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Broadside Coupled Split Ring Resonator Metamaterial Structure for Sensitive Measurement of Liquid Concentrations

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Abstract. This paper describes a simple and quick method to determine the concentrations of aqueous solutions using a Broad Side Coupled Split Ring Resonator (BCSRR) metamaterial structure operating at microwave frequencies. A capillary tube is placed between the symmetrically arranged BCSRR rings fabricated on two separate strips of the same substrate in such a way that the sample comes along the split-gap of the rings where the field concentration is maximum. As the sample liquid enters to the capillary tube, a resonance frequency shift is observed with respect to the variation in concentration. Resonance frequency shifts of the BCSRR due to varying concentrations (0-2 M) of Sodium Chloride (NaCl) and Potassium Chloride (KCl) solutions are measured using Vector Network Analyser (VNA) by arranging the transmitting and receiving probes of the VNA on the two sides of the BCSRR test setup.

INTRODUCTION

Metamaterial based Split Ring Resonator (SRR) structures have gained great significance as near field sensors in various industrial, scientific and medical applications.[1-4] SRRs, the negative permeability part of the metamaterial structure, are of small size compared to the excitation wavelength of the interacting electromagnetic fields and possess unique electromagnetic properties leading to various sensor applications. Different variants of SRRs have gained extra attention in recent decades and a plethora of attempts have been made to utilize them as sensing probes for concentration measurements.[5,6] Accurate liquid concentration measurements have become much important in research in recent years due to its practical applications in medical, food, oil and pharmaceutical industries.[7-9]

Though SRRs have been widely used as concentration sensors, Broadside Coupled Split Ring Resonators (BCSRR) are seldom seen in literature for this purpose. This paper presents a method for accurate measurement of concentration of aqueous solutions by using BCSRR rings fabricated on two separate substrates of the same material capable of spacing variation between the rings.[10] The near field perturbations caused by allowing the liquid sample to flow through a microfluidic channel set between the rings of the BCSRR will result in changes in resonant frequency from which sensitive measurement of concentrations can be achieved. Though there are various methods to find concentration available in the literature, this method intends to utilise the sensitive response of BCSRR to the perturbations in its near field.

EXPERIMENTAL SETUP

The rings of the BCSRR used for the measurement setup is fabricated on two pieces of FR4 epoxy of thickness 0.8 mm and dielectric constant 4.4. The inner radius and the width of the rings are 2 mm and 1 mm respectively. The spacing between the rings of the BCSRR is fixed as 1 mm and a capillary tube of outer diameter 1 mm and inner

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diameter 0.6 mm is inserted in between them. The capillary tube is carefully positioned vertically in such a manner that it is in line with the diametrically opposite splits of the BCSRR, the region where the field concentration is a maximum. Figure1. shows the schematic representation of the experimental setup.

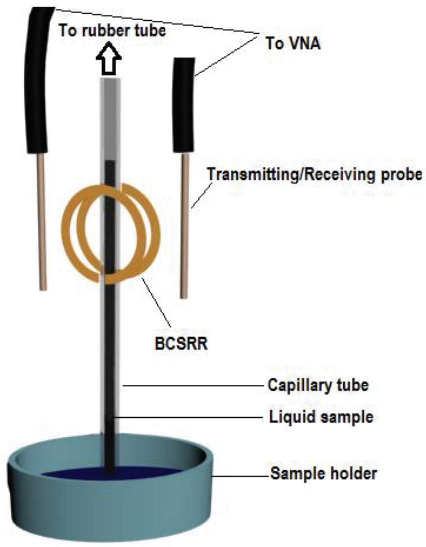

FIGURE 1. Schematic representation of the experimental setup

The test samples of Sodium Chloride (NaCl) and Potassium Chloride (KCl) solutions of various molar concentrations are prepared by weighing stoichiometric amount of salt and dissolving it in the required volume of distilled water. The lower end of the capillary tube is immersed into a sample holder containing the experimental liquid and a narrow rubber tube and clip arrangement along with a rubber bulb attached to the upper end of the capillary tube is used to raise the liquid upto a minimum height of the top end of the BCSRR. In order to study the resonant properties of the BCSRR setup, two electrical probes are connected to a Vector Network Analyzer (VNA), one acting as the transmitter and the other as the receiver. They are arranged parallel to the plane of BCSRR. The sample holder and the capillary tube are arranged on a setup having sensitive X-Y-Z micrometre movement for avoiding undesired errors which may occur due to unexpected misalignments in the test probe region.

MEASUREMENTS AND RESULTS

The resonant frequency f of the BCSRR depends on its intrinsic capacitance (C) and inductance (L) and is given by,

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

When the liquid enters through the capillary into the space between the SRR rings, its effective capacitance increases, resulting in a corresponding decrease in the resonant frequency, which will be in relation to the concentration of the sample. The resonant frequencies corresponding to four standard samples of known concentrations are obtained for drawing a calibration curve between the resonant frequency shift and the concentration. With the help of this calibration graph, any unknown concentration of the same liquid can be extracted by obtaining its corresponding resonance shift.

Transmission spectra corresponding to the BCSRR along with the empty capillary tube placed between the BCSRR rings is given in Fig.2. It also shows the transmission curves obtained for NaCl solutions of different concentrations. It depicts the shifts in frequencies due to the changes in concentrations. Table1 gives the molar concentrations and the corresponding resonant frequencies of standard samples of NaCl. A calibration graph showing the frequency shift is then plotted as a function of the concentration and is given in Fig. 3(a) for these four known concentrations of the experimental liquid. Fig.3(b) is a similar calibration graph obtained for KCl which exhibits the same behaviour as that of NaCl.

TABLE 1. Molar Concentration and resonant frequency of standard samples

Molar Concentration (M)	Resonant Frequency (GHz)
0.2	0.0039
0.8	0.00974
1.4	0.0158
2.0	0.02188

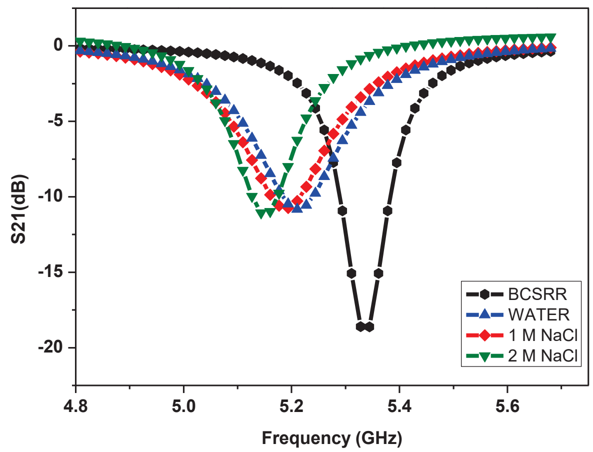

FIGURE 2. Transmission spectra corresponding to the BCSRR test setup with and without liquid samples

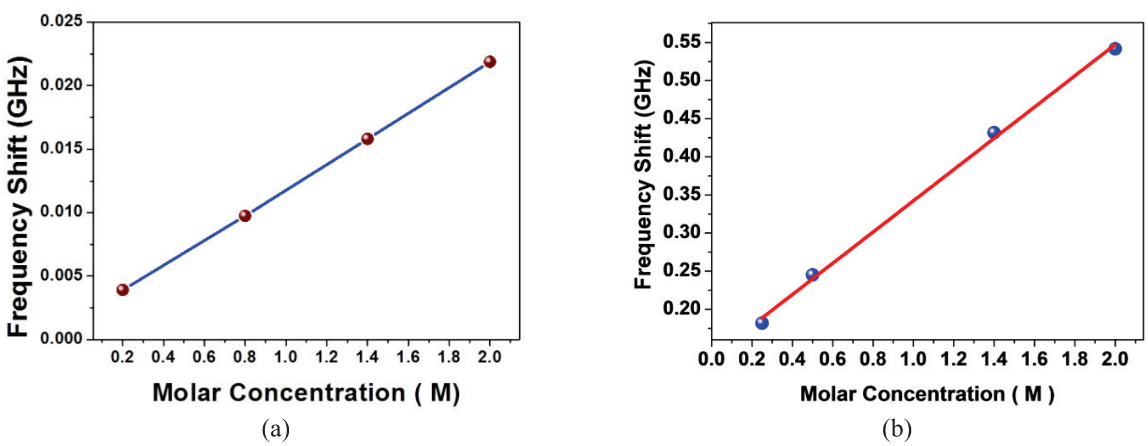

FIGURE 3. Calibration graphs obtained from the frequency shifts for (a) NaCl solution and (b) KCl solution

It is observed that the shift in frequency is appreciable even at low concentrations and the shift increases with increase in concentration. From the calibration graph obtained with known concentrations, we can determine any unknown concentration of the same solution by interpolation technique after obtaining the corresponding frequency shifts. Table 2 gives the concentration determined from the resonant frequency shifts using the calibration curves for three NaCl samples whose concentrations are taken as unknown. The actual values of concentrations of these three samples are also given in Table 2 for comparison.

TABLE 2. Resonant frequency and corresponding molar concentration of NaCl samples extracted from the calibration curve.

Resonant shift (GHz)	Concentration from Calibration(M)	Concentration Calculated (M)
0.0068	0.5003	0.5
0.0118	1.0055	1.0
0.0168	1.5038	1.5

The dependence of dielectric properties on the resonant frequency enables the possibility of utilizing the BCSRR structure as a probe to precisely determine the concentration of the various solutions. One distinct advantage of this BCSRR based method is that it can be used for the accurate determination of the concentration of liquids even if it is of very low value. Once the calibration graph is made ready, it takes very little time for the measurement of concentration of the liquid samples.

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