URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Wireless detector for ethanol solutions

F. Benassi(1), D. Masotti(2), and A. Costanzo(3)
(1) DEI-"Guglielmo Marconi", Bologna
(2) DEI-"Guglielmo Marconi", Bologna
(3) DEI-"Guglielmo Marconi", Cesena

Abstract

This work introduces the design of a wearable passive microwave sensor working in the 2.45 GHz ISM band for the detection of acqueous solution on the skin surface. The sensing is performed by a loaded open-end coupled-line filter in which one open end is replaced with an open-end stub. The stub is firstly characterized through full-wave simulations and the entire filter is optimized be means of HB simulations. In order to create an energy-autonomous system, a narrow-band antenna is connected to the filter input port and the channel content is analyzed at the filter output in terms of dc-output power. The proposed system boasts a frequency selective behaviour and facilitates wearability due to its realization on a thin and flexible substrate.

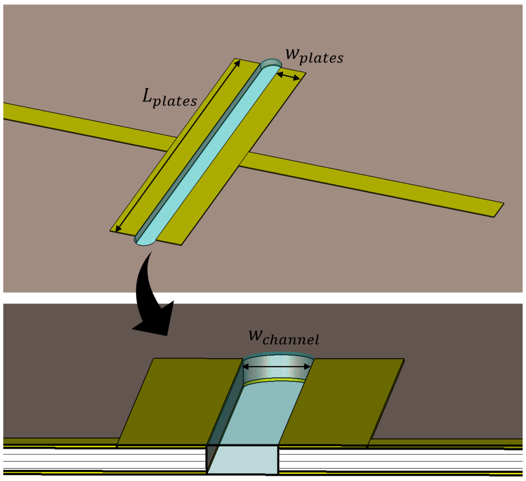

Figure 1. Prospective view of the microfluidic channel embedded on a stub.

1 Introduction

In recent years, microwave sensors have been created to analyze nano-liter aqueous solutions with applications in several fields, as the biomedicine for a passive analysis of the blood concentration [1], or for alternative approaches in the analysis of water composition [2]. To test reduced amount of fluids, microwave planar technologies become essential to enable a radio-frequency characterization up to a cell-level analysis, as presented in [3]. The use of microwave for fluid characterization is raising interests due to the fact that common procedures for liquid or molecules characterization require the use of markers, which have a disruptive impact on the sample itself, whereas exploiting electromagnetic waves can provide a new passive and non-invasive approach [4]. Although this technology can be applied to multiple fields, the basic principles exploit the frequency response of a specific molecule due to its own dielectric characteristics, when insert into a resonant cavity. In particular the resonant cavity experiences a shift in the designed resonant frequency due to the interaction between the electromagnetic fields and the matter under test. The inducted shift in the resonant frequency is correlated to the dielectric properties of the analyzed fluid and can be exploited to perform detection for a non-invasive biosensor application. Resonant structures can vary from split rings, [5], to T-resonators, as in [6]. A small rectangular microfluidic channel in which the fluid is directly provided with small pipes is a common element for this applications and have a significant importance for the sensing achievement. In microfluidic applications, modern 3D-printing manufacturing has enhanced the capabilities to create new structures to perform high-sensitive dielectric properties characterization as in [7], in which a microwave microfluidic sensor based on a substrate integrated waveguide is used to analyze the dielectric properties of specific fluids. The presented work combines the up-mentioned microwave sensing mechanism to realize an open stub that replaces one open end of a third-order coupled-line filter to perform fluid detection, as in [8], but with enhanced focus on the filtering antenna (filtenna) optimization in terms of output power. In this way, the filter behaviour is directly related to the open stub resonance. To achieve a wearable, energy-autonomous identification of the fluid [9], a narrow-band antenna is seamlessly connected to the filter input to provide the power needed to activate the filter. The channel content is detected at the filter output through the measurements of the dc-output power variation on optimum load. The filter is designed by means of full-wave simulations and the overall sensor is optimized through EM/nonlinear co-simulations[10] and co-design [11] procedures.

Table 1. Stub dimensions

Component	Value
Total Stub length	41.1 mm
Line width	0.4 mm
L_{plates}	5.0 mm
w_{plates}	0.5 mm
$w_{channel}$	0.4 mm

2 Design of the resonant stub embedded into the filtenna

In order to create a system that is sensitive to the presence of a specific fluid, a microfluidic channel is derived on a thin flexible substrate, RT/duroid 5880 ($\varepsilon_r = 2.2$, thickness= 0.127 mm). The channel dimensions are 5 x 0.4 mm^2 and the depth is equal to the substrate thickness. The channel is then placed inside an open stub resonator. When the channel is filled with different fluids the electrical length of the stub varies, due to the different dielectric properties of the channel content. This variation on the electrical length implies a different resonance frequency of the stub. To enhance the sensitivity of the stub towards a specific fluid, the stub is tuned to resonate as an open circuit in presence of a specific water-ethanol solutions (70% ethanol concentration) filling the microfluidic channel, at the frequency of 2.45 GHz. The resulting physical dimensions of the tuned stub are listed in Tab. 1. Once the tuning is correctly performed, the fluids are changed and the stub performance is simulated in presence of water and air, respectively. Due to the different dielectric properties of this three fluids the stub experiences a variation of its electrical length which implies a shift in the resonant frequency for which it behaves as an open circuit. This fluid dependency can be observed in Figure 2 and Figure 3, where the real and imaginary part of the stub input impedance are represented.

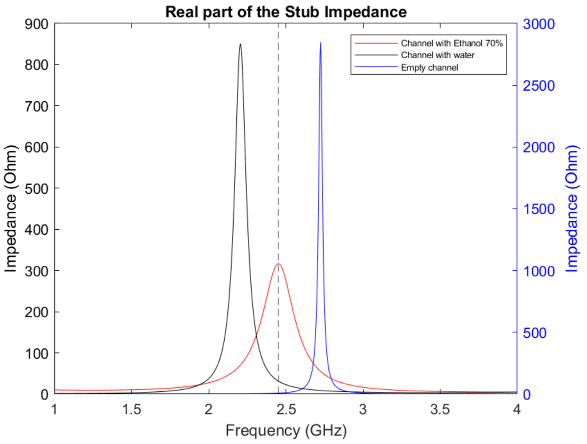

Figure 2. Real part of the stub input impedance in presence of water-ethanol solutions, water and air

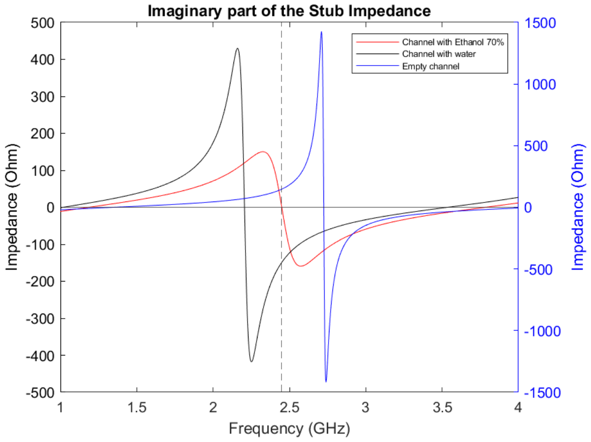

Figure 3. Imaginary part of the stub input impedance in presence of water-ethanol solutions, water and air.

3 Design of the coupled-line filter

As the stub works as an open at the resonance frequency of 2.45 GHz only in presence of the water-ethanol solution, the detection is performed by designing a third-order open-end coupled-line filter on which one open termination is substituted with the created stub. This implementation allows to detect the presence of the searched fluid because at 2.45 GHz the filter behaves accordingly, regardless of the modified termination. However, in presence of water or when the channel is left empty, the stub does not behave as an open circuit at 2.45 GHz. With these two fluids the loaded termination of the filter is not seen as an open and this implies a degradation on the filter performance. In order to quantify the filter response, the signal has to be transduced at the filter output port. A full-wave rectifier is seamless connected to filter output port and it is composed of two Schottky diodes, chosen for their low turn-on voltage, and two 47 pF Murata capacitors belonging to the GJM series. The system is then optimized by means of Harmonic Balance/nonlinear simulations with the aim of maximizing both the $\eta_{RF-to-dc}$ power conversion efficiency and the dc-output voltage for increasing values of received power. The optimized values for the filter in terms of length, spacing and width of each coupled line are displayed in Tab. 2 and a schematic representation of the proposed filtenna is shown in Figure 5. The rectifier shows a $\eta_{RF-to-dc}$ power conversion efficiency of 64.6%, for a 10 dBm received power, for the circuit sensing the water-ethanol solution, 62.8% for the circuit sensing water and 59.4% for the circuit with empty channel. For an optimum load of 4kΩ the DC-output powers for the three different fluids are displayed in Figure 4.

4 Conclusion

This article presents a design of a filtenna for the detection of water-ethanol solutions. The sensing is performed by a stub equipped with a microfluidic channel that operates as an open only in presence of water-ethanol solution at the resonant frequency of 2.45 GHz. The realized coupled-line

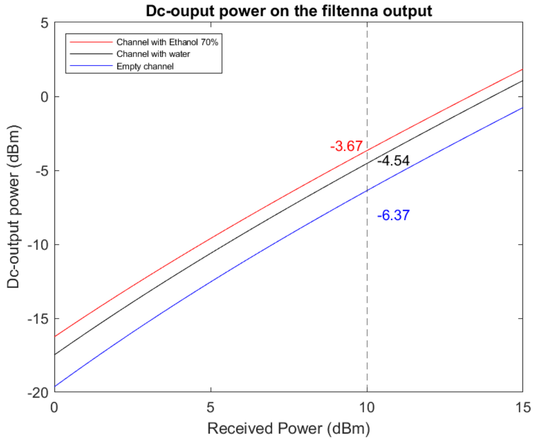

Figure 4. DC-output power in presence of water-ethanol solutions, water and air.

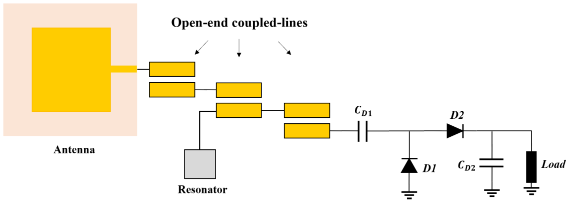

Figure 5. Schematic representation of the proposed filtenna.

Table 2. Filtenna optimized values

Component	Value	Component	Value
$w1_{sup}$	0.63 mm	$w1_{inf}$	0.41 mm
$w2_{sup}$	0.34 mm	$w2_{inf}$	0.4 mm
$w3_{sup}$	0.4 mm	$w3_{inf}$	0.3 mm
$L1$	20 mm	$L2$	25.6 mm
$L3$	25.8 mm	$s1$	0.1 mm
$s2$	0.1 mm	$s3$	0.1 mm

filter in which one open end is loaded with the designed stub enables the transduction of the input signal in accordance with the microfluidic channel content. The different dc-output power enables a correct identification of specific water-ethanol solutions.

References

[1] T. Chretiennot, D. Dubuc, and K. Grenier, “Optimized electromagnetic interaction microwave resonator/microfluidic channel for enhanced liquid biosensor,” pp. 464–467, 2013.

[2] O. Korostynska, A. Mason, and A. Al-Shamma’a, “Proof-of-concept microwave sensor on flexible substrate for real-time water composition analysis,” in Sensing Technology (ICST), 2012 Sixth International Conference on. IEEE, 2012, pp. 547–550.

[3] T. Chen, D. Dubuc, M. Poupot, J.-J. Fournie, and K. Grenier, “Accurate nanoliter liquid characterization up to 40 ghz for biomedical applications: Toward noninvasive living cells monitoring,” IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 12, pp. 4171–4177, 2012.

[4] K. Grenier et al., "Integrated Broadband Microwave and Microfluidic Sensor Dedicated to Bioengineering," in IEEE Transactions on Microwave Theory and Techniques, vol. 57, no. 12, pp. 3246–3253, Dec. 2009.

[5] A. A. Abduljabar, D. J. Rowe, A. Porch and D. A. Barrow, "Novel Microwave Microfluidic Sensor Using a Microstrip Split-Ring Resonator," in IEEE Transactions on Microwave Theory and Techniques, vol. 62, no. 3, pp. 679–688, March 2014.

[6] B. S. Cook, J. R. Cooper, and M. M. Tentzeris, “An inkjet-printed microfluidic rfid-enabled platform for wireless lab-on-chip applications,”IEEE Trans. Microw. Theory Tech, vol. 61, no. 12, pp. 4714–4723, 2013.

[7] G. M. Rocco, M. Bozzi, S. Marconi, G. Alaimo, F. Auricchio and D. Schreurs, "3D-Printed Microfluidic Sensor in Substrate Integrated Waveguide Technology," 2018 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Ann Arbor, MI, 2018, pp. 1–3.

[8] F. Benassi, N. Zincarelli, D. Masotti and A. Costanzo, "A wearable passive microwave fluid sensor wirelessly activated", 2019 IEEE Wireless Power Transfer Conference (WPTC), London, UK, 2019 (Accepted Paper).

[9] A. Costanzo and D. Masotti, "Energizing 5G: Near- and Far-Field Wireless Energy and Data Trantransfer as an Enabling Technology for the 5G IoT," in IEEE Microwave Magazine, vol. 18, no. 3, pp. 125–136, May 2017.

[10] V. Rizzoli, A. Costanzo, D. Masotti, P. Spadoni and A. Neri, "Prediction of the End-to-End Performance of a Microwave/RF Link by Means of Nonlinear/Electromagnetic Co-Simulation," in IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 12, pp. 4149–4160, Dec. 2006.

[11] A. Costanzo, D. Masotti, M. Fantuzzi and M. Del Prete, "Co-Design Strategies for Energy-Efficient UWB and UHF Wireless Systems," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 5, pp. 1852–1863, May 2017.