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A wireless inductive-capacitive (L-C) sensor for rotating component temperature monitoring

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Abstract- Temperature monitoring is critical in almost every type of machinery and application, especially in rotating components such as jet turbines, engines, and power plants, etc. These components involve harsh environments and where the physical connections for monitoring systems are impossible. This paper presents a resonant inductive-capacitive (L-C) circuit based wireless temperature sensor suitable for working in these harsh environments to monitor the temperature of rotating components. Design and performance analysis of the wireless temperature sensor has been conducted and the sensor prototype was successfully fabricated and calibrated up to 200ºC with sensitivity of 30 kHz/ºC. As a result it is confirmed that temperature monitoring of a rotating component can be carried out without requiring physical connection, power supplies or active elements in the sensor circuit.

Index terms: Wireless, resonant inductive-capacitive (L-C) circuit, temperature sensor, rotating components.

I. INTRODUCTION

Temperature monitoring is critical in almost every type of machinery and application, especially in rotating components such as jet turbines, engine, and power plants, etc. [1]. Many of such applications present the challenges of being exposed to high temperatures, and harsh environments, and having no physical connections to the temperature monitoring systems. Temperature monitoring of such machinery rotating components could reduce the risk of component failure, ensuring equipment safety. However, acquiring temperature measurements of a rotating machine component using conventional methods can be costly and technically challenging. For example, using thermocouple technology requires the uses of sophisticated slip ring mechanisms to ensure continuity of electrical contacts while the use of infrared thermal measurement devices do not provide the ability to measure temperature at targeted locations on rotating structures [2].

Many papers have been published related to the applications of resonant inductive-capacitive (L-C) circuit based sensors in the last decade, because these sensors eliminate the need for onboard power and physical connections. Due to the small size and stable characterization of the the L-C sensors, they are particularly suitable for transmitting power for short distances in industrial harsh environments, In the past significant amount of research have made contributions to advance the *L-C* based passive wireless sensing technologies and extend their applications in many areas, such as pressure sensor [3], humidity sensors [4], and temperature sensors [5]. However, the development of the *L-C* temperature sensor hasn't been demonstrated so far for a rotating component temperature monitoring in a harsh environment.

In this paper a wireless L-C sensor was designed and tested for temperature monitoring on a rotating component. The uniqueness of this device resides in the integration of a high temperature sensitive material (PLZT) into the L-C tank for rotating components temperature monitoring in a harsh environment at first time. As illustrated in Figure 1, the wireless temperature sensing system includes a L-C temperature sensor, antenna, portable reader and computer. The sensor consists of an inductor and a Lead-Lanthanum-Zirconate-Titanate (PLZT) ceramic made capacitor with temperature dependent characteristics. Temperature information and power were sent via an inductive coupling between the reader and the sensor antenna. Temperature change was wirelessly translated into a frequency shift in the reader output. Calibration of the sensor was successfully carried out and the wireless temperature monitoring concept for rotating components was demonstrated.

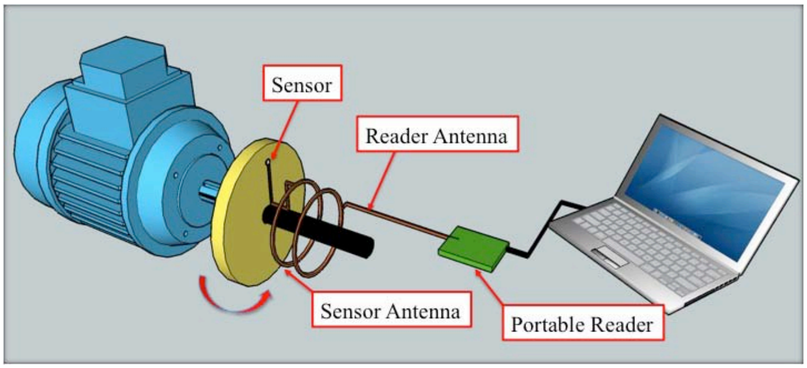

Figure 1. Proposed wireless temperature sensing system

II. L-C SENSING PLATFORM

The proposed wireless sensor for temperature sensing in this study employs an inductor-capacitor (L-C) tuned electronic oscillator which incorporates temperature sensitive materials. The capacitance formed by temperature sensing material is integrated into the electronic circuit as a frequency-controlling element. The change in the value of the capacitance due to temperature variation is translated into modulation in the oscillator frequency.

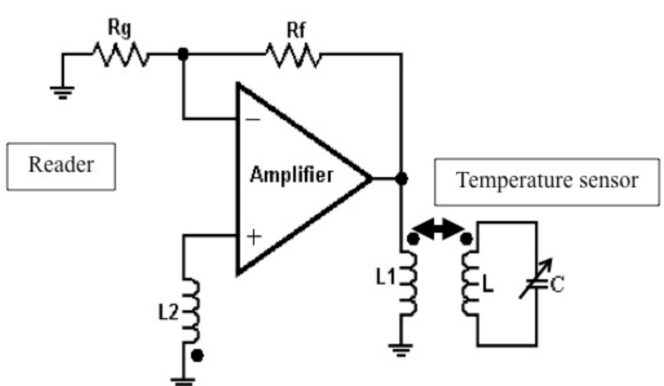

Figure 2. Principle of a RFID wireless sensor system

This wireless system detects changes in the resonant frequency of the sensor which are due to changes in temperature. As the temperature changes, the temperature sensing material's dielectric properties change. This results in a change in the electric field, which in turn affects the frequency of the resonating harmonic response [1]. Since the resonant frequency of the sensor is dependent on the temperature, the reader can detect temperature changes by monitoring the impedance across the terminals of its antenna [5]. A more detailed description of the wireless system is discussed in Section 4.

III. SENSOR DESIGN

The temperature sensor has a simple design consisting of a capacitive sensing element connected to an inductive antenna. Information and power are sent between the sensor antenna and the reader, which is connected to a computer in order to analyze and store the data. The core of the capacitive element is made of a PLZT layer. The structure of the sensor is shown in Figure 3. It consists of a ceramic material that offers excellent dielectric properties with a temperature dependent permittivity value (k) and can withstand high temperatures up to the 200°C. The ceramic is coated with a conductive layer of NiCr, allowing it to work as a capacitive sensing element. The parallel plate temperature sensing element design, incorporating thick film high-k temperature sensitive ceramic material and thick film electrode, makes the sensor easy to attach and suitable to be used on rotating components [5].

The capacitance of the sensor depends on the temperature dependent dielectric constant ε_r of the PLZT sensing material as demonstrated in equation 1.

$$C(T) = \frac{\varepsilon_o \varepsilon_r(T) A}{t} \qquad (1)$$

where,

ε_o = permittivity of free space, 8.85×10^{-12} F/m

$\varepsilon_r(T)$ = temperature dependent dielectric constant

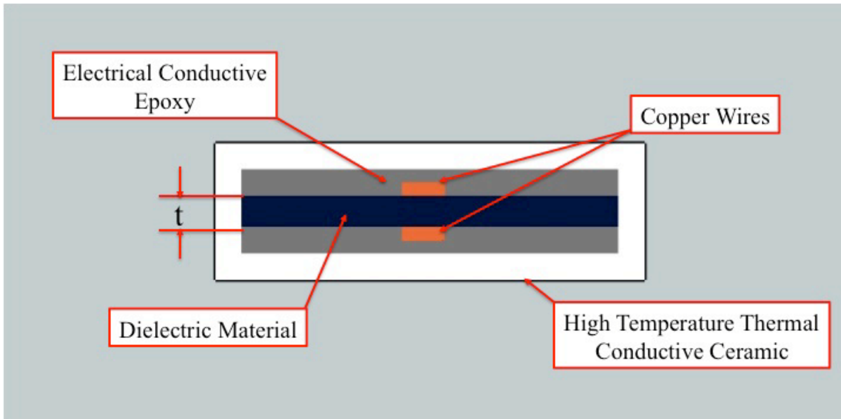

Figure 3. Temperature sensor cross-section

The changes in the sensor resonant frequency are monitored using an inductive antenna connected to a portable reader. For this experiment a circular inductor was chosen; its inductance can be determined as follows [5]:

$$L_s = N^2 R \mu_o \mu_r \left[\ln\left(\frac{8R}{a}\right) - 1.75 \right] \tag{2}$$

where,

N = number of turns,

R = inductor (sensor) radius

$\mu_o \mu_r$= permittivity

a = wire radius

As the temperature changes, the dielectric properties of the material change, resulting in a change in the electric capacitance and a shift in the resonant frequency of the sensor. The shift of the resonant frequency of the sensor can be calculated by:

$$f(T) = \frac{1}{2\pi\sqrt{L_s C_s(T)}} \tag{3}$$

For this experiment, the antenna possessed a radius of 2.25 cm, a wire diameter of 0.405 mm, and 1 turn with an inductance of 1.426×10^{-7} H. The nominal capacitance value

(T=25°C) was 0.87 nF. With these values, the expected baseline resonance frequency at ambient temperature for the sensor was approximately 14.27 MHz.

IV. PERFORMANCE ANALYSIS

The performance of the sensor was simulated by reflecting its impedance in the reader. The equivalent circuit diagram is shown below.

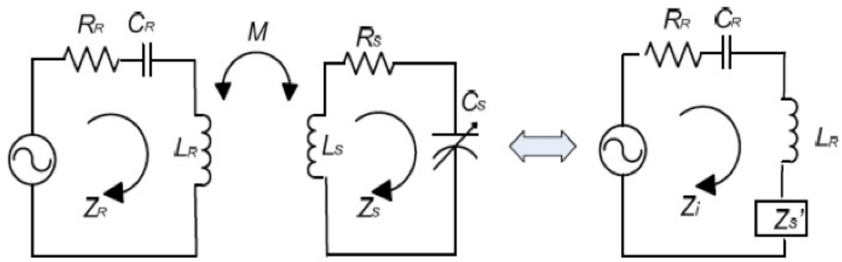

Figure 4. Equivalent circuit diagram of wireless sensor system

The impedance of the reader circuit is given by:

$$Z_R = j\omega L_R + R_R + \frac{1}{j\omega C_R} \tag{4}$$

The impedance of the sensor can be expressed as:

$$Z_S^{'} = \frac{(\omega M)^2}{j\omega L_s + R_S + \frac{1}{j\omega C_S}} = -\frac{\omega^2 k^2 L_R L_S}{j\omega L_s + R_S + \frac{1}{j\omega C_S}} \tag{5}$$

k is the coupling coefficient , defined by:

$$k = \frac{M}{\sqrt{L_R L_S}} \tag{6}$$

This coupling factor is dependent on the distance (*d*) between reader and sensor inductors; this behavior is described by the following equation:

$$k(d) = \left(\frac{r_S r_R}{d^2 + r_R^2} \right)^{\frac{3}{2}} \tag{7}$$

Therefore, the input impedance seen from the reader side is given by:

$$Z_i = Z_R + Z_S^{'} \tag{8}$$

Substituting equations 4 and 5, the following equation can be obtained:

$$Z_i = j\omega L_R + R_R + \frac{1}{j\omega C_R} + \frac{\omega^2 k^2 L_R L_S}{j\omega L_s + R_S + \frac{1}{j\omega C_S}} \tag{9}$$

A periodical sweeping frequency around the natural frequency of the sensor is generated to detect the frequency variations. When the excitation frequency matches the natural frequency of the sensor, a sudden increase in the impedance occurs. Figure 5 demonstrates our simulation results at different temperatures.

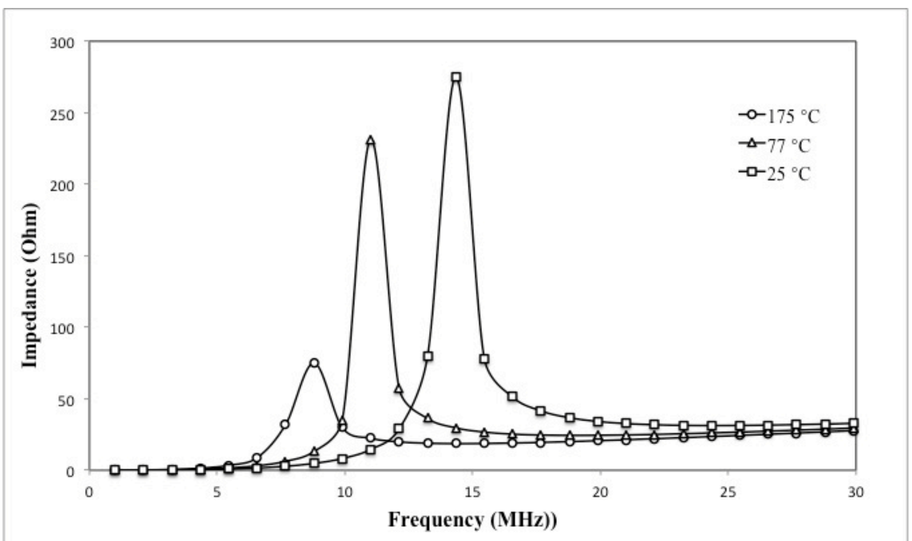

Figure 5. Simulation of the sensor response; Input Impedance vs. Sweeping Frequency

Table 1. System Parameters.

Parameter	Value
Reader Inductance L_R	1.4×10^{-7} F
Sensor Inductance L_s	1.4×10^{-7} F
Reader Resistance R_R	0.4 Ω
Sensor Total Resistance R_S	0.4 Ω
Sensor Nominal Capacitance C_S at 25°C	0.87 nF
Coupling Factor k	0.97
Reader Radius r_r	2.25 cm
Inductor Radius r_s	2.25 cm
Coupling Distance d	3.0 mm

V. EXPERIMENTAL SETUP

The temperature sensor prototype and its equivalent circuit are shown in Figures 6a and 6b respectively. The sensor was built using a 5 mm square piece of PLZT ceramic. Two thin wires were bonded into both surfaces of the ceramic using the *Duralco 124 Ultra Temp Conductive Epoxy,* which is a electrically conductive epoxy. The piece of ceramic was entirely covered with a layer of a *Resbond 920*, which is a high thermal conductor and an excellent electrical insulating epoxy. This last coating was used to protect the bonding between the electrodes and the ceramic and to prevent the sensor from making any electrical contact with any exterior component.

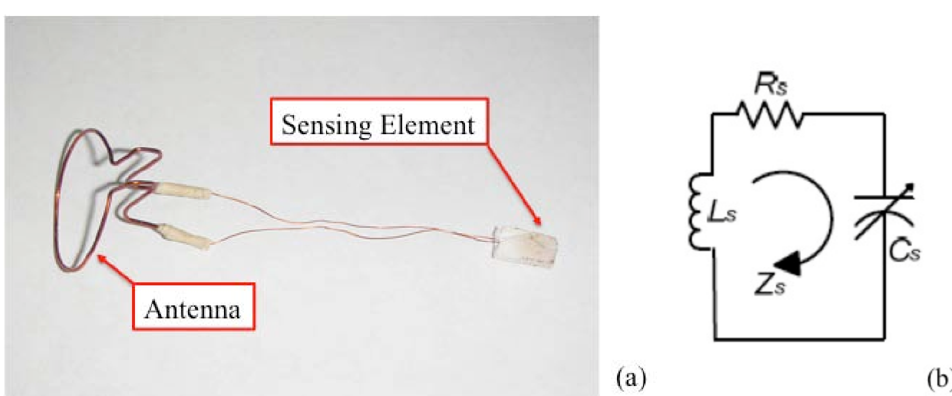

Figure 6. Wireless temperature sensor (a) and sensor equivalent circuit (b)

The sensor was attached to an aluminum disk as shown in Figure 7. A machine fault simulator from Spectra Quest was used to conduct the sensor testing. The machine was operated at a low rate of 288 rpm (4.8 Hz). Since the distance between reader and sensor antennas affects the coupling coefficient, both antennas were placed as close as possible while avoiding any physical contact. The reader antenna was placed around the fault simulator shaft and aligned concentrically with the sensor antenna at a distance of 3 mm. This wireless arrangement demonstrates the advantage of the developed sensor technology since it eliminates the need for potentially unreliable, high-temperature contacts on the sensor [6].

Before rotating, the disk was preheated to a temperature of 226°C using an electric heater. Subsequently, the machine was turned on to let the disk rotate and cool down while the temperature was registered using an infrared thermometer gun and the frequency was detected using the portable reader. A series port monitoring software was used to capture the resonant frequency and translate it into temperature information.

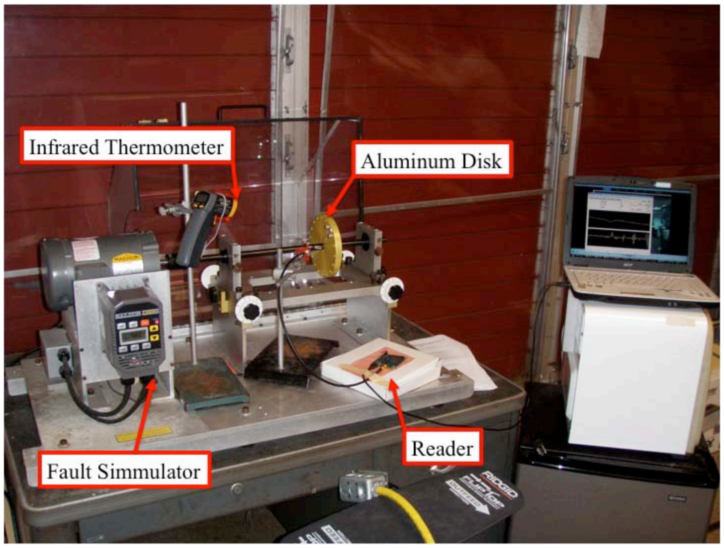

Figure 7. Experimental setup

VI. RESULTS AND DISCUSSIONS

As demonstrated in the simulation presented in Section 4, a periodical sweeping frequency was generated around the sensor's natural frequency. When the reader's frequency matches the sensor's resonant frequency, a sudden increase in the sensor impedance occurs. Figure 8 shows the experimental result of impedance vs. resonant frequency in the experiment.

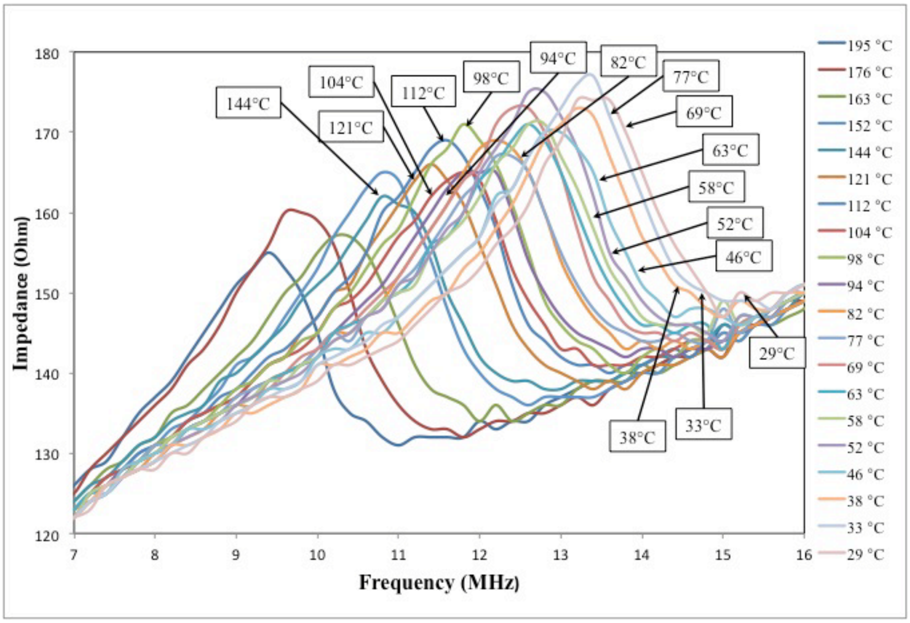

Figure 8. Sensor prototype temperature response; Sensor Impedance vs. Frequency

Since the dielectric properties of the material are temperature dependent, a shift in the sensor's resonant frequency is produced in response to temperature changes. It is noticed that there is a linear pattern in the variation of the frequency in each of the data points. The slight magnitude difference of each peak might be due to misalignments between the centers of both inductive antennas while the disk is rotating. These misalignments may result in a decrease in the coupling factor, which is further determined by the shape of the coils and the angle between them and is dependent on the distance and their relative size [7,8]. A decrease in the coupling factor results in a decrease of the sensor impedance, reflecting peaks with lower magnitudes.

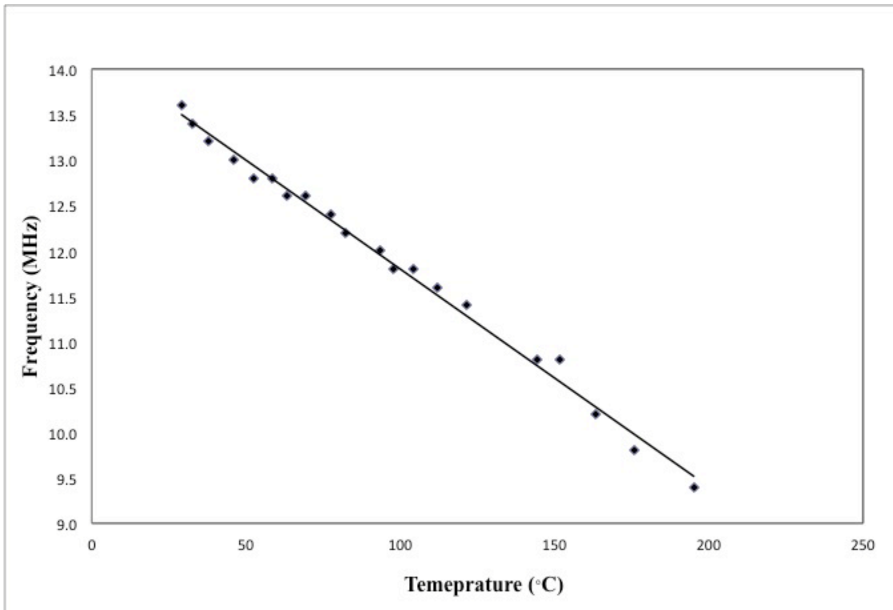

Figure 9. Frequency vs. Temperature Plot

Figure 9 demonstrates the variation of the resonant frequency due to variations in temperature. A linear dependency of the resonant frequency on the temperature is clearly seen. As previously described in Section 3, there is a temperature dependency on the material permittivity, resulting in a change of the capacitance and a shift in the resonant frequency of the sensor. This variation can be captured wirelessly as was done in this experiment. As a result, it is demonstrated that the sensor developed in the project can be used to monitor temperature in rotating components.

VII. CONCLUSION

This paper presents the development of an innovative passive wireless temperature sensor capable of operating in rotating components and harsh environments. The design was based on a RF-powered temperature sensor consisting of a capacitive sensing element and an inductive antenna. The wireless sensor developed for temperature sensing in this study is based on principle of near-field sensing technology and was realized by employing an inductor-capacitor (L-C) tuned electronic oscillator incorporated with temperature sensitive materials. The uniqueness of this device resides in the integration of a temperature sensitive material (PLZT) into the LC tank to measure temperature in rotating components. The sensor operated in harsh environments above the 200°C and captured the signal while attached to a rotating component. This demonstrates the feasibility and concept of a passive wireless temperature sensor interrogating system for rotating components. In order to use this device in a harsh operating environment, as is the case of compressor and turbines, more research must be done to develop a final commercial design. A design for a harsh operating environment will require research in temperature sensitive materials and packaging technologies.

The temperature sensing technology presented in this paper has many advantages such as being wireless and passive and possessing a simple design. Future testing will be carried out in order to optimize and extend the operating temperature range. Further research is also under way to test the effects of the rotating speed on the sensor performance. The current research demonstrates that temperature monitoring can be achieved without requiring physical contact, power supplies, or active elements in the circuit.

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REFERENCES

[1] Woodard, S., Wang, C., and Taylor, B., Wireless temperature sensing using temperature-sensitive dielectrics within responding electric fields of open-circuit Sensors having no electrical Connections, *Meas. Sci.* Technol. 21 (2010) 075201, May 2010.

[2] Surface Acoustic Wave Technology based Temperature Monitoring of Rotating Machine Components, Segenuity Sensor Engine Technology, [cited 2010 August 10] Available from: http://www.sengenuity.com/tech_ref/Using_Wireless_Temp_Sensor_for_Rotating_E

quipment_Applications.pdf

[3] Birdsell, E.D., Park, J., and Allen, M.G., Wireless ceramic sensors operating in high temperature environments, *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Fort Lauderdale, FL, 2004.

[4] Harpster, T.J.; Hauvespre, S.; Dokmeci, M.R.; Najafi, K. A, 2002. Passive humidity monitoring system for in situ remote wireless testing of micropackages. *J. Microelectromech. Syst.vol.11*, 61-67.

[5] Wang Y, Jia Y, Chen Q and Yanyun Wang 2008 A passive wireless temperature sensor for harsh environment applications *Sensors*

[6] Fonseca, M., English, J., Von Arx, M., and Allen, M., Wireless micromachined ceramic pressure sensor for high-temperature applications *J Microelectromechanical Systems Vol 11 No.*4. August 2002.

[7] Hofmaier, R., Maher, G., and Shirn, G., PLZT- A dielectric for high-temperature application *IEE*, 1988.

[8] Waffenschmidt E, Philips Research. “Coupling Factor”. Wireless Power Consortium, [cited 2009 November 3] Available from: http://www.wirelesspowerconsortium.com/technology/coupling-factor.html