Sensitivity analysis of Integrated Capacitive Sensors

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***Abstract*— The usage of CMOS technology allows the co-integration of the sensing element with the detection and control circuitry providing small foot print next generation dielectric sensors. In this contribution, the sensitivity analysis of the integrated permittivity sensors used in the non-destructive characterization of dielectric materials is presented. Permittivity sensors are based on the accurate characterization of the capacitive contribution of the material under test to the sensing (i.e., capacitive) element. Whereas sensitivity, critical parameter in the electromagnetic design of the sensor is based on the RF read-out circuitry.**

***Index Terms*— Coaxial cable, CMOS, Sensitivity.**

I. INTRODUCTION

Dielectric spectroscopy is a promising, non-destructive technique for a large number of applications such as assessing food quality, biomedical sensors and material characterization [1]–[3]. The method is based on the fact that the frequency dependent dielectric signature is specific to the material, thus allowing the complex permittivity to be an highly sensitive parameter in identifying any alterations in the material state. Dielectric spectroscopy in integrated technology is realized by a patch or a differential capacitor [1] [2]. Their design requires trading off the sensitivity of the sensor with the realizability.

In this paper, we will first describe the sensor (in section II) and further discuss the sensitivity of the integrated sensor which is the driving parameter for the electromagnetic design. Sensor sensitivity is dependent on an integrated read-out circuitry which reads the relative difference between the capacitive loadings associated to the different MUT's, as discussed in section III. It is further demonstrated, in section IV, that loading the coaxial sensor with a pin terminated by a patch leads to higher capacitances which also correspond to doubled sensitivities when compared to stand alone coaxial endings. However, an even higher sensitivity is achieved when the patch itself is shaped to maximize the loading of the MUT. This maximization occurs by implementing a petal shaped patch that maximizes the fringing electric fields into the MUT.

II. OPEN ENDED COAXIAL CABLE

The sensing element under investigation is schematized in Fig. 1, it represents a coaxial cable (a –inner radius, b-outer radius) with an infinite ground plane loaded by an infinite substrate of permittivity $\epsilon_{SiO_2} = 4.1$ and thickness h . The top of the sensor is assumed to be in direct contact with an infinitely extending MUT, which is characterized by ϵ_{MUT}.

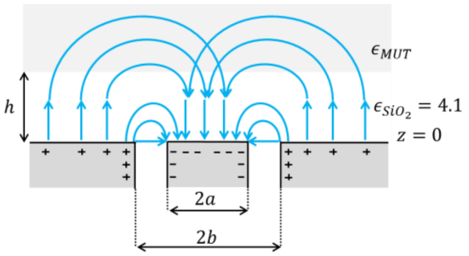

Fig. 1. Cross section of the open ended coaxial cable with schematic representations of the electric field lines (blue) and charge distributions (positive and negative).

The external admittance Y_{ext} of the coaxial cable is evaluated using the tool described in [4] at the aperture plane $z = 0$ (Fig. 1a) is given by Eq. 1:

$$Y_{ext} = \frac{2\pi}{\ln^2\left(\frac{b}{a}\right)} \int_0^{\infty} \frac{\left[J_0(k_\rho b) - J_0(k_\rho a)\right]^2}{k_\rho} I_{TM}\left(h, \epsilon_{SiO_2}, \epsilon_{MUT}\right) dk_\rho \quad (1)$$

where J_0 is the zero-th order Bessel function and $I_{TM}\left(h, \epsilon_{SiO_2}, \epsilon_{MUT}\right)$ is the spectral TM current representing the magnetic field at $z = 0$ due to a unit magnetic current also at $z = 0$.

III. SENSITIVITY OF THE SENSOR

The read out circuitry of the sensor is schematically described in Fig. 2. The circuit is driven by a voltage source (V_{src}), here taken as ideal, and composed by three selectable capacitance banks (static capacitors, shown in yellow in Fig. 2) that will be tuned depending on the capacitance of the external MUT (Y_{ext}).

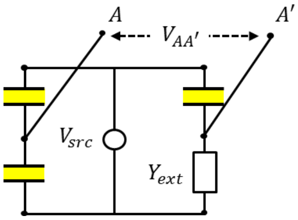

Fig. 2. Read out circuitry, RF equivalent network based on lumped capacitors.

The voltage across the terminals A-A' ($V_{AA'}$) is a function of the dielectric constant of the MUT by means of $Y_{ext}(\epsilon_{rMUT})$. Specifically the voltage $V_{AA'}$ can be expressed as

$$V_{AA'} = \frac{V_{source}}{2}\left[\frac{Z_{diode}-Z_{ext}}{Z_{diode}+Z_{ext}}\right] \qquad (2)$$

Where, $Z_{ext} = 1/Y_{ext}$ and $Z_{diode} \approx Z_{ext}(\epsilon_{MUT} = \epsilon_{ref})$. Accordingly :

$$S \approx \left[\frac{Z_{ext}(\epsilon_{ref})-Z_{ext}(\epsilon_{MUT})}{Z_{ext}(\epsilon_{ref})+Z_{ext}(\epsilon_{MUT})}\right] \qquad (3)$$

S is the key quantitative parameter for the contribution of the electromagnetic design to the sensitivity of the sensor. Fig. 3a shows the variation of the sensitivity as a function of the average radii $r_{ave} = (a+b)/2$ in the presence of the dielectric stratification, ϵ_{SiO2} and ϵ_{MUT} (as shown in Fig. 1), from Eq. (3) assuming $\epsilon_{ref} = 1$ and $\epsilon_{MUT} = 40$. In the same figure, Fig. 3a, we plot the sensitivity as a function of the characteristic impedance of the coaxial probe (Z_0). Fig. 3b also shows the comparison between the capacitances obtained from our analytical tool [4] and HFSS. The good comparison between the results gives us confidence in the sensitivity plots obtained using the analytical tool.

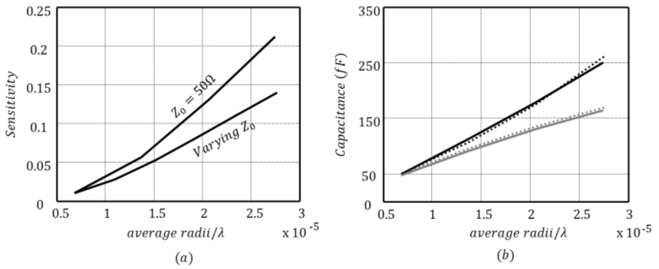

Fig. 3. a) The black lines represent the sensitivity of the probe versus the normalized average radii for 50Ω and varying characteristic impedance of the coaxial probe. b) Black and grey lines represent the capacitance evaluated for $\epsilon_{rMUT} = 40$ and $\epsilon_{rMUT} = 1$ respectively, bold lines obtained from analytical tool while dashed lines from HFSS.

IV. DIFFERENT LOADINGS FOR THE COAXIAL LINE

In order to obtain a sensor characterized by the larger radii suggested by Fig. 3a, while still resorting to CMOS technology a possibility is to load the coaxial line in Fig. 1, by an extending pin through the silicon dioxide and then terminating it with a metal patch, as shown in Fig. 4.

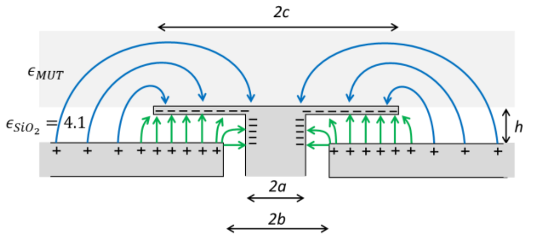

Fig. 4. Enhancing the area of the sensor by extending the central conductor of the coax through the SiO_2 substrate and terminating it with a patch.

An even better option to obtain a larger sensitivity for the sensor is to load the pin with a patch which has periodic indentations as can be seen from the top view of Fig. 5. This will provide currents that flow in radially azimuthally separated strip-lines of varying widths. This arrangement provide currents that flow in radially separated petals with the advantage of higher sensitivity of the sensor due to higher dependence of ϵ_{MUT} on the fringe capacitance with respect to the parallel plate one. Each of the petals behaves as separate micro-strip in which the propagation constant is dictated by the average between ϵ_{SiO_2} and ϵ_{rMUT}. As can be seen in Fig. 6, the sensitivity of the periodic patch is twice as large as that of the continuous patch and four times as large as that of the small coaxial line.

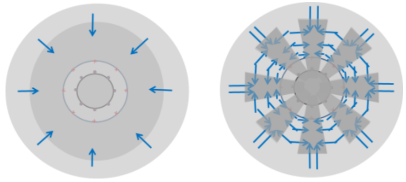

Fig. 5. Top view of a patch loaded coaxial pin. a) uniform patch loading. b) Petal shaped patch. The blue lines correspond to the electric field lines on the patch.

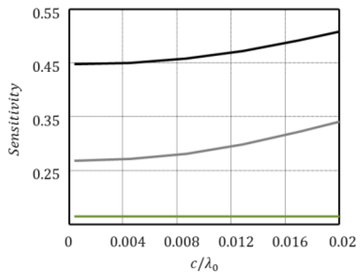

Fig. 6. Green, grey and black lines represent the sensitivities of the coaxial cable, circular patch and flared circular patch.

V. CONCLUSION

The sensitivity of the integrated sensor to the MUT was enhanced by realizing a larger coax equivalence, by extending the central conductor through the SiO_2 and terminating it with a patch on the top metal of the $CMOS$ metal stack. Further more, the sensitivity of the pin-patch configuration was increased by introducing periodic indentations in the patch.

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