Flexible passive LC resonator for wireless measurement during curing of thermosets

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Abstract. Monitoring of fibre composites is an important task to spread the application of fibre composites. Cure monitoring of the polymer matrix of fibre composites during the fabrication can be realized with interdigital sensors. The measured impedance can be directly related to the curing process. However, wiring the sensor may disrupt the material, therefore, sensing should be done wireless. As many fibre composites are processed under high temperature and high pressure conditions no electronics can be used inside the material. Here we present the design, fabrication, and characterization of a wireless sensory system using a chipless strategy for online cure monitoring. For this purpose, different combinations of sensors and readers are designed, consisting of a planar inductor-capacitor (LC) resonator, where capacitance is an interdigital capacitor, and an inductor as antenna operating wirelessly through inductive coupling. The designs are realized onto flexible polyimide substrate using microfabrication technology. To characterize the coupling effect, the response of the reader antenna has been carried out when sensor is placed in its vicinity. Furthermore, the curing process of adhesive is demonstrated and results are discussed. It is shown that the curing process of a thermoset polymer can be monitored by a flexible chipless LC resonator wirelessly.

1. Introduction
The quality of fibre composites is determined by the curing of the polymer matrix. Monitoring the curing is, therefore, an important task to improve the quality and enable the application of fibre composites to structural components. Monitoring can be realized by dielectric sensor [1]. However, wiring the sensor may disrupt the production process.

Radio frequency identification (RFID) is an emerging compact wireless technology for the identification of objects and real-time monitoring under harsh environment where wired connection and evaluation circuit cannot be established [2]. For instance, sensing under hazardous environmental conditions, such as corrosive media, high pressure or high temperature is possible [3]. Wireless monitoring in fibre composites was realized in glass fibre [4] and in carbon fibre [5]. However in both cases electronics needs to be integrated in the composites. These electronics will not sustain the fabrication of high performance composites due to high pressure and temperature during fabrication. Therefore, a completely passive and wireless sensor element is required [2]. The LC resonant sensor is
the representative device of wireless passive sensors, which can measure effectively and does not require the direct signal electrical connection and power supply [6,7].

The proposed system for cure monitoring of thermosets consists of a spiral inductor working as antenna and an array of interdigitated electrodes as the capacitive element, forming together the LC resonators. Variation in capacitance would result in a shifting resonant frequency. In order to obtain the resonance frequency wirelessly, an extra coil at the readout circuit is inductively coupled to the inductor of the LC circuit [8]. The resulting change in the spectra is detected by the variation in the reflection coefficient of the reader coil. This research work describes the design, fabrication and characterization of LC resonator and reader circuits and challenges of the LC passive wireless system.

2. Theoretical Background

Chipless radio frequency identification technologies have found applications in many industries for automatically identifying and online tracking of objects [9], where a wired connection between the sensor, its electronic circuitry and power supply batteries cannot be sustained. One very important feature of passive RFID systems is the power supply to the sensor. Passive RFID sensors do not have their own power supply, and therefore all power required for the operation must be drawn from the electromagnetic field of the reader [10].

![Figure 1. Schematic overview of passive RFID system.](image)

The proposed RFID system, shown in figure 1, consists of a reader and an LC resonator. In operation, a sweeping frequency wave is transmitted by the reader as an interrogational signal to detect whether an RFID sensor exists in the vicinity. With the presence of a sensor, the energy at a frequency point is absorbed by it, and therefore a footprint is signed in the frequency spectrum. The footprint is picked out by the reader according to frequency position variations of the backscattered signal [9].

3. Geometry and Mathematical Modelling

The inductance and capacitance of the resonator are the structural parameters that define its resonance frequency by [11]:

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

(1)

The capacitor is an interdigital structure and inductor geometry finalized to be in square shape, which works as an antenna. In order to obtain the resonance frequency wirelessly, the readout circuit is inductively coupled to the inductor of the LC circuit. The frequency range for an inductive coupled RFID system is selected in high frequency (13.56 MHz) band.

3.1. Interdigital Structure

The term “interdigital” refers to a finger-like periodic pattern of parallel in-plane electrodes, used to build up the capacitance associated with the electric fields that penetrate into a material sample. The basic geometry of an IDC is defined by the parameters shown in figure 2 (a). These parameters include electrode length \( L \), electrode width \( w \), separation between electrodes \( s \) and the thickness \( h \). The selected design parameters, correspond to the values of the fabricated interdigital sensor, are listed in table 1(a).
Figure 2. (a) Schematic of interdigital structure, (b) Planar spiral inductor.

An analytical approach is presented by Igreja et al. where original conformal transformations and the partial capacitance methods are used to evaluate closed form expressions for computation of fringing field capacitance of IDC [12]

$$C = (N - 3) \frac{C_I}{2} + 2 \frac{C_I C_E}{C_I + C_E}$$  \hspace{1cm} (2)

where $C_I$ is the partial capacitance between two interior electrodes and $C_E$ is the partial capacitance of an outer electrode. This equation is applicable for $N > 3$, $N$ is the number of electrodes. Total capacitance has been calculated for achieving resonance frequency, from equation (1), around 13.56 MHz for the calculated inductance values in subsequent section-3.2. Final designs have been carried out with capacitance value of 100 pF.

3.2. Inductor Design

S. S. Mohan [11] described a simple modification of the Wheeler formula for planar spiral integrated inductors. Figure 2 (b) illustrates the layout of square shape inductor, $w_L$ is turn width of and $s_L$ is the turn spacing. The modified Wheeler formula for inductance calculation is expressed as:

$$L = K_1 \mu_0 \frac{n^2 d_{avg}}{1 + K_2 \delta}$$  \hspace{1cm} (3)

where $\mu_0$ is the magnetic permeability of free space, $n$ is the number of turns, $d_{avg}$ is the average diameter of spiral inductor. The fill ratio is defined as $\delta = (d_{out} - d_{in})/(d_{out} + d_{in})$. $K_1$ and $K_2$ are both layout dependent coefficients for modified Wheeler expression and their value is 2.34, 2.75 respectively for planar square inductors [11]. Geometrical parameters of inductor coil are computed for inductance value of approximate 1.4 μH in order to achieve resonance frequency 13.56 MHz. To examine how LC combinations influence sensor’s performance, four LC circuits with different inductance values were designed and numbered as 1, 2, 3 and 4. These are summarized in table 1(b).

Table 1. Geometrical parameters of (a) interdigital capacitor and (b) inductor coil.

| (a) IDC Parameters | Value | (b) Inductor Parameters | Geometrical dimension | Design-1 | Design-2 | Design-3 | Design-4 |
|--------------------|-------|-------------------------|-----------------------|---------|---------|---------|---------|
| Geometrical dimension |       |                         | Geometrical dimension |        |         |         |         |
| $w$                | 10 μm | $w_L$                   | 100 μm               | 50 μm  | 100 μm  | 50 μm  |
| $s$                | 10 μm | $s_L$                   | 100 μm               | 50 μm  | 100 μm  | 50 μm  |
| $h$                | 300 nm| $d_{in}$                | 20 mm                | 20 mm  | 30 mm   | 30 mm  |
| $L$                | 10 mm | $d_{out}$               | 21.8 mm              | 20.9 mm| 30.7 mm | 31.4 mm|
| $N$                | 520   | $n$                     | 5                    | 5      | 4       | 4      |
4. Experimental Setup

4.1. Fabrication

The LC resonators and readers are fabricated using microfabrication technology on a silicon wafer, which only acts as a handling device. A 5 µm thick polyimide layer is spin-coated. On top of this polyimide substrate a 300 nm thick gold layer is sputtered and then coated with 1.8 µm thick photoresist. The pattern is structured using laser lithography. After exposure, the pattern is developed and gold is etched wet-chemically. In the last step, the photoresist is removed and the devices are released from the silicon wafer.

![Fabricated LC resonator](image)

The fabricated designs (\(w_L = 100\) µm and \(s_L = 20\) mm) are shown in figure 3. Wires are glued on the contact pads with electrical conductive silver paste. Because the pattern generation was done on single layer, one end of IDC at inner side and outer end of the coil needs to be connected through a small bridge to form LC tank circuit. In addition wires are also glued to the sensor side for characterization purpose.

4.2. Measurement Setup

A Rohde & Schwarz vector network analyzer ZVRE (9 kHz – 4 GHz) has been used for the characterization of fabricated designs. Reader was connected to the analyser through Cu-wire and LC resonator was magnetically coupled to the reader and aligned during measurements in order to maximize the coupling effect. The resonance frequency of designed circuits is commonly identified by monitoring \(S_{11}\) parameter, which would drop to the minimum near the resonant frequency.

5. Results and Discussion

5.1. Reader Characterization

![Frequency response of sensor during the curing process of adhesive](image)

Figure 3. Fabricated (a) LC resonator and (b) reader.

![Combination of sensor and reader at resonance](image)

Figure 4. (a) Combination of sensor and reader at resonance, (b) Frequency response of sensor during the curing process of adhesive.
To observe the behaviour of both the circuits, reflection coefficients of reader and sensor are measured directly at the same time. Figure 4 (a) depicts the frequency response of both reader and sensor. Coupling between reader and sensor coil is only possible if they both operate at same resonance frequency. To achieve this, additional capacitors have been added in reader circuitry to tune its frequency near to the resonance frequency of sensor.

For coupling measurement, sensor has been placed on reader at a distance of approximate 1 mm. Due to magnetic coupling effect between reader and sensor coil, a shift in reader frequency was observed. Maximum shift of 34.3 kHz was measured for design-1 while the minimum recorded shift was 12.5 kHz for design-4. This result can be correlated to antenna geometry, which is combination of smaller coil diameter and larger track width for design-1, offers lowest internal resistance. In contrast design-4 has higher coil diameter and smaller track width leads to small shift in frequency due to coupling effect. Design-2 and design-3 show the shift of 25 kHz and 22.5 kHz respectively.

5.2. Cure Measurement
Measurement of curing process of adhesive has been performed. In a first instance sensor is connected to the vector network analyzer only for characterization purpose. Adhesive (Uhu Schnellfest) is applied on the sensor and its behaviour has been observed. During the curing of the adhesive the dielectric parameter, permittivity, changes which contribute to the change in frequency, which is measured at a sensor side. Figure 4 (b) shows that resonance frequency of sensor changes during the curing process.

Adhesive covers the whole area of sensor therefore capacitance increases, which results into drop in resonance frequency to 11.93 MHz from 19 MHz. When adhesive starts to cure, the capacitance decreases and therefore frequency increases. After around 12 minutes the frequency stays constant, at 14 MHz, indicating that the curing process has completed. Figure 5 (a) illustrates that the frequency changes over time during the curing process of adhesive. The frequency at the end of the curing process is 5 MHz lower than the frequency of the sensor in air. This can be correlated to the change of the permittivity from air to cured adhesive.

![Figure 5](a) Frequency changes over time during the curing process of adhesive, (b) Magnitude changes over time during the curing process

In order to analyse the behaviour of reader, the experiment repeated again on another design. This time, only the reader is connected to vector network analyzer and the sensor is coupled to it. The reader is tuned as per the resonant frequency of sensor and adhesive is applied onto the sensor. The magnitude of the reader dropped from -45.12 dB to -48.9 dB initially and then started increasing in every minute. After around 7 minutes it remained constant at -47.16 dB. This behaviour is a result of coupling effect in terms of magnitude, as shown in figure 5 (b). As the resonant frequency of the sensor shifts the coupling at the reader changes, this results in the change of amplitude of the reflection coefficient. This change in the magnitude of reader during the curing process of adhesive is quite similar to the frequency response of sensor shown in figure 5 (a).
6. Conclusion
We presented the characterization of a wireless chipless system for cure monitoring in this work. Frequency response of LC resonator has been carried out in order to observe the behaviour of the sensing element. To observe the coupling effect, sensor was placed on reader at a fix distance of 1 mm and measurements were performed at reader side. Shift in resonant frequency of reader was measured due to coupling. The curing process of adhesive has been performed to analyse the sensor as well as coupling between the antenna coils. When adhesive applied onto the sensor, an expected drop of approximate 7 MHz was measured in sensor frequency. This results in a significant change in the magnitude on the reader side, which is inductively coupled to the sensor. The behaviour of the magnitude change at reader side is similar to the change in sensor frequency during the curing process of adhesive. Therefore we can state that cure monitoring with passive wireless system is possible and we could measure the change in spectra wirelessly during the curing process.

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