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A Meander Line-Based Frequency Selective Surface for Strain Sensing

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Abstract—**Frequency selective surfaces (FSSs) are periodic arrays of conductive elements that have distinct reflection and transmission responses. In this work, an FSS sensor designed to operate in Ka-band to measure a wide range of uni-directional strain using a meander line-based unit cell is presented. Specifically, the proposed unit cell of the sensor consists of a convoluted meander line geometry designed on a thin dielectric substrate. Strain sensing is achieved by monitoring the change in the resonant frequency of the FSS when under strain that is parallel to an interrogating signal linearly polarized and aligned with the convoluted dimension of the meander line element. Simulation results of strain measurement over two ranges, small- (0% - 0.5%) and large-scale (0% - 5%), are presented. The simulated results indicate that the sensitivity of the sensor to small-scale strain is 21 MHz/0.1% strain and 230 MHz/1.0% strain for large-scale.**

I. INTRODUCTION

Frequency selective surfaces (FSSs) are arrays of conductive elements or patches that act as spatial filters of electromagnetic energy. Element shape, dimensions, and substrate material etc., are some of the properties that dictate the electromagnetic (i.e., reflection and/or transmission) response of an FSS. Traditionally, FSSs have been incorporated as radomes, filters, and reflectors [1], and more recently, as sensors [2]. In the sensing regime, FSS-based sensors have shown strong potential for structural health monitoring (SHM) applications [3] as their electromagnetic response not only depends on their design itself but also the local environment. Their inherent remote interrogation also makes them an attractive solution for SHM [2-4]. Recently, FSS designs using convoluted geometries such as meander lines have become more popular due to their miniaturized structure and stability with respect to angular interrogation [5].

As it relates to strain sensing in particular, the meander line element facilitates strain measurement capability for both ranges of strain (small- and large-scale). This is important in that a single sensor that is capable of a wide measurement range of strain is often difficult to achieve yet desirable in practice. To this end, this paper presents the design and simulation of an FSS sensor using a meander line element that is capable of small-and large-scale uni-directional strain measurement.

II. MEANDER LINE BASED STRAIN SENSOR

In order to achieve a sensor capable of measuring a wide range of strain, a convoluted meander line element was chosen. This design was inspired by traditional strain gauge sensors that contain multiple sets of meander lines to enhance the accuracy for strain sensing [6]. Moreover, in order to provide adequate measurement resolution for small-scale strain, the frequency of operation is chosen within Ka-band (26 - 40 GHz). The sensor design includes a conductor backed substrate to facilitate operation in reflection mode. Such operation is specifically vital for measurement environments with restricted access (i.e., one-sided) to the structure.

The unit cell design of the proposed meander line-based FSS sensor is illustrated in Figure 1, with the call-out defining the terminology used to describe the line geometry. As shown, the dimensions are given as $A_x = 7$ mm, $A_y = 10$ mm, $L_x = 6.75$ mm, $L_y = 2.25$ mm, $w = 0.25$ mm, and $g = 0.25$ mm. The substrate is FR-4 ($\varepsilon_r = 4.3$, and $\tan\delta = 0.025$) with a thickness of 10 mils.

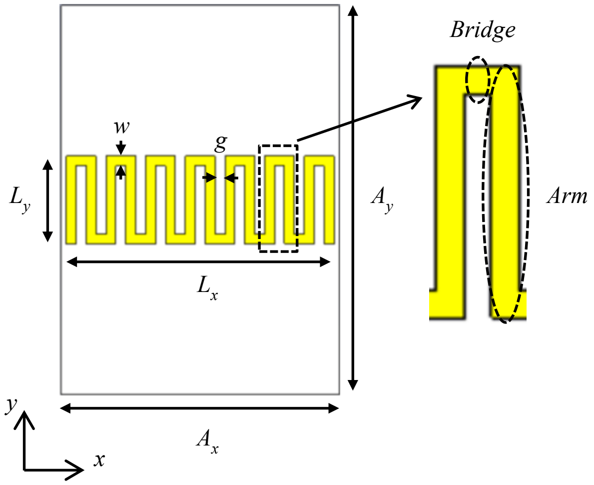
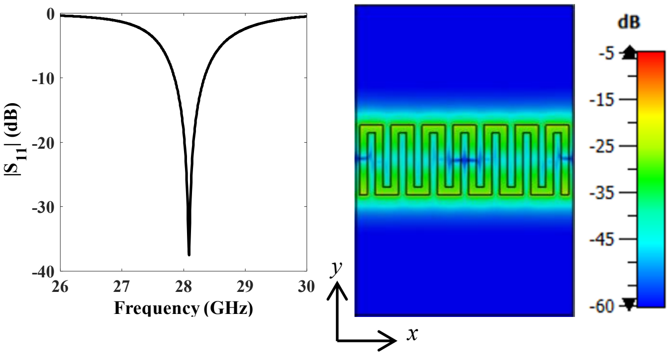


Figure 1. Unit cell of the proposed FSS sensor.

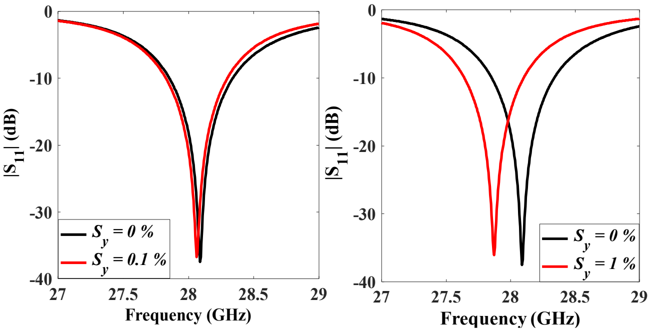
To demonstrate the functionality of the proposed sensor, full wave simulation was performed in CST Microwave Studio© using a periodic boundary condition and planewave excitation. The interrogating signal is assumed to be linearly polarized parallel to the bridge of the meander line as defined in Figure 1. This interrogating signal is herein referred to as a *Y*-Pol interrogation (per the axes defined in Figure 1). The simulated reflection response ($|S_{11}|$) of the sensor in an unloaded condition (i.e., no applied strain) is shown in Figure 2, along with the magnitude of the electric field (E-field) at the resonant frequency of 28.09 GHz. The resonant behaviour of the sensor is clear in Figure 2a, with a resonant frequency of 28.09 GHz. Regarding Figure 2b, the E-field distribution indicates that the resonant behaviour of the sensor is due to the individual dipole segments of the meander line geometry (arms) oriented parallel to the polarization of the interrogation (*Y*-Pol). This is evident from the high E-field concentration along the arms of the meander line element, as shown in Figure 2b.



(a) (b)

Figure 2. (a) Frequency response of the FSS sensor in the unloaded condition, and (b) E-field magnitude at 28.09 GHz.

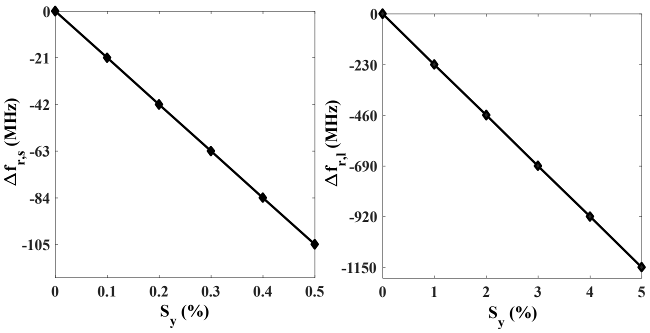
Additional simulations were conducted to evaluate the response of the sensor under both small-and large-scale uni-directional strain oriented parallel to the polarization of the interrogation (*Y*-Pol), with the results shown in Figure 3. As seen in Figure 3a, when the small-scale strain in the *y*-direction, S_y, is changed from 0% to 0.1%, the resonant frequency (f_r) decreases by 21 MHz, from 28.09 GHz to 27.94 GHz. Similarly, Figure 3b shows the simulated response of the sensor to large-scale strain (also in the *y*-direction, or S_y) for the same interrogation (*Y*-Pol). For this condition, f_r decreases by 230 MHz for a 1% increase in strain.



(a) (b)

Figure 3. FSS sensor's frequency response for: (a) small-, and (b) large-scale strain.

Lastly, as a final aspect of the sensor, it is important to quantify the sensitivity of the sensor to strain. To this end, the difference in f_r for a given strain with respect to the no-strain condition is defined as $\Delta f_{r,s}$ for small-scale and $\Delta f_{r,l}$ for large-scale strain. The simulated results for Δf_r for a range of both small- and large-scale strain is shown in Figure 4a and 4b, respectively, with simulation points indicated in the figures. As can be seen, Figure 4a shows a linear response to small-scale strain for the range of 0 – 0.5%, with a sensitivity (i.e., slope) of 21 MHz/0.1 % strain. Similarly, Figure 4b also shows a linear response, with a slope of 230 MHz/1 % strain.



(a) (b)

Figure 4. Frequency shift versus (a) small-, and (b) large-scale strain.

III. CONCLUSION

In this paper, a meander line-based FSS sensor is proposed for sensing small-and large-scale strains. The proposed sensor consists of a convoluted meander line geometry located on a thin dielectric substrate that is sensitive to a wide range of uni-directional strain. Strain is measured by interrogating the sensor with a signal that is linearly polarized parallel to the direction of measured strain. Both small- and large-scale strains were considered, with a sensitivity of the sensor to small-scale strain of 21 MHz/0.1% strain, and 230 MHz/1.0% strain for large-scale strain. Further study is needed to quantify the effect of the presence of unintended uni-directional strain normal to the intended measurement direction, as well as the potential for bi-directional measurements using two orthogonally polarized interrogating signals. Moreover, the linearity and sensitivity of the sensor over the full (small-through-large scale) range of strain considered must be quantified.

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