direction of propagation while the electric field is in direction perpendicular to the direction of propagation. These generated electric field lines interact with the periodic structure fabricated on the ground plane and thus causes resonance of induced current on the conducting surface.

$$Z = \frac{60}{\sqrt{\epsilon_{eff}}} \ln\left[\frac{8h}{t} + \frac{t}{4h}\right] \ldots (2)$$

When, $t/h \geq 1$, then

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[\left(1+12\frac{h}{t}\right)^{-1/2}\right] \ldots (3)$$

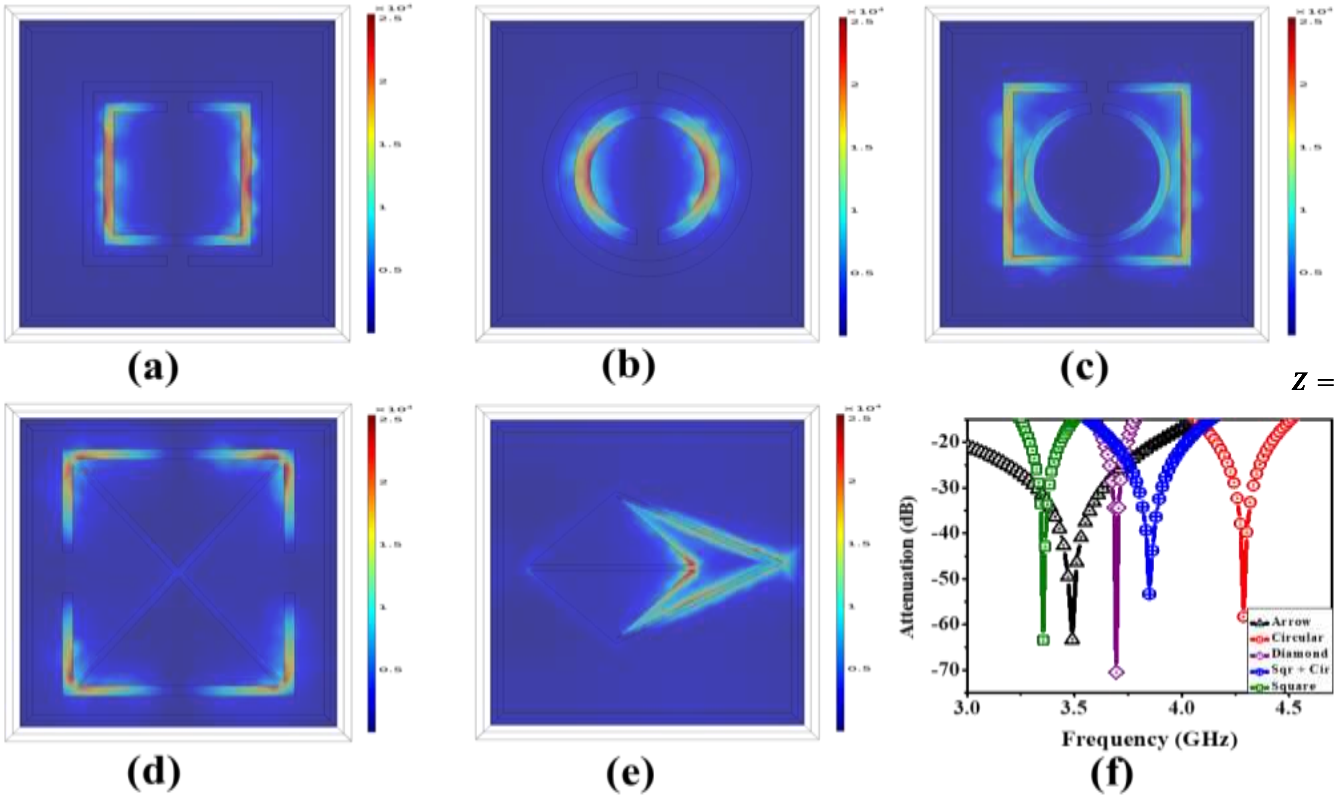

Figure 2: *Electric Field Distribution along the surface of (a) DS-CSRR, (b) DC-CSRR, (c) SC-CSRR, (d) A-CSRR, and (e) D-CSRR. (f) Transmission spectrum for different CSRR structures.*

When we start designing such type of resonating structures, the initial step is to optimize the micro-strip transmission line characteristics. There are several design considerations that must be taken care of while designing a micro-strip transmission line such that most of the electric field gets concentrated in the direction of dielectric substrate. This depends mostly on the dielectric value of the substrate as; higher the value of dielectric, higher will be the attenuation in the electric field along the transmission. The thickness of the substrate is of importance because thinner substrates allow the operation at high frequencies but also leads to higher losses along the medium. Some of the design parameters can be optimized by using the expression from (1) to (4) as listed [28]. Thus, appropriate selection of dielectric material, thickness of the substrate, and width of the microstrip transmission line plays a crucial role for ensuring the propagation of dominant mode only.

Effective dielectric and characteristic impedance of microstrip transmission line depends on two conditions

When, $t/h \leq 1$, then

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[\left(1+12\frac{h}{t}\right)^{-1/2} + 0.04\left(1-\frac{t}{h}\right)^2\right] \ldots (1)$$

$$Z = \frac{120\pi}{\sqrt{\epsilon_{eff}\left[\frac{t}{h}+1.393+0.667\ln\left(\frac{t}{h}+1.444\right)\right]}} \ldots (4)$$

where,

'ϵ_r', is the relative permittivity of the medium, **'*h*'**, is the thickness of substrate, and **'*t*'** is the width of the microstrip transmission line.

Once the transmission line characteristics are optimized, then we move towards the optimization of resonant frequency of operation. This resonant frequency depends on the lumped parameters (inductance and capacitance) of the periodic structure etched over the ground plane. This can be given by the equation (5)

$$f_{resonant} = \frac{1}{2\pi\sqrt{L_{eff}C_{eff}}} \ldots (5)$$

Where, **'L_{eff}'** and **'C_{eff}'** are the effective inductance and effective capacitance of the lumped periodic structure.

Although, we have performed several studies and sensing applications [6], [7], [29]–[32] in past, but, in this work, we have designed five different types of periodic structures on the ground plane of the resonator. They are Double Square (DS-CSRR), Double Circular (DC-CSRR), Combination of Square and Circular (SC-CSRR), a Diamond (D-CSRR), and an Arrow (A-CSRR) shaped Complementary Slit Ring Resonator (CSRR), These structures include all types of configurations like single loop with single slit, single loop with double slit, and a combination of double loops with different types of structures consisting of square shape, circular shape, and both together. This work was done to understand the effect of different shapes so as to achieve optimized sensing performance in case of chemical/fluid sensing. COMSOL Multiphysics simulation software was used to perform the simulation of these antenna based resonant structures. The study/physics used for the simulation of these CSRR structures was “electromagnetics, frequency domain”. Figure 2 shows the electric field distribution of the simulated structures around the ground plane when the optimized microstrip transmission line was excited by radio frequency signal bearing 0 dB power. This microstrip transmission line was designed in such a way that the characteristic impedance stays around 50Ω.

Table II: *Design parameters for different CSRR structures.*

Type of CSRR	Surface Area (mm^2)	Number of Slit	Number of Loops
SC-CSRR	135.7	2	2
DC-CSRR	140.04	2	2
DS-CSRR	136	2	2
A-CSRR	143	2	1
D-CSRR	140.5	1	1

This impedance of 50Ω was achieved by using a Flame Retardant 4 (FR4) substrate with thickness of 1 mm and a permittivity of 4.33; also, the width of the microstrip was not more than 2.3 mm. Another parameter that was kept in mind was the overall etched area, which was intentionally kept almost same in all the structures. Other design parameters that were used for designing the periodic structures are overall surface area of the dielectric material, number of slits, and number of loops as shown in the Table II.

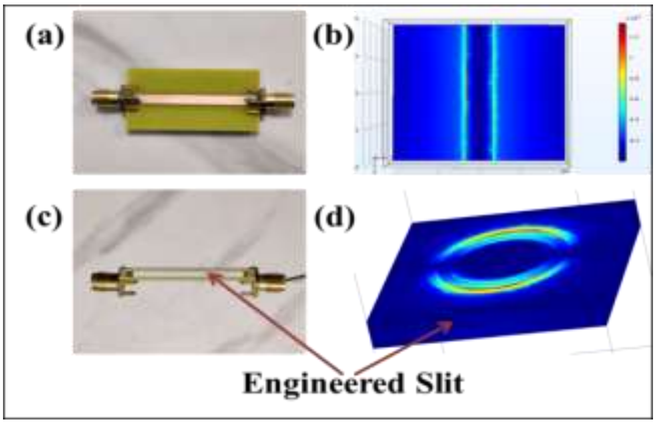

Figure 3: Fabricated sensor’s (a) Microstrip transmission line, (b) Electric field distribution in simulated microstrip transmission line, (c) and (d) Engineered slit in fabricated and simulated sensor structure.

RESULT AND PERFORMANCE ANALYSIS

Further, we also checked for sensing performance of all these CSRR models. This was performed by sensing ethanol liquid in the engineered slit between the microstrip transmission line and the periodic structure as shown in Figure **3**.

In this model, a gap was fabricated in between two FR4 substrates of 1 mm thickness with permittivity of 4.33. On one of the FR4 substrate, the microstrip transmission line was modeled while the periodic structures were modeled over the other FR4 substrate. The gap was fabricated such that the thickness of the gap was not more than 0.4 mm.

Sensing parameters that were analyzed during the study were FWHM, Quality factor (Q), and Sensitivity with respect to ethanol medium. The material properties for ethanol medium were; permittivity was taken to be 24, permeability as 1, and electrical conductivity to be zero. Results show that the structure with double loops were prone to broadening of the transmission spectrum and showed less quality factor; which is an essential parameter of any sensor. It was observed that the maximum shift of resonance frequency or sensitivity of 189 MHz/μL was observed in case of D-CSRR as shown in Table III.

Table III: Obtained sensor parameters of all CSRR structures.

Type of CSRR	Sensitivity (MHz/μL)	Quality Factor (Q)	FWHM
SC-CSRR	70	24	0.16
DC-CSRR	125	48	0.09
DS-CSRR	166	112	0.03
A-CSRR	180	93	0.33
D-CSRR	189	181	0.02

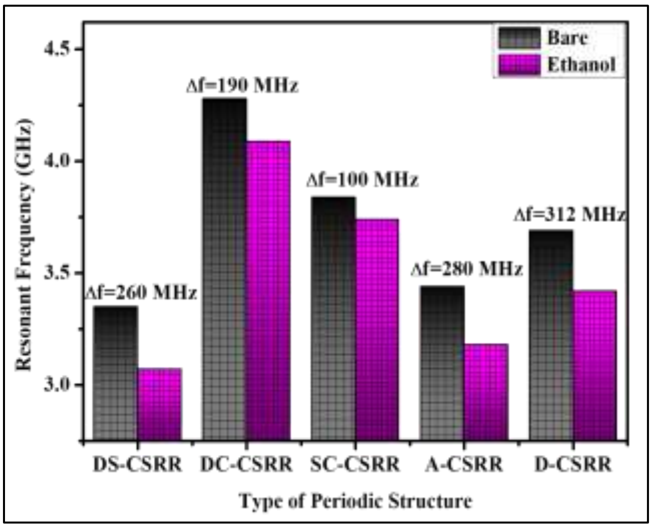

Figure 4: Difference in resonant frequency before and after sensing.

A-CSRR also showed high sensitivity of about 180 MHz/μL, although its quality factor and FWHM were not comparable to that of D-CSRR. Among the double looped periodic structures, the DS-CSRR showed highest value of sensitivity (166 MHz/μL) and quality factor (109) which was even higher than that of A-CSRR.

DS-CSRR also showed very small value of FWHM (0.03) which was very close to that of D-CSRR and this can be attributed to higher value of lumped capacitance in this periodic structure. Figure **4** shows the difference between the resonant frequency of different sensor structures before and after sensing ethanol. It can be seen that the shifts are comparable in case of DS-CSRR, A-CSRR, and D-CSRR. Overall, if we want a periodic structure for development of CSRR sensor, then the periodic structure with diamond shape and larger area of the slit is best suited, as this configuration gives the best possible values of sensitivity in our study.

CONCLUSION

In conclusion, several periodic structures are simulated and explored for optimization of sensor parameters. Five different types of periodic structures are designed, modeled, and simulated using COMSOL Multiphysics. During preliminary studies, it was observed that with increase in size or effective area for lumped electrical parameters, the resonant frequency of operation decreases exponentially. For this purpose, we have kept the effective area to be constant and concentrated over the design of the microstrip transmission line and periodic structure. The microstrip transmission line was designed such that its impedance is about 50 Ω and this was achieved by using the strip width of 2.3 mm. Further, it was seen that the resonator A-CSRR and D-CSRR having single loop showed higher values of quality factor and sensitivity when compared to double looped resonators. Among double looped resonators, DS-CSRR showed superior sensitivity and quality factor, which can be attributed to the higher values of its lumped electrical equivalent such as capacitance and inductance. The quality factor of A-CSRR was found to be smaller than that of DS-CSRR and this can be attributed to the presence of two slits in a single loop which led to broadening of transmission spectrum. In terms of FWHM, the best value among all these periodic structures was again shown by D-CSRR. Thus, it is concluded that among these five periodic structures, D-CSRR is the best resonator which can be used for various sensing applications.

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