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Conference Paper *in* Proceedings of SPIE - The International Society for Optical Engineering · April 2013

DOI: 10.1117/12.2009233

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Design and simulation of a slotted patch antenna sensor for wireless strain sensing

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ABSTRACT

In this work, a slotted patch antenna is employed as a wireless sensor for monitoring structural strain and fatigue crack. Using antenna miniaturization techniques to increase the current path length, the footprint of the slotted patch antenna can be reduced to one quarter of a previously presented folded patch antenna. Electromagnetic simulations show that the antenna resonance frequency varies when the antenna is under strain. The resonance frequency variation can be wirelessly interrogated and recorded by a radiofrequency identification (RFID) reader, and can be used to derive strain/deformation. The slotted patch antenna sensor is entirely passive (battery-free), by exploiting an inexpensive off-the-shelf RFID chip that receives power from the wireless interrogation by the reader.

Keywords: strain sensor, wireless passive sensor, slotted patch antenna, RFID.

1. INTRODUCTION

In order to monitor the integrity of engineering structures, numerous structural health monitoring (SHM) technologies have been developed over the past few decades [1]. To evaluate structural conditions, a myriad of structural responses can be measured. Among various measurands, strain is one of the most important indicators of structural health. Many types of sensors can be used to measure strain, such as metal foil strain gages, piezoelectric strain sensors, and fiber optic sensors [2]. Although performance of these strain sensors had been proved, many require lengthy cables and are inconvenient for field application on large-scale structures. In recent years, wireless strain sensing systems have been developed to reduce installation time and cost. However, most wireless sensing devices require an analog-to-digital converter for signal digitization, a microprocessor for on-board processing, a wireless radio for data transmission, and external batteries for power [3-6]. Although batteries could be recharged by energy harvesting, most batteries have a rather limited life span and may cause environmental concerns.

In our previous work, a folded patch antenna was designed as a passive wireless strain sensor [7]. A low-cost RFID (radiofrequency identification) chip is integrated with the folded patch antenna to constitute a passive antenna sensor. The interrogation radiofrequency (RF) wave emitted by a reader provides operation power for the RFID chip. Once the RFID chip is activated by an interrogation signal, the chip sends a modulated RF signal back to the reader through the folded patch antenna. The folded patch antenna sensor was designed using Rogers RT/duroid® 5880, a glass microfiber-reinforced poly-tetra-fluoro-ethylene (PTFE) composite, as the substrate material. The folded patch antenna enables 50% footprint reduction when compared with a regular patch antenna. Nevertheless, due to the low operation frequency of the sensor at 900 MHz, the dimension of the RFID folded patch antenna sensor are still relatively large, i.e. 61mm×69mm [7].

In this work, a slotted patch antenna is designed to further reduce the sensor footprint. Slots introduced into the antenna can detour the surface current in order to generate longer travel path for the current. The footprint of the slotted patch antenna (36mm×38mm) is reduced to one quarter of the previously presented folded patch antenna sensor [8]. A

Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2013, edited by Tzu Yang Yu, Andrew L. Gyekenyesi, Peter J. Shull, Aaron A. Diaz, H. Felix Wu, Proc. of SPIE Vol. 8694, 86941J · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2009233

commercial software package, Ansoft HFSS, is used to verify strain sensing in the numerical simulation. The rest of this paper is organized as follows. Section 2 reviews the wireless strain sensing mechanism of the antenna sensor. Section 3 presents the design concept of the slotted patch antenna. Section 4 demonstrates simulated strain sensing performance of the slotted patch antenna. Finally, the paper is concluded with a summary and discussion.

2. STRAIN SENSING MECHANISM

The wireless strain sensing system is based on passive RFID technology. Section 2.1 reviews components of the RFID system adopted in this research. Section 2.2 describes strain measurement technique through the RFID interrogation.

2.1 RFID antenna sensor and reader

Fig. 1 shows the conceptual illustration of RFID communication between a reader and a sensor. The reader emits an interrogation electromagnetic wave to the sensor, which includes an antenna for data transmission and an RFID chip for signal modulation. The RFID chip adopted in this research is the SL3ICS1002 chip model manufactured by NXP semiconductor. If the power received by the sensor-side antenna is higher than the turn-on power of the RFID chip, the chip is activated and uses the power from the reader to send a modulated signal back to reader. The RFID chip on the sensor requires a minimum power to turn on, which is defined as the threshold power. A Tagformance Lite reader unit [9] from Voyantic Ltd. is adopted as the RFID reader. Interrogation power threshold measurement can be achieved by the reader. To identify interrogation power threshold at each frequency point, the reader tunes the interrogation power until the power is just enough to activate the RFID chip. The interrogation power threshold versus frequency curve reaches its minimum point at antenna resonance frequency. Once the antenna sensor is deformed due to applied strain, the antenna resonance frequency changes correspondingly. Therefore, strain sensing is achieved through the relationship between antenna resonance frequency and strain on the structure.

2.2 Relationship between strain and resonance frequency of the antenna sensor

Once an antenna sensor is bonded on a structural surface, the sensor deforms together with the structure. As a result, the antenna length changes with structural strain. Eq. (1) shows that resonance frequency of a regular patch antenna (without folding), f_0^{Patch}, is related to antenna length [10]:

$$f_0^{\text{Patch}} = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_{\text{reff}}}} \quad (1)$$

where c is the speed of the light, L is the physical length of the copper cladding on the antenna, $\varepsilon_{\text{reff}}$ is the effective

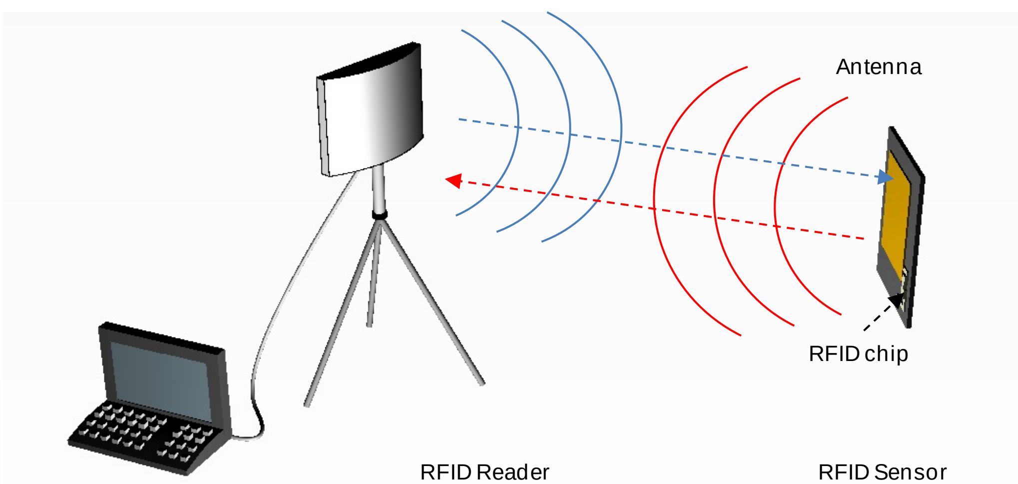


Fig. 1. Conceptual illustration of RFID reader and sensor

dielectric constant of the antenna substrate, and ΔL is the additional electrical length corresponding to $\varepsilon_{\text{reff}}$. Because the width-to-thickness ratio is much smaller than 1, the effective dielectric constant $\varepsilon_{\text{reff}}$ has approximately the same value as the dielectric constant ε_{r} according to following Equation [10] :

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_{\text{r}}+1}{2} + \frac{\varepsilon_{\text{r}}-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \approx \varepsilon_{\text{r}} \tag{2}$$

where h and W are thickness and width in the substrate, respectively. The wave length of the patch antenna is determined as:

$$\lambda_0^{\text{Patch}} = \frac{c}{f_0^{\text{Patch}}\sqrt{\varepsilon_{\text{r}}}} \tag{3}$$

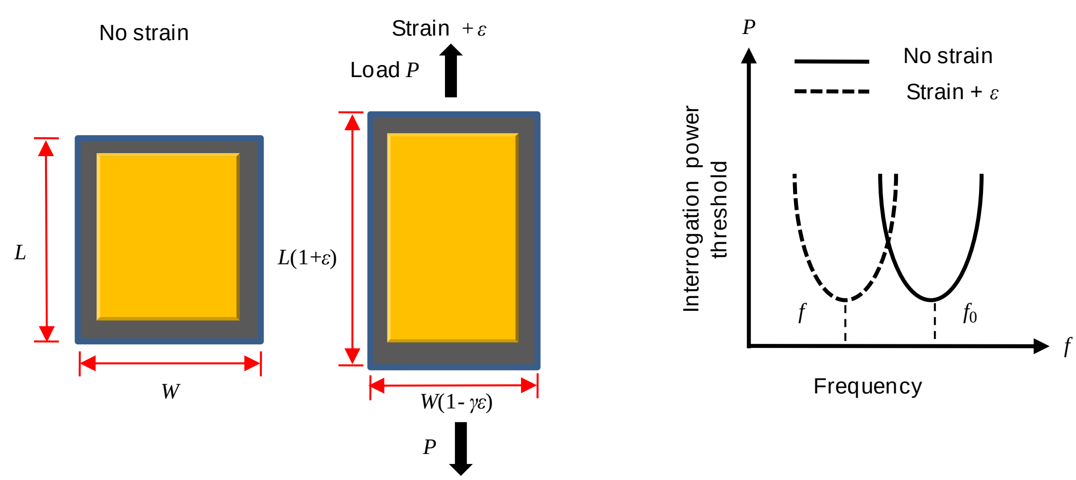
When strain ε occurs in the longitudinal direction, the resonance frequency is shifted to:

$$f^{\text{Patch}} = \frac{c}{2(1+\varepsilon)(L+2\Delta L)\sqrt{\varepsilon_{\text{r}}}} = \frac{f_0^{\text{Patch}}}{1+\varepsilon} \approx f_0^{\text{Patch}}(1-\varepsilon) \tag{4}$$

The equation shows that if strain ε is small, the resonance frequency shifting is approximately linear to strain. This linear relationship indicates that strain can be derived by measuring shift in the antenna resonance frequency. This serves as the fundamental strain sensing mechanism of the wireless antenna sensor. Although the width of the antenna is also changed according to Poisson's ratio, the width change does not affect the resonance frequency change. Fig. 2 (a) and (b) illustrate relationship between sensor deformation and antenna resonance frequency. When strain ε is positive, the resonance frequency f decreases. On the other hand, if strain ε is negative, the resonance frequency f increases.

3. DESIGN OF A SLOTTED PATCH ANTENNA SENSOR

Although the RFID standard allows for a broad frequency range (840~960MHz) in America, Europe, and Asia, 880MHz is within the cell phone frequency band in the U.S. Therefore, the resonance frequency of the folded patch antenna is shifted outside the cell phone frequency band to around 915 MHz, so that issues with environmental noise are avoided. In the microstrip patch antenna design, the effective electrical length of a patch antenna is $\lambda/2$. Resonance frequency of



(a) Antenna deformation in the longitudinal direction (b) Illustration of interrogation power threshold measurement

Fig. 2. Conceptual illustration of relationship between sensor deformation and resonance frequency change

the patch antenna is dependent on the surface current path as shown in Fig. 3. According to Eq. (3), the required half wave length on Rogers 5880 substrate is 110 mm at 915MHz resonance frequency. In other words, to maintain a resonance frequency at 915MHz, length of the entire current path needs to keep at 110mm. As a result, current detouring on the RFID antenna sensor helps to reduce sensor size while maintaining operation frequency at 915MHz.

Our previous RFID antenna sensor design achieves current detouring through a folded patch configuration. In this design, 0.787mm-thick Rogers RT/duroid®5880 PTFE material is used as the substrate. The material has a low dielectric constant and a low loss tangent, which improve signal-to-noise ratio and increase wireless interrogation distance. The previous folded patch antenna has vias which are connected between a top copper cladding and a bottom copper ground plane (Fig.4). Vias change the boundary conditions at the end of the metal patch. This prevents the current from going to zero, and thus increases the electrical length travelled by the current. The folded patch configuration reduces the footprint from a regular patch antenna by half, to 61mm×69mm (Fig. 5(a)). The initial antenna resonance frequency, f_0^{Folded}, and the shifted resonance frequency under strain, f^{Folded}, are estimated as

$$f_0^{\text{Folded}} = \frac{c}{4(L + 2\Delta L)\sqrt{\varepsilon_r}} \tag{5a}$$

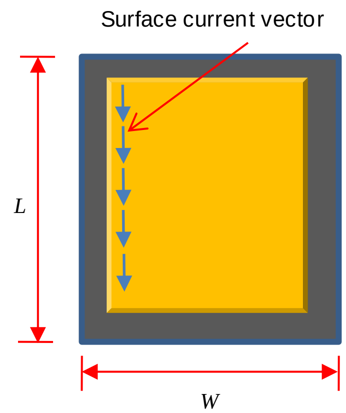
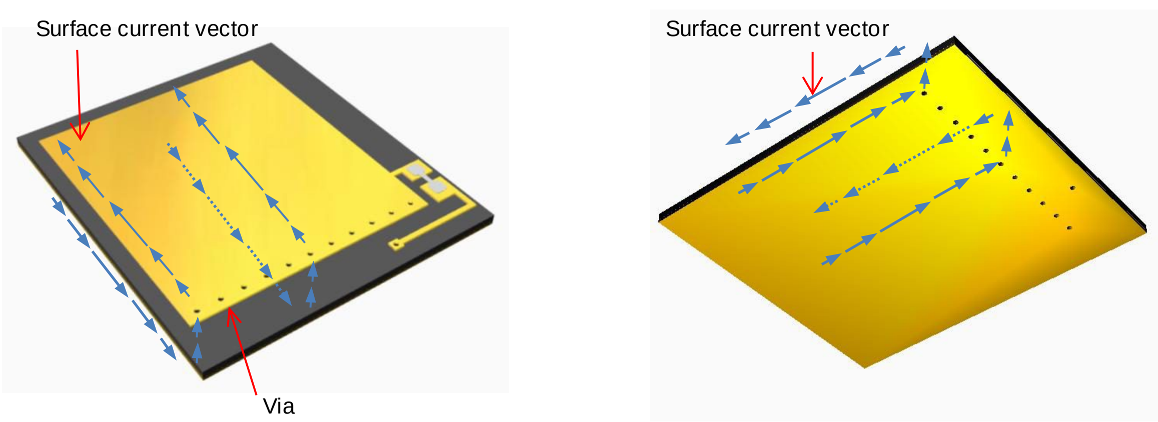


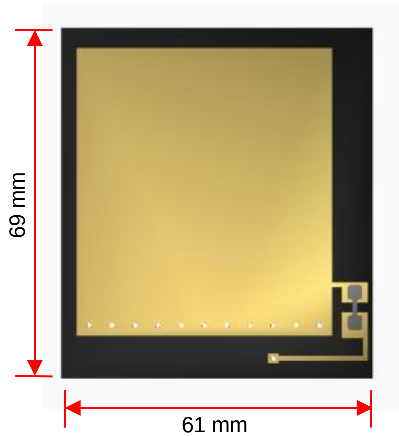
Fig. 3. Illustration of the surface current vector in the patch antenna sensor



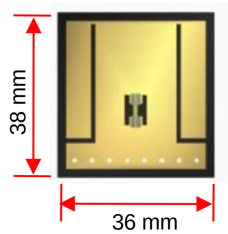
(a) Top skewed view

(b) Bottom skewed view

Fig.4. Illustration of the surface current vector in the folded patch antenna sensor (dotted lines represent current on the opposite surface of the view)



(a) Folded patch antenna



(b) Slotted patch antenna

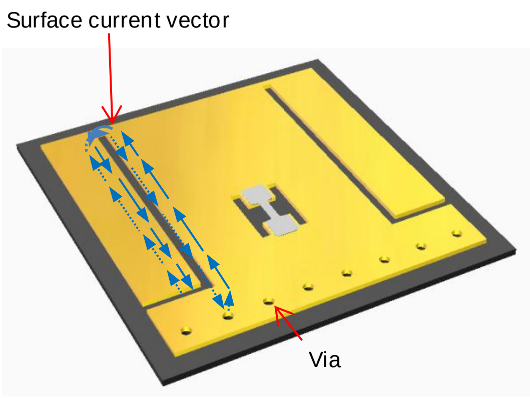
Fig. 5. Footprint comparison of the folded patch antenna sensor and slotted patch antenna sensor

$$f^{\text{Folded}} = \frac{c}{4(1+\varepsilon)(L+2\Delta L)\sqrt{\varepsilon_r}} = \frac{f_0^{\text{Folded}}}{1+\varepsilon} \approx f_0^{\text{Folded}}(1-\varepsilon) \tag{5b}$$

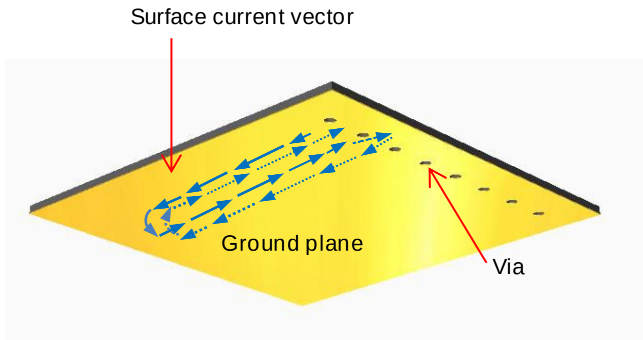
Although the folded patch antenna sensor shows good performance for wireless strain sensing, the sensor size is still relatively large. For further size reduction, a slotted patch configuration is investigated (Fig. 5(b)). Dimension of the antenna sensor is reduced to 36mm × 38mm. As shown in Fig. 6(a), the slots in the copper cladding generate a detoured surface current path. For the slotted patch antenna sensor, the initial resonance frequency and the shifted resonance frequency under strain can be estimated as:

$$f_0^{\text{Slotted}} = \frac{c}{8(L+2\Delta L)\sqrt{\varepsilon_r}} \tag{6a}$$

$$f^{\text{Slotted}} = \frac{c}{8(1+\varepsilon)(L+2\Delta L)\sqrt{\varepsilon_r}} = \frac{f_0^{\text{Slotted}}}{1+\varepsilon} \approx f_0^{\text{Slotted}}(1-\varepsilon) \tag{6b}$$



(a) Top skewed view



(b) Bottom skewed view

Fig. 6. Illustration of the surface current vector in the slotted patch antenna (dotted lines represent current on the opposite surface of the view).

Fig. 6 (b) shows the perspective view of the slotted patch antenna. An RFID chip is located in the middle of the sensor for RFID signal modulation. Vias are also adopted to connect top copper cladding with bottom copper ground plane.

4. STRAIN SENSING PERFORMANCE OF SLOTTED PATCH ANTENNA SENSOR

Electromagnetic simulation is conducted using a commercial software package, Ansoft HFSS, to verify the strain sensing performance of the slotted patch antenna. Section 4.1 describes the simulation model and setup. Section 4.2 reviews electromagnetic radiation theory and illustrates the simulated surface current density vector in the slotted patch antenna sensor. Section 4.3 presents simulated strain sensing performance of the slotted patch antenna.

4.1 Simulation model and setup

Fig. 7 illustrates the simulation model of the slotted patch antenna sensor. The cubic air box is the domain of the electromagnetic simulation. The outside layer of the air box is assigned as a perfectly matched layer (PML) for absorbing waves coming from the antenna sensor, so that no wave reflects back to the sensor from the PML. The RFID chip is modeled as a lumped port with an impedance of 13.3-j122 Ω , which has the same electrical impedance as the RFID chip model made by NXP Semiconductors. Perfect electrical conductor (PEC) is used to model the copper material, in order to reduce simulation time. To simulate effect of the metallic base structure, the ground plane is set to 96mm×98mm, which is about 3 times larger than planar dimensions of the sensor. The simulation adopts an adaptive mesh method, which increases mesh density until the result converges in a pre-defined tolerance. In current simulation, the model contains 42,844 tetrahedral elements. The frequency sweep range is from 905 MHz to 920MHz, with 0.01 MHz step size.

4.2 Electromagnetic radiation

Fig. 8 illustrates surface current density vectors, which as expected, show a detoured current path along the slot edge. The length of current path is approximately four times as entire antenna length. The resonance frequency of the patch antenna is mainly dependent on the electrical wave length. Therefore, the size of the slotted patch antenna is reduced to a quarter of the previous folded patch antenna design, while the resonance frequency is still around 915MHz.

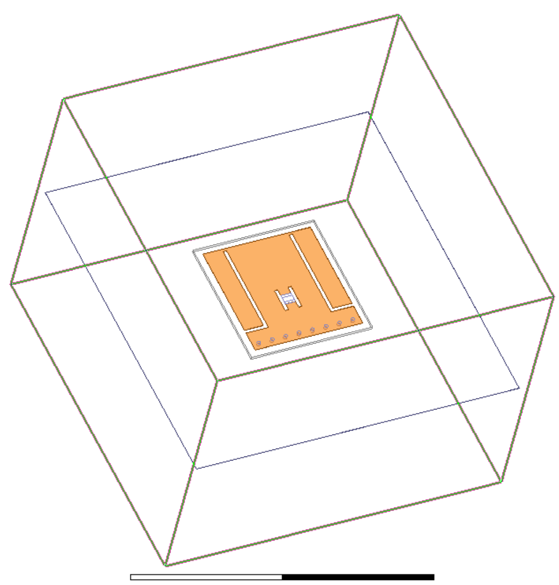


Fig. 7. Simulation model of the slotted patched antenna sensor in Ansoft HFSS

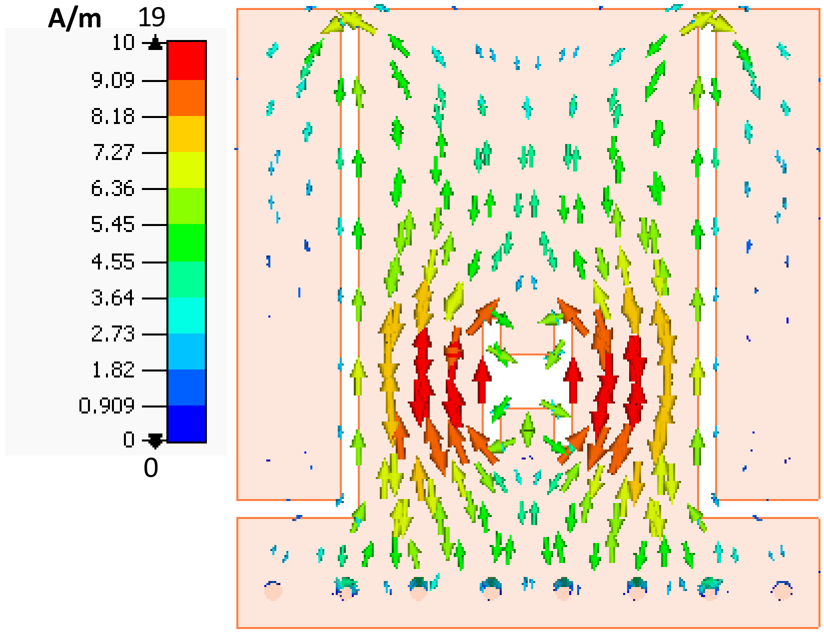


Fig. 8. Surface current density vector of the slotted patched antenna sensor simulated in Ansoft HFSS

4.3 Strain sensing performance

To validate the stain sensing performance through simulation, a slotted patch antenna sensor is deformed from zero strain to 3,000 με. In this study, the sensor dimension is simply scaled according to applied strain. In other words, dimensions along the length of the antenna sensor are increased according to strain, while the dimensions along the width and the thickness are proportionally decreased by Poisson's ratio. Adaptive mesh method is completed after seventeen iterations. Scattering parameter (S_{11}) is an important indicator of antenna radiation efficiency at the certain frequency ω. The S_{11} parameter is calculated as [11]:

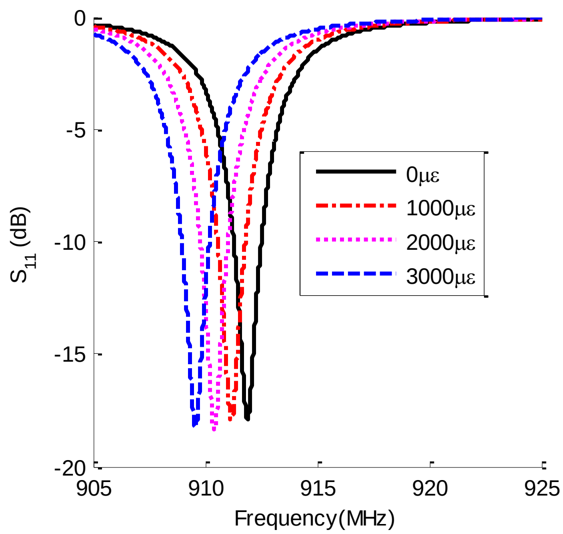
$$S_{11} = \frac{V^r}{V^i} \tag{7}$$

where V^i and V^r are equivalent incident and reflected voltages, respectively looking from the lumped port (modeling RFID chip) into the antenna. S_{11} is a result of impedance matching between the lumped port and the antenna. For the same incident voltage, a lower reflected voltage means more energy is radiated by antenna, i.e. higher radiation efficiency. Therefore, smaller S_{11} value means better matching and higher antenna efficiency. Because S_{11} changes with frequency, the corresponding frequency of its minimum value is the resonance frequency of the antenna sensor.

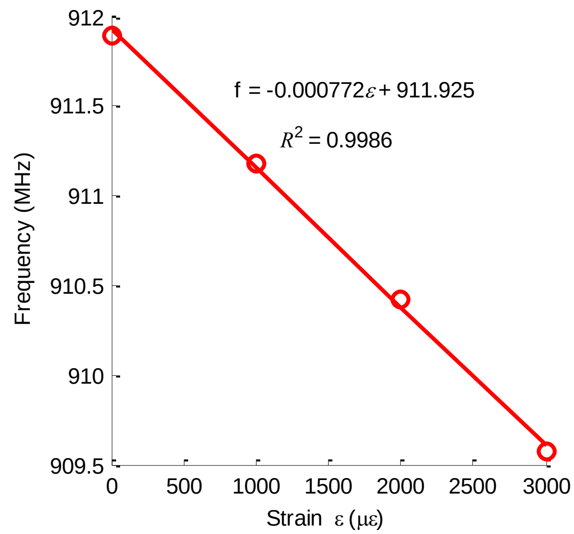
Fig. 9(a) shows S_{11} plots at different strain levels. The resonance frequency of the slotted patch antenna reduces as the strain increases. For example, at zero strain level, the resonance frequency is 911.92 MHz, while the resonance frequency decreases to 909.61 MHz at 3,000 με. Fig. 9(b) illustrates linear regression between resonance frequencies and corresponding strain levels. The figure shows the coefficient of determination (R^2) is 0.9986, which indicates a good linearity between resonance frequency and strain. In addition, strain sensitivity is defined as frequency change over strain change:

$$S_{\varepsilon} = \frac{f_2 - f_1}{\varepsilon_2 - \varepsilon_1} \tag{8}$$

where f_1 is the initial resonance frequency at strain ε_1; f_2 is the resonance frequency at strain ε_2. As shown by linear regression in Fig. 9(b), the strain sensitivity is -772 Hz/με, which is lower than theoretical prediction of -915 Hz/με. One



(a) S_{11} parameters under strain transfer



(b) Resonance frequency versus strain

Fig. 9. Strain simulation results of the slotted patched antenna sensor in Ansoft HFSS

potential reason is that in simulation, strain/deformation in the antenna not only changes antenna length in the longitudinal direction, but also changes dimensions of other antenna components (including matching lines, vias, and substrate). While Eq. (6) considers only effect of antenna length change, dimension changes of other components also affect antenna impedance matching, and thus, affect S_{11} curve and resonance frequency. As a result, these more complicated influences to strain sensitivity are not taken into consideration by the simplified theoretical prediction in Eq. (6).

5. SUMMARY AND DISCUSSION

This paper presents a slotted patch antenna sensor design based on wireless passive RFID techniques. In previous research, although a folded patch antenna sensor shows good performance for strain and crack sensing, the sensor size is relatively large. By implementing minimization techniques, surface current on the slotted patch antenna sensor is detoured. The footprint is reduced to a quarter (36mm×38mm) of the folded patch antenna sensor while maintaining the same resonance frequency. Strain sensing performance of the slotted patch antenna sensor is proved through numerical simulations in the Ansoft HFSS software package. Electromagnetic simulations demonstrate highly linear relationship between strain and resonance frequency change. In future work, tensile experiments will be performed to validate the strain and crack sensing performance of the slotted patch antenna sensor.

6. ACKNOWLEDGEMENT

This material is based upon work supported by the Federal Highway Administration under agreement No. DTFH61-10-H-00004. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the Federal Highway Administration.

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