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A Low Cost Planar Resonant RF Sensor for Permittivity Measurement of Solid and Liquid Materials

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Abstract

A low cost planar resonant RF sensor for permittivity measurement of solid and liquid materials is proposed in this paper. A quarter wavelength resonator realized using microstrip line technology acts as a quasi static near field sensor. The resonant frequency of the sensor varies with the dielectric properties of the test sample in contact. A mathematical model based on finite element method is developed to determine the permittivity of dielectric test samples. The proposed sensor is designed to operate in 2.42 GHz ISM band. As a proof of concept, a prototype is fabricated on FR4 substrate of 1.6 mm thickness. The performance of the fabricated prototype is validated by measuring the permittivity of some commercially available substrates and vegetable oil samples. The measurement results showed a good agreement with the data available in the literature. The single port architecture of the planar sensor facilitates direct immersion in liquid samples. Moreover, this technique does not pose any limitations on thickness of solid test samples. The proposed submersible sensor is simple, compact, low cost and easy to fabricate which promotes its wide spread usage for microwave material characterization.

1 Introduction

Microwave material characterization has wide range of applications such as designing of efficient microwave circuits or devices, label free chemical sensing, quality assessment, biomedical sensing applications etc. Different material characterization techniques are reported in literature for the estimation of electromagnetic properties of materials viz. cavity perturbation technique, free space methods, transmission line methods, planar near field sensors etc. Among these, resonance techniques are widely preferred methods due to the accurate determination of material properties at single or discrete frequencies. Traditional metallic cacities used in the widely used cavity perturbation techniques are bulky and expensive [1]. Therefore, the recent trend in the development of resonant material characterization techniques is to use planar resonant structures such as microstrip ring resonators [1], split ring resonators (SRRs) [2], complementary split ring resonators (CSRRs) [3] and different metamaterial inspired resonators [4],[5]. These planar sensors could be used to replace expensive microwave cavity resonators due to its various attractive features such as compactness, low cost, lightweight, ease of fabrication and compatibility for lab-on-chip applications. Most of the planar sensors reported for the dielectric characterization of liquid as well as solid materials are not submersible and they pose restrictions on the thickness of solid test samples [2]-[4]. The proposed sensor allows the permittivity measurement of arbitrary thick dielectric samples and its submersible architecture facilitates the direct immersion in liquid test samples.

In this paper, a microstrip line based resonant sensor is proposed for the retrieval of permittivity of solid and liquid materials. The planar sensor consists of a quarter wavelength quasi-static resonator which is used as a sensing probe for the precise characterization of test samples. A numerical model based on finite element method is used to develop empirical formulas for determining the permittivity of the material under test. This technique allows the use of substrate materials in their commercially available thickness as it does not pose any limitation on the thickness of solid test samples in the permittivity measurement. Moreover, it eliminates the possibility of air gaps generation due to the stacking of multiple dielectric layers in order to minimize the effect of sample thickness variations. In addition, the single port architecture of the proposed sensor facilitates easier immersion in liquid samples and thereby eliminates the need of complex and expensive microfluidic channels [5]. This technique incorporates the advantages of conventional cavity perturbation technique such as high accuracy, improved sensitivity and the attractive features of microstrip near field sensors such as compactness, low cost and easier fabrication process. The proposed sensor could be a simple and economical method for material characterization.

2 Sensor Design and Operation Principle

The geometry of the proposed microstrip line based resonator is illustrated in Fig. 1. A microstrip line is printed on a grounded FR4 epoxy (ε_r = 4.4, tan δ = 0.02) substrate of $32 \times 20 \times 1.6mm^3$. The input microwave signal is applied at one end of the microstrip line and the other end kept open. A metallic via of 0.5 mm radius is introduced between the microstrip line and the ground at the center of the signal strip. A circular metallic structure of radius 3.5 mm is designed symmetrically around the metallic via. The loading of this circular metallic structure increases the impedance matching of the proposed resonator. The microstrip line based sensor is designed to operate at 2.42 GHz of the ISM band and the optimized design parameters are given in Fig. 1.

Based on the electrostatic boundary conditions, the tangential electric fields are forced to be minimum at metallic via whereas maximum at the open end of the signal strip. Hence, the length of the signal strip between the metallic via and the open end (L_2) acts as a quarter wavelength resonant section. The resonant frequency (f_r) is related to the length of the resonant section (L_2) as:

$$L_2 + \Delta L_2 = \frac{n\lambda_g}{4} \quad (1)$$

$$f_r = \frac{nc}{4(L_2 + \Delta L_2)\sqrt{\varepsilon_{eff}}} \quad (2)$$

where λ_g is the guided wavelength, n is the order of resonance ($n = 1, 2, 3...$), c is the velocity of light in free space, ΔL_2 is the increment in resonant length due to fringing fields and ε_{eff} is the effective dielectric constant of the medium, which is given by [8];

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2} \frac{1}{\sqrt{1 + 12(\frac{h}{W_0})}} \quad (3)$$

where ε_r is the dielectric constant of the substrate, h is the height of the substrate and W_0 represent the width of microstrip line.

Resonant perturbation is the basic working principle of the proposed sensor. According to this theory, when a dielectric sample is kept in a region of electric field of a resonator, the sample perturbs the electric fields and causes a shift in the resonant frequency of the unloaded resonator. In this work, the planar RF sensor is used for the dielectric characterization of solid and liquid materials.

2.1 Permittivity Measurement of Solids

The electric field distribution of the proposed sensor at a resonant frequency of 2.4246 GHz is shown in Fig. 2. The open end of the microstrip line shows the maximum electric field intensity. Therefore, a rectangular region of $10 \times 5mm^2$ containing maximum electric field intensity has been chosen as the permittivity sensing zone in order to obtain maximum sensitivity. The microstrip line resonator loaded with dielectric sample of $10 \times 5mm^2$ is modelled using Ansys HFSS software. The shift in resonant frequency of the sensor with the variation in dielectric constant as well as the thickness of of the test sample is analysed and is illustrated in Fig. 3. A numerical model is developed using curve fitting technique and relative permittivity of test sample (ε_r') as a function of relative shift in resonant frequency ($\Delta f/f_0$) can be expressed as

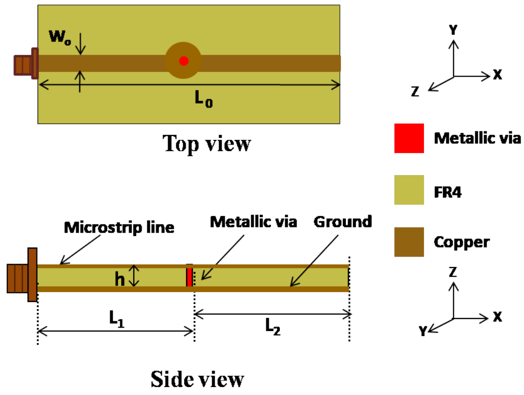

Figure 1. Schematic diagram of the proposed microstrip line sensor (L_0 = 32 mm, W_0 = 3 mm, $L_1 = L_2$ = 16 mm, h_0 = 1.6 mm).

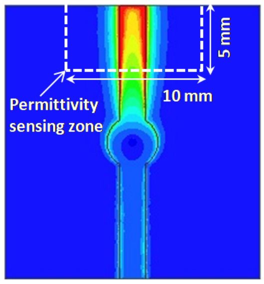

Figure 2. Electric field distribution at 2.4246 GHz (dark blue represents 0 V/m and dark red represents 69.28 kV/m respectively).

$$ln \mid \varepsilon_r' + p_1 \mid = \frac{\Delta f/f_0 - p_2 + p_3(1 - e^{-p_4(h_s/h)})}{p_5(1 - e^{-p_4(h_s/h)})} \quad (4)$$

$$\Delta f = f_0 - f_S \quad (5)$$

where h_s is the thickness of test sample, h is the height of the substrate, f_0 and f_s represent the resonant frequency of unloaded sensor and sensor loaded with test specimen respectively. p_1=2.5739, p_2 = 0.0008, p_3=0.1395, p_4=1.9817 and p_5=0.1068.

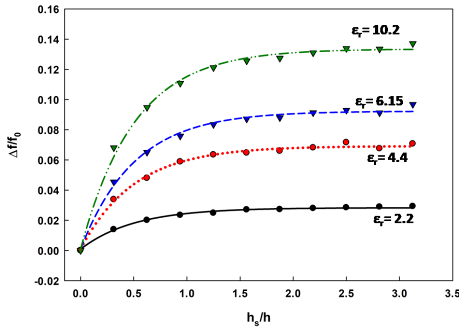

Figure 3. Response of the sensor for the variation in the thickness (h_s) of solid test sample.

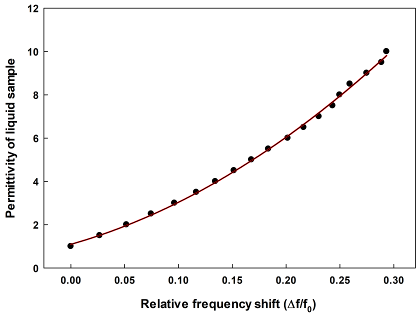

Figure 4. Response of the sensor for the variation in the permittivity of the liquid sample.

2.2 Permittivity Measurement of Liquids

The proposed sensor facilitates direct immersion in the liquid sample under test due to its single port topology. The microstrip sensor immersed in the liquid sample is modelled using Ansys HFSS software. The response of the aforementioned sensor with the variation in the permittivity of the liquid under test (LUT) is shown in Fig. 4. The following equation obtained using curve fitting technique provides good approximation for the permittivity of liquid sample under test (ε'_{LUT}).

$$\varepsilon'_{LUT} = m_0 + m_1\left(\frac{\Delta f}{f_0}\right) + m_2\left(\frac{\Delta f}{f_0}\right)^2 \qquad (6)$$

where m_0=1.0939, m_1=14.1099 and m_2=53.2035 respectively. f_0 and f_s represent the resonant frequency of stand alone sensor and the sensor immersed in liquid sample respectively.

3 Experimental Results and Discussion

The microstrip line resonator was fabricated on FR4 epoxy substrate of 1.6 mm thickness using standard photolithographic technique. The measurements were performed using Anritsu Vector Master MS2038C at room temperature. The reflection characteristics of the proposed sensor is shown in Fig. 5. The fabricated prototype exhibited a resonance at 2.4178 GHz which shows a good agreement with the EM simulation results. A slight shift in the resonance is observed due to tolerance in the standard fabrication. The photograph of the fabricated sensor is depicted in

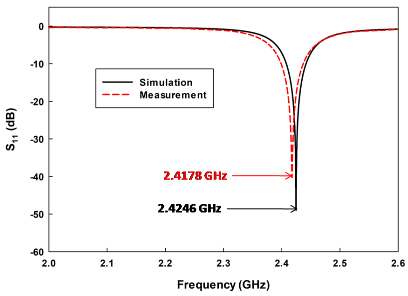

Figure 5. Reflection characteristics of the unloaded sensor.

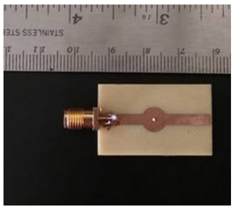

Figure 6. Photograph of the fabricated sensor.

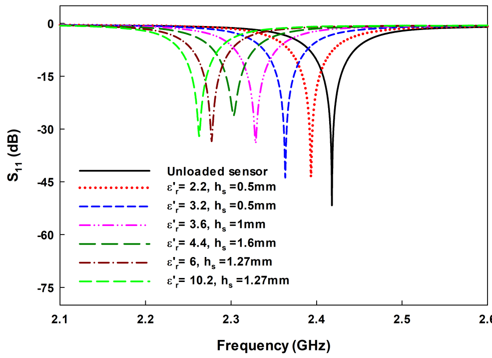

Figure 7. Measured response of the sensor loaded with different solid dielectric samples.

Fig. 6. Some of the commercially available dielectric materials were used as test specimens. Each dielectric substrate material was cut into $10 \times 5mm^2$ and the copper coating is removed using aqueous ferric chloride. The thickness of each solid sample is measured accurately using Vernier callipers. The test sample is loaded in permittivity sensing zone (depicted in Fig. 2) which has maximum electric field intensity. The measured response of the microstrip line sensor after loading with different solid test samples is shown in Fig. 7. The shift in resonant frequency of the sensor after loading with different test samples are measured and the permittivity of test samples were calculated using equation 4. The measured permittivity values are tabulated in Table 1, where the measured permittivity value of each sample is compared with the respective manufacturer's data sheet values.

To experimentally validate the ability of the proposed planar RF sensor in the dielectric characterization of liquid

Table 1. Measured dielectric constant of solid samples

Test samples	Thickness (mm)	ε_r	Measured ε_r
NYF220D	0.5	2.2	2.0899
TU933T	0.5	3.2	3.1746
Nelco N4103	1	3.6	3.5293
FR4 epoxy	1.6	4.4	4.2241
TMM6	1.27	6	5.8807
RT 6010	1.27	10.2	10.029

Figure 8. Experimental set up for the measurement of permittivity of liquid samples.

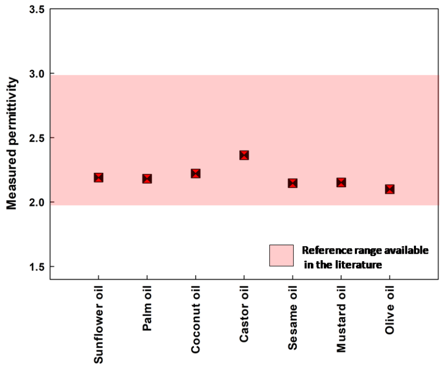

Figure 9. Measured permittivity of vegetable oils.

materials, different vegetable oils were used as liquid test samples. The fabricated sensor is immersed upto a reference level of 7mm of different liquid samples and the corresponding shift in the resonant frequency of the sensor is measured in each case. The experimental set up used for the permittivity measurement of liquid samples is illustrated in Fig. 8. The permittivity of each liquid sample is calculated using equation 6. The measured permittivity values are plotted in Fig. 9 and they showed acceptable accuracy when compared with the reference permittivity values of vegetable oils available in the literature (permittivity range from 2 to 3)[7],[8].

4 Conclusion

A microstrip line based resonant sensor designed at 2.42 GHz of the ISM band is fabricated and tested. The proposed sensor acts as a quarter wavelength resonator and the open end of the microstrip line sensor with maximum electric field intensity is used as a near field sensor head for relative permittivity measurements of solid and liquid samples. Resonant perturbation is operating principle of the prototype and the shift in resonant frequency of the sensor while loading with test samples is used to evaluate the material properties in the operating bandwidth. Empirical formulas are developed to determine the relative permittivity as a function of shift in resonant frequency of the sensor. The experimental validity of the fabricated sensor in solid and liquid dielectric characterization is shown by measuring the permittivity of some commercially available solid dielectric materials and some vegetable oils. The experimental results showed a good agreement with the permittivity values available in the literature. The proposed sensor could be considered as a potential candidate for microwave material characterization due to its compactness, low cost and ease of manufacture.

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