A Microstrip Folded Resonator Sensor for Measurement of Dielectric Constant

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Abstract- **A microstrip folded ring resonator sensor for measurement of dielectric constant in a compact area of material under test is proposed. The resonant characteristics of resonator vary with dielectric constant of material. Limitations in the microwave frequency response performances of the proposed sensor have been carefully studied in a range from 500 MHz to 3 GHz. It has been found that the proposed sensor has great potentials for practical applications in view of low cost and monolithic integration capability with a driving circuit.**

I. INTRODUCTION

In numerous measurements, a nondestructive monitorization of dielectric properties of materials is required. The microwave sensors are widely used for electromagnetic radiation of the microwave region. Microwave dielectric measurement methods generally fall into two categories: non-resonant and resonant methods. Reflection and transmission/reflection techniques are non-resonant methods [1]–[3]. Resonant methods, mainly including resonator and resonant perturbation methods, have relatively higher accuracy than non-resonant ones [4]–[6]. In resonant methods, the sample under measurement is introduced to a resonator thus altering the electromagnetic boundaries of the resonator, and the electromagnetic properties of the sample are deduced from the change of the resonant properties of the resonator. Due to its high accuracy and its flexibility in sample preparation, the resonant method is widely used for low-loss samples, powders, small size samples and samples of irregular shapes. The sensors based on waveguide and coaxial lines are bulky and are not convenient for integration with electronic circuits.

Planar transmission lines are used in order to develop compact sensors for measuring permittivity values [7]. Several investigators have used microstrip resonators for determination of dielectric constant and dielectric loss of materials. The resonator structure is very simple, low cost, and easy to remove samples. The microwave sensors based on a microstrip ring resonator sensor for the complex permittivity materials have been developed [8]-[10]. The microstrip ring resonator sensor is based on one wavelength of transmission line. Nevertheless, its large physical size can present a disadvantage, exceptionally for designs at low microwave
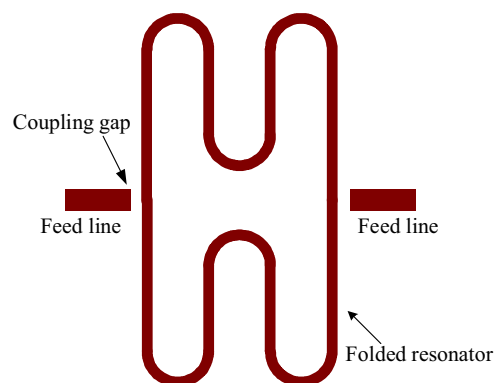

Figure 1. Plan view of microstrip folded resonator

frequencies. In this research, a folded structure is introduced which includes an ordinary sub circle, as shown in Figure 1. The microstrip folded resonator consists of symmetrically located input/output, microstrip feed lines, coupling gaps, and a microstrip line of one wavelength. The microstrip ring resonator uses a big size of samples, while the microstrip folded sensor is more suitable for a small area of dielectric under test (DUT).

This paper proposes a new microstrip folded resonant sensor to obtain high measurement performances for a liquid sample of dielectric constant including small size, low cost, and high sensitivity. The sensor allows monitoring the DUT properties by placing it above the microstrip (see an example
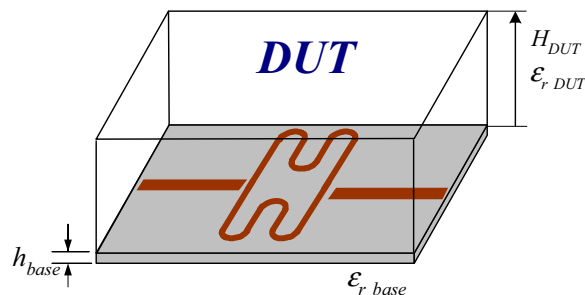

Figure 2. 3-D geometry of the proposed microstrip folded resonator sensor

of DUT location in Figure 2). We also compare the measurement results with the 85070E dielectric probe kit from Agilent. A 3-D geometry of the proposed microstrip sensor is shown in Figure 2. The microstrip folded resonant sensor is on a dielectric layer, called the base substrate. It has known that parameters include a thickness (h_{base}), a complex relative permittivity (ε_{rbase}) and a loss tangent ($\tan \delta_{base}$). The DUT is a dielectric layer of material with unknown dielectric constant ($\varepsilon_{r\,sample}$) and loss tangent ($\tan \delta_{sample}$), called the sample layer.

II. COMPARISON OF MICROSTRIP RESONATORS BETWEEN RING AND FOLDED STRUCTURES

The resonators with lengths of one wavelength at fundamental frequency of 1GHz in Figure 3 have been studied. A substrate of RT/Duroid 5880 (ε_r =2.2) has been used for all resonators, resulting in following parameters: coupling gap width = 0.35mm, substrate thickness = 1.575mm, microstrip line width = 5mm and total resonator length = 228mm, resonator width = 1mm. When comparing the physical sizes of all resonators, it has been found that the resonator A, a conventional ring resonator, has radial of circle = 36.5mm. For resonator B, we have folded the top and the bottom parts of resonator A, resulting in reduction of physical area about 36.44% of the original resonator. Resonator C, a double folded resonator, can reduce physical area about 49% of the resonator A. For resonator D, we have stretched the top and the bottom of resonator B, resulting in reduction of physical area size about 56.24% of the resonator A.

All resonator responses have been determined by using IE3D software. The simulated results of frequency responses for resonators A, B, C, and D are shown in Figure 4. The responses of the first six resonant modes (n = 1-6) for all resonators are shown in Table I. It can be seen that the folded resonators (resonators B, C, and D) have error values of resonant frequencies less than 0.67% at all resonant modes, except the resonator D which has error value for resonant frequency more than 2% at the fourth resonant mode.

Resonators B, C, and D have different insertion loss depended on a mode number of frequency response when comparing to Resonator A, a conventional ring which has linear insertion loss. However, the resonator D has the most compact size when comparing with other resonators and resonant frequencies are agree well for all mode numbers. Therefore, we finally choose the resonator D as a candidate sensor for dielectric measurement. The folded ring resonator parameters have been obtained in the following: W_{feed} = 4.825mm, L_{feed} = 10mm, L_1 = 10.64mm, L_2 = 42.56mm, W_{folded} = 1mm, r = 5.312 mm and g = 0.35mm. Both input and output ports are exactly equal to 50 Ω. The proposed resonator layout with all simensions is shown in Figure 5.

TABLE I
THE RESULTS SIMULATED IN FREQUENCIES RESPONSE ALL RESONATORS

Mode number (n)	Resonator A		Resonator B		Resonator C		Resonator D	
	f_n (GHz)	$\lvert S21 \rvert$ (dB)	f_n (GHz)	$\lvert S21 \rvert$ (dB)	f_n (GHz)	$\lvert S21 \rvert$ (dB)	f_n (GHz)	$\lvert S21 \rvert$ (dB)
1	1	-14.59	1	-17.27	1	-15	1	-19.94
2	2	-9.46	2.01	-10.18	2	-11.70	2	-7.63
3	3	-7.78	3	-5.80	2.99	-5.85	2.98	-6.24
4	3.99	-6.96	3.98	-11.24	3.97	-4.94	3.9	-14.66
5	4.99	-5.95	4.97	-10.72	4.94	-8.13	4.96	-9.35
6	5.98	-5.77	5.96	-9.60	5.94	-17.27	5.94	-7.50

(a) Resonator A

(b) Resonator B
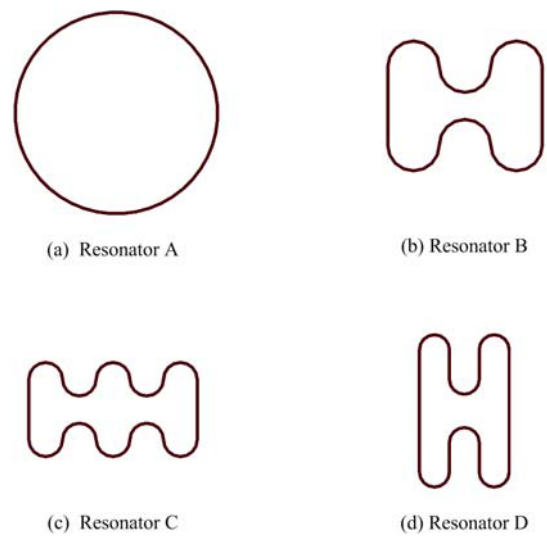
(c) Resonator C

(d) Resonator D

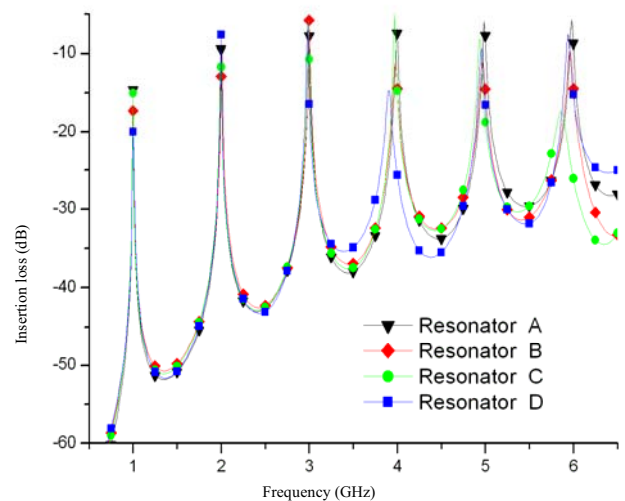Figure 3. A comparison of the folded ring and conventional ring resonator designed to operate at 1 GHz

Figure 4. Simulated transmission response of resonator A, B, C and D
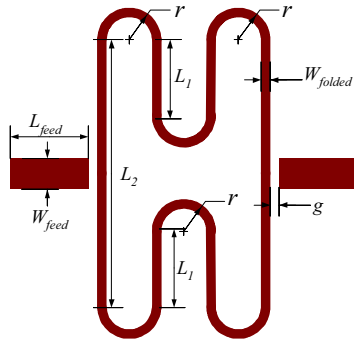
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Figure 5. The dimension of folded resonator for fabrication.

III. EQUATION OF DIELECTRIC CONSTANT AND MEASUREMENT

Using frequency domain measurement, (e.g. using a vector network analyzer), we can calculate the relative permittivity of the dielectric from the output resonance frequencies of the straight line resonator. Assuming λ_g is the wavelength in the straight line at the frequency f_r, we can write the following relation in accordance to the theory,

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_{eff}}} \qquad (1)$$

λ_g : wavelength of the wave with frequency f_r in free space,

$$\lambda_o = \frac{c}{f_r} \qquad (2)$$

From the folded resonator, when the total length (ℓ_F) is integer multiples of λ_g, the resonator becomes resonant. At this time, the output signal of the resonator achieves its maximum value. Hence, the resonant condition for the folded resonator can be written as,

$$\ell_F = n\lambda_g \qquad (3)$$

From (1), (2), and (3) we can write the relation between the measured resonance frequencies of the folded resonator, f_r and the relative permittivity of the used dielectric in this resonator, ε_{eff} as follows,

$$\varepsilon_{eff} = \left(\frac{nc}{\ell_F f_r}\right)^2 \qquad (4)$$

c : speed of the light in free space

f_r : resonant frequency

ε_{eff} : the effective dielectric constant

ℓ_F : total length of folded resonator

n : mode number or order of the resonant frequency

We then have simulated the proposed resonator with the dielectric constant (ε_r) of DUT using IE3D. The values of the dielectric constants have been varied from 1 to 6, resulting in several resonant frequencies. The relationships of the dielectric constant and the resonant frequencies for the first to three modes can be found as following,

$$\varepsilon_r = 261.7e^{-5.27f_{r1}} \qquad , \ n=1 \quad (5)$$

$$\varepsilon_r = 212.3e^{-2.53f_{r2}} \qquad , \ n=2 \quad (6)$$

$$\varepsilon_r = -3.73f_{r3}^3 + 30.55f_{r3}^2 - 88.03f_{r3} + 90.40 , \ n=3 \quad (7)$$

All three resonant frequencies can be measured by using the proposed resonator. Then these equations can be employed to determine the dielectric constant of the unknown DUT.

IV. DIELECTRIC CONSTANT MEASUREMENTS

The proposed folded resonator has beeen fabricated with all dimensions shown in Figure 5. The frequency responses have been measured using the HP8719ES network analyzer. In this measurement, the frequency range between 0.5 and 4.5 GHz is sufficiently covered for three resonant modes. Each DUT has been placed over the folded resonator with a height of 10 mm. All resonant frequencies of each material are shown in Figure 6. As the result, the resonances are shifted from the air-filled material and the unsalted butter obtains the most shifted resonance. It can be clearly seen that when ε_{eff} is increased, the resonance frequency f_r decreases, which related to (4). As using (5)-(7), the dielectric constant values can be calculated by taking the resonant frequency in each mode. The data of resonant frequencies from measurement and coresponding dielctric constants can be shown in Table II. The results can be also shown in Figure 7 comparing with measurement using the 85070E dielectric probe kit, which utilizes a standard reflection technique. As we can see that the proposed technique and a comercial dielectric probe kit exhibit a very good agreement.
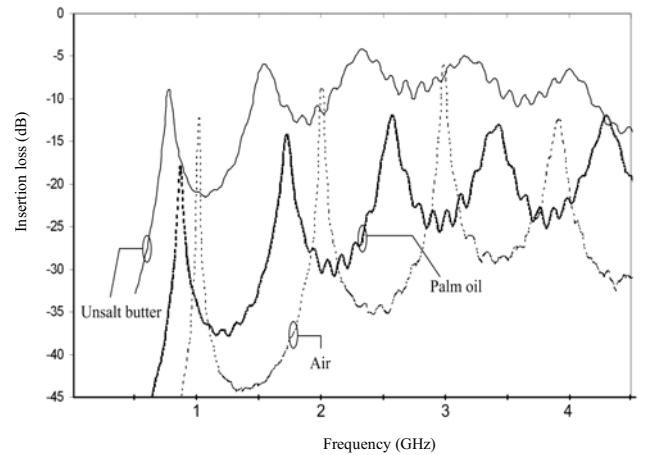

Figure 6. Dielectric constant spectral responses in folded ring resonator.

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TABLE II
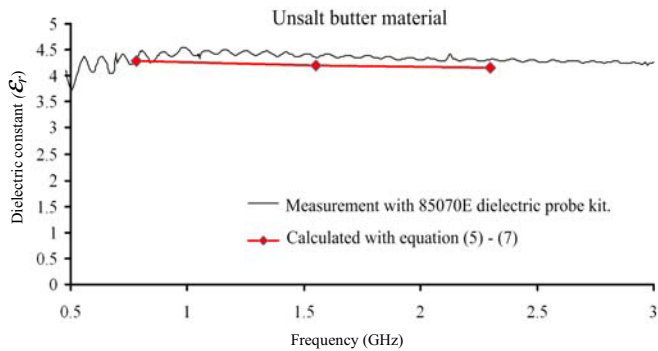THE RESULTS OF COMPUTATION AND MEASUREMENT OF MATERIALS.

Mode Number	DUT			
	Unsalt butter		Palm oil	
	f_{rn} (GHz)	$\mathcal{E}_r$	f_{rn} (GHz)	$\mathcal{E}_r$
$n = 1$	0.78	4.291	0.864	2.756
$n = 2$	1.55	4.206	1.727	2.687
$n = 3$	2.30	4.157	2.579	2.627

(a)

(b)

Figure 7. Dielectric constants determined by the proposed technique comparing with measurement uisng 85070E dielectric probe kit for (a) unsalted butter and (b) palm oil

V. CONCLUSION

For determining dielectric constant of materials, the folded resonators sensor based on a microstrip ring resonator structure has been analyzed. The proposed resonator sensor has been simulated and fabricated, resulting in formulation of dielectric constant equations for DUT. The proposed sensor has high performances with low cost, small volumetric measure and simplicity for manufacturing; therefore, it may be useful for dielectric constant characterization of many kinds of materials.

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