

A Robust Capacitive Sensor Platform for On-Line Dielectric Constant Measurement of Liquid Mixtures

Pascal Schläpfer¹, Julia Schläpfer¹, Marcel Giger¹

*¹ Innovative Sensor Technology iST AG, Stegrütistrasse 14, CH-9642, Ebnat-Kappel
pascal.schlaepfer@ist-ag.com*

Summary:

Continuous on-line monitoring of liquid composition is important for process control and analytics. In this work, a ceramic-based capacitive sensor platform for dielectric constant measurement is presented. The sensor consists of an alumina substrate with printed metal and glass layers. Readout was performed using a capacitance to digital converter (CDC) device while the sensing side was immersed in DI water/ethanol mixtures. Literature-based dielectric constants of approximately 80, 57, and 42 were compared with 3D COMSOL simulations and capacitance measurements, demonstrating proof-of-concept liquid differentiation.

Keywords: dielectric constant, capacitive sensing, liquid monitoring, CDC, multifunctional sensor platform

Background and Motivation

Continuous, on-line measurement of liquid properties is important for industrial process monitoring. In particular, the dielectric constant is a useful parameter because it supports differentiation and quantification of liquid compositions. Relevant examples include methanol concentration control in direct methanol fuel cells [1] and ethanol monitoring in fermentation processes, where dielectric measurements have been shown to correlate strongly with ethanol concentration [2]. Dielectric characterization of binary water–alcohol mixtures has been demonstrated over broad frequency ranges and can be used to identify mixture composition [3]. However, existing dielectric measurement approaches still show practical limitations: commercial probe- and RF-based methods are often comparatively expensive and complex and may require non-negligible sample volumes [4]. In this contribution, a robust capacitive sensor platform for on-line dielectric constant measurement is presented. The approach is based on a ceramic material platform that additionally allows the integration of further sensing functions, such as temperature or conductivity measurement, on the same substrate. This makes the concept attractive not only for proof-of-concept dielectric sensing, but also as a basis for compact multifunctional liquid sensor systems. Due to material choice and production methods, the underlying material platform has been shown to be robust against chemically demanding

electrolyte-containing and alkaline media, such as concentrated NaCl and NaOH solutions.

Simulation

To support the experimental work, a 3D COMSOL model of the capacitive sensor was established. On the active side of the sensor, a semi-infinite half-space filled with liquid medium was assumed, and the dielectric constant of this region was varied between 1 and 80. The dielectric constant of the glass passivation was modeled as 12, based on a combination of datasheet information and empirical experience. On the back side of the sensor, a semi-infinite air region with dielectric constant 1 was assumed.

Fabrication

The sensor is built on an alumina substrate (96% purity) with silver through-contacting. On the front side, gold interdigital electrodes form the active capacitive structure, which is covered by a glass passivation layer. Metal and glass layers were formed using screen printing. Finger width and separation were chosen to be 150 μm .

Experimental setup

During measurement, the active side of the sensor was immersed into the liquid under test, while the back side remained exposed to air. The liquid volume was chosen much larger than the active sensor area. The readout was performed using a CDC device with an external reference capacitance of 15 pF. The CDC used utilizes discharge-time-based capacitance measurement. Three liquid states based on DI water and ethanol were investigated experimentally. Details are given in Table 1. The experimental

measurements were performed at room temperature ($\sim 25^\circ\text{C}$).

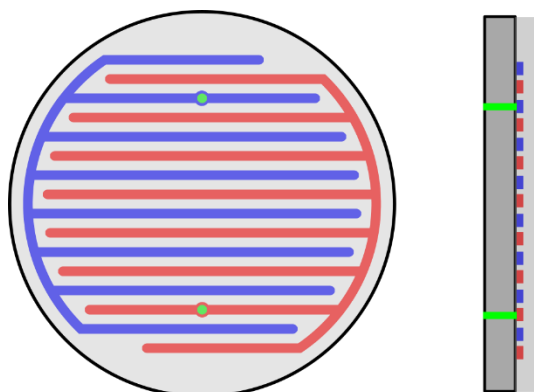


Fig. 1: left: top view of sensor element (active side); right: cross-sectional view of sensor element (not to scale). Finger width and separation was chosen to be $150\ \mu\text{m}$, outer diameter of the chip is $10\ \text{mm}$.

Proof-of-Concept Results

The COMSOL simulation of sensor capacitance for a medium dielectric constant between 1 and 80 shows an expected monotonic increase in capacitance with increasing dielectric constant of the medium. The gradient of this curve changes with dielectric constant. This is due to the passivation layer over the electrodes. In simulations without this passivation glass (not shown here), the capacitance gradient with dielectric constant appears linear. However, this passivation layer is instrumental for the used readout electronics, since dominant electrical conduction between the electrodes would introduce significant errors in the measurement. Both measurement values and simulation output are given in Figure 2. Numerical values are given in Table 1.

The results demonstrate that the sensor platform can differentiate liquid states with different dielectric constants by means of capacitive readout. The agreement between literature-based medium permittivity estimations, simulation trend, and measured response lies within 8%. At the current stage, the study should be interpreted as platform validation rather than a full quantitative dielectric metrology study. A broader concentration series, temperature-dependent characterization, and evaluation of possible conductivity-related cross-sensitivities will be instrumental for future work. The use of ceramic substrate materials and high-temperature, chemically resistant sensing and protection materials enables the combination with multiple additional sensing parameters, such as temperature, conductivity, or liquid flow.

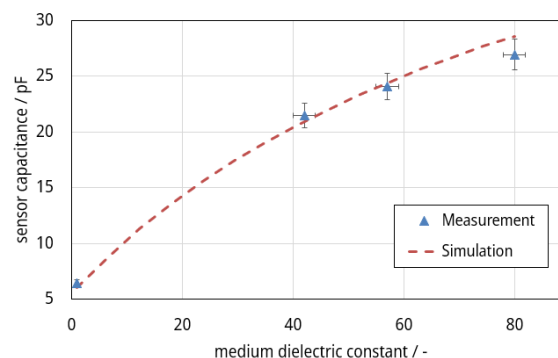


Fig. 2: measured capacitance values in air and in three different liquid media. The red dashed line shows simulated sensor capacitance values.

Tab. 1: comparison between simulated and measured capacitance values for measurements in air and in three liquid media. ϵ_r values were estimated according to [5].

Medium (ϵ_r)	$C_{\text{simulation}} / \text{pF}$	$C_{\text{measured}} / \text{pF}$
Air (1)	5.99	6.45 ± 0.32
70 vol.% ethanol (42)	20.95	21.47 ± 1.07
37 vol.% ethanol (57)	24.40	24.07 ± 1.20
DI water (80)	28.59	26.94 ± 1.35

References

- [1] S. Andoh, A. Fujita, T. Miitsu, Y. Kuroda, S. Mitsushima, Practical and Reliable Methanol Concentration Sensor for Direct Methanol Fuel Cells, *Electrochemistry* 89 (3), 250–255 (2021); doi: 10.5796/electrochemistry.21-00012
- [2] Z.P. Jákó, B. Lemmer, R. Dobozi, C. Hodúr, S. Beszédes, Using Dielectric Constant Measurement to Monitor Ethanol Fermentation and Anaerobic Co-Digestion of Lignocellulosic Biomass, *Fermentation* 9, 902 (2023); doi: 10.3390/fermentation9100902
- [3] J.-Z. Bao, M.L. Swicord, C.C. Davis, Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol, *Journal of Chemical Physics* 104 (12), 4441–4450 (1996); doi: 10.1063/1.471197.
- [4] A. Salim, M.U. Memon, H. Jeong, S. Lim, Simplified Approach to Detect Dielectric Constant Using a Low-Cost Microfluidic Quarter Mode Substrate-Integrated Waveguide, *Sensors* 20, 4985 (2020); doi: 10.3390/s20174985
- [5] Lechner, M.D. (ed.), Static Dielectric Constants of Pure Liquids and Binary Liquid Mixtures: Supplement to IV/6. Landolt-Börnstein, New Series, Group IV: Physical Chemistry, Vol. 17, Springer, Berlin Heidelberg (2008); doi: 10.1007/978-3-540-75506-7