Highly Sensitive Planar Microwaves Sensor

Ali M. Albishi[1], *Member, IEEE*, Omar M. Ramahi[2], *Fellow, IEEE*
[1]Electrical Engineering Department, King Saud University, Riyadh, Kingdom of Saudi Arabia, aalbishi@ksu.edu.sa*
[2]Electrical and Computer Engineering Department, University of Waterloo, Waterloo, Canada, oramahi@uwaterloo.ca*

***Abstract*—In this paper, a sensor design concept for enhancing the electromagnetic energy stored in the sensing volume is presented. The design concept is based on using a three-dimensional capacitor to enhance the stored electric energy in the sensing volume that is exposed to the material under test. For validation, a resonator based on a split-ring resonator (SRR) was utilized to design a sensor. The concept was tested using numerical simulation to characterize dielectric materials.**

I. INTRODUCTION

Nowadays there is a rapid growth in the use of lab-on-a-chip, point-of-care lab testing, rapid testing for quality control application, environmental monitoring, agriculture and public health and safety [1]. These applications raise the need for very sensitive measurements. The majority of the applications utilize microfludic technology, which requires inexpensive and sensitive sensors to be suitable for field applications [1].

Planar electrically-small resonators have been considered as strong candidates for designing planar sensors. Since the resonators are electrically-small compared to the excitation wavelength, the resonators based sensors are scalable to a very wide range of frequency from microwaves to THz. At the resonance frequencies, the electromagnetic fields are enhanced in a small volume surrounding the resonators' structures [2]. Disturbing such fields by the presence of materials under test (MUTs), the resonance frequencies manifest shifts accordingly. The split-ring resonators (SRRs) and their complement (CSRRs) have been used to design different types of sensors (see [3] and references therein). Although, SRRs show higher quality factor, planar electrically-small resonators in general have inherent sensitivity limitation [4]. This work aims to extend the sensitivity of SRR-Based sensors.

II. INCREASED CAPACITANCE FOR SENSITIVITY ENHANCEMENT

Fig. 1(a) shows an SRR mutually coupled to a microstrip line. The SRR is a quasi-static resonator and can be modeled using lumped elements shown in Fig. 1(b). At the resonance frequency, the stored electric energy within the small gap in the SRR is enhanced [2]. The fringing flux in the substrate and the free space can be modeled by an effective capacitance C_{sub} and C_{air} ($C_r = C_{sub} + C_{air}$), respectively. However, since most of the fringing flux will be concentrated in the material with the highest dielectric constant (i.e., the substrate), the effective capacitance C_{sub} will be the dominant contributor to the total capacitance of the SRR [4]. Thus, when the MUT is placed on the small gap (in free space), it will minimally interact with the resonators, thus minimizing the shift in the resonance frequencies, and consequently, result in low sensitivity. To increase the interaction with the MUTs, sharp tips and breaking the symmetry of the SRRs have been proposed, however, most of enhanced stored energy remains in the substrate [5]. Overcoming such limitation can be accomplished by creating a channel inside the substrate to contain the MUTs which substantially increases the interaction with the resonators and consequently enhances the sensitivity [6]. However, from a practical point of view, designing a channel inside the substrate increases the complexity of the sensor, its applicability (for instance to only liquids) and its cost [6].

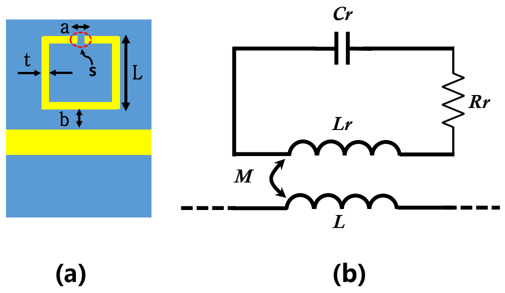

Fig. 1. (a) The SRR coupled to a microstrip line (b) The lumped elements model.

The concept is based on increasing the capacitance experienced by the MUTs by adding a three-dimensional capacitor (C_{pp}) on the top of the small gap of the SRR (labeled as S in Fig. 1)[7]. which will increases the effective capacitance C_{air} leading to an increased interaction with the MUT, hence, the sensitivity of the sensor increases. The concept was tested using a numerical simulation to characterize the dielectric properties of a slab.

III. SENSOR DESIGN AND VALIDATION

The response of the sensor is evaluated using the scattering parameters which can be measured using a vector network analyzer (VNA) with an internal impedance of 50 Ω. Therefore, a 50 Ω microstrip line was used for the excitation of the SRR. This impedance was achieved with a line width of 1.63 mm on a Rogers RO4350 substrate with a thickness of W = 0.75 mm and a relative permittivity of 3.66 and a loss tangent of 0.0031. With the design specification L = 7.5 mm, a = t = 0.5

mm, K = 100 mm and e = 50 mm, the resonance frequency of the sensor corresponding to the minimum transmission zero was 3.46 GHz. The C_{pp} has the following dimensions: C is varied with two values (1 and 4 mm) and the channel gap g = 0.5 mm. The C_{pp} causes the SRR to store more electric energy at the new lower resonance frequency given by

$$f_z = \frac{1}{2\pi\sqrt{L_r(C_{r0} + C_{pp} + C)}} \tag{1}$$

where C_{r0} is the capacitance of the SRR before the inserted C_{PP}. The increase in the capacitor's length (C) will make the resonator to store more energy, hence, lowering the resonance frequency as shown in Fig. 3. The new resonator, therefore, is expected to be more sensitive to detect changes in the surrounding environment since the inserted C_{PP} becomes the dominant capacitance of the resonator. Additionally, when the capacitor's length (C) is 4 mm, the quality factor at -3 dB is increased from 69 to 95, which is expected to yield higher resolution. Note that the increase in the quality factor of the resonator is critical since the inserted C_{PP} is exposed to the surrounding environment, hence, any disturbance of the stored energy in the C_{pp} caused by the MUTs can lead to a higher frequency shift. The sensor was utilized to detect changes in a dielectric slab inserted in the channel gap shown in Fig. 2. The relative permittivity of the slab was varied from 1 to 10 in increments of 1. Fig. 4 shows the simulation results extracted using the full-wave simulation ANSYS HFSS [8].

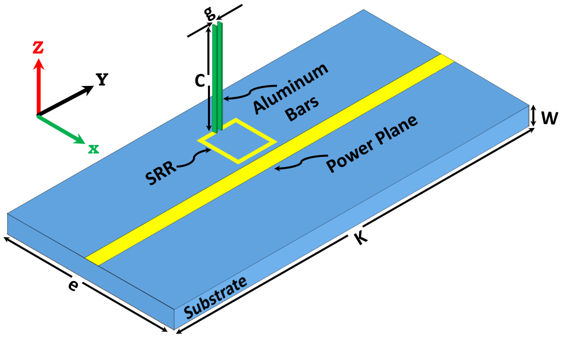

Fig. 2. The schematic of the SRR mutually coupled to a microstrip line where g = 0.5 mm, C = 1,4 mm and K = 100 mm.

IV. CONCLUSION

In this paper, we increased the sensitivity of planar microwave resonators. The concept is based on increasing the overall capacitance of the resonator that interacts with the MUTs by adding a capacitor on top of a planar sensor. Validation is provided by numerical experiments to characterize the dielectric properties of an MUT.

REFERENCES

[1] P. R. Gascoyne and J. V. Vykoukal, "Dielectrophoresis-based sample handling in general-purpose programmable diagnostic instruments," *Proceedings of the IEEE*, vol. 92, no. 1, pp. 22–42, Nov 2004.

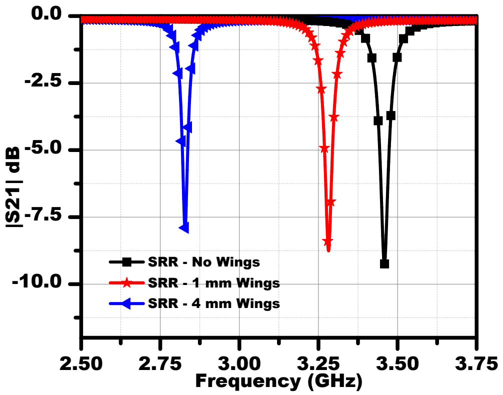

Fig. 3. The scattering parameter $|S_{21}|$ dB of the sensor with and without the inserted C_{pp}.

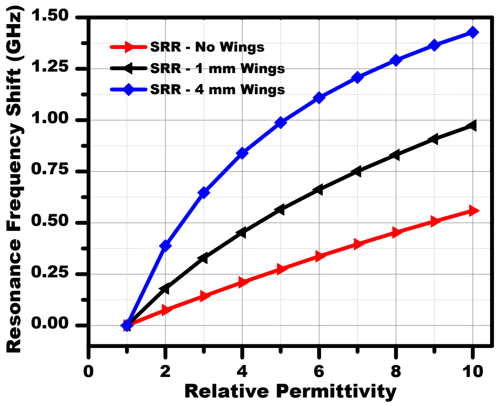

Fig. 4. The sensitivity of the sensor with with and without the added capacitor.

[2] J. Pendry, A. Holden, D. Robbins, and W. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 47, no. 11, pp. 2075–2084, Nov 1999.

[3] A. M. Albishi and O. M. Ramahi, "Microwaves-based high sensitivity sensors for crack detection in metallic materials," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1864–1872, March 2017.

[4] J. F. O'Hara, R. Singh, I. Brener, E. Smirnova, J. Han, A. J. Taylor, and W. Zhang, "Thin-film sensing with planar terahertz metamaterials: sensitivity and limitations," *Optics Express*, vol. 16, no. 3, pp. 1786–1795, Jan 2008.

[5] I. A. I. Al-Naib, C. Jansen, and M. Koch, "Thin-film sensing with planar asymmetric metamaterial resonators," *Applied Physics Letters*, vol. 93, no. 8, p. 083507, August 2008.

[6] M. Abdolrazzaghi, M. H. Zarifi, and M. Daneshmand, "Sensitivity enhancement of split ring resonator based liquid sensors," in *SENSORS, 2016 IEEE*. IEEE, Oct 2016, pp. 1–3.

[7] A. M. Albishi and O. M. Ramahi, "Highly sensitive microwaves sensors for fluid concentration measurements," *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 4, pp. 287–289, April 2018.

[8] "ANSYS HFSS version, 15.0.0, http://www.ansys.com, last access 12-Jan-2017."