Liquid Characterization through 3D-printed Microfluidic Sensors

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INTRODUCTION

This research project has the purpose of realizing wireless components and sensors through additive manufacturing techniques. In particular, it is focused on the design and the development of a microfluidic sensor based on a square resonant cavity. Microfluidic sensors are devices used for biological and chemical applications and are very well known in literature. The novelty of this work consists in having a resonant cavity (Fig.1) completely fabricated through stereolithography, thus realized in a one-pass, low-cost, and rapid fabrication process. This cavity has an embedded meandered pipe, where the liquid of interest (LUT) can be injected and then characterized from the electromagnetic point of view, thus extracting the dielectric permittivity and the loss tangent of the LUT.

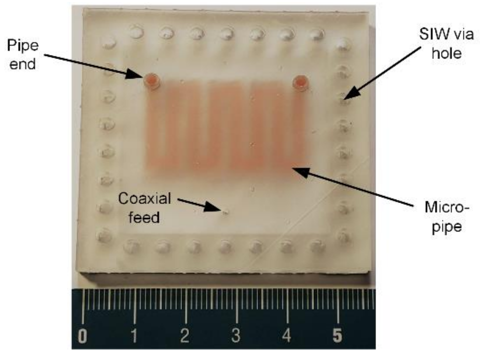

Fig. 1. Photograph of the prototype with colored water to highlight the embedded micro-pipe.

MATERIALS AND METHODS

In order to extract the dielectric properties of the LUT, the S-parameters have been measured when filling the pipe with different LUTs, using a coaxial probe as microwave port of the circuit.

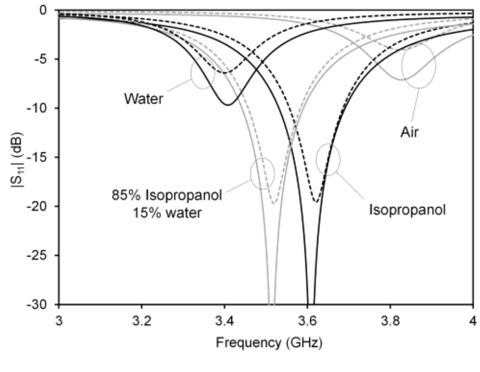

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Fig. 2 shows the measured $|S_{11}|$ for four different cases (air, isopropanol 100%, a mixture of 85% isopropanol and 15% water, and distilled water). As expected, the resonance frequency of the cavity decreases when moving from air-filled, or empty, to water-filled pipe, i.e., when increasing the dielectric permittivity of the LUT. More specifically, the resonance frequencies change from 3.826 GHz with the empty pipe to 3.408 GHz with the water-filled pipe. In addition to the frequency shift, the quality factor of the cavity changes when modifying the liquid in the pipe.

RESULTS

The resonance frequency and the unloaded quality factor of the cavity can be both derived from the measured S-parameters and then used, with a novel and rigorous approach, to extract the dielectric characteristics of the LUTs. Firstly, the loss tangent is obtained from the cavity quality factor, once deembedded the losses of the sensor, and then the dielectric permittivity can be derived from the resonance frequency shift, taking into account also the loss tangent of the liquid.

Table I and II illustrate the results obtained with this approach, compared with the nominal values of loss tangent and permittivity obtained through Dielectric Probe Kit.

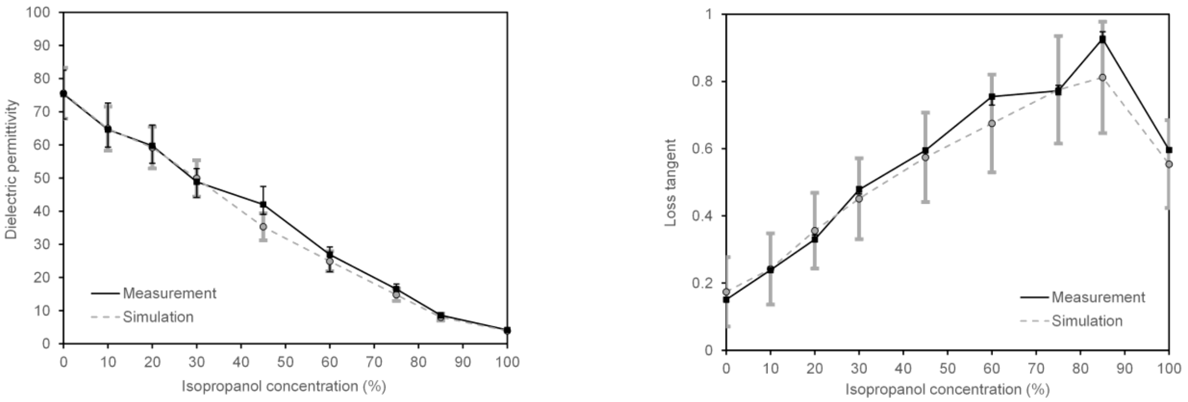
TABLE I
LOSS TANGENT RETRIEVED WITH THE PROPOSED METHOD AND REFERENCE VALUES MEASURED WITH THE COAXIAL PROBE

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
Water 100%	0.150	0.174	-13.9
Isoprop. 10%/Water 90%	0.238	0.242	-1.61
Isoprop. 20%/Water 80%	0.331	0.356	-6.93
Isoprop. 30%/Water 70%	0.478	0.451	+6.09
Isoprop. 45%/Water 55%	0.594	0.574	+3.49
Isoprop. 60%/Water 40%	0.755	0.675	+11.86
Isoprop. 75%/Water 25%	0.776	0.775	+0.12
Isoprop. 85%/Water 15%	0.910	0.815	+12.03
Isopropanol 100%	0.597	0.554	+7.79

TABLE II
DIELECTRIC PERMITTIVITY RETRIEVED WITH THE PROPOSED METHOD AND REFERENCE VALUES MEASURED WITH THE COAXIAL PROBE

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
Water 100%	75.3	75.6	-0.4
Isoprop. 10%/Water 90%	64.7	64.9	-0.4
Isoprop. 20%/Water 80%	59.7	59.2	+0.9
Isoprop. 30%/Water 70%	48.9	49.9	-2.1
Isoprop. 45%/Water 55%	42.0	35.3	+19
Isoprop. 60%/Water 40%	23.57	24.9	+8.3
Isoprop. 75%/Water 25%	16.5	14.8	+11.6
Isoprop. 85%/Water 15%	8.60	8.04	+7.5
Isopropanol 100%	4.20	3.90	+7.1

The evaluation of the accuracy of the proposed method is performed through the analysis of measurement error bars. Fig. 3 reports the values of dielectric permittivity and loss tangent retrieved from measurements, compared with the reference values obtained by using the coaxial probe, for the different liquids considered. The black error bars, relative to the coaxial probe results, have been generated considering the typical accuracy reported in the datasheet of the probe; the grey ones instead, which are relative to the values retrieved from the sensor S-parameters, have been generated by using the datasheet of the Vector Network Analyzer.



(a) *(b)*

Fig. 3. Comparison between the retrieved and reference values of the dielectric characteristics, with error bars: (*a*) Dielectric permittivity; (*b*) Loss tangent.

As shown Fig. 3, the uncertainty in the values of dielectric permittivity and loss tangent retrieved with the proposed method are considerably lower than the uncertainty of the probe, especially in the case of loss tangent measurements.

DISCUSSION

In this research activity, a novel kind of microfluidic sensor has been designed and realized. The structure consists of a one-port cavity with an embedded micro-pipe, where the fluid can be injected and extracted, with the aim to determine its electromagnetic properties. A novel method was developed to retrieve the dielectric permittivity and the loss tangent of the liquid from the measured scattering parameter |S11|. The main feature of this method is the deembedding of the losses of the 3D-printed structure, which represent the largest source of error. Several measurements have been performed, and mixtures with different concentration of isopropanol have been used in order to test the efficiency of the proposed method over a wide range of values of dielectric permittivity and loss tangent.