Reconfigurable Sensors for Extraction of Dielectric Material and Liquid Properties

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***Abstract* — This paper proposes an analysis and modeling of a reconfigurable sensor for the non-destructive remote extraction and monitoring of dielectric material and liquid properties, towards substance identification or distribution cartography.**

***Index Terms* — Reconfigurable architectures, sensors, dielectric measurements, electromagnetic modeling, Liquid Crystal Polymer, plastics, fluidics.**

I. Introduction

Need for measurement and extraction of material properties has motivated the development of diversified Non-Destructive characterization techniques. Various applications where Non-Destructive characterization and monitoring of material properties appear as an important requirement are gaining more and more interest: example, Medicine [1], Pharmaceuticals [2], Food Industry [3], Agriculture [4], and Instrumentation Technologies [5], etc. Although aforementioned applications operate in frequencies not exceeding the Microwave domain, emerging challenges (*e.g., Security applications*) requires innovative solutions in the THz domain (imaging [6]). In the scope of guided waves propagation theory, it is well established that the effective permittivity of an electromagnetic structure can be related to each relative permittivity of materials composing the structure. The proposed sensor uses this principle. When the sensor is embedded within a materiel (dielectric or fluidic), the measured signal undergo some variations due to a modification in the permittivity of the embedding environment. This modification impacts both the real part and imaginary part of the effective permittivity. The proposed methodology is based on a broadband extraction of complex permittivity. So, the variations result into a change of the signal phase and magnitude. A formal link can then be identified between the resulting signal signature and the substance properties of the embedding materials, which in turn lead to broadband characterization and identification. More detailed analysis can be conducted to determine quantification of biological species (DNA, cells, molecules, etc.). This contribution is organized as follows. Section II presents the sensor modeling technique. Section III exposes experimental physical surface analysis and accurate dielectric characterization via wave-guided method of some various polymers that are used for sensor packaging. Section IV discusses experimental results obtained using the proposed sensor solution. When combined with contactless Built-In-Self-Test calibrations [7], the sensor solution can lead to miniaturized footprint integration with perspectives for lab-on-a-chip systems bio-sensing [8].

II. Sensor Description and Modeling

The sensor is composed of a double-faced antenna branches including circuitry for reconfigurability as sketched in Fig.1. With Open/Short conditions various electrical states can be impressed to switches in order to calibrate the sensor for a specific frequency band of operation.

From the complex eigen-values of propagation constant extracted from simulated or measured S-parameters, the broadband complex effective permittivity ε_{eff} [9] is derived:

$$\varepsilon_{eff} = (\gamma / j\beta_0)^2 = ((\alpha + j\beta)/ j\beta_0)^2 = \varepsilon_{eff}^r + j\varepsilon_{eff}^i \quad (1)$$

$$\alpha = \frac{k_0}{\sqrt{2}} \sqrt{\left|\varepsilon_{eff}\right| - \varepsilon_{eff}^r} \quad (2)$$

$$\beta = \frac{k_0}{\sqrt{2}} \sqrt{\left|\varepsilon_{eff}\right| + \varepsilon_{eff}^r} \quad (3)$$

where β_0 is the wave-number in free-space.

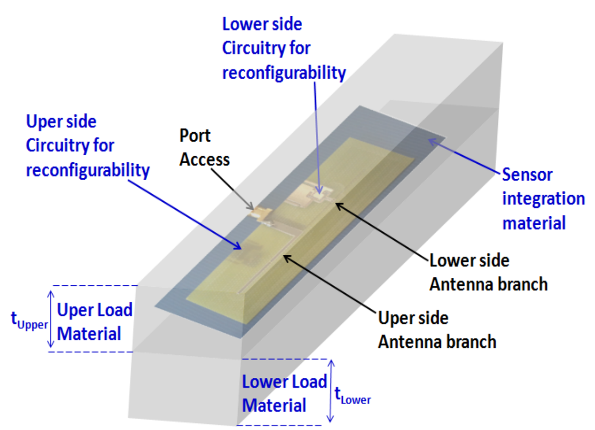


Fig. 1 View of reconfigurable sensor for extraction of Dielectric Material and Liquid properties.

The extracted losses in (2) include both metallic and dielectric contributions. With proper estimation of conductor losses dielectric losses can be deduced assuming additive combination. The real part of the complex permittivity, related to the medium polarization, specifies the velocity of propagation of EM waves through the material, while the imaginary part determines the conductivity of the medium. The imaginary part of the complex permittivity represents the radar signal attenuation by energy absorption.

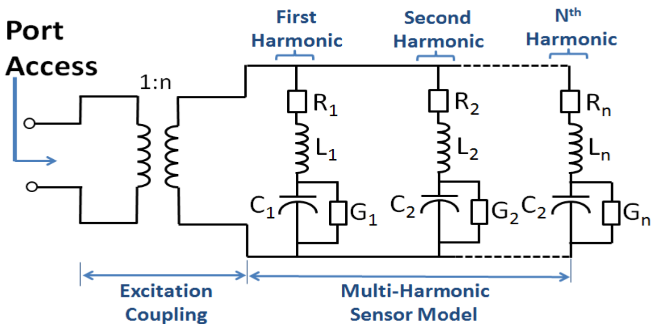


Fig. 2 Multi-harmonic broadband SPICE-like equivalent circuit model for the passive part of the sensor

In order to extract scalable SPICE-like model for the passive part of the sensor, the admittance parameter Y_{Sensor} is first obtained from the input reflection coefficient Γ_{in} at the reference plane of the sensor access port shown in Fig.1. Then, Y_{Sensor} is used to extract physics-based broadband realizable equivalent circuit model fulfilling passivity and causality preservations following the methodology in [9].

III. Polymer Dielectric and Mechanical Characterizations Towards Sensor Design

Various types of plastics are commonly employed in the design of electronic systems packaging and the knowledge of their dielectric and mechanical properties is a preliminary step in order to evaluate the best candidates for specific application. In Peak Force mode based on Atomic Force Microscopy, an interaction between a tip and a material surface allows extracting its topography, roughness and various electro-mechanical properties, such as adhesion (Fig.3), that express the surface nano-scale forces. The polymers that were considered in this analysis were:

1. *Epoxy thermosetting plastics* including silica balls dedicated to IC packaging (Fig.3).
2. *LDS plastics (Laser Direct Structuring):* These thermoplastics are compliant with *3D-MID* technology (namely 3D-Device-Interconnect-Material) which provides the possibility to draw 3D interconnections or passives on the surface of the moldings [10]. This is particularly interesting when the interconnection (such as an antenna) needs to be in close contact with the outside world (i.e. an RFID tag antenna).
3. *LCP (Liquid crystal Polymers)*: Liquid Crystal polymers have a regular crystalline structure that allows reducing dielectric losses (compared with other plastics). They present low humidity absorption rate and a TCE close to that of silicon (few ppm/°C). LCP polymers support a broad range of manufacturing processing (molding, extrusion, or thin film lamination at low temperatures) and a relatively low cost compared with LTCC, even though they remain more expensive than epoxies. Fig. 4(a) shows a sample of the LDS-compliant LCP Vectra830i from Ticona.

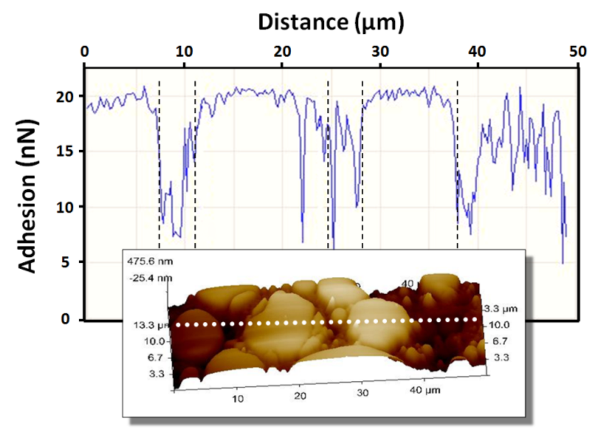
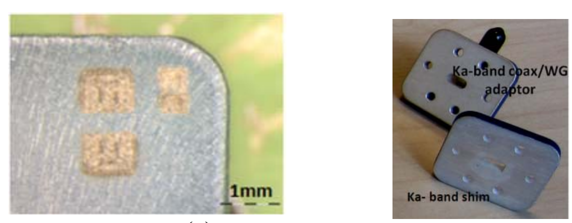


Fig. 3 3D topography of an epoxy molded sample and tip/surface adhesion signal by Peak Force Microscopy.



(a) (b)

Fig. 4 a) LDS Vectra 830i with laser-activated patterns b) guided equipment for dielectric characterization.

The plastic materials were micro-machined to be inserted in a quarter-wave guided shim (Fig. 4(b)). Two-port transmission/reflexion of a TE mode wave through the loaded shim allows determining the propagation constant in the material, and hence its dielectric permittivity. This method is little sensitive to conductive or radiative losses but is limited by calibration errors, parasitic resonant modes inside the dielectric and air gaps at the dielectric/guide interface. Fig. 5 depicts the

extracted dielectric permittivities, dissipation factors and Debye relaxation models in Ka band of two LDS polymers: Ticona *Vectra 830i* LCP and Lanxess PBT/PET *Pocan 7140*. This graphic proves the benefit of LCP over PET/PBT in terms of dielectric losses and the impact of absorbed water resonances at 25 and 37GHz. These results are consistent with those obtained for analog materials with concurrent methods at lower frequencies [10].

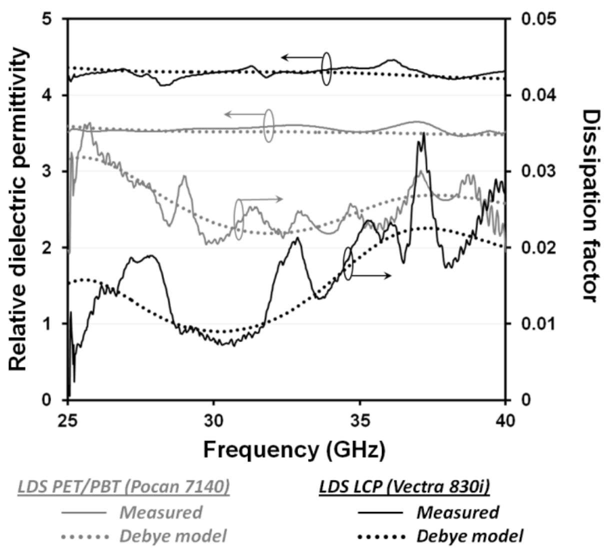


Fig. 5 Measured and modeled relative dielectric permittivity and dissipation factor of *Vectra830i* and *Pocan7140* in Ka band.

IV. MAIN RESULTS AND EXPERIMENTAL VERIFICATIONS

The proposed sensoring solution presents a reconfigurable feature for the frequency of operation (Low-Band and High-Band). The obtained characterization results are correlated to 3D EM simulations and to extracted BBS (Broad-Band-SPICE) equivalent circuit model. In Fig. 6(a) measurement results are compared to full-wave EM simulations for Low-Band and High-Band operating frequencies showing satisfactory accuracy. Fig.7 depicts measurement results for water and salt water when used as load conditions for the sensor in Low and High Bands. Compared to the unloaded situation in Fig.6(a), strong deviation in resonant frequencies confirms high values of effective permittivity for water and saline water. It is observed that the degree of salinity has greater impact on the imaginary part (*related to conductivity*) of the complex effective permittivity than on the real part. This observation is coherent with previously published results [11]. Fig. 8(a) shows extracted real and imaginary parts of complex effective permittivity for various plastic materials with relative permittivity ranging from 2 to 5. Associated S-parameter results are given in Fig. 8(b). However, since dielectric properties can be affected by several parameters (e.g., *sample sizes, surface area, molecular composition…*), it is anticipated to deal with calibration procedures in order to compensate for systematic errors depending on the frequency range.

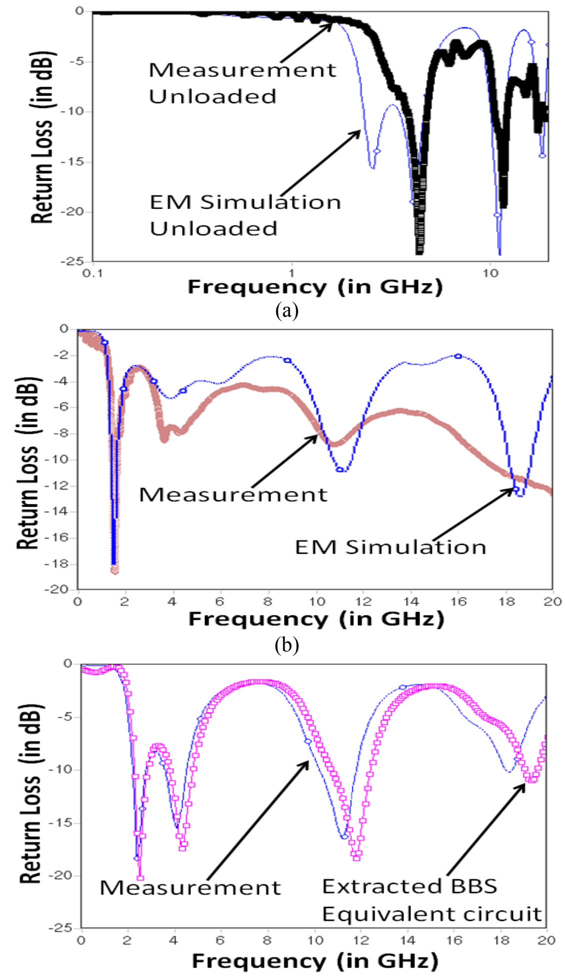


Fig. 6 Correlation between measurement and EM simulations for unloaded conditions in High-Band (a) and Low-Band (b) states. Comparison between EM simulations and extracted BBS model (High-Band) (c).

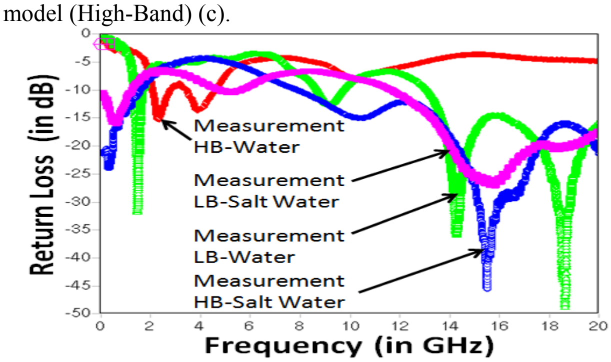
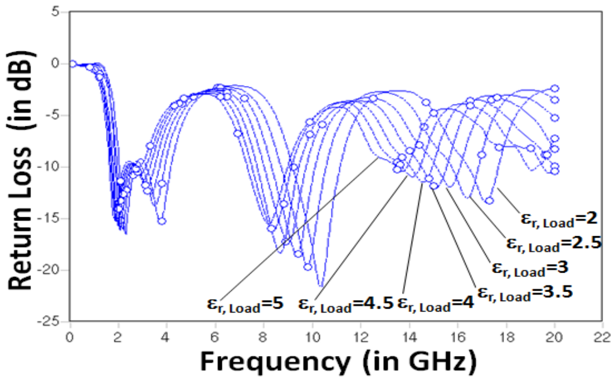
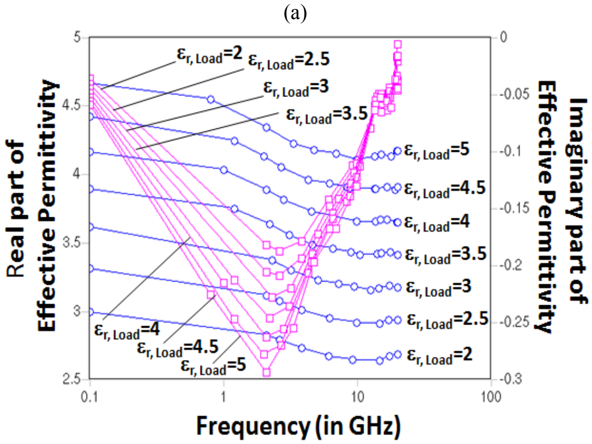


Fig. 7 Measured insertion parameter with water and saline water as load conditions for Low-Band and High-Band operating frequencies.



(a)



(b)

Fig. 8 Insertion parameter (a) and extracted complex effective permittivity (b) for various plastic materials (relative permittivity between 2 and 5).

V. CONCLUSION

This work has proposed low-cost sensoring system for broadband extraction of dielectric material and liquid properties (complex valued effective permittivity) with reconfigurable frequency band of operation. Dedicated traditional characterization technique for dielectric materials based on wave-guide remote sensing solution is also carried out for benchmarking and validation purposes. Conducted experimental analysis combines both electrical and mechanical characterizations for multi-physics approach where statistical deviations from sample to sample together with form-factor and thermal effects can be assessed. Both experimental solutions are favorably compared showing very good agreement. Various materials including LCP (Liquid crystal Polymers), LDS plastics (Laser Direct Structuring), water and saline water are carefully characterized in the band 100 MHz to 20 GHz. Obtained measurements show good correlation with predicted 3D EM simulation results. Broadband SPICE-like equivalent circuit is proposed for scalability of extracted models. This scalable Broadband SPICE-like equivalent circuit can be combined with modified Debye model to capture various physical and chemical effects taking place within the characterized materials such as ionic-conductivity losses due to salinity or moisture effects. Ongoing work includes extension of proposed characterization solution to THz frequency domain.

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