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Embedded Aperture-Based FSS Sensor

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Abstract—Frequency selective surfaces (FSSs) are two-dimensional periodic arrays of electrically conductive elements or apertures that have a specific electromagnetic reflection and/or transmission response. In this work, an aperture-based sensor design was proposed that is capable of sensing strain when embedded in a layered dielectric structure (i.e., an embedded sensor). An aperture approach was selected due to the potential for operation in reflection mode without a conductive backplane. The sensor was designed to operate within the K-band to improve the potential strain measurement resolution, as the unit cell dimensions are inversely related to the operating frequency and directly related to strain sensitivity. Simulation results for the small-scale strain range of 0-0.5% are presented, with a sensitivity of 20.4 MHz/0.1% strain.

Keywords—Frequency Selective Surfaces (FSSs), Aperture-Based FSS, Strain Sensor, Strain Measurement

I. INTRODUCTION

Frequency selective surfaces (FSSs) are periodic arrays of elements that serve as spatial filters for incident electromagnetic (EM) energy [1]. Typical FSS element designs include slots/apertures, patches, loops, meandering lines, etc. These elements are printed on a substrate material, which can be backed by an EM conductive backplane if a reflective response is desired, or on a substrate alone for a transmissive response. Additionally, this response is affected by element shape/type and dimensions, along with the EM and physical properties of the substrate and local environment. Historically, FSSs have been applied as radomes, filters, and reflectors [1], and more recently, as sensors [2], [3]. FSSs are particularly well-suited for sensing due to their inherent sensitivity to changes in element dimensions and spacing, as well as changes to materials in the local vicinity of the FSS. Moreover, FSS-based sensors offer a number of attractive features including wireless and remote interrogation along with the potential for one-sided measurement (if designed for a reflection response measurement). This aspect is of particular interest as practical sensing scenarios may only permit access to one inspection side.

Recent examples of FSS sensing include strain [2]-[4] and temperature [4]-[5]. As it relates to strain sensing, most recent work has focused on patch-based designs (such as the use of dipole elements). As one-sided measurements are often a design goal, these designs also frequently require a conductive backplane to provide a strong reflection response. This may be a drawback for applications where sensor cost or weight is of concern (for example, space applications where weight and accessibility is critical). However, aperture-based designs have the potential for a reduced dependency on the presence of a conductive backplane [6].

As it relates to the purpose of this work, an aperture-based FSS sensor was designed for sensing small-scale strain (herein defined as 0% to 0.5% strain) on a specific substrate intended to represent the (dielectric and physical) properties of support webbing as may be found in inflatable space structures [7]. In this way, the sensor may be integrated during fabrication and is designed based on the materials at hand. This also requires that any additional materials (part of the structure) that will be in the immediate vicinity of the sensor be included in the design, including any that may exist in between the interrogating source and sensor (i.e., an embedded scenario). To this end, Section II introduces the proposed sensor design and Section III highlights the simulated functionality of the proposed FSS as a strain sensor. Section IV concludes the work.

II. APERTURE-BASED FSS SENSOR

As mentioned, this sensor design is intended to be integrated into a layered structure. Specifically, the structure considered here consists of two layers. The first layer serves as a superstrate to the sensor with a measured dielectric constant of 2.75-j 0.001 and thickness of 4.5 mm [8]. The substrate layer is assumed to be Vectran™ (a woven material often used as supports for space-based inflatable structure designs) with a thickness of 2 mm and measured dielectric constant of 3-j0.0009 [8]. The sensor, now functioning as an embedded design in the layered structure, is printed on PET (polyethylene terephthalate) that serves as a thin support layer for the FSS elements (estimated dielectric constant of 3.4-j 0.005 and thickness of 0.1 mm [9]). The targeted resonant frequency was selected to be within the K-band (18-26.5 GHz) to improve the potential strain measurement resolution. This is because the overall FSS unit cell dimension is inversely related to the frequency of operation and directly related to the strain resolution. As such, a smaller unit cell will facilitate improved resolution. To begin realization of a sensor capable of one-sided measurement without the inherent requirement of a conductive backplane [6], an aperture element was chosen. An illustration of the layered structure within which the sensor is to be integrated is shown in Fig. 1a, along with the unit cell of the proposed FSS design in Fig. 1b.

To demonstrate the functionality of the proposed sensor, full wave simulations in CST Microwave Studio™ were completed,

utilizing periodic boundary conditions and a plane wave excitation. The interrogating signal is polarized parallel to the *b* dimension (Fig. 1b). The simulated reflection response ($|S_{11}|$) of the proposed design is seen in Fig. 2 without and with the presence of the conductive backplane.

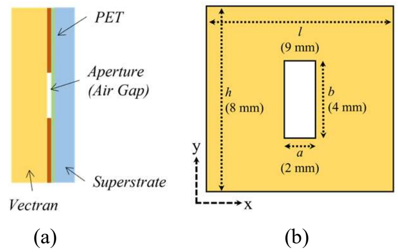

Fig. 1. Layered structure with integrated sensor (a) and sensor unit cell (b).

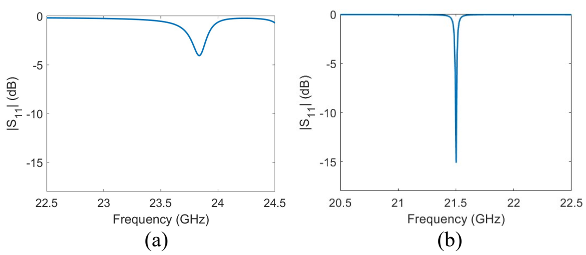

Fig. 2. Simulated reflection response of the proposed sensor without (a) and with (b) the conductive backplane.

Fig. 2a indicates a resonant frequency, f_r, at 23.84 GHz, but with a low Q-factor (243), making this resonant difficult to detect in practice. However, when the conductive backplane is included on the back side of the Vectran™ (Fig. 2b), f_r reduces to 21.5 GHz but with a substantially improved Q-factor (792). The poor performance without the backplane is attributed to the (electrically) thick substrate and remains an area of improvement for aperture-based FSS sensing. However, to show proof-of-concept for embedded strain sensing, the model used for Fig. 2b is used for strain simulations in the next section.

III. Strain Simulations

To verify the proposed FSS sensor is applicable for strain sensing, simulations were completed for a strain range of 0-0.5%, with results shown in Fig. 3. As seen, f_r decreases with strain, and the variation in resonant depth is attributed to insufficient frequency discretization in the simulation.

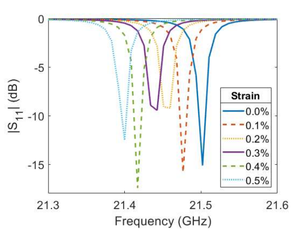

Fig. 3. Sensor response as a function of mechanical strain.

The last aspect of the proposed sensor to consider is the sensitivity of the sensor to mechanical strain. Here, we assume perfect bonding of the conductive elements to the Vectran™ substrate so strain matching between the two surfaces is achieved. To this end, the shift in resonant frequency, Δf_r, relative to the unloaded (0%) case is considered. The simulated results for Δf_r over the strain range of 0-0.5% are shown in Fig. 4. The results are linear and exhibit a resonance peak decrease, on average, of 20.4 MHz per 0.1% strain (i.e., the sensor sensitivity).

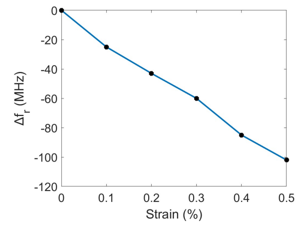

Fig. 4. Δf_r over a strain range from 0-0.5%.

IV. Conclusion

In this paper, an embedded aperture-based FSS sensor was proposed for small-scale strain measurement. The sensor was designed to be integrated into a layered structure and was designed to operate in the Ka-band for improved measurement resolution. Over the range of strain considered (0-0.5%), the sensor sensitivity is 20.4 MHz/0.1% strain. Future revisions of the proposed sensor will remove the necessity of the conductive backplane to reduce weight and the need for additional material to be integrated into the structure.

Acknowledgement

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