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Non-Invasive Dielectric Characterization of Chemical Solvents using Microstrip-Fed Dielectric Resonator based Sensor

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Abstract

This paper presents a square ring dielectric resonator (DR) based sensor for non-invasive characterization of the liquids. The DR is excited in $TE^{x}_{\delta 11}$ mode using a conformal strip connected to microstrip line. The technique is based on the perturbation theory in which a hollow cylindrical core is made in the DR to hold the liquid test specimen. The proposed sensor system is simulated using the frequency domain solver of CST Microwave Studio for wide range of dielectric constant of the test specimens and an empirical relationship between the dielectric constant and shift in the resonant frequency is proposed. The proposed sensor is simple and doest not require any external sample holder to place the liquids. Moreover, the sensor shows the appreciable sensitivity of 50 MHz, which is more than the earlier reported DR based sensors. It is found that the proposed sensor gives a maximum of 2% error in the extracted value of the dielectric constant of various chemical solvents.

1 Introduction

The dielectric materials having different molecular structure shows dynamic response to the applied electric field, thereby showing unique dielectric spectrum in the RF and microwave range [1]. This uniqueness property allows to characterize the material property such as complex permittivity using RF and microwave sensor and finds application in chemical, biomedical and pharmaceutical sciences. Nowadays, the RF and microwave sensors are more popular because of their non-invasive and non-destructive capability of material characterization.

The material characterization techniques can broadly be classified into two types *viz.* non-resonant and resonant, among which the resonant method is relatively more accurate and has been widely practiced [2]. The most popular and conventional resonant technique includes the metallic cavity which basically employs the perturbational approach to determine the dielectric properties of the materials [3]. However, the size, weight, and design complexity of the conventional metallic structure make it less popular and the researchers are now moving towards the planar resonant sensors. Over the past few years, the planar resonant sensors were designed using the popular structures such as interdigital capacitor (IDC) [4, 5], split-ring resonator (SRR) [6, 7], complementary split-ring resonator (CSRR) [8, 9], electric LC (ELC) resonator [10] and substrate integrated waveguide (SIW) and cavity [11–14]. The planar sensors are popular because of their low profile geometry and fabrication simplicity. However, the associated fringing field and presence of inevitable air gap between the test specimen and sensor reduces the measurement accuracy relative to the conventional resonant based sensors. Moreover, the planar sensor and metallic cavity based sensor requires a sample holder to place the material for characterization. The misalignment of the sample holder with respect to the resonator might affect the characterization process, resulting in reduced accuracy.

Another interesting resonant based sensor uses dielectric resonator to characterize the material property. As compared to conventional metallic resonant cavity sensor, the DR based sensor has several potential characteristics such as light weight, compact, lesser design complexity etc. Moreover, the perturbed region in the DR can be used as a sample holder for testing the material. Thus, an external sample holder is not required to place the test specimen, which otherwise be required for planar and metallic cavity based sensors. Over the past, several DR based sensor has been reported and investigated for various applications [15–19]. The split-post DR design in [15] cannot be used for the characterization of liquids. The design in [16] has employed dielectric rod resonator for the dielectric measurement and for the samples such as liquid, it is bit difficult to make them in the form of rod and this limits its use for the characterization of liquid samples. In [17], the dielectric ring resonator has been coupled through two output probes to excite the particular mode for the moisture content measurement. The proposed design has the sensitivity of 1.0 MHz frequency shift per 1.0% change of moisture content. In [18], a dielectric resonator based microwave probe has been presented for the characterization of oil samples. The presented design consist of DR resonant circuit which is coupled to a commercially available gold-coated tungsten needle. The resulted the design was quite complex and moreover, it has very less sensitivity. A cylindrical dielectric resonator working in $TM_{01\delta}$ mode has been loaded with a capillary tube for the liquid sample characterization which offers a sensitivity of only 6.6 MHz.

It is mainly due to the above mentioned facts that in this paper a square ring DR based resonant sensor is proposed for the characterization of chemical solvents. In the proposed design, the liquid specimen is placed inside the hollow core made in the square DR which is excited in $TE^x_{\delta 11}$ mode using the conformal strip connected to 50 Ω microstrip line. The proposed sensor system is numerically simulated using the frequency domain solver of CST Microwave Studio (CST-MWS) for wide range of dielectric constant of the test specimens. From the extensive numerical analysis, an empirical relationship between the permittivity of the specimen and the shift in resonant frequency is presented. It is found that the proposed sensor gives a maximum of 2% error in the extracted value of dielectric constant at the designed frequency of resonant sensor.

2 Sensor Design

Figure 1 shows the schematic of the proposed sensor based on the square DR. The DR is made of Rogers RT/Duroid 6010 of relative permittivity and height $H_{DR} = 7.62$ mm. The lateral dimension of the DR is 16 mm. The square

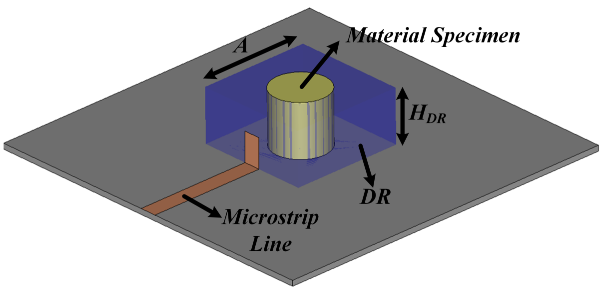

Figure 1. Schematic of the proposed sensor design

DR is excited in $TE^x_{\delta 11}$ mode using the conformal strip connected to 50 Ω microstrip line. For the given dimension of the DR the theoretical resonant frequency calculated using the equations given in [20] is 4.73 which reasonably agrees with the simulated value of 4.80 GHz.

The electric field distribution in the DR at 4.8 GHz is depicted in Figure 2. From the figure, it is observed that the electric field is stronger at the center of the DR and therefore, for the better interaction between the field and test specimen a hollow core of radius R is made at the center. This hollow core is used to hold the test specimen (chemical) for the testing purpose. From the full wave simulation, it is observed that the large perturbation in the DR help in better interaction of the field with the specimen, thereby improving sensitivity which is defined as the shift in resonant frequency for the unit change in dielectric constant of the test specimen. It is found that the for $R = 4$ mm the sensitivity is around 50 MHz whereas for $R = 1$ mm its value is 8 MHz. Here it is notes that the increase in radius beyond certain limit results into violation of the small

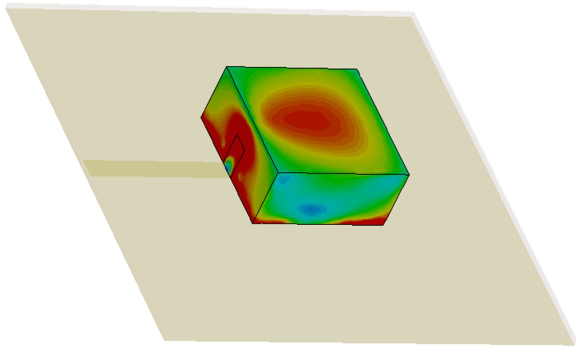

Figure 2. Magnitude of electric field distribution in square DR at 4.8 GHz

perturbation theory leading into large error in the extracted dielectric constant, thereby reducing the accuracy. In the proposed work, accuracy of the extracted parameter is ensured by using the suitable empirical relationship rather than analytical approach. The diameter of the hollow core region is limited as 4 mm for the error tolerance level of 2%.

Figure 3 shows the resonant frequency (f_R) and the shift in resonant frequency (Δf) for the wide range of dielectric constant (ε_r: 1 to 45). The plot is generated

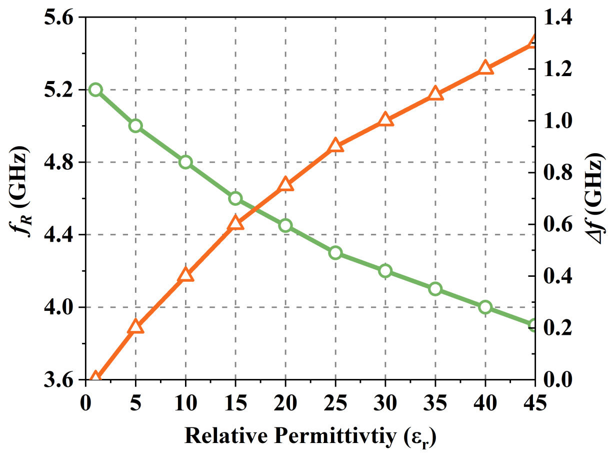

Figure 3. Plot of relative permittivity versus f_R and Δf

using the reflection coefficient (S_{11}) by placing material of different relative permittivity in the hollow core. Using the extensive numerical data, an empirical relation between Δf and ε_r is determined using curve fitting. The expression is given as,

$$\varepsilon_r = p_1 \Delta f^3 + p_2 \Delta f^2 + p_3 \Delta f + p_4, \tag{1}$$

where $p_1 = 7.6446$ $p_2 = 1.6626$ $p_3 = 17.972$ $p4 = 1.0309$.

3 Results and Discussion

The empirical relation developed in the previous section is now utilized to extract the dielectric constant of the unknown test specimen. Table 1 shows the reference value and the extracted values of the relative permittivity. It is to be noted that the error in the extracted values using the proposed method is below 2% which is much lesser than that the error reported in the earlier literature [4, 5, 8, 9, 11, 13].

4 Conclusion

In this paper, a resonant type sensor has been proposed which comprises of a square DR with a central hollow core region to hold the liquid sample. The proposed sensor has been simulated using the frequency domain solver of CST Microwave Studio for wide range of dielectric constant and an empirical formula between the dielectric constant and the shift in resonant frequency has been proposed. The DR based sensor has the advantage of simple design and moreover, it doest not require any external sample holder to place the test samples. The proposed sensor shows the appreciable sensitivity of around 50 MHz. Using the proposed sensor, the dielectric constant of various chemicals such as acetone, ethanol, chloroform, hexane, benzene, chlorobenzene, tetra hydrofuron and ethyl glycol has been extracted and a maximum of 2% error has been reported.

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Table 1. Chemical characterization using DR based resonant sensor

Chemicals	Ref. Value	Extracted Value	% error, proposed	% error, reported/ Reference
Hexane	1.86	1.82	2.15	3.84, [4]
Benzene	2.3	2.26	1.74	4.4, [4]
Chloroform	4.8	4.75	1.04	3.32, [5]
Tetra hydrofuron	7.5	7.37	1.73	4.80, [8]
Chlorobenzene	5.62	5.54	1.42	2.7, [9]
Ethanol	24	23.84	0.60	6.39, [11]
Ethylene Glycol	37.29	37.09	0.54	3.78, [11]
Acetone	21.3	21.31	0.05	7.51, [12]

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