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An inductive telemetric measurement system for humidity sensing

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Abstract
In some specific applications, the measuring environment can have unsuitable characteristics for a correct electronic functioning; it is not possible to connect a sensitive element to the conditioning electronics by standard cables or by a radiofrequency link. A possible solution could be a contactless link with a passive sensor inside the measuring environment and a readout outside. This paper discusses the telemetric system consisting of two contactless coupled planar inductors. The two inductors form a coupled transformer in air, with the primary one connected to the measurement electronics and the secondary one working as the sensitive element. A polymer deposited on the secondary one is sensible to the humidity, and changes its dielectric permittivity causing a variation of the inductor parasitic capacitance. A conditioning electronics measures frequency resonances, while the system extracts the corresponding capacitance values, compensating the distance variation as well. The whole system has been tested in the laboratory, and several results have been reported. These show about 200 fF variation over 1.7 pF for a change of the RH between 60% and 90% at a constant temperature of 22 °C. Moreover, the measured data are compensated on distance variation changing from 15 mm up to 30 mm. The complete explanation of the whole measurement system is described here. The low cost of the sensors and conditioning electronics implies a high diffusion in many application fields, from food packages to automotive.

Keywords: telemetric system, relative humidity, contactless sensors, distance compensation

1. Introduction

Numerous applications, in many fields, require the connection of a sensitive element, placed in an inaccessible environment, to the conditioning electronics through a wireless support. The solution offered by a standard wireless technique does not present, in many cases, a definitive solution because the wireless systems need powering energy, and can require periodic substitution of the battery. Moreover, exhausted batteries are important environmental problems since they require appropriate disposal. Telemetric systems can represent a valid solution, since they do not require either connections through cables or batteries. Telemetric systems are usually constituted by two inductors: one connected to the sensitive element (sensor), commonly a capacitive transducer, and the other to the measurement circuit (readout inductor).

Telemetric systems are applied in industrial fields, for example, when the measuring environment is not accessible, since it is inside a hermetic box [1–6]. In [1], the telemetric system is used to monitor the pressure inside a high-temperature environment. Paper [2] describes an example, in the field of biomedical applications, for the monitoring of internal package humidity for either *in vitro* or *in vivo* testing: the system consists of a high-sensitivity capacitive humidity sensor that forms an LC tank circuit together with a hybrid coil wound around a ferrite substrate. The resonant frequency of the circuit depends on the humidity sensor capacitance. This sensor uses an integrated inductor to couple, by the magnetic field, to an external inductor and therefore transduces the humidity information. Other examples of humidity monitoring using a passive telemetric system are quoted in [3, 4]. In industrial and food fields, product quality can be monitored through humidity measurements [5, 7–9].

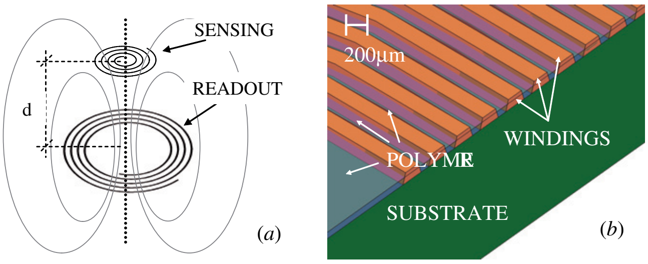

Figure 1. Schemes of inductive telemetric system (*a*) and section of sensor with polymer (*b*).

The proposed telemetric technique advantageously allows the insertion of a cheap sensor inside every package, and executes the measurement without the necessity of opening the hermetic box.

While in the previous applications [1–5], the sensor consists of a capacitive transducing element linked to the inductor, in this paper the inductor itself works also as a sensor. The relative humidity (RH) variations change the dielectric of a polymer deposited over the inductor causing a variation of the parasitic capacitance. To increase the very low change of the parasitic capacitance, a deposition method of the polymer has been studied with the aid of simulation software: the parasitic capacitance value and its change with different depositions were analyzed in [10].

In the literature, different measurement techniques are reported. Almost all are based on impedance measurements, to identify a particular resonant frequency, or a frequency point that has a particular property such as a minimum of the phase [1, 2, 4]. A limit of these techniques is that it is necessary for the distance between the two inductors to be constant. The method proposed in [11] suggests a measurement technique to compensate the distance changes.

In this paper, a proposed telemetric measurement system of RH is presented. The sensor is a standalone planar inductor, and according to the technique described in [11], a developed conditioning circuit measures three resonant frequencies, and a microprocessor calculates the RH compensating the distance variation. The system consists of different functional blocks: one generates the sinusoidal reference signal, the second measures the impedance module, and the third calculates the RH. To experimentally verify the characteristics of the proposed measurement system, a telemetric apparatus with a humidity-controlled hermetical measurement chamber, and a distance-control structure has been arranged and tested.

2. Sensing technique

The telemetric sensor consists of two planar inductors as shown schematically in figure 1(*a*): one is connected to the measuring circuit (readout), and the other is the sensor, on which a humidity sensitive polymer is deposited. A scheme of the magnetic coupling is also included.

The sensor is a planar spiral fabricated in PCB technology with an external diameter of 50 mm [12]. It has 65 windings each of 175 μm width and spaced 175 μm from the others. The readout inductor, whose section is reported in figure 1(*b*), has 25 windings, each of 250 μm width and spaced 250 μm from the others. Four different polymers were tested [10]: polyepichlorohydrin (PECH), cellulose acetate (CA), cellulose acetate butyrate (CAB) and polyethylene glycol (PEG). For this application, PEG shows the highest sensitivity [10]. Polyethylene glycol, different from the others, is soluble in water: this characteristic influences the sensitivity positively, but increases the hysteresis as well. Its dielectric constant changes from 2.2 to 4, and depends on temperature and humidity.

2.1. Theoretical and simulation analysis of sensors

The sensitivity of the sensor depends on the induced change by RH on the parasitic capacitance. In order to increase the sensitivity itself, the relation between parasitic capacitance and RH has been studied with the support of an electromagnetic simulator. Figure 2(*a*) reports a post-process image of an inter-winding section of the planar sensitive inductance, showing an enlargement between the two tracks. The trapezoidal form is due to the cutter dip; the track sections have a thickness of about 75 μm and a distance between the two tracks of about 175 μm. The electromagnetic simulator (Maxwell 2D) calculates the capacitance between the two tracks assuming

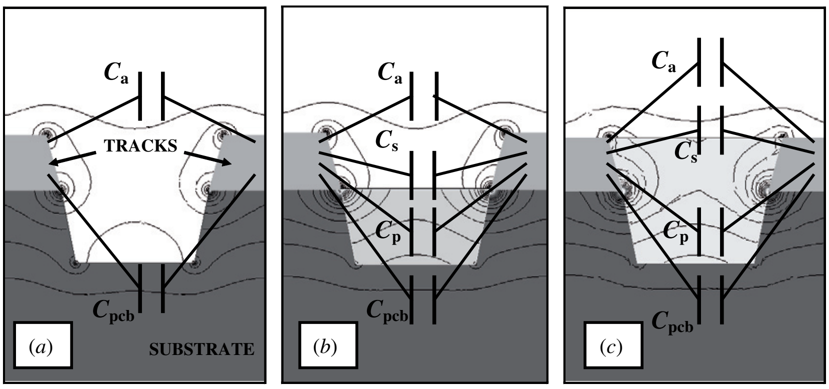

Figure 2. Electric energy of sensor without the polymer (*a*), with the optimum deposition (*b*), and with the total deposition (*c*).

that the system has rectangular symmetry, that is the two tracks extend infinitely along the axis pointing out of the figure plane. This capacitance is directly related to the parasitic capacitance of the sensing inductor. The background (white color in the figure) is air; the substrate is a FR4-epoxy with a relative permittivity (ε_r) of 4.4, tracks are in copper ($\varepsilon_r = 1$), and the polymer has ε_r equal to 2.2. Maxwell 2D operates adapting a mesh and calculating the total energy of the system stopping when a fixed target error of 0.1% is reached. The capacitance between the two tracks is obtained from the calculated energy and the voltage difference imposed, $\left(En = \frac{1}{2}CV^2\right)$.

The capacitance without polymer is

$$C_s' = C_\mathrm{a} + C_\mathrm{pcb}, \tag{1}$$

where C_a and C_pcb are the capacitances due to the electric field path into the air and the substrate, respectively.

Figures 2(*b*) and (*c*) show the same inter-winding section after the deposition of the polymer. In this case,

$$C_s' = C_\mathrm{a} + C_\mathrm{pcb} + C_\mathrm{p} + C_S, \tag{2}$$

where C_s takes into account the active section of the polymer (that is the thickness where the humidity acts), and C_p is the remaining part of the polymer. The thickness of the active section has been fixed around 100 nm; this value has been deduced from the literature. Papers [13, 14] report that only the first molecular layers of the polymer interact with the humid air and that the thickness of these layers is about 70 nm.

Since the sensitivity of the sensor depends on the change induced by RH on the parasitic capacitance, the ratio of the relative variation of the capacitance with respect to the relative variation of RH has been formulated into

$$\frac{\mathrm{d}C_S'}{C_S'} \bigg/ \frac{\mathrm{d}RH}{RH} = \frac{\mathrm{d}C_S}{\mathrm{d}RH} \cdot \frac{RH}{C_\mathrm{a} + C_\mathrm{pcb} + C_\mathrm{p} + C_S}. \tag{3}$$

Consequently, to increase the sensitivity it is necessary to increase $\mathrm{d}C_S$ and to decrease the total capacitance. Simulation analysis has been arranged to study how the polymeric deposition level influences the sensitivity. Figures 2(*b*) and (*c*) show two different depositions: the polymer is deposited only on the inner part of the valley (*b*), or completely into the valley (*c*). In the three pictures of figure 2, the lines are points at the same value of energy density. In (*b*) the capacitance is 20.94 pF m^{-1} when the active section of the polymer is dry (assuming $\varepsilon_r = 2.2$), and 21.03 pF m^{-1} when the same active section is exposed to damp air (assuming $\varepsilon_r = 4$) yielding a difference of about 90 fF m^{-1} for a change of RH of 80%. In (*c*), in the same situations, the difference is slightly less, being about 70 fF m^{-1}.

2.2. Telemetric model and measurement method

A physical model of the telemetric system is reported in figure 3. The parameters have the following meaning: R_r, R_s are the equivalent resistances of the readout and sensor; C_r, C_S' are the parasitic capacitances of the readout and sensor; L_r, L_s are the readout and sensor leakage inductances; L_m is referred to coupled flux; N_1 and N_2 are the equivalent numbers of the inductor windings. The coupling capacitance has been neglected [11].

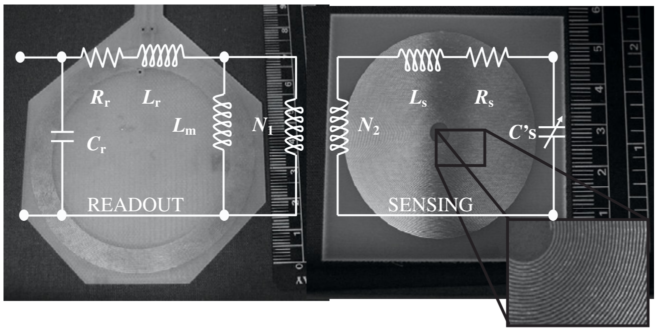

Figure 3. Picture of the sensor and the readout, and the physical model of the telemetric system.

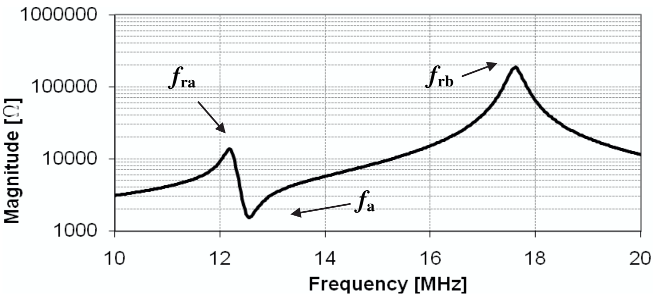

Figure 4. Impedance at readout terminals of the readout.

The impedance as seen from the terminal of the readout inductance is qualitatively plotted in figure 4, which shows the three resonant frequencies (f_ra, f_rb, f_a). According to [11], C_S' is

$$\begin{aligned} C_S' &= \frac{L_1 C_\mathrm{r}}{L_2} \frac{(2\pi f_\mathrm{ra})^2 + (2\pi f_\mathrm{rb})^2 - (2\pi f_\mathrm{a})^2}{(2\pi f_\mathrm{a})^2} \\ &= k\frac{(2\pi f_\mathrm{ra})^2 + (2\pi f_\mathrm{rb})^2 - (2\pi f_\mathrm{a})^2}{(2\pi f_\mathrm{a})^2}. \end{aligned} \tag{4}$$

The value of C_S' is obtained as the product of a constant term k and one calculated by the measures of f_ra, f_rb, f_a. The constant term k can automatically be obtained by calibration, or calculated by measuring the parameters of the equivalent circuit of every single inductor: L_1 and L_2 represent the inductance values of the readout and sensor.

The simulation results demonstrate that the deposition in figure 2(*b*) presents the highest sensitivity. The volume of polymer required to reach this level of deposition has been estimated based on geometric considerations. A solution of PEG in acetone 3% was spread on the sensors. The thickness of the deposited layer has subsequently been viewed with an optical microscope, and only the sensor with a deposition level similar to case (*b*) has been considered.

The equivalent circuit parameters of every single inductor separately (consisting in the series of an inductance (L_ser) and a resistance (R_ser) both in parallel with a capacitance (C_par)) have been measured by the impedance analyzer HP4194A, and their values are reported in table 1. The sensor has been analyzed with and without the polymer. According to (4), C_S' is calculated substituting C_r, L_1 and L_2 for the C_par and L_ser of the readout inductor and L_ser of the sensor and polymer, respectively.

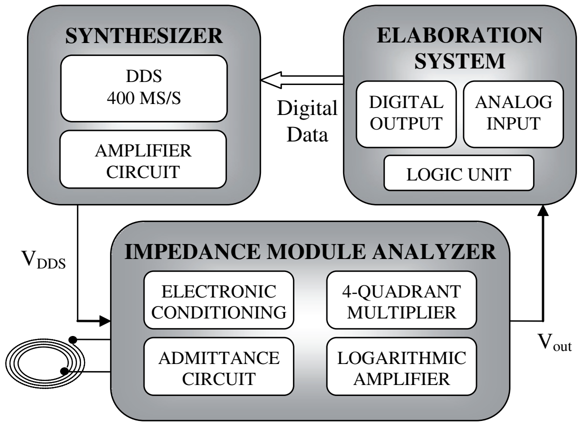

Figure 5. Block scheme of the electronic circuit for resonant frequencies analyzer.

Table 1. Values of the equivalent model for the sensor and the readout.

Inductor	L_{ser} (μH)	R_{ser} (Ω)	C_{par} (pF)
Sensor no PEG	95.67	30.01	1.55
Sensor + PEG	96.47	30.01	1.75
Readout	29.4	22.05	2.93

3. Conditioning electronics

In this section, the proposed conditioning electronics is presented. C'_s is obtained from equation (4) and requires the measurement of the three resonant frequencies (f_{ra}, f_{rb}, f_a) of the impedance module seen at the readout terminals. In fact, the impedance of the sensor is measured as a reflected load through a measurement of the impedance of the readout circuit [11]. The values of the three resonant frequencies are obtained through a direct measurement of the impedance module in a defined frequency range. Subsequently, the values of the three resonant frequencies are identified: f_{ra}, f_a, are the first maximum and minimum, respectively, while f_{rb} is the second maximum.

In the literature, several proposals of signal conditioning for admittance variation sensors are reported [15, 16]. The aim of these methods is to measure the value of the admittance. In this paper, a conditioning electronics for the measurement of the impedance module is proposed with the aim of obtaining the value of the three resonant frequencies. A block diagram of the proposed circuit is shown in figure 5. In this scheme the readout is reported as spiral.

The circuit has the following: a functional block for the generation of the reference signal (synthesizer), a block for the analysis of the impedance module (impedance analyzer) and one for the command and elaboration of the data (elaboration system). The synthesizer generates a sinusoidal variable-frequency signal (V_{DDS}) that drives the impedance analyzer module. The value of the frequency is controlled by the conditioning circuit. The analyzer uses the signal coming from the synthesizer and gives a dc signal (V_{out}) proportional to the impedance module of the readout. The elaboration system acquires V_{out}, identifies f_{ra}, f_{rb}, f_a and calculates C'_s according to equation (4).

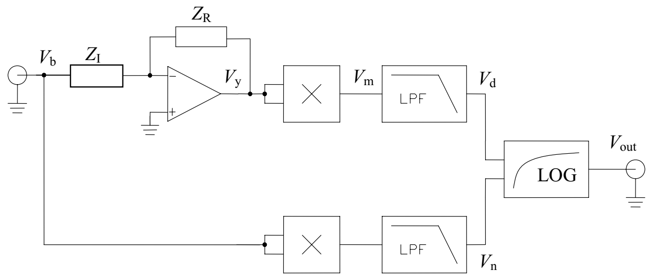

Figure 6. Block diagram of the impedance module analyzer.

The synthesizer consists of a DDS (direct digital synthesizer), produced by Analog Device (AD9954) and of an amplifier circuit for the change from differential to single mode. For practical reasons, the elaboration system consists of a PC equipped with an acquisition card from National Instruments (PCI-6024E) and dedicated software (LabView), but a microcontroller could be used as well. The software LabView controls the synthesizer for the generation of the frequency-known signal, and subsequently samples the output signal coming from the electronics for the impedance measurement.

In figure 6, the block diagram of the impedance analyzer is reported. The input signal V_b represents the input for two different paths: the up line and the down line. In the up line, the readout inductor is connected to the input of the operational amplifier in inverting configuration. Since Z_R and Z_I correspond to the impedance of the feedback path and the sensor respectively, V_y is proportional to the admittance of the telemetric system, thus

$$V_y = V_b\left(-\frac{Z_R}{Z_I}\right). \tag{5}$$

Subsequently, the signal is squared by a four-quadrant multiplier (AD835): V_m has a mean value proportional to the admittance module of the readout inductor and a double frequency component. Then the third-order low-pass filter extracts the mean value of the signal (V_d). The same conditioning circuits elaborate V_b in the down line obtaining a reference signal, V_n, equal to the square module of V_b. The following block, using a logarithmic amplifier (LOG104) produced by Texas Instruments, calculates the difference of the logarithms of V_n and V_d. The logarithmic amplifier makes it possible to analyze a high dynamic amplitude range due to the high impedance module range. Since the difference between two logarithms corresponds to the logarithm of the ratio, the signal V_{out} is proportional to the logarithm of the impedance Z_I:

$$V_{out}(t) = \frac{1}{2}\left(\log\frac{V_n}{V_d}\right) = \frac{1}{2}\log\frac{(|V_b|)^2}{\left(|V_b|\frac{|Z_R|}{|Z_I|}\right)^2}$$
$$= \frac{1}{2}\log\frac{(|Z_I|)^2}{(|Z_R|)^2} = \log|Z_I| - c. \tag{6}$$

It is possible to compensate the variations of V_b with this method. Moreover, the constant term c of equation (4) can be neglected, because the resonant frequencies are evaluated as relative maximum and minimum quantities.

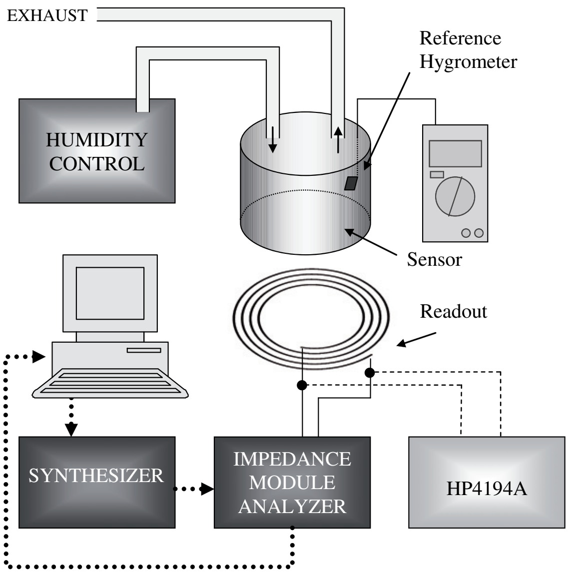

Figure 7. Block scheme of the experimental system.

4. Experimental setup

In figure 7, the proposed experimental system, used for the RH measurements and the testing of conditioning electronics, is represented. The sensor is positioned inside a Plexiglas chamber, which is used as a hermetic container for the damp air. In the chamber, there is a hygrometric sensor (HIH-3610 Honeywell) for reference measurements. The inductances are positioned parallel, and their axes are coincident. The three resonant frequencies are monitored by an impedance analyzer (HP4194A), connected to the readout inductor or alternatively to the dedicated electronics.

In figure 8, an image of the measurement chamber is reported: two pipes, which introduce and withdraw the damp air, and the wires for the connection of the reference sensor, are visible. The chamber is composed of two parts: a container, where a sensor is positioned on the bottom and a cover fixed to the container by 10 screws. A rubber gasket allows the hermetic closing of the two parts. The sensor chamber requires a period of time of at least $1\frac{1}{2}$ h before reaching the new RH value.

The damp air flowing inside the chamber is produced by the system reported in figure 9. It is observed that the damp air flow is the result of a mixture of two separate flows, the first one of dry air and the second one of saturated-water air. This last one is obtained by bubbling air through a container full of water; in this way the air becomes saturated. The mixture of the two gaseous fluids is checked by two flux meters. The test vapors generated from the bubbler at ambient temperature using nitrogen as the carrier gas are diluted to obtain the requested concentrations by computer-driven mass flow controllers. Concentration of H_2O into the chamber could be calculated with

$$C_{H_2O} = \frac{p_{sH_2O}}{p_{atm}} \frac{\Phi_{H_2O}}{\Phi_{H_2O} + \Phi_N}, \tag{7}$$

where $p_{s_{H_2O}}$ is the saturation vapor pressure and depends on the temperature, p_{atm} is the atmospheric pressure, Φ_{H_2O} and Φ_N are the two flows. All the experimental results are obtained at a constant measured temperature. The temperature values during the tests were about 22 ± 0.5 °C.

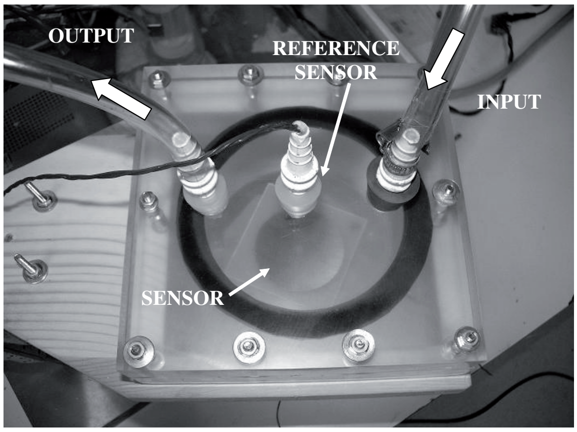

Figure 8. Picture of the measurement chamber linked with the humidity control.

An iron pedestal and a cylinder guarantee solid and fixed support for the system. The chamber of measurement is lodged in a wood structure, bound to the cylinder. The readout is fixed to a Plexiglas arm, which is bound to a micrometric screw. The choice of non-magnetic materials, wood and Plexiglas, make it possible to notably reduce the influence of the supports and the chamber on the magnetic field. The distance of the readout from the sensor is controlled by a micrometric screw that has a resolution of 10 μm and a range of 25 mm.

5. Experimental results

The experimental results have been obtained using the measurement system reported in figure 7. The sensor and readout, which are used in the experimental tests, are reported in figure 3; their characterization is reported in table 1. Initially the impedance analyzer HP4194A was connected to the readout, and the experimental results have been used as reference values for the characterization of the conditioning electronics. In measurement operations, the wires which connect the readout inductor with the HP4194A have been compensated.

In figure 10, detailed diagrams of the impedance module are reported for a distance of 10 mm: two resonant frequencies can be observed. A downward translation of the resonant frequencies while the RH increases can be noticed.

Figure 11 shows the capacitance values calculated by equation (4). The resonant frequencies are obtained measuring the impedance module with HP4194A for different RH and distance values and extracting f_{ra}, f_{rb}, f_a. The controlling system of damp air generates six values of RH: 18%, 40.3%, 57.9%, 79.3%, 88.9% and 90%. After the setting, the experimental apparatus requires 2 h before reaching a stable RH value. For each RH stable value the three resonant frequencies have been measured. The uncertainty for the measurements obtained with the impedance analyzer is about ±700 Hz with a confidence level of 68.26%. The distances

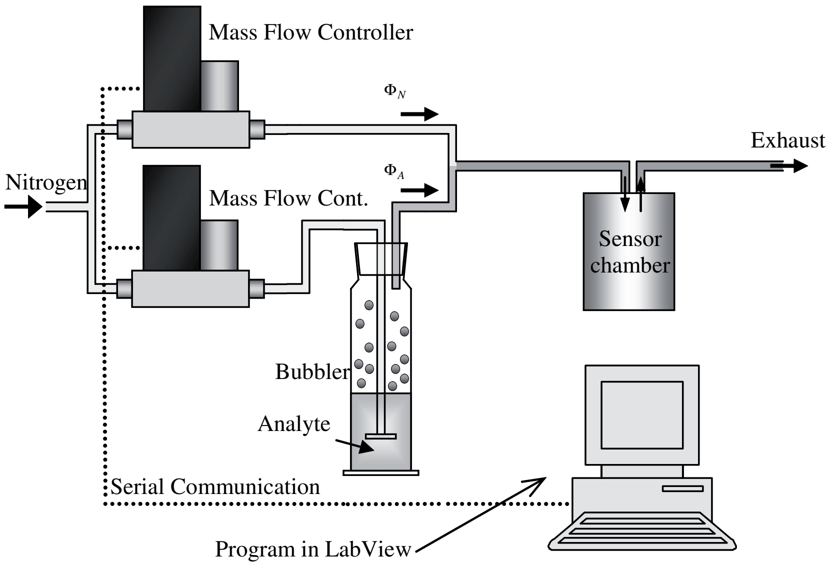

Figure 9. Block scheme of the experimental system for damp air generation.

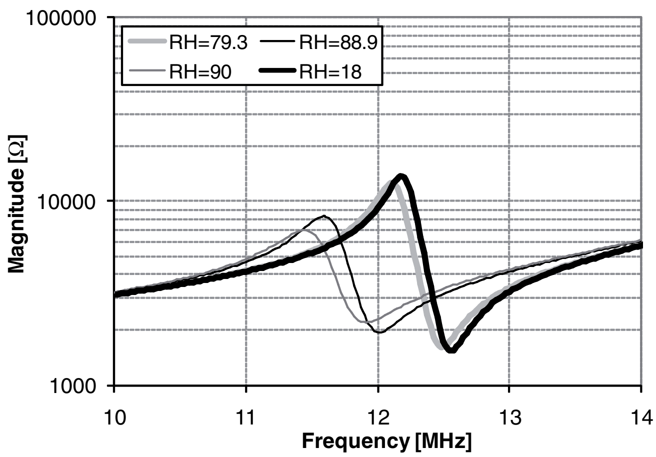

Figure 10. Diagrams of the impedance module for a distance of 10 mm obtained by HP4194A.

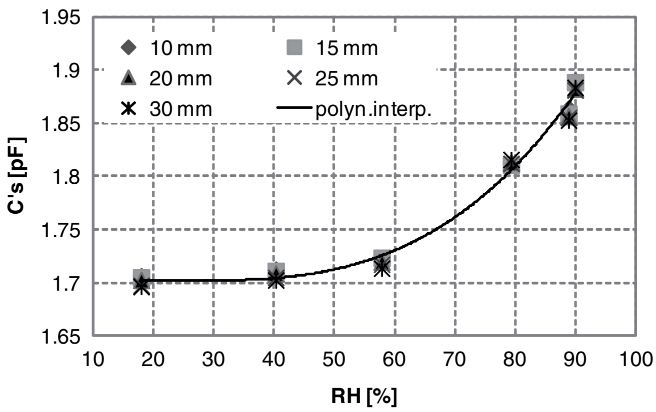

Figure 11. The calculated capacitance values as a function of RH and for different distance values (HP4194A).

between the sensor and the readout have also been changed from 10 to 30 mm. The nonlinearity of the polymer is clearly visible. The capacitance values change from around 1.7 pF for a value of RH = 18% to around 1.88 pF with a value of RH = 90%. In figure 11, a polynomial interpolation line is shown, which is used as a reference for the experimental results obtained with the proposed conditioning circuit.

Consequently, the proposed conditioning circuit has been connected to the readout. Figure 12 reports the output from the impedance module analyzer (V_{out}). The conditioning circuit has been used to collect all the measurement data with a frequency resolution of 0.5 kHz for two values of RH, and a fixed distance of 30 mm. In the analyzed range (12–13 MHz) two resonant frequencies are shown. As expected, a downward translation of the resonant frequencies, while the RH increases, can be noticed. The amplitude voltage depends on the value of c in equation (4): it is negative because in the analyzed range the impedance Z_I is lower than Z_R. The extracted f_{ra}, f_a, are 12.2835 MHz, 12.4660 MHz for 15.5% and 12.2585 MHz, 12.4385 MHz for 56.5%, respectively.

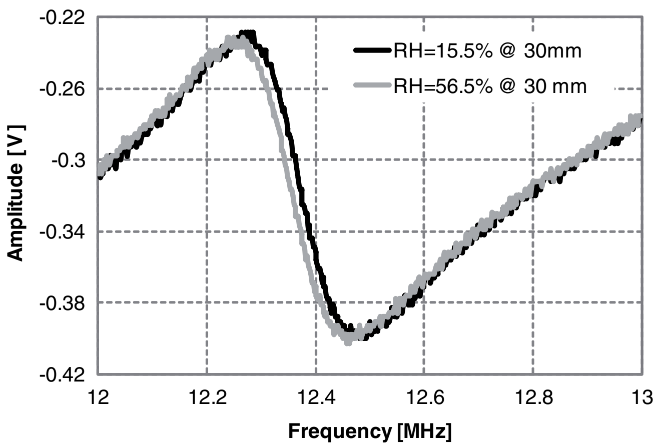

Figure 12. Diagrams of the amplitude for a distance of 30 mm obtained by conditioning electronics.

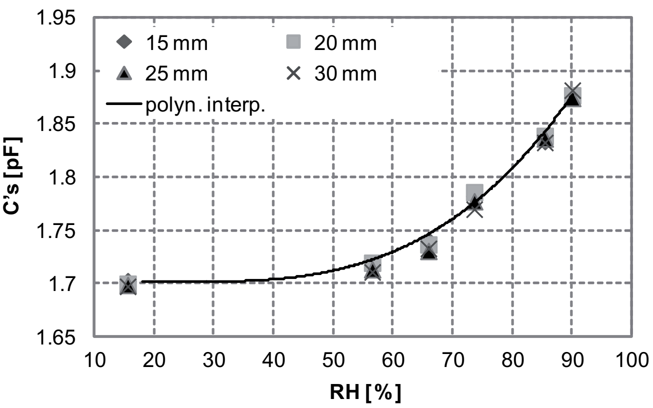

Figure 13. The calculated capacitance values as a function of RH and for different distance values (conditioning electronics).

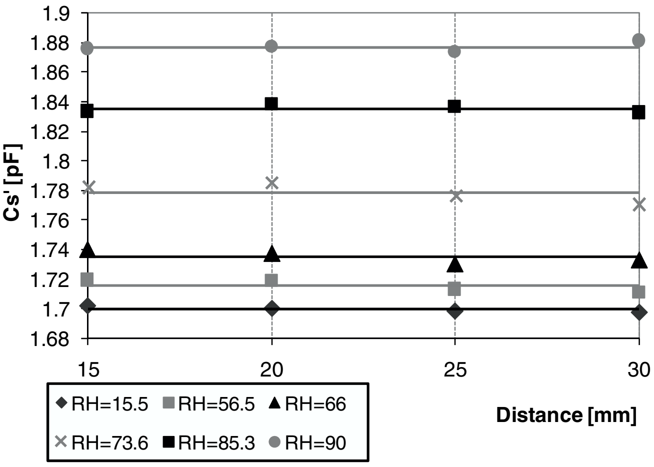

Figure 14. Capacitance values calculated using the proposed conditioning electronics as a function of RH and distance.

Figure 13 reports the experimental results when the RH and the distance change. In this case, the six stable RH values are slightly different from the previous: 15.5%, 56.5%, 66%, 73.6%, 85.3% and 90%. The three resonant frequencies have been measured using four different distance values between the sensor and the readout (15, 20, 25 and 30 mm). The uncertainty for the measurements obtained with the proposed conditioning electronics is about ±1000 Hz with a confidence level of 68.26%. It has not been possible to execute the measurements to 10 mm because of the encumbrance of the package of the electronic card. In accordance with the experimental results obtained by HP4194A, the polynomial interpolation line has been reported in figure 13: the values which are obtained with the conditioning electronics and the proposed method, are in accordance with the line. Comparing the two sets of measurements, it is possible to note good agreement for RH values of greater values, in the range where the sensitivity of the sensor is greater.

In figure 14, the capacitance values as a function of distance are reported. The maximum variation of the capacitance is limited to 20 fF over a distance variation from 15 to 30 mm.

6. Conclusions

In this paper, a new telemetric system for RH measurements has been discussed. It consists of two contactless planar inductors, one of them working as a stand alone sensitive element. The proposed telemetric system exploits the parasitic capacitance of a planar inductor since an RH sensitive polymer is deposited over the inductor functioning as a sensor; consequently, the sensor does not need the addition of an item with capacitive transduction. With the aid of an electromagnetic simulator, the sensor sensitivity has been studied, and an optimized geometry of polymer deposition has been identified. The sensor shows about 200 fF variation over 1.7 pF for a change of the RH between 60% and 90%. A low-cost electronic circuit has been developed and tested. The experimental results have been compared with those obtained by a reference impedance analyzer and show good agreement. The electronics implements a measurement method that compensates the distance variation of the two inductors when they face each other, with their central axes coincident. The designed electronics offers a low-cost solution better than a complex impedance analyzer, even offering similar performance.

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