IMTC 2006 – Instrumentation and Measurement
Technology Conference
Sorrento, Italy 24-27 April 2006

A Distance Compensated Telemetric Humidity Sensor Based on the Parasitic Capacitance Variation

Daniele Marioli, Emilio Sardini, Mauro Serpelloni, Andrea Taroni
Department of Electronic Automation, University of Brescia
Via Branze 38, 25123 Brescia (BS) Italy
Phone: +39-030-3715897, Fax: +39-030-380014, Email: mauro.serpelloni@ing.unibs.it

Abstract *– In this article a telemetric system for relative-humidity measures is proposed. The contactless transmission problem is analyzed also when the distance between readout circuit and sensing circuit changes. Three hydrophilic polymers are deposited on parasitic capacitance of sensing system. The sensitivities to the Relative Humidity and distance are calculated. The measurement method has been tested in the laboratory and the experimental results are reported.*

Keywords *– inductive telemetry, environmental monitoring, humidity measurement, food quality inspection.*

I. INTRODUCTION

Telemetric technique is useful when it is not possible to connect the sensitive element to the conditioning electronics. Measurements into inaccessible environment, like hermetic boxes, or incompatible with the working conditions of the electronics, such as measurement in presence of high temperature or measurement into liquids, can be done with telemetric systems. Moreover measurements inside human body are practicable using implantable passive sensors, communicating their measurement information by using telemetric system.

Recent literature reports some telemetric techniques and describes prototypes. These systems are used in many fields, from industrial control processes [1],[2],[3],[4] to biomedical systems [5],[6]. For some of the previous examples, the traditional wireless techniques can offer an aid, but they need a supply system that periodically requires maintenance, while a passive sensor in the measurement environment means: low cost of maintenance and no cost for batteries.

In this paper we propose an approach that uses a passive sensitive element for humidity measurement. The purpose is to put the element inside a hermetic box and to use an external circuit to read the measurement. A possible application can be the analysis of food status into hermetic box, to monitor the modified atmosphere inside the box, during the industrial process, with a readout system positioned outside.

The telemetric system, presented in this paper, consists of two main parts: the first, the sensing circuit, inside the hermetic box and the second, the readout, outside. The two parts are connected by a magnetic field. A planar inductance spiral shaped is the sensing circuit; another one constitutes the readout circuit. In most cases the two inductances are modeled as an ideal transformer, but taking into consideration the parasitic capacitances and the leakage fluxes, a more accurate model is required. Moreover, the distance between the two inductors (sensing and readout) can change due to the practical use and its effect on the measurement needs to be compensated. A previous work [7] reports the model used in this paper and proposes a method to measure the capacitance of the sensor tied to the sensitive inductance.

In this paper, we propose to use the parasitic capacitance as parameter dependent on the quantity under measurement, i.e. the humidity in this case. Instead of building a specific element working as a capacitor, a hydrophilic polymer has been deposited over the sensitive planar inductor. The deposition increases the parasitic capacitance of the inductance and makes it sensitive to the humidity. Three different polymers were tested: polyepichlorohydrin (PECH), cellulose acetate (CA) and polyethylene glycol (PEG). Experimental results are also reported.

II. THE EXPERIMENTAL SYSTEM

A. Sensor description

The sensing inductances are obtained from a printed circuit board (PCB) by a milling process, in three different types, that in the following we will be referred as T1, T2 and T3. All the devices have the same square geometry, 27 turns and the same FR4 support, with a dielectric constant of 4.4. While the models T1 and T2 are different for: i) the width of the track, respectively 200µm and 150µm; ii) the distance between two tracks, 150µm and 200µm. The model T3 is similar to T2, but differs for the thickness of copper tracks: 75µm, instead of 35µm of T1 and T2; and during the milling process, we have over charged the cutter to go deeper and to remove more material.

In Fig. 1 an enlargement of the sensing inductor is shown. In (a) the bright zones indicate the space between the tracks, while the dark zones are the tracks. In (b), after the deposition of the polymer, the spaces between two tracks appear with different colors.

A general view is reported in Fig. 2. The external diameter of the sensing inductance is equal to the internal diameter of the readout; in this configuration the coupling capacitance between readout and sensing circuit can be neglected.

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Also the readout inductance is realized with milling process in copper. The readout circuit, reported in Fig. 2, has 27 turns with an inter-winding of 200μm, the thickness of copper tracks is 35μm, and the width of the track is 200μm.

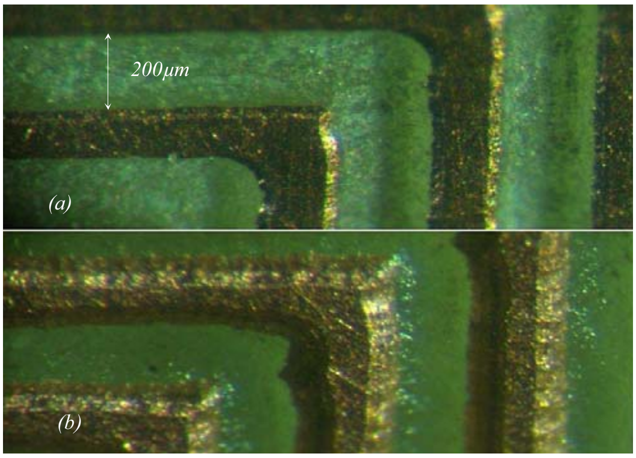

Fig. 1. Inter-winding spaces with the polymer (a) and without (b).

B. The sensor model

In Fig. 2 the models of the two circuits are also reported, in accordance to [7]. The parameters have the following meaning; L_c: inductance representing the coupling flux; L_{p1}: readout leakage inductance; L_{p2}: sensing circuit leakage inductance; C_c: coupling capacitance between sensing circuit and readout; C_{p1} and C_S: inter-winding capacitance of readout and sensing circuit spiral. C_c can be neglected: due to the distance between the two circuits and to the geometry of the planar inductors.

The impedance as seen from the terminal of the readout inductance is qualitatively plotted in Fig. 3: it shows two resonances (f_{M1}, f_{M2}) and one anti-resonance (f_m), these values depend on C_S.

In a contactless system, the distance between the sensitive and the readout components can change: the coupled and leakage fluxes change too, so L_{p1} L_c and L_{p2} can change, modifying the value of the resonance and anti resonance frequencies.

In [7] the possibility to individuate a parameter, called "*F*", which has no sensibility to C_S but changes with distance, is reported. Parameter "*F*" doesn't depend on C_S, but on C_{p1}, L_{p1}, L_c and L_{p2}. If C_{p1} can be considered fixed "*F*" depends only on coupled and leakage fluxes, that change according to the geometry of the system, and in particular to the distance between the primary and secondary coils.

The sensor value [7], can be obtained as:

$$C_S = \frac{L_1 C_{p1}}{L_2} \frac{F}{(2\pi f_m)^2}, \qquad (1)$$

where C_S and C_{p1} are the inter-winding capacitance of sensing and readout spiral inductances. L_1, L_2 are the self-inductances of the readout and sensing inductances, and "*F*" is equal to:

$$F = \left((2\pi f_{M1})^2 + (2\pi f_{M2})^2\right) - (2\pi f_m)^2 . \qquad (2)$$

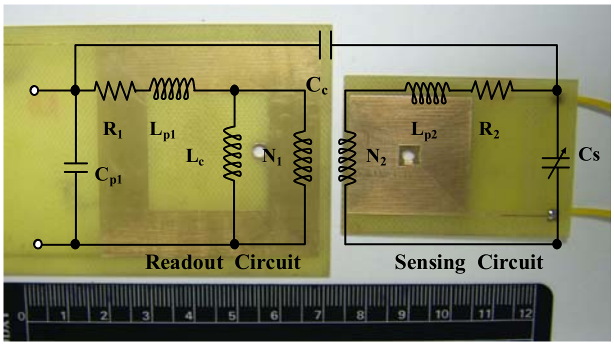

Fig. 2. Planar inductances realized and equivalent telemetric system model.

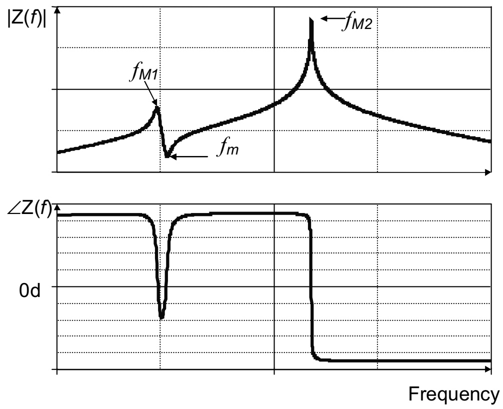

Fig. 3. qualitative impedance diagrams as seen from the readout circuit.

C. Polymers

The three polymers present different characteristics.

Cellulose acetate (CA) is used as hydrophilic polymer in many applications; in fact it has the characteristic to retain the water molecules. The dielectric constant changes from 3.2 to 7 in according to different molecular weight and it depends on temperature and humidity.

Polyepichlorohydrin (PECH) is an elastomer characterized by a high resistance to solvent and oils at moderate temperatures. The polymer phase at 50%RH and 20°C is gum. The dielectric constant (in N_2 and 20°C) is 7.4+-1.1 and changes with the humidity.

Polyethylene glycol (PEG) is non-toxic and is used in a variety of products. It is different from the others because it is soluble in water, this characteristic influences positively the sensitivity, but increases also the hysteresis. The dielectric constant changes from 2.2 to 4 in according to different molecular weight and depends on temperature and humidity.

The deposition of the three polymers was obtained with a solution of 1% in acetone, which is a common solvent. The solution was stretched on the sensing inductance to permit the penetration into the inter-winding spaces. In air the solvent evaporates and the polymer remains attached to the rough surfaces (Fig. 1).

D. Experimental apparatus

The experimental apparatus consists of a measuring chamber, two fluxmeters, a bubbling chamber and a dry air bottle. The measuring chamber is made of glass, cylinder shaped with three holes on the top base as shown in Fig. 4: one is the entrance of humid air, one is the exit and the last hosts the reference hygrometer. Its diameter is 100mm and the height is 130mm.

The humidity is controlled mixing humid and dry air in different proportion: two fluxmeters, one for each type of air, control the proportion regulating the relative humidity. The humid air is obtained by gurgling dry air into water.

The hygrometer is an HIH3610 by Honeywell and it has a linear output for 2% RH accuracy at 25°C.

The sensing circuit is put into the measuring chamber, while the readout circuit is mounted on an L-shape made of wood under the sensing circuit. This support has the possibility to control the distance between the two circuits with a micrometer screw.

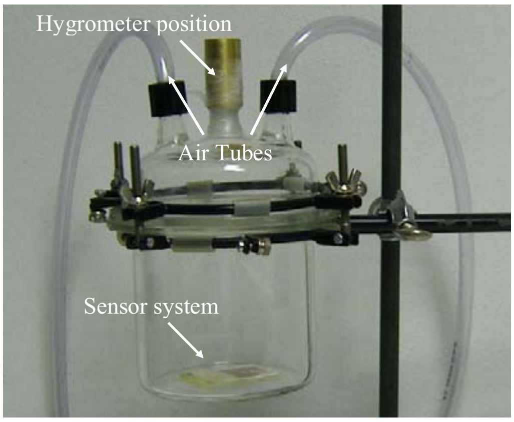

Fig. 4. The chamber used as hermetic box.

III. EXPERIMENTAL TEST

A. Sensor characterization

The model parameters are measured connecting the terminals of each planar inductance (sensing and reading) to the impedance analyzer (HP4194A) before and after the deposition of the polymers. The values of the readout inductance are 27.7Ω, 4.82pF, 2.59μH and, referring to the model of Fig. 2, correspond to R_1, C_{p1}, L_{p1} respectively. The values referred to the sensing inductances are reported in Table. 1.

The CA is deposited above T1 PCB, the PECH and the PEG respectively above T2 and T3 PCBs. Different values of C_S can be noticed between T1 and T2, due to different geometric model. While the T3 presents a similar capacitance value to T2; in T3 the higher thickness of copper tracks poises the dipper valley, i.e the removal of more FR4 material.

Table. 1. Parameter values of the sensing inductance calculated before and after the polymeric deposition at environmental condition.

	R_2 (ohm)	Cs (pF)	L_{p2} (μH)
No Polymer – T1	10.1	7.68	39.1
Cellulose acetate (CA) – T1	10.1	7.88	38.9
No Polymer – T2	6.8	4.98	25.3
Polyepichlorohydrin (PECH) – T2	6.8	5.02	27.5
No Polymer – T3	4.3	4.46	25.5
Polyethylene glycol (PEG) – T3	4.3	4.86	25.7

B. Experimental results

In Fig. 5 the capacitance values are reported as a function of RH. They have been calculated by equation (1) using the measured f_{M1}, f_{M2} and f_m. These values have been measured when the distance between readout and sensing circuits is 5mm, i.e when the readout is in contact to the outside of the hermetic chamber. In Fig. 5 the experimental data are reported as circle point, while the vertical bar represents the uncertainty in the C_S measurement, due to the resolution (1.2kHz) of the impedance analyzer in measuring f_{M1}, f_{M2} and f_m. An increasing of the C_S with the increasing of RH is in accordance with the theoretical aspects. All the experiments have been done at laboratory temperature, at about 23°C with a variation of ±2°C during a day.

The three sensors present different behaviors: the third is more sensitive than the other and this is due to the chemical characteristics, as described before, and to the geometry of the T3 PCB.

Moreover experimental results are obtained at different distance between the readout and sensing circuit and compensated with the method of parameter *"F"*.

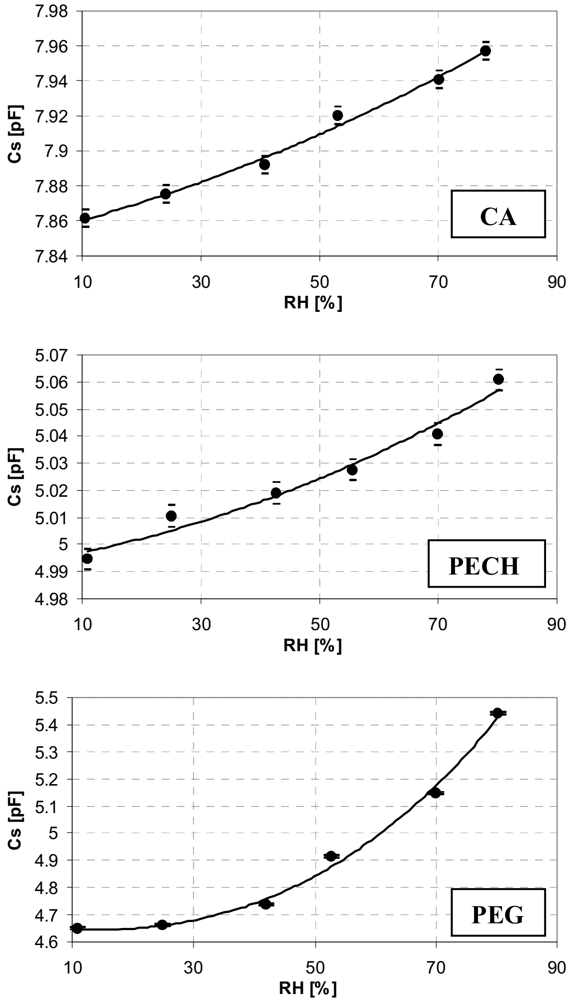

Fig. 5. Capacitance versus RH, calculated at 5 mm of distance, for the three different sensors.

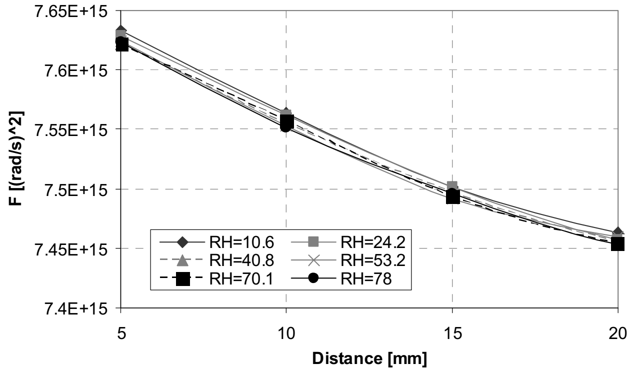

Fig. 6. Cellulose acetate - Trend of parameter "F" with different humidity values at different distances.

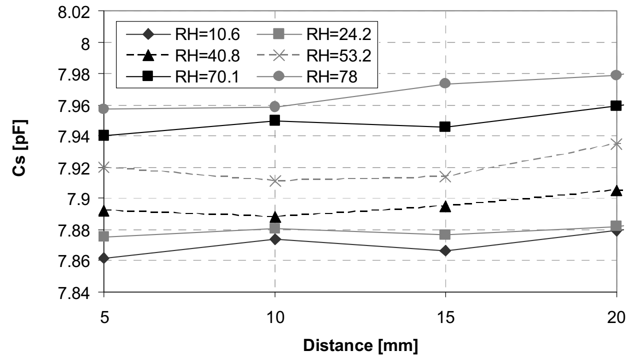

Fig. 7. Cellulose acetate - Trend of the capacitances (Cs) with different distances between hermetic chamber and readout at different RH.

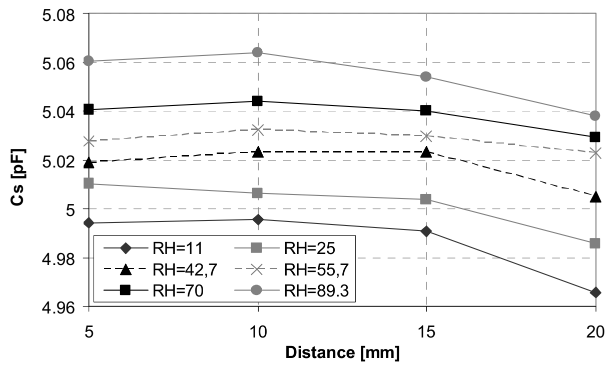

Fig. 8. Polyepichlorohydrin - Trend of the capacitances (Cs) with different distances between hermetic chamber and readout at different RH.

In Fig. 6 parameter *"F"*, calculated with the cellulose acetate, is reported. As it can be seen parameter *"F"* depends mainly on distance and is less sensitive to relative humidity for every distance. This parameter permits to calculate the capacitive values of the sensing system (C_S) in accordance with [7]. Analyzing the experimental results the maximum distance in accordance with an acceptable uncertainty is fixed at 20mm.

Fig. 7-8-9 report the C_S calculated with equation (1). The results with polyethylene glycol, reported in Fig. 9, are better than the others; because the capacitance values have higher percentage variation.

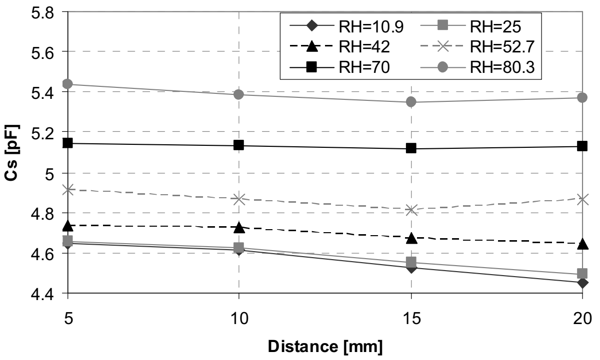

Fig. 9. Polyethylene glycol - Trend of the capacitances (Cs) with different distances between hermetic chamber and readout at different RH.

IV. DISCUSSION

The experimental results demonstrate that the third sensor, PEG, is better than the others. However to optimize the performance an improving of the sensitivity is needed, this implies an increasing of the parasitic-capacitance variation. A simulation of the parasitic capacitance with different situation of deposition between two tracks is presented here. If the potential between two conductors is fixed, the electric energy *(En)*, is proportional to the parasitic capacitance. The electric energy can be calculated with this formula:

$$En = \frac{1}{2}\int_{\Omega}(\vec{D} \bullet \vec{E})d\Omega . \qquad (3)$$

In Fig. 10 a post-process image of an inter-winding section of the planar sensitive inductance, showing an enlargement between the two tracks (white in the figure), is reported. The trapezoidal form is due to the cutter dip; the track sections are visualized in white and have a thickness of 75µm. The thickness of the polymer, that is supposed to absorb water, is 15µm.

The two pictures report the scalar product of the electric field *(E)* and the electric flux density *(D)* calculated at every point. In *(a)* is reported the full deposition: the parasitic capacitance between the two tracks is 25.45pF/m, while the parasitic capacitance calculated only in the active layer is 1.87pF/m. In *(b)* the half deposition presents a parasitic capacitance of 21.45pF/m, less than the previous, while the parasitic capacitance calculated only in the active layer is increased 1.83pF/m. These simulations enlighten how the deposition process is important to obtain a higher sensitivity.

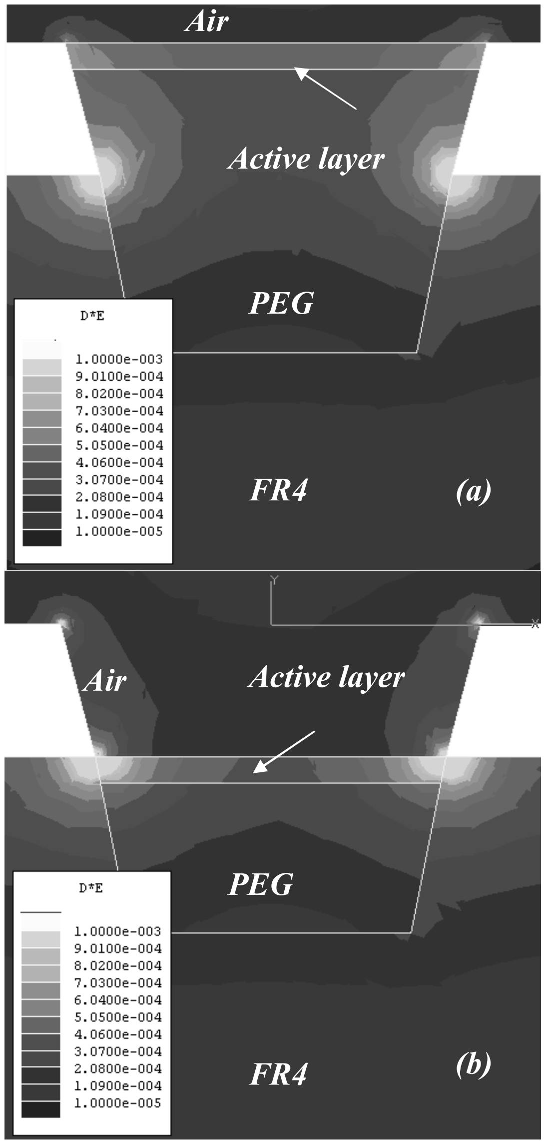

Fig. 10. Simulation of the capcitance behavior, full deposition (a) and half deposition (b).

The different level of deposition influenced the parasitic capacitance and the sensitivity. Fig. 11 reports the relative capacitance calculated as ratio of the total parasitic capacitance between the two tracks and the parasitic capacitance calculated only in the active layer. The deposition level of 0µm represents the case *(b)* in Fig. 10, while the deposition level of 75µm represents the case *(a)*. The higher sensitivity is in correspondence with a deposition level of 15µm.

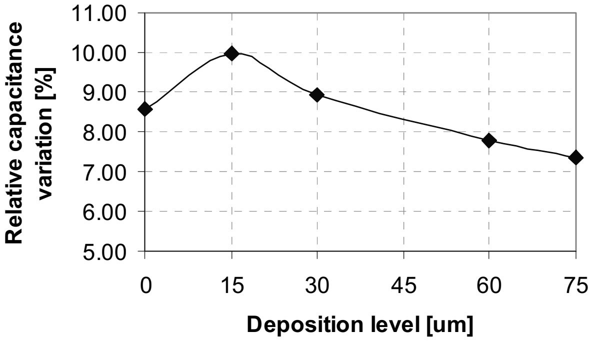

Fig. 11. The relative capacitance variation at different levels of deposition.

V. CONCLUSION

In this work we propose a contactless system that exploits the parasitic capacitance of a planar inductance to measure the RH. Each element is identified with its physical principle, a low cost sensing system is proposed and some analytical considerations are reported. Moreover, using the method proposed in literature [7], it is possible to compensate distance variations. The controlled technique of polymer deposition and the choice of proper support for planar inductance open new possibilities for improving the sensitivity.

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