

A Microwave Sensor Array for Water Quality Testing

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Abstract— Improved data acquisition with autonomous sensor networks for fine-grained data sampling and collection is critical for ensuring urban water sustainability. It leads to better analysis, predictability, and optimization of water resources. To address this need, here, we propose a microwave sensor array composed of five complementary split ring resonators (CSRRs) operating in the frequency range of 1 GHz to 10 GHz. The use of an array provides the opportunity to acquire more information regarding the water pollutants. Here, the design of the proposed sensor array is presented along with the results of testing that with water samples with heavy metal pollutants including Chromium (Cr), Lead (Pb), and Mercury (Hg).

Keywords— complementary split-ring resonators, microwave sensors, water quality sensing.

I. INTRODUCTION

Population growth, urbanization, and climate change have put significant stress on the natural resources such as food, energy, and water (FEW) that sustain human livelihood [1][2]. The sustainable supply of these resources is also impacted by human activities and myriads of factors. To understand the complex interconnection amongst these factors for a more informed decision-making, fine-grain data is needed to support and validate different modelling approaches for systematic simulation studies.

To address this need, in this paper, we propose a microwave sensor array, based on complementary split ring resonators (CSRRs), operating within the range of 1 GHz to 10 GHz for testing the water quality. In many applications, electrically small resonators such as split-ring resonators (SRRs) (e.g., see [3]–[7]) or complementary split-ring resonator (CSRRs) (e.g., see [8]–[11]) have been proposed to act as near-field sensors for material characterization and detection. At the resonance frequency, the electromagnetic energy density is enhanced dramatically at certain locations in the resonator. Any disturbance of the field around such locations due a material under test causes changes in the resonance frequency. This is used as indicator of the sensed material.

Here, the test results of the sensor array for several major water pollutants such as Chromium (Cr), Lead (Pb), and Mercury (Hg) are presented. These are all categorized as heavy metal pollutants of water.

The proposed sensor array is cost-effective and compact. Thus, it can be mass-produced, and distributed over vast bodies

of water. Besides, the sensor array is passive which eases its maintenance, significantly. Furthermore, it can be easily adapted with wireless data acquisition systems with unmanned aerial vehicles (UAVs) such as drones. The use of an array provides the opportunity to combine the acquired data with machine learning techniques for accurate detection and evaluation of the important water parameters and pollutants.

II. HEAVY METAL POLLUTANTS

Here, the term heavy metal refers to any metallic chemical element that has a relatively high density and is toxic or poisonous at low concentrations in water. Examples of heavy metals include Mercury (Hg), Cadmium (Cd), Arsenic (As), Chromium (Cr), Thallium (Tl), and Lead (Pb). In this paper, we consider measuring Cr, Pb, and Hg.

Main sources of Cr contamination in drinking water include discharge from steel and pulp mills and erosion of natural deposits. Long-term exposure to high doses of Cr can cause allergic dermatitis [12].

Main sources of Pb contamination in drinking water are corrosion of household plumbing systems and erosion of natural deposits. Some potential health effects from long-term exposure to high doses of Pb include delays in physical or mental development of infants and children. Besides, children could show slight deficits in attention span and learning abilities. In adults, it causes kidney problems and high blood pressure [12].

Main sources of Hg contamination in drinking water include erosion of natural deposits, discharge from refineries and factories, and runoff from landfills and croplands. Long-term exposure to high doses of Hg can cause kidney damage [12].

III. DESIGN OF MICROWAVE SENSOR ARRAY

Here, we propose a microwave sensor array to be used for water quality testing. Each sensor is designed based on a microstrip transmission line loaded with a CSRR, resonating at a different frequency within the range of 1 GHz to 10 GHz. More specifically, the sensor array is designed with the elements resonating at five frequencies around 1 GHz, 3 GHz, 5 GHz, 7 GHz, and 9 GHz. Fig. 1 illustrates the sensor array. The CSRRs are etched out of a ground plane covering a substrate with a microstrip line on the opposite surface of the substrate. This configuration for the sensor array is simple and inexpensive to fabricate thanks to the printed circuit board (PCB) technology.

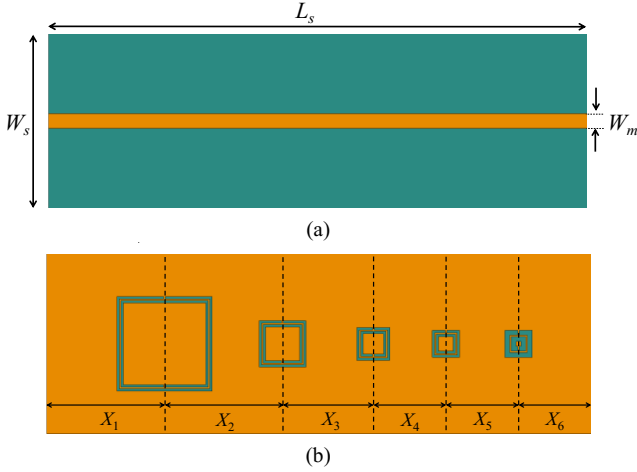


Fig. 1. Proposed microwave sensor array (a) front surface and (b) back surface with Sensor 1 to Sensor 5 (lower to higher frequencies) shown from left to right, respectively.

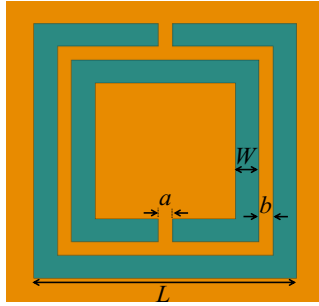


Fig. 2. Parametric model of each CSRR.

TABLE I. DIMENSIONS OF THE DESIGNED CSRRS

Sensor No.	f_r (GHz)	W (mm)	L (mm)	a (mm)	b (mm)
Sensor 1	1.36	0.27	10.5	0.16	0.16
Sensor 2	3.09	0.27	5.15	0.16	0.16
Sensor 3	5	0.27	3.65	0.16	0.16
Sensor 4	6.82	0.27	3	0.16	0.16
Sensor 5	8.91	0.54	3	0.16	0.16

TABLE II. CENTER-TO-CENTER DISTANCE BETWEEN CSRRS

X_1 (mm)	X_2 (mm)	X_3 (mm)	X_4 (mm)	X_5 (mm)	X_6 (mm)
11	13	10	8	8	6

The sensor array allows for measuring the change in the dielectric properties of the water over a wide frequency range, i.e., 1 GHz to 10 GHz. The change in the dielectric properties can be monitored through measuring the resonance frequencies' shifts.

The design of the sensor array is carried out in Altair FEKO software [13]. The substrate is chosen to be Rogers RO4350 with dielectric properties of $\epsilon_r = 3.66$ and $\tan \delta = 0.0031$. The width W_s and length L_s of substrate are 20 mm and 56 mm, respectively. The thickness of the substrate is 0.75 mm. A microstrip line with characteristic impedance of 50 Ω (width of strip line is $W_m = 1.68$ mm) is placed at the center of the front surface of the substrate. At the back side of the substrate, there is a ground plane with CSRRs etched out of that. Fig. 1(b) shows the CSRRs which are sorted from left to right, respectively, corresponding to lower to higher frequencies. They are named as Sensor 1 to Sensor 5, respectively.



Fig. 3. Fabricated sensor array.

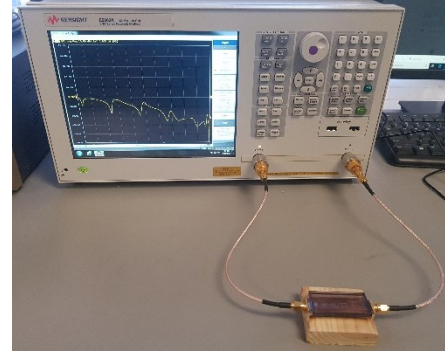


Fig. 4. Measurement of $|S_{21}|$ for the sensor array with a vector network analyzer (E5063A ENA from Keysight Technologies).

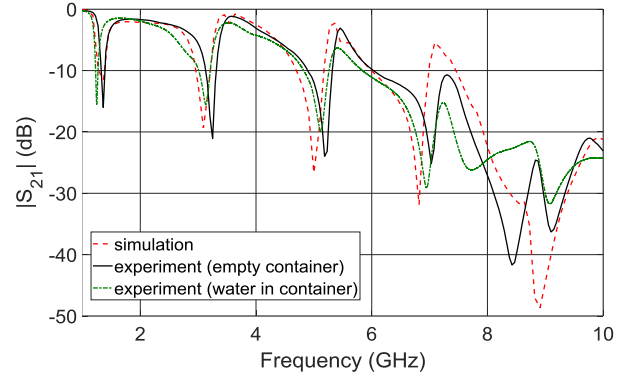


Fig. 5. Simulated and measured $|S_{21}|$ for the sensor array.

The sensors are initially designed separately to expedite the simulation time. Fig. 2 shows the important design parameters for each sensor, including: length of the outer ring L , width of the rings W , the track between the rings b , and the width of narrow lines a . The rings are square-shaped. As a rule of thumb, larger L values correspond to lower resonance frequencies. Also, typically when W gets larger, the resonance frequency decreases.

In the design process, we consider the fabrication limits and restrict the minimum features in the design (width of tracks and gaps) to be 0.16 mm or larger. After each sensor is designed, they are all placed on the same substrate as shown in Fig. 1(b) to compose the sensor array. Further fine-tuning of the complete design is then implemented. The final design parameters along with the resonance frequencies for the sensor array are shown in Tables 1 and 2.

After successful design of the sensor array, it is fabricated using PCB technology. Fig. 3 shows the fabricated sensor array mounted on a wood stand and with SMA connectors soldered to

it. In order to test water samples, a plexiglass container with thickness of approximately 1.5 mm is installed at the back surface of the device including all the CSRRs.

To monitor the response of the sensor array to water solutions, the variation of $|S_{21}|$ versus frequency is measured using a VNA (E5063A ENA from Keysight Technologies) as shown in Fig. 4. Fig. 5 shows the variation of the simulated $|S_{21}|$, compared with the one measured for the fabricated sensor array with the empty container as well as the case in which the container is filled with distilled water. It is observed that reasonable match is observed between the simulated and measured results (for empty container). The slight mis-matches can be due to the use of container in the measurement (it was absent in the simulation model), fabrication tolerances, and soldering.

In the simulation model, we can also observe the current distribution around each sensor as shown in Fig. 6. Investigation of the current distribution on a CSRR at the resonance frequency shows the critical locations at which the electromagnetic energy is concentrated. It is observed from this figure that the current distributions are maximum around the CSRRs which makes these regions sensitive to variations of the fields due to the material (complex permittivity) changes.

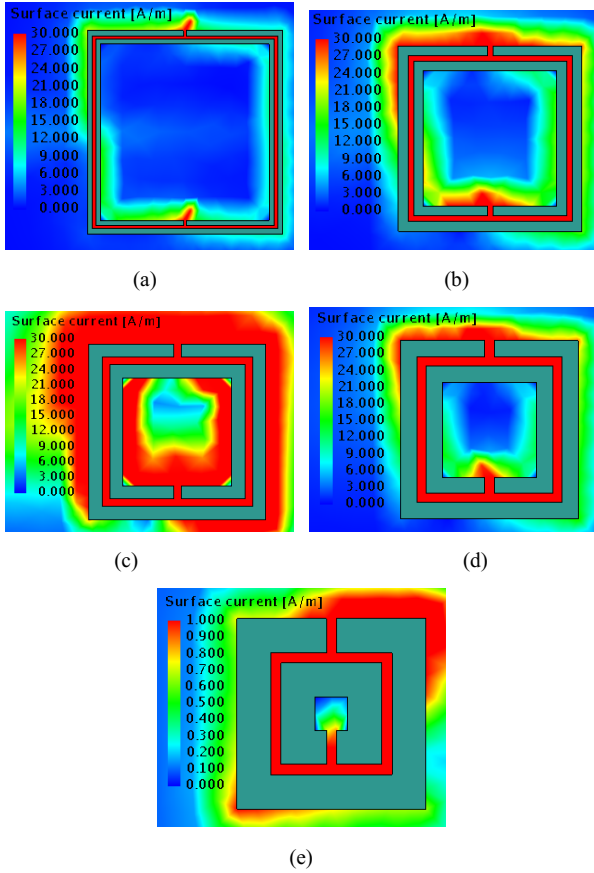


Fig. 6. Current distributions for: (a) Sensor 1 at 1.36 GHz, (b) Sensor 2 at 3.09 GHz, (c) Sensor 3 at 5 GHz, (d) Sensor 4 at 6.82 GHz, and (e) Sensor 5 at 8.91 GHz.

IV. THICKNESS OF WATER CONTAINER

Since the sensitivity of sensors with CSRR elements significantly relies on the high quality factor (Q) of the elements, placement of the CSRR elements next to a medium with substantial loss can significantly lower the Q of the elements, which can potentially result in significant reduction of the sensing accuracy. This issue has been pointed out in [10] and [11]. In particular, it has been shown in [11] that increasing the thickness of a Teflon film between the CSRR element and a metal (aluminum) under test, actually improves the sensitivity of the sensor due to increasing the value of Q . Since here the CSRR elements are used for sensing water which is a high loss material (specially, if it contains heavy metal contaminants), we use a container with a certain thickness of bottom surface t . Choosing a container with proper value for t is crucial. A thin container (small t) may lead to damping of the resonances completely. In our experiments, we first tried using a container with thickness of approximately $t = 0.5$ mm. This led to significant reduction of Q at resonance frequencies of the sensors. On the other hand, a thick container (large t) may decrease the sensitivity of the responses to the water samples due to the increase of the distance between the water sample and the areas of field concentration. Thus, an optimal value of t maximizes sensitivity by compromising these two effects. As mentioned earlier, in this work, we used a plexiglass container with $t = 1.5$ mm. Optimizing value of t via simulation is not straight-forward. This is due to the fact that the commercial dielectric probe kits may not provide reliable measured property values for high conductivity solutions (water samples with heavy metal inclusions). This prevents us from constructing a valid simulation model.

V. WATER QUALITY TESTING

In this section, we present the results of measuring the responses of the proposed microwave sensor array ($|S_{21}|$) when the sensor is exposed to water solutions discussed in section II. The response of the sensor is measured with a Keysight E5063A vector network analyzer (VNA). In order to reduce the effect of random noise on the measurements, an intermediate frequency (IF) bandwidth of 100 Hz is applied on VNA. Each time, the sensor container is filled with one of the water solutions with Cr, Pb, or Hg pollutants. After each solution, the container is cleaned and dried to make it ready for testing the next water solution without any mixing of the pollutants.

Figs. 7 to 9 show the shifts (Δf) observed for resonance frequencies of sensors 1 to 5 when testing the water solutions containing Cr, Pb, and Hg, respectively, compared to the distilled water. The tested concentrations of Cr are 5 $\mu\text{g/mL}$ and 10 $\mu\text{g/mL}$. The tested concentrations of Pb are 5 $\mu\text{g/mL}$ and 10 $\mu\text{g/mL}$. The tested concentration of Hg are 500 $\mu\text{g/mL}$ and 1000 $\mu\text{g/mL}$. In general, the results in Figs. 7 to 9 show an increase in the resonance frequency shift as the concentration level of the heavy metal pollutant increases. Fig. 7 shows that for Cr solution, Sensors 3 and 5 show the largest Δf values. However, Figs. 8 and 9 show that for Pb and Hg solutions, Δf values are

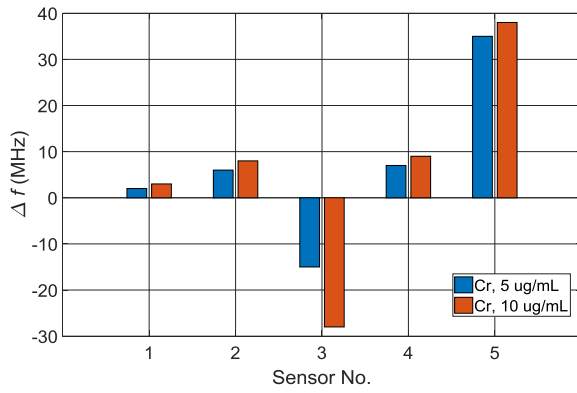


Fig. 7. Measured change in the resonance frequency of sensors for water solutions with two concentration levels of Cr.

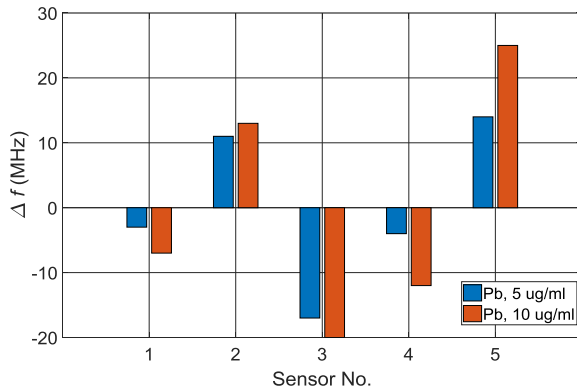


Fig. 8. Measured change in the resonance frequency of sensors for water solutions with two concentration levels of Pb.

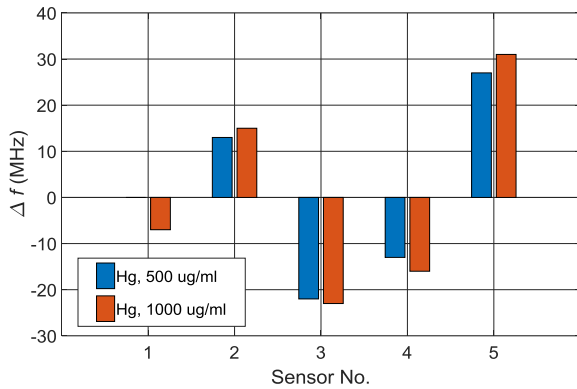


Fig. 9. Measured change in the resonance frequency of sensors for water solutions with two concentration levels of Hg.

noticeable for Sensors 2 to 5. For all tested water solutions, Sensor 5 provides the largest responses to pollutants.

VI. CONCLUSION

In this paper, we proposed a microwave sensor array based on five compact CSRRs for water quality testing. The sensor elements operate at different frequencies covering a wide frequency band from 1 GHz to 10 GHz. This is, to our best knowledge, the first time that a microwave sensor array covering such wide frequency range has been proposed and studied for water quality testing. Since the sensor array can be fabricated

using conventional PCB technology, it can be mass-produced and distributed over vast bodies of water such as lakes, water reservoirs, etc.

For a compact and cost-effective sensing device, VNA needs to be replaced with inexpensive data acquisition systems. For this purpose, the sensor array structure has the advantage of easy integration with RF and microwave circuits. Alternatively, due to operation in the microwave regime, the sensor array can be easily adapted to wireless data acquisition techniques, similar to RFID sensor technology (e.g., see [14]).

Finally, the responses provided from five sensors can be used along with a pattern recognition algorithm to improve the detection and evaluation of water pollutants.

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