LETTER

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Novel chipless displacement sensor circuit using spurline resonantor

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Abstract: A novel uni-dimensional chipless displacement sensor circuit based on spurline resonators is presented. Sensor circuit design consists of two components: series of spurline resonators and a selector element. In response to displacement, the selector element slides over the spurline resonator slots that translating this movement into a corresponding change in the circuit's frequency response. The designed circuit offers a capacity of 16 bits in the 2–4.2 GHz frequency band. Half of the bits are designated as the sensory bits, while the other half are attributed as the ID bits. The formulated sensor has a dynamic range from 0–3.75 mm and a minimum resolution of 0.25 mm. The proposed sensor is a prime candidate for deployment in smart cities for ubiquitous infrastructural health monitoring.

Keywords: displacement sensor, chipless tag, structural health monitoring

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Structural health monitoring [1] is the process of readily predicting, identifying and analyzing instances of infrastructural damage in wake of artificial excitations or natural disasters. The rapid shift towards the Internet of Things (IoT) [2] paradigm has lead to an increase in demand for intelligent buildings that are furnished with sensing technologies. Such sensing technologies consist of inexpensive yet reliable sensors capable of generating a near real-time stream of structural health data. Using purpose-built algorithms, this data can be processed to generate useful insights about the structural longevity of critical civil infrastructure. The data, when accumulated over time, can also be used to predict structural damage and its repercussions well before natural calamities strike.

Sensors coupled permanently with structural elements are, for most cases, wired in nature. Such sensors are not only complex to manufacture but also require time-consuming installation, painstaking commissioning and intricate signal processing [3]. Structural health monitoring setups of this sort can be simplified to a significant extent by rendering the entire measuring and sensing process wireless.

Radio frequency identification (RFID) technology has been investigated for developing sensors that monitor structural health both passively and wirelessly. In recent years, significant research has been carried out around developing RFID-based crack and displacement sensors. Detection of cracks necessitates the radiating structure to undergo a physical deformation [4, 5, 6], whereas sensing displacement involves converting subtle movement between parts of antenna into relevant electromagnetic descriptors [7, 8]. Such sensors, however, require an application specific IC to function and fall prey to disadvantages such as higher development

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cost, large tag dimensions and reduced read range due to impedance mismatch. RFID sensors of the chipless sort, on the other hand, are economical to mass manufacture, have a smaller physical footprint and offer enhanced read range [9, 10, 11].

In this letter, a novel uni-dimensional chipless RFID sensor circuit for infrastructural health monitoring is presented. The sensing circuit is composed of multi-resonant spurline structures. The sensing setup does not require sophisticated instrumentation and yields good resolution at a lowered cost. The sensor circuit also boasts other desirable features such as compact footprint and the ability to withstand harsh environments.

2 Working principle

The RFID-based chipless infrastructural health monitoring sensor presented in this paper is designed to detect uni-dimensional, linear displacement as it emerges between two points. The unidirectional linear displacement manifests itself as a crack or general deformation in wake of an external force (for instance earthquake, flood, tremor, or landsliding).

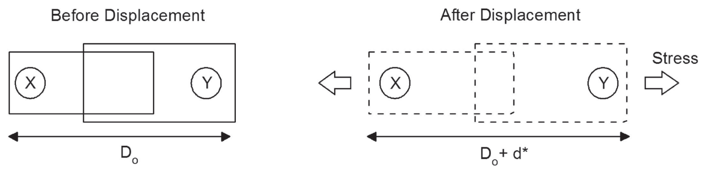

Fig. 1. Configuration of the displacement sensor.

Setting up the chipless RFID displacement sensor begins with selecting two reference points, labeled as X and Y as shown in Fig. 1. The distance between the two points X and Y, in the absence of an external force, is denoted by D_o. Upon application of an external force, a mutual translational shift is introduced between points X and Y, thereby increasing D_o by a fraction denoted by d^*. The new distance between the two points, now, is $D_o + d^*$. Note that d^* is delimited to, and assumed to be, an instance of uni-dimensional linear displacement.

3 Sensor circuit design

At the core of the proposed sensing circuit lies a series of spurline resonant structures. Each resonant structure is essentially an inverted L-shaped slot that is etched onto a microstrip line. The L-shaped slots making up the sensor circuit differ in their dimensions, offering distinct band-stop characteristics at different frequency. An in-depth analysis of the the bandstop characteristics of the spurline resonators, along with the mathematical model, can be found in [12]. Upon shortening a spurline resonator its associated capacitance is reduced, causing the corresponding resonant notch in the spectral domain to shift to a notably higher value. This phenomenon is leveraged to design a sensor that translates the frequency shift to an appropriate value of displacement.

The sensing circuit is provisioned with a movable metallic rectangular strip, called the selector, as shown in Fig. 2. The selector element is capable of sliding

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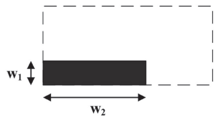

Fig. 2. Layout of rectangular selector.

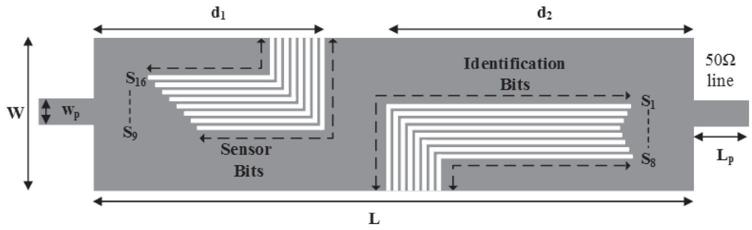

Fig. 3. Layout of spurline resonator circuit for displacement sensor.

over the resonator circuit. Two components of the proposed displacement sensor, the spurline resonant circuit and the selector element, are attached independently to the structure under observation. When subjected to unidimensional displacement, the selector slides over the resonant circuit along the broader side, causing an overlap between the selector element and the spurline resonators. Depending upon the extent of overlap, shortening of the spurline resonators causes one or more sensing notches in the spectral domain to disappear. The remaining notches can be used to determine the linear displacement that has taken place.

As illustrated in Fig. 3, spurlines located at lower right corner (labeled S_1 through S_8) are used for identification whereas the ones positioned at the upper left corner (marked S_9 through S_{16}) are used for sensing displacement. The dynamic range of the formulated sensor is governed by the number of spurline line resonators present at the upper left corner. The resolution of the proposed sensor is governed by the width of the resonant slot. The presented design consists of 8 resonant slots. Both the slot-width and inter-slot spacing is equal to 0.25 mm. The dynamic range of the sensor is 0–3.75 mm, and the resolution is 0.25 mm. The optimized dimensions of the proposed sensor are depicted in Table I.

Table I. Optimum spurline lengths for displacement sensor

Parameters	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
(mm)	24	22.8	21.5	20.4	19.4	18.5	17.8	17
Parameters	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
(mm)	16.85	16.15	15.3	14.65	13.9	13.3	12.8	12.25
Parameters	W	L	w_p	L_p	d_1	d_2	w_1	w_2
(mm)	10	42	1.8	3	17	22	1	5

4 Results and discussion

For reliability analysis, five prototypes of the proposed displacement sensor circuit are realized on Taconic substrate having a thickness of 0.78 mm and a dielectric constant equal to 3.2. Fabricated spurline resonator circuit for the zero-displacement scenario is depicted in Fig. 4. The frequency response has been measured

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using Vector Network Analyzer (Anritsu MS2026B) in a controlled laboratory environment. Since there is no overlap between the selector and any of the spurline resonators, all sensor bits are '0' depicting no displacement.

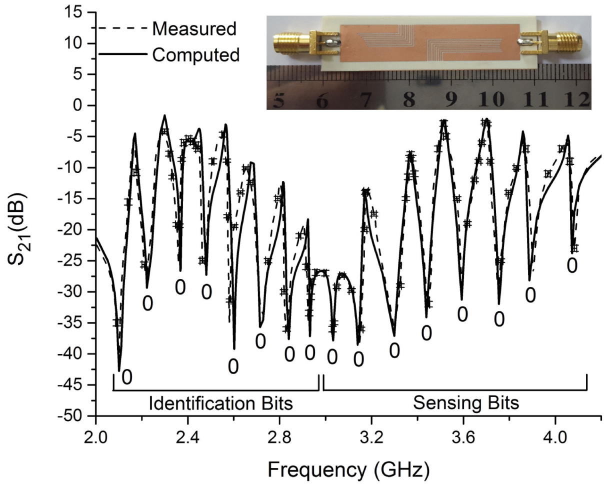

Fig. 4. Measured and computed frequency response without any displacement of spurline resonator.

When subjected to uni-dimensional displacement of 0.25 mm, the selector element slides over the spurline slots covering the first sensing resonator in its entirety. The measured and computed results for this case are illustrated in Fig. 5. The shortening causes the capacitance of the slot to decrease radically. This, in turn, causes the corresponding resonant notch to shift at a higher frequency well outside the spectral range of interest. Absence of corresponding notch in the spectral domain, depicted as '1', signifies a uni-dimensional displacement equal to 0.25 mm. Similarly, Fig. 6 shows the results for the case when four sensing slots have been covered by the selector, marking a displacement of 1.75 mm. Sensor's copper deposition wears off completely after 450 maximum displacement instances, validating reliability and longevity of the sensor.

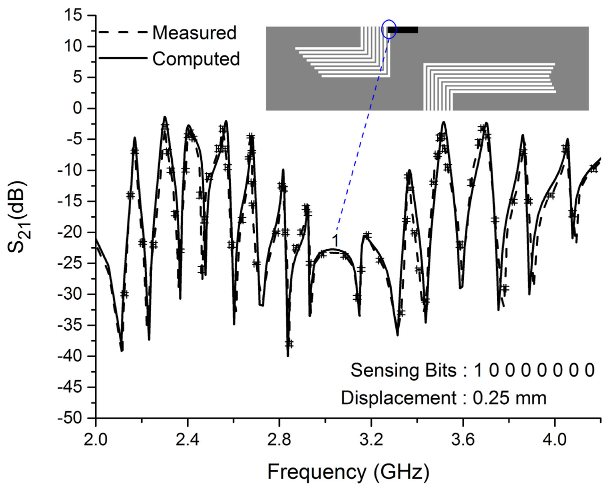

Fig. 5. Measured and computed frequency response with 0.25 mm displacement.

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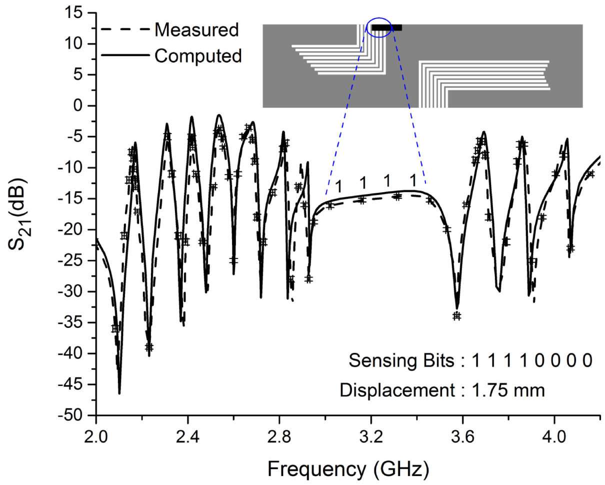

Fig. 6. Measured and computed frequency response with 1.75 mm displacement.

5 Conclusion

A novel sensor circuit capable of sensing displacement along a single dimension is proposed. Variation in frequency signature of multi-resonant spurline resonators is leveraged to record linear displacement as small as 0.25 mm. The proposed chipless RFID sensor circuit, capable of operating in full-wireless mode, is a potential candidate for deployment in IoT-based smart buildings.

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