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Reflection-Type Open-Ended Parallel-Plate Type Sensor for Direct Broadband Dielectric Spectroscopy of Liquid Chemicals with Simplified Calibration

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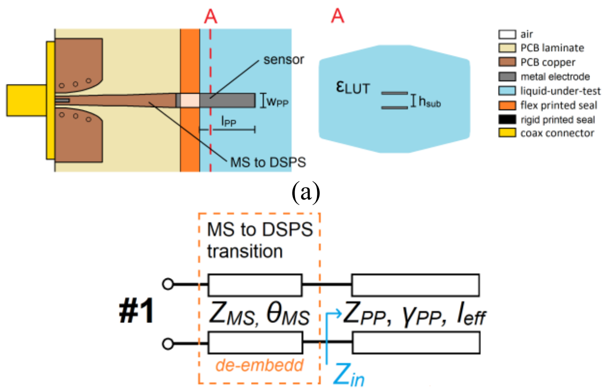
Abstract

A novel one-port microwave sensor is proposed, which is dedicated for direct broadband dielectric spectroscopy of liquid chemical. An open-ended parallel-plate transmission line is realized out of sheet metal to extend past the host printed circuit board, thus the sensed complex permittivity is directly the permittivity of measured liquid-under-test. The sensor is fed by a double-sided parallel stripline which interconnects through a broadband transition to a microstrip input line, which are later de-embedded using a single open standard. A simplified calibration technique that requires only one measurement in air is employed to establish all calibration constants. The sensor was utilized for measurements of various alcohols in a high cm-wave range proving the usability of the proposed circuit for liquid material characterization.

1. Introduction

Knowledge of materials electrical parameters is useful for quality assessment and process control in many branches of industry, especially the food industry as well as biomedical applications. Traditional methods of food quality assessment, bacteria detection and detection of chemical compounds rely on chemical analysis, which is time-consuming and expensive since such analysis can only be performed in well-equipped laboratories. Taking all of this into account there is a need for novel fast and accurate measurement techniques, which allow for non-destructive characterization of material-under-test. Among methods allowing for gathering the information about the materials, the methods, which utilize electromagnetic (EM) waves are of great interest, since the EM waves penetrate the material and allow for non-destructive material characterization with high measurement speed. In literature, the microwave techniques allowing for dielectric samples properties investigation have been widely described [1]. In general, the selection of EM measurement technique allowing for material characterization is dependent on material-under-test type (solid, liquid) and frequency range, in which the material needs to be characterized (resonant, wideband) [2]. The resonant methods rely on the measurement of the resonant frequency and quality factor changes, which are caused by the change of EM boundary conditions when the sample is introduced. Based on these changes, the measured dielectric sample can be characterized. The resonant measurement techniques utilized as sensing elements waveguide cavities or microstrip elements such as ring resonators, patch antennas, etc. The resonant methods are in general more accurate, nevertheless, materials can be characterized at discrete frequencies only, thus for materials featuring frequency-dependent permittivity change other techniques need to be used. Various dielectric materials, especially liquid ones feature frequency dependent permittivity. Thus, the wideband methods, known as transmission/reflection methods are a subject of extensive studies [3]-[6]. Especially attractive are methods enabling direct broadband dielectric spectroscopy (BDS) [7]-[10] where liquid-under-test (LUT) constitutes fully the propagation medium and thus its relative permittivity is sensed directly by a sensor as in opposite to partial constitution leading to effective permittivity sensing that requires models to translate to relative one. In many cases the sensors require two- or more port S-parameter measurements.



(b)

Figure 1. General view of the proposed sensing setup (a). Transmission line based model of the proposed sensor (b). The open end fringe capaciatance is modeled throgh an effective sensors length.

In this paper, we propose a novel one-port microwave sensor dedicated for direct BDS. An open-ended parallel-plate transmission line is used to sense the liquid-under-test permittivity when the sensor`s electrodes are submersed in the sample. The complex permittivity is determined from the input impedance of the sensor measured at host PCB edge. A one standard port extension is used for de-embedding along with simplified calibration technique that exploits the sensor`s dual modes, i.e. resonant and broadband requiring only one measurement in air. Sensing setup demonstrator is developed, and its performance is experimentally validated. The measurement results for a set of various alcohols are provided and discussed.

2. Direct Broadband Dielectric Spectroscopy

A general model of the proposed sensor for direct BDS is shown in Fig. 1. The sensor is composed of an open-ended section of a parallel-plate transmission line that overhang past its host printed circuit board. This way the sensor can be entirely immersed in the LUT so it constitutes full the propagation medium what ensures direct sensing of its relative permittivity. A 3D-printed flex-rigid seal is used to prevent LUT from leaking past the sensing wires and altering the feed lines. Since the sensor is a balanced line, an on-PCB double-sided parallel-strip line (DSPS) is used to feed the sensor and mechanical anchor it to the board. Such an arrangement requires either differential excitation by using a balun or two-port single ended excitation with mathematical processing. Disadvantage of the above-mentioned methods of the sensor excitation are increased setup complexity or port count. The proposed sensor`s wire arrangement suits well an alternative approach where a different guide can be used as a measurement interface, namely microstrip (MS) when appropriate transition is realized. Thus, to obtain a single-port interface for the proposed setup, a broadband, uniform-impedance MS to DSPS transition is developed. For further analysis, however, the interface connections must be de-embedded setting the reference plane at the very input of the sensors as indicated in Fig. 1. This can be either done though full one-port Short-Open-Load calibration or in simpler approach through Short or Open standard normalization with the benefit of requiring only one standard instead of three however at the expense of reduced accuracy.

To determine the complex relative permittivity of the LUT ε_{MUT} from the measured and de-embedded setup`s reflection coefficient $\Gamma_{deemb}$, the model shown in Fig. 1b is used. To reduce the analysis complexity, the fringe field capacitance of an open end is modeled through an effective sensor`s length l_{eff} that is longer than the physical one l_{PP}. In such a case the input impedance Z_{in} of the sensor`s model reduces to one of an open-ended line expressed as:

$$Z_{in} = Z_{PP}\coth(\gamma_{PP} l_{eff}) \quad (1a)$$

$$Z_{PP} = \frac{1}{cC_0\sqrt{\varepsilon_{MUT}}};\ \gamma_{PP} = j\frac{\omega}{c}\sqrt{\varepsilon_{MUT}} \quad (1b)$$

where C_0 is the per-unit-length capacitance of the parallel-plate sensor in a uniform and unitary dielectric medium, γ_{PP} is its complex propagation constant, ω is the angular frequency, and c is the free-space velocity of light. The characteristic impedance Z_{pp} is proportional to the sensor electrode`s distance to the width ratio. By replacing the left side of Eq. (1) with the measured input impedance Z_{in_meas} (recalculated from Γ_{deemb}) one gets equation which can be solved for ε_{MUT}. The analytical solution is non-trivial; however, it can be approximated utilizing e.g. the Maclaurin series expansion of $coth(x)$ function with its first two elements ($coth(x) \approx \frac{1}{x} + \frac{x}{3}$, assuming $|x| < \pi$) with error below 6.3% for $\gamma_{PP} l_{eff}$ below 0.5π providing expression:

$$\varepsilon_{LUT} \approx \left.\frac{\frac{1}{j\omega l_{eff} C_0}}{Z_{in\_meas} - \frac{j\omega l_{eff}}{3c^2 C_0}}\right|_{\gamma_{PP} l_{eff} < \pi} \quad (2)$$

The above enables fast calculation that is of relatively low-error below open stub`s first resonance frequency. The equality of (1) can also be resolved numerically for ε_{MUT} for exact solution over a broad frequency range, however at a higher computational cost.

Independently from solution type, derivation of ε_{MUT} requires two sensing setup specific constants to be known: l_{eff} and C_0. A simplified calibration procedure proposed in [6] is adopted here to establish both constants using only one solid calibration sample of known relative permittivity ε_{r_cal} by exploiting the sensor`s dual modes. This is advantageous in two ways: there is no need to know the dimensions of the fabricated setup while their effects are incorporated, thus fabrication requirements are very relaxed and air ($\varepsilon_{r\_cal} = 1$) can be used as calibration medium which is convenient as there's no need for reference data. Firstly, the l_{eff} is derived considering the fact that the proposed sensor is a quarter-wave resonator and thus $Im(Z_{in})$ crosses zero at resonance frequency f_r. Solving eq. (1) for the above yields the formula:

$$l_{eff} = \frac{c}{4 f_{r\_cal}\sqrt{\grave{\varepsilon}_{r\_cal}}} \quad (3)$$

where f_{r_cal} is the first resonance frequency of the sensor when exposed to the calibration material. Following, the eq. (1) can be rewritten for C_0 as:

$$C_0 = \frac{\coth\left(j\frac{\omega}{c}\sqrt{\varepsilon_{eff\_cal}}\, l_{eff}\right)}{cZ_{in\_cal}\sqrt{\varepsilon_{eff\_cal}}} \quad (4)$$

where Z_{in_cal} is the input impedance of the sensor when exposed to the calibration material. After plugging the result of eq. (3), eq. (4) can be resolved over the entire measured bandwidth.

3. Experimental Results

A demonstrator of the proposed sensor was developed to operate within the low-GHz range. The parallel plate sensor was hosted on a 60 mil thick Rogers RO4003C laminate ($\varepsilon_{r\_sub} = 3.38$, $\tan\delta = 0.003$ @ 10 GHz). Since the distance between electrodes is determined by the laminate thickness, a thick one was used to mitigate creation of air cavities when immersing in the LUT and ensure good flow and draining. A 50 Ω impedance feeding path was realized from the end-launch coax connector up to sensor`s electrodes on-PCB anchor point where the de-embed S-parameter reference plane is set at (total length of 25 mm). A 5 mm long broadband MS to DSPS transition was designed featuring uniform impedance nonlinear geometry taper that was generated using MATLAB script [10]. Taper`s width at MS is w_{MS} = 3.42 mm, while at DSPS is w_{DSPS} = 4.51 mm. To account for the 3D printed dielectric seal, the width was reduced at the feed`s end and the same width $w_{PP}$ = 4 mm was used for the sensor itself. As a result, the sensor`s characteristic impedance in air is $Z_{PP} \approx 140\ \Omega$. Sensor`s length was set at $l_{sens}$ = 10 mm which results in its first resonance frequency $f_r \approx 7$ GHz. The PCB was fabricated using photolithography technology while the sensor`s electrodes were fabricated out of a stiff 0.5 mm thick sheet metal and soldered to anchor points. A 5 mm long and 4 mm thick seal (2 mm flex, 2 mm rigid) was 3D printed using the Fuses Filament Fabrication technology out of FLEX and PET-G materials and screwed down compressing the flex parts around the electrodes. Photographs of the assembled demonstrator, later referred to as SENSOR, are shown in Fig. 2. For de-embedding purpose, a simple one standard approach was chosen, and so an extra OPEN standard was fabricated in the same fashion.

For the measurement campaign, the Agilent N5224A PNA Microwave Network Analyzer was used to capture the S-parameter at 10 MHz steps, 1 kHz IF bandwidth. At first, the OPEN was measured and the results were used for further data normalization. Then, the SENSOR exposed to air was measured to determine the fabricated sensing setup specific constants. The measured reflection coefficient and determined sensor`s input impedance is shown in Fig. 3a from which its resonance frequency and later effective length were found to be f_{r_cal} = 7.3 GHz and l_{eff} = 10.26 mm, respectively. Following, the C_0 shown in Fig. 3b was determined within the captured bandwidth and parallel-plate transmission line impedance was recovered. As seen, it is lower than the design, most likely due to fabrication accuracy of the metal electrodes.

The proposed sensor performance was experimentally validated by measurements of various alcohols. Before processing, all liquids were left in the laboratory to reach their temperature of 23°C ± 1°C maintained by the air conditioning system. The same protocol was followed for each measurement: the SENSOR was immersed in the LUT held in a beaker so that the flange created by the printed seals and PCB edge is only slightly below the liquid surface, and the S-parameters were captured when liquid-static conditions were reached. Afterward, the SENSOR was pulled out and dried using compressed air to prevent samples' cross-contamination. LUT`s relative permittivity was determined from the measured de-embedded reflection coefficient using the approximate analytical equation (3). The results for butanol, isopropanol and ethanol are provided in Fig. 4 where the measurement-based data is overlayed with reference data from [11]. Moreover, the approximation validity and low-error region borders are marked determined from the sensor`s resonant frequency location. In general, the higher permittivity, the narrower mentioned regions are. To extend the low-error region either numerical processing needs to be applied or shorter sensor needs to be used.

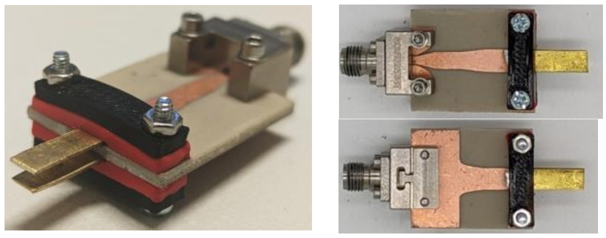


Figure 2. Photographs of the fabricated one-port sensors prototype. The paralel-plate open-ended sensor is fed by a double-sided paralel-stripline line which interconnects through a broadband transition to a microstrip line. Bi-material 3D printed seal is seen that prevents liquid seepage onto the feed line.

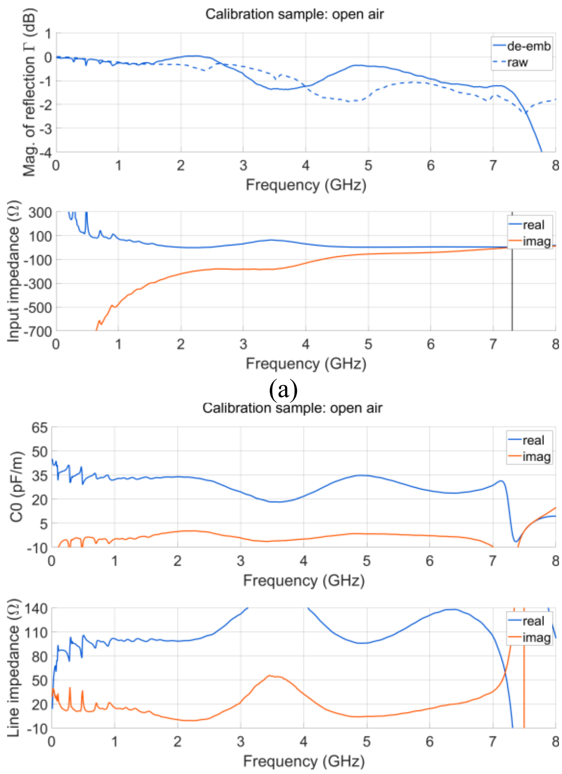


Figure 3. Measured sensor`s reflection coefficient when exposed to air and its input impedance with resonant frequency location marked (a). Calibrated sensor`s specific per-unit-length capacitance and paralel-plate lines characteristic impedance (b).

The obtained LUT permittivity results can be assessed in the context of reference data. It is observed that lower error is obtained for imaginary than real part of permittivity. The best results are obtained for butanol which features relatively low permittivity as for an alcohol. Nevertheless, simple calibration and direct permittivity determination is a large advantage of the proposed approach.

The resulting data accuracy is affected, mainly by the following factors:

- fabrication and assembly quality of the sensing setup,
- fabrication repeatability between OPEN and SENSOR that degrades the normalized S-parameters,
- quality of sensor fixturing for immersion in LUT,
- leak-proofing of the 3D printed seal as seepage of the liquid under the seal leads to erroneous de-embedding,
- positioning of the sensors during measurement with respect to liquid surface,
- permittivity extraction algorithm type,

Therefore, minimizing the impact of the above listed factors leads to reduced error LUT complex permittivity. The above is a subject of further study.

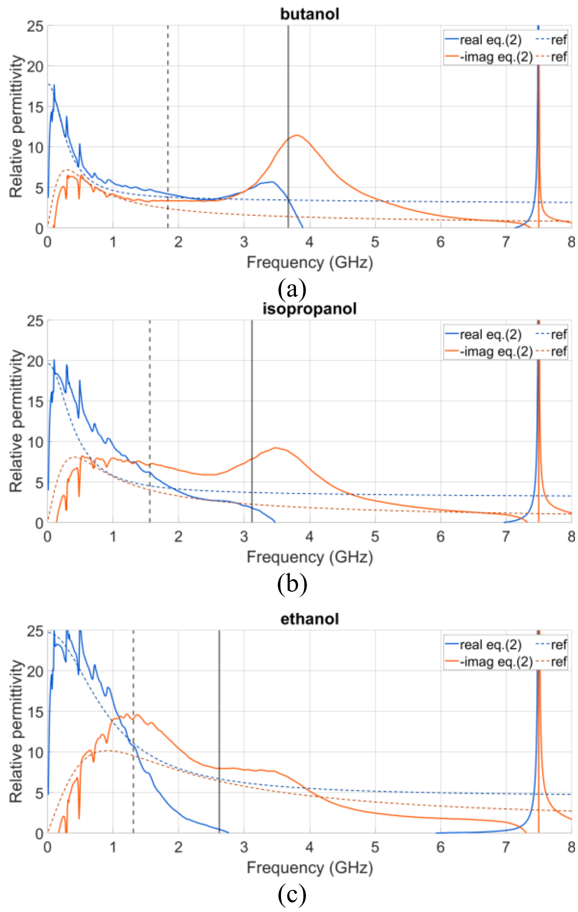


Figure 4. Measured (solid lines) with the senor`s demonstrator and reference (dashed lines) complex permittivity of alcohols. End of low error region (dashed vert.) and end of eq. (2) validity (solid vert.) marked.

4. Conclusion

A novel sensor for direct BDS was proposed and assessed. An open-ended parallel-plate transmission line section was used to be submerged in the LUT so that it constitutes full the propagation medium. Along, a simple de-embedding and calibration procedure requiring only one extra PCB for normalization and sensor measurements in air to determine the sensing setup specific constants. Major advantages of the proposed techniques are – high sensitivity, direct complex permittivity measurement, one-port operation, loosened fabrication tolerances as geometrical parameters are determined through calibration, single calibration standard, potential for ultra-broadband operation when numerical algorithms are used for permittivity extraction. The proposed approach was experimentally assessed through various liquids measurements using developed sensing setup demonstrator.

5. Acknowledgements

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