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A Comparative Analysis of Hairpin Resonator and Split Cuboid Resonator

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Abstract --- In this study, an optimum design of hairpin resonator is being proposed. Design has been optimized by changing dimensions of a basic hairpin resonator in a manner so as to increase its sensitivity. Simulation in HFSS software was done to study effects on resonant frequency and quality factor with varying resonator dimensions. Three different polar liquids i.e distilled water, methanol and dimethyl sulfoxide, are used for sensitivity analysis. Introduction of these liquids into resonator gap results in perturbation of electric field. Shift in resonant parameters and their sensitivities is observed for these resonators with these liquids. The design in which maximum shift is obtained in these parameters was considered as optimized design. Optimized design resembled a cuboid with a split. This novel design is referred as split cuboid resonator. Results of both resonators are compared for validation of concept.

Keywords—hairpin resonator, split cuboid resonator, sensitivity, optimized, resonant parameters.

I. Introduction

Resonators have been used in many applications in electronic, pharmaceutical, biomedical, telecommunication industries. These resonators in various configurations include hairpin resonator [1], split ring resonator (SRR) or loop-gap resonator [2], split cylinder resonator [3] etc. These resonators are also used for material characterization and help in measuring complex permittivity and permeability in terms of resonant frequency, quality (Q) factor.

Hairpin resonator can be characterized as a variant of the wide microstrip line, which supports TEM travelling waves along its length. This type of resonator is obtained by bending a metallic strip at one end while the other end is left open [4]. Hairpin resonator resembles a short-circuited transmission line (TL) structure as shown in Fig. 1. It shows resonance and can be used in numerous applications [5]. Such a TL structure will exhibit resonance when its length is equal to the multiple of

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$1/4^{th}$ wavelength and an odd integer. Length l of hairpin resonator for resonance at a particular frequency should thus be equal to:

$$l = n\frac{\lambda}{4} \quad (n > 0) \tag{1}$$

where n is an integer, λ is wavelength of travelling wave and c is the speed of light. Resonant frequency for this structure is given as:

$$f_r = \frac{\omega_o}{2\pi} = \frac{v_p}{\lambda} = \frac{nc}{4l} \quad (n = 1,3,5 \text{ etc}) \tag{2}$$

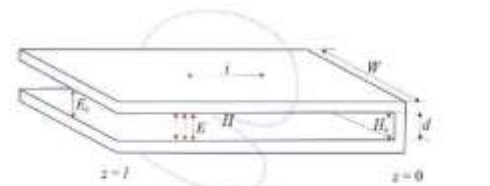

Figure 1. Hairpin resonator

In above figure, W is width, z is length, d is split/gap, E is electric field and H is magnetic field. So, fundamental resonance, mode (n=1), is given by:

$$\mathrm{f_r} = \frac{\mathrm{c}}{4\mathrm{l}} \tag{3}$$

Electric field strength E is maximum at the open-circuited end at resonance, denoted by E_o while magnetic field strength H is maximum at the short-circuited end at resonance, denoted by H_o.

Characterization of polar materials/liquids can be obtained by two significant microwave techniques, i.e., resonant methods and non-resonant methods [6]. Resonant method using resonators in different configuration, helps to explore composition of materials at discrete frequencies [6] while non-resonant method does that at broadband frequencies. Some of the advantages while using resonant methods include high accuracy and lower uncertainty. However, data cannot be obtained for continuous permittivity spectrum as this method provides data only at discrete frequencies [7]. Data related with compositional analysis and volumetric fractions of material under test (MUT) can be obtained using resonant parameters of resonant structure at discrete frequencies [8].

This paper discusses sensitivity enhancement of hairpin resonator. Fig. 2 shows a basic hairpin resonator enclosed in a shield. Sensitivity enhancement has been achieved by changing geometrical dimensions of this resonant structure. Sensitivity enhanced and optimized hairpin resonator resembled a cuboid structure with a split/gap as shown in Fig 3. Due to shape of this novel structure, it is referred as split cuboid resonator (SCR). Effects and analysis of geometrical variation in basic hairpin resonator are discussed in this work. These effects include shifts in resonant frequency, quality factor and sensitivity towards permittivity. These improvements can provide high resolution dielectric properties of MUT. Previously, sensitivity and accuracy of existing system were improved using a variety of structures including hairpin, dielectric, coaxial, split ring and split ball resonators [8, 9]. In this paper hairpin resonator and proposed SCR, enclosed in a shielding cavity, has been compared on the basis of sensitivity and parameters of resonant structures.

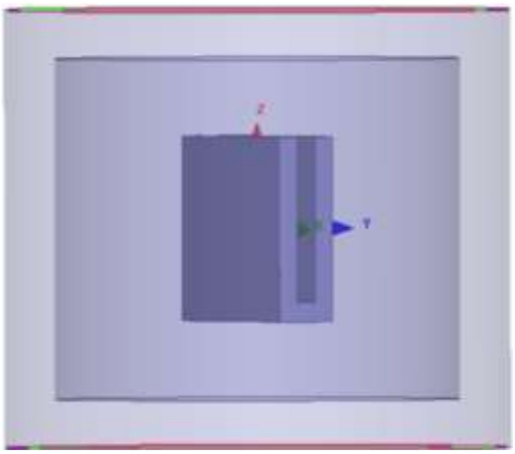
Figure 3. Hairpin resonator

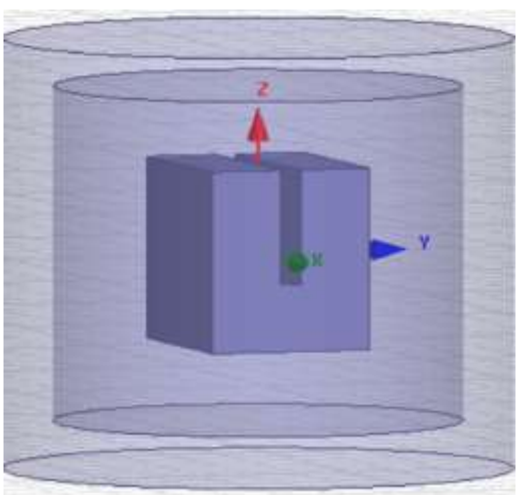
Figure 2. Split cuboid resonator (SCR)

II. Theory

SCR is an optimized form of hairpin resonator. Like hairpin resonator, it acts like a short-circuited TL structure. At the same time, it can also be considered as a lumped device in which the closed end of cuboid acts as inductor and the slit part acts as capacitor. Electric field is maximum at the open end of the resonator and minimum at the closed end of resonator. When a sample is introduced into the resonator split, it disturbs the electric and magnetic field inside them. Disturbance produces change in resonant frequency f_r and Q factor [10]. A small change in the composition of liquid can be found out through sensitivity analysis. High sensitivity for small variation in sample composition provides high resolution analysis [11, 12].

Two important resonant parameters to describe resonator are resonant frequency, f_r and Q factor, Q. Resonant frequency of a resonator is generally defined as[13]:

$$f_r = \frac{1}{2\pi\sqrt{(LC)}} \tag{4}$$

In equation (4), inductance of the device is represented as ‘L’ and capacitance as ‘C’. In a similar way, we can also define Q factor from the equation given below [14]:

$$Q = \omega_o \frac{U}{P_L} \tag{5}$$

where ω_o represents the angular resonance frequency, U is the total electromagnetic energy stored in resonator and P_L represents average dissipation energy [14]. If a resonator is introduced with a lossless medium then only conducting wall losses will be considered in P_L. If medium is lossy then conducting wall losses P_C and dielectric medium losses P_D are added to get P_L. These losses can be incorporated in (6) as follows [14]:

$$P_L = P_C + P_D \tag{6}$$

$$Q = \omega_o \frac{U}{P_C + P_D} \tag{7}$$

It is pretty obvious that introduction of lossy medium lowers the Q-factor of resonator. Thus, Q-factor is the measure of energy losses in resonator.

In most of resonant methods, perturbation technique is mainly used to study behavior of resonators in terms of electromagnetic properties [15]. As discussed earlier, introduction of MUT perturbs electromagnetic fields of resonant system. Parameters of perturbed system are obtained by adding few factors in perturbed system. For a resonant cavity, these have been shown in Fig. 4 [16]. It works more efficiently for low loss and medium loss materials. For this technique to work properly, Q factor of unperturbed system should be high, because if it is not high then power dissipation may be higher than loss due to introduction of MUT within the system.

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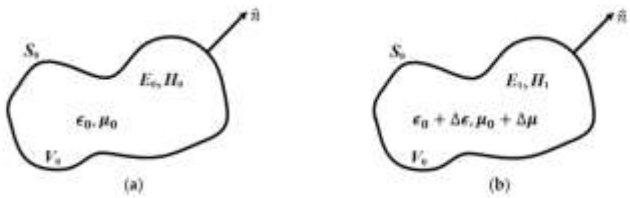

Figure 4. Cavity perturbation (a) empty cavity, (b) perturbed cavity

Resonant parameters of a resonator are related with complex permittivity and permeability of MUT. Polar liquids are characterized mainly by their complex permittivity as their complex permeability have similar values. Complex permittivity of MUT is obtained as a product of permittivity of free space ε_o and relative complex permittivity ε_r^*. These quantities are related as under:

$$\varepsilon^* = \varepsilon_o \varepsilon_r^* \quad (8)$$

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' \quad (9)$$

Relative complex permittivity is composed of two parts i.e., real part ε_r' and imaginary part ε_r''. ε_r' provides information regarding energy storage property of material, whereas ε_r'' provides information about its dielectric loss. When sample material is introduced within a resonator, electric field is perturbed. Perturbation of electromagnetic fields results in shifting of resonant frequency and Q factor. Using shifts in resonant behavior, real and imaginary parts of relative permittivity can be obtained. Relationship is given as follow [15], [17]:

$$\frac{f_1 - f_2}{f_2} = A(\epsilon_r' - 1)\frac{V_s}{V_c} \quad (10)$$

$$\frac{1}{Q_2} - \frac{1}{Q_1} = B\epsilon_r'' \frac{V_s}{V_c} \quad (11)$$

where f_1, f_2 represents resonant frequency before and after introduction of MUT into resonator split, Q_1, Q_2 represents Q factor before and placement of MUT, V_c represents volume of system, V_S represents volume of MUT. Parameters A and B represents depends on shape, sample placement in resonator system and its working. It is not easy to find values for A and B logically so they are found by using material sample of known permittivity. Above equations also indicates that ϵ_r' is directly proportional to shift in resonant frequency, Δf, and ϵ_r'' is inversely proportional to shift in Q factor, ΔQ.

III. Design and Simulation

A. Hairpin Resonator

Simulations of hairpin resonator were designed in HFSS version 13.0. Initially, a hairpin resonator was designed. Thickness of metal strip was kept at 2 mm and length was obtained as 19 mm for maximum sensitivity. Dimensional parameters of this resonator are given in table I. Resonant behaviors were firstly observed for system without MUT. Then samples were introduced within resonator split. Samples of three polar liquids comprising of distilled water, methanol and dimethyl sulfoxide, contained in microcapillary tube, were placed horizontally inside the split. Resonant behaviors were observed for each case. These are given in table II. Shifts in resonant behavior can be noticed for each MUT.

TABLE I. PARAMETERS OF HAIRPIN

Parameters	**Values**
Outer radius of cylinder (R_o)	25 mm
Inner radius of cylinder (r_o)	20 mm
Thickness (T)	2 mm
Width (W)	20 mm
Length (Z)	19 mm
Gap (d)	2 mm
Thickness of shield	5 mm

TABLE II. RESONANT FREQUENCY AND Q FACTOR OF HAIRPIN RESONATOR

Material	***Resonant Frequency (GHz)***	***Q Factor***
Without sample	*3.5506*	*3197.7232*
Distilled water	*3.2675*	*1642.0887*
Methanol	*3.2769*	*1306.5223*
Dimethyl sulfoxide	*3.2785*	*1308.6369*

B. Split Cuboid Resonator (SCR)

For obtaining a highly sensitive hairpin resonator, thickness of metal strip was varied from its mentioned value. For this purpose, optimetrics features of HFSS were utilized. Parametric function was applied to hairpin resonator to obtain an optimized design. Thickness of resonator was varied from 1 mm to 8 mm, while length was varied from 19 mm to 27 mm. During this process, resonant behaviors were observed with and without MUT. A design was finalized which provided maximum shifts in resonant frequency and Q factor. Optimum design was found for 19 mm length and 7 mm thickness. Optimization process resulted in change of resonator shape. Optimization resulted in a cuboid shaped resonator and hence optimized design was named as split cuboid resonator (SCR) and shown in Fig. 5. Dimensional parameters for SCR are as given in table III.

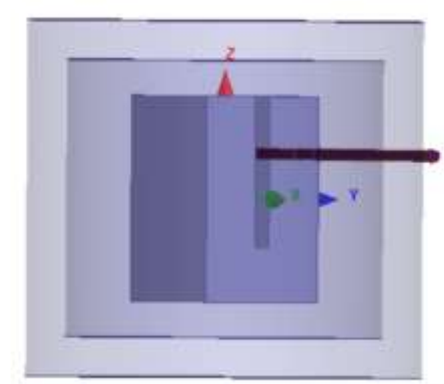
Figure 5. SCR with sample introduced

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TABLE III. PARAMETERS OF SCR

Parameters	**Values**
Outer radius of cylinder (R_o)	25 mm
Inner radius of cylinder (r_o)	20 mm
Thickness (T)	7 mm
Width (W)	20 mm
Length (Z)	19 mm
Gap (d)	2 mm
Thickness of shield	5 mm

It can be noticed that thickness of metal strip used for hairpin resonator is 2 mm whereas SCR, which has been obtained as optimized version of aforesaid resonator, is 7 mm thick from all sides. Distilled water, methanol and dimethyl sulfoxide are introduced into the resonator separately for sensitivity analysis. These liquids are contained in microcapillary tube with dimensions of 1.6 mm diameter and 75 mm length. With the introduction of these samples, electric and magnetic fields inside the resonator are disturbed which results in shifting of resonant frequency and Q factor from its original values. Simulations is performed using these samples, and results were compiled. These results are tabulated in table IV.

TABLE IV. RESONANT FREQUENCY AND Q FACTOR OF SCR

Material	**Frequency (GHz)**	**Q Factor**
Without sample	3.3794	23088.839
Distilled water	3.6525	6378.7951
Methanol	3.6908	2225.7786
Dimethyl sulfoxide	3.6933	3716.9268

IV. Analysis and Discussion

In both designs, three liquids have been used as MUT in simulations i.e., distilled water, methanol and dimethyl sulfoxide. For sensitivity analysis, data was obtained. Graph shown in Fig 6, shows resonant frequency of SCR at different thickness. This displays resonant frequency as a function of thickness. It can be observed that as the thickness keeps on increasing resonant frequency also increases accordingly. At 7 mm thickness, optimum value for resonant frequency is obtained.

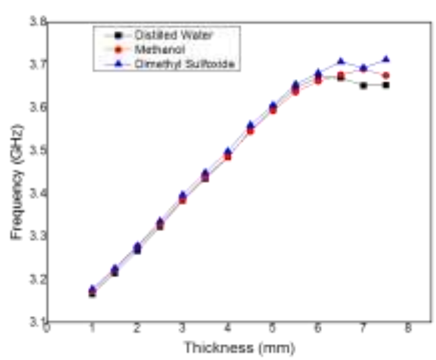

Figure 7. Resonant frequency at different thickness

Similarly, graph shown in Fig. 7, shows behavior of Q factor over range of thickness. It can be observed that Q factor at 2 mm thickness is less than that at 7 mm.

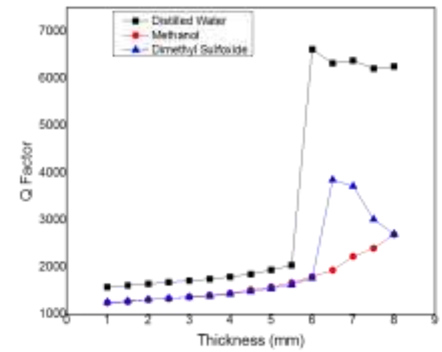

Figure 6. Q factor at different thickness

It is evident from both graphs that maximum shifts in resonant frequency and Q factor was obtained for SCR.

Sensitivity of resonant frequency and Q factor for SCR was also obtained. Graph in Fig. 8, shows relation between shift in resonant frequency as a function of thickness. At 7 mm our proposed design is more sensitive to resonant frequency than at 2 mm.

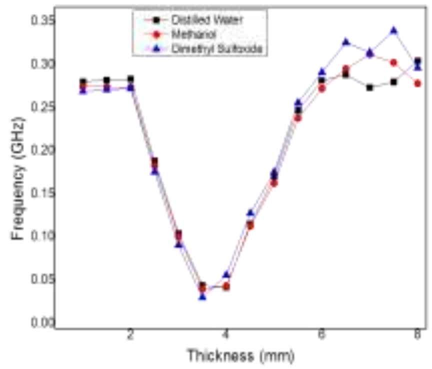

Figure 8. Frequency sensitivity at different thickness

Likewise, Fig. 9 shows relation between shift in Q factor as a function of thickness. It can be observed that at 7 mm the proposed SCR is more sensitive than at 2 mm i.e., original hairpin resonator.

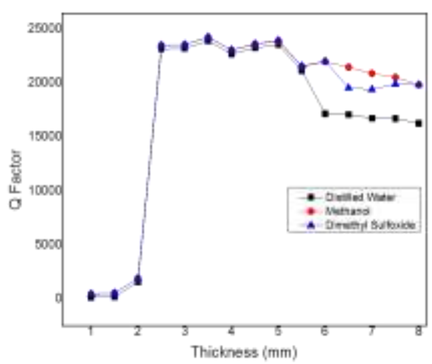

Figure 9. Q factor sensitivity at different thickness

V. Conclusion

An optimized hairpin resonator, named as split cuboid resonator has been proposed in this paper. Both designs have been compared on the basis of resonant frequency, Q factor and their sensitivity. Comparison is based on simulation which utilizes three different polar liquids which have been introduced into the resonator gap. To study behavior and to get maximum shift in resonant frequency and Q factor, thickness of SCR was varied over thickness range. It could be concluded that optimized design i.e., SCR has larger shifts in resonant frequency, Q factor as compared to original hairpin resonator and its sensitivity.

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