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Wireless passive RFID-based sensor for crack detection

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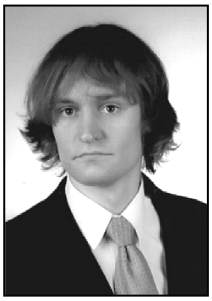

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Abstract

This paper presents the concept of an unpowered, wireless sensor based on RFID technology for detection of cracks in ceramic parts, plates and equipment. The main objectives of this work were to develop as cheap as possible, quantitative sensor without any power source, that would be also extremely simple and have possibly long lifecycle (theoretical infinite). This type of sensor could be used in Structural Health Monitoring, in tasks connected with crack detection in concrete structures and another tasks related to detection of damages in any ceramic parts (bulletproof vest plates, ceramic bearing, insulator in power engineering). Below we present the first stage of investigations (concept of sensor, choosing the way to design and calculate inductance of planar coil, simulation of the operating principle, making prototypes that check manufacturing possibilities).

Keywords: wireless sensor, RFID, planar coil designing, SHM, concrete structure, ceramic crack detection.

Bezprzewodowy, pasywny czujnik uszkodzeń powierzchni oparty na technologii RFID

Streszczenie

W artykule zaprezentowana została koncepcja bezprzewodowego czujnika opartego na technologii RFID, służącego do wykrywania uszkodzeń w elementach ceramicznych. Głównym celem pracy było zaprojektowanie możliwie taniego czujnika nie posiadającego własnego źródła zasilania, o prostej zasadzie działania i jak najdłuższym cyklu życia (teoretycznie nieskończonym). Koncepcja czujnika opiera się na stworzeniu obwodu rezonansowego składającego się z cewki planarnej, nadrukowanej bezpośrednio na elemencie ceramicznym oraz kondensatora będącego integralną częścią chipu RFID. Pojawiające się uszkodzenie, przerywa ścieżki cewki, co prowadzi do braku sygnału zwrotnego w czytniku dostrojonym do określonej częstotliwości. Taki rodzaj czujnika mógłby być używany w zadaniach związanych z monitoringiem stanu konstrukcji oraz diagnostyką maszyn, w przypadku wykrywania uszkodzeń struktur betonowych (specjalne próbne płytki ceramiczne umieszczone bezpośrednio na/w konstrukcji) oraz innych zadaniach związanych z wykrywaniem uszkodzeń w dowolnych elementach ceramicznych (płytki używane w kamizelkach kuloodpornych, łożyska ceramiczne, izolatory używane w energetyce). Dużą zaletą czujnika jest fakt, że nie musi on być widoczny, może znajdować się w miejscach trudno dostępnych. W poniższym referacie zaprezentowane zostały rezultaty pierwszych badań nad czujnikiem tego typu (koncepcja projektowa czujnika, wybór sposobu zaprojektowania i obliczeń cewki planarnej, symulacja zasady działania, wykonanie wstępnych prototypów ukazujących możliwości produkcyjne takiego czujnika).

Słowa kluczowe: czujnik bezprzewodowy, RFID, projektowanie cewki planarnej, SHM, konstrukcje betonowe, wykrywanie uszkodzeń ceramiki.

1. Introduction

The increasing interest in design of wireless and battery-free sensors is one of the most significant trends within the subject of Structural Health Monitoring (SHM) in recent researches. Wireless Sensor Networks (WSN) offers almost endless opportunities, both in tasks related to monitoring condition of structures and connected with collecting the environmental information such as temperature, brightness, sound and vibration [1]. The basic difference between concrete examples of the applied wireless sensors is the way of powering. There are two possibilities to solve this problem. First and already well developed approach is the power source connected to a sensor. These types of sensors are described in many papers such as [1, 3]. The second approach is generally more complicated and stands numerous challenges to an inventor. In this case the power is supplied to a sensor directly from the reader by using magnetic coupling [4]. It is obvious that a sensor that is both wireless and battery-free has advantages of these two groups of sensors. On the one hand it has almost endless lifetime and no needs for additional space for battery, on the other hand there is no need for wire connection, it could be placed anywhere in places with difficult access, also on moving elements.

Preferably chosen technology when designing a wireless sensor is RFID (Radio Frequency Identification) technology in various forms and concepts. There are papers referred using “1-bit only transponder” called EAS [5], well known as application in anti thief devices in shops. Often there are threshold sensors, that change their state by defined conditions [6, 7]. To this group there belongs also a low-cost corrosion sensor designed to detect corrosion in reinforced concrete structures [8 – 10]. The second group is represented by WISP (Wireless Identification and Sensing Platform), which are sensors connected with an RFID transponder circuit and powered from reader [11]. That are many papers describing WISP sensors [12 – 14].

In this short introduction there are signalized the most important recent research and developments within the subject of wireless sensors used today. Though there are many wireless sensors presented above, there is still lack of such a solution that is widely used in SHM application. This paper presents the concept that could fulfill the specified market area and has great chance to be ubiquity.

2. Concept of a sensor

We assumed that construction of a designed sensor should be as simple as possible. The requirements are as follows: minimal cost of the proposed sensor, practically endless lifetime (which excludes using the battery), possibility to place sensor on ceramic parts in almost arbitrary environment and in difficult accessible locations as well.

In order to satisfy these requirements, there was designed a sensor of the following principle of operation. Firstly, there will be discussed the concept of a sensor that could be placed on flat parts, for instance ceramic plate put into a bulletproof vest. The main concept was to develop a threshold sensor, changing its state by appearance of crack damage. Therefore the sensor has form of a simple resonant circuit, connected with an RFID chip. A planar coil printed directly on ceramic elements plays the role of the inductance element of the circuit . The role of capacitance elements plays, depending on frequency range of system, while depending on the system frequency range, additional SMD capacitors or a capacitor integrated with the RFID chip internal circuit play the role of capacitance elements. The sensor system designed like that is tuned to the determined resonant frequency (operating frequency), according to the frequency of standard commercially available RFID reader. When a crack occurs, tracks which forms a planar coil becomes interrupted, there is no more a backscattered signal in RFID reader, thus we can conclude that the ceramic part is damaged.

As can be seen this concept of a sensor fulfilled almost all posted stipulation. The only costs are a cost of simply RFID chip (depends on a manufacturer; amounts about a few dollars) and those of printed tracks – we have decided to use screen printing, which is the well-known and inexpensive method of application of conductive inks [15]. The sensor can be placed at almost every flat ceramic part by its manufacturing, or later (the only requirement is connected to surface roughness). Its simplicity is also strong side of this concept – there is not any power source that can be discharged; loss of the backscattered signal clearly indicates that damage has occurred. The lifetime of the whole construction is only limited by the lifetime of an integrated circuit of the RFID chip which is theoretically endless. The next advantage is a fact that there is no need to place the sensor in a visible position. Depending on the reader's range, it can be interrogated from up to 1 meter and more, independently what is between the sensor (transponder) and reader. The only limitations result from the presence of metal parts near the sensor, which could change the magnetic field around and thus limit the read range of the reader.

The crack damage sensor designed this way can be attractive for industry, military and construction application. It is simple, low-cost, has almost endless lifetime and thus has great chance to be ubiquitous. The probably most significant application is using this sensor in maintenance of concrete structure. There is strong demand for sensor that allows to prevent propagation of cracking damages in this kind of a structure, due to their rapid recognition. We can manufacture ceramic plates and stick them on concrete building elements in the most endangered places, or even embed them into a concrete during construction. Use of the RFID technology allows us to avoid necessity of placing a sensor in visible places, it can be placed for instance under plaster or another outer layer of the facade. Once placed, the sensor can be examined at certain times, depending on different application (for instance once a week), unlimited number of times, for many years. The lack of the backscattered signal in the RFID reader gives clearly information that crack has occurred in a structure and that the whole construction is in danger. To achieve even more effectiveness, there is possibility to use a stress-sensitive ceramic material for the plate, which gives the possibility to avoid a crack even before its occurring.

3. Simulations and prototypes

In the first investigations on this concept of a sensor we wanted to check the possibility of printing a planar coil at ceramic plate elements, recognize limitations, choose the best method of manufacturing process and simulate operating principles of the entire system. This knowledge is important for the process of designing and manufacturing the working sensor prototypes.

Due to the fact that we intended to place the sensor on any ceramic parts, we decided to use silver conducting ink for the planar coil. There are many papers that report successful use of silver ink for fabrication of printed RFID applications [16, 17]. According to the chosen material, we used the screen printing application method mentioned above.

The subject of planar coil inductors lies in the area of great interest for many years. There are many papers describing the approximating formulas which allow us to calculate inductance of the planar, especially square-shaped inductor [21 - 25]. We decided to use an equation named the Grover method, which was given in [24]:

$$L_{Grov} = \sum_{j=1}^{s} Lj + M \tag{1}$$

where s is the number of segments, M is the mutual inductance between segments and Lj is the selfinductance of each segment given by [26]:

$$L_j = 0.002l(\ln\left(\frac{2l}{w+t}\right) + 0.50049 + \frac{w+t}{3l}) \tag{2}$$

where l, w and t are track length, width and thickness, respectively. This equation was applied to the antenna design tool, developed by ST Microelectronic.

We also developed simulations of the planar inductor in COMSOL Multiphysics, approximating the planar square-shaped inductor as several concentric squares differing only with length of the side. Inductance depends mainly on the quantity of magnetic flux lines flowing through the inductor, thus a leading design variable is the coil shape and dimensions. The tracks of the inductor are approximate as one dimension (length only) conductive lines embedded in 3D space. This model of the planar coil is close to reality and should create good approximation, as well as is relatively fast for computer calculations [Fig. 1].

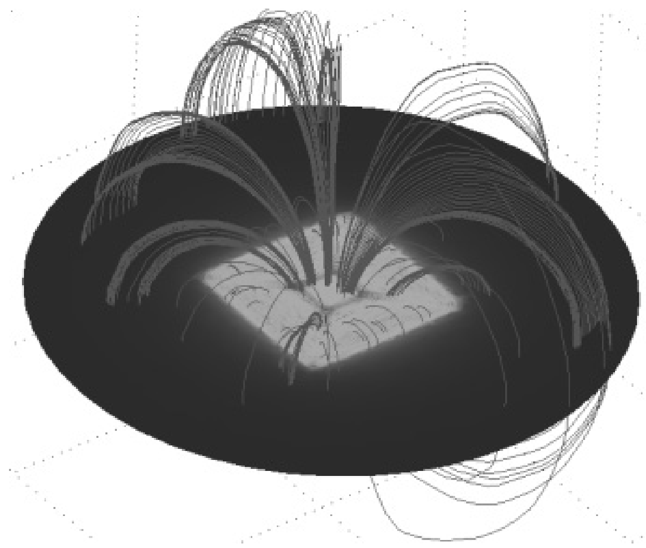

Fig. 1. Simulation of magnetix flux in planar coil embedded in 3D space
Rys. 1. Symulacja linii pola magnetycznego przechodzącego przez cewkę planarną w przestrzeni 3D

Using CST Microwave Studio we simulated the entire system. We developed a model of the planar coil embedded in air space, that is as close as possible to reality. The designed system is prepared for work with the operating frequency equal to 13.56 MHz. Assuming that the internal capacitance value of the real RFID chip provided by ST Microelectronic (M24LR64-R model) we intended to use is about 27.5 pF, we could calculate the needed inductance for achieving the determined frequency, transforming the simple, well known equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

to:

$$L = \frac{1}{4\pi^2 C f^2} \tag{4}$$

After substitution we obtained the inductance value of about 5.01 μH. We tested the value of S11 parameter measured on a discrete port and investigated the impact of occurring a damage to change in the resonant response of the entire system.

We also developed several planar coil inductors at ceramic substrate from fireplace ceramic-glass called ROBAX in the form of a small square (50x50 mm) [Fig. 2]. To manufacture the planar coil, we used glassy conductor silver ink, which allowed us to solder SMT elements, additive capacitors for instance. A connection between coil traces was produced by means of polymer-based silver conductor ink, due to the fact, that the resist layer was also from polymer-based ink (use of glassy resistive inks resulted in surface cracking of substrate material).

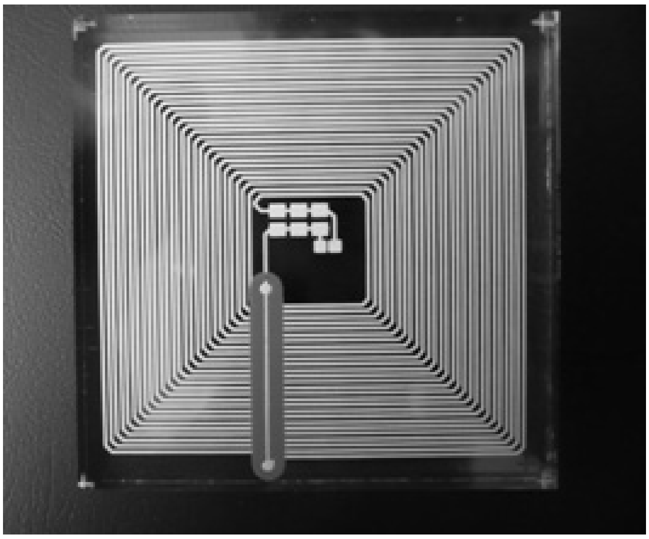

Fig. 2. Second prototype after manufacturing process
Rys. 2. Drugi prototyp po wyprodukowaniu

We manufactured two main prototypes of the planar coil. Concerns connected with filling conductive ink after printing were allayed. The tracks rather shrink by annealing. The adhesion to substrate material was also very good. We measured real inductance of coils by using an RLC Bridge of 41R model produced by CHY company.

Some technical and physical data of printed coils concerning two prototypes are given in Tab. 1.

Tab. 1. Basic data related to prototype coils
Tab. 1. Podstawowe cechy prototypowych cewek

Number of turns	36	27
Average track resistance	430 Ω	46 Ω
Average inductance	33.72 μH	18.62 μH

4. Results and discussion

In the comparison above, the easily noticeable difference is the average track resistance. We obtained quite a different real value of the trace sheet resistance of about 25.2 mΩ and 5.5 mΩ for the first and second prototype of the coil, respectively. This significant distinction comes from application of some improvements in the manufacturing method of the second prototype. After noticing some features of fabrication conductive traces on ROBAX substrate, like for instance shrinkage of traces by annealing, we decided to develop a model with wider tracks, using a screen with the larger mesh factor (initial concerns about spillage of tracks by annealing were canceled), backed with thicker foil, which affected on more accurate mapping of screen traces on the substrate, due to thicker tracks (in the first prototype we noticed some constrictions in tracks, probably due to local loss of thickness). The trace sheet resistance value is of great importance, through its straightforward impact on the track real resistance and therefore indirectly the coil quality factor (the lower the resistance, the higher the quality factor), which is significant for all resonance circuits.

We compared the usefulness of different designing and calculating methods for planar coil inductance, in relation to design of a planar coil printed on any ceramic substrate. Below in Tab. 2 there are given the results of coil calculations by using the methods described above in comparison to the real values of inductance, measured by an RLC bridge:

Tab. 2. Values of inductance received from different methods and measured in prototype coils
Tab. 2. Wartości indukcji otrzymane przy pomocy różnych metod oraz zmierzone w cewkach prototypowych

Real inductance	33.72 μH	18.62 μH
Simulation in COMSOL	37.62 μH	21.40 μH
Grover Method	33.95 μH	19.15 μH

By analyzing these results we can conclude that approximating methods of coil inductance calculations give values greater than those measured in the prototype. The Grover Method applied in the ST Microelectronic antenna design tool is nearest to reality. So it was chosen to develop the next prototypes of a sensor. Considering the Comsol simulation, though it gives the value a few microhenries greater than the real one, one can state that it is useful because of the possibility to calculate other values connected with RFID system design (mutual inductance, coupling coefficient), which will be described in the next papers.

The second result of our investigations was simulation of the entire system in order to check the supposed operating principles, which assumed that occurring crack damage and interruption of track led to changes in impedance (thus in RFID reader tuned to the specified operating frequency there is lack of the backscattered signal). Firstly we checked the S11 parameter of the undamaged system. We investigated this parameter in the frequency range, in which we supposed the resonant peak (10 – 15 MHz). By analyzing the obtained results, we conclude that the system has resonance in 13.46 MHz [Fig. 3]. A slight displacement of the resonant peak is caused by some changes in the planar coil inductance compared to the assumed value (due to simplifications in preliminary calculations). More interesting, however, is the simulation where a crack occurred. We parameterized the length of damage that resulted in four cases (undamaged planar coil by length zero, damage on one, two and three tracks). The width of crack damage was constant and amounted 0.1 mm. By analyzing the results, there is clearly visible, that the resonant peak was significantly displaced [Fig. 4] by occurring the crack damage. That is the main result of our investigations. By displacement of the resonant peak, there is no more the backscattered signal in RFID reader, thus we can conclude, that our assumption related to the operating principle was correct.

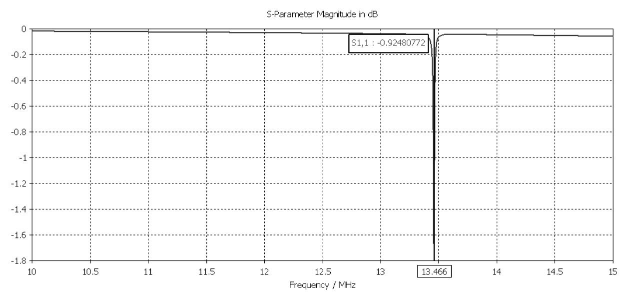

Fig. 3. S11 parameter with resonant peak of undamaged coil
Rys. 3. Parametr S11 z widocznym pikiem rezonansowym dla cewki nieuszkodzonej

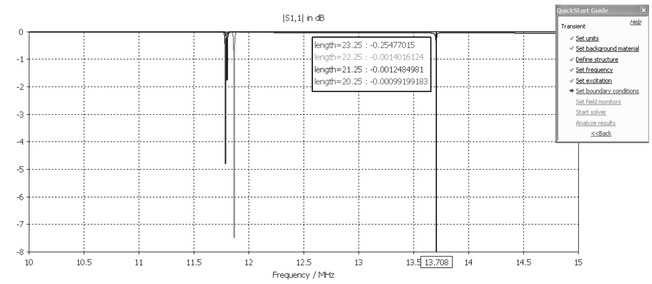

Fig. 4. Difference in S11 parameter and occuring of resonant peak due to tracks damages

Rys. 4. Różnice w parametrze S11 oraz umiejscowieniu piku na skutek uszkodzenia ścieżki

5. Conclusion

In our investigations we examined different methods of planar coil design, both in the way of simulation, as well as inductance calculation. There was chosen the Grover Method, as the best method for calculating the inductance of a planar coil printed on ROBAX substrate, as nearest to reality. We also developed the appropriate components of the manufacturing process, including the screen mesh size, the thickness of backed foil, the method for connecting the inner and outer planar coil tracks. Our investigations also resulted in significant decrease in the track sheet resistance , that now corresponds to the value given by producers of silver ink. We performed the complete simulation of the described system, checking the impact of crack damage, which interrupted tracks of the planar coil, on its impedance, thus its resonant response. This preliminary investigations show the possibility to develop a crack damage sensor whose concept was also described here.

The next step will be design of an RFID system, working at the specified operating frequency with a transponder manufactured directly on any ceramic elements. We will also investigate the usefulness of such a system in concrete structure monitoring and another tasks connected with maintenance of systems including ceramic parts. At the same time we would like to develop more simulations, in order to find response to a new question that appeared during the preliminary simulation and to even better understand the entire system.

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