Wireless Passive Autonomous Sensors with Electromagnetic Transduction

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Abstract—**Wireless sensors market is growing very fast these last years tanks to the availability of cheap, small and efficient micro-sensors, batteries, analog and RF circuits, and to the presence of standardized communication protocols. Even if these active sensors are very attractive for a lot of applications, they suffer from weak energy autonomy and they are not compatible with harsh environment. In order to overcome these problems, we have developed a new kind of wireless sensors using electromagnetic transducers and radar interrogation. These passive sensors (battery-less and without electronic components) have been studied for pressure, temperature and gas applications.**

Keywords: wireless sensor , passive sensor, electromagnetic transduction, radar interrogation

I. INTRODUCTION

Since late 1999, “Ambient Intelligence” (also called or “Internet of Thinks”) is the subject of intense research in the world with the objective to interconnect many objects like sensors, actuators, tags, mobile phones, …. [1-2]. These entire new intelligent objects will have the possibility to give information about its environment and to share this information on the basis of wireless telecommunications. In this context, wireless sensors appear as a key technology for a lot of applications both in domestics and industrials fields as, e.g. healthcare, intelligent home, environment, structural health monitoring, agriculture and food monitoring. [3-5].

One can divided wireless sensors technologies into two main classes: active sensors which require power source and passive sensors that are battery-free.

Active sensors can be described by three different functional parts: a transducer which converts the input to be analysed into electrical signal, electronic circuits for the signal conditioning and a communication unit for data transmission (Figure 1). The power source, supplied by an embedded battery, is the key limiting factor for the sensor autonomy. This drawback can be reduced using rechargeable battery coupled with harvesting module. Nevertheless the sensor life time is driven by embedded quantity of energy (mainly the battery size), the data transmission rate and the interrogation distance. However very long interrogation distance (up to several hundred of meters) can be achieved with this technology. Solutions also exist without battery, called semi-active, where harvested power is directly supplied to transducer and electronic circuits through dedicated electronic converter. In this case the reading distance is reduced to several meters and the data transmission rate is low. Then, despite the disadvantages of this kind of active sensors, a lot of companies propose now wireless active sensor products (with or without battery) that are suitable for different applications. That was made possible by the availability on the market of low cost and efficient (low consumption, low size) transducers, electronic circuits (from DC to RF) and batteries but also the availability of standardized transmission protocol (Wifi, Zigbee, ..). The main research studies in this field to increase the active sensor autonomy are concentrated on the development of new energy micro-source with high power (electrochemical, nuclear, thermo-electric, thermo-ionic, …), high efficiency of energy harvesting (solar, vibration, thermoelectric, Radio-Frequency, ..) and low consumption electronic circuits.

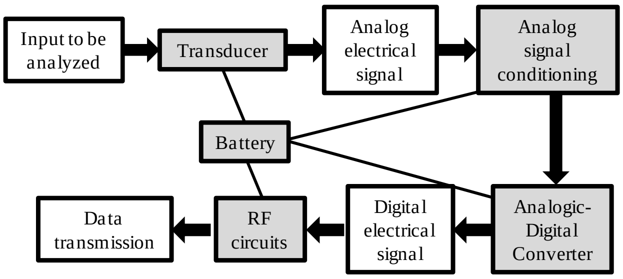

Figure 1 : Synoptic of active wireless sensor

Otherwise, passive sensors can be described by two main parts : a passive transducer with only passive elements and a remote reader capable to analyze the transducer response (Figure 2). The wireless communication between the two parts can exploit electric, magnetic, electromagnetic, acoustic or optic link. The most popular are magnetic and electromagnetic links, related to the availability of several solutions for electronic readers.

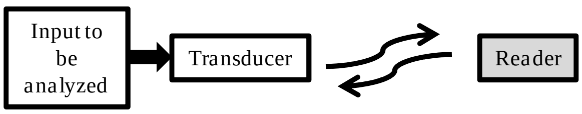

Figure 2 : Synoptic of passive wireless sensor

Inductive coupling is used generally with capacitive sensors in order to realize LC resonator, but the main drawback of this technique is the very short reading distance (few centimeters).

Electromagnetic interrogation, based on the analysis of backscatter wave by the transducer, allows overcoming this limitation. The first sensors using this electromagnetic interrogation are Surface Acoustic Wave (SAW) sensors [6-9]. These sensors are based on piezoelectric substrate on which inter-digital electrodes, connected to an antenna, allow converting the electromagnetic waves into acoustic waves (for the input signal) and acoustic waves into electromagnetic waves (for the output signal). The reader generally analyzes the propagating time inside the piezoelectric transducer that is related to the acoustic wave velocity inside the piezoelectric material. As this velocity is modified by temperature and stress but also by thin layers at the piezoelectric material surface, it is possible to realize different kind of sensors (temperature, stress, pressure, gas, biological) depending on materials and design choices. Nevertheless these sensors suffer from the low efficiency of the coupling coefficient between electromagnetic and acoustic waves (between 0.1% to 5%) leading to reading distance lower than 10 meters.

In order to overcome these low coupling rates, we have chosen to realize full electromagnetic transducers. The principle of electromagnetic transduction is based on the modification of the electromagnetic descriptor (as, e.g. the resonant frequency of a millimeter-wave resonator) by the phenomena one wants to measure. This modification can be obtained by the variation of the electromagnetic propagation medium surrounding the resonator. There are two main possibilities to affect this propagation. The first one is to move a mechanical part close to the resonator. The second one is based directly on the modification of the electrical permittivity of the material used to fabricate the resonator. With these two main principles, a lot of sensors can be developed as physical and chemical sensors.

In the following, we give examples of sensors with electromagnetic transduction we are working on.

II. Pressure Sensor

We started this study in 2005 and details about obtained results can be found in references [10] to [18]. The sensor we developed is based on a planar half-wavelength resonator coupled with a high resistivity silicon membrane (Figure 3). When the silicon membrane is far away from the resonator, the electromagnetic propagation medium of the resonator is only built by Pyrex (underneath resonator) and air (above resonator). From a given air gap between the silicon membrane and the resonator, evanescent waves start to couple with silicon membrane modifying strongly the effective permittivity of the medium (Figure 4) and then the resonant frequency of the resonator (Figure 5).

The sensor has been fabricated using classical micro-technology process and characterized with a specific pressure probe module allowing on wafer S_{21} parameters. The sensor exhibits a very high sensitivity close to 0.37GHz/bar (Figure 6).

More recently, passive pressure sensors with other resonator types have been published, but with lower sensitivity [19-21].

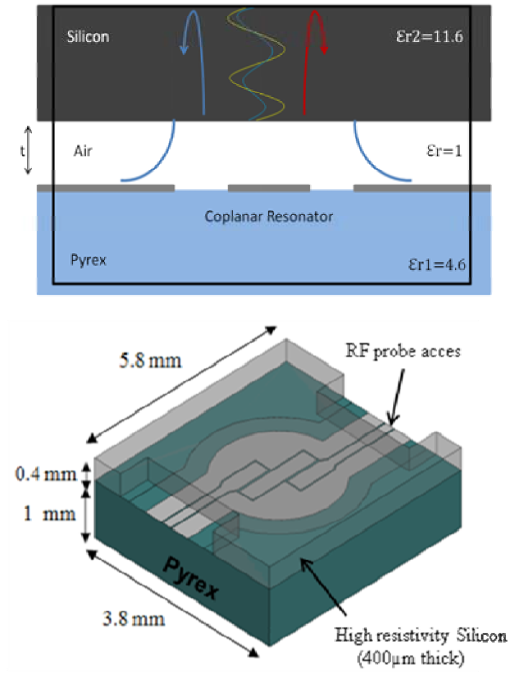

Figure 3 : Pressure sensor topology

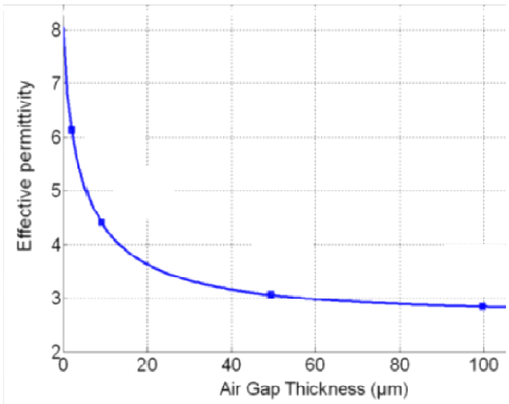

Figure 4 : Effective permittivity versus air gap.
Simulation results with 300µm thick silicon membrane and uniform membrane displacement

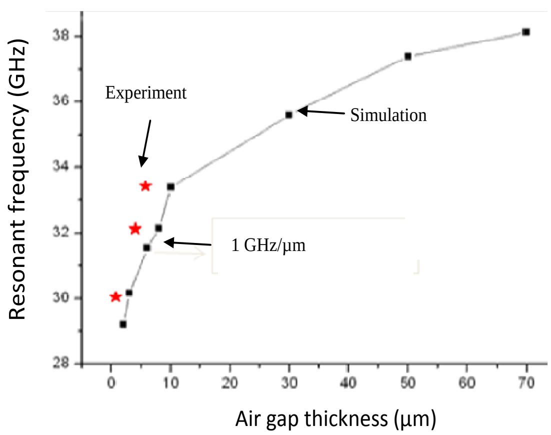

Figure 5: Resonant frequency versus air gap.
Results with 300µm thick silicon membrane and uniform membrane displacement

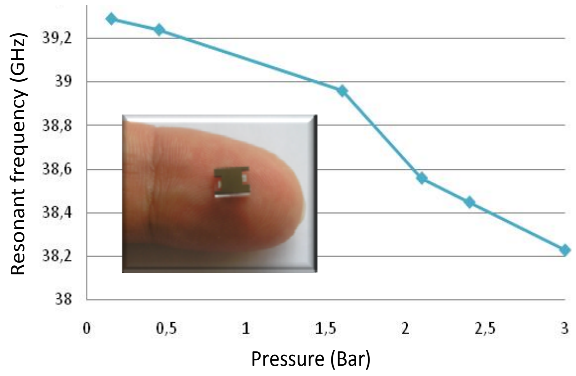

Figure 6: Resonant frequency versus pressure
Experimental results 45µm thick silicon membrane

III. TEMPERATURE SENSOR

We started this study in 2009 in collaboration with Georgia Institute of Technology and more details are given in [22-24]. No similar works have been found in literature up to now.

The temperature transducer consists of split ring resonators fabricated on top side of substrate and excited by a coplanar transmission line located on wafer back side (Figure 7). The slits of the rings are covered with bimorph micro-cantilevers whose layers are made from two different materials. A temperature shift induces the cantilever deflection and then a modification of the coupling capacitance between the two arms of the ring, which leads to the change of the resonant frequency.

The principle has been validated at 30GHz by simulation with a 500µm-thick Pyrex substrate and with uniform displacement of a purely metallic cantilever (Figure 8). The sensor exhibits a very high sensitivity close to 2.6GHz/µm.

To overcome technological problems, a demonstrator has been first fabricated at 3GHz using classical technology. The rings and the coplanar line are deposited on a 787µm-thick Neltec substrate (Figure 9). The bilayers cantilever is obtained by the lamination of a 100µm thick aluminum sheet and a 50µm thick polyethylene (PET) sheet (Figure 10). Two different temperatures are simulated by two different anchorage thicknesses using PET sheet. The S_{21} parameter obtained with these two configurations shows a relative resonant frequency shift around 0.2%/µm (Figure 11).

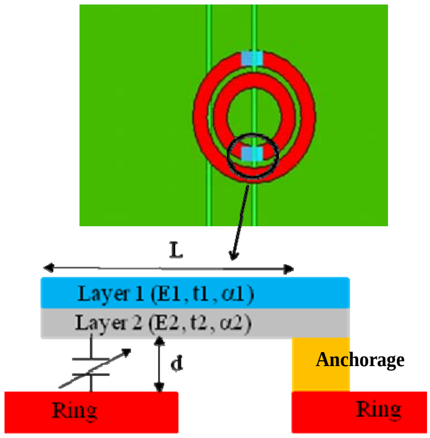

Figure 7 : Temperature sensor topology. Ring resonators on substrate front side and CPW on back side.

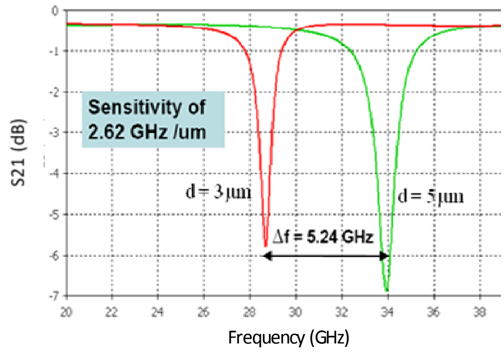

Figure 8 : Simulated S_{21} magnitude versus frequency for the 30GHz temperature sensor prototype
(500µm thick Pyrex substrate and uniform cantilever displacement)

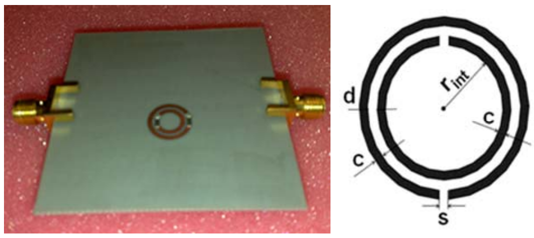

Figure 9 : View of 3GHz temperature sensor prototype
(r_{int}=2.5mm, c=1mm, d=0.5mm, s=1mm)

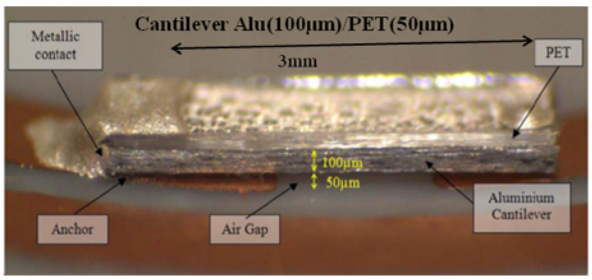

Figure 10 : View of cantilever for the 3GHz temperature sensor prototype

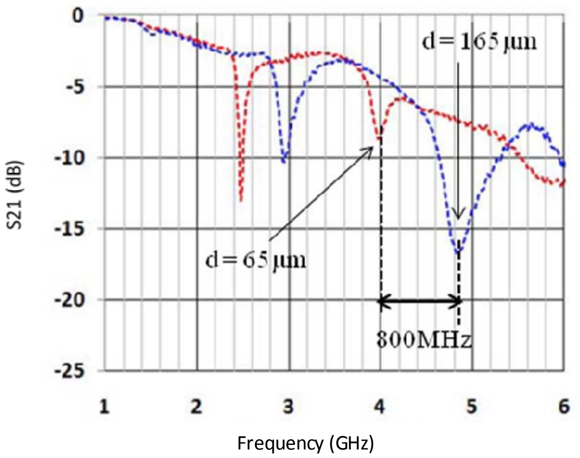

Figure 11 : S_{21} magnitude versus frequency for the 3GHz temperature sensor prototype (787µm thick Neltec substrate and uniform cantilever displacement)

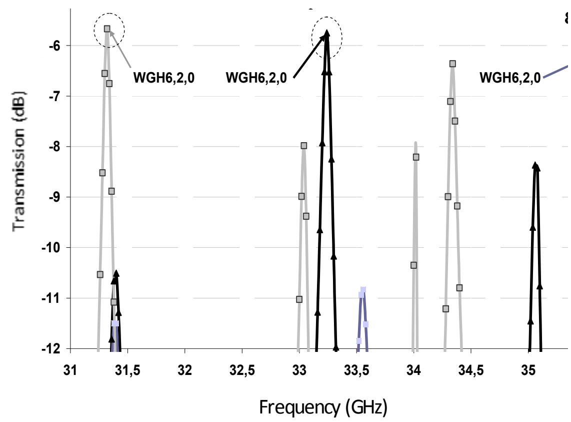

Figure 13 : S_{13} parameter versus frequency for different dielectric permittivity (simulations)

IV. GAS SENSOR

This study started in 2007 and more details can be found in [25-29]. No other passive gas sensors with electromagnetic transduction are reported up to now in the literature.

The gas transducer consists of two Coplanar Wave Guide (CPW) coupled with a cylindrical Dielectric Resonator (DR) (Figure 12), allowing the excitation of whispering galleries modes inside the dielectric resonator. The spacer, located in the center part of the DR, allows adjusting the vertical coupling between CPW and DR. The sensor principle is based on the dielectric relaxation effect (that corresponds to the dielectric resonator permittivity modification with gas absorption), which leads to the change of the resonance frequency.

Simulations performed with a TiO_2 DR have shown that resonant frequency of whispering galleries modes are very sensitive to the modification of the dielectric resonator permittivity (Figure 13). A prototype has been fabricated using CPW on a micro-machined silicon substrate, in order to reduce the silicon losses, and a DR in $BaSmTiO_x$. TiO_2 DR sensitive to gas are under fabrication in order to validate the sensor response.

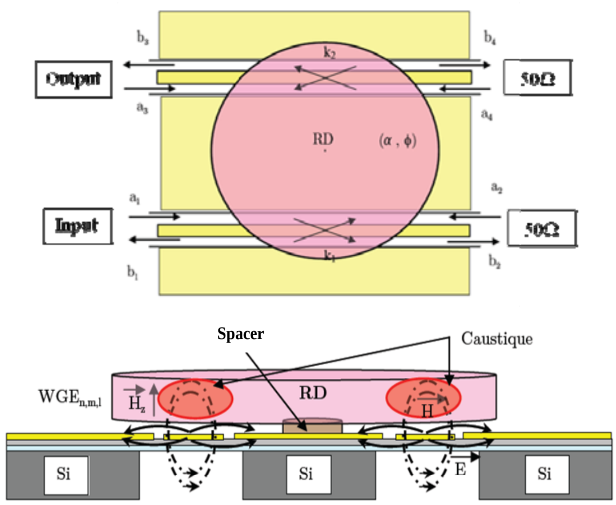

Figure 12 : Gas sensor topology

V. RADAR INTERROGATION

The interrogation system is based on the FMCW (Frequency Modulated Continuous Wave) Radar. From the measured Radar Cross Section (electromagnetic echo) of the sensors, the physical quantity can be remotely and wirelessly derived and the identification of the sensor can also be performed [14], [17-18], [30-31].

The simplified block diagram of the interrogation unit, operating in homodyne principle, is shown in Figure 14. The Voltage Control Oscillator generates a frequency signal which increases linearly for a frequency sweep period. This signal propagates from the transmission horn antenna to the sensor target that is composed by an antenna loaded by the sensor die. This signal is then reflected back by the target, recovered by the receiving antenna of the reader and mixed with the input signal to obtain the intermediate frequency. The analysis of this frequency beat level permits then to detect the variation of the sensor load (that is linked to the shift of the sensor resonant frequency and then to the measured value).

A Radar, operating between 26GHz and 31GHz has been designed and fabricated (Figure 15). The interrogation principle up to 30m has been first validated using 1 cm^2 passive target and few mW for Radar emission. An example of Radar response is given in Figure 16 for the pressure sensor. The sensor die was connected via RF probes to an external horn antenna, placed at 3m from the Radar.

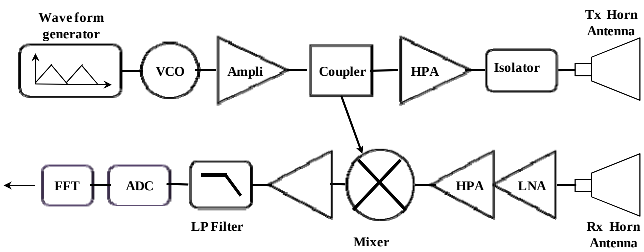

Figure 14 : Simplified block diagram of the interrogation unit

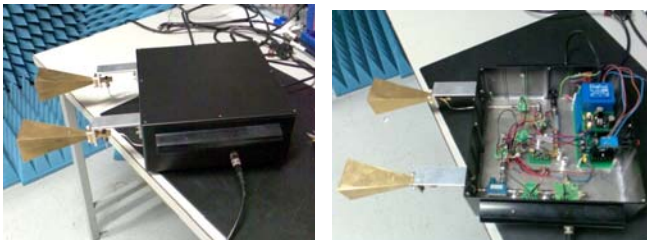

Figure 15 : Photographies of the fabricated Radar prototype

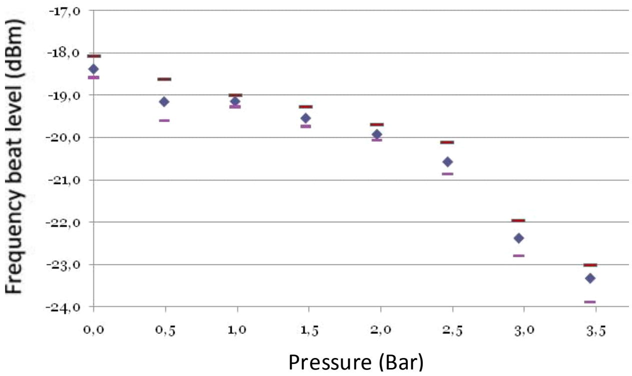

Figure 16 : Radar response of pressure sensor

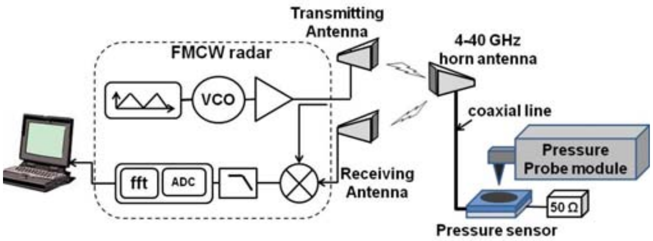

Figure 17 : Set up used for pressure sensor interrogation by Radar

VI. Conclusion

The principle of new passive sensors has been validated for several applications (pressure, temperature, gas). These sensors are based on electromagnetic transduction and on Radar reader. The main advantages of this new kind of sensors are: a very simple transducer part without battery and without embedded electronic circuits that allows addressing applications with harsh environment and a wireless reading distance greater than 30m.

This electromagnetic transduction with a Radar reader can be adapted to other physical or chemical sensors as stress sensors [32]. Nevertheless our main objective now is focused on the realization of sensors with given specifications (sensitivity, accuracy, …) for specific applications.

VII. Acknowledgment

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