Microstrip Ring Resonator Based Sensing Technique for Meat Quality

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Abstract— **Dielectric properties of material are being used in various industrial applications. In food industry, its usage is increasing day-by-day especially for meat products. In this paper for quality evaluation of meat, microstrip ring-resonator is presented as a sensing technique; which is simple, cost-effective and faster than other techniques. The multilayer structure of 1 GHz microstrip ring-resonator is designed and then simulated with an overlay meat sample, using high frequency structure simulation (HFSS) software. From simulation results, it is observed there is a noticeable shift in the resonant frequency (~ 40 %); i.e. changing its effective permittivity. Simulation results are then validated with numerical results, where the minimum difference observed is 1.04 %.**

Keywords- Dielectric spectroscopy, Microstrip ring-resonator, Meat quality

I. INTRODUCTION

Dielectric spectroscopy is the most promising research subject in the field of material characterization and quality testing. These dielectric properties are now widely using in agriculture, food processing, geo-science, bio-engineering and pharmaceutical industry. Specifically, in food industry with further technological development in dielectric spectroscopy it is being use to get high-quality grains, fruits, vegetables, meat & dairy products [1]. Foods are not perfect dielectrics (neither perfect conductor nor an insulator) and their polarization is associated with energy absorption & their dielectric constant [2]. Among food, meat is the main source of proteins along with many essential amino acids, for humans. By an increase high-quality meat demand day-by-day, industry has adapted new trends and methods during the past few years. Using a dielectric method for freshness and quality assessment of meat has several advantages, such as: it is non-destructive, easy, rapid, effective and reliable [3].

Extensive research work carried out for dielectric measurements of meat, while considering the affects of temperature, frequency and time period. For the confirmation of dielectric dependence on temperature and time-period of pork meat, a rectangular coaxial probe method over broadband microwave frequencies (0.3-24 GHz) is reported in [4], the results shown that structural changes in meat with time-period can affect permittivity. Detailed study in [5], reported changes in dielectric properties as a function of meat-ageing, measurements were taken in a 10-24 GHz range which differentiated fresh and frozen-thawed fish samples. Determination of bovine fat contents, by coaxial and waveguide techniques presented in [6], in results it is observed that water contents significantly affect the dielectric constant. Another study for beef samples carried out at 10 KHz to 1 MHz range which is reported in [7] using an LCZ meter technique, the result shows that permittivity decreases with increasing in storage-time. In another study dielectric properties for the pork meat samples are analyzed by coax probe at 0.5-20 GHz, results observed over the time period shows relation between permittivity and time-period [8].

For meat products, during storage with conventional freezing (gradually freeze) the water inside the muscles converted into ice with large crystals [9]. These crystals expanded and ruptured the cell membrane, hence upon thawing drip-loss incurred in the form of purge. Also, with the passage of time (post-mortem) structural changes and deterioration in cellular membrane insulation [5], increases the conductance of meat that affected on dielectric properties. In this paper our aim is to find an economical and simple method which can detect these changes with reasonable accuracy.

II. MEASURING TECHNIQUE FOR DIELECTRIC PROPERTIES

For determination of dielectric properties of any material, no single technique can characterize all materials over an entire frequency band. Measurements with accuracy for both lossy and low-loss material is challenging because each frequency-band and their associated losses required a different method [3]. For dielectric properties an important parameter of any dielectric material is the complex permittivity (ε^*) which describes the behavior of material when an electromagnetic field applied on it, which is defined by [1]

$$\varepsilon^* = \varepsilon' - j\,\varepsilon'' \qquad (1)$$

where, $j = \sqrt{-1}$, ε' is the real part called dielectric constant or dielectric permittivity (ε') and imaginary part is a loss factor (ε''). When an electric field applied to a material, a dielectric constant defines its ability to store energy and loss-factor defines energy dissipation of a material (lossy behavior). Another parameter is loss tangent ($tan\delta$) or dissipation factor, which is the ratio of dielectric constant and loss factor [10], it is defined as

$$\tan\delta = \varepsilon'' / \varepsilon' \qquad (2)$$

The ability of material to conduct an electric current has defined an important parameter, called Conductivity (σ), it is measured by conducting a known amount of current at constant voltage [3].

As we discussed before, the behavior of dielectric properties of biological tissues are frequency dependent [11].

From radio-frequencies to the lower microwave range they produce relaxation phenomena, which is due to interaction of electric field and tissues at cellular & molecular level. However, this relaxation is associated to decrease in permittivity while an increase in conductivity, which is not instant, but in some steps, called dispersion [12]. There are three main regions, known as α, β and γ dispersions. Among them, α-dispersion is up to lower the KHz range, and it produces due to ionic (i.e counter-ion) polarization at a cellular membrane site, the next β-dispersion occurs in KHz to MHz region, produced mainly by cellular (i.e. interfacial) polarization [13]. In GHz range there is γ-dispersion and it is due to molecular (i.e dipole) polarization of water molecules in tissues.

Biological tissue has extremely high permittivity values, at low frequencies the complex relative permittivity is in hundred's range, on which exact evaluation of dielectric properties is very difficult and obtained information will be poor [14]. To overcome this issue, we can measure these properties at higher frequency (i.e γ-dispersion). Moreover, with gradual (slow) freezing of meat causes purging of entrapped-water from ruptured cellular membrane, which also affected the dielectric properties of meat. Since at γ-dispersion water molecules are highly-responsive because the main constituent of tissues is water molecules which holds up to 70 % of its mass [11], so when tissues purges bound-water it reduces the water holding capacity (WHC) of meat [9]. This reduction in WHC causes the changes in dielectric properties of meat. Therefore, by using microwaves, we can measure these changes with more accuracy. In this paper using 1 GHz frequency, *Microstrip Ring-Resonator (MRR)* is proposed. Application of ring resonators in characterizing the dielectric properties of materials is not a new idea, they have been used to investigate the dielectric properties of crude-oil [15] and soil samples [16], results from this technique are satisfactory with other approaches and it shows a noticeable shift in the resonant frequency and change in the quality factor. However, in literature this technique is used to measure thin and low-loss materials only but the novelty of this research is to investigate the properties of lossy tissues and relatively thick samples for meat characterization. The proposed design of a multilayer configuration of MRR is depicted in Fig.1. Where, ε_{r1} is the dielectric constant of substrate, h_1 is substrate thickness, t is the copper thickness, ε_{r2} is the dielectric constant of a sample, h_2 is superstrate thickness and on top ε_{r3} is permittivity of air with infinite thickness.

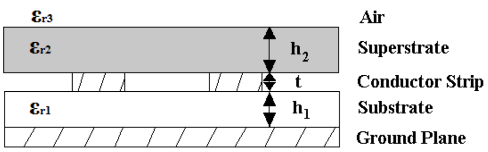

Fig. 1. Structural view of a proposed multilayer microstrip ring-resonator.

It is simple, cost-effective and fast (measurements in few seconds) even having higher Q-factor (~250) than conventional microstrip line [17]. Its rapid process can make it an on-line measurement device with higher accuracy. In microstrip line the in-homogeneity of medium causes dispersion due to which transmission mode is not pure but its quasi-TEM [18]. Consequently we can get effective permittivity rather than permittivity. This effective permittivity in the presence of overlay dielectric material can be described as the ratio of resonant frequencies with and without material [17]. A typical experimental setup of microstrip ring resonator connected to Vector Network Analyzer (VNA) is shown into Fig.2.

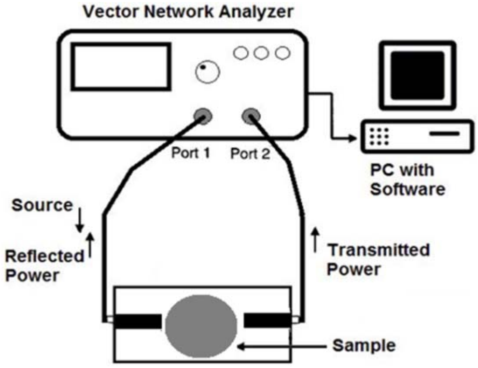

Fig. 2. Microstrip Ring-resonator Method.

III. THEORETICAL MODEL FOR MICROSTRIP RING RESONATOR

There are various techniques and dispersion models to analyze the characteristics of microstrip line. Some models are presented for multilayer configuration also, i.e microstrip-like transmission line. For these structures, using quasi-static approach, wave propagation assumed to be pure TEM for calculating electrostatic capacitance, there are two most common techniques: conformal mapping approach (CMA) and variational method [19]. For CMA main advantage is the analyzing the effect of geometrical dimensions of microstrip on electrical parameters along with its low computation time compared to all other numerical techniques [18]. Whereas, the variational method is more efficient using Fourier transfer domain (FTD) [19].

In conformal mapping method, to account the fringing field affects the effective strip width can be calculated as [18]

$$w_{ef} = w + \frac{2\,h_1}{\pi}\ln\left[17.08\left(\frac{w}{2\,h_1} + 0.92\right)\right] \tag{3}$$

Whereas, the quantity factor is given as

$$v_\varepsilon = 2\frac{h_1}{\pi}\arctan\left[\frac{\pi}{\frac{\pi}{2}\frac{w_{ef}}{h_1} - 2}\left(\frac{h_1}{h_2} - 1\right)\right] \tag{4}$$

Where, h_1 and h_2 are the thicknesses of substrate and superstrate respectively, w is a physical width of metallic strip. For a wide strip, $w/h_1 > 1$, the filling factor for a substrate layer is given as

$$q_1 = 1 - \frac{1}{2}\frac{\ln\left[\frac{\pi}{h_1}w_{ef} - 1\right]}{\frac{w_{ef}}{h_1}} \tag{5}$$

Similarly for a superstrate layer, it is given by

$$q_2 = 1 - q_1 - \frac{1}{2}\frac{h_1 - v_\varepsilon}{w_{ef}}.\ln\left[\pi\frac{w_{ef}}{h_1}\frac{\cos\left(\frac{v_\varepsilon}{2}\frac{\pi}{h_1}\right)}{\pi\left(\frac{h_2}{h_1} - \frac{1}{2}\right) + \frac{v_\varepsilon}{2}\frac{\pi}{h_1}} + \cos\left(\frac{v_\varepsilon}{2}\frac{\pi}{h_1}\right)\right] \tag{6}$$

To calculate the effective permittivity we can use

$$\varepsilon_{eff} = \varepsilon_{r1}\,q_1 + \varepsilon_{r2}\frac{(1 - q_1)^2}{(1 - q_1 - q_2) + q_2} \tag{7}$$

Another technique to determine effective permittivity for a lossy dielectric (>15) covered microstrip is presented in [20]. This method is validated, both experimentally and numerically, for a thick and high permittivity superstrate. It is principally based on the variational method [21] but an extension for lossy dielectrics. Expression for a line capacitance is given by

$$\frac{1}{\mathrm{C}}=\frac{1}{\pi\,\varepsilon_0 \mathrm{Q}^2}\int_0^{\infty}\frac{[f(\beta)]\mathrm{e}^2}{\left(\varepsilon_{r1}\frac{\varepsilon_{r1}\,tanh(\beta\,h_2)+1}{\varepsilon_{r1}+tanh(\beta\,h_2)}+\varepsilon_{r2}\,coth(\beta\,h_1)\right)(\beta\,h1)}d(\beta\,h_1) \tag{8}$$

where, ε_{r1} is permittivity of substrate, ε_{r2} is permittivity of superstrate, *h2* is thickness of a superstrate, and h_1 is substrate thickness, ε_0 is free space permittivity, β is Fourier variable and $f(\beta)/Q$ is the Fourier transformation of charge distribution function $f\,(x)$, which is obtained from Yamashita [21], it is given as

$$\frac{f(\beta)}{\mathrm{Q}}=1.6\left(\frac{sin\left(\frac{\beta w}{2}\right)}{\frac{\beta w}{2}}\right)+\frac{2.4}{\left(\frac{\beta w}{2}\right)^2}\left(cos\left(\frac{\beta w}{2}\right)-\frac{2\,sin\left(\frac{\beta w}{2}\right)}{\left(\frac{\beta w}{2}\right)}+\frac{sin^2\left(\frac{\beta w}{4}\right)}{\left(\frac{\beta w}{4}\right)^2}\right) \tag{9}$$

A closed-form expression, unified dispersion model (UDP), is presented in [22] using the transverse transmission line method. In this model the variational expression to calculate capacitance given as

$$\frac{1}{\mathrm{C}}=\frac{1}{\pi\,\varepsilon_0}\int_0^{\infty}\frac{\left[\frac{f(\beta)}{Q}\right]^2}{\beta}\,\frac{1}{Y}\,d\beta \tag{10}$$

Where Y is admittance of a dielectric covered microstrip line, using Green's admittance function, which is given by

$$Y=\varepsilon_{r1}\,coth(\beta\,h_1)\left(\frac{\varepsilon_{r2}+coth(\beta\,h_2)}{1+\varepsilon_{r2}\,coth(\beta\,h_2)}\right) \tag{11}$$

From an equation (8) and (10) we can evaluate the capacitance C for both variational techniques, C_0 can be determined by replacing permittivity of both layers to permittivity of air. Thus, we can evaluate effective permittivity by

$$\varepsilon_{eff}=\frac{C}{C_0} \tag{12}$$

For this study, numerical results from above-mentioned methods are then compared to a simulation result.

IV. Designing & Simulation Of Microstrip Ring Resonator

A. Designing Microstrip Ring Resonator

This method is based on principle that effective permittivity can be changed if any dielectric material place over the substrate surface, thus changes the resonant frequency of a ring.

For ring resonator, resonance is produced when a mean circumference of the ring is equal to an integral of the guided wavelength [23]

$$2\,\pi\,r\;=\;n\,\lambda g \qquad \text{for } n\;=\;1,2,3\,... \tag{13}$$

Where r is ring radius, n is mode number and λ_g is the guided wavelength. From (13) we can calculate the resonant frequencies for n modes. Since λ_g is frequency dependent, thus it can be related to the frequency by

$$\lambda_g=\frac{\lambda}{\sqrt{\varepsilon_{eff}}}=\frac{1}{\sqrt{\varepsilon_{eff}}}\,\frac{c}{f} \tag{14}$$

Where ε_{eff} is an effective dielectric constant and c is free-space light speed. Considering (13) with λ_g it will become

$$f=\frac{n\,c}{2\pi\,r\,\sqrt{\varepsilon_{eff}}} \tag{15}$$

Alternately, from (15) we can easily calculate effective permittivity by using resonant frequency f, it can be written as

$$\varepsilon_{eff0}\;=\left(\frac{n\,c}{2\,\pi\,f_0\,\mathrm{r_m}}\right)^2 \tag{16}$$

Finally, the effective permittivity can be determined in the presence of overlay material (i.e loaded-resonator) by [17]

$$\varepsilon_{eff1}\;=\varepsilon_{eff0}\left(\frac{f_0}{f_1}\right)^2 \tag{17}$$

In this study a 1 GHz microstrip ring-resonator is designed on Ansys HFSS simulation software. From (15) the ring radius calculated as, 34.8692 mm. Strip width and effective permittivity are determined by using LineCalc tool (Agilent Advanced Design System) i.e; w = 2.3981 mm & ε_{eff} = 1.875.

A ring-resonator is designed using Roger RT/Duriod 5880 substrate with its dielectric constant of 2.2 and the height of 787 µm. The outer radius of the ring is 34.8692 mm with conductor thickness taken as 17.5 µm. The width is calculated as 2.3981 mm for the feed line and ring strip considering the characteristic impedance of 50Ω. A feed line with a typical length of a 35 mm along-with coupling gap of 630 µm is used. The total size of the circuit is 141m x 87.5 mm x 0.787 (LxWxH), as sufficient space is retained at both sides of a ring to strengthen the electric field at ring edges. All design parameters of microstrip ring resonator are listed in Table-1.

TABLE 1. MICROSTRIP RING RESONATOR DESIGN PARAMETERS

Parameter	Design Value
Substrate: Roger RT/Duriod 5880	ε_{r1} = 2.2
Substrate height	h_1 = 787 µm
Dissipation factor (DF)	tan δ = $9\text{x}10^{-4}$
Copper thickness	t = 17.5 µm
Frequency	f = 1 GHz
Chrac. Impedance	Zo = 50 Ω
Feed line length	l = 35 mm
Superstrate: Meat sample	ε_{r2} = 61.09
Superstrate height	h_2/h_1 = 1~15

B. Simulation of multilayer Microstrip Ring Resonator

To study the dielectric properties of meat, 1 GHz microstrip ring resonator is designed in HFSS software. Initially, simulation results were obtained for un-loaded resonator (i.e (without any overlay-dielectric). After that, for loaded resonator, a dummy sample placed over ring-resonator, the dielectric constant of this sample preset to ε_r = 61.09 (same as for beef at 1 GHz) data has taken from open literature [4]. A disc-shape sample with radius same as the ring is placed on the top of a ring (shown in Fig.3). Different thicknesses of these samples are then simulated with the range from $h_2/h_1 = 1\sim15$.

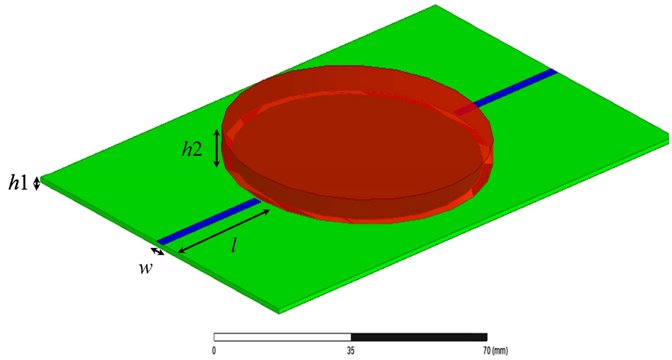

Fig. 3. MRR with overlay meat sample in HFSS Simulator.

V. Results & Discussion

Using simulation and numerical-methods the effective dielectric constant of microstrip ring-resonator with and without test material is determined. Simulation result of microstrip ring-resonator without an overlay material is illustrated in Fig.4. In unloaded condition resonator shows periodic resonance at one GHz intervals, during simulation first resonance produced at 1.02 GHz while second at 2.05 GHz and then third is at 3.06 GHz and the last resonance occurred at 4.07 GHz. While at these periodic resonances the result of S_{12} seems much lossy, this is due to lose coupling to resonator. Also the corresponding dB level for an unloaded resonator increases with succeeding resonances is due to stored energy of $\lambda_g/2$ waves. For a loaded resonator, an overlay meat sample of various thicknesses is used to determine resonant frequency behavior. From the simulation, minimum frequency shift of a 1 GHz resonance in the presence of overlay material observed as 16 % for a smaller h_2/h_1 ratio, where maximum shift was 40 % for the highest ratio. Simulation result for a frequency shift of first resonance is shown in Fig.5. Besides shifting of frequency there is also variation in dB level for various sample thicknesses. This reduction in dB level from first to last peak is around 34 %. Thus for the smallest and highest ratio, an effective dielectric constant was calculated $\varepsilon_{eff} = 2.650$ and $\varepsilon_{eff} = 5.122$ respectively. In Fig.6, comparison of theoretical and simulation results of an effective dielectric constant for different superstrate thicknesses is presented. By numerical methods, results from Svacina's conformal mapping are in good agreement with simulation results, where the minimum difference is around 1.04 %. But after a certain range it starts departing from simulation results. Whereas, results from Bahl and Verma are much similar to each other, as they both based on variational method. But relatively they have much difference than simulation results. The difference in evaluated values from Bahl and Verma techniques is due to our computation limitation. We have used different range in an integral function of equations (8) and (10), therefore in results there is noticeable dissimilarity between simulation and variational results.

From results it can be observed that as the thickness of overlay layer increase, the effective permittivity also increases, and this relation can be validated with published literature [20, 24, 25]. However, the difference between numerical and simulation values is minimal for small sample thickness, but as the thickness increases numerical results are deviated from HFSS results.

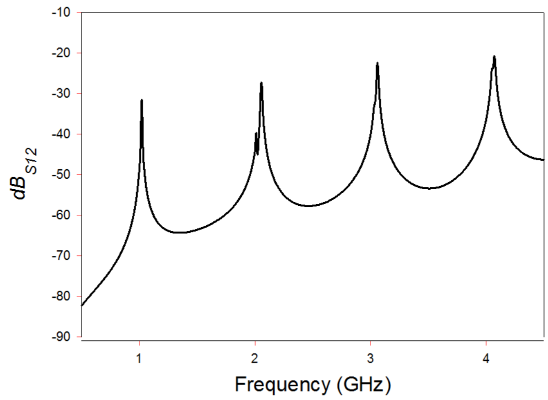

Fig. 4. S_{12} parameter from HFSS Simulation for MRR without test material/unloaded condition with periodic resonances.

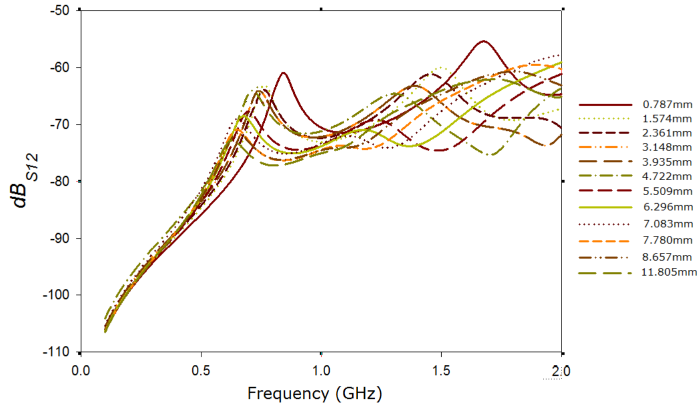

Fig. 5. S_{12} parameter from HFSS Simulation for MRR with overlay meat sample – with multiple thickness range.

From results it can be observed that as the thickness of overlay layer increase, the effective permittivity also increases, and this relation can be validated with published literature [20, 24, 25]. However, the difference between numerical and simulation values is minimal for small sample thickness, but as the thickness increases numerical results are deviated from HFSS results.

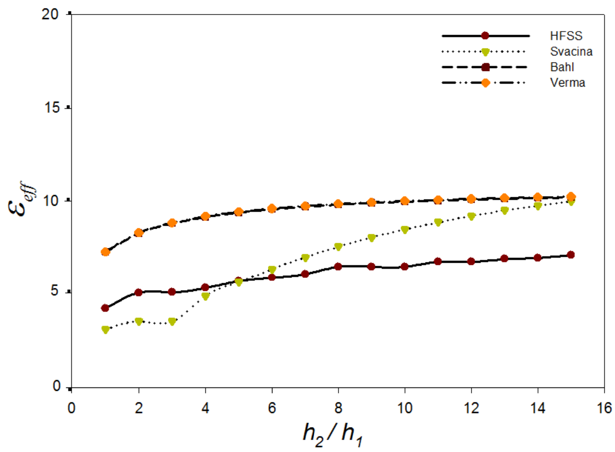

Fig. 6. Comparision of numerical and simulation results for effective dielectric constant of MRR coverd with meat sample (as a function of a thickness).

In view of above results, it is obvious that, MRR can be used as a sensing technique for characterization of meat samples at higher frequency (GHz) range.

VI. Conclusion

Dielectric methods for freshness and quality assessment of meat are widely used in food industry. During storage with conventional freezing (gradually freeze) the water inside the muscles converted into ice with large crystals. These ice crystals are expanded and ruptured the cell membrane and when thaw entrapped water seep-out in the form of purge, which affected the dielectric properties. We can use γ-dispersion, as water molecules are highly-responsive in this region, to detect these changes in meat. For that, microstrip ring-resonator is proposed, which is simple, economical and fast method (3-4 seconds for each measurement). During this study, dielectric properties of meat with different sample thicknesses are determined by using simulation and numerical methods. The multilayer structure of 1 GHz microstrip ring resonator is designed and then simulated with a meat sample, using high frequency structure simulation (HFSS) software. The result shows that when meat sample is used as an overlay material, there is significant shift (~40 %) in resonance frequency of resonator. Thus, changes its effective permittivity. In this study also effective permittivity as a function of thickness is observed, as the thickness of overlay layer increase, the effective permittivity also increases. The relation to a sample thickness is also validated with published literature. Results from both simulation and numerical are in good agreement, with a minimum difference observed as 1.04 %. Therefore, it can be concluded that in microwave range MRR can be used as a sensing technique for characterization of a meat samples with reasonable accuracy.

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