High Sensitivity Wireless Strain Sensor for SHM Applications

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ABSTRACT

Our research aims to develop a new generation of ultrasensitive strain sensors with wireless communication of data and energy, low power consumption, and easy installation within structures to be used as in-situ measurement systems. The sensor has been developed based on RFID sensing technology that allows wireless data and power transmission by inductive coupling between the internal inductance of the sensor and the external readout coil. Microfabrication technology is used to fabricate the sensor by patterning a metallic LC circuit on a flexible substrate. Nano cracks are introduced to the electrode to create a piezoresistive effect that leads to a transmission line behavior of the capacitance electrodes. The sensor has been embedded with GFRP and CFRP, a bending test has been performed, and the sensor is used to measure the strain during the test. The sensor proves its ability to detect small strains in the composite structures due to the unconventional change in capacitance of the LC oscillator. This unconventional change in capacitance results in a large shift in resonance frequency, producing a sensitive wireless strain sensor with a Gauge factor of 50 for less than 1% strain.

INTRODUCTION

SHM enables to analyze and assess the health and predict the functional lifetime of any structure [1, 2]. SHM techniques have been used in various applications such as aerospace [3], wind turbines [4], bridges [5] and pipelines [6]. Monitoring composite structures is crucial for many applications such as aircraft, energy sector, civil, and marine. Most of the failure modes that occur in composites are internal damage that can not be observed visually [7] that makes SHM challenging for such applications.

Several traditional SHM techniques are used to detect damage in composite structures such as X-ray, ultrasonic [8], acoustics, eddy current [9], and infrared thermography [10]. Embedded sensors capable of wireless data and energy transmission are an essential study area [11]. Radio frequency identification (RFID) sensors have been

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deployed in a variety of applications such as space, healthcare, food quality, and agriculture [12, 13, 14]. Passive RFID sensors do not need power supply since they harvest the required energy from the RFID reader. In addition, such passive RFID sensors are also chip less that makes them very compact and nonintrusive. Chip less RFID sensors that are based on LC circuit encode information exclusively through an antenna via LC oscillator [15]. This is an important feature which prompts their potential for integration into smart composites.

In this paper, we developed an ultra sensitive strain sensor based on RFID technology. Our sensor has been designed to act as LC oscillator that includes a variable capacitance connected to a conductive coil to form LC circuit. The paper also discusses how the transmission line has been achieved by introducing a piezoresistive behavior to the metallic electrodes and increasing the sensitivity. This work demonstrates how to use the developed sensor to monitor composite structures such as Glass Fiber Reinforced polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP).

MATERIAL AND METHODS

The fabrication process began with depositing two metallic films; Chromium (Cr) and Gold (Au) on flexible Polyimide (PI) substrate (DuPont^{TM} Kapton® HN). Magnetron sputtering (ESCRD4. ESC) machine has been used to deposit Cr and Au with 60 nm and 100 nm respectively on PI substrate 50 μm thickness. To pattern the deposited film, a mask with the designed pattern has been used through a photolithography process to shape the capacitor part on both sides of the PI substrate. Then, a wet etching process was used to remove the excessive metal in the excluded regions. An electroplating process (CEMCON^{TM}1500) was used to deposit a copper layer with 2 μm thickness on one side of the PI substrate and patterned to create a circular coil that acts as an inductor. To close the circuit, the upper and the lower electrodes have been connected via a conductive path to form LC circuit.

To achieve the transmission line concept and increase the sensor sensitivity, a piezoresistive behavior has been introduced via creating nano cracks in the capacitor part. The cracks have been formed by performing cyclic loading at 4% strain with a strain rate of 0.1 mm/min using 5944 Instron Universal machine. After 3000 cycles, static strain has been applied using a small tensile stage (Kammrath & Weiss) and real-time resistance and capacitance variation have been monitored using LCR meter (Agilent E4980A). RFID technology has been used to collect data from the sensor through electromagnetic coupling between the transmitter and receiver. A readout coil connected to Vector Network Analyzer (VNA) (Agilent N5225A) was used to send an EM wave to excite the LC oscillator and resonate the sensor at its resonance frequency and receive the reflected signal of the oscillator circuit.

GFRP specimens have been fabricated from impact-modified polypropylene copolymer(IPP) reinforced with E-glass fibers. Eight unidirectional plies were stacked together to produce a composite plate with 2 mm thickness and the developed sensor was placed between the plies. Three-point bending test has been conducted and the data were collected from the sensor using an external readout coil connected to VNA. Also, the sensor was integrated with unidirectional CFRP plates fabricated using 3D printing to explore the sensor performance in printed CFRP composites.

RESULTS AND DISCUSSION

The resonance frequency f of a resonating LC circuit can we written as:

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

where C is the capacitance and L is the coil's inductance. As the frequency depends on the capacitance, any change in the internal capacitance of the LC resonators will result in a measurable shift. We ensure here a large variation of capacitance under stretch by introducing piezo resitive electrodes that turn the capacitance into a transmission line [15]..

The piezo resistive behavior of the parallel electrodes can be introduced by introducing nano cracks to the metal films, these cracks will change the electrode resistivity and make the sensor very sensitive to strain since the resistance will vary significantly at low strain levels. The nano cracks have been created through cyclic loading of the parallel electrodes. By increasing the number of cycles the crack density will increase leading to high resistivity in the conductive electrodes as shown in Figure 1.(a). The number of cracks will continue rising until saturation is reached. This piezo resistivity will lead to high variation in the capacitance during deformation and give a remarkable change in the resonance frequency compared to the conventional parallel capacitor as presented in Figure 1.(b) the shows there is no significant change in the resonance frequency until 4% strain. While in Figure 1.(c), it is obvious that there is shifting in the resonance frequency even at strain less than 1%.

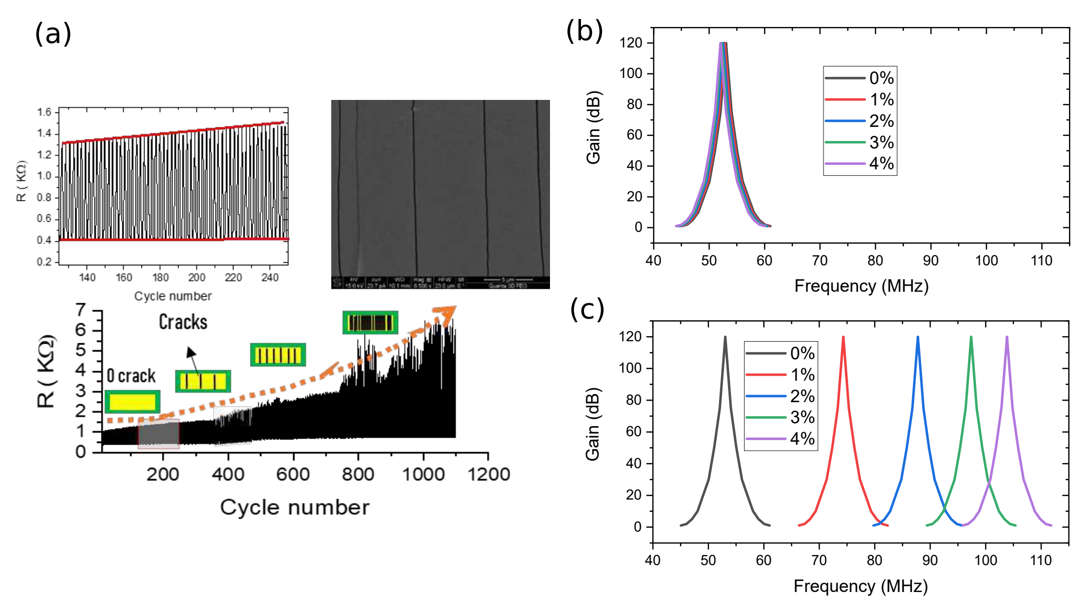

Figure 1. (a) Resistance Variation with Number of Cycles, SEM Image of Cracks formed in Cr/Au film (b) Shift in resonance frequency with geometrical effect only (c) Shift in resonance frequency with transmission line effect

The ultrasensitivity of the cracked sensor makes it viable to be used to monitor composite structures since it will be able to detect micro-cracks and delamination at an early stage. As shown in Figure 2. (a), the sensor has been placed on one side of a GFRP plate and three-point bending test has been conducted. The resonance frequency has been measured instantaneously using a read-out coil placed on the other side of the sample and connected to VNA. The results are presented in Figure 2. (b), shows a linear increase in the resonance frequency of the sensor due to the applied strain, and even at strains less than 1%, the sensor shows the capability to detect the change that occurred. Also, the sensor has been placed inside CFRP as illustrated in Figure 2. (c) with X-ray image to show the sensor inside the CFRP sample, while Figure 2. (d) shows the reflected signal (S_{11}) received from the sensor. From these results, we can say that cracked sensors based on RFID technology have a big potential to be used in structural health monitoring of composite materials due to their sensitivity in strain detection, flexibility, and easy installation.

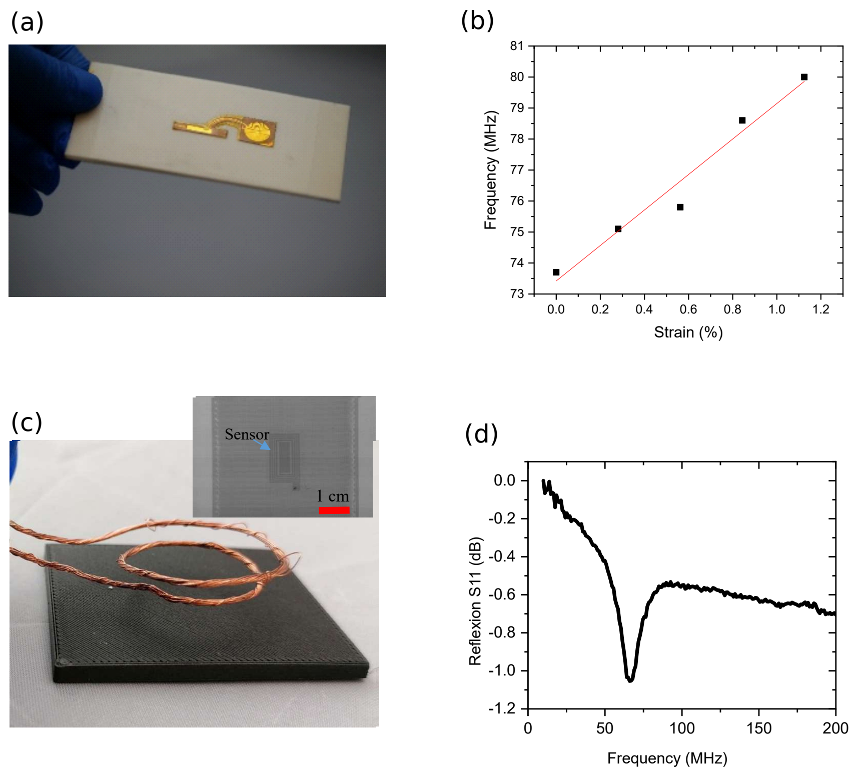

Figure 2. (a) Sensor placed on GFRP Sample (b) Shift in resonance frequency with Strain (c) CFRP Sample with Embedded Sensor (d) Reflected Signal (S11) from the sensor embedded in CFRP

CONCLUSION

In this work, we presented the potential of using RFID technology with cracked-based sensors in the structural health monitoring of composite materials. The developed sensor has a high sensitivity in addition to its flexibility with its small size and dimensions that enable it to be integrated into composite structures easily. The sensor has been fabricated using microfabrication technologies. To achieve high sensitivity via applying a transmission line model, nano cracks have been created in the parallel electrodes to introduce a piezoresistive effect and create a variable capacitance that changes significantly with the geometrical deformation. This leads to shift in the resonance frequency of the LC oscillator circuit. RFID technology has been used to collect the data through a readout coil connected to VNA that transmits and receives the reflected EM wave and by analyzing the reflected signal, we can observe the change in the resonance frequency and as a consequence detect the occurred strain. To demonstrate the sensor's capability to detect small strains in composite materials, unidirectional GFRP and CFRP samples have been fabricated and a three-point bending test has been conducted on GFRP samples and the real-time frequency has been recorded using VNA. The sensor showed its ability to detect strains less than 1%, while in unidirectional CFRP, the incident EM wave was able to penetrate the CFRP and the reflected signal (S_{11}) illustrate the resonance frequency of the LC oscillator.

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