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A Multi-Use Fully 3D Printed Cavity Sensor for Liquid Profiling.

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Abstract—In this paper, a multi-use perturbed rectangular cavity resonator is fabricated using additive manufacturing (3D printing) for profiling small volume liquid samples. The designed cavity operates in the fundamental mode TE_{101} and is suitable for characterizing liquids in smaller volumes (<1 ml). A cylindrical perturbation is created on the top wall of the cavity into which the liquid samples are introduced. Depending on the dielectric constant of the sample, the resonance frequency of the cavity changes and the change in resonance is monitored in real-time. The dielectric constant of the sample under test is theoretically estimated based on the change in resonance and compared to standard reported values. The fabricated resonator is of multi-use nature and requires small sample volume of 0.35 ml for profiling. The low-cost, light-weight, multi-use sensor can be easily adapted for quality control applications across the supply chain.

Index Terms— 3D printing; Dielectric characterization; Multi-use sensors; Resonant Structures; Supply chain

I. INTRODUCTION

Liquid sample identification and quantification are of significant interest for many practical quality control applications in food, petroleum, biomedical, and pharmaceutical industries [1-3]. Non-contact and non-invasive sensing of liquid samples is desired to monitor hazardous chemicals in oil, petroleum, and pharmaceutical supply chain. Moreover, real-time monitoring of liquid samples is necessary to enforce better quality control standards across the supply chain. For example, in the food supply chain, accurate estimation of liquid food property such as dielectric constant discourages adulteration and promotes consumption of high quality food products [4]. Therefore, there is a growing need to develop low-cost, real-time, non-invasive sensing technique without elaborate steps and requiring a very small volume of liquid sample to estimate accurately the material properties.

In literature, a number of standard microwave techniques have been developed for characterizing liquid samples such as waveguides [5], open-ended coaxial line [6], dispersive fourier transform spectroscopy [7], and cavity perturbation [8]. Among these methods, resonant perturbation methods such as perturbed cavity resonators are preferred and best suited for characterization due to a number of advantages such as real-time measurement, simplicity, easier sample preparation, accuracy, and a small sample volume requirement [9].

Cavity perturbation is one the most widely used technique for characterizing materials due to its relative simplicity in obtaining the intrinsic properties of material under test. From the time Bethe and Schwinger proposed the cavity perturbation technique, multiple studies have been published modifying the classical perturbation theory for different practical applications [8]. These techniques have been typically demonstrated by inserting a small sample into the cavity or by creating a small deformation along the cavity walls to insert the sample. An extensive review on the origin of cavity perturbations and the development of different methods of perturbations is presented in [9-10].

Furthermore, modifications of cavity resonators coupled with different guided wave structures and resonators have been reported in literature for determining the dielectric properties of liquids such as cavity coupled substrate integrated waveguides (CSIW) [11-13], fringing field based perturbed cavity resonator [14], coaxial coupled cylindrical open-ended cavity resonator [15], whispering-gallery based semi-open metal shield cavity resonator [16], and split ball resonator coupled perturbed cavity resonator [17]. Table 1 lists the different perturbation techniques along with the sensing principle that has been reported in literature in the last five years for liquid characterization. The modified cavities have enhanced sensitivity but has complex geometry that is difficult to fabricate using traditional manufacturing techniques.

Table 1. Different cavity perturbation techniques for liquid sensing.

Circuit	Perturbation	Sample	Reference
Cavity coupled substrate integrated waveguide (CSIW)	Cylindrical	Solvents,	[11], [22-24]
		Glycerine	[11]
		Water	[22]
		Oil	[24]
	Rectangular slotted	Water	[13]
		Solvents	[13]
Rectangular cavity	Cylindrical	Solvents	[25-26]
		Water	[26]
	Fringing fields	Oil	[14]
		Water	[14-15]
Resonator coupled cavity	Cylindrical	Hemoglobin	[16]
		Solvents	[17]

Typically, cavity resonators are fabricated using traditional techniques such as micromachining, metal plate soldering, dip brazing, and electric discharge machining [18-19]. These techniques are complex and labor intensive, and consumes more material and generates large wastes. Moreover, metal machining increases the weight of the cavity and, in the case of multiple layers, can lead to misalignment errors between parts. An alternate fabrication technique that overcomes these limitations is additive manufacturing (AM) or 3D printing. It is a simple low-cost technique that can readily prototype complex geometries from a range of materials. A number of microwave circuits such as antennas, resonators, and waveguides, have been fabricated and demonstrated using 3D printing [20-21]. 3D

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printing is ideal for fabricating low-loss air substrates ($\epsilon_r = 1$) due to the flexibility in the third dimension and has been demonstrated for fabricating different microwave devices, e.g., multi-layered cavity resonator [21]. Leveraging on the advances in AM, a low-cost reusable resonator sensor for characterizing small sample of liquids is presented.

Here, a rectangular cavity resonator is 3D printed using VeroWhitePlus polymer material and is metal coated using metal sputtering followed by electroplating. A small cylindrical perturbation (sample holder) is created in the top layer of the cavity in which the liquid samples are loaded. Based on the sample loading, the resonance frequency of the cavity changes and it is monitored in real-time for sample characterization. All the designs and simulations were performed using a commercial finite element method solver, ANSYS High Frequency Structural Simulator (HFSS). A variety of standard dielectric liquid samples were measured and characterized demonstrating the sensitivity of the fabricated resonator and its potential use in monitoring liquids along the supply chain.

II. THEORY

Material perturbation of a resonance cavity is a well-established theory [27]. When a cavity is perturbed with a material of different relative permittivity (ϵ_r) and permeability (μ_r) , the resonance frequency of the cavity shifts by Δω given in (1), where ω_0 represents the resonance frequency of the air filled cavity. In (1), $\overrightarrow{E_0}$ and $\overrightarrow{H_0}$ represent the original electric and magnetic fields and V_0 represents the perturbed volume. For a pure nonmagnetic dielectric material, (1) is reduced to simplified (2).

$$\frac{\Delta\omega}{\omega_0} \approx -\frac{\int_V\left((\epsilon_r - 1)\epsilon_o|\overrightarrow{E_0}|^2 + (\mu_r - 1)\mu_o\left|\overrightarrow{H_0}\right|^2\right)dv}{\left(\int_V(\epsilon_0|\overrightarrow{E_0}|^2 + \mu_o\left|\overrightarrow{H_0}\right|^2\right)dv} \qquad (1)$$

$$\frac{\Delta\omega}{\omega_0} \approx -\frac{\int_V\left((\epsilon_r - 1)\epsilon_o|\overrightarrow{E_0}|^2\right)dv}{\left(\int_V(\epsilon_0|\overrightarrow{E_0}|^2\right)dv} \qquad (2)$$

Equation (2) denotes that the fractional change in stored electric field due to a dielectric material perturbation is related to fractional change in the resonance frequency. The resonance frequency ω_0 is calculated as in (3) where a, b, d are the dimensions of the rectangular cavity. For unperturbed TE_{101} mode, electric field E_y is shown as given in (4).

$$f_{mnl} = \frac{c}{2\pi\epsilon_r\mu_r}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \qquad (3)$$

$$E_y = Asin\left(\frac{\pi x}{d}\right)\sin\left(\frac{\pi z}{d}\right) \qquad (4)$$

Now, when the electric field is perturbed due to a specific material, the fractional change in resonance frequency is quantified by computing the numerator integral as in (2). When different materials is introduced in the cavity, the total energy of the unperturbed cavity, which is the denominator of (2) remains constant and the numerator changes with different loadings. The integral in (2) can be computed by substituting E_y from (4).

Considering a dielectric material perturbation of dimensions (a_0, b_0, c_0) of rectangular shape positioned with center at (x_0, y_0, z_0), the integral in (2) is computed as shown in (5) and the relative dielectric constant of the material under test is obtained from the fractional resonance frequency change.

$$\epsilon_r \approx 1 + \frac{\Delta\omega}{\omega_0}\frac{abd}{2k_0k_ak_db_0} \qquad (5)$$

where, $k_a = \int_{x_0-\frac{a_0}{2}}^{x_o+\frac{a_0}{2}} \sin^2\frac{\pi x}{a}\,dx$ and $k_d = \int_{z_0-\frac{c_0}{2}}^{z_o+\frac{c}{2}} \sin^2\frac{\pi z}{d}\,dz$

Here, constant k_o is experimentally obtained, which denotes the coupling of the dielectric material through the 3D printed material.

III. SIMULATION AND FABRICATION

The dimensions of the cavity were chosen to be 50*50*14 mm such that the resonance frequency of the air-loaded cavity is at 4.17 GHz. The most important step to realize good sensitivity is to optimize the shape and location of the perturbation in the top wall of the cavity. Initial simulations were performed to analyze the sensitivity of various perturbation positions and an optimal position was chosen for the design. For all the simulations, the size and shape of the perturbation is fixed. The cylindrical perturbation chosen has a radius of 5 mm and a depth of 4.5 mm leading to a total volume of 0.35 cm^3. Two different samples were loaded into the perturbation, air and liquid ($\epsilon_r = 25$) and the simulations were performed at various perturbation positions. The sensitivity is obtained by calculating the difference in the resonance frequency between air and liquid loading and is expressed as Δf . The center of the top layer of the cavity is at (25, 25, 14) and the center of the cylindrical perturbation is at (x, y, 14). A predefined combination of (x, y) coordinates for the center of the cylindrical perturbation is chosen. Fig. 1. shows the sensitivity for different sample holder positions along the top wall of the cavity.

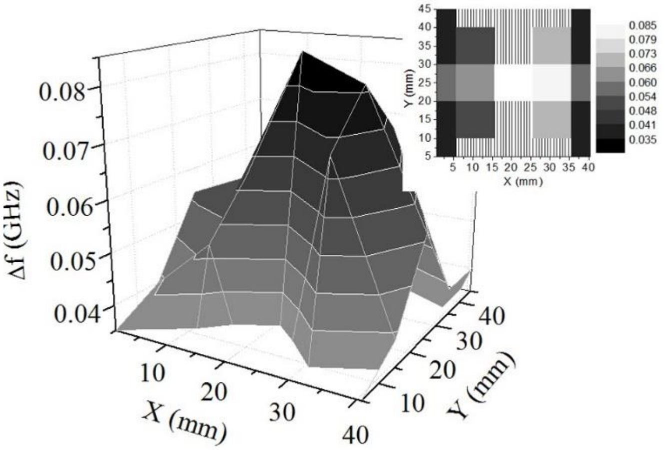

Fig. 1. 3D Sensitivity of the sensor for different perturbation positions.

It can be inferred from Fig 1. that sensitivity of the sensor is high at the center of the cavity, as expected. In order to cater to a wide variety of liquids with higher loss tangent, the center is not an ideal choice since strong coupling of a lossy liquid impacts the Q-factor of the sensor. Hence, (10, 25, 14) was chosen as an optimal position for the center of the cylindrical perturbation. The schematic of the designed 3D printed rectangular cavity resonator, the fabricated image along with its dimensions are shown in Fig. 2.

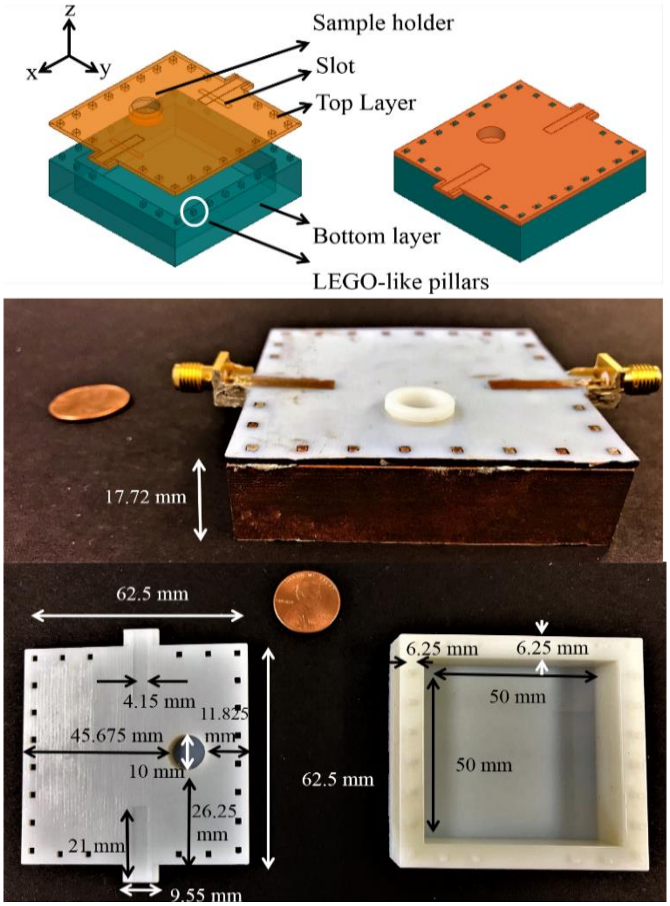

Fig. 2. Schematic and image of the 3D printed rectangular cavity with dimensions.

The rectangular cavity was 3D printed using Stratasys Object Connex350 printer in two separate pieces as shown in Fig. 2. After metallization, these are snapped together using LEGO-like support pillars and corresponding holes as discussed in [21]. The metallization of the printed parts is a two-step process; first, 60 nm titanium is sputter deposited for adhesion of copper onto the plastic followed by 500 nm of copper. In the second step, the thickness of the metal layer is increased to 5-6 μm by electroplating copper. The patterning of the metal layers on the 3D printed plastic is done using a damascene-like mechanical polishing process presented in [20]. The cavity is excited by 50 Ω microstrip lines extended on either side on the top layer and SMA connectors are attached, using conductive silver paste (resistivity ~0.017 Ω.cm), for probing. Two rectangular slots (2 mm * 15 mm) are cut in the seed metal layer below the microstrip lines for coupling into the cavity. Fig. 3 shows the simulated and measured results for the designed resonator. The measured and simulated resonance frequencies are at 4.14 GHz and 4.17 GHz, respectively. The downward shift in frequency is due to the lossy conductive silver paste on the connectors that affect the coupling into the cavity as well as reduced air gaps between the top and bottom layer due to warping effects of the VeroWhitePlus material during the sputtering process making the cavity a little larger than the designed dimensions.

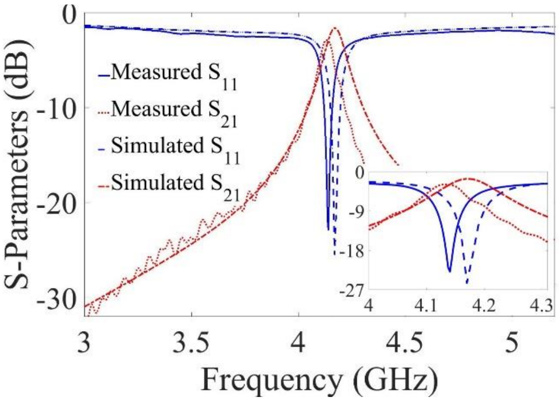

Fig. 3. Simulated and measured s-parameters of the 3D printed perturbed cavity resonator.

IV. RESULTS AND DISCUSSION

A set of experiments were performed by using the cylindrical perturbation of dimensions 5 mm (radius) * 4.5 mm (depth) positioned with center at x_0 = 10.575 mm, and z_0= 25 mm. The equivalent rectangular perturbation dimensions are a_0= c_0 = 8.86 mm, b_0 = 4.5 mm. The perturbation was completely filled with the solvent under test (0.35 ml), and each solvent was measured three times and the results were averaged out. Fig .4. shows the measured resonance frequency shift under different solvent loadings.

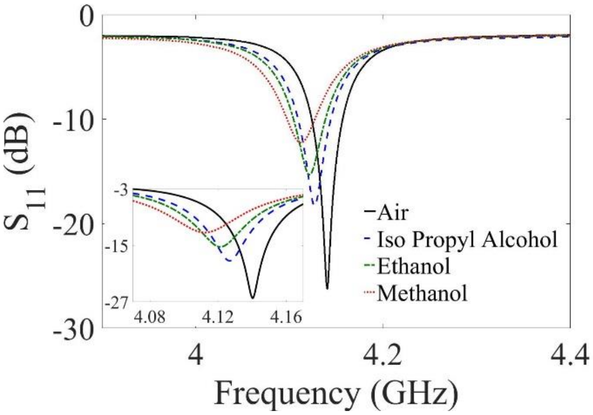

Fig .4. Measured frequency shift for different solvent loading.

It can be inferred from Fig .4. that as the dielectric constant increases, the resonance frequency decreases, as expected. Using the experimental shift, the value of constant k_0 was estimated as 40.2. Table 2. shows the experimentally obtained dielectric constant and the dielectric constant reported in literature for the different solvents used in the experiment along with the corresponding resonance frequencies.

Table 2. Estimated and standard dielectric constants for samples under test and measured resonance frequency.

Solvent	Estimated ϵ_r	Literature ϵ_r[28]	f_o (GHz)
Iso Propyl Alcohol	18.88	18.62	4.127
Ethanol	23.99	25.10	4.122
Methanol	36.77	32.35	4.112

The 3D printed multi-use cavity resonator is a low-cost easily customizable choice for monitoring liquid quality in real-time using a small sample volume. This technique is attractive since it can be easily tailored to suit a variety of liquids with varying dielectric properties by optimizing different perturbation parameters such as the size, shape, position, and coupling with the cavity. The sensitivity can be further improved by selecting the choice of the perturbation parameters based on the minimum detectable dielectric change which is required to evaluate the quality of the liquid under test. For example, the sensor can be easily adapted to monitor adulteration of milk with water or between different oil mixtures. Furthermore, 3D printing allows customizable perturbation geometries, allowing to tailor the sensitivity for even a small dielectric property change in liquid sample under test.

The 3D printing of microwave devices offers several advantages, such as rapid customization and simple tool setup. But, it also has few associated challenges such as the mounting of SMA connectors to the cavity with the lossy silver epoxy leading to poor quality factor. This can be improved by printing the cavity using a high-temperature resin instead of VeroWhitePlus and soldering the connectors directly onto the metalized plastic. Using a high temperature material will also prevent warping of the 3D printed substrates during and after the sputtering process. Advances in low loss 3D printed material and printing parts with smoother surface will lead to further improvement in the quality factor of the resonant cavity.

The real-time nature of the sensor makes it compatible to monitor liquids along the supply chain. More specifically, in the food supply chain, this technique can be adapted as a quality control measure in estimating the dielectric properties of liquid food and thereby predicting the quality, freshness and spoilage rate over time. The technique is rapid and requires only a small sample volume (0.35 ml) making it a cost effective solution. Furthermore, in automotive supply chain, the sensor can be used for estimating the quality of engine oils and other fluids. The size of the sensor and volume of the sample under test can further be reduced by designing the sensor to operate at a much higher frequency.

V. CONCLUSION

This paper presents a simple, low-cost technique for characterizing small liquid sample volumes (0.35 ml). Using a 3D printing approach allows easier fabrication of the geometry without much complexity and can be completed in a short time. The multi-use nature of the sensor allows adapting the same measurement technique for different samples. In future, further optimization depending on the coupling between the samples and the cavity can be investigated and different perturbation configurations with complex geometries can be studied to detect liquids having a wide range of dielectric constants. The technique is useful and can be easily adapted in estimating the quality of liquid food real-time along the supply chain such as milk, oil, alcohol, and wine.

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