Design of 3-D FSS with high selectivity based on ELC resonators and spoof-SPPs

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Abstract. The paper proposes a simple band stop frequency selective surface (FSS) design method based on spoof surface plasmon polaritons (spoof-SPPs). The novel FSS design is obtained by combing three-dimension (3-D) FSS and ultra-thin periodic corrugated metallic strip which supports spoof-SPPs. By placing electric-LC (ELC) resonators on the FSS surface at the bottom centre of the corrugated strip, the tight coupling occurs and we show that the SPP modes are rejected near the resonance frequencies of ELC resonators. The steep roll-off at both sides of the stopband can be demonstrated by the ELC resonators, which can find potential applications in wideband antenna radome. In addition, the 3-D FSS shows relatively stable performance with different oblique incidence angles.

1. Introduction

Surface plasmons (SPs) are electromagnetic wave coupled on the surface between conductor and dielectric medium [1-2]. Due to the tight sub-wavelength confinement and large field enhancement characteristic, SPs have attracted a lot of attention and found potential application of great values [3-6]. To excite SPs at THz or even microwave band, an effective approach is to pattern a metal surface with sub-wavelength periodical holes or grooves, which may improve the confinement of surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs) [7-11]. Since the propagation constant of electromagnetic waves spoof-SPPs is much larger than that in free space, spoof-SPPs can easily couple electromagnetic waves in free space to the surface of the periodic structure. In addition, the significant advantage of spoof-SPPs is that its dispersion characteristics are totally determined by the construction size of metallic holes or grooves.

Frequency selective surfaces (FSSs) have been widely investigated from the last century [12-13]. They have gradually evolved from simple designs to complex structures. Generally, the sharp cut-off characteristics of traditional FSS are realized by increasing the thickness of the medium. This may increases the passband insertion loss of the structure, which we don't expect to see. Recently an X-band frequency selective surface (FSS) using the concept of spoof-LSPs is presented in [14]. Moreover, FSS, absorber and frequency selective rasorber based on 3-D architecture have been of great interest due to their advantage of stable frequency response and miniaturized elements [15-16].

Generally, the rectangle coefficient $k=B_2/B_1$ is used to describe the frequency selectivity, in which $B_2$ is the -10 dB bandwidth and $B_1$ is the -3 dB bandwidth. For a perfect filtering FSS, the rectangle...
coefficient $k$ should be close to 1. For better comparison, the rectangle coefficient $k$ and angle stability of various works are listed in Table 1. The proposed 3-D FSS in this paper show more stability angle and smaller rectangle coefficient.

### Table 1. Comparison with previously proposed FSS.

| Ref   | $k$  | Angle stability(°) |
|-------|------|---------------------|
| [17]  | 1.89 | 30 (TM)             |
| [18]  | 1.36 | 60                  |
| [19]  | 1.7  | 45                  |
| This work | 1.14 | 60 (TM)             |

2. Geometry and designs

The purpose of this paper is to propose a new design of dual polarization band-stop FSS with steep roll-off response. As shown in Figure 1, the new design is a hybrid of 3-D waveguide, periodic corrugated metallic strip and ELC resonators. The first step is to design the periodic corrugated metallic strip. As the cut-off frequency of spoof-SPPs can be adjusted by the length of the grooves of the metallic strips, the coupling efficiency of spoof-SPPs and air space can be improved by optimizing parameters such as period, length and width of strips. The second step is to design a 3-D FSS structure, which can produce a wide pass band. At the spoof SPP asymptotic frequencies of the fundamental mode, the FSS structure results in a lowpass response together with a sharp roll-off. At last, the ELC resonators are introduced on the bottom surface of the strips, the strong coupling effect of ELC resonators and spoof-SPPs, will produce a steep stop band in the original transmission band. Furthermore, the simulation results verify that the proposed structure exhibit stable performance in the case of large angles of incidence.

![Figure 1](image-url) Schematic configuration of the 3-D FSS structure. (a) 3-D view of a unit cell of 3-D FSS. (b) Side view of the corrugated metallic strip, in which the length and width of the dielectric substrate are 82.5 mm and 18 mm. The unit of the corrugated metallic strip is designed as $p=5.5$ mm, $a=4$ mm, $w=2$ mm, the distance between the adjacent ELC resonator is $g=1.3$ mm, (c) front view of the 3-D FSS structure (d) the ELC unit cell.

In this work, we propose a simple method to control the rejections of 3-D FSS. As described above, the structure consists of 3-D FSS structure and ultra-thin periodic corrugated metallic strips. Two sets of dielectric plates are placed crosswise to form the basis of the 3-D FSS framework as shown in Figure 1(a). A 3-D geometrical topology of the proposed 3-D FSS unit cell is depicted in Figure 1(a), where the $x$-$y$ plane denotes the periodic plane. The periods of the unit cell along $x$- and $y$- directions
are 18 mm. And the 3-D FSS has characteristics similar to rectangular waveguides in microwave circuits. This specification of waveguide can support electromagnetic wave transmission below 12GHz. Electromagnetic waves in free space below the cutoff frequency can pass through the structure. The 3-D FSS contains several pieces of substrate etched with metallic strips. Such metallic strips can efficiently excite the spoof SPP modes from the free space wave. This specific design is for high-efficiency couplings between the spoof SPP modes on the free space wave and the metallic strips blades. The depths of grooves are designed from 1.5 mm to 4.5 mm from the narrowest to the widest. The supporting F4B substrate ($\varepsilon_r=2.65$, $\tan\delta=0.001$) is set 0.3 mm thickness. Both copper layers are of 0.018 mm thickness.

Figure 2. Evolutions of the dispersion curves for the spoof-SPP mode with variations of height with the same geometric parameters $a=4$ mm, $p=5.5$ mm, $w=2$ mm, $t=0.3$ mm. The inset shows the unit cell with corresponding substrate.

3. Analysis and discussion
Before discussing the proposed 3-D FSS structure, we first studied the evolution of the dispersion curves of a corrugated metallic strip unit cell chosen in Figure 1(b) with the variations of $h$. As shown in the inset of Figure 2, the period, width, and depth of the metallic grooves of the strips are $p$, $p-a$, and $h$, respectively. In this simulation, the depth varies from 1.5 mm to 4.5 mm, the interval is 1 mm. Then the dispersion curves of the fundamental mode are calculated in Figure 2. It is obvious that the spoof-SPPs are in the nonradiative zone, which can confine electromagnetic waves at the interface. Simulation results clearly show that the deeper the groove, the lower the asymptotic frequency. Therefore, the cut-off frequency can be designed by adjusting the depth of the groove. The asymptotic frequency of the fundamental mode is 12 GHz when $h=4.5$ mm. In order to achieve efficient conversion of electromagnetic waves between free space and spoof-SPPs structure, the propagation constant at both ends of the periodic metallic corrugated strips should be close to the propagation constant in free air. As shown in Figure 1(a) and Figure 1(b), the width of the designed structure is narrow at both ends and wide at the centre place.
Figure 3. Simulated reflection and transmission coefficients of the 3-D FSS structure with spoof-SPP structure ($h=4.5$ mm).

Consider $x$-polarized (or $y$-polarized wave) uniform transverse electromagnetic plane wave normally impinging on the structure. Figure 3 shows the reflection and transmission coefficients of the 3-D FSS structure with spoof-SPP structure. The simulated results are obtained by using a fullwave simulator CST Microwave Studio (CST-MWS). It demonstrates that the $S_{21}$ of the structure is up to -0.05 dB from 2 to 11 GHz. In the range of 12.5 to 13 GHz, the transmission coefficient is lower than -30 dB. This shows that the 3-D FSS can effectively inhibit the transmission of EM waves after the cutoff frequency.

We hope to create a steep stop band on the wide pass band, which can produce two separate pass bands. ELC resonator based metamaterial structure has been first proposed by [20] as microwave absorber. For this purpose, the ELC resonators are designed and arranged on the bottom surface of the SPP waveguide, as illustrated in Figure 1(b). The ELC particles are designed and arranged on the bottom surface of the substrate slab. When electromagnetic waves are converted into spoof SPPs mode, the electric field of spoof SPP mode can couple with the ELC resonator. Therefore, the ELC particles can be introduced to control the rejections of SPPs wave in the propagating band. By optimizing the dimensional parameters of the design ELC resonator, Table 2 lists the values of the ELC resonator parameters. The distance between the adjacent structures is $g=1.3$ mm.

Table 2. Parameters of ELC resonator.

| Parameters | Value (mm) |
|------------|------------|
| $d_1$      | 4.70       |
| $d_2$      | 3.25       |
| $d_3$      | 0.73       |
| $d_4$      | 1.00       |

Figure 4 shows the simulation results of the S-parameters using full-wave simulations. We noticed that the proposed ELC resonators provide an excellent band-notched function from 7.6 GHz to 7.4 GHz in a narrow frequency regime. The frequency range with a transmittance below -20 dB is 6.7 to 7.3 GHz. In addition, the strong coupling between the ELC resonators and spoof-SPPs waveguide also affect the transmission efficiency outside the band-stop region, especially in the cutoff frequency region. Several resonator responses occur, which can be minimized by tuning the dimensions of ELC resonator and the dielectric thickness of 3-D FSS.
Figure 4. Transmission spectrums ($S_{21}$) and reflection spectrums ($S_{11}$) of the 3D FSS structure with the ELC resonators and spoof-SPP structure.

Furthermore, the filtering performance of the proposed 3-D FSS under different incident angles is illustrated in Figure 5. Figure 5 shows the 3-D FSS structure has a relatively stable performance with different oblique incidence angles and has good band-notched results for incident angles up to 60°. For the case of transverse magnetic (TM) configuration, as the incident angles increase, the amplitude of the transmission coefficient changed slightly in the stopband. As the incident angle increases to 60°, some resonance peaks occur at the higher frequency, which is due to high order resonance between the air impedance and the 3-D FSS structure.

Figure 5. Transmission coefficient ($S_{21}$) under TM polarization and various incident angles (0~75°).

Since the bandwidth of the stop band is related to the size of the resonance unit, a broadband stopband FSS can be realized by adding differently scaled ELC resonators. Five different ELC elements are designed with variations length ($d_i = 4.88, 4.80, 4.7, 4.51, 4.32$ mm, $i=1,2,3,4,5$), facilitating the realization of high-performance band-stop characteristics in the specified frequency range, as show in Figure 6. The simulation results of the transmission ($S_{21}$) and reflection ($S_{11}$) coefficients illustrated in Figure 6 demonstrate that a rejection bandwidth of 1 GHz with $S_{21} < -5$ dB. And ELC resonators of different sizes have very little effect on out-of-band transmission. The transmission coefficients from 1 to 6.4 GHz and from 7.8 to 10 GHz are higher than -1 dB with minimum insertion loss.
Figure 6. Simulated transmission coefficients ($S_{21}$) and reflection coefficients ($S_{11}$) for the broadband case. Bottom inset shows the schematic picture of the broadband band-stop filter.

4. Conclusions
In summary, we have theoretically proposed a band-stop 3-D FSS based on spoof-SPPs and ELC particles. The structure uses a three-dimensional architecture, which is compact and easy to process in engineering. The proposed 3-D FSS features highly selective filtering response with low insertion loss in the passband. By tuning the dimension of the ELC particles, narrow or wide stop bands can be easily achieved conveniently. The ultra-thin periodic corrugated metallic strips, which can support spoof SPP, play an important role in the 3-D FSS structure. It also exhibits stable angular response under a large variation of the incident angle.

Acknowledgements
This work was supported in part by the Project funded by China Postdoctoral Science Foundation (Grant No. 2018M642214), Jiangsu Planned Projects for Postdoctoral Research Funds (Grant No. 2018K005B).

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