MIMOSA - Miniature microwave sensors for agricultural and environmental applications

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***Abstract* — This project report gives a short summary of results of the first phase of the beneficiary's research that is aimed at development of two different types of miniature microwave sensors for application in biomedicine, environmental monitoring, agriculture, etc. First group of sensors, i.e. the ones that measure an electrical parameter that is dependent on the physical parameter of interest, was investigated. Namely, various resonant topologies were incorporated with microfluidic channels to sense the complex permittivity change in the channel. All the sensors will be fabricated in LTCC.**

***Index Terms* — agriculture, biomedicine, environmental monitoring, LTCC, microfluidic, microwave, sensors.**

I. INTRODUCTION

The maturity of microwave technology is opening up new possibilities for a wide application of microwaves in other fields, where agriculture, environment and Earth Observation are the ones of the highest importance for the wellbeing of the human kind. There are many challenges towards this goal, including the design of low cost, low power and easily integrated microwave devices and systems. In particular, very accurate, robust and low cost miniature sensors of various physical quantities are very much needed and their development would open way for a wide adoption of concepts such as the precision agriculture and Internet of things.

In principle, there are two types of sensors that we are investigating. The first group consists of sensors of physical parameters which can be measured by directly measuring some electrical variable which is dependent on the sensed parameter (such as e.g. effective dielectric permittivity in the case of soil moisture sensors, microfluidic sensors, etc.).

The second group of sensors is the sensors of physical parameters which cannot be measured by directly measuring some electrical variable, due to the fact that the electrical properties of the sensor are not influenced by the physical parameter in question. In this stage of the research, we plan to combine various technologies which are at our disposal, to come up with an innovative solution for NOX sensors. Namely, the beneficiary will investigate the use of nano-membranes designed to be sensitive to nitrogen and its oxides, and then investigate the possibility of incorporating such nano-membranes in microwave sensors designed using low-temperature co-fired ceramic (LTCC) technology and/or flexible and organic printed electronics.

Under the scope of this project, part of the first phase of the beneficiary's research was carried out. We have tackled the problem of the first group of sensors described above. Namely, we have considered various resonant topologies and their integration with microfluidic devices for application in biomedicine and environmental monitoring. We have foreseen fabrication in LTCC technology for the most promising sensor topologies.

II. LTCC

Although LTCC presents a well-established process used for many years in the microelectronics packaging industry, it is an emerging and highly promising new technology in sensor design. Environmental sensors need to operate reliably in harsh environments such as high temperatures, high pressures and aggressive media. These demands cannot be met using conventional polymer-based technologies such as PCB. The potential of ceramic-based LTCC is evident from intensified research efforts worldwide in the last four years, which resulted in LTCC sensors with superior characteristics.

Another significant advantage of LTCC over conventional PCB technology is size reduction. By using up to 20 conductive layers instead of just one and high-permittivity LTCC dielectrics, the final sensors will be extremely miniaturized in comparison to the conventional ones, thus enabling "smart dust" applications.

Yet another advantage of LTCC is that it allows for fabrication of complex three-dimensional structures such as cavities. In this way, LTCC opens up a whole new perspective for the sensor design: fluidic channels for liquids and/or gases can be incorporated in the same device with hermetically encapsulated 3-D electrical circuits.

All this makes LTCC an ideal choice for the design of various sensors for agriculture, air pollution monitoring, soil analysis, freshwater and marine monitoring, and biosensors, in line with "smart dust" and Internet of things concepts. By combining nano-membranes to provide sensitivity to certain chemicals and LTCC which results in very robust circuits, both in the mechanical and in the chemical sense, our research will, in the future, provide a new platform to build hermetic, highly stable and reliable sensors and packages.

III. MICROFLUIDIC DEVICES

We have investigated the behavior of various resonant topologies in different architectures: microstrip - 2D and 3D, and coplanar waveguide (CPW), both grounded and ungrounded. 3D EM simulations were carried out using

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Ansoft's HFSS simulator. Fig. 1 shows the HFSS models of each of the resonators in one of the architectures. Resonators represented on Fig. 1a and 1b have the resonant frequency close to 20 GHz, whereas ones depicted on Fig. 1c and 1d have the resonant frequency just above 4 GHz. Each of these resonators was modeled in all the above mentioned variants together with various channels on top of, or below the resonant structures to carry the fluid under test (FUT). Various positions and sizes of channels were considered as well. FUTs used and their respective complex dielectric constants were:

- deionized water: $\varepsilon_{20GHz} = 40.6 + j*33.7$ [1]; $\varepsilon_{4GHz} = 75.35 + j*14.59$ [4];
- deionized water – ethanol mixture (20% volumetric fraction of ethanol): $\varepsilon_{20GHz} = 19.7 + j*23.2$ [1]; $\varepsilon_{4GHz} = 60 + j*20$ [5];
- air: $\varepsilon = 1+j*0$.

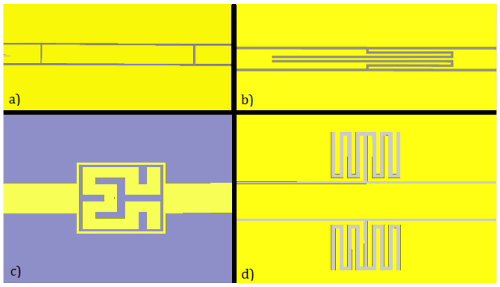

Fig. 1. a) CPW half-wavelength resonator; b) CPW λ/4 - type resonator [1]; c) microstrip grounded Hilbert patch resonator [2]; d) DGS CPW resonator [3]

Deionized water is used as the reference fluid. The resonant frequency shift is calculated in the following way:

$$\Delta f_r = |f_{r-water} - f_{r-FUT}| \quad (1)$$

Sensitivity, defined as the resonant frequency shift with the change of real part of the complex permittivity ($\Delta f_r/\Delta\varepsilon'$), is compared for the most sensitive variant of each sensor, table 1. Fig. 2 gives the $|S_{21}|$ responses in these cases. Highest sensitivity was obtained for the sensor based on the grounded Hilbert patch resonator and is above 2% f_r / ε'.

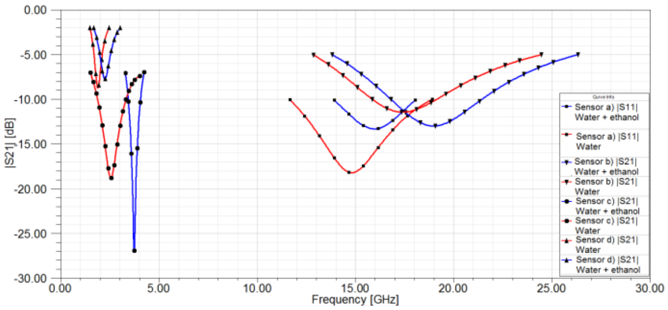

Fig. 2. Responses of the sensors for the microfluidic channel loaded with water (red curve) and water/ethanol mixture (blue curve). Notation a) - d) corresponds to fig. 1.

It is shown here that the sensor based on the grounded Hilbert patch resonator, fig. 3, is several times more sensitive than the microfluidic sensor described in [1] that was used as a reference in this research. Moreover, it is nearly two times smaller with its overall dimensions of $0.12\lambda_g$ x $0.12\lambda_g$, where λ_g is the guided wavelength.

TABLE I

SENSOR COMPARISON IN TERMS OF SENSITIVITY

Sensor	Frequency shift [% f_r]	Sensitivity [% f_r/ε']
Fig. 1a)	7.18	0.34
Fig. 1b)	8.15	0.39
Fig. 1c)	31.6	2.05
Fig. 1d)	12.5	0.8

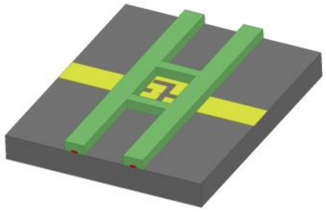

Fig. 3. Sensor based on grounded Hilbert patch resonator - gray represents the substrate, yellow is copper, green are PDMS walls of the microfluidic channel, red is the FUT.

IV. FUTURE WORK

Regarding this group of sensors next step is fabrication of the most promising devices in LTCC and their characterization.

Next phase in our research is development of the second group of sensors: nano-membrane based sensors, particularly for NOX detection in soil and their incorporation with LTCC.

V. FUTURE PLANS

In the future the Scholarship beneficiary plans to continue his academic career and enroll in PhD studies at University of Novi Sad, majoring in microwave engineering. Special interest is in the field of microwave sensor design and their application in various fields.

This decision and interests were highly influenced by the beneficiary's presence at the IMS 2014 in Tampa, FL, USA. By being exposed to the latest research developments presented at IMS, but also to the outstanding exhibition which gathered a very significant number of industry representatives, ranging from multinational companies to SMEs, the applicant gained a deep insight and a specific knowledge in the field of microwave engineering. Moreover, he enjoyed the opportunity to listen live to the presenters and also to start creating his own networks with the colleagues from the field.

VI. REFERENCES

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