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CHARACTERIZATION OF A WIRELESS VACUUM SENSOR PROTOTYPE BASED ON THE SAW PIRANI PRINCIPLE

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KEY WORDS

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ABSTRACT

A prototype of a wireless vacuum microsensor combining the Pirani principle and Surface Acoustic Waves (SAW) with extended range and sensitivity was designed, modeled, manufactured and characterized under different conditions. The main components of the prototype are a sensing SAW chip, a heating coil and an interrogation antenna. All the components are assembled inside a 15 mm by 11 mm by 3 mm Printed Circuit Board (PCB). The behavior of the PCB was characterized at ambient conditions and inside vacuum. The quality of the SAW interrogation signal, the frequency shift and the received current of the coil were measured for different configurations. This allowed to determine the optimal operating conditions of the sensor as well as the integration conditions inside a vacuum chamber.

Background

Many industry and research facilities have part of their process performed under vacuum conditions. Those include semiconductor technology, food industry or aerospace industry. The existence of vacuum installations induces the need for reliable vacuum pressure monitoring.
Vacuum refers to any subatmospheric pressure. This can range from rough vacuum close to atmospheric pressure down to extremely high vacuum around 10^{-10} Pa. Handling such a wide range usually involves several pressure transducers simultaneously integrated inside a chamber. Multiple sensor use in a vacuum chamber raises many issues: integration, maintenance, redundancy, power consumption, wiring and readout, to name but a few. Extending the sensing range using a single miniaturized device operating wirelessly is therefore an attractive alternative opportunity.

The Pirani principle is commonly used to sense pressure in the fine and rough vacuum range. It is based on the heat transfer between a heated sensing element (wire, plate or chip) and its surrounding gas molecules. The heat transfer being proportional to the number of molecules, the temperature variation of the sensor depends therefore on the pressure. Heating is necessary to observe a pressure induced temperature variation.
Surface Acoustic Waves (SAW) propagate on the surface of piezoelectric crystals. An Interdigital Transducer (IDT), which is a set of metallic electrodes etched on the surface of the piezoelectric substrate, converts voltage into waves back and forth. SAW are sensitive to the environment properties.

When a material is heated, it is subject to thermal expansion. Its physical properties such as its elastic, piezoelectric and permittivity coefficients are modified. The variation of those properties is mostly expressed as a Taylor series expansion. The resonance frequency of a SAW IDT can be expressed as:

$$f_r = \frac{\sqrt{C}}{\lambda\sqrt{\rho}}$$

where C is an elastic coefficient of the crystal, ρ is the density of the crystal and λ the wavelength of the SAW which is equal to the fourth of the pitch of the IDT electrodes. At the first order, the sensitivity of the resonance frequency to the temperature around a reference temperature T_0 is expressed by the coefficient TC_{f1} (in ppm/K):

$$\frac{\Delta f}{f_r(T_0)} = TC_{f1}(T - T_0)$$

where T is the temperature and Δf the resonance frequency shift. With this in mind, a miniaturized wireless vacuum sensor with extended range and sensitivity was designed, simulated and a prototype manufactured [1, 2]. The assembly of a prototype entailed challenges linked to the operation of two different electromagnetic waves, the miniaturization of all the components and wireless power transfer in a vacuum environment where most components are in stainless steel. These challenges raised the question of the feasibility of such a solution and its convenience. After manufacturing, assembly issues were addressed, some first characterization tests were performed.

General design

The sensor design consists of a 15 mm by 11 mm by 10 mm polymer box crossed by a 600 µm diameter cylindrical microchannel (Figure 1). The sensing chip is inserted inside the channel and is connected to a heating coil and to an interrogation antenna. Figure 1 shows a schematic of the device. A PCB inside the core of the sensor contains the heating unit and the interrogation unit. The heating unit consists mainly of a coil and its coupled capacitor. The interrogation unit consists mainly of an antenna, its transmission line and its impedance matching components. The sensing chip is connected to the heating and interrogation units via wires crossing the packaging through holes.

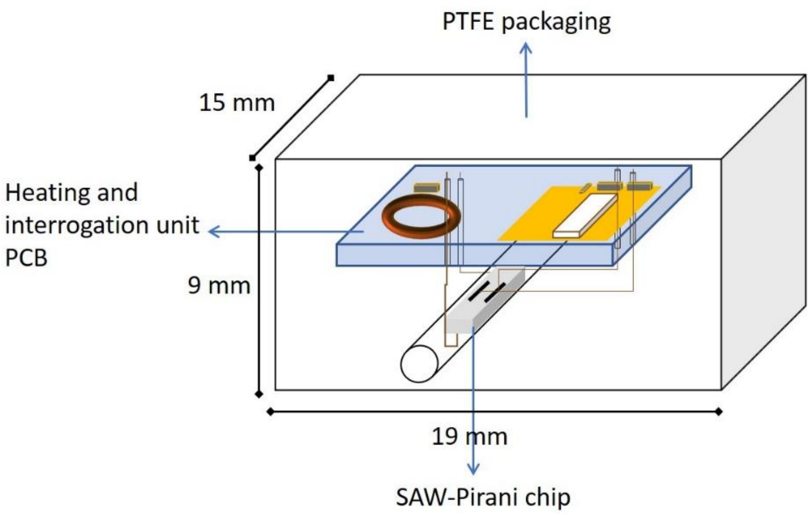

Figure 1: Structure of the sensor designed

Operating mode

The sensor is first inserted into a vacuum environment. The SAW chip inside the microchannel is heated via the Joule resistance, receiving AC current from the coil. The sensing chip will reach an equilibrium temperature after exchanging heat with the surrounding gas molecules. The temperature variation of the chip induces a resonance frequency shift. The interrogation signal is sent to the sensor via the interrogation antenna using a network analyzer. It is a frequency sweep between 2 GHz and 3 GHz. The reflection coefficient S11 values allow to determine the resonance frequency of the chip which depends on the pressure of the gas surrounding the chip. The calibration curve of the resonance frequency vs pressure allows to deduce pressure. Figure 2 shows a schematic of the operating protocol of the sensor.

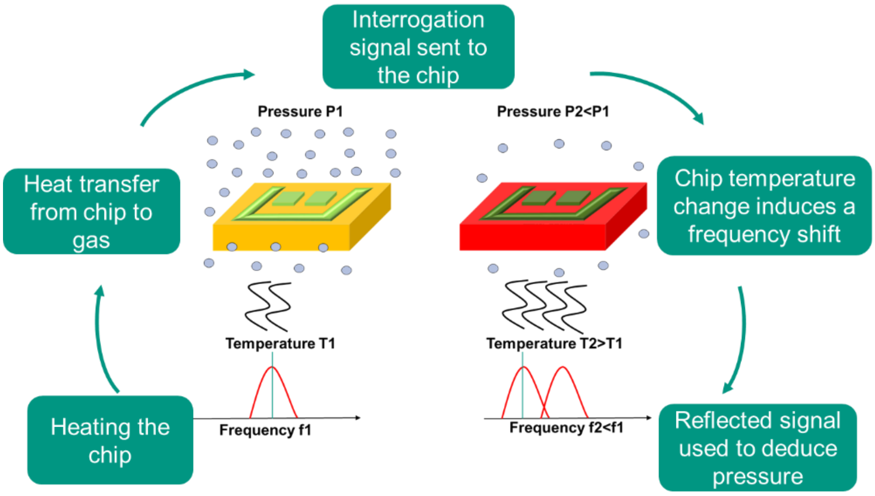

Figure 2: Operating protocol of the sensor

Prototype

The prototype tested consists mainly of a PCB incorporating the sensor components in addition to the external packaging as shown in Figure 3. The PCB contains a heating unit and an interrogation unit connected to the sensing chip.

The Antenna P/N 2450AT18B100 from the company Johanson was selected as interrogation antenna. It operates between 2400 and 2500 MHz and has dimensions of 3.2 mm by 1.6 mm by 1.3 mm and a return loss of -18 dB at resonance. The WE-WPCC 760308101216 wireless power charging receiver coil manufactured by Wuerth Elektronik was chosen. It can be powered from a distance of up to 2 cm and delivers power of up to 0.11 W. It has a diameter of 6 mm and a height of 2 mm. The sensing chip is the SS2452BB2 from the SAW Components company. The coil is connected to a 220 nF capacitor in parallel. The antenna needs a 3.3 nH inductor, a 2.7 nH and a 1.2 pF capacitor to be coupled as well as a no ground surface of 6.5 mm by 6.5 mm and a 50 Ohm transmission line to the sensing chip.

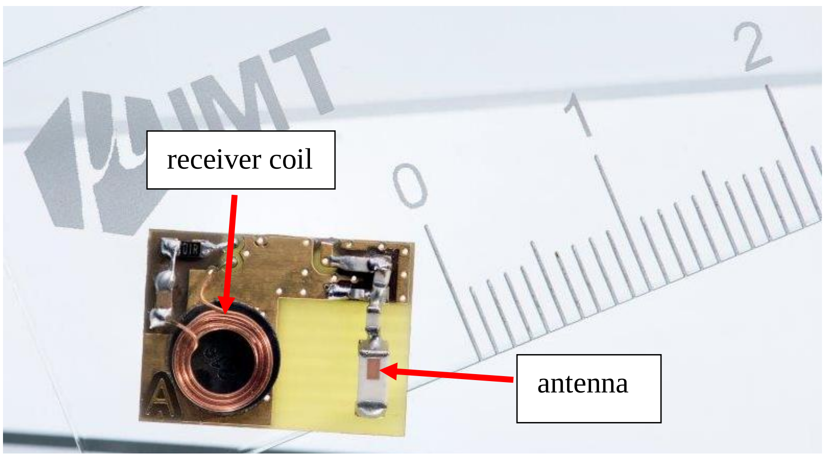

Figure 3: PCB of the sensor

Characterization tests

The first characterization tests were performed on each component separately. An inductive power transfer circuit was prepared for the coil to ensure sufficient power reception to the chip. Since the coupling distance is a critical parameter of the sensor, the current received by the coil was measured for different distances between the Tx coil and the Rx coil. Results are shown in Figure 4.

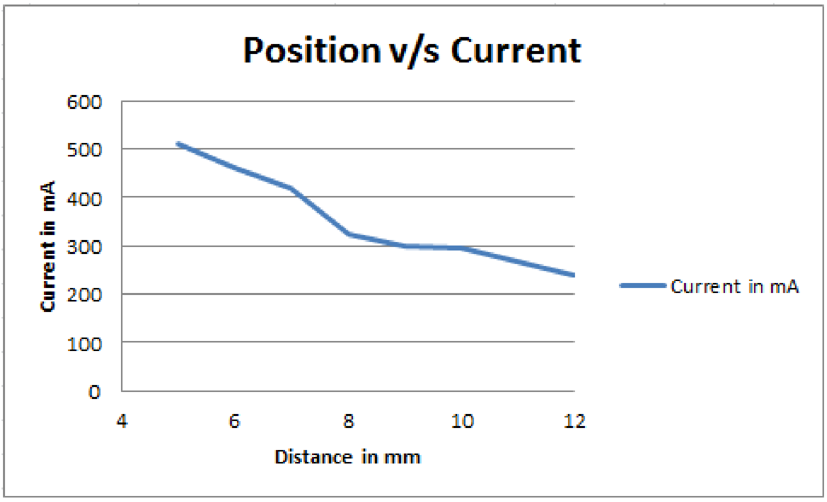

Figure 4: Current received at the coil

SAW signal

After the heating unit was characterized at ambient conditions, the interrogation unit was also characterized. The role of the interrogation unit is to identify the frequency of the SAW peak that is related to the temperature and the pressure. The SAW chip interrogation was performed every 5 minutes. However, the quality of the signal received from the interrogation unit is very sensitive to the measurement conditions. For this reason, different setup were tested in order to obtain the SAW signal with the best quality. The most sensitive parameters for the SAW signal quality are the interrogation distance and the nature of the material separating the interrogating and receiving antenna.
In practice, the material separating both antennas is a vacuum window that facilitates the operation of the sensor. Figure 5 shows the SAW peak signal obtained for a Quartz window and a PMMA window. The SAW peak is sharper and easier to detect through a PMMA window. The local variation of the S11 amplitude is on the range of 1 dB in the left graph and in the range of 5 dB in the right graph which makes it sharper.

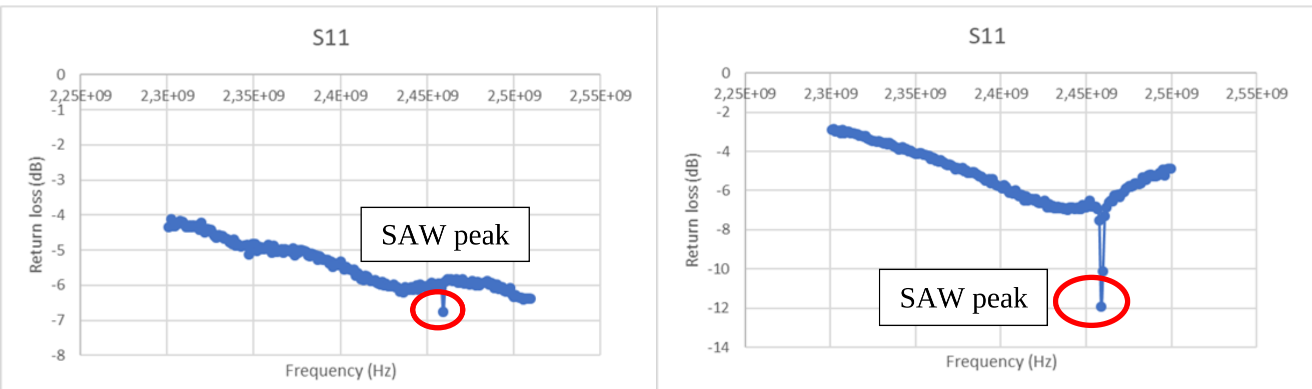

Figure 5: SAW peak measured through a Quartz window (left) and SAW peak measured through a PMMA window (right)

Conclusion:

The sensor was tested at ambient conditions and is being tested under vacuum which will lead to the sensor calibration curve. The measurement signal is very sensitive to the ambient conditions and materials. The interrogation distance as well as the vacuum window material are the most sensitive parameters. The material between the transmitting and receiving unit raises vacuum integration concerns since the windows are usually in quartz, the interrogation distance questions the feasibility of the miniaturization since the easiest way to increase the interrogation distance is to use a bigger receiver antenna. The optimal operation mode still needs to be determined. A frequency sweep between 2.4 GHz and 2.5 GHz may be sufficient and grant higher accuracy.

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