LETTER

Highly-selective, closely-spaced, tri-band bandpass three-dimensional frequency selective surface

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Abstract A highly-selective, closely-spaced, tri-band bandpass three-dimensional frequency selective surface (3D FSS) is proposed based on the topology of the microwave filter in this paper. The unit cell of the proposed 3D FSS is constructed by combining an air-filled square waveguide and a cuboid dielectric resonator. Both top and bottom layers of the dielectric resonator consist of double square loops, while the middle layer contains an embedded square loop. Due to its inner electromagnetic coupling in the unit cell, multiple transmission zeros/poles are introduced for obtaining high frequency selectivity, two second-order passbands, and wide out-of-band rejection. Concentric square loops with very close sizes are designed to realize small band ratios. In order to understand the working principle of the proposed 3D FSS, the surface current distributions at the frequencies of transmission poles are analyzed. Finally, an FSS prototype is fabricated and measured. The measurement results show a stable response under the incident angles up to 60° for both TE and TM polarizations is realized. Besides, the proposed 3D FSS has a relatively compact unit cell size.

Keywords: frequency selective surface (FSS), tri-band, high frequency selectivity, small band ratio, dual polarizations

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Frequency selective surfaces (FSSs) have been extensively investigated over the past decades [1]. For practical applications, FSSs can be utilized as hybrid radomes for stealth [2, 3, 4], antenna sub-reflectors in satellite communications [5, 6, 7], microwave absorbers [8, 9, 10], electromagnetic shielding [11, 12, 13], and signal strength for indoor wireless environments [14, 15]. To increase the capabilities of multi-frequency antennas in satellite communication system, the FSSs are correspondingly demanded to operate at multi-bands [16, 17, 18]. Furthermore, when the three channels are closely located in the frequency domain, tri-band bandpass FSSs with small band ratios are highly desirable for some applications.

To meet above-mentioned requirements, several tri-band

bandpass FSSs were investigated. Based on the convoluted design, a miniaturized tri-band FSS with bandpass responses was proposed in [19]. Two FSSs were designed using the complementary structures, which provided a tri-band bandpass response [20, 21]. However, these first-order tri-band FSSs in [19, 20, 21] had limitations on flat passbands and wide out-of-band rejections, due to the lacking of multiple transmission zeros/poles. For improving the flatness of the passbands, one or more second-order passbands were realized. The authors in [22] presented a flexible three-screen cascaded FSS for X-, K-, and millimeter-band application. In [23], a tri-band bandpass FSS was realized by cascading three layers of periodic square loop arrays, which exhibited high frequency selectivity and good angular stability. By using the hexagonal loops to replace the ordinary square loops used in [23], one tri-band bandpass FSS with broadband characteristics was achieved [24]. However, these FSS [22, 23, 24] used to suffer from undesired grating lobes in the high frequency band as the incident angle increased. As described in [25], a three-dimensional (3D) tri-band FSS with second-order bandpass responses was proposed based on the short-circuited resonator and open-circuited resonator. Unfortunately, this FSS only operated under single polarization and lacked transmission zero. In [26], a dual-polarized FSS was proposed by employing a three-layer patch-aperture-patch structure, which exhibited a response similar to that in [25]. However, its angular stability was dissatisfactory resulted from its large electrical size, and the frequency selectivity performance was also needed to be further improved because there was no transmission zero. With the help of electromagnetic coupling, another second-order tri-band bandpass FSS with multiple transmission zeros was presented by cascading a two-layer periodic array with three concentric square loops [27], but it also appeared the grating lobes as the incident angle increased, and its unit cell electrical size is relatively large. In addition, the band ratios of the reported tri-band bandpass FSSs were large, leading to limitation on their applications. Hence, there is a challenge for the tri-band FSS design to avoid grating lobes and realize flat passband, high frequency selectivity, small band ratio, good angular stability, dual polarizations, and compact unit cell size at the meantime.

In this paper, a dual-polarized tri-band 3D FSS with second-order bandpass responses is presented based on the topology of the microwave filter, whose unit cell consists of an air-filled square waveguide and a cuboid dielectric resonator with three metallic layers. Due to its inner elec-

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tromagnetic coupling in the unit cell, multiple transmission zeros/poles are introduced, leading to high frequency selectivity, two second-order passbands, and wide out-of-band rejection performances. Concentric square loops with very close sizes are designed to achieve small band ratios. The surface current distributions at the frequencies of transmission poles are analyzed to illustrate the working principle. The results show a good consistency between the simulations and measurements.

2. Unit cell design and simulation

2.1 Design procedure

Fig. 1(a) gives a topology of the first-order tri-band bandpass microwave filter. It consists of one hybrid resonator and one serial LC resonator (L_3 - C_3), and these two resonators are separated by a short transmission line (TL). The hybrid resonator includes two shunt serial LC resonators (L_1 - C_1 and L_2 - C_2) in shunt with an inductor (L_0). For the sake of analysis, assuming that the equivalent inductance and capacitance of the short transmission line can be represented by L_t and C_t , respectively.

It is obvious that a transmission pole f_{p1} and a transmission zero f_{z1} can be introduced when the serial LC resonator (L_3 - C_3) resonates with the inductor (L_0). The two resonant frequencies of f_{p1} and f_{z1} ($f_{p1} < f_{z1}$) are represented as

$$f_{p1} = \frac{1}{2\pi\sqrt{(L_0 + L_3 + L_t)(C_3 + C_t)}} \quad (1)$$

$$f_{z1} = \frac{1}{2\pi\sqrt{L_3 C_3}} \quad (2)$$

Another transmission zero f_{z2} ($f_{z2} > f_{z1}$) can be produced when the serial LC resonator (L_1 - C_1) resonates, which is expressed as

$$f_{z2} = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (3)$$

According to the analysis in [28], a new transmission pole f_{p2} can be obtained between the two transmission zeros at

the frequencies of f_{z1} and f_{z2} , which is written as

$$f_{p2} = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_3}{(L_0 + L_1 + L_3 + L_t)(C_1 C_3 + C_t(C_1 + C_3))}} \quad (4)$$

Similarly, when the serial LC resonator (L_2 - C_2) resonates, the third transmission zero f_{z3} ($f_{z3} > f_{z2}$) is produced. Furthermore, the third transmission pole is also obtained between two transmission zeros at the frequencies of f_{z2} and f_{z3} , which are given by

$$f_{z3} = \frac{1}{2\pi\sqrt{L_2 C_2}} \quad (5)$$

$$f_{p3} = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_2}{(L_1 + L_2 + L_t)(C_1 C_2 + C_t(C_1 + C_2))}} \quad (6)$$

To sum up, when all LC resonators resonate simultaneously, a tri-band bandpass filter with first-order responses is achieved. Three passbands and three stopbands are achieved around the transmission poles (f_{p1} , f_{p2} and f_{p3}) and transmission zeros (f_{z1} , f_{z2} and f_{z3}), respectively. However, it is difficult to form flat passbands and wide stopbands. Thus, the topology shown in Fig. 1(a) should be mirrored by the serial LC resonator (L_3 - C_3). Then, a tri-band bandpass microwave filter with second-order responses can be obtained, as depicted in Fig. 1(b). Due to the electromagnetic coupling between the two hybrid resonators, original single resonant mode (f_{p2} , f_{p3} , f_{z2} and f_{z3}) will split into even- or odd-resonant modes, leading to two second-order passbands and stopbands.

2.2 Unit cell description and frequency response

As it is well known, FSSs are essentially spatial microwave filters, so the topology described in Fig. 1(b) can be employed to synthesize a tri-band bandpass FSS with second-order responses. Based on the equivalent circuit analysis [29, 30, 31], a square loop and grid array can be regarded as a serial LC resonator and an inductor, respectively. Short transmission lines used in [23, 24, 27] are replaced by the square waveguide transmission lines to avoid grating lobes for good angular stability performance. Moreover, its frequency selectivity can be further improved due to the high quality factor (Q-factor) of the square waveguide cavity. The geometry of a tri-band bandpass 3D FSS can be designed and is shown in Fig. 2(a). The unit cell of the proposed 3D FSS is composed of an air-filled square waveguide and a cuboid dielectric resonator. As shown in Fig. 2(b), both the top and bottom layers of the unit cell contain a grid and double square loops, which can realize two hybrid resonators described in Fig. 1. Fig. 2(c) depicts the cross section of the middle layer of the unit cell. Single square loop embedded in center of the square waveguide can provide the serial LC resonator (L_3 - C_3). The periods of the unit cell along the x - and y -axes are denoted as p . The wall thickness and height of the square waveguide are denoted as t and h . The dimensions of the outer and inner square loop on the top and bottom layers are expressed as (l_1, w_1) and (l_2, w_2) , respectively. The square loop in the middle layer is determined by side-length l_0 and line-width w_0 . The relative dielectric constant of the cuboid dielectric resonator is 4.4. Due to the symmetrical unit cell

Fig. 1 Topology of the tri-band bandpass microwave filter: (a) first-order; (b) second-order.

Fig. 2 The unit cell of the proposed 3D FSS: (a) 3D view; (b) layout of the top and bottom layers; (c) cross section of the middle layer.

Table I Physical dimensions of the proposed 3D FSS (Unit: mm)

p	h	t	l_0	l_1	l_2	w_0	w_1	w_2
9.6	4	0.5	7.1	7.5	6.7	0.2	0.2	0.2

structure, the dual-polarized performance is easy to achieve.

Subsequently, the desired physical dimensions of the proposed 3D FSS are optimized according to the optimized goal of high frequency selectivity, small band ratios and lower insertion losses, which are listed in Table I. Additionally, the initial values of the electrical parameters in Fig. 1(b) can be calculated by using the given formulas in [31], and the final parameter values can be extracted by the curve-fitting method [32].

As shown in Fig. 3, the frequency response of the proposed 3D FSS is obtained by the commercial ANSYS HFSS Simulation Software. It is observed that there are three passbands centred at $f_1 = 5.14$ GHz, $f_2 = 5.94$ GHz, and $f_3 = 6.97$ GHz, respectively. The first passband contains one transmission pole in the passband and one transmission zero in its upper stopband, while the other two passbands include two transmission poles in each passband and two transmission zeros in each upper stopband. Multiple transmission zeros contribute to high frequency selectivity, and the selectivity is further improved by the square waveguide cavity with high Q-factor. Meanwhile, the two transmission zeros occurred at the right side of the third passband result in a wide out-of-band rejection with the 20 dB stopband bandwidth of 47% at f_1 . The 3dB bandwidths of the three passbands are 0.16 GHz (5.06~5.22 GHz), 0.34 GHz (5.77~6.11 GHz), and 0.28 GHz (6.83~7.11 GHz), and the corresponding fractional bandwidths are 3.11, 5.72, and 4%, respectively. In addition, due to the design of the concentric square loops with very close sizes, leading to three closely-spaced

Fig. 3 Simulated frequency response of the proposed 3D FSS

Fig. 4 Surface current distributions at five transmission-pole frequencies: (a) $f_{p01} = 5.15$ GHz; (b) $f_{p02} = 5.95$ GHz; (c) $f_{p03} = 6.02$ GHz; (d) $f_{p04} = 6.92$ GHz; (e) $f_{p05} = 7.05$ GHz.

passbands, and the band ratios of the adjacent passbands are only $f_2/f_1 = 1.16$ and $f_3/f_2 = 1.17$.

2.3 Surface current distributions

In order to understand the working principle of the proposed 3D FSS, the surface current distributions at the frequencies of the transmission poles are demonstrated in Fig. 4.

As can be observed from Fig. 4(a), the surface current at f_{p01} focus on the grids and intermediate square loop, implying that the transmission pole at f_{p01} is decided by two grids and one intermediate loop. The surface currents at f_{p02} and f_{p03} are distributed on the grids and outer loops on both top and bottom layers, and the square loop in the

Table II Comparison of the FSS designs with similar responses

Ref	Num. (TPs/TZs)	Unit Cell Size and Thickness	Band Ratios ($f_2/f_1, f_3/f_2$)	Polarization	Angular Stability (TE/TM)	Grating Lobes
[19]	3/3	$0.066\lambda_0 \times 0.066\lambda_0 \times 0.005\lambda_0$	1.28, 1.29	dual	$60^\circ/60^\circ$	existent
[20]	3/2	$0.121\lambda_0 \times 0.121\lambda_0 \times 0.009\lambda_0$	1.36, 1.2	dual	$30^\circ/30^\circ$	nonexistent
[22]	4/3	$0.12\lambda_0 \times 0.12\lambda_0 \times 0.008\lambda_0$	2.3, 1.76	dual	$60^\circ/60^\circ$ (only sim.)	existent
[23]	5/4	$0.125\lambda_0 \times 0.125\lambda_0 \times 0.05\lambda_0$	1.66, 1.48	dual	$60^\circ/60^\circ$	existent
[24]	5/4	$0.173\lambda_0 \times 0.15\lambda_0 \times 0.032\lambda_0$	1.55, 1.5	dual	$60^\circ/60^\circ$	existent
[25]	6/0	$0.1\lambda_0 \times 0.08\lambda_0 \times 0.09\lambda_0$	1.7, 1.66	single	45°	nonexistent
[26]	6/0	$0.62\lambda_0 \times 0.62\lambda_0 \times 0.037\lambda_0$	1.21, 1.2	dual	$30^\circ/30^\circ$ (only sim.)	nonexistent
[27]	6/6	$0.27\lambda_0 \times 0.27\lambda_0 \times 0.14\lambda_0$	1.61, 1.28	dual	$45^\circ/45^\circ$	existent
This work	5/5	$0.164\lambda_0 \times 0.164\lambda_0 \times 0.068\lambda_0$	1.16, 1.17	dual	$60^\circ/60^\circ$	nonexistent

Fig. 5 Fabricated 3D FSS: (a) building parts and their main physical dimensions; (b) photograph of the fabricated FSS prototype; (c) measurement setup.

middle layer, which reveals f_{p02} and f_{p03} are generated by two grids, two outer loops and one intermediate loop, as given in Fig. 4(b) and Fig. 4(c). In Fig. 4(d) and Fig. 4(e), it is found that f_{p04} and f_{p05} are produced by double square loops on both top and bottom layers. These analysis results are consistent with the analysis of the topology shown in Fig. 1.

3. Fabrication and measurement

In this section, a practical example built up of two kinds of building parts, is fabricated to validate the proposed 3D FSS. These building parts and their main physical dimensions are shown in Fig. 5(a). The building part 1 is one piece of aluminium plate with a thickness of 1.0 mm, in which 28 opening slots cut halfway along the plate are periodically created. The building part 2 is a cuboid dielectric resonator with a thickness of 4 mm, which is made of TP-2 microwave ceramic material with relative dielectric constant of 4.4 and loss tangent of 0.005, and it is fabricated by using multi-layer PCB technology. First of all, the part 1 pieces are cross-

Fig. 6 Simulated and measured transmission coefficients of the proposed 3D FSS under oblique incidence for (a) TE polarization and (b) TM polarization.

joined together through the slots to obtain an aluminium frame, which supports the air-filled square waveguide array. Then, the part 2 pieces are plugged into the frame one by one. After the combination of two building parts, the implementation of the proposed 3D FSS is finally finished. The fabricated 3D FSS prototype is $280.2 \text{ mm} \times 280.2 \text{ mm}$ in size and consists of 27×27 (729) unit cells, as shown in Fig. 5(b). Besides, the dimension of the unit cell $p \times p \times h$ is $0.164\lambda_0 \times 0.164\lambda_0 \times 0.068\lambda_0$, where λ_0 is the free-space wavelength at the center frequency of the first passband. The prototype is measured by the free-space method, as shown in Fig. 5(c). The measurement setup mainly includes a pair of horn antennas, an FSS prototype, screens covered by ab-

sorbers and a vector network analyzer. The FSS prototype is placed into the rectangular through-hole window in the center of the rotatable screen. Two horn antennas operating from 1 to 18 GHz are located about 1.2 m apart from each side of the rotatable screen, so as to ensure that the FSS is excited with uniform plane waves. Moreover, the measurement device is surrounded by the absorbing screens. Firstly, the propagation loss is eliminated by the normalization of the measured results without the FSS prototype. Secondly, the environment noise is eliminated by the measured results of an identically-sized metallic plate. Finally, the measured transmission coefficients of the proposed 3D FSS can be obtained. Also, the time-domain gating function of the vector network analyzer is also applied to calibrate the measured results for considering the multipath effects.

The simulated and measured transmission coefficients of the proposed 3D FSS under oblique incidence for both TE and TM polarizations, are plotted in Fig. 6. It is observed that our proposed 3D FSS is polarization independent and very stable against different incidence waves. The insertion loss within passband gradually becomes larger when the incident angle increases, which is mainly caused by the variation of wave impedance of the incident wave. The measured insertion losses of the three passbands (1.2, 1.2, and 1.05 dB) are larger than the simulated ones (0.6, 0.2, and 0.3 dB) under the normal incidence, which results from the conductor losses which are not exactly considered in the simulated model. The measured frequency selectivity deteriorates due to the lower Q-factor of the fabricated FSS prototype, which is caused by more conductor and substrate losses. In addition, the other discrepancies between the measured and simulated results may be attributed to fabrication tolerance, assembly tolerance and measurement error. In Table II, the performances of the proposed 3D FSS are compared with some previously reported designs with similar responses. Apparently, it is observed that the proposed 3D FSS does not have any grating lobes and exhibits the advantages in small band ratio, good angular stability, dual polarizations, and compact unit cell size.

4. Conclusion

In this paper, a dual-polarized 3D FSS is presented, realizing a tri-band bandpass filtering response with good angular stability. Due to the inner electromagnetic coupling in the unit cell, multiple transmission zeros/poles are produced, leading to high frequency selectivity, two second-order passbands and one wide out-of-band rejection. Closely-spaced passbands are obtained by the design of concentric square loops with very close sizes. The surface current distributions at the transmission-pole frequencies are described for explaining the working principle. Finally, a fabricated FSS prototype along with experimental verification proves the validity of simulated results.

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