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RESEARCH ARTICLE

Detection of Reinforced Concrete Blocks Using Two-Port Microwave CSRR Sensor

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ABSTRACT In this paper, the design, fabrication and testing of a two-port transmission line-based microwave sensor for the detection of various structural concrete bricks is presented. The microwave sensor is based on the complementary split-ring resonators (CSRRs). First, three dimensional small-scale concrete building bricks are modeled in CST microwave studio along with the design of the microwave CSRR sensor. Classical controlled concrete blocks along with concrete mixed with wood are also studied. The detection capability is then evaluated both numerically and experimentally. Good agreement between numerical and measured results are achieved. Based on the obtained results, the microwave CSRR sensor was sensitive enough to detect various concrete/reinforced concrete blocks with achieved sensitivity of maximum resonance shift of 350 MHz for concrete blocks, while a shift of 150 MHz was obtained for the case of reinforced concrete blocks. From the findings of this research study, the developed microwave CSRR sensor is a good candidate for pre-screening of structural buildings and classification of reinforced concrete samples in a controlled laboratory environment.

INDEX TERMS Concrete, CSRR, microwave sensor, reinforced concrete, structural engineering.

I. INTRODUCTION

Recently, there have been much interest in the development of smart, miniaturized and self-deployed sensors from both industry and academia. This is due to the dramatic advancement in electronics from chips to system level as well as in the design of sensory elements. Moreover, design and development of sensors technology have played a major role in tackling a wide range of engineering and science problems, including medical diagnostics [1], [2] and biosensing applications [3], [4], [5], defects in metallic objects, for example in aircraft fuselage [6], [7], [8], [9] and structural materials [10], [11], [12], among others.

Concrete blocks are considered artificial man-made stone type mass products and are very essential building units in engineering construction, for instance, buildings, bridges, and roads. In principle, concrete composite often consists of cement paste, coarse/fine aggregates (e.g. gravel, sand, etc) chemicals (if necessary), and water that are mixed based on specific proportions [13]. It is well known that the strength and density of concrete bricks is dependent on the mixing proportions of aggregates [14], [15]. While cement paste constitutes about 25% of the total concrete volume, aggregates take about 60% of total concrete volume [14]. Therefore, it is very important to consider the appropriate mixture of aggregates in order to maintain the desired strength and the expected resistance to any kind of exposure conditions.

Among many different categories of concrete blocks, three of the most used ones in the engineering constructions are the hollow, solid and foamed blocks. Solid blocks are more heavier than the hollow ones and are less expensive, while the foamed concrete has much low density [16]. In recent years, the use of light-weight concrete blocks, also known as *Autoclaved Aerated blocks*, is popular, due to their light

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weight, sound proof, environmentally friendly and providing high degree of temperature insulation [17]. Most often, civil structures are constructed from reinforced cement-based concrete materials. The structures are usually designed to carry certain amount of load for certain period of time.

Due to the improper mixing of water within the concrete blocks, such blocks are more profound to degradation and damage, especially defects and cracks. Moreover, due to unpredictable excessive load and environmental effects, the strength of concrete blocks degrades with time. Such degradation and defects present great threats to civil structures.

One of the commonly adopted procedure to track any concrete defects is through manual inspection by professionals. However, the inspection task is in fact costly, time consuming and often requires professional personnel to carry out a lengthy process of identifying threats due to concrete deficiencies. The time that manual inspections could take depends on the severity of the concrete degradation. There are also other nondestructive testing (NDT) techniques that are practiced in cracks' detection in concrete or cement-based materials, including ultrasonic [18], [19], infrared thermography [20], [21], impulse radar testing [22], [23] and vibration techniques [24]. Two commonly deployed methods using ultrasonic technique in order to detect defects in reinforced concrete materials are ultrasonic tomography (UT) and ultrasonic pulse velocity (UPV). While the UT provides surface distribution of the scanned area, UPV provides more details about any potential internal defects through velocity measurement of long-wavelength pulses that are injected through a transmitting sensor. Authors in [19] presented a two-port ultrasonic-based transmission model to detect and map phase variation of ultrasonic signatures within concrete structures with defects using S-Transform, which combines both Fourier and Wavelet Transforms. On the contrary side, the use of infrared thermography is common nowadays, which aids to detect voids and other anomalies in concrete structures, including inspecting water entry into buildings. Its main principle of operation lies on detecting invisible infrared energy from surrounding objects. Another interesting NDT technique is the use of microwave imaging, which has been valuable in many engineering and science disciplines, including structural engineering [25], [26], [27]. Several research studies have also investigated the effect of moisture contents on the health status of concrete [28], [29]. It is expected that presence of moisture may lead to variation to chemical structure of the concrete and thus may cause deterioration and failure over a long time. We highlight here that some of the earlier introduced sensing modalities were either large in size and often limited in their resolution.

It is worth noting here that earlier studies have focused on development of radio-frequency/microwave sensors in order to detect cracks within metallic surfaces and subsurfaces [6], [7], [8], [9]. Due to the nature of metallic surfaces and materials, high reflectivity signature is expected from such surfaces and thus detection of small abnormalities in metallic surfaces is quite straightforward and more noticeable. There have been limited studies focusing on the detection of either fine defects in aggregates or estimating moisture in concrete blocks [10], [11], [12]. However, earlier studies have used sensing units with large aperture area and have not looked over potential deployment of resonant sensors for detection and classification of reinforced concrete blocks.

In this research work, we present the design, simulation and test of the sensing capability of microwave-based Complementary Split-Ring Resonators (CSRRs) sensor for the detection of various reinforced concrete blocks. The microwave sensor is based on the design of engineered resonant elements that are etched from a metallic ground layer. The detection mechanism of the presented microwave CSRR sensor stems from the ability of the sensor to greatly interact in the near-field region with materials having different electric/magnetic properties. Moreover, through the transmission of electromagnetic energy via two port transmission line, visualization of scattering electromagnetic waves provide meaningful quantitative measures of the detection and sensitivity capability of the microwave CSRR sensor.

To the best of our knowledge, this research problem has not been addressed in the literature, where two-port narrowband microwave sensor is adopted, as opposed to many earlier studies that focused on the use of a single-port sensing taking into consideration the reflected echo (whether long or short wavelength) from the concrete structure. We highlight here that narrowband sensing is of an advantage in this work in order to provide better means of detection to fine substances within the reinforced concrete structures. Our main contributions in this work are summarized below:

1) Design of a two-port CSRR microwave sensor to assess the sensor's strength in differentiating between various structural concrete/reinforced concrete materials. Thus, the method aims to gain more insight from the electromagnetic radiation and its interaction with reinforced concrete layers;
2) Earlier proposed sensing methods proposed wideband or ultra-wideband microwave antenna structures. However, we focus here on proposing a narrowband near-field microwave sensing based on engineered structure, also known as metamaterials.
3) Develop 3D numerical scenarios for concrete and reinforced concrete blocks using CST Microwave Studio (MWS) [30], taking into consideration all materials' electric properties and losses;
4) Build various concrete/reinforced concrete blocks, after careful preparation of specific aggregate mixture substances;
5) Test and assess the detection strength and sensitivity of the developed microwave CSRR sensor numerically and experimentally when enteracting with various concrete building blocks.

The rest of the paper is organized as follows. Section II provides overview of concrete and reinforced concrete and procedures used by structural engineers in preparing such

TABLE 1. Details of the prepared reinforced concrete samples with their replacement ratio, and aggregates' percentages.

Type	Replacement ratio	Steel slag (g)	Cement weight (g)	Water weight (ml)	Compressive strength (MPa)	Sample weight (g)
Conc-1	0%	0	500	145	1.273	282
Wood-3	2.5%	13	487	160	0.784	214
Wood-4	5%	25	475	150	0.289	185
Wood-5	7.5%	38	462	170	0.495	193
Wood-6	10%	50	450	180	0.635	197
Wood-7	12.5%	63	437	170	0.669	210
Wood-8	15%	75	425	145	0.696	225

blocks. Section III presents the 3D numerical model along with the microwave CSRR sensor. Section IV presents both numerical and experimental results. Finally, section V summarizes the research work and highlights the findings from this paper.

II. OVERVIEW OF CONCRETE/REINFORCED CONCRETE MATERIALS

Concrete is defined as composite materials consisting of cement, water, fine and coarse aggregate and admixture. Concrete is subjected to a wide range of different conditions, such as environmental, pollution and weather conditions. In order to maintain the integrity and strength of concrete building blocks, such blocks are composed of various ingredients. The function of this composite material depends on its constituents. If the constituent is strong enough, then the concrete will be more sustainable and robust enough.

A. MIX DESIGN AND PROPORTION

The mixture was prepared according to ACI 211.1 standard recommended mixture design for concrete [31]. The specimens were made of 7 groups of Saudi wood powder and steel slag. Each group consists of different amount of steel slag from cement weighing between 0% to 15% and constant amount of wood powder at 5% of fine aggregate weight passed sieve 425 micron. Note that for the reinforced concrete samples, the cement was replaced by different percentage of steel slag, fine aggregate was replaced with wood powder and coarse aggregate was kept constant. Table. 1 shows details of the reinforced concrete samples with their prepared aggregates' percentages.

B. MECHANICAL PROPERTIES OF THE PREPARED SAMPLES

The mechanical properties of the samples were examined according to ASTM standards using Infaratest Compression and bending machine. The compressive strength and unit weight of the concrete specimens was performed after a period of 7 days. The results have been collected and tabulated as shown in Table. 1. It can be inferred from Table. 1 that the wood powder generally decreases the weight of the sample and the steel slag generally increases the strength and density of the specimens. Fig. 1 depicts the compression tests that were performed during the preparation of the reinforced concrete samples.

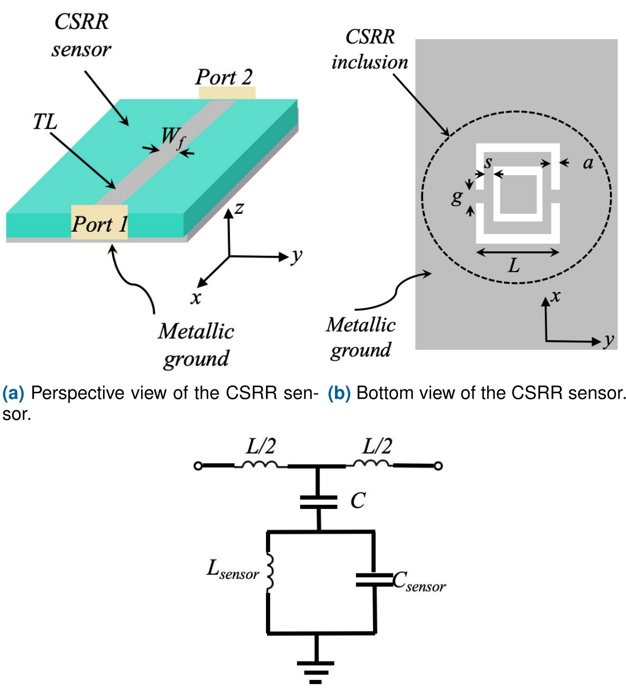
FIGURE 1. Snapshot showing the compression test for one reinforced concrete sample in a controlled laboratory.

III. PROPOSED MICROWAVE DETECTION SETUP

In this section, we present the design and numerical setup of the microwave CSRR sensor for the detection of various reinforced concrete blocks. Fig. 2 depicts the design of the microwave CSRR sensor. In this work, the 2.4 GHz ISM band is targeted, where a two-port (50 Ω) transmission line sensor was designed and its sensing strength was assessed through sensing various reinforced concrete blocks. The CSRR unit inclusion is etched out from a grounded metallic sheet, as shown in Fig. 2(b). The microwave sensor is compact in size, very thin and has an area of 40 × 40 mm^2. The sensor is fabricated on Rogers/Duroid laminate with its electric properties of $\epsilon_r = 3.55$, $\tan\delta = 0.0027$, and thickness of 0.813 mm. The main resonance frequency of the developed microwave CSRR sensor can be understood from its quasi-static equivalent circuit, which is presented as shown in Fig. 2(c). The resonance frequency of the CSRR sensor is determined by the two concentric complementary rings structure (see Fig. 2(b)), which is given mathematically as:

$$f_{res} = \frac{1}{2\pi\sqrt{L_{sensor}C_{sensor}}} \tag{1}$$

where L and C are the inductance and capacitance of the printed circuit board, respectively, while L_{sensor} and C_{sensor} are the total distributed inductance and capacitance of the two concentric complementary rings, respectively.



(a) Perspective view of the CSRR sensor. (b) Bottom view of the CSRR sensor.

(c) Equivalent circuit model of the CSRR sensor.

FIGURE 2. Proposed CSRR-based microwave sensor.

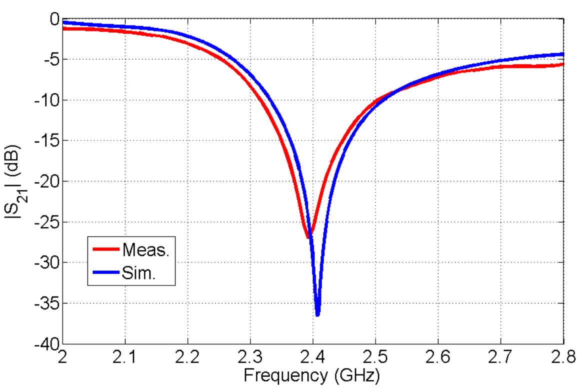


FIGURE 3. Simulated and measured transmission coefficient for the microwave CSRR sensor.

For calibration purposes, the microwave CSRR sensor was designed and simulated alone (considered as a reference) to resonate at a frequency of 2.4 GHz. The sensor was fabricated and also tested using two port vector network analyzer. Fig. 3 shows the simulated and measured transmission coefficient magnitude, $|S_{21}|$, for the microwave CSRR sensor. Good agreement between simulated and measured $|S_{21}|$ was achieved.

Next, we present the 3D numerical setup for the microwave CSRR sensor on top of reinforced concrete blocks. In order to achieve high degree of sensitivity, the sensor was placed directly touching the reinforced concrete blocks. Fig. 4 depicts a sketch of the 3D numerical setup used in CST MWS. For convenience, the concrete blocks have a square cross-sectional area, which fits the footprint area of the microwave

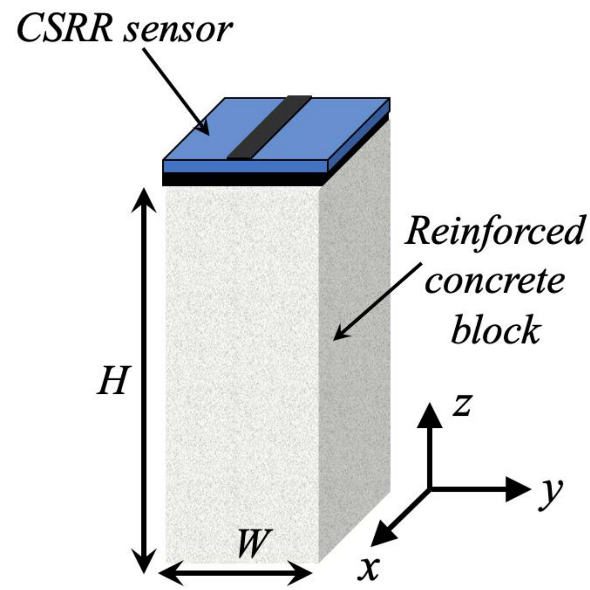


FIGURE 4. 3D schematic of the proposed microwave detection setup using the microwave CSRR sensor.

TABLE 2. Dimensions of the optimized microwave CSRR sensor and the reinforced concrete block under test.

Symbol	Dimension (mm)
L	7.5
a	0.3
s	0.6
g	0.5
W_f	1.85
W	40
H	160

sensor. Table. 2 presents the optimized dimensions of the CSRR sensor along with the 3D dimensions of the reinforced concrete blocks.

Among other materials, concrete and reinforced concrete materials have their own distinctive complex permittivity profile. It is then essential to keep in mind the constitutive parameters in terms of electric permittivity and magnetic permeability of such samples while designing the microwave sensor and the numerical system model. In fact, there are plenty of research studies in the literature that aimed to characterize and estimate the complex permittivity of concrete/reinforced concrete materials, among other structural materials, for instance the work in [32], [33], [34], [35], [36], and [37]. We note here as well that all electric properties of the concrete/reinforced blocks are considered in the simulation models, including the losses and materials' density. Fig. 5 depicts the complex electric permittivity profile (both real and imaginary components) of concrete material that is adopted in the numerical studies and is available from the numerical materials library package of CST MWS [30]. The concrete material is considered being completely dry, i.e. dryness made for over 10 months. To be more specific on the adopted electric permittivity values of the concrete blocks at the operating frequency of the microwave CSRR sensor (2.4 GHz), the dielectric constant is around 5.5 (see Fig. 5), while its imaginary component is 0.30.

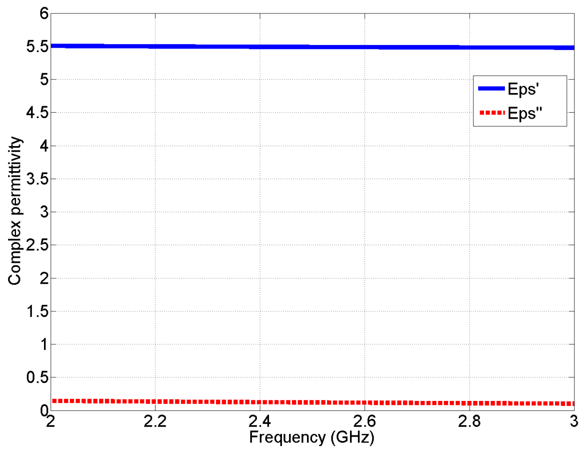


FIGURE 5. The complex permittivity profile of dry concrete material as a function of frequency.

FIGURE 6. Snapshot showing 5 random samples of concrete/reinforced concrete blocks.

In Fig. 6, we present samples of the reinforced concrete blocks, as discussed in Section II, where the numbers indicate the mixture percentage of the ingredients: concrete, wood and steel. To have a fair comparison study, all the fabricated blocks have the same cross-sectional area of $W \times W$ and same height, H.

IV. RESULTS AND DISCUSSIONS

It is expected that electric properties of concrete materials could make substantial changes to the strength and sustainability of the concrete blocks, depending on their dry period and the mixture ingredients. We investigate next the effect of dielectric constant of the concrete block on the microwave sensor's resonance. Fig. 6 depicts a parametric study showing the effect of electric permittivity on the sensor's sensitivity. As shown, the sensor's sensitivity tends to increase as the dielectric constant of the concrete blocks increases.

In order to visualize the strength of the microwave CSRR sensor, we present a one-dimensional plot of the electric field strength along the side length of the CSRR sensor as depicted in Fig. 8, where the CSRR inclusion is located at the center of the sensor. We can observe from Fig. 8 significant field strength that is more dominant at the CSRR's cuts, i.e. gaps of the CSRR sensor. This is an indication of the strong resonance

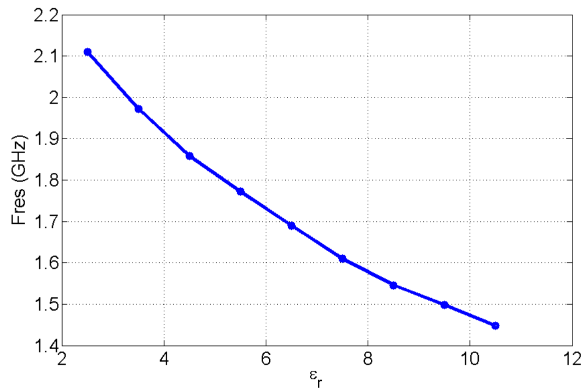


FIGURE 7. Numerical parametric study showing the effect of dielectric constant on the sensing capability of the developed sensor.

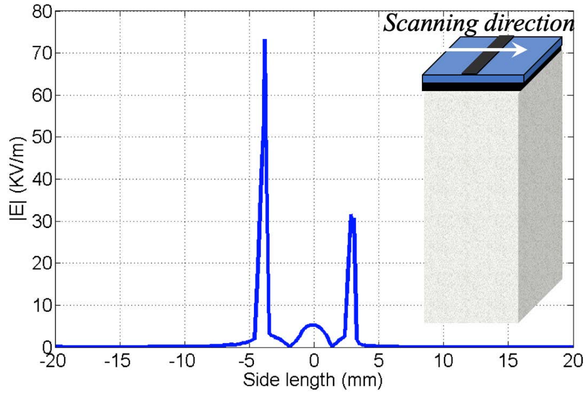


FIGURE 8. A one-dimensional plot showing the electric field strength along the side length of the microwave CSRR sensor.

of the developed microwave sensor while placed on top of a concrete sample. Another observation is that the electric field at the inner cut of the CSRR is more stronger than the field at the outer cut. This is attributed to a stronger resonance due to an associated inner capacitance between the rings.

We present next a numerical setup for a reinforced concrete block sample with wood rod, as shown in Fig. 9. The rod is made of a cylindrical shape with diameter D and height H as the reinforced concrete block. A numerical study is then made by varying the radius of the wood rod and investigating the effect on the sensor's resonance frequency and strength in terms of $|S_{21}|$. The electric permittivity of the reinforced concrete block is numerically modeled by defining the concrete block with its complex permittivity profile as defined in Fig. 5, and then enforcing the electric permittivity of dry wood in the modeled cylindrical rod, with its dielectric constant of 1.8 and its imaginary component of 0.30, where such dielectric properties have already been measured at the ISM frequency band in [38].

Fig. 10(a) depicts the effect of increasing the radius on the resonance frequency of the microwave sensor. From Fig. 10(a), we can observe that by increasing the radius of the wood rod substance inside the concrete block, the resonance frequency of the microwave CSRR sensor shifts to higher frequencies, reaching around 2.25 GHz when the radius of the wood rod is equal to 10 *mm*. The increased shift in the

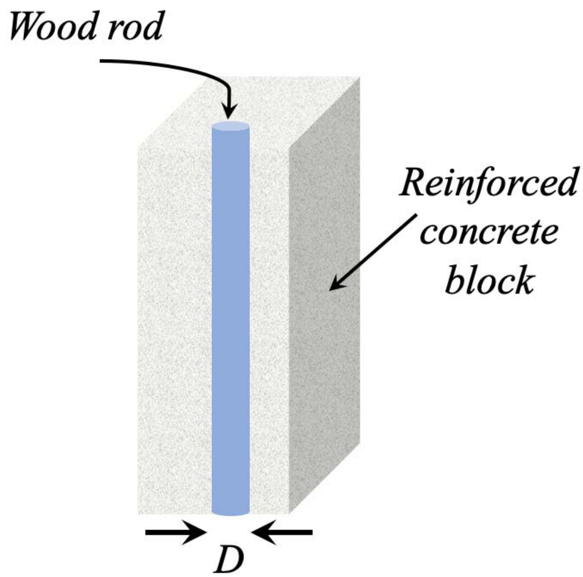
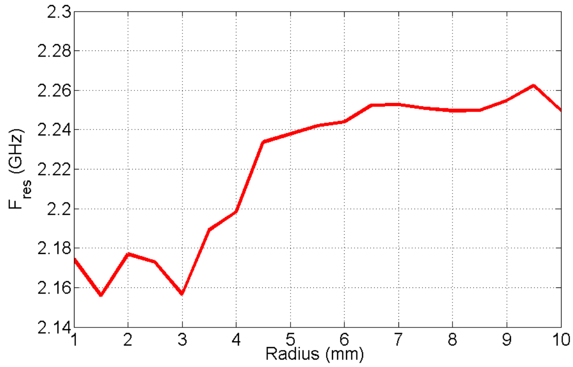
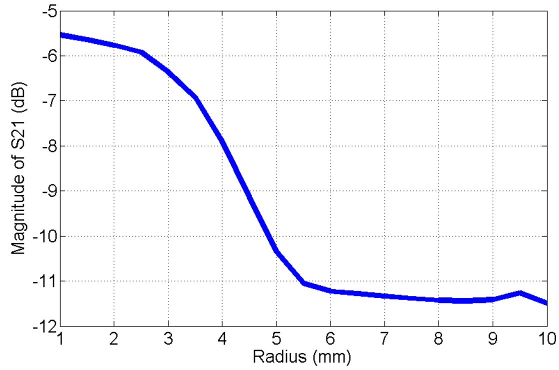


FIGURE 9. 3D view of a numerical model for a reinforced concrete sample with wood substance in CST MWS.



(a) Effect of wood substance on sensor's resonance frequency.



(b) Effect of wood substance on sensor's strength

FIGURE 10. Numerical parametric study showing the effect of the wood's radius on the sensor's resonance frequency and its detection strength. Note that the *x*-axis indicates the radius of the wood = *D*/2 (see Fig. 9).

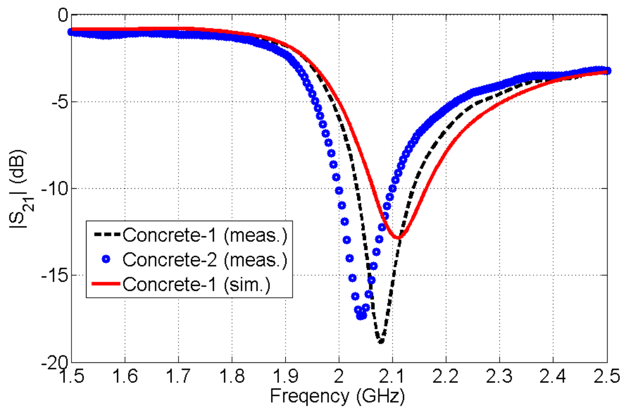


FIGURE 11. Measured and simulated transmission coefficient for the detection of concrete-1 block sample using the microwave CSRR sensor.

resonance frequency of the CSRR sensor while increasing the diameter of the modeled wood substance is attributed to the increased replacement ratio, as illustrated in Table. 1. The strength of the microwave sensor while sensing various concrete block samples is measured next through recording the magnitude of the transmission coefficient, S_{21}. As shown in Fig. 10(b), the strength of the microwave sensor's resonance increases, as the wood's radius increases, where the dip of $|S_{21}|$ was at -11.5 dB when the radius of the wood rod is equal to 10 mm.

For validation purposes with measurements, we carried out a comparison between simulation and measurement for one particular concrete sample (concrete-1), as depicted in Fig. 11. Very good agreement between simulation and measurement results can be seen for the detection of concrete-1 block sample. Moreover, the shift in the dip of the transmission coefficient of the sensor is very minimal for the concrete-1 sample when compared between simulation and measurement results, while the shift is quite large, since the simulated block sample is mimicking the composite substances of concrete-1.

After carrying out a series of trials with different concrete/reinforced concrete block samples (see Fig. 6), it is evident from the measured data that each concrete/reinforced concrete type has its own unique signature. Fig. 12 depicts the measurement results for the microwave CSRR sensor when placed on top of the prepared samples. As shown in Fig. 13, variation of the percentage shift in the resonance frequency of the CSRR sensor is correlated with the type of concrete, which is an indication that our developed sensor is effective in differentiating between various reinforced concrete blocks.

Next, we present a comparison of our developed microwave sensor with various sensors proposed in the literature. Majority of the developed microwave sensors focused on detection of abnormalities in metallic surfaces. Furthermore, no earlier attempts focused on the deployment of microwave CSRR sensor for detection/classification of reinforced concrete samples.The microwave CSRR sensor in this work has been mainly developed to examine its sensing strength and capability for concrete and reinforced concrete samples. Moreover, the achieved sensitivity capability of the developed CSRR sensor has resulted in a frequency shift by 150 MHz for reinforced concrete block (reinforced wood-8 sample), while the sensing frequency resulted in a shift by 350 MHz for pure concrete blocks. Based on the numerical and experimental results, our sensor has been found suitable for rapid characterization and classification of various reinforced concrete blocks.

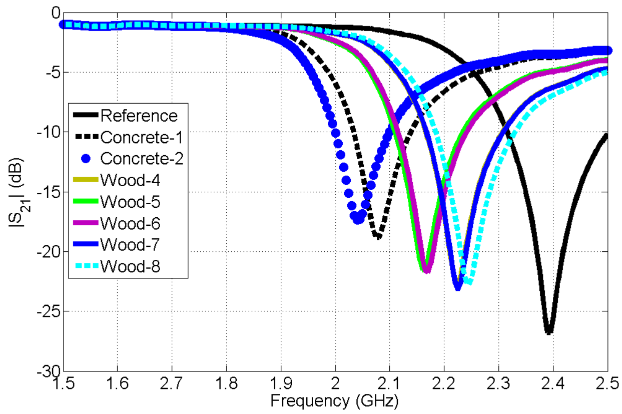


FIGURE 12. Measured transmission coefficient for the microwave CSRR sensor when sensing various concrete/reinforced concrete blocks.

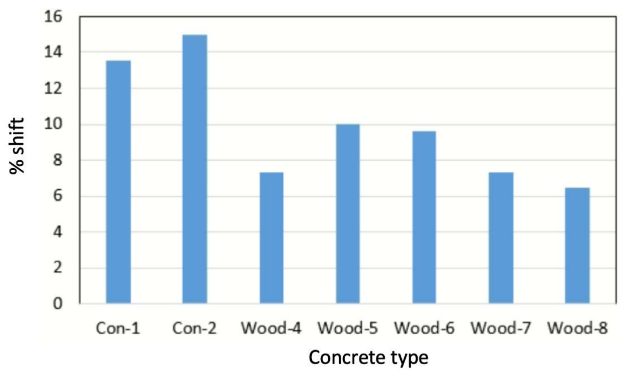


FIGURE 13. The % frequency shift in microwave sensing of various concrete/reinforced concrete samples.

TABLE 3. Comparison of the developed microwave sensor for reinforced concrete samples detection with other published techniques.

Ref.	Sensor Type	Sensor Size	Application	Sensitivity
[7]	SIW-CSRR	0.20λx0.20λ	metallic objects	f_{res} shift by 220 MHz
[8]	RFID sensor	0.55λx0.23λ	metallic objects	f_{res} shift by 15 MHz
[10]	microwave probe	-	moisture on concrete	-
[11]	antenna	-	defects in concrete	detect 2cm rods
[12]	waveguide sensor	-	moisture on concrete	-
This work	CSRR	0.06λx0.06λ	differentiating between reinforced concrete samples	f_{res} shift by 150 MHz

V. CONCLUSION

In conclusion, we presented a microwave CSRR sensor to aid in the detection of various reinforced concrete blocks. The microwave sensor has been designed in the 2.4 GHz ISM-band, to allow for sufficient electromagnetic wave penetration within the reinforced concrete blocks. The sensor is compact in size and fabricated using low cost printed circuit board technology. By measuring the transmission coefficient between two ports of the microwave CSRR sensor, an appreciated shift in the sensor's resonance gives distinctive signature of the detection capability in assessing various reinforced concrete blocks.

Based on the obtained numerical and experimental results, the microwave CSRR sensor was sensitive enough to concrete blocks with a maximum resonance shift of 350 MHz, while a shift of 150 MHz was obtained for the case of reinforced wood-8 case. From this experimental study, it is believed that microwave CSRR sensors will provide significant advancement to detection of concrete-based materials and further detection of cracks.

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