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WAVEGUIDE FILTER USING FREQUENCY SELECTIVE SURFACE WITH MINIATURIZED ELEMENT

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Abstract—In this paper, a waveguide filter using miniaturized-element frequency selective surface (FSS) is presented. The proposed FSS is composed of periodic array of metallic patches separated by small gaps and metallic lines. The array of patches constitutes a capacitive surface and the lines a coupled inductive surface, which together act as a resonant structure. At about 5.0 GHz, a narrow bandpass response is designed. Dimensions of the FSS element are much smaller than the operating wavelength, which is less than $1/13\lambda$. For this miniaturized element, grating lobes are restrained and do not appear event to 25 GHz. Moreover, the FSS has stable performances for various incident angles. Design procedure and measurement results of the FSS are presented and discussed.

1. INTRODUCTION

Frequency selective surfaces (FSSs) are usually planar periodic structures that function as spatial filters for electromagnetic (EM) waves [1, 2]. For about 50 years, FSSs have been an attractive topic because of their comprehensive applications, such as filters, absorbers, polarizers, subreflectors, hybrid-radome for radar cross-section (RCS) controlling, etc. [3–15]. For decades, many novel FSS structures have been proposed to design FSSs with excellent performances. Performances of different FSS elements and effects of dielectric loading on FSS have been studied by Luebbers and Munk [1, 16]. Isotropic FSS

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were proposed in [17], which has almost the same performance under arbitrary incident angles and polarizations. Complementary FSSs by using Babinet principle had been investigated in [18, 19]. Coupled-resonator spatial filter (CRSF) FSS was firstly introduced in [20] and further investigated in [21–24], in which two microstrip patches are coupled through an aperture to form a higher-order bandpass filter. Substrate integrated waveguide (SIW) technology was proposed by Luo et al. [25–27] to design high performance FSSs, in which the SIW cavity is formed by arranging metallic via array around each periodic slot. Miniaturized FSS whose dimensions are much smaller than operating wavelength are poposed in [5]. Such miniaturized FSS elements can be arranged much more unit cells in finite area than conventional FSS structures based on half wavelength resonance. Therefore, in finite area miniaturized FSS are more attractive because they keep much more similar properties to infinite FSS structures. Convoluted FSS were also proposed in [28–30] to obtain with very small FSS unit cell. Waveguide filters are important in some applications, especially in microwave region. In this paper, we design a bandpass waveguide filter by using miniaturized FSS element. The proposed filter is composed of periodic array of metallic patches separated by thin air-gaps and metallic lines. At about 5.0 GHz, a narrow bandpass response is designed. Dimensions of the FSS element are much smaller ($\leq 1/13\lambda$) than the operating wavelength. For this miniaturized element, grating lobes are restrained and do not appear event to 25 GHz. Moreover, the FSS has stable performance for various incident angles. Section 2 describes the process of designing the waveguide filter. Moreover, Section 2 gives the analysis of the bandpass response of the FSS. Section 3 discusses the performances of the FSS under various incident angles. Finally, in Section 4 an experiment is taken to verify our design.

2. DESIGN AND ANALYSIS

Figure 1 illustrates the configuration of the FSS structure. The FSS is composed of single-layered metallic structures. It is printed with periodic array of metallic patches separated by small gaps and metallic lines. Using such a configuration, when the single-layered FSS structure are expanded to an infinite structure in the x- and y-directions. The array of metallic patches will constitute a capacitive surface and the metallic lines a coupled inductive surface, which together act as a resonant structure.

CST Microwave Studio based on Finite Integration Method is used to calculate the performance. The FSS is assumed to be an infinite

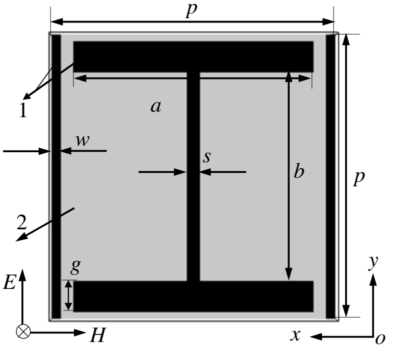


Figure 1. Front view of the FSS element.

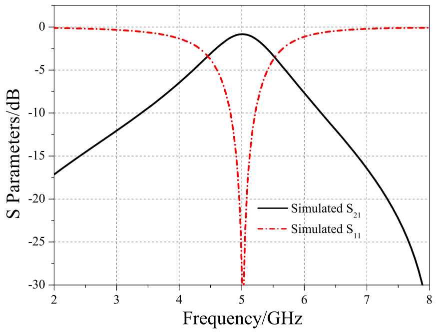


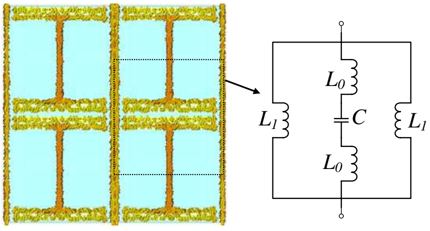
Figure 2. Simulated s-parameters of the structure for normal incidence.

periodic structure. The FSS unit cell is excited by incident plane waves with various incident angles. The incident plane wave vector $\mathbf{k}$ is fixed in the x-z plane and the electric field vector $\mathbf{E}$ is fixed in the y direction. The four sides of the unit cell are set to be unit cell boundary. Geometrical values of the structure are $p = 4.5\,\text{mm}$, $a = 3.8\,\text{mm}$, $b = 3.3\,\text{mm}$, $w = 0.15\,\text{mm}$, $s = 0.2\,\text{mm}$, $g = 0.5\,\text{mm}$. The substrate of the FSS is FR4, whose permittivity is 4.2, loss tangent 0.025 and thickness $h = 2.0\,\text{mm}$.

Figure 2 gives the s-parameters under normal incidence. It can be found that a bandpass resonance occur at about 5.0 GHz. The insertion loss is about 0.85 dB. -3 dB bandwidth of the passband is from 4.50–5.41 GHz. In order to clarify the physical mechanism of FSS, we will give analysis to the resonance as follows. Fig. 3(a) shows the surface current distribution diagrams on the surface of the FSS at 5.0 GHz. It can be observed that two opposite current flows occurred on the metallic lines and patches. Based on this current distribution, the corresponding equivalent circuit model is given in Fig. 3(b). The array of metallic patches constitutes a capacitance C, the metallic lines a coupled inductance L_1, the two short lines L_0, which together act as a resonant structure.

3. FSS WITH STABLE PERFORMANCES

The transmission coefficient of this FSS for different incidence angles of TE plane wave with y-direction electric field component is illustrated in Fig. 4. It can be seen from Fig. 4 that the passband is rather stable. As the incident angles increase, bandwidths of the passband become



(a) (b)

Figure 3. (a) Surface current distribution at 5.0 GHz and (b) the equivalent circuit model.

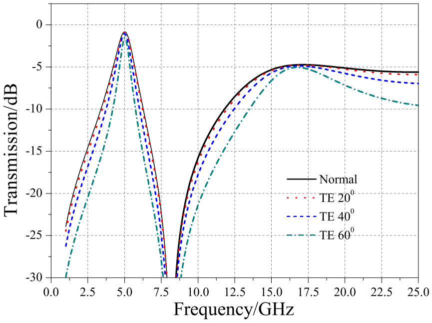
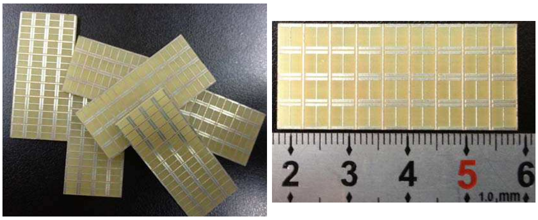


Figure 4. Transmission responses under different incidence angles.



(a) (b)

Figure 5. Prototype of the fabricated filter. (a) Samples and (b) zoom in view.

a litter narrower. Nevertheless, the resonant frequencies are rather stable even the incident angles up to 60 degrees. Moreover, grating lobes are restrained and do not appear event to 25 GHz.

4. EXPERIMENTS

In order to measure the response of the waveguide filter, the equipment shown in Fig. 6 is used. We use the waveguide measuring system to verify the validity of the design [5]. It is composed of a HP 8720ES vector network, two cables and a BJ48 waveguide. Dimension of the BJ48 waveguide is 47.549 × 22.149 mm. The waveguide cut-off frequency is about 3.18 GHz, which is below the FSS resonance frequency. Therefore, the measured frequencies range of the experiment is from 3.5 GHz to 7.0 GHz. Prototype of the fabricated FSS is shown in Fig. 5. The proposed FSS is fabricated by using FR4 substrates. It is made up of a periodic array of 9×4 (in the x- and y-axis directions) unit cells, so the overall size of the structure is $40.5\,\mathrm{mm} \times 18\,\mathrm{mm}$.

(a) (b)

Figure 6. (a) Experimental equipment and several kinds of waveguides and (b) a sample in foam model.

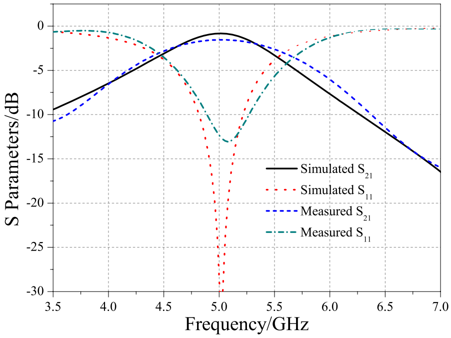


Figure 7. Measured and simulated responses of the waveguide filter.

Measured and simulated transmission coefficients are shown in Fig. 7. The measured and the simulated results have the same trend, but there are some little differences between them. The measured resonance frequencies shift to a little higher frequencies than the simulation ones. Insertion loss is larger than the simulation results, which is about 1.5 dB. These discrepancies can be attributed to the fabrication precision of the FSS and the losses of waveguide measuring system. The measured results are not perfect compared with the simulation ones, but the results still support the hypothesis that the structure functions as waveguide filter at 5.0 GHz.

5. CONCLUSION

A bandpass waveguide filter operating is designed and measured. At about 5.0 GHz, a narrow bandpass response is obtained. Dimensions of the FSS element is less than $1/13\lambda$. The profile is only 2.0 mm and is about $1/30\lambda$. Grating lobes are restrained and do not appear event to

25 GHz. Moreover, the FSS has stable performance for various incident angles. Such a FSS may help to design waveguide filters in practical applications.

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