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Two-Dimensional In-Plane Strain FSS-Based Sensor

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***Abstract*—Frequency selective surface (FSS) based sensors have found application as sensors in the last decade. In this paper, a new sensor design is proposed for two-dimensional in-plane strain sensing. The unit cell of the FSS-based sensor includes two slot dipoles, oriented normal to one another and each with different dimensions, to create two unique resonant frequencies when interrogated with an incident electric field normal to the direction of measured strain. In this way, 2D strain can be characterized concurrently and independently. The error due to strain orthogonal to the direction of interest, along with the error due to the presence of shear strain, has also been characterized. The sensor has a maximum of 12% error for an applied strain due to 4% strain orthogonal to the measurement direction, and no more than 8% error for a maximum of 4% of shear strain.**

***Keywords*—Frequency selective surface, two-dimensional strain sensing, slot dipole.**

I. Introduction

Frequency selective surfaces (FSSs) are periodic arrays of conductive elements or apertures which provide a reflective or transmissive frequency response when illuminated by electromagnetic energy. FSSs have traditionally been utilized as filters, reflectors, absorbers, radomes [1], and more recently, as sensors [2-4]. FSSs are suitable for sensing applications since their frequency response depends on element geometry, substrate properties, and the nearby environment. Hence, changes to these parameters will affect the resonant response of the FSS. In addition, FSS-based sensors provide a wireless sensing solution. Another advantage is the capability to design a sensor such that multiple parameters can be measured simultaneously such as concurrent strain and temperature sensing [4]. Some of the more recent sensing applications, particularly in the area of structural health monitoring (SHM), include strain sensing [2, 4], delamination/disbond in layered structures [3] and concurrent temperature and strain sensing [4].

As it relates to strain sensing, there are not many sensors capable of two-dimensional (2D) strain measurements that exist today [5-7]. Current solutions include fiber-based [5], ultrasound [7], and microwave measurements [7]. To this end, this work proposes an FSS-based sensor for 2D in-plane strain sensing. While the proposed sensor is planar in nature and can be applied to a large area of interest, a localized interrogation scheme can be used to monitor the strain profile over the area of interest [8]. This can be done on a small or large scale, depending on the measurement needs.

II. Proposed Sensor Design and Performance

The proposed FSS design, including a unit cell call-out, is shown in Fig. 1, where D is 18 mm. The sensor is intended to operate in the X-band (8.2 – 12.4 GHz). The substrate is RT5880 (ε_r = 2.2, and tanδ = 0.0009) with a thickness of 10 mils. The unit cell consists of a set of slot dipoles oriented normal to one another (i.e., in the x- and y-directions as shown in Fig. 1). The dimensions of the slot dipoles oriented in the x-direction are different from those of the y-direction to ensure frequency diversity in the response. In this way, as the dipoles are orthogonal and resonate at different frequencies, and coupling (i.e., sensor error) is expected to be reduced. Also, this sensor operates in reflection mode, meaning it is suitable for sensing needs that require one-sided interrogations. As it relates to strain measurement, since the slot dipole is used, the interrogation of FSS sensor to measure strain in the x direction (S_x) is achieved via a signal linearly polarization in direction of y (Y-Pol), and for strain in the y direction (S_y), a signal linearly polarized in the x direction (X-Pol) is used.

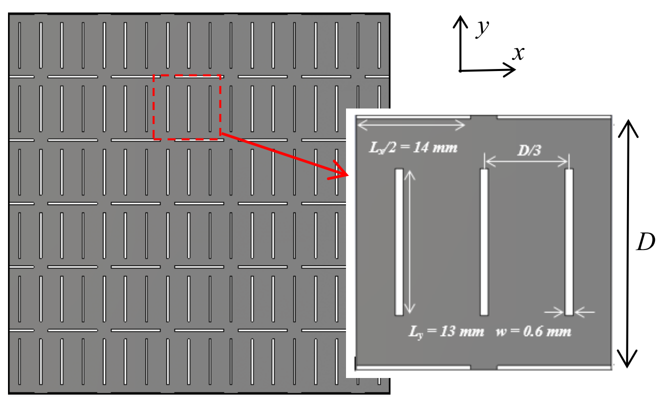

Fig. 1. FSS-based sensor design with unit cell call-out.

To investigate the performance of this 2D strain, full wave simulations using CST Microwave Studio© were conducted using a periodic boundary condition and Floquet excitation. More specifically, simulations were conducted assuming the interrogating polarization to be perpendicular and parallel to the direction of applied strain. When under a perpendicular interrogation, the resulting frequency shift (due to normal strain) is large and hence facilitates the desired measurement. However, when using a parallel interrogation, the frequency shift represents the error that will be present in cases where both components of strain (x- and y-directions) exist simultaneously. The same can be said for the case where the sensor is under an off-normal strain. In other words, the total off-normal strain (S_{total}) can be decomposed into parallel and perpendicular normal strain components ($S_{total} = \sqrt{S_x^2 + S_y^2}$). Then, the normal strain will be distinguished using the frequency response of both interrogating polarizations. To this end, the resonant frequency shift versus strain is studied for the two interrogating polarizations assuming strain in the x and y directions is present. The resonant frequency shift is defined as the shift in resonant frequency due to strain from the resonant frequency of sensor without any strain applied and is herein denoted as Δf_{r1} for Y-Pol and Δf_{r2} for X-Pol.

The simulated sensor response under normal strain is shown in Fig. 2. Specifically, the frequency response for Y-Pol in Fig. 2a shows that when normal strain in x-direction, S_x, is changed from 0% to 4%, the resonant frequency of Y-Pol, f_{r1}, shifts from 9.3 GHz to 8.96 GHz. Should S_y be present during the measurement of S_x, the error in f_{r1} due to S_y = 4% is 40 MHz. Similarly, S_y is characterized by an X-Pol interrogation, as is shown in Fig. 2b. The resonant frequency for X-Pol interrogation, fr_2, shifts from 11.65 GHz to 11.26 GHz when S_y changes from 0% to 4%. Should S_x also be present during this measurement, the error in f_{r2} due to S_x is 10 MHz for S_x = 4%.

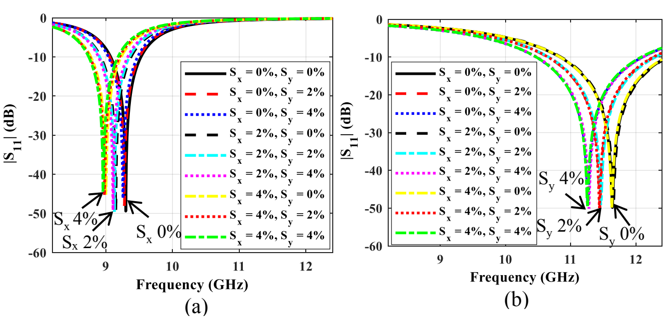

Fig. 2. Effect of normal strain on the FSS sensor's frequency response for different interrogations: (a) Y-Pol, and (b) X-Pol.

A last point of consideration for this sensor design is the effect of shear strain on the performance of 2D normal strain sensing. To illustrate this, the frequency shift resulting from the presence of sshear strain for a 2D normal strain measurement ($\Delta f_{r1,\ SS}$ and $\Delta f_{r2,\ SS}$ for Y-Pol and X-Pol interrogation, respectively) in terms of S_x and S_y for four cases of shear strain (S_{xy}) is shown in Fig. 3. These results are different from those of Fig. 2 are without shear strain (i.e., S_{xy} = 0%). Therefore, in Fig. 3, only $\Delta f_{r1,\ SS}$ and $\Delta f_{r2,\ SS}$ due to non-zero S_{xy} are shown since both are equal are 0 MHz when S_{xy} = 0%. However, as S_{xy} increases, the Y-Pol response shows no effect for S_{xy} = 2% (Fig. 2a), and less than a 10 MHz shift in frequency for the maximum shear strain considered of S_{xy} = 4% (Fig. 3b). Similarly, for X-Pol interrogation, the frequency response as S_{xy} increases to 2% and 4% (Fig. 3c and 3d, respectively), the frequency shift increases but still is less than 30 MHz.

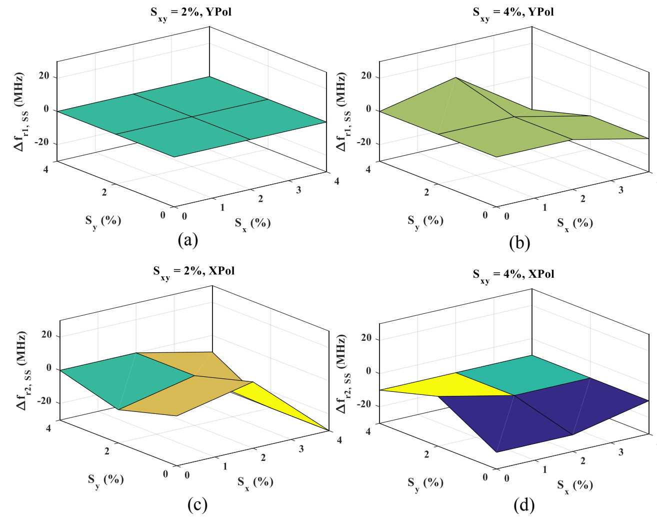

Fig. 3. The frequency shift as a result of shear strain versus normal strain in the x and y directions for Y-Pol when (a) S_{xy} = 2%, (b) S_{xy} = 4%,; for X-Pol when (c) S_{xy} = 2%, (d) S_{xy} = 4%.

III. Conclusion

This work proposes a slot-based FSS sensor capable of independent measurement of 2D (orthogonal) strain. Errors due to orthogonal (to the intended strain measurement) normal strain in addition to shear strain have been characterized. The results show that normal 2D strain can be characterized concurrently and in the presence of shear strain, but at the cost of accuracy.

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