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TOWARD SMART COMPOSITES FOR STRUCTURAL HEALTH MONITORING VIA HIGHLY SENSITIVE CAPACITIVE WIRELESS SENSOR

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Abstract.
Embedded sensors are one of the most effective and accurate methods for monitoring large structures. Composite structures such as pipelines, tanks, aircraft, ships, and ground vehicles confront some challenges with embedding strain sensing systems incorporating strain gauges or optical fibers that can introduce delamination, cracking, and structural failure of the host in addition to the need for dedicated and expensive equipment. RFID sensing technology has been used to enable wireless data and power transmission while addressing issues related to host/composite material integrity and high sensing sensitivity. A flexible sensor based on LC circuit has been developed where the capacitance is acting as a sensing unit. Nanocracks have been introduced into parallel electrodes to create an intense piezoresistivity effect. That leads to a transmission line behavior of the capacitive component. This unconventional change in the capacitance of the LC oscillator allows a large shift in resonance frequency of the flexible circuit, producing a sensitive wireless strain sensor with a Gauge factor of 50 for less than 1% strain. An external read-out coil has been used to read the shifting in resonance frequency due to applied strain. The sensor has been integrated with composite materials to detect the small strain that occurred due to structural degradation. The experimental results show the ability of our cracked wireless strain sensor to detect small strain signals through the composites structure with high accuracy. The developed sensor is intended to be a part of a wireless sensor network (WSN) for monitoring large composites structures.

Key words: Capacitive sensor, Piezoresistivity, SHM, Wireless, RFID

1 INTRODUCTION

Structural health monitoring (SHM) is the process of sensing, collecting, and analyzing data from a structure on a regular basis to determine its condition over time [2, 3, 4]. Nowadays, SHM is being used in various applications such as bridges [5], pipes [6], aircraft [7], and marine structures [8] as a non-intrusive monitoring technique to facilitate condition-based preventive

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maintenance. Monitoring composite structures during operations is critical for detecting critical events and severe degradation. Many techniques can be used to monitor composite structures such as acoustic emissions, eddy current, ultrasonic, infrared thermography, and optical testing. [9, 10, 11]

However, wiring continues to be a significant barrier to the practical application of these technologies. Embedded sensors are frequently used, but they have drawbacks. In addition to the high cost of the equipment, embedding strain sensing systems such as strain gauges or optical fibers may contribute to host delamination, cracking, and structural failure. Wireless sensors are a new technology that promises to overcome many of the drawbacks of traditional wired sensors. Using radio frequency identification (RFID) technology in wireless strain sensors is emerging [12, 13]. Passive chipless RFID-based sensors offer several advantages such as being inexpensive, simple, easy installation, and low consumption [14, 15, 16]. LC resonance-based chipless RFID sensors, in particular, encode information solely through an antenna via LC circuit oscillation[17, 18, 19].

This paper introduces a wireless strain sensor with high sensitivity based on RFID technology that allows wireless transmission of data and power. The sensor is a simple LC circuit where the capacitor acts as a sensing unit. The paper also discusses the effect of the nano-cracks that are generated in the parallel electrodes on introducing piezoresistivity effect that leads to transmission line behavior of the capacitance and increases the sensor sensitivity. The sensor has been embedded into composite structures and used to measure the strain during bending test, and the effect on the structural integrity has been investigated.

2 MATERIAL AND METHODS

2.1 Cracked Sensor Fabrication, Electro-Mechanical Testing and characterization

Microfabrication technology has been used to fabricate the cracked sensor and pattern the LC circuit on a flexible substrate. Magnetron sputtering (ESCRD4, ESC) has been used to deposit two metallic films Chromium (Cr) with 60 nm and Gold (Au) with 100 nm on 50 $\mu\mathrm{m}$ Polyimide (PI) substrate ($\mathrm{DuPont}^{\mathrm{TM}}$ Kapton® HN). A photolithography process has been used to pattern the capacitor part via a specific mask on both sides of the PI substrate and the undesired metal regions have been removed using a wet etching process. A copper layer (Cu) with 2 μm thickness has been deposited on one side and patterned to create a circular planner coil to act as an inductance part and on the other side conductive electrode was created to connect the upper and lower layers and create LC circuit. Figure 1 illustrates the structure of the cracked sensor where a parallel capacitor has been created using the top and bottom electrodes attached to the planner coil.

To increase the sensitivity, nano-cracks have been introduced to the conductive metallic film by performing cyclic loading to the capacitor electrodes. 3000 cycles at 4% strain with a strain rate 0.1 mm/sec have been performed using 5944 Instron Universal testing machine. After cycling, a small tensile stage (Kammrath&Weiss) was used to apply static strain and real-time resistance variation has been measured using high-frequency LCR meter (Agilent E4980A) and used also to measure the electrode capacitance and coil inductance.

2.2 Sensor Integration and Wireless Strain Measurements

GFRP samples have been prepared from impact-modified polypropylene copolymer (IPP) reinforced with continuous unidirectional E-glass fibers. For some samples, the fabricated sensors have been embedded into GFRP samples to verify that the signal could be read using a NanoVNA with an external readout coil. For others, the sensors have been installed on the bottom face and three-point bending tests have been conducted using a universal testing machine (Instron 2885). The data were collected remotely based on RFID technology to monitor the change in the resonance frequency with the applied load.

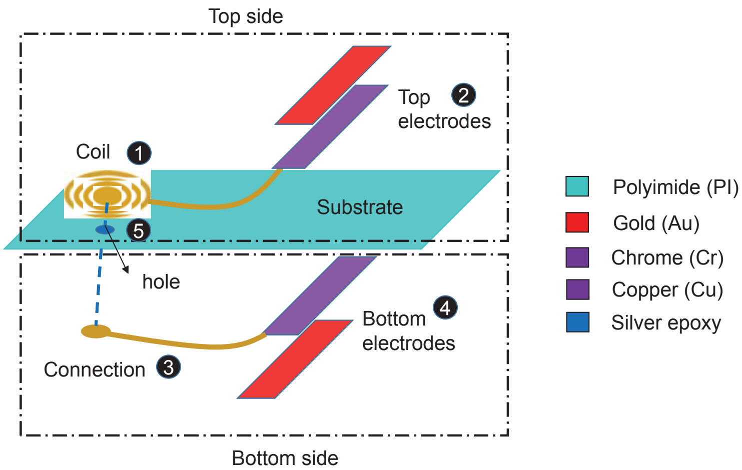

Figure 1: Cracked Sensor Structure

3 RESULTS and DISCUSSION

3.1 Effect of Nano Cracks on the Sensor Piezoresistivity

The sensor electrodes are composed of two metal films; Cr an Au deposited on a Polyimide substrate. The Cr is used as an interlayer to increase the adhesion between Au and PI, but also, due to its brittleness, it acts as a crack initiator due to its low fracture strain. Once the electrode is subjected to tensile strain, micro-cracks will be generated in Cr layer and propagate to the most conductive metallic layer (Au). These cracks will bring piezoresistivity to the electrodes since high resistance variation will be obtained at small strain. This ensures the high sensitivity of our sensor as shown in Figure 2.

Two mechanisms govern this behavior, in the first regime, when the crack edges are not completely separated and the electron can flow through the connected regions and this is called overlapping in which the resistance variation increases gradually with strain to achieve a gauge factor (GF) of 262. In the second regime, the crack edges begin to separate which increases the resistance variation significantly and this is happen because at low gap distance, the electrons still can jump from one crack side to another until a certain distance at which an open circuit occurs and the sensor can reach an average GF of 2568.

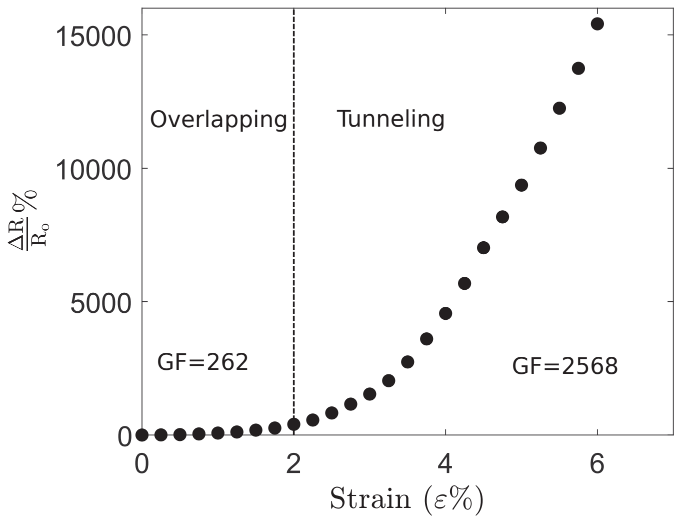

Figure 2: Resistance variation of cracked sensor with strain

The cracks created in the electrodes of LC sensor have a significant effect on the behavior as they create a transmission line effect. In such a regime, increasing either the interrogation frequency or the strain results in signal attenuation in the capacitive part [1], reducing drastically the effective capacitance, and by then, the resonance frequency.

3.2 Sensor Integration in Composite Structures

An external coil has been placed 10 mm away from the sensor and used to send and receive the reflected signal S_{11} to measure the resonance frequency of the sensor. The fabricated sensor resonates at 50 MHz and by changing the capacitance of LC circuit, the resonance frequency will be shifted according to Eq.1. As shown in Figure 3, the sensor with cracks is able to detect small strains ($<0.5\%$) and by increasing the applied strain, more shifting in the resonance frequency is obtained. While in the sensor without cracks Figure 3, there is no remarkable shifting in the resonance frequency even at 4% strain.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The high sensitivity of the cracked sensors promotes their potential to be used to monitor composite structures. Indeed, most of their damage modes such as micro-cracks, delamination, and matrix cracking begin early at low strains. Figure 4 demonstrates the ability of the sensor to detect strain generated during the bending test of GFRP samples. As shown in Figure 4(a),

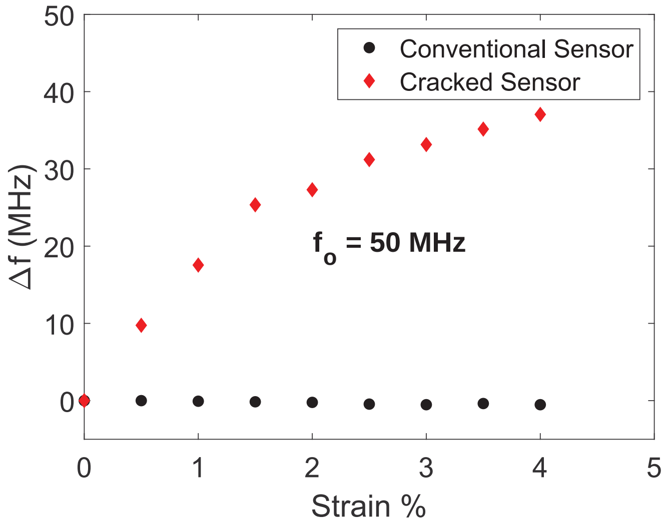

Figure 3: Response of cracked and conventional sensors

the sensor has been placed on the bottom side of the sample and real-time measurements of the resonance frequency during testing have been collected using read-out coil located on the top side and connected to VNA. As presented in Figure 4.(b), a remarkable shift in resonance frequency has been observed at low strain values during bending test.

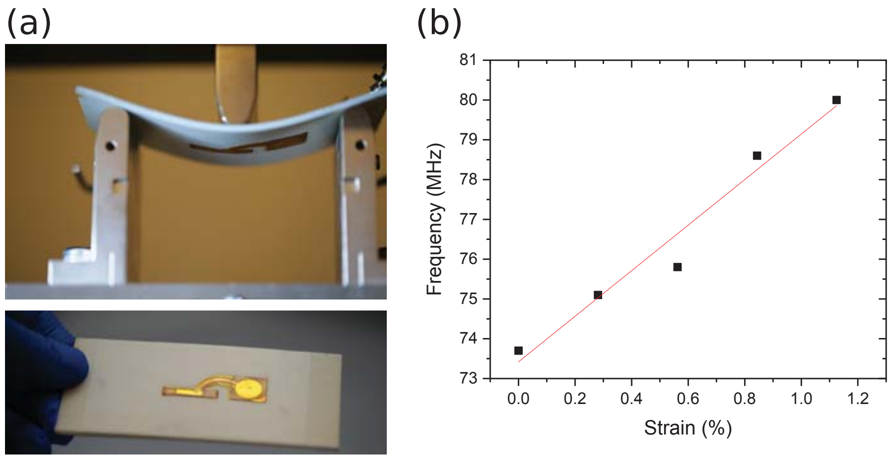

Figure 4: (a) GFRP Bending Test setup (b) Resonance frequency shift under strain

4 CONCLUSIONS

In this paper, we discussed the ability to use RFID technology to develop an ultrasensitive wireless strain sensor. The sensor has been designed based on LC oscillator circuit while the capacitance part act as the sensing unit. Nanofabrication technology has been utilized to increase the sensitivity of the sensor by introducing nano-cracks in the electrodes and generating intense piezoresistivity. This piezoresistive behavior will activate the transmission line model that leads to high capacitance variation under strain that results in a big shift in the resonance frequency. The big change in the capacitance of the LC oscillator produced a remarkable shift in the resonance frequency and high sensitivity measurements to achieve 50 GF for strain less than 1%.

The sensor has been integrated with composite materials and proved its capability of detecting strain during bending test via wireless interrogation using an external readout coil connected to VNA to collect real time measurements. The technology of RFID shows great potential to be used in wireless sensors and can be expanded to WSN via a network of sensors to cover large structures.

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