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Temperature Dependence of Relative Permittivity: A Measurement Technique Using Split Ring Resonators

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Abstract**—**A compact method for measuring the relative permittivity of a dielectric material at different temperatures using a single circular Split Ring Resonator (SRR) metamaterial unit working as a test probe is presented in this paper. The dielectric constant of a material is dependent upon its temperature and the *LC* resonance of the SRR depends on its dielectric environment. Hence, the temperature of the dielectric material in contact with the resonator influences its resonant frequency. A single SRR placed between transmitting and receiving probes connected to a Vector Network Analyser (VNA) is used as a test probe. The dependence of temperature between 30 ºC and 60 ºC on resonant frequency of SRR is analysed. Relative permittivities 'ε' of test samples for different temperatures are extracted from a calibration graph drawn between the relative permittivity of samples of known dielectric constant and their corresponding resonant frequencies. This method is found to be an easy and efficient technique for analysing the temperature dependent permittivity of different materials.

Keywords**—**Metamaterials, negative permeability, permittivity measurement techniques, split ring resonators, temperature dependent dielectric constant.

I. INTRODUCTION

AMONG the material characterization studies, the precise determination of dielectric constant at different working environments is important from the application point of view. Out of these different parameters, the variation of dielectric constant with temperature finds its use in different sensor applications in the fields of medical instrumentation, electronic and electrical industry etc. This dependence of dielectric constant on temperature for different materials is already reported [1], [2].

There are several techniques described in the literature to determine the dielectric constant at different temperatures [3], [4]. Among these different techniques, open-ended coaxial probe method, cavity resonance methods, quasi-optical resonator method, split-cylinder resonator method etc. are commonly employed [5], [6]. Many of these methods require specific working conditions to be satisfied for the precise determination of the above-mentioned variation of temperature on relative permittivity. In this paper, we present an efficient and simple method for the measurement of dielectric constant variation with temperature using a SRR metamaterial unit [7], [8].

SRRs are constituent molecules of metamaterials showing negative permeability. SRRs present exotic resonant nature which is highly dependent upon the structural parameters of the resonator and the dielectric environment associated with them [9]-[11]. Since the resonant frequency of the SRR changes with different physical working parameters, they find a number of applications in different microwave employed fields. In literature, the effect of dielectric constant on the resonant frequency of SRR is investigated [12]-[16]. As the properties of the metallic resonator structure and the dielectric substrate upon which it is fabricated are all temperature dependent, SRR is also sensitive to temperature variations. The temperature dependence of SRRs is extensively studied [17] in terms of the thermal expansion of the SRR ring and the temperature dependence of substrate permittivity. In that work, with support of sufficient theory, they have shown that the resonant frequency decreases due to increase in temperature by the contributions due to the change in dielectric constant of the substrate and the thermal expansion of the rings. Singh et al. studied the effect of temperature on terahertz metamaterial fabricated on strontium titanate substrate [18].

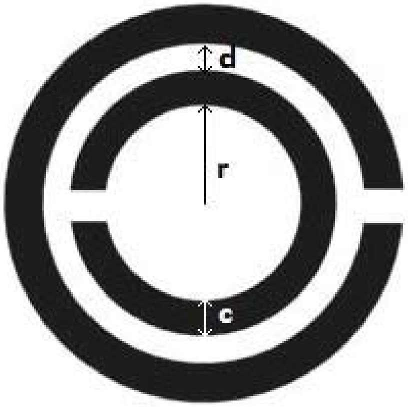

Fig. 1 Schematic representation of the SRR with its structural parameters - inner radius *r*, ring width *c* and spacing *d*

The structure of circular SRR with its parameters is represented in Fig. 1. It composes of two concentric metal rings of width *c* and spacing *d*. The radius of the inner ring is *r*. The two metal rings have small splits on the diametrically opposite sides of the structure. The *LC* resonant nature of the SRR arises from the capacitance and the inductance of the two rings due to charges and currents induced in them by applied electromagnetic field. The resonant frequency of the SRR is given by:

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$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where L is the inductance and C is the capacitance [7], [19]. Out of these, capacitance C is strongly dependent upon the temperature dependent permittivity of the environment of the SRR ring which include both the substrate and the test sample which we place above the SRR. The proposed method is much easier and efficient than the previously used methods. Here we use an extraction procedure from the calibration curve of known dielectric samples and their resonant frequencies.

II. EXPERIMENTAL SETUP AND MEASUREMENTS

SRR of dimensions $r = 2$ mm, $d = 0.5$ mm and $c = 0.75$ mm is etched on a glass epoxy board ($\varepsilon_r = 3.7$) using photochemical etching method. A single SRR is used as a test probe and is placed between transmitting and receiving probes which are connected to a VNA and the schematic diagram is given in Fig. 2 [20]. Resonant frequency of SRR at room temperature (33 °C) is found to be 3.56 GHz (f_{r0}). When a planar sample material of thickness (t) is placed on the surface of the SRR, its resonant frequency decreases from f_{r0} due to increase in capacitance of the resonating structure. It is observed that the resonant frequency decreases with increase in t up to a particular thickness $c+d/2$ and above that it becomes constant. It is due to the fact that for thickness greater than or equal to $c+d/2$, the electric field due to the induced charges on the SRR is completely within the dielectric sample.

Fig. 2 Schematic diagram of the SRR placed between transmitting and receiving probes

For drawing the calibration graph, we have selected the dielectric samples of glass, glass epoxy board, perspex and plastic. They are then placed on the surface of SRR and their resonant frequencies in GHz obtained are 2.647, 2.863, 3.118 and 3.254 respectively. In Fig. 3, the transmission curves for these four samples which are used for calibration are plotted. The dielectric constants of these samples are measured using cavity perturbation method [21] and the values obtained are 6.07, 3.571, 2.45 and 2.1 respectively. In Fig. 4, we plot these resonant frequencies with their corresponding dielectric constants. It is observed that resonant frequency decreases as the dielectric constant of the material increases. Relative permittivity of any unknown test sample placed over the SRR can be extracted using the corresponding resonant frequency from this calibration graph.

TABLE I
RESONANT FREQUENCY AND RELATIVE PERMITTIVITY OF VARIOUS SAMPLES CORRESPONDING TO DIFFERENT TEMPERATURES

Temperature (°C)	f_{r0} (GHz)
35	3.5613
40	3.5515
45	3.54
50	3.5199
55	3.4911

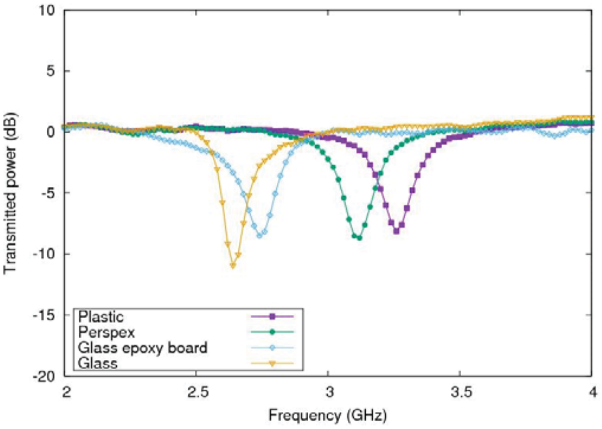

Fig. 3 Transmission curves of SRR when different dielectric materials of known dielectric constant are placed on its surface

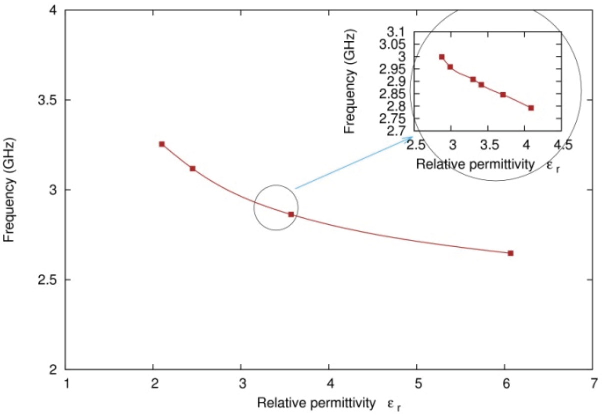

Fig. 4 Calibration graph between the resonant frequency and the relative permittivity: The inset shows the magnified view of the frequency-permittivity graph for the temperature dependent permittivity region of the sample

To study the temperature dependence of dielectric constants we choose four test samples *viz.* two glass epoxy samples, perspex and plastic. The temperature of the test sample placed over the SRR is gradually increased using light focused from an incandescent lamp. The temperature measurements are done using an ordinary thermometer. Schematic diagram for experimental setup with sample on the SRR and light incident on the surface is shown in Fig. 5. Resonant frequency of SRR without the sample is taken as f_{t0} for different temperatures and values obtained are given in Table I. Then, different test samples are placed on the SRR and their corresponding values are measured as f_{t1}. Temperature is gradually increased and the measurements are given in Table II. The shift in resonant frequency (f_{r0} - f_{t0}) is calculated for each temperature and it is subtracted from the resonant frequency f_{t1} as a correction.

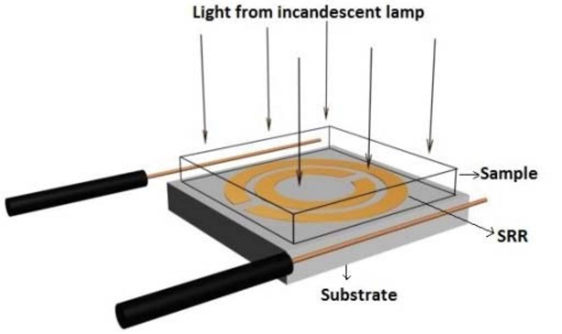

Fig. 5 Schematic diagram of the experimental setup with sample placed on the SRR and light incident on its surface

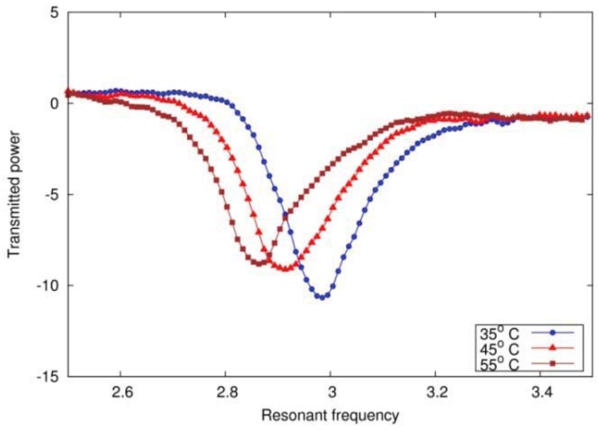

Fig. 6 Tansmission curves at different temperatures of SRR when glass epoxy sample - 1 is placed on the surface

Fig. 6 shows the transmission curves for SRR at three temperatures (35, 45 and 55 ºC) when glass epoxy sample-1 is placed on the surface. It shows a resonant frequency shift of 41.4 MHz for a temperature change of 20 ºC.

III. Results and Discussions

The relative permittivities corresponding to the corrected resonant frequencies *f* for different temperatures are extracted from the calibration curve (Fig. 4) for all the four test samples. One example is given as the inset of Fig. 4 which shows the magnified view of the frequency-permittivity graph for the temperature dependent permittivity region of glass epoxy sample-1.

TABLE II
Resonant Frequency and Relative Permittivity of Various Samples Corresponding to Different Temperatures

Sample	Temperature ºC	f_{t1} (GHz)	$f=f_{t1}-(f_{r0}-f_{t0})$ (GHz)	Relative permittivity from the graph (ε_r)
Glass epoxy 1	35	2.974	2.9847	2.9885
	40	2.958	2.9078	3.3000
	45	2.9104	2.8864	3.4114
	50	2.8899	2.8458	3.7066
	55	2.8654	2.7925	4.0873
Glass epoxy 2	35	2.903	2.9003	3.7797
	40	2.9001	2.8876	3.8718
	45	2.88	2.856	4.0947
	50	2.87	2.8259	4.3565
	55	2.8499	2.777	4.7490
Pespex	35	3.0920	3.0893	2.7182
	40	3.0878	3.0753	2.7668
	45	3.0807	3.0567	2.8732
	50	3.0607	3.0166	3.0768
	55	3.0495	2.9766	3.2997
Plastic	35	3.2640	3.2613	2.0796
	40	3.2543	3.2418	2.1188
	45	3.2006	3.1766	2.2959
	50	3.1882	3.1441	2.3814
	55	3.1632	3.0903	2.5124

From the values given in Table II, we can see that as the temperature increases from 35ºC, to 55ºC, the resonant frequency decreases and the dielectric constant increases accordingly. Analysing Table II, we observe that an increase of temperature by 20ºC causes a small decrease in resonant frequency for all the samples. However, the corresponding change observed in dielectric constant is noticeable. Out of the four test samples, the two glass epoxy samples show similar behaviour and are observed to be much sensitive to temperature changes. They have shown a change in dielectric constant of around 0.05 per degree Celsius. The other two samples, perspex and plastic, show relatively small change in dielectric constant which is around 0.025 per degree Celsius.

IV. Conclusion

In this work, we have presented a method for measuring the relative permittivities of dielectric materials at different temperatures using metamaterial SRR as a test probe. By using this method, we can find out the temperature dependent dielectric constant of any planar dielectric sample, provided its resonant frequency is on the calibration curve. This method proves to be a precise and easy measurement technique compared to many other characterization methods to find the temperature dependence of dielectric constant. This method may be extended to a wide range of temperatures by properly modifying the experimental setup.

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