01 Jan 2022

# Practical Fss-Based Sensor Sensitivity

Mahboobeh Mahmoodi

Kristen M. Donnell
*Missouri University of Science and Technology*, kmdgfd@mst.edu

## Recommended Citation

M. Mahmoodi and K. M. Donnell, "Practical Fss-Based Sensor Sensitivity," *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, AP-S/URSI 2022 - Proceedings*, pp. 81 - 82, Institute of Electrical and Electronics Engineers, Jan 2022.
The definitive version is available at https://doi.org/10.1109/AP-S/USNC-URSI47032.2022.9887026

2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/USNC-URSI) | 978-1-6654-9658-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/AP-S/USNC-URSI47032.2022.9887026

# Practical FSS-Based Sensor Sensitivity

Mahboobeh Mahmoodi and Kristen M. Donnell
Microwave Sensing (*μSense*) Laboratory
Department of Electrical and Computer Engineering
Missouri University of Science and Technology, Rolla, MO, 65409
[mmwf2, kmdgfd]@mst.edu

***Abstract*—Frequency selective surfaces are a periodic array of unit cells that, when illuminated externally, have a specific frequency response that depends on element geometry, spacing, and substrate properties. Theoretically, FSS is assumed as an infinite array of unit cells with a plane wave excitation. However, in practice, an FSS is finite and hence, due to edge effects, the limited number of unit cells, and non-uniform illumination, the response will deviate from the theoretical. As it relates to FSS-based sensing in particular, a localized illumination is often used in order to improve the sensing resolution. However, due to the aforementioned factors, the sensitivity of the sensor may suffer as a result. Hence, the effect of these factors is studied on the FSS sensor response. Then, taking strain measurement as an example, the degradation in the sensor sensitivity to strain is evaluated in comparison with that of a theoretical FSS. The simulation results show that a finite FSS with non-uniform illumination has reduced sensitivity to strain. This degradation in sensitivity of reduces as the number of illuminated unit cells increases. However, the sensitivity of a finite FSS with uniform illumination is nearly constant with respect to the number of illuminated unit cells.**

***Keywords*— Frequency selective surface, FSS-based sensing, sensitivity, finite FSS, strain sensing.**

## I. INTRODUCTION

Frequency selective surfaces (FSSs) are periodic arrays of resonant elements that, when (remotely) illuminated by external electromagnetic energy, have a particular frequency response [1]. FSSs have been used in different applications such as radomes, filters, absorbers [1], and, recently for sensing applications including strain sensing, crack detection, concurrent temperature and strain measurement, etc. [2-4]. Such sensors are ideal for many sensing needs due to their planar structure that can be easily implemented on a surface or embedded within layered structures.

Theoretically, an FSS is analyzed by considering a unit cell with periodic boundary conditions (to mimic an infinite array) under uniform plane wave excitation. However, in practice, an FSS is dimensionally finite and undergoes a non-uniform excitation. This scenario may cause the FSS response to deviate from that of the ideal due to the non-uniform excitation, the introduction of edges (i.e., edge effects), and the finite number of unit cells [5]. To this end, to overcome these practical limitations, FSSs are generally designed to include many unit cells and utilize a wide and mostly uniform illumination [6]. However, for sensing applications, illuminating the entire FSS will provide a comprehensive frequency response (from all unit cells), thereby creating a low resolution sensor. To alleviate this issue, a localized (focused) illumination can be utilized in order to query smaller sections (or sensor cells) of the FSS sensor [5]. The dimensions of each sensor cell (and hence the improved sensor resolution) are defined by the illumination footprint [5]. However, due to the aforementioned factors brought about by the truncation of the FSS, the frequency response (and more importantly, the sensing sensitivity) will deviate from that of the theoretical. Hence, in this work, the effect of these factors is studied on the FSS sensor response.

## II. FINITE FSS-BASED SENSING

In order to investigate the truncation effects on the FSS response, a finite FSS featuring a conductor backed loop-based unit cell on a 32 mil FR-4 substrate is considered, as shown in Fig. 1a. This design is simulated with a uniform plane wave excitation in Ansys HFSS© for FSSs with unit cell dimensions of 1×1, 5×5 and 10×10 unit cells. Due to simulation limitations, the monostatic radar cross section (RCS) is calculated to quantify the finite FSS response, rather than $|S_{11}|$ directly. Therefore, in order to compare the behavior of the infinite FSS (where $|S_{11}|$ is known) with the finite FSS (where RCS is known), the monostatic RCS of the infinite FSS ($\sigma^{FSS}$) is calculated when normalized to a reference RCS ($\sigma^{REF}$). Hence, to find $\sigma^{FSS}/\sigma^{REF}$, the following definition is used [7]:

$$\frac{\sigma^{FSS}}{\sigma^{REF}} = \left(\frac{S_{11}^{FSS} - S_{11}^{BG}}{S_{11}^{REF} - S_{11}^{BG}}\right)^2 \tag{1}$$

where $S_{11}^{FSS}$ , $S_{11}^{BG}$ and $S_{11}^{REF}$ are the reflection coefficients of the FSS, background (free space), and a copper reference structure (dimensions of 10 cm × 10 cm), respectively. In addition, $S_{11}^{REF}$ and $S_{11}^{BG}$ are simulated using periodic boundary conditions with uniform excitation. To compare $\sigma^{FSS}/\sigma^{REF}$ from the infinite FSS to that of the finite FSS, 1) the monostatic RCS from the finite FSS and the reference structure are simulated, and 2) $\sigma^{FSS}/\sigma^{REF}$ of the finite FSS is calculated, with the results for $\sigma^{FSS}/\sigma^{REF}$ of the finite and infinite FSSs shown in Fig. 1b. As seen, the infinite FSS resonates at 10 GHz, and the FSSs with 5×5 and 10×10 unit cells resonate at 9.8 GHz. However, 1×1 unit cell FSS resonates at 9.82 GHz with a larger resonant depth. This is due to edge effects, which change the induced current on the single element drastically; while for larger finite FSSs, the induced current on the edge elements differs from those located centrally [8]. In addition, this change in resonant frequency of the finite FSSs (with respect to that of the infinite FSS) is on the order of ~180 to 200 MHz, and is also attributed to edge effects.

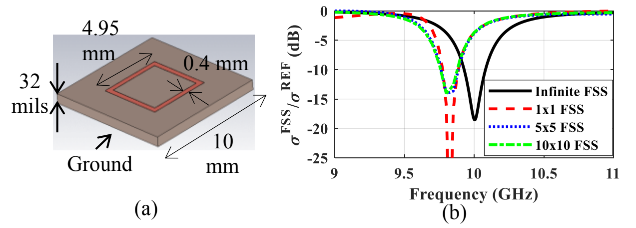

Fig. 1. (a) The FSS unit cell, and (b) the ratio of $\sigma^{FSS}/\sigma^{REF}$ for the finite FSS with uniform illumination.

While utilizing a uniform excitation is advantageous for studying the finite FSS behavior in terms of the number of unit cells and edges, such an illumination is not representative of practice where a non-uniform illumination is used. To this end, a pyramidal horn antenna at X-band (8.2 - 12.4 GHz) is considered as the illuminating source, as is shown in Fig. 2a. For this source, the illumination footprint (and hence sensor cell) is defined as the region where 75% of the incident electric field is contained on the surface of the FSS (i.e., the edge of this region has a field strength 6 dB less than the maximum value) [5]. Using this illuminating antenna, two footprints are considered (created by changing the distance between the aperture of the horn and FSS) for a sensor with dimensions of 200 mm × 150 mm (20×15 unit cells, per Fig. 1a). The illumination footprints are shown in Fig. 2b (normalized to the maximum value). The top footprint in Fig. 2b is created via a distance of 60 mm between the antenna and FSS, and illuminates a sensor cell with dimensions of 50 mm × 50 mm (~5×5 unit cells). Similarly, the bottom footprint of Fig. 2b illuminates almost the entirety of the sensor, and is created via a distance of 240 mm between the antenna and FSS.

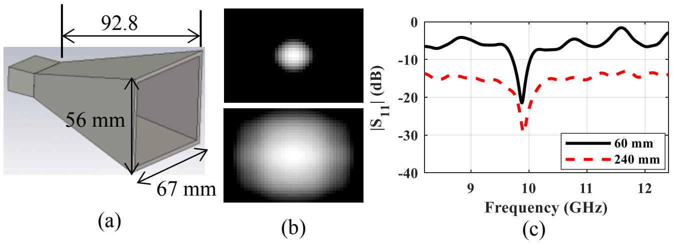

Fig. 2. (a) Illuminating source, (b) illumination footprint on the sensor for distances of 60 mm (top) and 240 mm (bottom), and (c) $|S_{11}|$ of the finite FSS with the two illumination footprints.

## *A. Finite FSS Sensor Sensitivity*

To study the effect of non-uniform illumination and number of illuminated unit cells on the sensitivity of an FSS-based sensor, a strain measurement is taken as an example. To this end, the simulated frequency response of an infinite FSS sensor, without and under 5% unidirectional strain applied parallel to the interrogating electric field polarization, is shown in Fig. 3a. The frequency shift between these two cases is ~336 MHz. However, as mentioned above, the response (and in particular, the sensitivity) may differ when a finite FSS sensor (with uniform and non-uniform illumination) experiences the same strain. As such, the frequency response of 3 finite FSSs (dimensions of 1×1, 5×5, and 10×10 unit cells) under uniform illumination was simulated. All three have a frequency shift for 5% strain of ~325 MHz as compared to the same under no strain. Additionally, when comparing the frequency shift (for 5% strain) of the finite and infinite responses, a difference of 11 MHz can be seen, therein illustrating a decrease in measurement sensitivity for the finite sensors.

While the deviation from an infinite to finite sensor under uniform illumination is of scientific interest, it is more practical to study the sensitivity for a realistic (non-uniform) footprint with a finite FSS. To this end, the frequency shift of a finite sensor to 5% strain is defined as $\Delta f_{r,finite}$ (and holds for uniform and non-uniform illumination). Similarly, $\Delta f_{r,infinite}$ represents the frequency shift for an infinite FSS with and without the presence of 5% strain. Hence, the degradation in sensitivity of a finite sensor is defined as $\Delta S = \Delta f_{r,infinite} - \Delta f_{r,finite}$, and shown in Fig. 3b. As seen, the finite FSS, when illuminated by a non-uniform illumination, shows a larger degradation in strain sensitivity. In addition, as the total number of illuminated (non-uniform) elements increases, the degradation in sensitivity reduces.

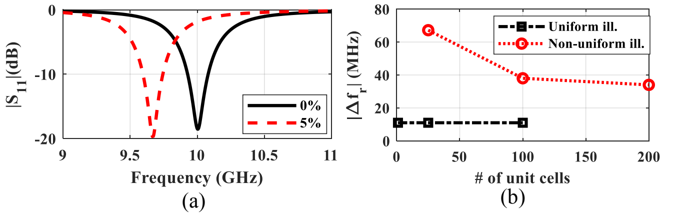

Fig. 3. (a) Effect of strain on the infinite FSS response, and (b) degradation of the finite FSS sensor resonant frequency sensitivity to 5% strain.

## III. CONCLUSION

FSS-based sensing utilizes a localized illumination to improve the sensing resolution but at the cost of sensor sensitivity. Taking strain measurement as an example, the degradation in sensor sensitivity to strain is evaluated in comparison with that of a theoretical FSS. The results indicate the importance of evaluating the sensitivity for a given resolution/sensor cell size and measurand.

## REFERENCES

[1] B. A. Munk, Frequency Selective Surfaces Theory and Design. *NewYork: Wiley*, 2000.

[2] Kinzel, Edward. “Design of a Frequency-Selective Surface strain sensor,” IEEE,APSURSI, pp. 2074-2075, 2014.

[3] S. Jang, et al., “Frequency Selective Surface Based Passive Wireless Sensor for Structural Health Monitoring,” Smart Materials and Structures,2013.

[4] M. Mahmoodi, and K. M. Donnell, “Novel FSS-Based Sensor for Concurrent Temperature and Strain Sensing,” *IEEE, Antennas and Propagation Society International Symposium (APSURSI)*, June 2017.

[5] M. Mahmoodi, et al., “Effect of Illumination Pattern on the FSS-Based Sensor Resolution,” *Instrumentation and Measurement Technology Conference (I2MTC)*, 2018.

[6] K. Sarabandi, et al., “A frequency selective surface with miniaturized elements,” *IEEE Transactions on Antennas and Propagation* Vol. 55, No. 5, pp. 1239-1245, 2007.

[7] M. Polivka, et al., “Improvement in robustness and recognizability of RCS response of U-shaped strip-based chipless RFID tags,” *IEEE Antennas and Wireless Propagation Letters* 15, pp. 2000-2003, 2016.

[8] B. A. Munk, *Finite Antenna Arrays and FSS*. John Wiley & Sons, 2003.