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PERFORMANCE ANALYSIS OF A FLEXIBLE POLYIMIDE BASED DEVICE FOR DISPLACEMENT SENSING

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Abstract. *In this work, two variations of the displacement sensor, based on the heterogeneous integration process of traditional fabrication technologies PCB (Printed Circuit Board) and LTCC (Low Temperature Co-fired Technology) with a flexible polyimide foil are presented. The proposed sensor uses the coil as an essential part, spacer and a polyimide foil as a flexible membrane with a piece of ferrite attached to it. With the displacement of the polyimide foil, the ferrite gets closer to the coil causing an increase in its inductance and a decrease of the resonant frequency of the system (coil, ferrite and antenna). Simulation results showed that sensors with equal outer dimensions but different internal structures exhibit different performances. Two prototypes of the sensor with different ferrite dimensions are designed, fabricated and characterized. Finally, their performances are compared.*

Key words: *Displacement measurement, wireless sensor, heterogeneous integration*

1. INTRODUCTION

Displacement measurement is of a profound importance in a wide range of applications, such as industrial systems, portable electronic devices, robots, biomedical devices, intelligent instruments, performance evaluation, etc. The high demand for displacement sensors is due to their application for measuring the position and movement of objects, for nondestructive evaluation of deformation, alignment and calibration of position as well as measuring other physical quantities which can first be converted into movement such as pressure, force, acceleration, etc.

Different types of displacement measuring methods and sensors have been developed: eddy-current, optical, resistive, capacitive, inductive, etc. Eddy current sensors are resistant to dirt, dust, humidity, oil or dielectric material in the measuring gap and have been proven reliable in a wide range of temperatures. However, non-contact eddy current sensors have one problem, inhomogeneity (electrical run out) that affects their accuracy

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and applications [1]. Optical, as well as Michelsons interferometers, are one of the popular displacement measurement methods because of their high precision [2, 3]. These sensors are very sensitive to environmental perturbations and suffer from deterioration of signal to noise ratio and disappearance of the desired signal and deviations in the optical path length. Interferometers which are based on the fringe counting method have high resolution and stability, but their precision is dependent on the wavelength of the light [4]. They are bulky and quite expensive due to their sophisticated structure and their working performance is easily affected by the environment.

Displacement sensors with giant magnetoresistance (GMR) elements have their position resolution limited by excessively low signal to noise ratio [5]. Capacitive sensors are the best regarding accuracy/resolution and the applicability for small targets. They show a fringe effect around the edge of the patterned electrode and drift in the signal caused by various parameters, such as thermal effect, stage coupling, random wave noise, external electric waves, etc. which is hard to control [6-9]. In order to improve signal conditioning and effective noise reduction for better accuracy and resolution, complex electronic circuits are needed [10-12]. Inductive displacement sensors with complex structures of two sensor elements are presented in [13].

Piezoresistive sensors are important and widely utilized class of devices in mechanical sensing. Displacement or force sensors with sidewall embedded piezoresistors, piezoresistive microcantilevers and self-detection onboard electronic systems are designed and manufactured [14, 15]. A piezoresistive cantilever based on both the lateral and the vertical bending for two-dimensional detection is presented [16]. In [17] is proposed the sensor based on a seal cavity made by sacrificial layer, a deposition of polysilicon nanofilm acts as piezoresistors on the diaphragm.

There is an increasingly wide interest in polymeric foils and their application in the field of sensor technology. The various types of sensors applying polymeric foils can be realized for different purposes and unique possibilities. Flexible polymeric foils offer a lot of advantages in making sensors: they are very low-cost, thin, large area, lightweight, flexible, conformable, transparent, wearable, foldable, stretchable and produced on a large scale. Polymer substrates are very flexible and can be bended in a very small radius of curvature. Most previous sensors are silicon-based which is rigid for flexible, bendable applications and to cover continuous, contoured, conformal surfaces. In order to achieve mechanical sensors which can fulfill that application and can sustain sudden impact or large deformation, flexible substrates can be used.

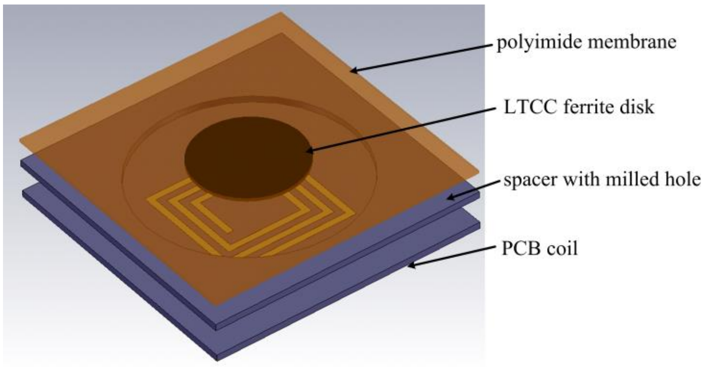
In order to develop strain sensors and multiplexed arrays with good performances, but lightweight construction, mechanical flexibility and robustness, sensors which combined silicon sensing elements and thin plastic substrates are developed [18]. Different types of sensors for mechanical sensing with flexible substrates of various polymer-based materials, such as polyester, parylene, polyimide (PI) or polydimethylsiloxane (PDMS) were proposed [19-25]. Presented sensors are used for sensing the tactile, bending, interface pressure between implanted cuff and nerve tissue, normal and shear loads, application to robotics, medicine and industry. An overall mechanical flexibility, elasticity and biocompatibility of the sensor are obtained by integrating polymeric substrates.

One of the simplest sensor structures having a coil and a ferrite object in close proximity have been reported for monitoring changing environmental parameters such as pressure, displacement and force [26-28].

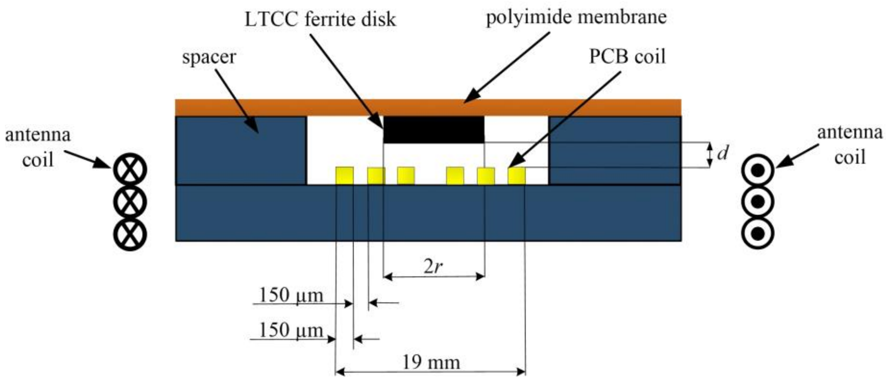
In our previous paper [29], an inductive displacement sensor in discrete technology was presented. Traditional fabrication techniques, PCB (Printed Circuit Board) and LTCC (Low Temperature Co-fired Technology), are combined with a polyimide foil to create a displacement sensing structure. Presented sensor uses non-contact wireless displacement measurement so it does not require proper, smooth, good contacts, vias and metal lines on the coil, which can deforms the coil structure and yield to the parasitic elements which should be eliminated from the actual parameters. Commercially available polyimide is used as a membrane so the complex fabrication process that includes photolithography, spinning, curing and etching for membrane fabrication is avoided. The sensor utilizes the variation of the coil's inductance and accordingly the shift of the resonant frequency of the antenna-sensor system to detect the desired parameter - displacement. In this work, two variations of the sensor with different ferrite dimensions are designed and examined, in order to investigate their performance. Such wireless displacement sensors applying the heterogeneous integration process are fabricated and tested. Finally, their performances are compared.

2. Design of Displacement Sensor with Polyimide Membrane

The integrated displacement sensor consists of a coil, a small cylindrical ferrite plate, a suitable spacer and finally a flexible membrane. The exploded 3D view of the sensor and its cross section and an antenna coil are presented in Fig. 1. The manufacturing process of the sensor consists of two stages, the fabrication of the components and the packing process. PCB technology is used for the coil fabrication because PCB circuits are planar, easy to mount, reliable and cheap. The coil is designed as a square spiral type with outer dimensions of 19 mm, 25 turns, and conductive lines width and distance between the lines both equal to 150 µm. As the membrane, a polyimide foil of 125 µm thickness and Young's modulus of 3 GPa [30] is used. Polyimide substrate shows elastic-plastic behavior and tends to creep so may exhibit parametric drift, but it can take large strains before fracture and has an elastic modulus smaller by nearly a factor of 70 compared with the silicon and the metal foils [31, 32]. For used polyimide foil, considerable smaller load is needed for the same deflection compared with other membranes. The ferrite disk consists of 12 layers of LTCC ferrite tape (ESL 40012, thickness of green tape: ~70 µm) sintered at 1100 °C in order to achieve the highest permeability [33]. The thickness of the ferrite disk after sintering is 0.66 mm. Several PCB FR4 plates of different types and thicknesses (with overall thickness of 2.6 mm and a milled hole of a 16 mm radius in the center) are used as a spacer, in order to provide spacing of 1.2 mm between the ferrite and the coil (since the thickness of the membrane, the ferrite and the glue is 1.4 mm).



a)



b)

Fig. 1 a) Exploded 3D view of the sensor and b) cross section of the sensor and the antenna coil

3. Calculation of a Sensing Mechanism

The resonant frequency of the coil can be expressed as

$$f_0 = \frac{1}{2\pi\sqrt{L_s C_s}}\,, \tag{1}$$

where L_s and C_s are the inductance and capacitance of the sensor coil, respectively. It can be seen that any variation in the coil inductance changes the resonant frequency.

Displacement can be detected in a simple and precise way without additional mechanical contact on the sensor. Wireless measurements of the sensor regard the readout of the changes of the resonant frequency of the sensor-antenna system. Measurements are done using an external surrounding coil–antenna. The equivalent circuit model of the sensor-antenna system is presented in Fig. 2. The impedance of the sensor-antenna system can be determined as [34]

$$Z(\omega) = R_a + j\omega L_a + \frac{(\omega M)^2}{R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)}, \tag{2}$$

where L_a and R_a represent the inductance and resistance of the antenna, respectively, R_s is resistance of the sensor coil, and M is the mutual inductance between the antenna coil and the sensor coil. The magnitude of the impedance's phase dip at the resonant frequency ω_0 is

$$\Delta\varphi \cong \tan^{-1}\left(\frac{k^2 \omega_0 L_s}{R_s}\right), \tag{3}$$

where k is the coupling coefficient of the antenna coil and the sensor coil. Using Wheeler's method [35], the inductance of the sensor coil is calculated, L_s = 7.8 μH.

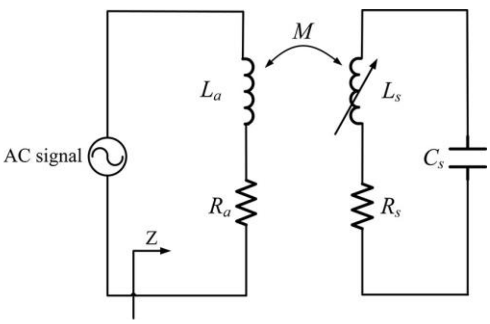


Fig. 2 The equivalent circuit model of the sensor-antenna system

A planar magnetic structure in close proximity to the coil yields high enhancement of the inductance values. In order to investigate in which manner dimensions of the ferrite influence the sensor coil inductance, simulations of the inductance for different ferrite dimensions and distances from the coil are performed using CST (Computer Simulation Technology) Microwave Studio [36]. The simulated inductance of the coil for different ferrite radii (r = 6 mm and r = 9.5 mm) and distances between the ferrite and the coil, d, is presented in Fig. 3. As can be seen, a larger ferrite yields higher inductance value and higher inductance change rate with distance (2.07 μH) compared to the smaller ferrite (0.66 μH) as the consequence of greater intersects of the magnetic field between the coil and the ferrite.

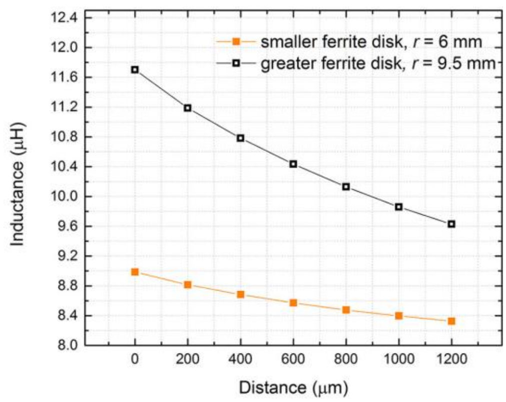


Fig. 3 Simulated inductance changes for different ferrite radii and distances between the ferrite and the coil

4. EXPERIMENTAL RESULTS AND DISCUSSION

The measurement setup is shown in Fig. 4. The fabricated sensor is mounted and sealed on a test fixture and an antenna coil is placed around the sensor. A MTS (Manual Translation Stage) is positioned exactly above the sensor membrane to precisely control the polyimide membrane deflection by direct contact to the sensor. The antenna is connected to the Impedance Analyzer HP4191A and the amplitude of the impedance and phase dip of the system (antenna-sensor) are measured.

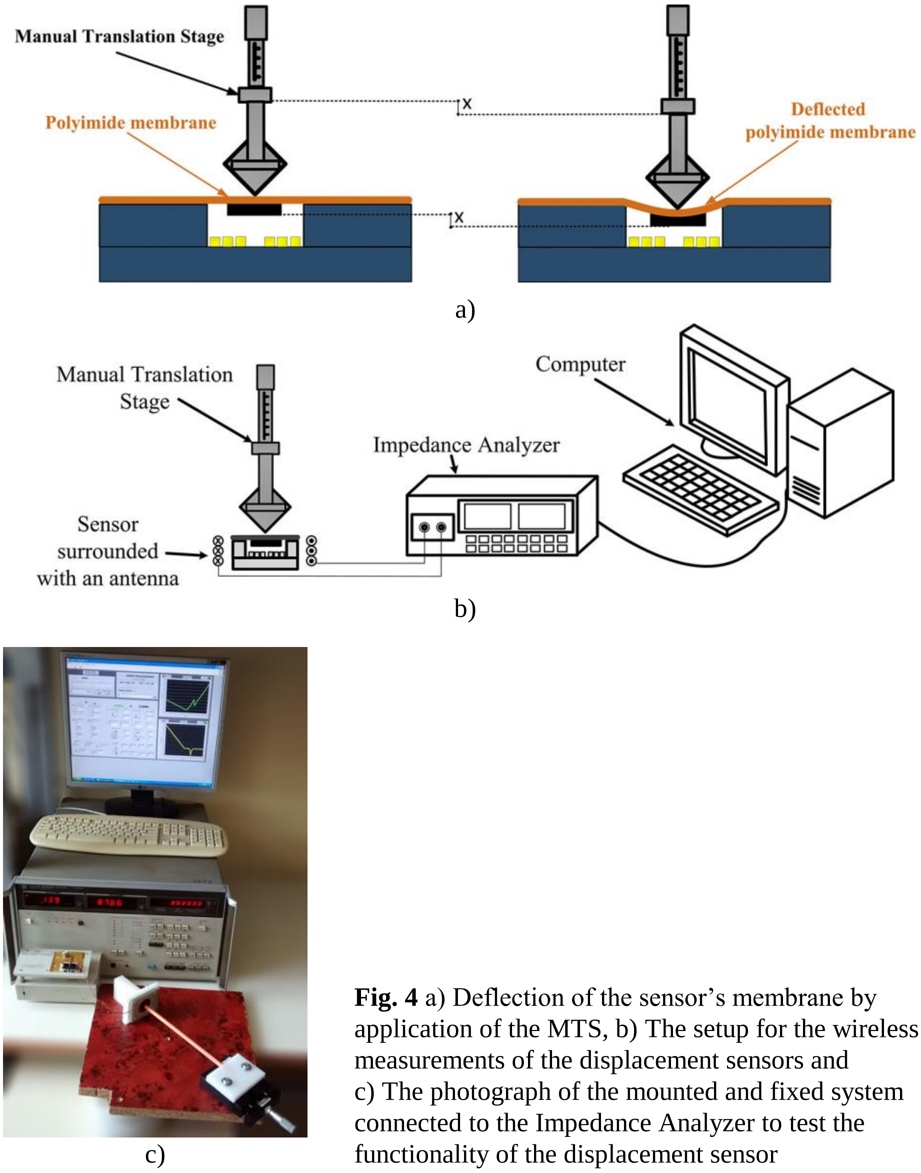


Fig. 4 a) Deflection of the sensor's membrane by application of the MTS, b) The setup for the wireless measurements of the displacement sensors and c) The photograph of the mounted and fixed system connected to the Impedance Analyzer to test the functionality of the displacement sensor

The measured phase shift without any displacement of the membrane for two different ferrite dimensions is shown in Fig. 5. To wirelessly measure resonant frequency of the sensor, the resonant frequency of the antenna should be far enough from the sensor's resonant frequency. The sensor with the smaller ferrite has smaller inductance value, and consequently resonant frequency of the system I (sensor coil, smaller ferrite r = 6 mm, antenna) is higher compared to the resonant frequency of the system II (sensor coil, larger ferrite r = 9.5 mm, antenna) - 71.7 MHz vs. 64.7 MHz, respectively. A square spiral winding is used as the antenna with a resonant frequency of 145 MHz, which is sufficiently far away from measured resonant frequencies of both sensor systems.

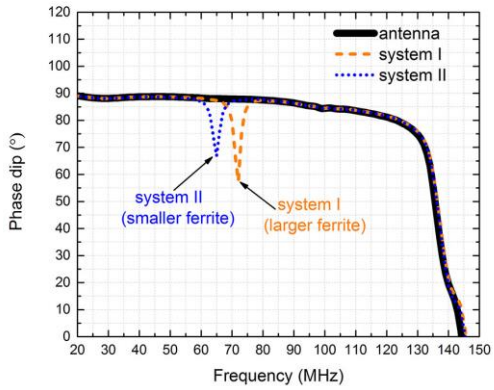


Fig. 5 Measured phase of the impedance of the antenna and the systems with two different ferrites

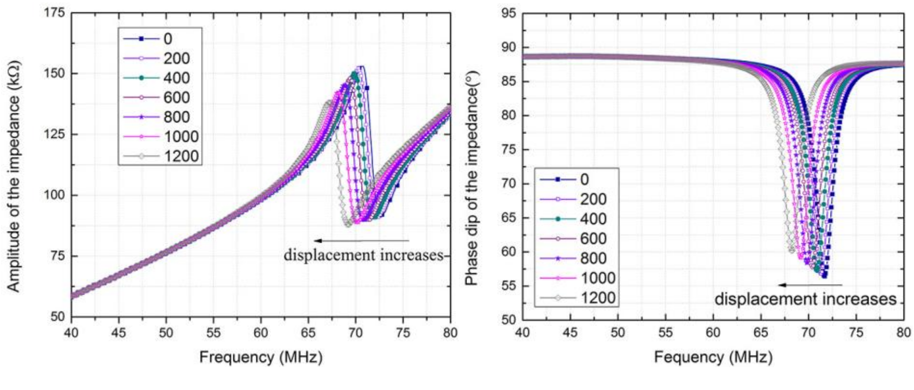


Fig. 6 Wirelessly monitored changes of the amplitude and the phase dip of the impedance of the system I (smaller ferrite) for different displacement (in μm)

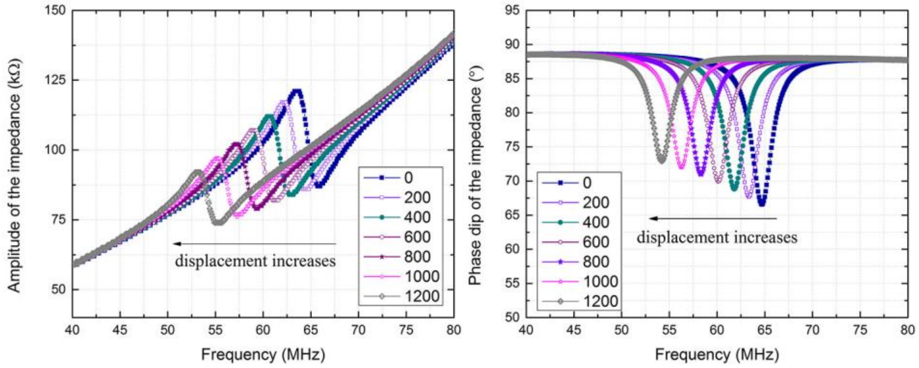


Fig. 7 Wirelessly monitored changes of the amplitude and the phase dip of the impedance of the system II (larger ferrite) for different displacements (in μm)

The measured data for two investigated systems are shown in Figs 6 and 7. Resonant frequencies are determined from the minimum point of the phase dip for displacement variations up to 1.2 mm. The higher the displacement, the closer the ferrite core is to the sensor coil, causing the increase in the inductance and consequently decreasing the resonant frequency. Resonant frequency characteristics of both systems are shown in Fig. 8. In the measurable displacement range, change of the resonant frequency of the system II (with the larger ferrite) is 10.5 MHz and sensitivity is 8.75 kHz/μm. Compared to the System II, measured change of the resonant frequency and sensitivity of the System I (with the smaller ferrite) are smaller (3.5 MHz and 2.92 kHz/μm, respectively). An increase in the overlapping area between the coil and the ferrite, results in greater change in the inductance, hence the greater decrease in the system's resonant frequency.

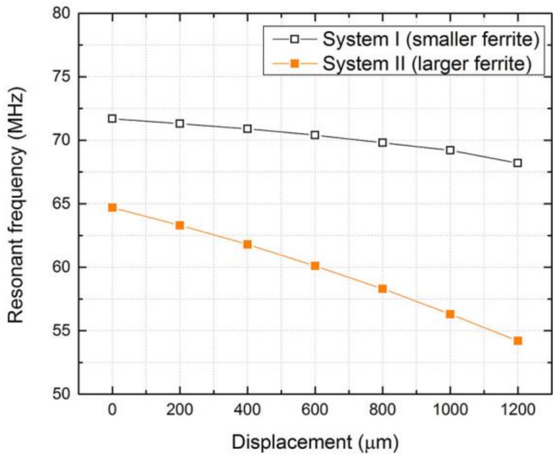


Fig. 8 Resonant frequency characteristics of systems with two different ferrite radii

5. CONCLUSION

In our previous work [29], application of polyimide foil as a membrane in displacement sensor was investigated. The principle of operation of the presented sensor is based on the deflection of a membrane, hence approaching the ferrite closer to the sensor coil and the subsequent measurement of the phase-dip of the sensor-antenna system.

Using sensor structures with the same outer dimensions but larger ferrites yields a 3 times greater change in the resonant frequency (10.5 MHz vs. 3.5 MHz) and sensitivity (8.75 kHz/μm vs. 2.92 kHz/μm) of the system for the same amount of displacement. Therefore, in order to enhance the performance of the sensor, the dimensions of the coil and the ferrite have to be appropriately selected.

Future work will be directed towards optimization of the coil layouts and the development of new designs with different technologies in order to fabricate sensors with the coil fabricated on the membrane.

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