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Detection of sub-millimeter crack on metal surface using Complementary Spiral Resonator

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ABSTRACT

Antennas employing credits of engineered materials and exhibiting special features are gaining interest with the evolution of communication systems. One of these applications is presented in this work. A new complementary split ring resonator (CSRR) based sensor is proposed for discovering surface cracks of very small size of the order of few micrometers. A resonator is used as a sensing unit to detect non-uniformities in a metal surfaces coated by an insulator layers, as it operates at lower frequencies. Sensing process involves disturbing the electromagnetic field in proximity of small resonators, causing a variation in the resonant frequency. In this paper, a correlation of crack width and depth with shift in the resonant frequency of conventional CSRR and Complementary Spiral Resonator (CSR) is analyzed. A CSR arrangement can be an advantage to be employed in sensor designing because of operating at a low frequency as compared to CSRR.

KEYWORDS Complementary Split Ring Resonators, Complementary Spiral Resonator, Crack Detection, Microstrip and Split Ring Resonators (SRRs).

1. INTRODUCTION

The structural strength or stability of the aircraft fuselage and other metallic structural components such as steam generator turbines of nuclear power plant, steel bridges along with others can be compensated by corrosion precursor pitting. In host system components corrosion of the metal surfaces is due to their exposure to hard environments that varies significantly. Usually, the corrosion is unseen under primer and paint so cannot be easily observable unless corrosion become critical and causes blistering of the paint. Corrosion precursor pitting is a critical issue in structure failure and deterioration. Such corrosion takes the shape of sub-millimeter size cracks. That means the size (i.e. width and depth) of the indent is very small. To detect the extent of corrosion pitting several techniques has been developed. Frequent inspections of the structural components become cost-prohibitive and time-consuming. Microwave and millimeter wave technology techniques have emerged for crack detection to address these limitations [1-9].

The various crack detection methods have several drawbacks such as in [10] an open ended waveguide sensor could detect a crack of width less than one millimeter, but the downside of this is that it operates at very high frequency which increases the fabrication cost of the circuit. In [11], near-field microwave dual-behavior resonator filters are designed to identify a micrometer sized cracks but these filters offers low sensitivity. Due to one or the other drawbacks associated with above mentioned methods, a transmission line loaded with complementary split-ring resonators has been deployed for the purpose.

Metamaterials are artificial materials with peculiar electromagnetic properties as a result of electromagnetic wave interaction with conventional materials [12]. The first theoretical investigation on metamaterials was done in 1968 by Veselago. But his investigation was not well–received .The next contribution was made almost 30 years later, in 1999, until Pendry et al. demonstrated experimentally that “Split-Rings” are useful to obtain negative effective permeability μ_{eff} [13]. In 2000, Smith et al experimentally proved that the use of thin wire arrays along with SRR (Split Ring Resonator) arrays provides negative effective permittivity, ε_{eff}, and negative effective permeability, μ_{eff}, simultaneously over a common frequency band. The complementary screen of the SRR is known as CSRR. The dimensions of the CSRR are much smaller than the wavelength of the radiation frequency. CSRR acts like an electric dipole with the excitation of an axial electric field and have resonant frequencies due to the internal inductance and capacitance.

In this paper, a CSRR based sensor has been designed for crack detection. Two widths of cracks measuring 25 μm and 50 μm, different depths of crack for each width are considered. The key element in the designing of the sensor for crack detection is CSRR. Here, CSRR is implemented as a near field sensor for detecting crack on aluminum plate. The detection of sub-millimeter size cracks is based upon the deviation in the resonant frequency of the resonator. The advantages of the CSRR sensor are high susceptibility, low operational frequency and relatively low cost of circuit as compared to the other techniques for detecting cracks. This paper is structured in six sections. After problem formulation in Section 1, Section 2 presents CSRR sensor design by cutting out SRR from the ground plane of microstrip line considered in designing. An excitation of CSRR using microstrip line is discussed in Section 3, where microstrip line acts as feed to the sensor. In Section 4, sensing technique and numerical analysis is presented. Section 5 includes results and discussion. The transmission coefficients of sensor with different crack width and depth are observed and compared with crackless aluminum plate. Section 6 gives the conclusion of paper.

2. SENSOR DESIGN

The CSRR structure is used for designing sensor for detecting fraction of millimeter size cracks in metallic structures. A single CSRR is used as a sensing component. The electric field distribution developed by CSRR is exterior to the sensor plane. Unlike SRR [13], electric fields are highly concentrated to the splits in CSRR. This basic feature of CSRR is an incentive for its prime consideration for crack detection as the sensor detects crack in the surface lying adjacent to it. The resonant frequencies of a structure like CSRR are due to the internal capacitance and inductance. So, larger the dimensions of CSRR, higher are the inductance and capacitance and lower is its resonant frequency.

2.1 Regular CSRR Design

The purpose is to design a sensor operating around 5 GHz for regular CSRR design. The CSRR is designed by etching SRR on the ground plane, where copper is replaced by air as shown in Figure 1.

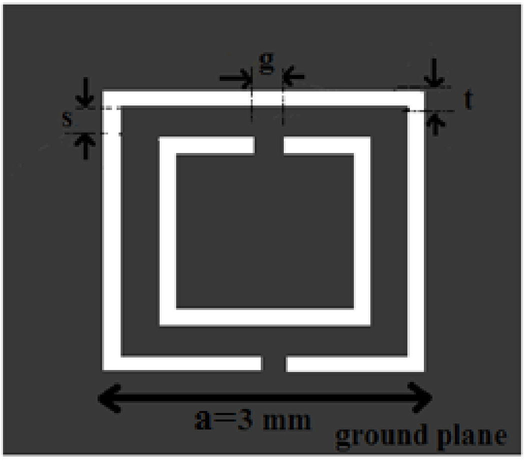

Figure 1. Layout of CSRR on ground plane.

The dimensions of the resonator can be achieved using eigen value solver of Ansys HFSS as well as approximate formula reported in [14]. Before finalizing a design that can meet a certain frequency criterion (i.e. resonance close to 5GHz) several trials have been performed in either approach. The dimensions of resonator are given in Table 1. However, due to several limitations like of fabrication etc, the final dimensions after optimization of the sensor are illustrated in Table 2.

Table 1. Dimensions of the parameters of CSRR

Sr. No.	Parameters of CSRR	Values (in mm)
1	Length, a	3
2	Space between outer and inner ring, s	0.2
3	Gap (split), g	0.2
4	Thickness, t	0.2

Table 2. Optimized dimensions of CSRR/CSR

Sr.No.	Parameters of CSRR/CSR	Values (in mm)
1	Length, a	3
2	Space between outer and inner ring, s	0.16
3	Gap(split), g	0.16
4	Thickness, t	0.2

2.2 CSR design

The new modified design of CSRR is also commonly known as complementary spiral resonator (CSR). This CSR performs better than the previous one. The resonance frequency of CSR is half of that of regular CSRR with identical dimensions as the total equivalent inductance of CSR is four times more than for CSRR. As a result, it operates at low resonance frequency. According to the formula in equation (1):

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_T}} \tag{1}$$

Where L_T and C_T are the total distributed inductance and capacitance respectively. The length of outer ring of CSR is taken equal to the regular CSRR dimensions and inner ring is also made accordingly using same values of split and spacing of regular CSRR. Then, the two rings are connected to form a spiral like structure and are etched from ground plane where electromagnetic field is significant. Figure 2 presents the schematic of the CSR design.

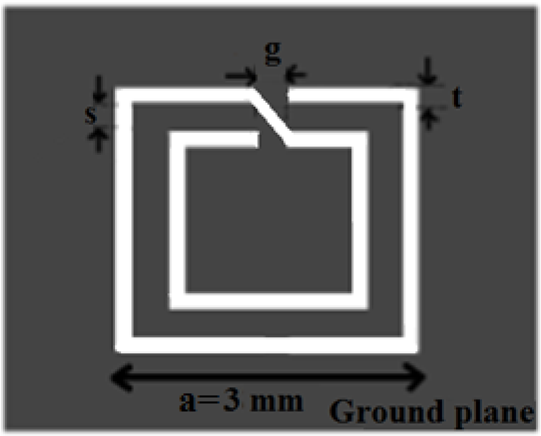

Figure 2. CSR design etched on ground plane

3. SENSOR EXCITATION

A microstrip line structure is selected to stimulate the CSRR based sensor. It is basically the feed of the sensor. The excitation of CSRR requires an electric field vertical to the sensor surface. This is somewhat similar to split-ring resonator design which requires magnetic field for excitement. The CSRR is removed out from the ground plane and this structure has already been used as a stop band filter in [15]. The frequency at which transmission coefficient, S_{21} should be very small, relies upon the CSRR's resonant frequency. So, a variation in the resonant frequency will be observed as the metal surface under test placed below the CSRR disturbs the electromagnetic field. When the sensor is placed over a defect, it produces an electric field orthogonal to ground which excites the CSRR resulting in change of resonant frequency. The proposed model of CSRR on Rogers RO4350 substrate in Figure 3 is analyzed to find transmission coefficient with electromagnetic solver Ansys HFSS. The width of the microstrip line is kept to be 1.68 mm so as to match the internal impedance of 50Ω. The substrate is 0.75 mm thick with relative permittivity (ε_r) of 3.66 and tan δ = 0.0031.

The proposed CSR model is etched on ground in the same way as CSRR with same parameters as depicted in Table 2 and simulated with EM solver.

4. NUMERICAL ANALYSIS OF CSRR/CSR

In numerical analysis, an aluminum plate surface is covered by a thin Teflon film of thickness 0.0762 mm which resembles a coating of emulsion or an insulator film that hide crack from the optical analysis. After the resonator is outlined to work within a specific range of frequency, the resonant frequency is noted when sensor is kept over a crackless solid aluminum plate. This case is chosen as reference case. The sensing process is carried by moving the sensor above the solid metal plate, as illustrated in Figure 3. The sensing process of the sensor is examined from its capability to detect a crack of certain dimensions and leading to a variation in the frequency from the reference case. In addition, sensitivity is also determined by how much the resonator's near field gets affected by defects in materials. The interaction of material with electromagnetic fields depends on the properties of material. These properties lead to disturbance in the near-field, resulting in changes in the material constitutive parameters. These changes are marked for demonstrating the detection of crack.

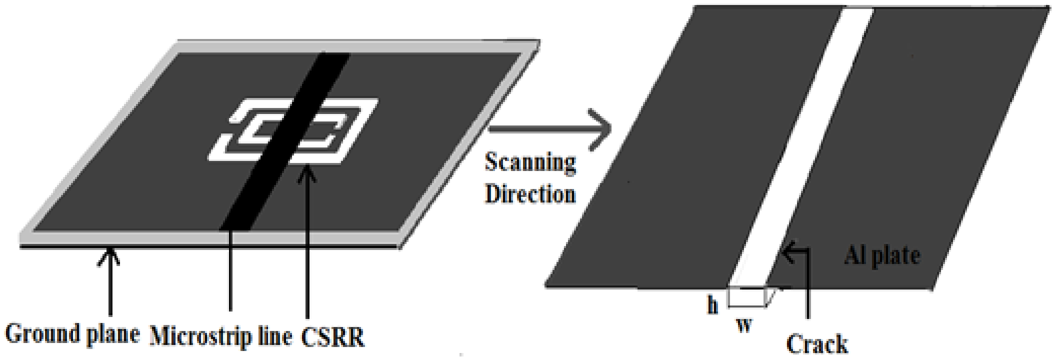

Figure 3. Schematic of the sensor fed by microstrip line and the scanning process.

5. RESULTS AND DISCUSSION

In this paper, the sensor based on conventional CSRR and new CSR is planned to discover the cracks in an aluminum plate. The measurements are carried out on defected aluminum plate to confirm the simulation. Here crack with different widths (w) of 25 μm, 50 μm with depths (h) of 1 mm, 2 mm respectively are considered on aluminum plate. The transmission coefficient results are observed in cases as follow:

CSRR AS SENSOR

- When regular CSRR sensor is passed over the aluminum plate with no crack on the surface of plate(Reference case)
- When the regular CSRR sensor moves over the metal surface with a crack of
  - ➢ w=25 μm and h=1 mm, 2 mm
  - ➢ w=50 μm and h=1 mm, 2 mm

Result of CSRR with crack of w=25 μm and h=1 mm, 2 mm

A variation in the resonant frequency of the CSRR is observed when sensor detects a crack as shown in Figure 4. The minimum transmission frequency of the sensor for crack width of 25 μm and depth of 1 mm is illustrated by box markers (green color line) as shown in Figure 4. While for the same width of crack the depth has been changed from 1mm to 2 mm, for which the readings are shown by triangular markers (blue color line) for metal plate without crack is indicated by dotted line(red line). We notice some deviation in frequency for the case without the crack indicated by dotted line (red color). The defects or cracks in metallic surfaces, introduces capacitance parallel to the effective capacitance of sensor. The capacitance induced due to defect causes resonant frequency to shift to lower frequency region.

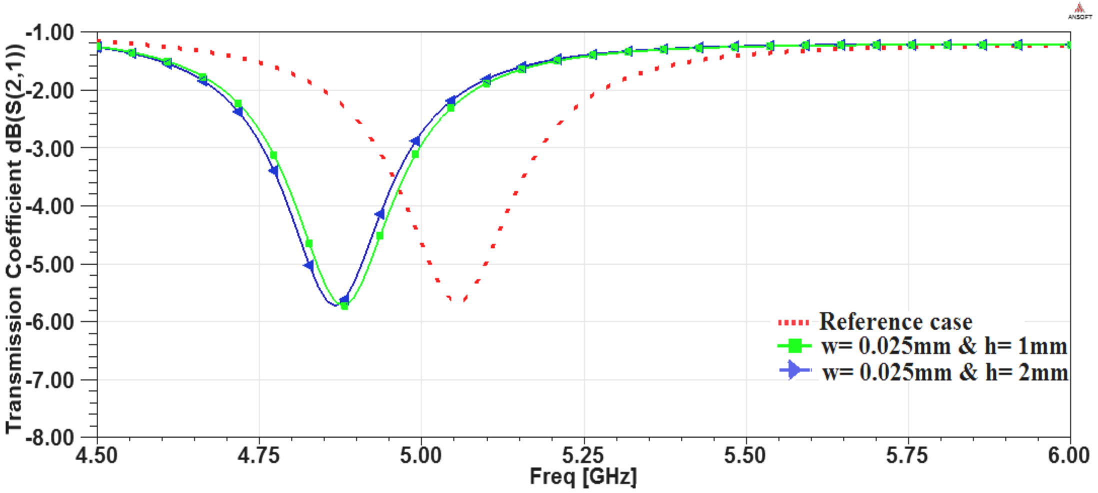

Figure 4. Transmission coefficient versus frequency of CSRR for (i) Aluminum plate without crack(reference case). (ii)Aluminum plate with 25 μm crack width, for crack depth of 1mm and 2 mm.

Result of CSRR with crack of w=50 μm and h=1 mm, 2 mm

The plot of transmission coefficient versus frequency of the CSRR for a 50 μm wide and 1 mm deep crack is illustrated by box markers (green color line), for 50 μm wide and 2 mm deep crack is illustrated by triangular markers (blue color line) and for metal plate without crack is indicated by dotted line (red line) as shown in Figure 5. Thus frequency correlation is analyzed for different crack widths and depths. It is clear that the regular CSRR based sensor is able to detect fraction of millimeter size crack on metal surfaces.

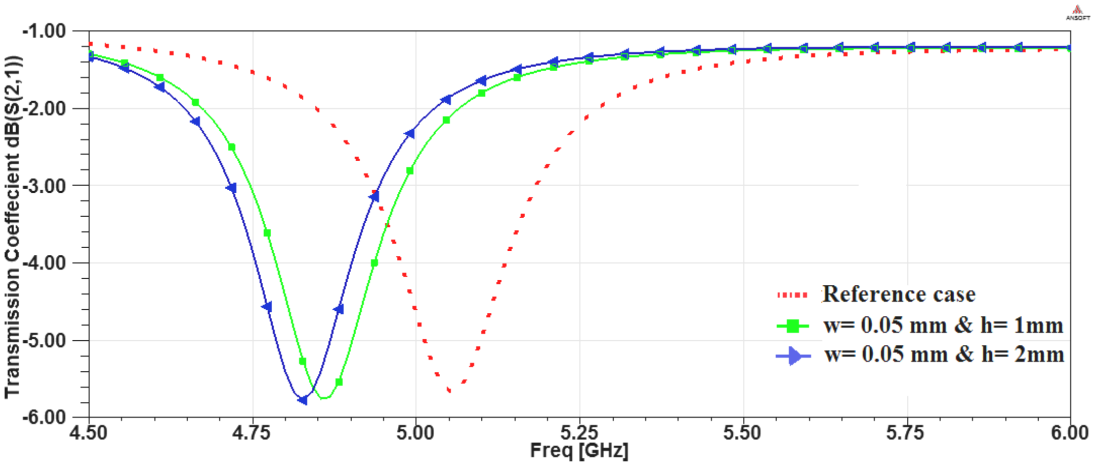

Figure 5. Transmission coefficient versus frequency of CSRR for (i) Aluminum plate without crack(reference case). (ii)Aluminum plate with 50 μm crack width, for crack depth of 1mm and 2mm.

CSR AS SENSOR

CSR can also be used for the same purpose that is to detect cracks. The working of CSR and regular CSRR is almost similar. This variation in the resonant frequency indicates the detection of fraction of millimeter sized crack by sensor. A frequency comparison between CSR and regular CSRR is presented in Figure 6. CSR is designed to resonant around 3.5 GHz where as the regular CSRR operates around 7 GHz when no aluminum plate is considered.

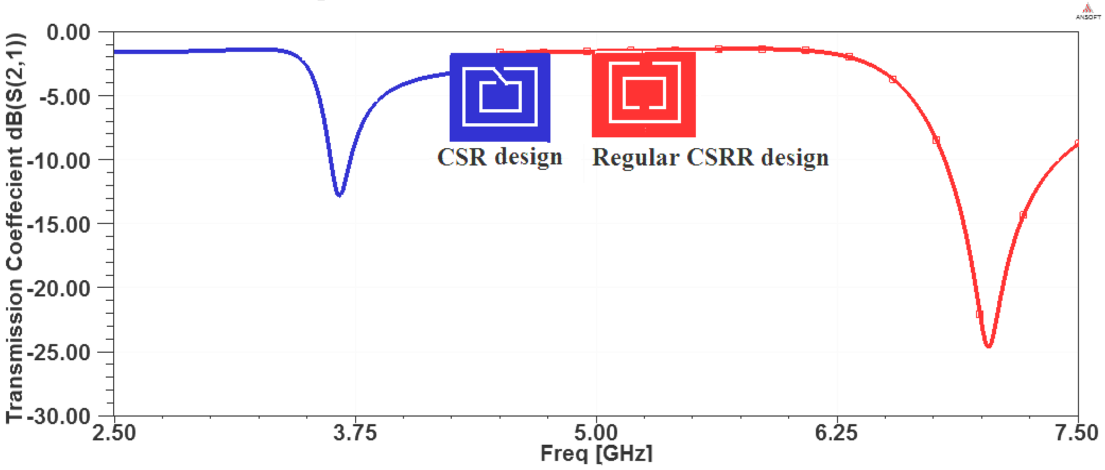

Figure 6. Tranmission minimum frequency comparison between CSR and regular CSRR.

- When the CSR based sensor is passed over the aluminum plate with no crack on the surface of plate.
- When the CSR based sensor moves over the metal surface with a crack of
    - ➢ w=25 μm and h=1 mm, 2 mm
    - ➢ w=50 μm and h=1 mm, 2 mm

Result of CSR with crack of w=25 μm and h=1 mm, 2 mm

The CSR based sensor's sensitivity is tested by placing it over a defected aluminum plate with 25 μm crack width and 1 mm crack depth initially and then, changing the depth from 1mm to 2mm. The change in resonant frequency is noticed from the reference case is due to the presence of crack as shown in Figure 7. A crack with depth of 1mm is indicated by box marker (green color line), with 2mm depth is presented by triangular marker (blue color line) and dotted line (red color line) is for the case when there is no crack on aluminum plate. It should also be noted that obtaining resonant frequency at certain position is of minor concern.

Result of CSR with crack of w=50 μm and h=1 mm, 2 mm

The CSR sensor is then moved over a defected aluminum plate with 50 μm crack width and 1 mm, 2 mm crack depth. Due to the presence of crack a variation in the

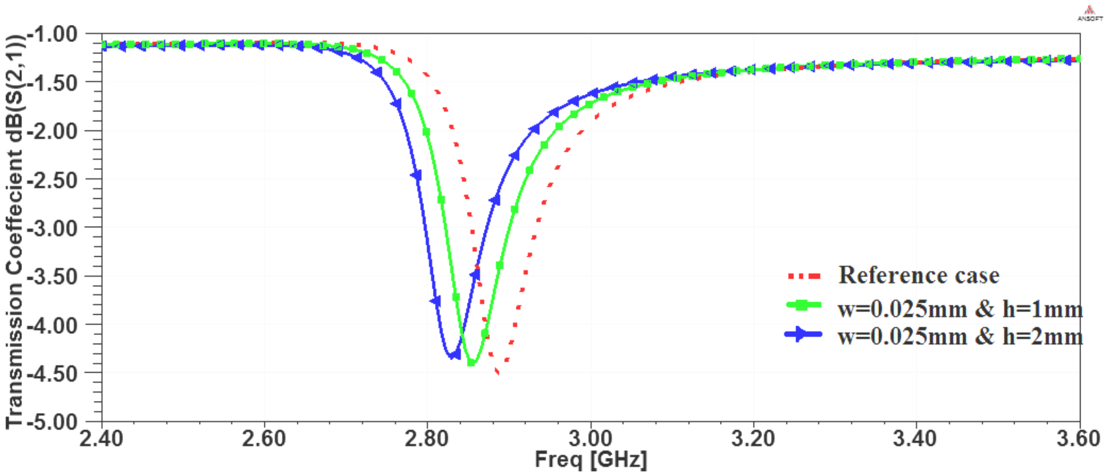

Figure 7. Transmission coefficients versus frequency of CSR for Aluminum plate with 25 μm crack width and 1mm, 2mm crack depth as compared with reference case (no crack on metallic plate)

resonant frequency is registered and depicted by box marker (green color line) for crack depth of 1mm, by triangular marker (blue color line) for crack depth of 2mm as shown in Figure 8. Thus, it is very clear that CSR is also capable of detecting small cracks such as of 25 μm and 50 μm in width. The CSR operates at lower frequency than the regular case and more downward shift is observed in the resonant frequency which serves as an advantage. So, a CSR can be employed in crack detection sensor.

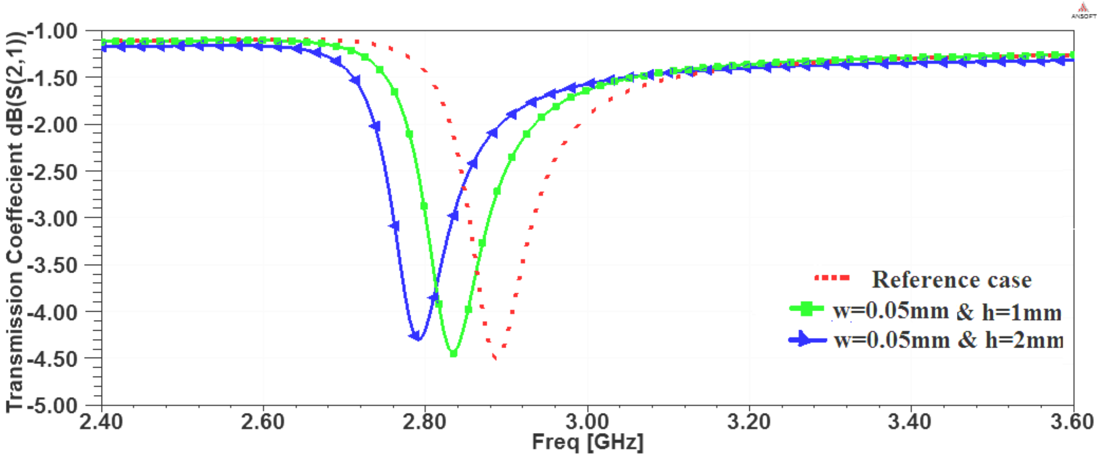

Figure 8. Transmission coefficient versus frequency of CSR for Aluminum plate with 50 μm crack width and 1mm, 2mm crack depth as compared with reference case(no crack on metallic plate).

The results show that resonant frequency unveils a shift when the sensor is moved over a crack, as the crack unsettles the magnetic field around the resonator. The interaction of materials with electromagnetic fields extracts various parameters like permittivity, permeability and conductivity which are important for the purpose of detecting defects in the materials. These defects affect the near-field distribution. So, change in the field is caused by changes in the extracted parameters of the material disturbing the field around resonator and thus, employed for the purpose of crack detection.

6. CONCLUSION

A complete analysis on the ability of sensor for detection of fraction of millimeter size cracks on metal surfaces has been presented in this work. A sensor based on CSRR/CSR illuminated by microstrip line is used to detect cracks in metal surfaces coated by non-conductor film. The sensing integrand is smaller than the wavelength of the proposed sensor. The sensor operates by unsettling the electric field around resonator, when it is placed under the metal surface covered by layer of thin film. Thus, a correlation of resonant frequency shift of crack depth and width is analyzed. The regular CSRR based sensor operates around 5GHz when placed on metal surface devoid of any crack and presents a frequency shift towards left from the reference case when it is moved over a crack i.e. the resonant frequency shifts toward the lower frequency range, for a 25 μm and 50 μm crack widths respectively. A high shift in the resonant frequency is obtained by proposed CSR structure leading to significant change in material parameters and these changes are employed as an indicator for detecting cracks. The proposed sensors have many advantages as compared to other microwave and non destructive testing techniques that have been used so far, operate at low frequency, inexpensive and highly effective. The proposed CSR model operates at a lower frequency than the regular CSRR design. This is one of the applications of the antennas with special features that are extensively in demand, with the advancements in the communication systems.

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