Millimeter wave dielectric characterization of biological tissues using an on-wafer CPW sensor.

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***Abstract*—We describe a dielectric sensor that is used to measure several biological fluids and tissues. The device consists of an LTCC wafer with a PDMS ring on top. S-parameter measurements are made, TRL calibrated and de-embedded. Two extraction methods are used to obtain the relative permittivity: conformal mapping and a method based on 2D simulations. Results are given for ethanol, 50% ethanol-water, porcine blood and calf liver over a frequency range from 2 to 110 GHz. There is a good match between the results obtained with the conformal mapping and the 2D simulations method. Results for reference fluids correspond with published data.**

***Index Terms*—millimeter wave measurements, dielectric measurements, permittivity, dielectric losses, biological materials**

I. APPLICATIONS OF MILLIMETER WAVES

Millimeter waves have applications in several areas. A list of some possible application domains is given below:

- telecommunications
- radar and imaging
- medical treatment
- military

Most of the mentioned applications require knowledge of the dielectric behavior of biological tissues. For telecommunications, radar and imaging applications, it is important to assess the safety of these applications. Often, simulation models are used to see how millimeter waves interact with the skin and other tissues. In order to do accurate simulations, a good knowledge of the dielectric behavior of the several biological substances and tissues is needed. Also in medical treatment, good knowledge of the dielectric behavior will provide more insight. Dielectric measurements in se can also be interesting for a variety of applications (e.g. lab-on-chip applications).

II. EXPERIMENTAL SETUP

A photograph of the dielectric sensor is given in figure 1. It consists of a (1 cm by 1 cm) LTCC wafer with a PDMS ring on top. The ring is produced using a metal mold. The LTCC wafer is produced at VTT in Finland and consists of several layers of Ferro A6M substrate material. Two types of transmission lines are designed: one normal CPW (coplanar waveguide) line and one CPW-strip-CPW line that uses pieces of stripline to avoid the influence of the PDMS ring. The conductor material is gold. The thickness of the lines is 5μm, the center conductor of the CPW lines is 230 μm wide and the width of gap between the center conductor and the ground planes is 50 μm.

The LTCC wafer is probed with Cascade Microtech Infinity Probes (GSG 100) in a Summit 11651B probe station with Microchamber and temperature controllable chuck (ThermoChuck$^{\circledR}$). The probes are connected with an Agilent E8361A network analyzer that is complemented with two N5260-6003 67-110 GHz waveguide T/R modules and a N5260A millimeter head controller to obtain a setup that can measure between 10 MHz and 110 GHz.

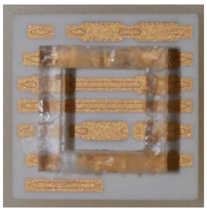

Fig. 1. Dielectric sensor: CPW lines on an LTCC wafer covered with a PDMS ring. The longest lines are the lines used for measurement. The shorter lines are TRL calibration structures.

III. EXTRACTION ALGORITHMS

The raw S-parameters measurements from the VNA are processed in three steps: calibration, de-embedding and permittivity extraction.

An off-wafer LRRM calibration is done using an impedance standard substrate (ISS). To move the reference plane of the measurements inside the PDMS ring, on-wafer TRL calibration structures are provided. These are visible in figure 1.

The next step, de-embedding, is needed to remove the pieces of air and ring left and right from the MUT (material under test) from the measurement data and is only necessary for the CPW lines. The method is based on inverse multiplication of ABCD-matrices (see [1] and [2] for a detailed explanation).

The last step in the data processing is to calculate the relative permittivity ε_r out of the obtained propagation constant γ of the MUT. Two methods are used (both methods assume that conduction losses are negligible, in other words: $\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$):

Simulation based method. The obtained γ_{mut} is compared with a γ_{sim} obtained from 2D simulations using a commercially available software package for electromagnetic simulation. By setting different values for ε_r' and $\tan\delta$ in the software, a giant look-up table of γ_{sim} values can be constructed.

Conformal mapping is a quite straightforward method based on the assumption that the transmission line geometry can be transformed into an equivalent (but more simple) parallel plates capacitor geometry. We used the methods described by Seo et al. [1] and Raj et al. [3].

IV. RESULTS

Since the measurements using the CPW-strip-CPW line are unusable for frequencies higher than 40 GHz, we only give the

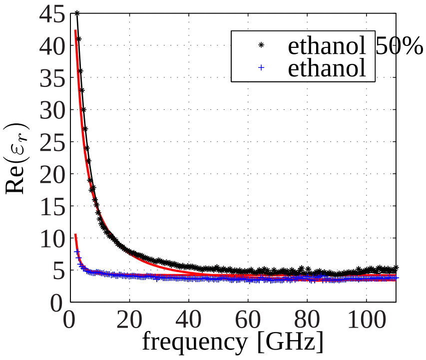

Fig. 2. Measurement and Debye model (red line, see table **??** for the parameters) for ε_r' of ethanol and ethanol 50%.

TABLE I
FITTED DEBYE PARAMETERS FOR MEASURED BIOLOGICAL TISSUES.

material	ε_∞	ε_s	τ (ps)
porcine blood	59.5	10.8	11.8
calf liver	53.7	10.9	14.5
chicken muscle	61.7	10.4	13.8
bovine muscle	58.7	9.9	14.3

results for the CPW line. To test the sensor, some reference liquids are measured. For pure water, the Debye model from Ellison et al. [4] fits well to the measured ε_r' for frequencies up to about 70 GHz. The fit with $\tan\delta$ is good up to about 40 GHz. For methanol the fit with the parameters described in [5] is good up to about 20 GHz and a little too high for higher frequencies. The last reference fluid is ethanol (and ethanol 50%) for which ε_r' is plotted (together with the Debye models as in [5] and [6]) in figure 2. The black solid line represents the result obtained via the conformal mapping method. The discrete symbols represent the result obtained through the simulation based method. It can be seen that both methods give very similar results (especially for ε_r'). The Debye model (red line) seems to fit to the measured data (although the fit is less good for $\tan\delta$).

In figure 3 the measurement of ε_r' for calf liver and porcine blood (2 days old) are represented. For these materials we searched for the Debye parameters that give the best fit for ε_r'. These parameters are listed in table I. The Debye models are plotted as red lines figure 3. It can be seen that the fit is good for ε_r'. The fit is less good for $\tan\delta$ (not displayed).

V. CONCLUSION

Millimeter waves have applications in a lot of areas. Often it is necessary to understand how millimeter waves interact with biological tissues (to ensure safety or to explain certain mechanisms). Therefore, knowledge of the dielectric permittivity of biological materials is important. Dielectric measurement in se also has a lot of applications (e.g. lab-on-chip measurements of all kinds of substances). An on-wafer dielectric sensor consisting of an LTCC wafer with a PDMS ring on top is designed. The sensor allows to measure biological fluids and substances in a relatively easy way. Broadband measurements were made using a vector network analyser. Permittivity values for reference fluids (water, ethanol and methanol) correspond well with published data. The method seems less accurate when measuring losses. The sensor also is capable of measuring biological tissues such as chicken muscle, bovine muscle and porcine blood. Note that a more elaborate paper on this research project has been published [7].

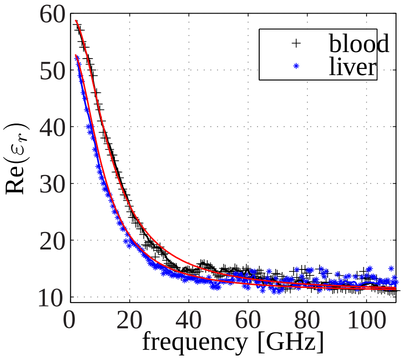

Fig. 3. Measurement and Debye model (red line, see table I for the parameters) for ε_r' of porcine blood and calf liver.

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I am very grateful to MTT-S for funding and encouraging this research through their undergraduate scholarship. In addition to this, the programme enabled me to attend the IEEE International Microwave Symposium 2012 in Montreal, Canada. This was a truly great experience. I had no idea the microwave community was this big and diverse.

In October 2012 I started working for the technology consulting firm Altran. I will be able to work for several companies and develop some feeling about how the telecom and microwave industry works. At a later stage, I hope to be able to combine my academic and industrial knowledge in a dynamic and team-based research group.

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