Embedded Split Ring Resonator Network for Health Monitoring in Concrete Structures

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Civil infrastructure systems such as bridges, buildings, dams, pipelines, airports, and heritage structures, are complex engineered systems that play a fundamental role for the economic and industrial prosperity of the society [1]. In order to build structures that are safe for the community, standardized design methodologies have been developed [1]. However, these structures are often subjected to various external loads and problematic environmental conditions that are difficult to consider during the design phase, resulting in structural deterioration [2].

Evaluating the health condition of civil infrastructures is of crucial importance in order to avoid any failure and for planning maintenance actions [3]. As an example, the closure of a bridge due to heavy damage can affect economically thousands of people and, eventually, its failure may cause loss of several lives (e.g., Morandi bridge, collapsed August the 14th, 2018).

For the above-discussed reasons, the process of implementing a damage detection strategy, i.e. Structural Health Monitoring (SHM), is nowadays a hot research topic of structural engineering [4]. By monitoring actual load and strength of structures, the uncertainty in design calculation, that represents a key factor for safety, can be reduced. Hence, the residual life of existing structures can be accurately evaluated and at the same time, a proper repair or strengthening, based on the monitored state, can extend the life of the structure [5]. Moreover, monitoring is a cost-effective solution to preserve civil infrastructures, particularly in developing countries, because monitoring and repair cost is much lower than the cost for reconstruction [5].

SHM involves the integration of sensors, smart materials, data transmission, computational power, and processing ability integrated with the structures [6].

In particular, sensors and technologies should be able to detect the problem without interfering with the structure. A lot of research articles have been reported on sensors for SHM. Strain gauge sensors for measuring the degree of strain have been widely used in conventional SHM systems [7]. Not only strain gauge systems are inexpensive and easy to install, but also knowledge on interpreting strain data has been consolidated. The system proposed in [7] can diagnose structures and can be easily extended to large buildings at low cost. MEMS inertial sensors, including accelerometers and gyroscopes, can be used as devices for health monitoring of structures due to their miniaturized size, low cost, mass production and three-dimensional detection [8]. A new impedance measurement methodology for a SHM system based on electromechanical impedance technique is described in [9]. The system offers precision, speed, low cost, and versatility and can be integrated into a system based on a microcontroller DSP and, together with a wireless communication system, allows monitoring of structures whose access is difficult. A fiber-optic accelerometer system has been presented in [10] consisting of a sensor head, a control unit for driving the sensor head and a signal processing unit equipped with a dedicated algorithm for processing the Moiré fringe signals into accelerations with a high resolution.

Wireless sensor network (WSN) based structural health monitoring systems have attracted increasing interest in recent years [11]. The implementation of a WSN for monitoring structural health parameters is shown in [12], where a network of different interconnected nodes is presented, providing different measurements (e.g., temperature, humidity, and deformation). In [13] a measuring system is presented, consisting of wireless sensor modules which act as transmitters and receivers. They are equipped with strain gauges for long-term monitoring of buildings or engineering facilities and contain interfaces for additional sensors. The system is applied for transport and traffic structures. A chipless passive wireless strain and damage detection sensor realized by using a frequency selective surface (FSS) is presented in [14]. The FSS consists of planar and periodic metal–dielectric arrays that are based on electromagnetic resonance shift in the presence of a geometric change of the FSS elements. In [15] a SHM system has been proposed, aiming to enable the automatic and real-time monitoring of a reinforced concrete structure. Attention has been focused on a load cell and an analog temperature sensor to directly measure the concrete inner stresses and the temperature where they are installed, respectively.

Recently, EM sensors have received interest for the monitoring and the prediction of moisture content in concrete structures [16]-[18]. In [16] a microstrip patch antenna for evaluating moisture content and the resulting deterioration in concrete structures is presented, embedded inside the concrete structure for real-time monitoring. Possible use of EM waves for determining leakage of a concrete flat roof, as a result of failure of the waterproof membrane layer, is described in [17], where a study on the EM wave propagation through the roof and its interaction with water is conducted experimentally. In [18] split ring resonator (SRR) sensors are considered as a potential solution for the detection and prediction of crack propagation in reinforced concrete beams, demonstrating that this kind of sensor can monitor crack widths lower than 1 mm and therefore that further study of these sensors would be very useful to monitor cracking in concrete structures.

In this article, we investigate the possibility to use a split ring resonator network, with a single feeding line, in order to monitor cracks in the concrete and identify crack location with a single measurement. To the best of the authors' knowledge, in the literature there are no devices that have reached a promising level of maturity that ensure a widespread monitoring at low cost. Exploiting microstrip technology, a diffused monitoring can be achieved together with the possibility to use a low-cost, light and adaptable sensor.

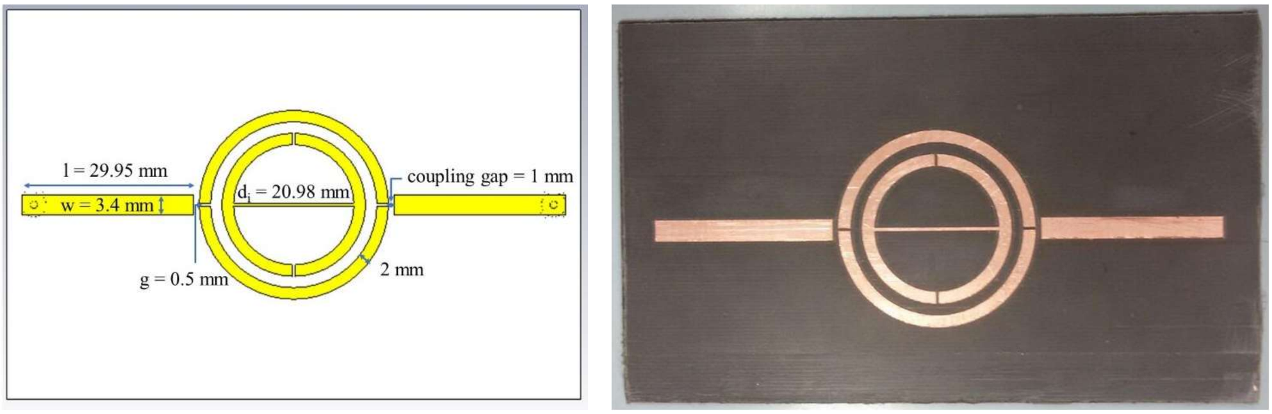
The paper is organized as follows: first the design of the SRR is presented, then simulations and experimental results are discussed in order to show the validity of the idea. A simple network is then designed and simulated embedded in a concrete block. Finally, conclusions are drawn.

Split Ring Resonator

SRRs have important properties and have been widely investigated in literature for the dielectric characterization of solid, liquid and granular materials, showing high measurement sensitivity, high quality factor and small dimensions, not requiring a particular sample preparation [19]. The study of these structures is based on the analysis of the resonance frequency, which varies if the SRR is in contact with a material sample in relation to the dielectric and geometric characteristics of the structure itself.

Design

The SRR basically consists of metal tracks on a dielectric substrate. These tracks consist of concentric rings, circular crowns, with cuts along a diameter, hence the name of the resonator: "Split Ring". There are various types of SRR, which differ mainly in their geometric characteristics [20]. The number of "splits", the split width, the gap between the inner and outer ring, and the width of the metal strips forming the ring are significant in determining the resonant frequency, therefore all these factors are considered in the SRR design.



(a) (b)

Fig. 1. Geometry of the SRR designed with CST (a); realization of the resonator (b).

The SRR behaves like an LC resonator, whose basic circuitry is shown in [21]. Among many SRRs used in the literature for various microwave applications, here the focus is on SRRs used in the dielectric permittivity characterization of a material under test [18, 19]. As can be seen from Fig. 1, the resonator basically consists of metal tracks on a dielectric substrate and, to complete the geometry, there are two larger microstrips on the sides of this ring, which are used to access the resonator in a transmission configuration, while a smaller one is placed along the diameter of the innermost circular crown [22, 23].

Starting from SRRs for microwave application present in literature [22, 23], attention has been focused mainly on geometry and characteristics of SRRs used for the dielectric characterization of solid, liquid and granular materials [24]-[27]. In particular, SRRs with high sensitivity, high quality factor, small size, and that do not require a particular sample preparation have been considered [22, 28]. The design has been conducted using the EM CAD CST Microwave Studio [29]. Multiple factors were considered for the substrate choice, starting from the performance of the resonator, focusing on the quality factor and possible dispersion effects and other practical needs. First of all, it has been necessary to examine the thickness of the substrate, since this affects both the losses and the practical requirements for measurement. For the latter it is easy to understand that the greater the thickness the greater the strength of the resonator. In fact, it is essential not to bend the resonator, in order to ensure a good repeatability of the measurements and, above all, to preserve a high accuracy. To determine the suitable substrate, simulations were performed with CST software, using various substrates available in the laboratory. From the analysis of the transmission coefficient (S_{21}) and the quality factor, the Duroid RT-5870 with thickness h = 1.19 mm was chosen. The characteristics of the RT Duroid 5870 substrate are: $\varepsilon_r = 2.5$; loss tangent = 0.0012; t = 0.035 mm, where t is the thickness of the copper.

The feeding microstrip width is defined following the formulas in [30], and the radius of the circular crowns are derived from [22]. The remaining quantities are determined on the basis of the limits imposed by the prototyping machine present in the laboratory, and above all, by the results obtained by the optimization carried out by CST. The final structure deriving from the simulations has an air transmission coefficient S_{21} shown in Fig. 2, with a quality factor equal to about 160. It has been realized with a milling machine and the prototype is shown in Fig. 1b.

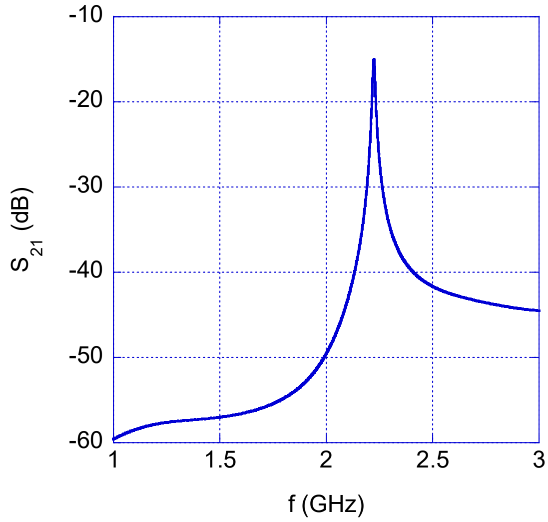


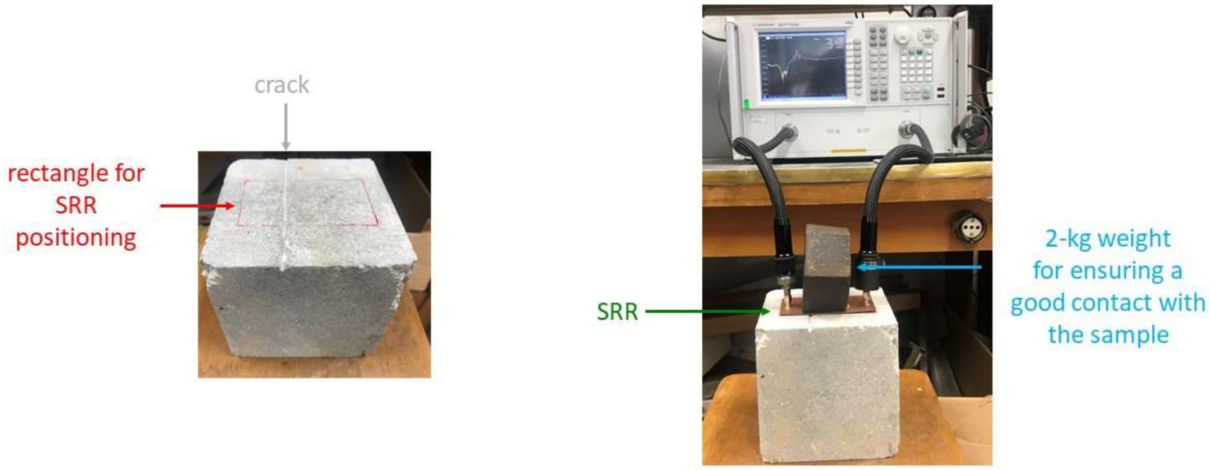
Fig. 2. Simulated transmission coefficient of the SRR in air.

Preliminary Validation

The SRR is simulated in contact with a concrete block, whose dielectric parameters (ε_r and loss tangent) have been found through measurements on a real concrete sample (Fig. 3a) C25/30 class (UNI 11104). The concrete is classified in strength classes, based on compressive strength, expressed as characteristic strength f_{ck} or R_{ck}; for each resistance class, the first of the two values represents f_{ck} (25 in this case) defined on cylindrical samples, and the second R_{ck} (30) defined on cubic samples, both expressed in N/mm^2.

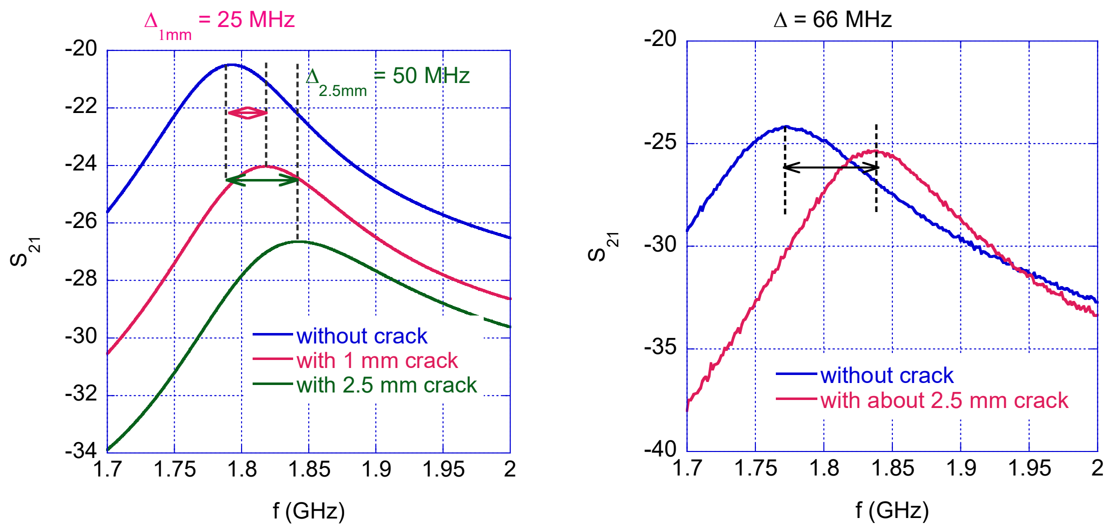
The simulated transmission coefficient, i.e. the ratio of the power transmitted at the output port (port 2) to that of the input power (port 1) at the resonator, is shown in Fig. 4a. The figure shows both the results with a whole concrete block and with the same block with one crack of variable width. The considered simulated crack is 3 cm in length, 10 mm deep and has a width of 1 mm or 2.5 mm.

In order to validate simulation results, measurements have been conducted with a Keysight E8363C PNA Vector Analyzer. The experimental set-up, composed by the PNA and the SRR in contact with the block with a 2-kg mass placed on the ground plane, is depicted in Fig. 3b. Even if in this preliminary validation the resonator is not embedded in the concrete, but only in contact with it, this is representative of realistic conditions since the material behind the ground plane does not influence the resonance. Ten repeated measurements on the whole concrete block have been carried out, showing a mean resonant frequency of 1.7774 GHz with a standard deviation of the mean σ_M = 2.5 MHz. These results confirm simulation results represented in Fig. 4a. Then the block has been damaged creating a crack that is approximately 2.5 mm wide. Repeated measurements have been conducted that highlighted a mean resonance frequency equal to 1.8436 GHz with a σ_M = 1.4 MHz, with a frequency shift of about 66 MHz. Results are shown in Fig. 4b.



(a) (b)

Fig. 3. Picture of the concrete block with the crack (a) and experimental set-up composed by a Keysight E8363C PNA Vector Analyzer and the SRR in contact with the block with a 2-kg mass placed on the ground plane (b).



(a) (b)

Fig. 4. Transmission coefficient obtained for the SRR in presence of the concrete block with and without the crack: CST simulations (a) and measurements (b).

SRR network

In order to discriminate the localization of the crack in the concrete, a SRR network that consists of different resonators, each one with a different resonance frequency is studied. In particular, simulations of a network composed by two split ring resonators are proposed for simplicity sake. In future developments of the work, it is planned not only to extend the number of SRRs as required for the application, but also to carry out experimental validations in a realistic environment.

The second SRR, that is a scaled version of the one represented in Fig. 1, has a resonance frequency in air equal to 2.81 GHz. In order to obtain the results for both SRRs with a single measurement, a Wilkinson power divider is designed [31] using the AWR Microwave Office software [32]. The measurement scheme is shown in Fig. 5, where the layout of the system is also depicted. As can be noted from the figure, the same Wilkinson power divider can be used for the receiving unit of the system. In this way, from the received signal it can be detected if there is a crack in the structure or not and, if it is present, to identify its location (based on which of the two resonance frequencies has shifted). The network can be easily extended adding an adequate number of sensors.

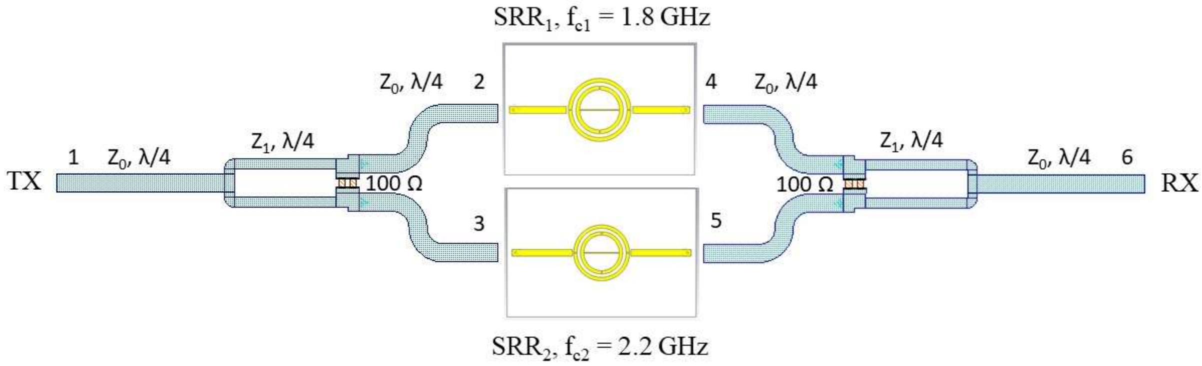
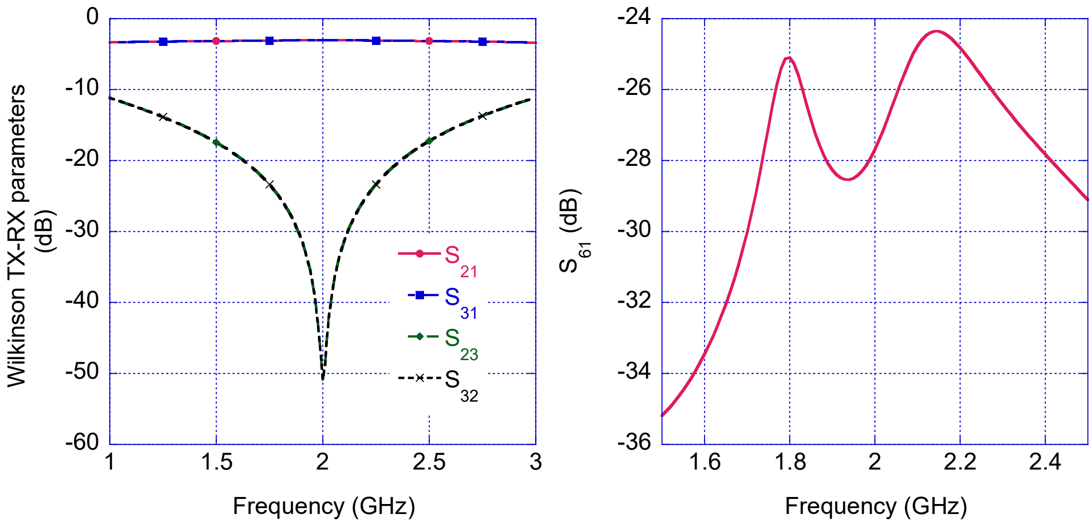


Fig. 5. Scheme of the proposed monitoring system.

The transmitting and the receiving properties of the Wilkinson power divider are shown in Fig. 6a. Since the two split ring resonators, when embedded in the concrete, work at about f_{c1} = 1.8 GHz and f_{c2} = 2.2 GHz, the power divider is designed in order to have an operational frequency band centered around 2 GHz. The transmitting coefficient is equal to –3 dB while the isolation between the port 2 and 3 is lower than -30 dB at f_{c1} and f_{c2}. These properties can be easily improved if the number of the SRRs increases, using an ultra wideband Wilkinson power divider using binomial multi-section matching transformers [31].

The whole system depicted in Fig. 5 has been simulated within Microwave Office to analyze the transmission properties (S_{61}) of the complete network. Results are shown in Fig. 6b. In particular, the simulation considers the two SRRs in the presence of the concrete block without the crack; as expected, the two resonance frequencies are clearly discernible, pointing out the possibility to detect the crack and even to localize it.



(a) (b)

Fig. 6. Wilkinson power divider transmission and reflection coefficients (a), transmission coefficient of the entire system (b).

Conclusions

In this paper, a structural health monitoring system based on a split ring resonator network is proposed, with the aim of achieving a very sensitive EM sensor to detect cracks in concrete structures. The network is composed of sensors with different resonance frequencies in order to both monitor and localize the crack. Simulation results show that this kind of sensor is able to detect a crack in the concrete analyzing its resonance frequency. If a frequency shift is present it means that dielectric characteristics of the structure where the sensor is embedded have changed, pointing out the presence of damage. Moreover, the crack can be also localized putting together split ring resonators with different resonance frequencies. By using an ultra wideband Wilkinson power divider, only two access points have to be present in the structure, one for transmitting the signal and the other one for receiving. In this way, with a single measurement, the concrete structure under examination can be monitored by using a time domain transmission module.

For a practical realization of the system, one of the most challenging issues to solve is understanding how many SSRs are needed to achieve a good system coverage, starting from the 3D geometry of the structure to be monitored. Moreover, once the number of the SRRs is known, another challenging issue concerns the optimization of the SRR resonance frequencies in order to avoid overlaps among each resonator.

If a wireless communication is needed, e.g., if the system is located in a place difficult to reach, like a high pillar of a bridge, a module that communicates wirelessly with another node could be used. Moreover, such a configuration allows the implementation of a low power network without critical issues [33]. In fact, while the EM SRR sensors are passive and therefore essentially low power, the signal generation and acquisition module has a power consumption of the order of mW [33].

In particular, if more sensor networks are needed to monitor the structure (each one composed by a defined number of SRRs), it will be possible to manage them using a multiplexer to switch the signals. The multiplexer will be preceded by the web-controlled signal generation and acquisition module. To the best of the authors' knowledge, currently, this kind of network is not available; therefore, its development can be an innovative contribution for the project.

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