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Microwave Sensors for Metal Conductivity Measurement

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Abstract – **In the present work, a microwave sensor is proposed for detection of conductivity of the material. The sensor consists of a planar complementary circular ring structure etched on the top of the single sided copper clad substrate material and a shallow groove machined at the bottom surface coinciding with the ring structure. The conducting material under test (MUT), curved in the form of a split ring is placed in the groove. The proposed microwave sensor is particularly designed to work at 5.2 GHz Wi-Fi frequency. The key concept is the interaction of the EM wave with the material of different conductivity which results in change in reflection coefficient owing to different depth of penetration at a particular frequency. A reference set is generated by recording the variation in reflection coefficient for different materials, which is the main parameter in distinguishing between materials of different conductivities. The sensor dimension is 4 cm X 4 cm (0.083277 λ_g), λ_g being the guide wavelength, the MUT is a wire of length 4 cm with thickness ≤ 1 mm placed in form of circular split ring within the groove. The sensor corresponds to sensitivity of 3.6 dB/unit change in electrical conductivity. The proposed sensor facilitates rapid and convenient detection of the conductivity of the material.**

Keywords – **Microwave sensors, Complementary split ring resonators, Metal conductivity, Grooved complementary ring structure.**

I. INTRODUCTION

Characterization of any solid, liquid, and gaseous materials can be very well carried out at RF and microwave frequency by facilitating the interaction between the electromagnetic fields and the materials. The propagation characteristics of electric and magnetic fields in materials as well as at the interface boundaries are exploited to characterize the different class of materials. All the materials can be considered as dielectric since the electromagnetic waves can penetrate even through a good conductor to some extent depending on the skin depth. Complex relative permittivity and permeability are the two very important parameters considered for material characterization at RF and microwave frequencies. It is very important to determine the conductivity of any conducting material due to various reasons. At high frequency the limited conductivity of the material causes a significant amount of loss. In domains like aerospace and defense such as avionic buses, targeting systems, electro-optic pods etc., it is crucial to determine the conductivity of metal to be used as a faster response is necessary. As with increase in the frequency the skin depth decreases, conductive capacity of a metal plays an important role in capturing the signal and its propagation. There are existing methods for metal conductivity testing, the most popular is the Eddy Current Method which determines conductivity by the phase shift between two fields.

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The US Department of Defense under Military Standard 1537 (MIL-STD-1537 A/B/C) has approved this method for electrical conductivity testing. Another method known as Van Der Pauw method determines the metal conductivity by voltage drop and resistivity. Each method has certain advantages and disadvantages such as Van Der Pauw Method is a contact method, and the measurement efficiency is dependent on the pin contact, surface roughness of MUT, and wearing out of contact. Eddy current method on the other hand is a non-contact method using field probes and test bench for measurement, but efficiency is based on three factors namely the distance of probe from MUT, the thermal coupling of MUT with the test bench environment, and the comparable and optimal size of probe according to MUT. Due to increase in frequency in wireless communication domain, comparatively thinner or almost planar MUT are to be tested for conductivity, since a decrease in the skin depth leads to a decrease in the sensitivity of the probe. With the increase in frequency the eddy currents also increase, thus, to optimize the criterion of probe size in accordance with the size of MUT, there is an acute requirement of measurement hardware calibration even with a minor shift in frequency.

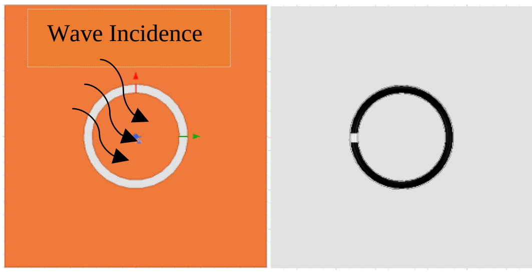
In the past several sensors have been employed for sensing the material in solid or liquid forms. The microwave sensor based on the capacitive-inductive (LC) resonant circuit is a good candidate for its application in wireless communication technology [1-2]. The meta-material or meta-surface-based sensors acting as LC circuits are highly advantageous over the conventional transmission line-based design, as for the same frequency they are smaller in size approximately $\lambda/10 - \lambda/2$ in size [3-4], providing a sharp narrowband output which is highly desirable in sensing applications. The transmission line model is also translated using meta-surface mostly for broadband applications. Resonant approach and non-resonant are the two major approaches in microwave sensor design using meta-surface/materials. The resonant approach comprises split ring resonator (SRR) and complementary split ring resonator (CSRR), which acts like an LC Tank where resonant frequency can be varied by varying the L and C values [5-6]. It mostly offers a narrowband response which makes it suitable for sensing application. In both SRR and CSRR approach, the metallization acts as current carrying conductor and non-metal or substrate gaps act as capacitors. Various microwave structures based on meta-surface-based designs and their analysis are mentioned in [7-15], along with modern industrial applications of these sensors elaborated in [16-21].

Compared to the existing sensors used for conductivity determination, the proposed microwave sensor has advantages of real-time monitoring, low cost, and high accuracy, which makes it a promising sensor for the characterization of the materials in terms of its conductivity. A proper calibration of the resulting reflection coefficient value with the corresponding material would yield the specific value of the metal conductivity. It uses a non-contact method of detecting metal conductivity using reflection of EM waves at a particular frequency as a parameter, without the constraints of maintaining the size of e field probe or test bench and sample temperatures as in usual eddy current methods, unlike conventional complementary split ring resonator structure, the material under test itself acts as split ring at the bottom surface of sensor, along with complementary ring of substrate on the top. To the best of the author's knowledge, for the first time such a simple structure is used for the detection of the conductivity of the material. The dielectric property of any material has two components, the dielectric constant, and the loss tangent. While the change in dielectric constant shifts the resonant frequency, the change in the conductivity of the material does not change the dielectric constant values significantly but changes the magnitude of the reflection coefficient at a single frequency. The change in the reflection coefficient's amplitude is mainly caused by the varying loss tangent values depending on the skin depth of the different conducting material. The main aim of this study is to generate a reference set of reflection coefficient values in correspondence with electrical conductivity values of metals and alloys at a particular frequency, so that only one parameter i.e., reflection coefficient is sufficient to detect the type of metal or alloy in question and determine its feasibility of usage in highly critical domains such as aerospace and defense. A comparative study with works based on electrical conductivity is included in Table 4.

II. Design and Simulation

A. Sensor Design

The sensor design is based on the resonant approach of meta-material/surface design. The resonant meta-surfaces help in reducing the size of the sensor as at the same frequency, the reduction in size of the sensor can be achieved along with a sharp narrow band response. The proposed sensor as shown in Fig. 1, is a complementary ring structure with outer and inner radius of 8 mm and 6.7 mm respectively giving an annular width of 1.3 mm, etched on a single sided square copper clad FR4 substrate of dimensions 40 mm X 40 mm (0.0832 λg) X 1.5 mm. The substrate has a dielectric constant of 4.4, loss tangent value of 0.030 and copper trace width of 0.035 mm. The physical parameters of the sensor are devised in accordance with the target frequency of 5 - 5.2 GHz. On the unclad side of the substrate a coincident split ring MUT of similar annular width is placed in a groove of 0.5 – 0.75 mm depth within the substrate, with a split width of 1mm as shown in Fig. 1(b). The ring resonator is excited using space feeding technique. The proposed sensor structure is excited with the plane wave incidence falling on the top surface of the sensor structure as shown in Fig. 1 (a). In practice, the plane wave incidence is achieved using an antenna placed in the far field. The antenna transmits the EM wave of the specific frequency depending on the design of the proposed sensor.



(a) (b)

Fig. 1. Configuration of the proposed sensor: (a) Top view, (b) Bottom view with toroidal split ring

This specific location of placing the MUT is chosen because the field concentration is maximum in the region below CRR. By placing the MUT just below the CRR coinciding with the ring perturbs the highly concentrated electric field, thus leading to a shift in the notch depth of reflection coefficient.

In the equivalent circuit diagram, based on the conventional behaviour, the copper clad is represented as current carrying inductor and the non-metal part or gaps as capacitor, including the thickness of substrate acting as a gap capacitance between the top layer metallization and the MUT placed in the bottom groove.

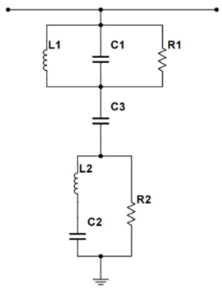


Fig. 2. Lumped circuit equivalent of proposed sensor

Next, the lumped equivalent circuit is shown to depict how the grooved configuration can be represented in the form of the equivalent circuit. In the lumped circuit equivalent Fig. 2. L1, C1 represent the top layer complementary ring structure with metallization as current carrying conductor and the gap of annular ring as capacitor forming a resonating tank, L2 is the material under test wire with C2 analogous to Cg (gap capacitance) of the split, R1 and R2 depict losses. Placing the MUT at the bottom unclad surface within or without groove increases the coupling depicted as coupling capacitance C3 between the top layer and MUT.

The above proposed design is simulated using Ansys HFSS. Initially two major parametric analysis is carried out i.e., the variations of frequency and reflection coefficients with respect to size of the sensor and substrate thickness. Further, it is to be noted that by employing Ansys HFSS simulation tool for the full-wave numerical simulations, the reflection spectra for the proposed sensor are determined for various MUT when the structure is excited with the plane wave incidence falling on the top surface of the sensor structure. First, an optimetric setup is designed with sensor size variation from 1 - 5 cm with a step size of 0.5 cm. The optimum sensor size for which the resonance lies within the 5-5.2 GHz range is found to be 4 cm as shown in Fig. 3. Next, an optimetric setup is designed with substrate thickness variation from 0.1 - 0.2 cm with a step size of 0.05 cm. The optimum substrate thickness is obtained as 0.15 cm as shown in Fig. 4.

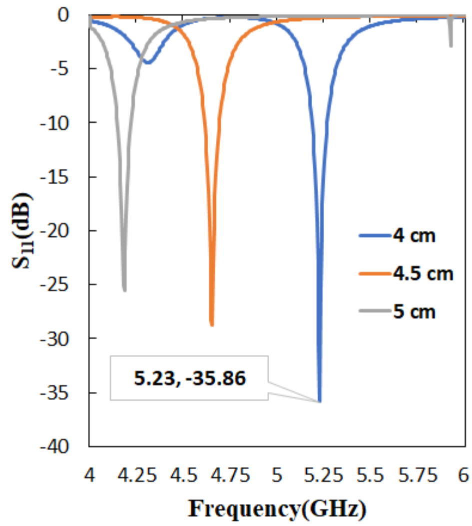


Fig. 3. Parametric analysis for optimum sensor size

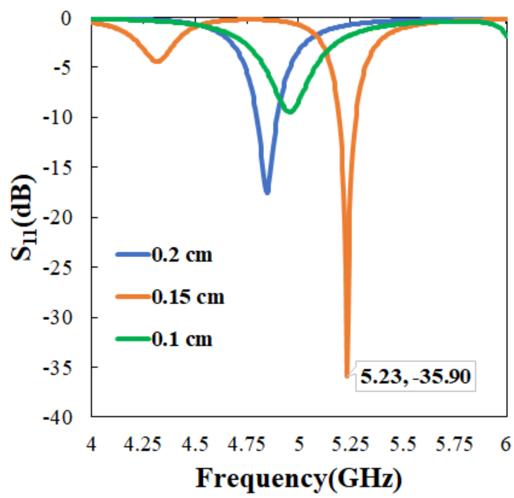


Fig. 4. Parametric analysis for optimum substrate thickness

B. Simulation of Material under Test

The simulation is carried out for various metals and alloys, by assigning different material properties to the bottom split ring. After verifying the optimum cell size and substrate thickness of structure for the target resonant frequency, two sub approaches of sensor design are simulated. In the first approach, a toroidal split ring (1 - 1.06 mm) shaped MUT of different metals and alloys is inserted within the groove. The structure resonates at 5.24 GHz with significant S_{11} notch depths variations [22] in various cases of metals and alloys inserted as depicted in Fig. 5. In the second approach a planar split ring (1.3 mm) shaped MUT is placed and pasted on the uncladded side such that it exactly matches with the annular ring of cladded top surface. The structure resonates at 5.225 - 5.23 GHz with significant S_{11} notch depth variations in different metal and alloy cases as depicted in Fig. 6. Since all the measurements are performed at the specific frequency for a particular material the skin depth remains constant for that material at that frequency and is different for different materials. At a specific frequency, different materials have different skin depth hence, the corresponding reflection coefficient would be different, which is the basis of the function of this sensor. From the frequency responses obtained in Fig. 5 and Fig. 6, and the tabulated data of Tables 1 and 2, one can infer that higher the bulk conductivity greater is the reflection of EM waves in case of metals and their alloys along with evident dependence on permeability, where higher relative permeability tends to decrease frequency as well as notch depth of reflection coefficient. Apart from permittivity and permeability the reflection of EM waves especially microwaves are dependent on electrical conductivity. At high frequencies even with a change of 0.1 S/m, a significant change in reflected power is observed.

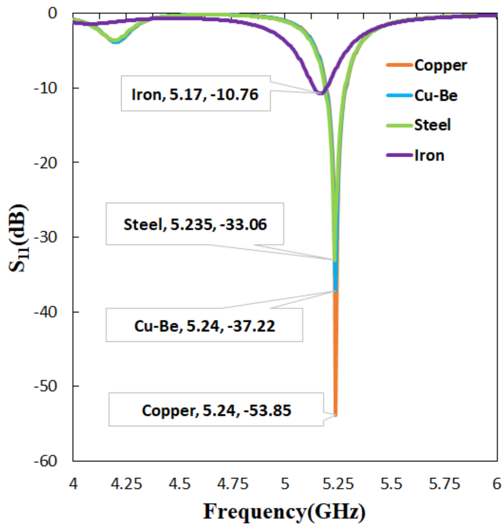


Fig. 5. Notch depth variation of S_{11} at constant frequency for 1.06 mm Toroidal Split Ring MUT

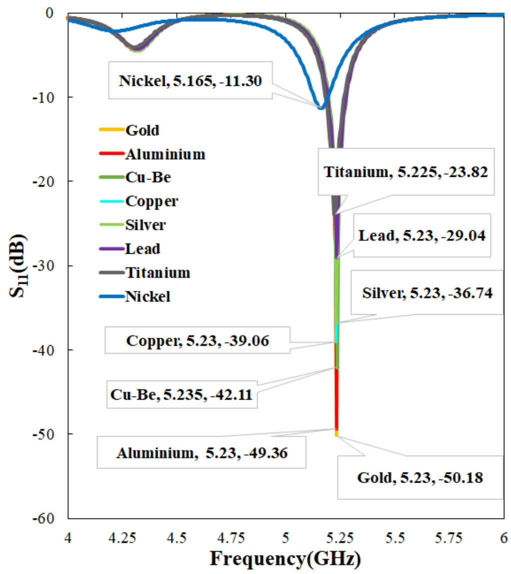


Fig. 6. Notch depth variation of S_{11} at constant frequency for 1.3mm Planar Split Ring MUT

TABLE 1
PARAMETRIC VALUES FOR 1.06 MM TOROIDAL SPLIT RING MUT

Material	Conductivity (S/m)	ε_r μ_r	Skin depth (mm)	Frequency (GHz)	S_{11} (dB)
Copper	5.8 X 10^7	1, 0.99991	0.913	5.24	53.85
Cu-Be 17500	2.8 X 10^7	1, 1	1.314	5.24	37.22
Iron	1.03 X 10^7	1, 600	0.075	5.165	10.73
Steel	1.1 X 10^6	1, 1.00018	0.035	5.235	33.06

TABLE 2
PARAMETRIC VALUES FOR 1.3 MM PLANAR SPLIT RING MUT

Material	Conductivity (S/m)	ε_r, μ_r	Skin depth (mm)	Frequency (GHz)	S_{11} (dB)
Silver	6.1 X 10^7	1, 0.9998	0.877	5.23	36.74
Copper	5.8 X 10^7	1, 0.99991	0.902	5.23	39.06
Gold	4.1 X 10^7	1, 0.99996	1.04	5.23	50.18
Al	3.8 X 10^7	1, 1.00021	1.12	5.23	49.36
Cu-Be 17500	2.8 X 10^7	1, 1	1.31	5.235	42.11
Nickel	1.45 X 10^7	1, 600	0.075	5.165	10.73
Lead	5 X 10^6	1, 0.99998	3.11	5.23	29.04
Titanium	1.82 X 10^6	1, 1.00018	0.035	5.165	23.82

The usefulness of the proposed design is confirmed for different materials, the confirmation of the detection of the conductivity is shown through validation of simulation and experimental results and included in Table 3 and supported by [23-25] where the role of electrical conductivity in EM wave reflection is aptly elaborated. Highly magnetic materials like iron, nickel and cobalt with comparatively lower bulk conductivity values show a drastic decrement in frequency and reflection coefficient values. This inferred relation could also help distinguish suitable magnetic materials from a set of unknown samples. All the measurements are performed at a specific frequency for which the sensor structure is designed, and the conductivity is measured at that frequency only which remains constant at that specific frequency for a particular metal.

III. FABRICATION AND TESTING

With inference drawn from parametric study and simulation, the structure is fabricated using CNC machining, as shown in Fig. 7. To test whether the structure without the MUT is responsive to the target frequency of 5 - 5.2 GHz or not, a laboratory setup is devised using Anechoic Chamber, transmitting, and receiving horn antennas and a Vector Network Analyzer. The sensor is suspended using cardboard strip at the edge of anechoic chamber, excited using horn antennas and the parameters are measured using the two ports of the Vector Network Analyzer (VNA: Agilent Technologies N5320A 10 MHz - 20 GHz PNA-L Network Analyzer) connected to them, as depicted in Fig. 8. It is to be noted that all the measurements required in this sensing technique are performed in the far field, and under normal incidence condition. The proposed sensor is based on absorber-based sensing technique where the plane wave impinges on the surface of the sensor and the corresponding reflection from the sensor is observed [31-35]. The amount of reflection depends on the nature of the MUT. To investigate the performance of the proposed sensor, the reflection coefficients are measured using a well-known calibration technique. The procedure involves step by step recording of the reflection coefficients values of the cardboard strip, and cardboard strip with sensor (with and without MUT) using averaging factor within the auto scan calibration mode of the VNA.

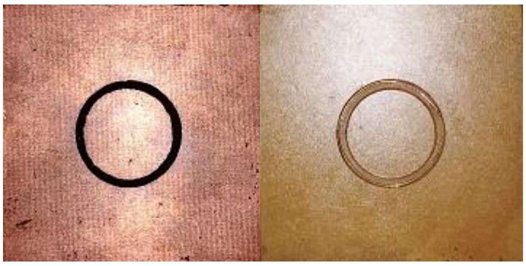
TABLE 3
COMPARISON OF SIMULATED AND MEASURED RESULTS

MUT without groove			
Material	Conductivity (S/m)	Frequency (GHz)	S_{11} (dB)
Steel	5.23	-22.0466	-21.3678
Cu-Be 17500	5.23	-42.1108	-40.3496
Copper	5.23	-39.0603	-37.4589
MUT with groove			
Steel	5.235	-33.0605	-32.5498
Cu-Be 17500	5.24	-37.221	-36.3952
Copper	5.24	-53.8513	-52.7643

To validate the results experimentally, the measured reflection spectra for the corresponding MUT are obtained by a bistatic radar cross section (RCS) measurement setup as illustrated in Fig.8 used for non-destructive sensing. In the measurement setup, the EM waves transmitted from the transmitting antenna kept in the far field impinges on the sensor and the waves reflected from the sensor are received by the receiving antenna.

For testing, four samples namely the 1 - 1.02 mm Copper wire, 0.036 mm Copper adhesive tape, 0.25 mm Copper-Beryllium 17500 alloy wire, and 0.25 mm Steel wire are considered. From the comparative study of simulated and measured results tabulated in Table 3, a minor deviation in reflection coefficient values is observed which may be attributed to experimental setup environment, and MUT's physical nature. By generating a reference table of variation of reflection coefficient with corresponding conductivity values vs frequency, Fig. 9 is plotted. Fig. 9 depicts the linearity property which is important for a sensor and the value of reflection coefficient for a specific material for both grooved and non-grooved structures. It indicates that certain materials are not sensitive to the grooved configurations. But the grooves enable easy placement of the MUT. Both configurations show an almost linear variation of reflection coefficient with conductivity, indicating that greater the bulk electrical conductivity greater is the reflection of EM waves.

Sensors monitoring the frequency shift rather than notch depth variation are mostly designed for broadband sensing, the proposed sensor is based on sensing a parameter at specific frequency. Hence, the resonant meta surface-based design popular for narrow band sensing is used. Moreover, variation of frequency over a broader range wouldn't have yielded much useful information as electrical conductivity would have changed with change in frequency. As a future work we plan to use the UNII Wifi band to sense the parameters using a handheld platform thus at specific frequency different notch depth values would help differentiate between different metals.



(a) (b)

Fig. 7. Fabricated sensor: (a) Top, (b) Bottom view

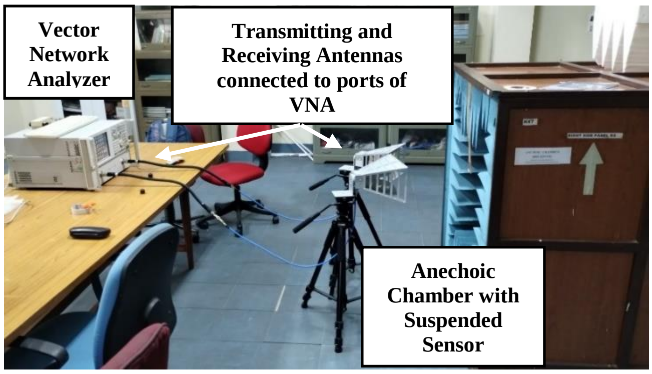


Fig. 8. Experimental Setup

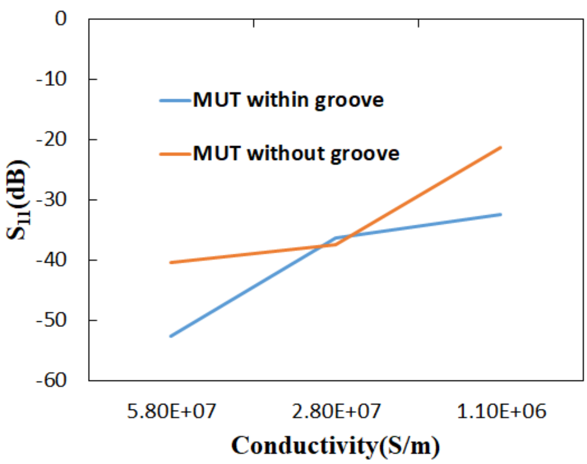


Fig. 9. Reflection coefficient variation with conductivity

IV. Conclusion

A novel microwave sensor is designed, fabricated, and tested for determination of the conductivity of the materials. The proposed structure resonates at the target frequency of 5 - 5.2 GHz and yields consistent results when toroidal split ring/wire MUT of thickness ≤ 1 mm is placed in the groove. Additionally, the sensor is easy to fabricate, does not require any complex setup and provides a sensitivity of 3.6 dB/unit change in conductivity. Even though the process is like the eddy current probe method the restrictions of maintaining probe size and test bench temperature are eliminated. The sensor would prove to be highly useful in generating a reference set of reflection coefficient values corresponding to electrical conductivity values of different metals and alloys thereby making the selection of highly conductive metals and their alloys feasible for critical applications as in aerospace and defense for avionic buses, smart ammunitions, targeting systems etc. The proposed sensor could be excited wirelessly as it resonates in UNII Wi-Fi band and could also help detect presence of unwanted metallic ions in potable or ground water with minor changes in structure. The layout is indeed a novel prototype, as in all the earlier reported work such simple grooved sensor structure excited with plane wave has not been used for metal conductivity detection.

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TABLE 4
COMPARISON WITH OTHER WORKS BASED ON ELECTRICAL CONDUCTIVITY OF METALS

Ref. No.	Appln.	Technology Used	*f* (GHz)	Sensitivity	Sensor Size (cm^2)	Contact/Non-Contact Sensing
[26]	Metal-ion detection in water	LTCC based LC resonant structure microfluidic sensor with peristaltic pumps	0.160	0.47 dB/% concentration.	4.1 X 2.8	Contact
[27]	In-situ monitoring of trace metals in polluted water	PTFE based 8 pair IDE sensor	0.05, 0.44, 0.76	0.38 dB/% concentration.	3 X 2	Contact
[28]	Metal crack detection	Direction sensitive Rectangular Patch Resonator	2, 2.485	6.1 MHz and 1.93 MHz/5^0 change in direction.	5 X 4	Contact
[29]	Zinc corrosion detection	PVD based zinc wire etched resonator	2.45	0.45 dB/unit change in electrical conductivity.	2.5 X 2.5	Contact
[30]	Detect and classify precious transition metals	Quadruple concentric circular split ring resonator	2-8	-	10 X 6	Non-contact
This work	Conductivity detection of MUT	Complementary Ring Structure based microwave sensor with toroidal cavity for MUT	5.2	3.6 dB/unit change in electrical conductivity.	4 X 4	Contact