

## Passive sensor frequency selective surface for structural health monitoring

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### ABSTRACT

Structural health monitoring (SHM) technologies have attained attention to monitor civil structures. SHM sensor systems have been used in various civil structures such as bridges, buildings, tunnels and so on. However the previous sensor for SHM is wired and encounter with problem to cover large areas. Therefore, wireless sensor was introduced for SHM to reduce network connecting problem. Wireless sensors for Structural Health monitoring are new technology and have many advantages to overcome the drawback of conventional and wired sensor. This project proposed passive wireless SHM sensor using frequency selective surface (FSS) as an alternative to conventional sensors. The electromagnetic wave characteristic of FSS will change by geometrical changes of FSS due to mechanical strain or structural failure. The changes feature is used as a sensing function without any connecting wires. Two type of design which are circular ring and square loop along with the transmission and reflection characteristics of SHM using FSS were discussed in this project. A simulation process has shown that incident angle characteristics can be use as a data for SHM application.

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## 1. INTRODUCTION

The importance of monitoring the health of civil structures has attained attention over the past two decades. Extreme catastrophes such as earthquakes can cause massive damage to the civil structures which resulting in life threatening conditions evolving in the structures either immediately after the impact or long after the actual calamity has happened [1]. To overcome this problem, structural health monitoring (SHM) systems have been introduced since the systems have great potential to enhance the regular operation and maintenance of structures like tunnels, buildings, bridges and others. The purposes of the SHM are damage analysis, damage localization and estimating the remaining lifetime of the structure [2-3]. The damage was determined by changes in the modal parameters like frequencies which were gained from measured time histories. From this, any incidence can be quickly detected and evaluated. In addition, SHM is an arising technology which combines advanced sensor technology with intelligent algorithms to interrogate the health condition of structures in real time or whenever necessary [4-5].

Currently, the common sensor that has been found in SHM system is fiber optic sensors. This type of sensor can sense temperature and normal strain. Due to small in size, light weight, durability and other characteristics, fiber optic sensors have been widely used in SHM system. Some other potential sensor technologies are using piezoelectric materials. This type of sensor can be directly integrated into a structure. However, considering the complexity and high cost to support equipment, both of these sensors are not the

suitable sensors to cover large area and harsh environment. As an improvement to the presently available sensor, this project purpose Frequency Selective Surface as a passive sensor for SHM. In recent times, frequency selective surfaces (FSSs) have shown potential as structural health monitoring (SHM) sensors [6-11]. The structure of an FSS is made from an array of metallic elements that provides a filtering response to pass or reject electromagnetic waves at a particular band of frequency. Filtering response was caused by capacitive and inductive coupling between the elements which depends on the FSS geometry such as element shape, dimensions and spacing. It is also depend on local environment of FSS will change by geometrical variation of FSS due to structural failure or mechanical strain. Henceforth, the dependency of FSS can be employ for SHM sensing.

In this paper, passive wireless sensor for strain and structural failure are made using a frequency selective surface (FSS). Frequency Selective Surfaces (FSSs) are made up of planar periodic structures with slot component placed on a substrate. The surface implemented with identical patch or aperture conducting elements that repeating periodically in either a one- or two-dimensional array [12-13]. It is capably acted as band pass or band stop filter respectively to electromagnetic waves which allowing waves at only the desired incidence angles to propagate. The electromagnetic characteristic of FSS was studied based on geometric shape changes. The proposed design will able to monitor any structural movement based on the incident angle. An important requirement for both dependent and independent incident angle was taken in two polarizations either Transverse Electric (TE) or Transverse Magnetic (TM).

## 2. FREQUENCY SELECTIVE SURFACE AS A SENSOR

Frequency Selective Surface (FSS) are planar periodic structures of identical metal-dielectric in either one or two dimensional array structures which perform spatial filtering of microwave energy. The array of element can determine a spatial electromagnetic filter and exhibits capacitive and inductive frequency characteristics. FSS are normally composed of a conducting sheet periodically with apertures or an array of metallic patches that are designed to reflect and transmit signals at the surface from certain frequencies. Aperture FSSs, dealing as high pass filters because it transmit at higher frequencies and reflect back the signals at lower frequencies radiation which produce capacitive response [14]. Regardless of patch type FSSs, it transmitting at lowers frequencies and reflects back with higher frequencies radiation and act as low pass filters. Therefore it has shown the acquirement of low pass filter. Geometry of the structure in single period known as unit cell used to determine the resonant frequency response.

According to broad variety of possible elements used to realize FSS arrays such as square, hexagon, cross dipole and others that having different shape of element will make FSS tend to have different frequency respond characteristics either low-pass, high-pass, band-pass and band-stop filters as shown in Figure 1.

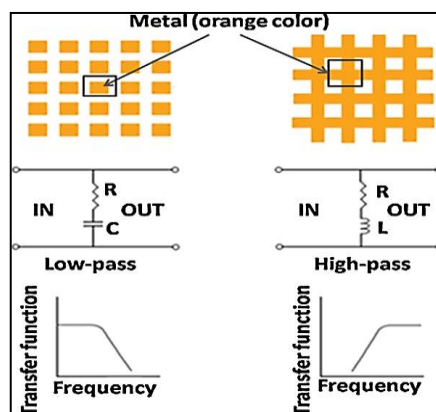


Figure 1. The patch-array produces a capacitive response, low pass filter. whereas  
b) the slot-array in inductive, high pass filter [15]

The electromagnetic performance of FSS might also rely upon the polarization and the angles of the electromagnetic waves arrive at the structure [15]. Presently, passive wireless sensor using frequency selective surfaces (FSS) has been proposed. Since various structural health monitoring (SHM) technologies are using wired system, the wireless SHM sensor using frequency selective surfaces (FSS) is believed to surpass available sensor. FSS have filtering properties to certain frequencies of incident electromagnetic

radiation and when the electromagnetic characteristic of FSS is changed by geometric shape change of FSS by mechanical strain or structural failure, the information of those changes can be assured by monitoring the filtering response changes. Other than that, the advantage of FSS over other wireless sensors is that it is totally passive because it only consists of conductive elements which can give advantages to energy storage [9]. This will make FSS having simple fabrication. The FSS sensor also capable to operate in harsh environment unlike the wired sensor that easily damaged since they are have complicated system.

### 3. SENSOR DESIGN AND FABRICATION

The design for FSS element shape are square loop and circular ring with the operating frequency 2.45 GHz for angle of incidence of the electromagnetic. Both of these two shape have been chosen since they have uncomplicated modelling and low cost manufacturing processed in large quantities. Moreover, square shape element has outstanding performance compared to others design in the matter of cross-polarization level, angular response stability and broad operating bandwidth [16-17]. At the same time, circular ring shape element was chosen to compare their characteristic performance with square loop shape in order to choose the best performance of Frequency Selective Surfaces. Several parametric studies must be consider for both design in order to achieve the independent and dependent for both polarization TE incidents and TM incidents such as differences unit cell size, differences in outer length of conducting element and differences of inner length of conducting element. The design was using the computer simulation technology (CST) microwave studio suite. This is because of the capability of CST and it is suitable to design the proposed design for this project. When all the simulation process already meets the FSS requirements, the project proceed with fabrication process of the proposed FSS. FR-4 has been chosen as the substrate for both design of FSS and the fabrication of FSS undergoes printed circuit board process, PCB. A prototype of square loop and circular ring FSS was fabricated by using FR-4 material with the height of conducting element 0.035mm and 6 x 6 of unit cell is shown in Figure 2 and Figure 3.

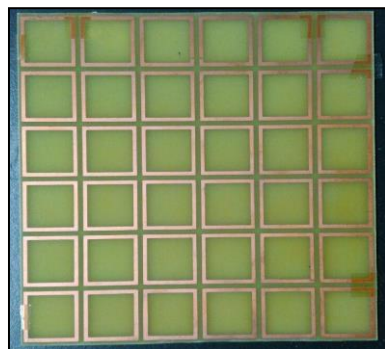


Figure 2. Fabricated square loop FSS

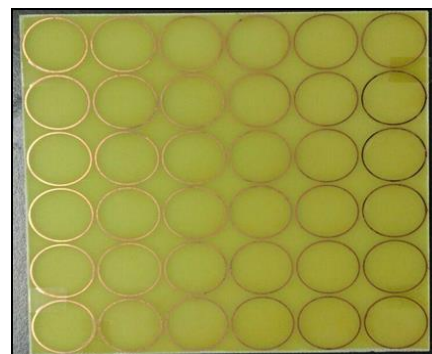


Figure 3. Fabricated circular ring FSS

## 4. FREQUENCY SELECTIVE SURFACES RESULTS AND DISCUSSION

### 4.1. Circular Ring FSS

Based on the parametric analysis, final Circular Ring dimension are chosen. Figure 4 is the final design of Circular Ring with its parameter and Figure 5 shows the simulation results of S11 and S21. As shown in Figure 5, the Circular Ring FSS designed in this section is a band stop filter and the operating frequency at 2.45 GHz. The frequency responses at -10 dB are between 1.84 GHz and 3.12 GHz, therefore the bandwidth is 52.24% approximately. One of the important characteristics to study for FSS to act as a sensor for SHM is the changes in incident angle. In this project design, there are four values of angles taken from 0 degree up to 60 degree for both TE and TM mode that have been simulated.

Figure 6 (a) and (b) show the simulation result as the incident angle change (from 0° to 60°) the frequency response change accordingly. As for TE incident, the operating frequency shifted to lower frequency. Meanwhile for TM incident, the operating frequency shifted to higher frequency and the bandwidth is not much change as the incidence angle changed. The deviation of the frequency response for TE and TM will be used as a data for SHM. The changes in angle are described as the changes of building structure. For example, when the FSS shows reading at 2.62 GHz, it means that the structure is already tilted around 40 degree at TM direction.

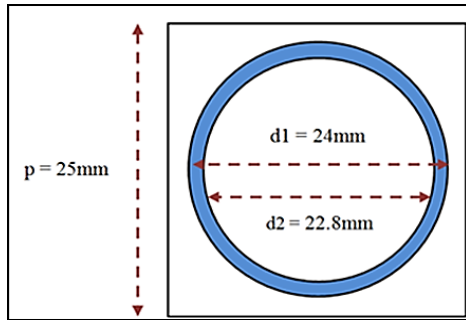


Figure 4. Final design of circular ring FSS

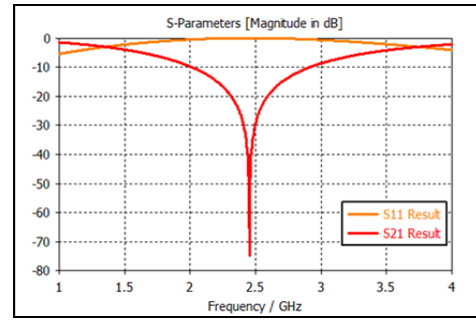


Figure 5.  $S_{11}$  and  $S_{21}$  circular ring simulation result

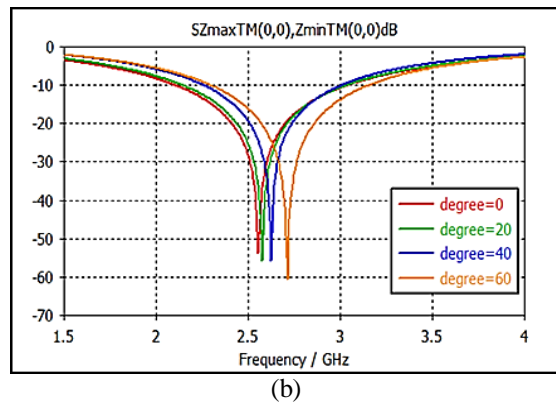
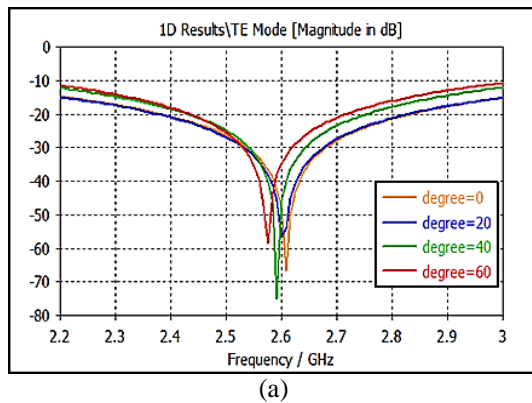


Figure 6.  $S_{21}$  result for different incidence angle from  $0^\circ$  to  $60^\circ$  : (a) TE Mode, (b) TM Mode

### 4.2. Square Loop FSS

Final Square Loop parameter and dimension are chosen and shown in Figure 7. Figure 8 shows the result  $S_{11}$  and  $S_{21}$  simulation result. Figure 8 shows  $S_{11}$  and  $S_{21}$  simulation result of the Square Loop FSS. It is designed to act as band stop filter with the operating frequency 2.45 GHz.

For Square Loop design, frequency responses at -10 dB are between 1.84 GHz and 3.124 GHz, hence the bandwidth is 52.24% approximately. From Figure 9, the simulation result have shown that the operating frequency shifted to lower frequency for TE incident. The bandwidth is decreased as well as the incident angle change. Meanwhile for TM incident, the operating frequency shifted to higher frequency and the bandwidth narrower as the incidence angle changed. The deviation of the frequency response for TE and TM will be used as a data for SHM. The changes in angle are described as the changes of building structure. For example, when the FSS shows reading at 2.6 GHz, it means that the structure is already tilted around 20 degree at TM direction.

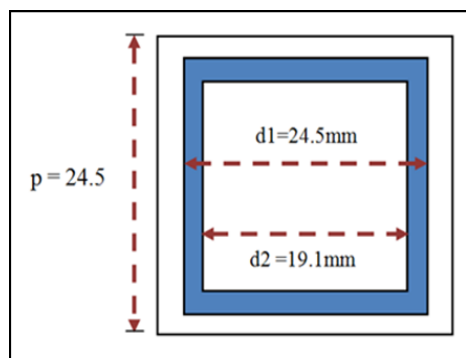


Figure 7. Final design of square loop FSS

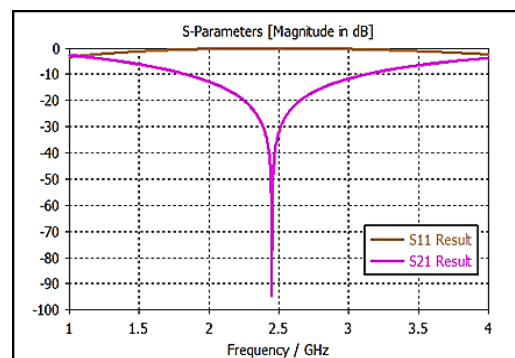


Figure 8.  $S_{21}$  and  $S_{11}$  square loop simulation result

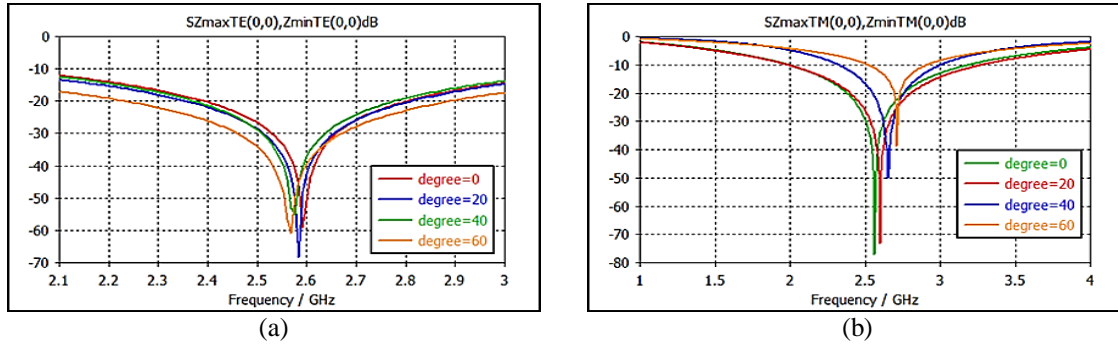


Figure 9.  $S_{21}$  and  $S_{11}$  Square Loop simulation result

4.3. Measurement

Keysight Technologies E5071C Economical Network Analyzer have been used for measurement of transmission coefficient ( $S_{21}$ ) of the proposed FSS. The two horn antenna is connected to the both port on the ENA and shows the result of transmission coefficient directly. A FSS prototype will be placed between two horn antennas with appropriate distance. The example measurement setup were done in the free space for both FSS is shown in Figure 10.

Figure 11 shows the comparison between simulation and measurement result of Circular Ring. The measurement was done to evaluate the simulation design that has been done in CST. The measurement design was measured with 25mm x 6 unit cell particularly at 0 degree angle. From the measurement graph the result of band pass frequency for Circular Ring was operating at 2.42 GHz with approximately -10dB. The measurement design in Figure 12 was measured with 24.5mm x 6 unit cell at 0 degree angle. From the measurement graph in Figure 10, the result of band pass frequency for Square Loop was operating at 2.82 GHz with approximately -10dB. Although the frequency bandwidth is different from simulation and measurement, nevertheless the operating frequency is approximately the same. The significant different is due to in simulation the FSS is define as infinitely array, hence produce a very good depth of insertion loss. However, the FSS is fabricated with 6 x 6 unit cell hence produce a less value of insertion loss compare to the simulation result.

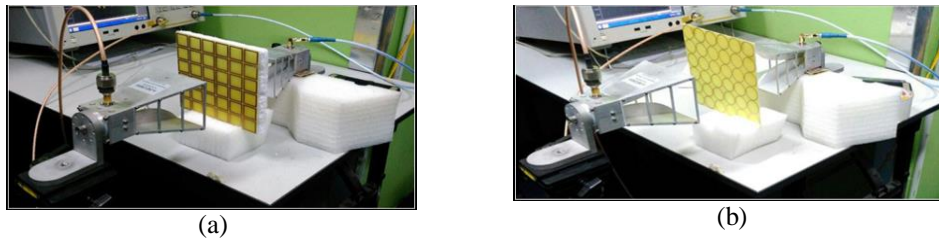


Figure 10. Free space measurement Setup (a) Measurement of Square Ring FSS, (b) Measurement of Circular Ring FSS

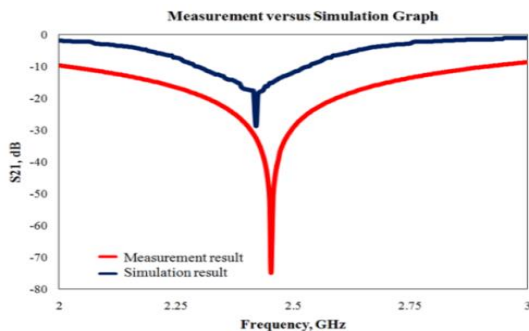


Figure 11. Measurement and simulation results of circular ring figure

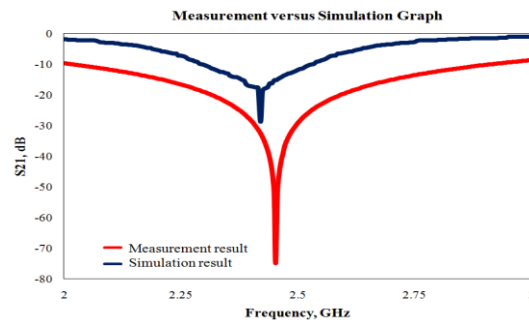


Figure 12. Measurement and simulation results of square ring

**4.4. Parametric Analysis**

Both design was analyze with the different unit cell size, outer and inner length of conducting element by maintaining the height of conductor element at 0.035mm. Frequency responses for the Circular Ring design in different unit cell size in Figure 13 shows that by increasing the unit cell size, the operating frequency shifted to higher frequency. In term of bandwidth responses, there is not much different result and almost same bandwidth % as the unit cell size is changes.

Figure 14 shows differences in outer length of conducting element by increasing the length of outer conducting element, the operating frequency shifted to lower frequency. In a meanwhile, the bandwidth is getting wider from 32% to 40%.

As the length increase in Figure 15, the frequency response shifted to lower frequency and when the length decrease, frequency shifted to higher frequency. At the same time, the bandwidth also is getting narrower from 42% to 38%. Figure 16 shows that by increasing the unit cell size, the operating frequency shifted to higher frequency. In a meanwhile, the bandwidth is getting narrower from 55% to 51%.

Simulation result for Figure 17, frequency responses shows as the length increase, the frequency response shifted to lower frequency and when the length decrease, frequency shifted to higher frequency. In term of bandwidth responses, there is not much different result and almost same bandwidth % as the inner length conducting material is changes.

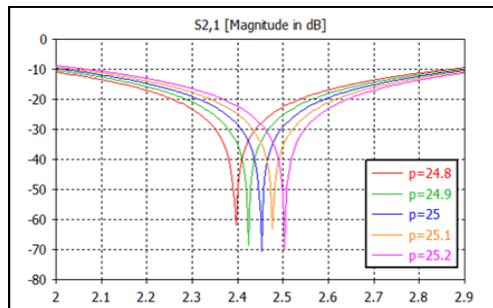


Figure 13.  $S_{21}$  result for different unit cell size

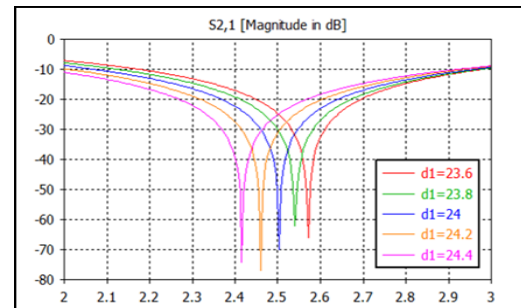


Figure 14.  $S_{21}$  result for different outer length conducting element

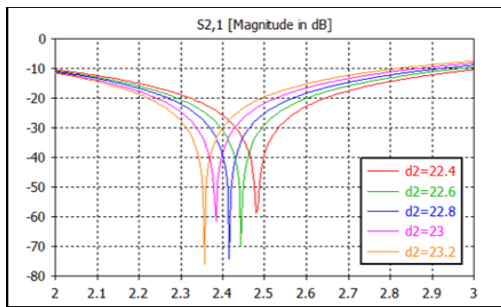


Figure 15.  $S_{21}$  result for different inner length of conducting element

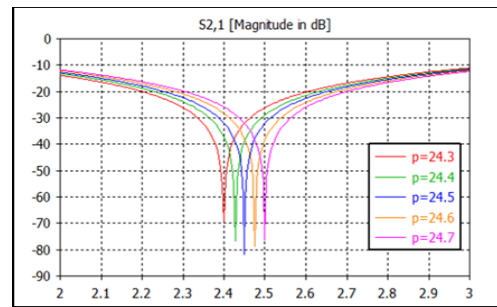


Figure 16.  $S_{21}$  result for different unit cell size

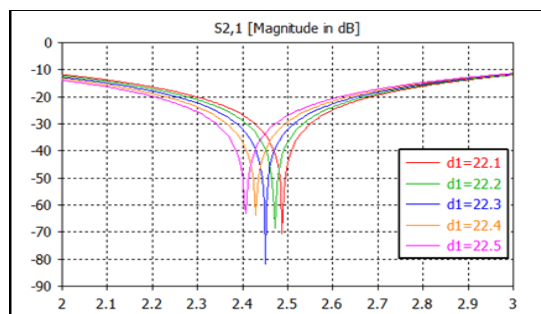


Figure 17.  $S_{21}$  result for different outer length conducting element

## 5. CONCLUSION

Two different types of FSS have been chosen to design and compare their performance. From the simulation process it can be identify that Square Loop FSS is the most suitable design to be apply as a sensor for SHM system application. The simulation result shows that Square Loop have better incident angle compare to Circular Ring design. The measurement result from fabrication process also shows that Square Loop FSS have better reflection coefficient. Thus, Square Loop is the suitable design for FSS to use as a sensor, where it has moderate sensitivity toward incident angle and produce a wide bandwidth as well to cover large frequency range. It is also been analyze that differences in each parameter measured will give effect towards frequency responses and as well as incident angle. FSS have been design to provide data in structural changes for monitoring system. The measured changes such as strain and moving of structure can be wirelessly transmitted to the base station for data analysis. By using passive and completely wireless FSS, the cost of monitoring will be saved and less power consumption needed.

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