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Wireless Pressure Sensing Based on Metamaterials Fabricated on PDMS Substrate

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Abstract

Pressure sensors are highly demanded across various application fields, each requiring specific types of pressure sensors tailored to their unique scenarios. In this study, we introduce an innovative passive wireless pressure sensor. This sensor features a sandwich structure, with the upper layer comprising a frequency-selective surface (FSS) adhered to a Polydimethylsiloxane (PDMS) layer supported by a ground plane. Applying pressure to the sensor induces compression in the PDMS substrate, leading to changes not only in thickness but also in relative dielectric permittivity. Consequently, this compression results in a shift in the resonance peak.

1 Introduction

Pressure, defined as the force acting on an area, stands as one of the most frequently measured physical quantities. Pressure sensors play a crucial role in converting this physical quantity into an electrical signal and find applications in diverse fields such as the automotive industry, aerospace, soft robotics, and health monitoring [1, 2, 3]. These sensors can be categorized into resistive, capacitive, and triboelectric types [4]. In capacitive pressure sensors, variations in capacitance occur as a result of compression, stemming from changes in the distance between the two electrodes. Despite their high sensitivity and low power consumption, capacitive sensors are notably sensitive to noise. In resistive pressure sensors, an alteration in electrical resistance accompanies the application of pressure, where an increase in pressure leads to a decrease in resistance. While resistive sensors exhibit higher power consumption and lower sensitivity, they boast longer life and a broader detection range than their capacitive counterparts. Triboelectric pressure sensors generate voltage when pressure is applied, owing to the separation between the dipoles constituting the material. Notably, these sensors operate without the need for an external power source. An essential characteristic sought in pressure sensors is wireless connectivity, especially in scenarios where installing wired sensors proves challenging[5]. While a standard configuration involves connecting the sensor to a transceiver module, this setup is power-intensive and requires an electronic board and a battery. In contrast, a passive sensing configuration offers a more compact and environmentally friendly design. Passive wireless sensors are advantageous in applications where the device must endure high temperatures [6]. In [7] a wireless pressure sensor was proposed which is based on the combination of a periodic surface and a superstrate. The application of pressure determines a shift of the resonance peak due to a change in effective permittivity. A material widely used in the production of pressure sensors due to its excellent properties is polydimethylsiloxane (PDMS) [8, 9]. In [10] PDMS is used as a dielectric layer in an LC passive pressure sensor. The application of pressure involves a change in the capacitance of the system and therefore a shift in the resonance peak. A similar mechanism can be observed in [11]. Here a mixture of graphene and PDMS is used as a dielectric substrate. The application of pressure causes a shift of the healing peak towards low frequencies. The aim of this work is to employ PDMS substrate to engineer a passive and wireless pressure sensor. The sensors, contrarily to the usual configurations based on wired readout, can be read from distances of tens of centimeters using a couple of antennas. The structure comprises a simple sandwich design with a thin PDMS layer separating a metallic bottom layer and a frequency-selective surface, forming a Fabry-Perot resonator. The structure exhibits a deep absorption peak at the resonance frequency, and the application of pressure leads to the compression and thickness variation of the PDMS film, causing a shift in the resonance peak. In section II, the layout of the proposed pressure sensor and its operating principle related to the characteristics of the PDMS are shown. In section III, some preliminary experimental results are shown. Section IV presents the conclusions.

2 Operative Principle of the Proposed Pressure Sensor

The proposed pressure sensor was designed to operate around 20 GHz. It comprises a periodic surface printed on a thin kapton substrate with thickness t_1= 0.05 mm; the periodic surface is composed of a single dipole with length l=4 mm. The dipoles are repeated in a periodic lattice characterized by a periodicity d of 5 mm. A thin layer of PDMS with a thickness t_2= 0.5 mm is placed in contact with the periodic surface and on the opposite side there is a metallic layer. A schematic view of the proposed pressure sensor is shown in Fig.1.

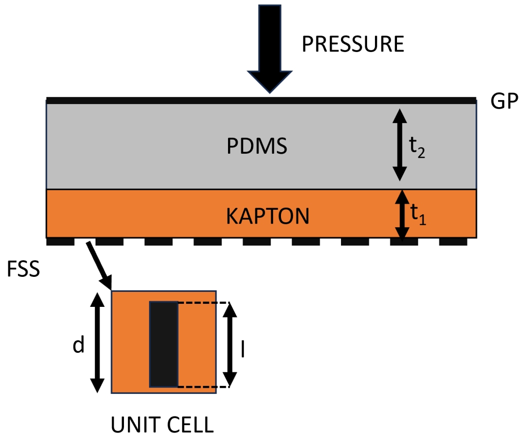

Figure 1. Lateral view of the proposed pressure sensor with the top view of the unit cell of the FSS.

2.1 Characterization of PDMS Material

PDMS is an elastomeric polymer with excellent characteristics such as flexibility, biocompatibility and mechanical properties. When pressure is applied on the PDMS there is a variation of its thickness which determines a shift of the resonance peak. A thickness reduction is expected to determine a shift towards higher frequencies of the resonance. However, at the same time, the compression determines an increase in permittivity which on the contrary induces a shift of the peak towards low frequencies. The combination of the two effects results in a shift of the resonance peak which allows us to measure the pressure. However, whether the resonance peak shifts towards high or low frequencies depends on which of the two effects predominates. In order to understand the behavior of the sensor based on the PDMS substrate it is necessary to understand the relationship between the variation in thickness and the variation in permittivity. To study this relationship it is possible to start from the Debye model of the PDMS and study how the permittivity varies as the thickness varies [12]. For simplicity we consider variations that occur in only one direction. Starting from the Debye model, the real part of the complex permittivity can be write as:

$$\varepsilon'(\omega) = \varepsilon_{\omega\to\infty} + \frac{\mu^2 N_A \rho}{3\varepsilon_0 k_B T M (1+\omega^2\tau^2)} \tag{1}$$

where NA is the Avogadro's number equal to $6.02 \times 10^{23} mol^{-1}$, K_B is the Boltzmann's constant equal to 1.38×10^{-23} J/K. T is the temperature in Kelvin and it is considered equal to 298 K, M is the molar mass ($7.04 \times 10^{-2} g \times mol^{-1}$) and ρ is the density assumed equal to that of water ($1000 Kg \times m^3$). μ is the permanent electric dipole moment and its value can be determined by knowing $\varepsilon_{\omega\to\infty}$ and $\varepsilon_{\omega\to 0}$ from the PDMS Debye model.

First of all, it should be considered that if subjected to compression, the density of PDMS increases according to the relationship:

$$\rho = \frac{\rho_0}{1 \pm \eta} \tag{2}$$

with $\eta = \frac{t_2 - t_{2c}}{t_2}$ where t_2 is the initial thickness of the PDMS and t_2c is the thickness after the compression.

Considering a variation along the z axis also μ and τ vary as follows:

$$\mu_{zz,\eta} = \mu_0 \pm k_1 \eta \tag{3}$$

$$\tau_{zz,\eta} = \tau_0 \pm k_3 \eta \tag{4}$$

with k_1=3.16×10^{-30}; and k_2=2.83×10^{-12}. Combining (1),(2),(3),(4) we obtain an expression of the dielectric permittivity as a function of the mechanical deformation:

$$\begin{aligned}\varepsilon'_{zz,\eta}(\omega) =& \varepsilon_{zz,\eta,\omega\to 0} - \frac{(\mu_0 \pm k_3\eta)^2 N_A [\rho_0/(1\pm\eta)}{3\varepsilon_0 k_B T M} \\ &+ \frac{(\mu_0 \pm k_3\eta)^2 N_A [\rho_0/(1\pm\eta)]}{3\varepsilon_0 k_B T M \left[1+\omega^2(\tau_0 \pm k_4\eta)^2\right]}\end{aligned} \tag{5}$$

In Fig.2 we observe that, considering a maximum deformation of 50 %, there is an increase in the dielectric permittivity of the material due to the increase in density that the material undergoes when it is compressed.

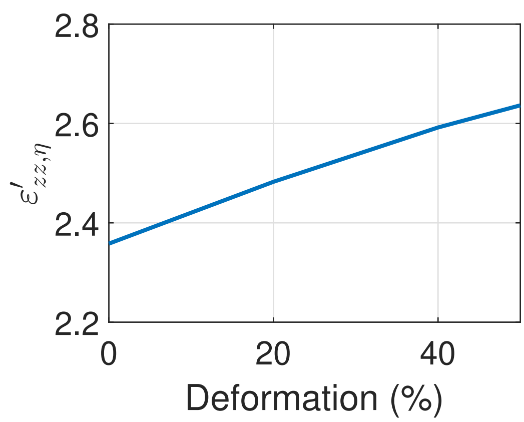

Figure 2. Relation between the permittivity and the deformation for PDMS material.

2.2 Numerical Results

Once the relationship between the permittivity and the thickness variation of the PDMS is known, it is possible to carry out numerical simulations to understand the behavior of the sensor. Numerical electromagnetic simulations were performed with CST software. In the simulations, a single unit cell is considered and periodic boundary conditions are used. A parametric simulation is carried out by varying both the permittivity of the PDMS and the thickness, in accordance with what was obtained from (5). From Fig.3 we can observe that, considering both the PDMS thickness reduction and its increase in dielectric permittivity, a shift of the resonance peak towards low frequencies is expected. In the simulations, it is hypothesized that the thickness of PDMS changes from a thickness 0.5 mm which corresponds to a permittivity of 2.36 to a thickness of 0.3 mm which corresponds to a permittivity of 2.59. The observed frequency shift is of 0.5 GHz. Without considering the two effects simultaneously, an upward shift would have been observed with thickness compression and a downward shift with the dielectric permittivity increase. We can summarize that the effect of increased permittivity seems to be predominant over the thickness compression effect. The reason is relies not only in the effect of the substrate but also in the FSS capacitance increase induced by the increased dielectric permittivity [13]. It is also observed that while the absorption peak moves towards lower frequencies its deepness increases showing a higher absorption. This effect is due to the increased regime where the resonator operates. Indeed, resonators cannot be considered alone but must always be considered with the external circuit. Considering the resonator employed to synthesize the sensor as a parallel RLC circuit, its quality factor Q_0 can be defined as:

$$Q_0 = \frac{R}{\omega_0 L} \tag{6}$$

where R and L represnts the parallel resistance and the equivalent indcutance of the resonator and ω_0 its resonant frequency. On the other hand the external quality factor Q_{ext} can be defined as:

$$Q_{ext} = \frac{Z_0}{\omega_0 L} \tag{7}$$

where Z_0 represents the free space impedance. As a consequence, the coupling coefficient can be defined as:

$$g = \frac{Q_0}{Q_{ext}} = \frac{R}{Z_0} \tag{8}$$

A resonator can operate in three distinct configurations depending on the value of the coupling coefficient [14]. If g=1 the resonator is critically coupled. This behaviour can be easily recognized as the absorption peak presents a sharp deep. If g<1 the resonator is under coupled and if g>1 the resonator is over coupled. In the simulated configuration the resonator is in the undercoupling regime when uncompressed. However, with compression, its behaviour moves towards critical coupling condition as because of the increase of the equivalent resistance. If further compression is applied, it is expected that the resonator can more in overcoupling regime ($R > Z_0$). This is not desirable since the sensor could operate in an ambiguos manner [15].

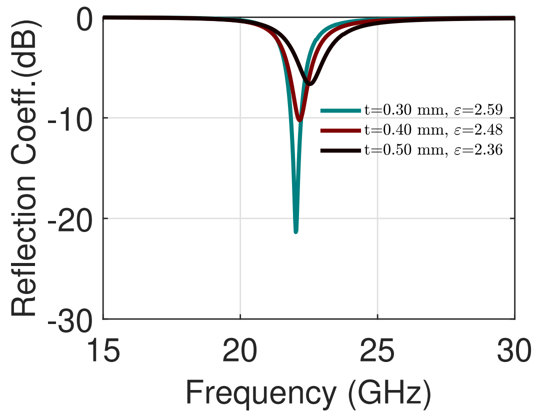

Figure 3. Reflection coefficient of the sensor as function of the PDMS compression obtained from CST simulations. Both the dielectric permittivity and thickness variations are considered.

3 Experimental Results

To assess the practical viability of the wireless sensor, preliminary experimental measurements have been carried out. The FSS surface was etched by using a standard photolithographic technique on a thin kapton substrate. This surface was then placed on top of a PDMS substrate created by blending two agents. A thin PDMS layer with a thickness of 0.50 mm has been fabricated. A layer of metal was applied to the back side of the PDMS to provide structural backing via the metal ground plane. Two commercial WR42 horn antennas, operating between 18 and 26.5 GHz, have been connected to a Vector Network Analyzer(VNA) and used to read the sensor wirelessly. To apply pressure in a controlled and repeatable manner, an ad hoc measurement setup was engineered. The sensor is placed on a polystyrene table which does not interfere with the measurements as it has a permittivity close to that of air. To apply pressure, a plastic tube is placed on the sensor and filled with water. The relationship between the amount of water in the pipe and the pressure is as follows:

$$P = \frac{F}{A} = \frac{mg}{A} \tag{9}$$

where m is the amount of water in kg; $g = 9.81$ m/s^2 is the gravitational aceleration and A is the area of the tag in m^2 in this case equal to 3×3 cm^2.

The results of the experimental measurements are shown in Fig.4. It is observed that as the quantity of water inserted into the tube increases, therefore as the pressure applied on the sensor in kPa increases, a shift of the resonance peak towards low frequencies is observed in agreement with what was simulated.

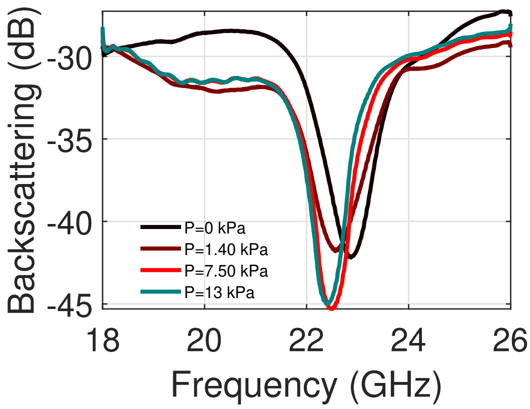

Figure 4. Measured backscattering as a results of the applied pressure in kPa.

4 Conclusion

A novel wireless pressure sensor configuration has been proposed. The sensor does not require the use of electronic components and batteries. The proposed sensor exploits the combination of a periodic surface and a thin layer of PDMS, a highly compressible material used for making sensors. The application of pressure on the sensor determines a variation in thickness and permittivity of the PDMS which in turn determines a shift in the resonance peak of the periodic surface. By analyzing the variation of the resonance peak it is possible to trace the applied pressure.

5 Acknowledgements

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