Array of chipless RFID sensor tag for wireless detection of crack on large metallic surface

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***Abstract*—In this paper, two array configurations of chipless RFID sensor tags are proposed for the detection of crack on a large metallic surface. A single sensor tag contains compass-shaped and a pair of L-shaped resonators. The metallic object under observation is identified by resonant frequencies of L-shaped resonators and crack on metallic object is observed by shift in resonant frequency of compass-shaped resonator. The unit cell tag provides read range of 120 cm and sensitivity of around 75 MHz/mm for 6 cm wide square-shaped surface. However, its performance degrades for larger surface. Therefore, a 3×3 array of sensor tag is proposed for larger surface area. The 3×3 array configuration can detect crack but can't identify crack location due to the identical elements. To resolve the issue an idea of series array having five rectangular resonators with non-identical dimensions hence multiple resonant frequencies is presented. It helps to identify presence and position of crack on relatively large metallic surface.**

Keywords—array of RFID tags, crack sensor, effective-length, EM transduction, series array.

I. INTRODUCTION

The research on chipless radio frequency identification (RFID) sensors has increased since last decade. The RFID technique is advantageous for various sectors of applications due to its automatic wireless object identification and sensing capability. One of the important area of applications is structural health monitoring (SHM) where oil tank of aircraft/ship, civil infrastructure, and conveyor belt in industrial plant can be easily monitored [1]. Any civil and metallic assets suffer from cracks and corrosion defects that may damage the asset if not monitored properly. The RFID sensing technology is one of the possible approaches for continues monitoring of such assets. Further, the RFID sensors are promising for regular inspection of assets compared to conventional techniques like non-destructive testing and evaluation (NDT&E) since it is expensive and unsuitable for periodic monitoring [2-5].

In [6], a chipless RFID tag having circular microstrip patch antenna (CMPA) as crack sensor and tip-loaded dipole resonators as identification (ID) bits is presented. However, the overall size of tag is large due to axially arranged ID resonators. To reduce the tag size as well as to detect crack and corrosion together a multi-resonance tag having diagonal dipole patches as sensor and L-shaped patches as ID bits is presented [7]. But, it requires a complex analysis due to shift in multiple resonant frequencies for both crack and corrosion. One of the critical issue with aforementioned sensors is the poor detectability for relatively large surface. In [8], a long array of serially arranged spiral resonators coupled with transmission line is presented to detect the coating delamination and corrosion predictions. The array configuration can monitor large surface but it requires transmission along with remitter and receiver antennas. Thus, to monitor large surface an array of sensor tag without antennas or transmission line can be a possible approach.

In this paper, an effort has been given to design a uniplanar tag suitable for crack detection over large surface. Two array configurations: 1) 3×3 array of identical resonators and 2) series array of five non-identical resonators are presented. For 3×3 array, compass-shaped resonator (proposed in our previous work) [9] is used. The array provides better detectability for large surface compared to unit cell. In series array, rectangular patches are considered as crack sensors. The series array is beneficial to for crack detection along with crack position on large metallic surface.

II. OPERATING PRINCIPLE

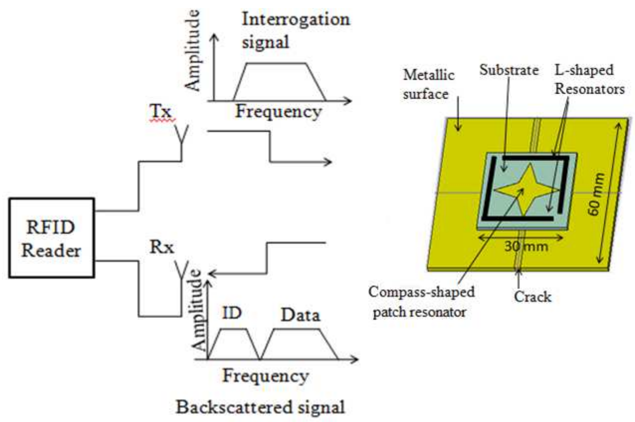


Fig. 1. Schematic of working principle of RFID system [9].

The RFID system has two major parts: 1) Interrogator also known as reader, and 2) transponder also called as tag attached to the metal surface under observation. The schematic representation of RFID system is shown in Fig. 1. The reader sends interrogation signal towards tag. Tag consists of resonators for crack sensing and/or identification. Tag produces backscattered signal after interrogated by incoming signal. The properties of backscattered signal changes according to the changes in crack width/orientation present on metal object. The effective length of sensor resonator changes when meatal crack is present beneath the sensor resonator. Therefore, the resonant frequency of crack sensor tag is different for metal surface with and without crack. The backscattered signal received at reader is analysed using radar cross section (RCS) values and shift in resonant frequency.

III. DESIGN OF SENSOR TAG

A. Unit cell Tag

The proposed RFID sensor tag has a compass-shaped patch resonator as sensor centered at origin and two L-shaped resonators as ID resonators diagonally placed around the sensor. It is designed on a 1.6 mm thick uniplanar cost effective FR-4 substrate having relative permittivity of 4.4 and loss tangent of 0.01. The overall size of sensor tag is 30×30 mm^2 as shown in Fig 3. The yellow and white parts represent printed metallic resonators and substrate respectively.

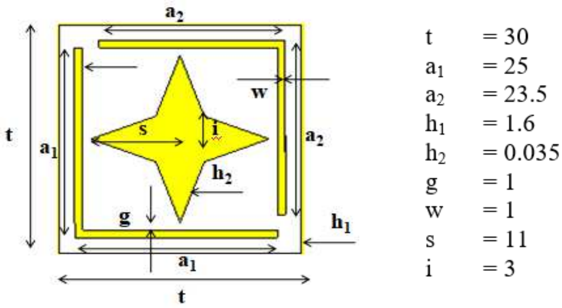


Fig. 2. Illustration of unit cell of proposed RFID crack sensor [9]. All dimensions are in mm.

B. 3×3 Array Tag

The proposed unit cell tag can monitor metal surface of max. size 6×6 cm^2 properly. However, its detectability reduces with increase in size of metal surface (discussed in Results section). Therefore, to monitor large surface, nine identical unit cell sensor tags are arranged in 3×3 array configuration with 25 mm distance from adjacent tag. The proposed 3×3 array configuration is illustrated in Fig. 3.

The 3×3 array of identical elements can detect crack on large surface. The monitoring area can be increased by increasing order of array i.e. n×n array, where, n is number of unit cell in one direction. We have limited our study up to 3×3 array for simplicity. The n×n array can easily detect presence of crack on large metal surface but the location of crack can't be identified due to the same resonant frequency of all resonators.

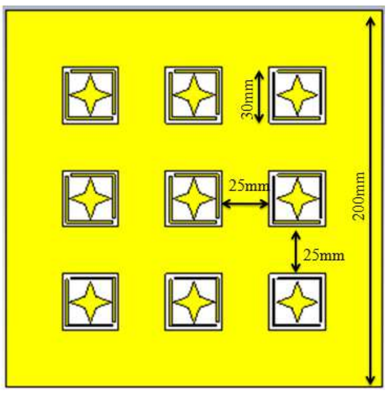
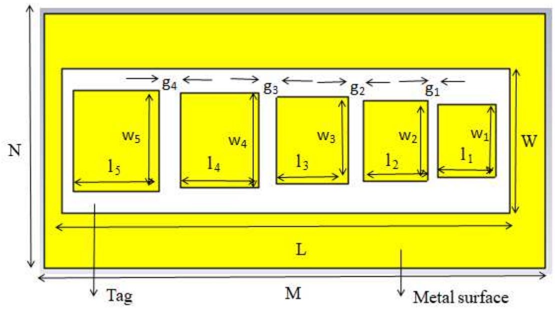


Fig. 3. Geometry of 3×3 array configuration.

C. Series Array Tag

The aforementioned issue of array of identical sensor tags can be resolved by an array of non-identical sensor resonators. For simplicity, a series array of five rectangular resonators of different resonant frequencies is proposed as shown in Fig. 5. It is also designed on uniplanar FR-4 substrate same as unit cell tag. The rectangular resonators are having increasing size and gap from preceding resonator. The proposed series array tag is designed to resonate at frequencies: 2.48, 2.68, 2.88, 3.15 and 3.46 GHz.



l_1	l_2	l_3	l_4	l_5	g_1	g_2	g_3	g_4
16	18	20	22	24	3	4	5	6
w_1	w_2	w_3	w_4	w_5	W	L	M	N
20	22	24	26	28	40	125	140	70

Fig. 4. Geometry of series array RFID sensor tag for metal crack detection. All dimensions are in mm.

IV. Simulation Results and Discussion

Design and simulation study of all the chipless RFID sensor tags including array configurations are carried out on CST Microwave Studio. The simulation setup for RCS measurement is shown in Fig. 5. The RCS probe is fixed at a distance of 30 cm from the sensor tags and excited with plane wave excitation.

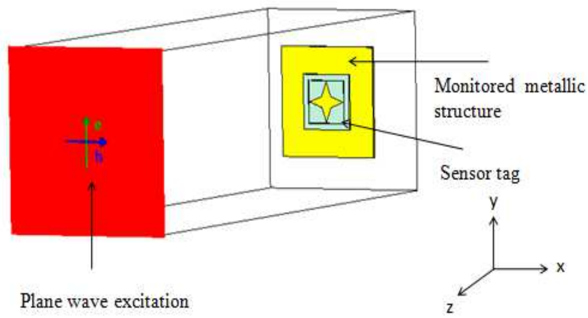


Fig. 5. Simulation setup for RCS measurement in CST Microwave Studio [9].

The unit cell tag was used to monitor small (6×6 cm^2) metallic surface. The simulated RCS responses of unit cell crack sensor tag attached to metal surface without and with crack are shown in Fig. 6. It can be observed from Fig. 6 that in absence of crack, the tag resonates at three frequencies: 3.37, 3.60, and 4.48 GHz. Out of three the two lower frequencies 3.37 and 3.60 GHz are used for identifications whereas higher one i.e. 4.48 GHz is used for crack sensing. Further, 3 mm wide crack was introduced in three different orientations on metal surface. The effect of crack orientation can be observed by shift in resonant frequency from the original value. The lower (left) and higher (right) frequency shift is found for horizontal and vertical crack respectively. In addition, two resonant frequencies are obtained for diagonal crack. The resonant frequency shifts due to the inverse relation between effective length and resonant frequency of the resonator. The compass-shaped unit cell tag provides read range of 120 cm and sensitivity of around 75 MHz/mm. A detailed analysis has been presented in [9].

The proposed unit cell is also studied for large metallic surface. Fig. 7 shows the RCS response of proposed unit cell tag when attached to 6 cm and 20 cm wide square metallic surface. It can be seen from Fig. 7 that the resonant frequencies diminish when tag is used to monitor 20 cm wide square metallic surface. It explains that the detectability of unit cell tag reduces with increase in surface area under test. Thus, to observe relatively large surface area, a 3×3 array is arranged on 20 cm wide square metallic surface as shown in Fig. 3 and the RCS response is shown in Fig. 7. It can be investigated from RCS response that the 3×3 array of sensor tag provides same resonant frequency as unit cell tag. Hence, proposed array of tag is suitable for monitoring crack on relatively large metallic surface compared to unit cell tag.

Even though monitoring surface area increased with array configuration, the crack location can't be determined because the resonant frequency of each sensor tag is identical. Therefore, array of sensor resonators having varying resonant frequencies is required to accurately identify crack location along with the crack width and orientation on large surface. The resonators should have varying size to produce different resonant frequencies.

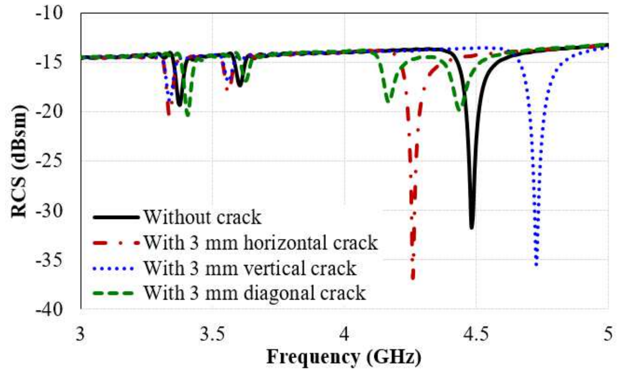


Fig. 6. Simulated RCS responses of unit cell sensor tag.

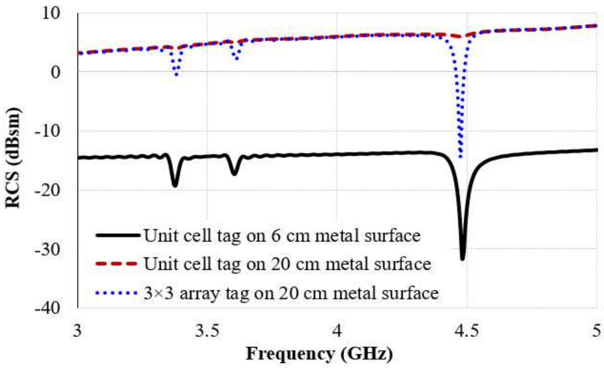


Fig. 7. Comparison of RCS responses of unit cell and 3×3 array of proposed sensor tags.

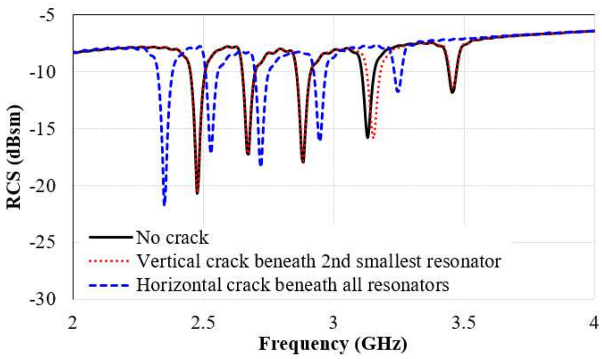


Fig. 8. Simulated RCS responses of series array of non-identical rectangular resonators.

With this idea a series array of five rectangular resonators of closely spaced resonant frequencies is proposed as shown in Fig. 4. The rectangular resonators are considered for simplicity. The series array sensor tag is studied for three cases: 1) crack free metal surface, 2) vertical crack on metal surface behind the second smallest resonator of size (l_2×w_2), and 3) horizontal crack on metal surface passing behind all resonators. The RCS responses all three cases are shown in Fig. 8. It can be observed from Fig. 8 that the series array tag provides five resonant frequencies 2.48, 2.68, 2.88, 3.15 and 3.46 GHz according to the dimension of respective sensor resonator. Further, when vertical crack is present behind the second smallest resonator only then the respective resonant frequency shifts from original 3.15 GHz to higher frequency. The increase of single resonant frequency represents that the vertical crack is present behind that specific resonator only. Similarly, increase of multiple resonant frequencies signifies presence of vertical crack behind multiple resonators. Furthermore, when horizontal crack passes behind all resonators then all resonant frequencies shift toward lower frequency side as shown by dashed curve in Fig. 8.

The present study is limited to few orientations of single crack. The study on response of the proposed sensor can be extended with multiple cracks present on the metal surface.

V. Conclusion

An effort has been made to identify presence of crack, orientation and location on large metallic surface. Initially, a unit element of compass-shaped sensor has been studied for different orientations of crack. The detectability of unit element is limited to small surface. The detectability for relatively larger surface has been improved with 3×3 array of identical compass-shaped sensor resonators. However, it fails to identify location of crack on large surface. Finally, a series array of sensor resonators with varying resonant frequencies has been presented to identify orientation and position of crack on large metal surface.

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