Liquid Sensing Using Active Feedback Assisted Co-Planar Microwave Resonator

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***Abstract*—A novel electromagnetic sensor operating at microwave frequencies with quality factor of 22K at 1.4GHz for real-time sensing of fluid properties is presented. The core of the sensor has a planar microstrip resonator, which is enhanced using an active feedback loop. The resonance frequency and quality factor of the sensor show clear differentiation between analytes composed of common solvents. To evaluate the sensor for water based concentration detection, we have demonstrated that KOH dilutions of as low as 0.1 mM is detectable. The proposed sensor has advantages of inexpensiveness and high resolution as well as capability for miniaturization and CMOS compatibility.**

***Index Terms*—Microwave passive resonator, active device, liquid sensing, S-parameters and high resolution sensing.**

I. Introduction

MICROWAVE resonator sensors have demonstrated major advantage of contact-less sensing for different applications ranging from biomedical diagnostics and microfluidics to sensors for the food industry and for environmental monitoring[1]–[4]. The microwave sensors bring the advantages of cost, simplicity, design flexibility and speed associated with label free detection and real time sensing. In particular, microwave sensing-based assays benefit from minimal sample preparation, fast and precise determination of the changes in dielectric properties due to the target interacting with the resonator, and the elimination of assay complexity, binding changes and costs associated with conjugated markers[5]. These advantages of microwave sensors are particularly important for pH and pOH sensing wherein electrochemical, ion-sensitive field-effect transistor (ISFET) and colorimetric/fluorimetric sensors have very short operating lifetimes in particle-rich and corrosive environments due to fouling, clogging and dye-leaching issues[6,7]. Microwave sensors also have advantage of CMOS compatibility and miniaturization which make them more attractive for lab-on-a-chip applications[8].

Among different types of microwave sensors, planar microstrip resonators demonstrate additional advantages of simplicity, ease of implementation and an inherent planarity (for analyte sampling) in their structure, which make them more attractive as sensor platforms[9]. They have been used for sensing gas [10], viscosity[11], and several others. One of the highlights of such sensors is their amenability to microfluidic channels that provides the opportunity of manipulation of liquids in a microscale structure while sensing. Having microfluidic channels also provides a constant flow of the target liquid and allows precise automated fluid delivery with reduced reagent consumption in an enclosed and potentially low-cost system[12,13].

Although planar microstrip resonators have demonstrated great potential in sensing of liquid materials, they suffer from low resolution and quality factor. Quality factor in any type of resonant sensor, plays a critical role since it determines the sensitivity, resolution and minimum detectable signal [14]. A microwave device with high quality factor can lead to a sensing platform with higher sensitivity and resolution with respect to its conventional counterparts.

Different techniques have been employed for increasing the quality factor of the planar resonators [15],[16]. Among these techniques, having an active feedback loop around the resonator demonstrates promising results for increasing the quality factor. This technique has already been applied to communication applications [17]. However, the knowledge on its behavior for sensing application is very limited and more specifically, no results have been reported for liquid sensing.

In this work, we report a state of the art sensing platform based on a microwave resonator, which is reinforced by an active feedback loop to significantly enhance the quality factor. In comparison with previous reported work [18], this device has very high quality factor and very high resolution since employs active feedback loop comparing to a pure passive structure reported in [18].The proposed device demonstrates high sensitivity not only to different types of liquids (such as methanol, ethanol, isopropanol, and water), also to small concentration variation. It has been shown that the concentration of water based solutions can be sensed. In the proposed device, complexity and cost of fabrication are kept low while the performance is improved tremendously.

II. Sensor Architecture and Theory of Operation

The sensor architecture consists of a planar ring resonator microwave microstrip resonator. The length of the microstrip line determines the resonance frequency of this resonator. This resonator is a half-wavelength resonator and the length of the microstrip line associated with the resonance frequency can be

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determined using the following equation:

$$l = \frac{c}{2\sqrt{\varepsilon_{eff}}} \times \frac{1}{f_r}, \qquad (1)$$

where l and ε_{eff} are the total length of the resonator and the effective permittivity of the materials in the sensor ambient respectively, c is the velocity of light and f_r is the resonance frequency. This conventional structure has a moderate quality factor of around 190 to 200(in measurement) and 200 to 250 (in simulation). To increase the quality factor of the resonator, a feedback loop with an active device (BJT-Transistor) is added to the passive resonator. This regenerative feedback loop creates 180 degree phase shift on its output and another 180 degree phase shift is introduced by the passive resonator, therefore a constructive (positive) feedback is created around the passive resonator which compensates the power loss and increases the quality factor. The loss (positive resistance) of the resonator can be completely compensated by the negative resistance provided by the regenerative feed back if the gain of the amplifier is driven from equation 2[17]:

$$G = \frac{\sqrt{Q_1 Q_2}}{2} \times \left(\frac{1}{Q_1} + \frac{1}{Q_2} + \frac{1}{Q_u}\right), \qquad (2)$$

where G is the gain of the transistor, Q_1 and Q_2 are the quality factors for the coupling between the resonator and the feedback loop and Q_u is the quality factor of the passive resonator. Having active feedback loop design with significantly enhanced quality factor is expected to enable high resolution sensing.

Fig. 1 shows the resonator schematic with a microfluidic tube on its surface as well as physical realization of the sensor. The designed microwave resonator is implemented on a low dielectric-loss substrate 5880 from Rogers Corporation. Both sides of the substrate were initially covered by 35 μm copper layers with a conductivity of 5.8×10^7 S m^{-1}; the dielectric constant and the loss tangent of the substrate are 2.2 +/- 0.02 and 0.0003 respectively. NE680, a low noise, high gain and low cost transistor with a typical cut-off frequency of 10 GHz at 10 mA bias current from California Eastern Laboratories (CEL) is used as an active amplifier in the feedback loop. DC bias couplers to provide bias for the transistor are high frequency high quality inductors (18 nH). A microfluidic tube with inner diameter of 0.4 mm is fixed on the surface of the sensor with a strong scotch tape. The flow path of the fluid chosen in Fig. 1 is designed to coincide with areas of high field intensity in order to maximize interaction with the microwaves.

III. MEASUREMENT RESULTS AND DISCUSSION

To experimentally verify the proposed sensor, two sets of measurements are presented; i.e. different liquid sensing, and concentration detection. For the first experiment, the tube is filled by five different liquids, namely methanol (ε'=30, ε''=8), ethanol (ε'=24, ε''=12), isopropanol (ε'=17.9, ε''=17.5), and deionized (DI) water (ε'=80, ε''=3.7) and the S21 profile of the sensor is measured using a vector network analyzer (VNA-E8362) from Agilent. The results show a quality factor of 22K for the bare sensor. Fig. 2*a* presents the results of S-parameter measurement for different liquids inside the tube. A very clear and distinct difference is observed between different liquids for the active feedback case in comparison to the passive resonator response wherein the active loop is off (Fig. 2*b*).

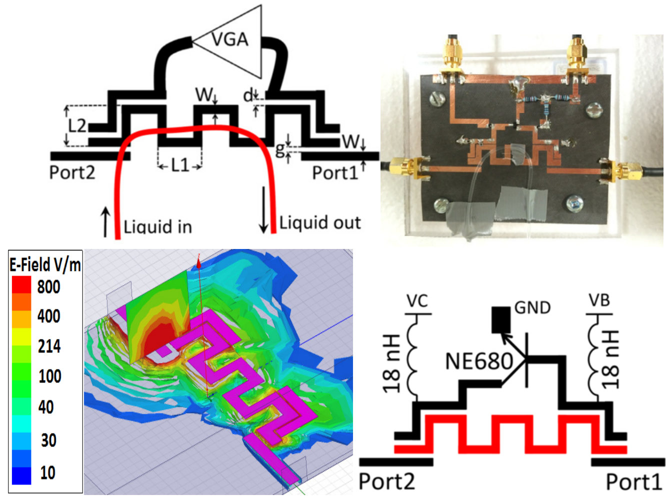

Fig 1 Schematic and Implemented low cost, high precision liquid sensor, E-field simulation is presented for demonstrating the hot spots of the resonator

The difference in permittivity (ε') and in the loss (ε'') creates differences between the S-parameters of these liquid samples. The difference in electromagnetic properties of the material in the tube is transferred to the frequency variation

The high Q factor of the proposed sensor also enables high-resolution measurement such as concentration tests. Therefore, in addition to being able to differentiate between solvents, the reported sensor is also used for concentration measurements of soluble materials in solvents for which we use KOH in water as a prototypical example.

Fig 3*a* shows the S21 parameter for the bare resonator, while different concentrations of the liquid are flowed in the tube. Resonance frequency and quality factor study of the sensor for KOH concentration of 0.125 mM to 100 mM diluted in water is reported in Fig. 3*b*. It is shown that increasing the concentration of the analyte reduces the resonance frequency and enables the detection of various concentrations. In addition, the quality factor also decreases as the concentration is increased. Comparing the presented results here with the previously published data [13], the proposed sensor has enabled significantly lower concentration detection. To our knowledge this is lowest concentration detection that has been reported using planar RF resonators.

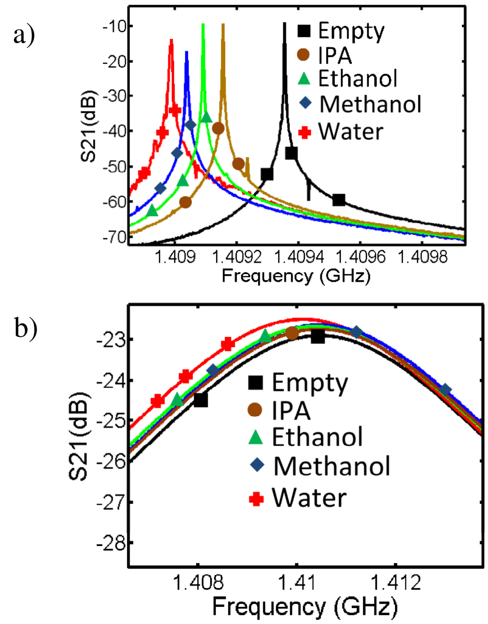

Fig. 2 S21 parameter of the designed sensor for the different liquids a) active mode b) passive mode

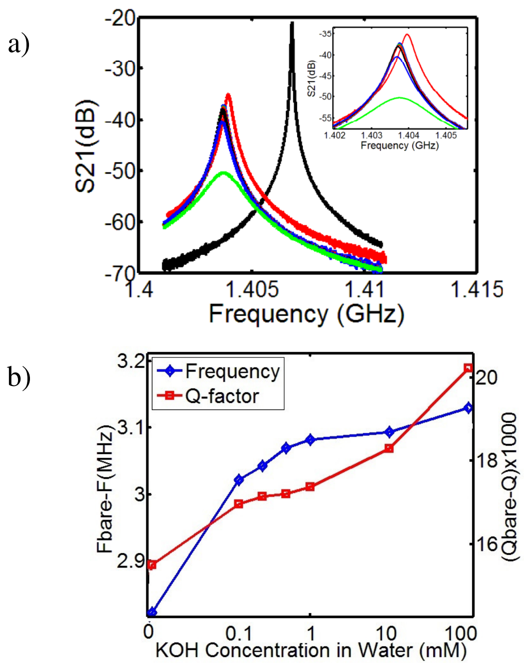

Fig. 3 ***a)*** **S21 parameter of the designed sensor in active mode for different concentrations of KOH in water** ***b)*** **Resonance frequency and quality factor variation for different concentrations of KOH in water**

IV. Conclusion

In this letter, a state-of-the-art liquid microwave sensor is presented. The core of the proposed sensor is a passive coplanar microstrip microwave resonator at 1.4 GHz with the initial quality factor of 200. This resonator is assisted by an active feedback loop with an increased measured quality factor of 22000 for bare resonator with a liquid tube on its surface. Based on this technique, a clear and distinguishable difference between different liquid samples and different concentrations of KOH in water solution has been observed. This technique for liquid sensing enables very small concentration measurements of different materials while holding the simplicity in fabrication and inexpensiveness. To our knowledge, this is the first time that RF resonator for liquid sensing for such high resolution has been reported.

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