An Ultrathin and Polarization-Insensitive Frequency Selective Surface at Ka-Band

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Abstract—In this letter, an ultrathin frequency selective surface is developed with a square cell unit loaded with three ring slot pairs. The outer ring slot pair is loaded with metal shorts. It achieves one polarization-insensitive passband with sharp transition at Ka-band. The design is verified with full-wave simulated results, as well as the measured results. The fabricated FSS has a flat passband, and its measured 3 dB bandwidth is from 33 to 37.5 GHz. A complete angular stability study of the FSS has been conducted. Meanwhile, it can directly attach to the aperture of the horn antenna to lower the whole profile of FSS-antenna configuration. Working as a radome, this FSS can be a good candidate for radar communications and radar-cross-section reduction in radar stealth research area at Ka-band.

Index Terms—Frequency selective surface (FSS), Ka-band, polarization insensitivity, radome.

I. INTRODUCTION

FREQUENCY selective surface (FSS) is a kind of periodic structure that has been widely investigated for decades. As spatial filters, it has a variety of applications, such as radomes, absorbers, reflectors, etc. Many types of FSSs have been developed. A miniaturized dual-band FSS having broadband responses, excellent stability for different incident angles, and sharp roll-off at X- and Ka-bands, respectively, has been proposed in [1]. Tri-band FSS unit cell of a square loop combined with a hexagonal ring and a hexagon are designed to reflect the Ku-band signal and transmit through the K- and Ka-band signals in [2]. These FSSs generally have ultrawide band or multiband characteristics. They are not very low profiles. The thicknesses of these FSSs normally range from several millimeters to more than 10 mm. In [3], when metal shorts are added to one ring slot, the reflection coefficient of the FSS is investigated. In [4], a triband FSS with close band spacing based on split-ring slots for only y-polarized incident waves is studied. However, in recent years, with the rapid developments of radar and missile communications, there is a demand for low-profile, polarization-insensitive, and light-weight FSS to be electromagnetic transparent at one sharp frequency band of the antenna and to lower the out-of-band radar cross section (RCS) of the antenna at millimeter-wave frequency bands. Nevertheless, the performances of these reported FSSs are not very satisfactory for this demand.

In this letter, we propose an ultrathin and polarization-insensitive FSS working at Ka-band. First, the transmission characteristics of several FSS models are proposed, investigated, and compared. Second, the chosen FSS is fabricated and measured. This proposed FSS has a measured 3 dB bandwidth from 33 to 37.5 GHz, relatively flat passband, sharp roll-off, and stable polarization and incident angle performances at Ka-band.

II. UNIT CELL DESIGN AND SIMULATION RESULTS

The unit cells of our FSS are investigated first. Each unit cell has two metallic layers (the yellow area) on the top and bottom surfaces of a dielectric substrate. The configurations of these two metallic layers are totally the same. All these unit cells are simulated as an infinite periodic structures using master/slave boundary conditions by ANSYS HFSS. To compare the transmission properties more easily, the lengths $l_{oc}$ of the unit cell models depicted in Fig. 1(a) are all the same. This means that their periodicities are identical. Ring slots I, II, and III are actually three pairs of ring slots printed on both sides of the substrate in cases i), ii), and iii). These three ring slot pairs have different radii, and their slot widths $w_{slot}$ are all the same. The resonance of an FSS unit cell with single ring slot printed on one side of the substrate occurs when its circumference is approximately equal to the wavelength $\lambda$ and its resonant frequency is $f_{r}$. A pair of
ring slots form a synchronously tuned coupled resonator [5]. Both electric and magnetic couplings exist between each pair of ring slots. The resonant frequency generated by the electric coupling is higher than \( f_s \). The resonant frequency generated by the magnetic coupling is lower than \( f_s \). Therefore, a passband is obtained for each pair of ring slots in cases i), ii), and iii), shown in Fig. 1(b). Obviously, on the spectrum, the location of the resonant band moves upward when the radius of the ring slot pair decreases, but within the resonant band, the transmission characteristic is not very well. Meanwhile, at the lower side of the passband, the roll-offs of single-ring-slot-pair unit cells are not sharp, which means their frequency-selective properties are poor, especially at lower side of the resonant band.

To obtain steep roll-offs at both edges of the passband of single-ring-slot-pair unit cell, three pairs of ring slots are concentrically put together to form one unit cell as shown in case iv) of Fig. 1(a). In Fig. 1(b), two transmission zeros appear right beside the Ka resonant band for case iv). The resonant band of case iv) is wider than the ones of single-ring-slot-pair unit cells of cases i), ii), and iii), but the unit cell with only three ring slot pairs still cannot achieve low loss within this whole band.

By splitting a ring slot with metal shorts, the resonant frequency is shifted upward [3], [4]. In Fig. 2(a), four shorts are added to ring slot III on one side of the substrate by two ways, shown in cases I and II. Therefore, one ring slot III becomes four etched slots as in cases I and II. In case I, four shorts are located on \( \pm x \)- and \( \pm y \)-axis. In case II, these slots rotate \( \varphi = 45^\circ \) around \( z \)-axis. The transmission responses of cases I and II are presented in Fig. 2(b) and (c). TE and TM plane waves separately impinge on each unit cell. Compared with the transmission response of the unit cell with only ring slot III in Fig. 1(b), three resonant frequency points \( (f_1, f_2, \text{ and } f_3) \) within one resonant band of case I or II appear, and all of them move up to Ka-band. This is because the resonant length of the etched slots is shorter than the one of ring slot III. The three frequency points \( f_2 \) in both cases stay still at 33.5 GHz, which can be applied to improve the transmission feature of Ka-resonant band of case iv) in Fig. 1(a). \( f_1 \) and \( f_3 \) move closer to \( f_2 \) in case II, but the transmission characteristics at the frequencies between every two neighboring resonant frequency points are poor.

Based on the above research, a novel square unit cell is developed. It has three ring slot pairs. The outer ring slot pair is loaded with metal shorts, shown in cases III and IV of Fig. 3(a).

When a TE plane wave illuminates them, Fig. 3(b) shows the transmission responses of cases III and IV in our interested frequency band (from 30 to 40 GHz). Comparing these two curves, it concludes that the 3 dB passbands of cases III and IV are both from 32.9 to 37.2 GHz. However, within the passband, there is an obvious reflection dip around 34.8 GHz for case III. The reason is that around 34.8 GHz, the TE wave excitations of the unshorted ring slot pairs (I and II) and of the shorted ring slot pair III are out of phase for case III rather than in phase for case IV.

Based on the above design and analysis, the configuration of case IV is finally adopted as the unit cell of our FSS. The design procedure of this FSS is given below.

First, calculate the periodicity \( l_{uc} \) of the unit cell by the equation given below

\[
l_{uc} = c/(f_0 \cdot \sqrt{\varepsilon_r})
\]

where \( c \) is the velocity of light, \( f_0 \) is the operating center frequency, and \( \varepsilon_r \) is the relative dielectric constant.

The upper side frequency \( f_u \) of 3 dB passband is dependent on the radius \( r_1 \) of ring slot I. The radius \( r_1 \) of ring slot I is nearly equal to the wavelength of the upper frequency \( f_u \) as

\[
r_1 = c/(2\pi f_u).
\]

To simplify the optimization of the parameters of this model, the widths of three ring slots \( w_{slot} \) and the spacing between two neighboring ring slots \( w_{mr} \) are all set the same. When \( w_{mr} \) is smaller, the coupling between two neighboring ring slots is stronger, but to consider the limitations and errors of the manufacturing, \( w_{slot} \) and \( w_{mr} \) are both set to 0.2 mm. Based on the above formulas and the widths \( w_{slot} \) and \( w_{mr} \), the dimensions of ring slot pairs II and III are all obtained. Finally, the width of the shorts \( w_{gap} \) is adjusted to achieve the lower side frequency \( f_1 \) of the passband. When \( w_{gap} \) is bigger, \( f_1 \) is higher.

The optimized dimensions of the unit cell are \( l_{uc} = 4.5 \text{ mm}, \ r_1 = 1.25 \text{ mm}, \ r_2 = 1.65 \text{ mm}, \ r_3 = 2.05 \text{ mm}, \ w_{slot} = 0.2 \text{ mm}, \ w_{mr} = 0.2 \text{ mm}, \ w_{gap} = 0.3 \text{ mm}. \)
III. MEASUREMENT RESULTS

A 625-element Ka-band FSS prototype with a dimension of $100 \times 100 \times 0.5 \text{ mm}^3$ is manufactured by chemical etching technique and measured. Rogers RO4350 with relative permittivity $\varepsilon_r = 3.66$, loss tangent $\delta = 0.004$, and thickness $t = 0.5 \text{ mm}$ is applied as the dielectric substrate for our FSS. A photograph of this FSS is presented in Fig. 4.

The measurement setup contains two standard horn antennas working separately as transmitting (Tx) and receiving (Rx) antennas. To achieve the plane wave incidence as in [6], the distance $d_0$ between the apertures of Tx and Rx is 8 m, as shown in Fig. 5(a) and (b). These two horn antennas are aligned for maximum reception and connected to a vector network analyzer. Our FSS is located in front of the Rx. The distance between them is $d$, as shown in Figs. 4 and 5(a).

The angular stability measurement [7] should be complete to clearly learn the performance limitations of our FSS. This means that for each polarization angle ($\varphi \in [0^\circ, 90^\circ]$), the whole oblique incident angles ($\theta = [0^\circ, 60^\circ]$) should be swept. The unit cell of our FSS is symmetrical along $\varphi = 45^\circ$. The transmission responses of $\varphi \in [45^\circ, 90^\circ]$ are the same as the ones of $\varphi \in [0^\circ, 45^\circ]$. Therefore, the situations that the polarization angle $\varphi$ is from $0^\circ$ to $45^\circ$ and the oblique incident angle $\theta$ is from $0^\circ$ to $60^\circ$ are investigated. Both steps of these two angles are $15^\circ$.

During the measurement, it is observed that when $\varphi < 45^\circ$ and $\theta \leq 45^\circ$, the transmission coefficients within the passband are all higher than $-3 \text{ dB}$. When $\varphi = 45^\circ$, the transmission coefficients within the passband are higher than $-3 \text{ dB}$ only within $\theta \leq 30^\circ$. Therefore, for clear readability, the good transmission responses in passband under small oblique incident waves are omitted in Fig. 6. Fig. 6(a) and (b) separately provides the measured transmission responses of our FSS under TE and TM polarized waves with normal and large oblique incidences.

From these curves, it summarizes that when the waves impinge on it normally ($\theta = 0^\circ$ and $\varphi = 0^\circ$), the measured passband ($S_{21} \geq -3 \text{ dB}$) is from 33 to 37.5 GHz. The performance limitations of the presented FSS are that when $\varphi$ is smaller than $45^\circ$, $\theta$ can reach to $45^\circ$; when $\varphi$ is equal to or more than $45^\circ$, $\theta$ should be no larger than $30^\circ$. These measured results verify the polarization-insensitive characteristic of our FSS.

Fig. 7 exhibits the transmission responses under various distances between our FSS and the aperture of Rx antenna for TE polarization incidence. The FSS plate is parallel to the aperture of the Rx horn antenna. “$d = 0 \text{ mm}$” means the FSS directly
Fig. 6. Measured transmission responses under various incident angles. (a) TE wave incidence. (b) TM wave incidence.

Fig. 7. Measured transmission responses versus different distances $d$. Attaches to the aperture of the Rx antenna. From these curves in Fig. 7, it apparently means that the distance between the FSS and the aperture of the horn antenna has little effect on the transmission characteristic of the FSS-antenna configuration. Thus, the FSS can be directly located in front of the aperture of the horn antenna to form a low-profile FSS-antenna configuration.

The FSSs in [1] and [2] have at least one operating frequency band in Ka-band. The unit cells of [3], [4], and our FSS are all based on shorted ring slots. Therefore, when the measurements of our FSS are done, the characteristics of our FSS and the ones from [1]–[4] are listed in a comparison table. In Table I, FBW is the fractional bandwidth, where the FBW is $BW/f_0$, $f_0$ is the central frequency of passband. In all these reference papers, the incident waves with different values of polarization angle $\varphi$ are not mentioned and studied. In [1] and [2], the thicknesses of FSSs are 2 and 7.1 mm; therefore, they are not very thin. Meanwhile, the unit cells of these FSSs are totally not similar to ours. In [3], only the reflection characteristic of the shorted ring slots is studied. In [3] and [4], although both unit cells of the FSSs are based on shorted slot resonators, they are not polarization-insensitive FSSs. Our FSS proposed in this letter is only 0.5 mm thin and polarization-insensitive until $\theta = 45^\circ$. The profile of FSS-antenna configuration is further lowered by directly attaching to the aperture of the horn antenna.

IV. CONCLUSION

A square unit cell loaded with two pairs of ring slots and one split-ring slot pair is applied in our design to develop a polarization-insensitive FSS at Ka-band. The relationships between the transmission responses and the locations of the metal shorts on the split-ring slot pair are investigated first. The optimized polarization-insensitive unit cell is obtained. The transmission responses of our FSS under different polarizations, various incident angles, and several distances between this FSS plate and the aperture of the horn antenna are all measured and analyzed. All results demonstrate high transmission within the passband and steep roll-offs at both edges of the passband of our FSS in the Ka-band, fulfilling the requirements on radome applications for flat passband, sharp roll-off, and RCS reduction.

REFERENCES