LETTER
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A novel miniaturized-element frequency selective surface with a second-order bandpass response

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Abstract: A novel miniaturized-element frequency selective surface (MEFSS) providing a second-order bandpass response was presented and experimentally verified. The proposed structure consists of sub-wavelength inductive wire grids and a hybrid resonator composing of a two-dimensional periodic arrangement of miniaturized Jerusalem slots etched into a ground plane, which produces a miniaturized unit cell. The full-wave and equivalent circuit model simulations were performed. A prototype of the proposed second-order bandpass FSS was also fabricated and tested using a free-space measurement setup. The measurement results of this device exhibited a stable frequency response with respect to the angles of incidence up to 45°.
Keywords: frequency selective surfaces, miniaturized structures, periodic structures
Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Frequency selective surface (FSS) is a one-dimensional or two-dimensional periodic structure with bandpass or bandstop spatial filtering properties which can propagate or prevent the electromagnetic wave through space. FSSs are widely used in many fields including radar cross section (RCS) reduction of the military objects, electromagnetic compatibility, microwave absorbers and lenses, reflect-arrays, RFID tag and so on [1, 2, 3, 4, 5].

Generally, the FSS structure has more stable transmission characteristics with different incident angles and polarizations than the traditional resonant structure. Recently, a new method of designing frequency selective surface is presented, where non-resonant constituting elements are used instead of the traditional resonant antennas [6]. Based on the studies, the new design methodologies are reported which focus on the low-profile, miniaturized-element and high order FSS with bandpass or bandstop frequency response. As demonstrated in [7, 8], a comprehensive method of synthesizing FSS with bandpass responses is presented which is benefit for the development of ultrathin, low-profile FSS with higher-order bandpass responses and very high out-of-band rejection. In reference [9], the single and dual bandpass performances are realized using a convoluted FSS which exhibits high resonant stability for various polarizations and incident angles. As reported in [10], a novel design of FSS with band-stop characteristics at dual frequency bands was presented. The unit cell consists of criss-cross elements integrated with square loops of folded meander lines for the dual-band operations.

In this letter, a novel structure of frequency selective surface is proposed which showed a second-order frequency response by cascading two identical MEFSS screens. In what follows, the details of the proposed structure's operational principles along with a synthesis procedure for designing the FSS are presented in Section II. In Section III, the simulation results of the full-wave and equivalent circuit model are shown. And then the experimental verification is conducted by

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fabricating a prototype of the proposed FSS and measuring its frequency response based on the free-space measurement system.

2 Miniaturized-element FSS design

The topology of the proposed structure is illustrated in Fig. 1. Fig. 1(a) shows a three-dimensional topology of different layers of the structure. The proposed MEFSS is composed of three parts: the first part is identical to the third part which is cascaded by the second part (airspace). For the first/third part, the structure consists of three different metal layers separated from one another by two very (electrically) thin dielectric substrates. The exterior two metal layers are composed of sub-wavelength arrays of non-resonant inductive wire grids. Situated in the middle layer is a hybrid resonator consisting of a periodic arrangement of miniaturized Jerusalem spiral slots etched into a ground plane which is the central symmetry structure. The inductive wire grids layers and the substrates are identical resulting in a symmetric structure with respect to the plane containing the Jerusalem spiral slots. The overall thickness of the FSS, h ($h = 2 \times h_1 + 2 \times h_2 + h_3$, $h_1 = h_3$), which includes the thickness of four dielectric substrates used to fabricate the structure and the airspace between the two same MEFSS.

Fig. 1(b) and (c) depict the top view of a unit cell of the proposed MEFSS. The dimensions of each unit cell are D_x and D_y, respectively along the x and y directions ($D_x = D_y = D$), which are the same as the period of the structure in the x and y directions. The top view of a single inductive wire grid is displayed in the Fig. 1(b). Each inductive wire grid is composed of a strip metallic layer with the width of w. Due to the structure has sub-wavelength periods and dimensions, D_x, $D_y < \lambda$ (λ is the wavelength), the grids areas the non-resonant and their 2-D periodic arrangement plays the part of an inductive wave impedance to an incident electromagnetic wave. Inspection of Fig. 1(c), the top view of the hybrid resonator which consists of the miniaturized Jerusalem spiral slot etched into a ground plane as a unit cell of the FSS is presented. The element is a resonant element rather than a non-resonant like the inductive wire grid. Furthermore, a patch area which is less than the dimension of unit cell is adopted. As observed in Fig. 1(c), the Jerusalem spiral slot occupies an area of $D_1 \times D_1$, where D_1 is only a fraction of the unit cell size ($D_1 < D_x$, D_y).

The operational principles of the proposed structure can be interpreted by considering an equivalent circuit model as illustrated in Fig. 2, which is valid for a vertically polarized TEM plane wave. The whole equivalent circuit model contains three parts: part one (1), part two (2) and part three (3). The part one and part three has the same structure, so the part one is analyzed in the next sections. The part two represents the airspace between the two cascading structures which are modeled with a short transmission line where the length is equal to the thickness of the airspace and the characteristic impedance $Z_0 = Z_3 = 377\,\Omega$. The two dielectric substrates were modeled as the transmission lines with lengths of h_1 and h_2. The two outer inductive layers are modeled by inductors L_1 and L_4. The hybrid resonator is modeled with the series combination of the parallel resonator L_2C_2 and the series resonator L_3C_3. The parallel resonator L_2C_2 represents the mini-

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aturized Jerusalem spiral slots resonator. The series resonator L_3C_3 represents the parasitic inductance L_3 associated with the electric current flowing in the ground plane of the miniaturized Jerusalem spiral slots and each ground plane is a capacitive patch (C_3) which will be in the form of a square metallic patch with side length of D_1, and the separation (D-D_1) between the two adjacent capacitive patches. Free-space on both sides of the FSS is modeled with two semi-infinite transmission lines with characteristic impedance of Z_0. The whole structure is symmetrical, which leading to a characteristic of polarization insensitive.

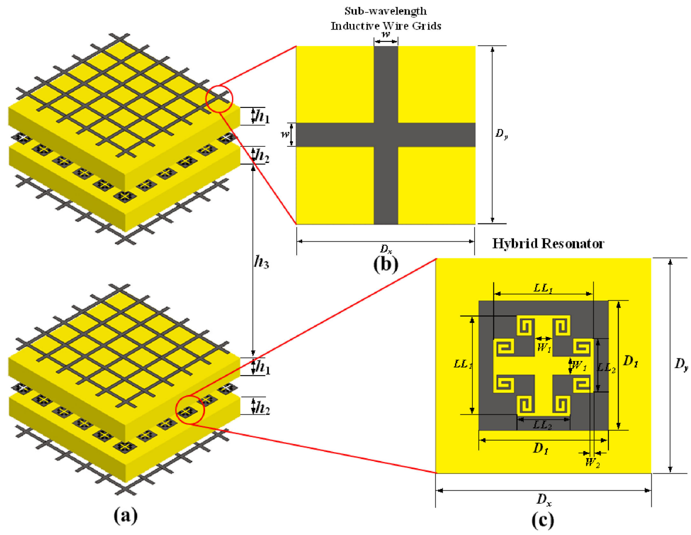

Fig. 1. Topology of the proposed MEFSS. (a) Three-dimensional view. (b) The unit cell of the inductive wire grids. (c) The unit cell of the hybrid resonator.

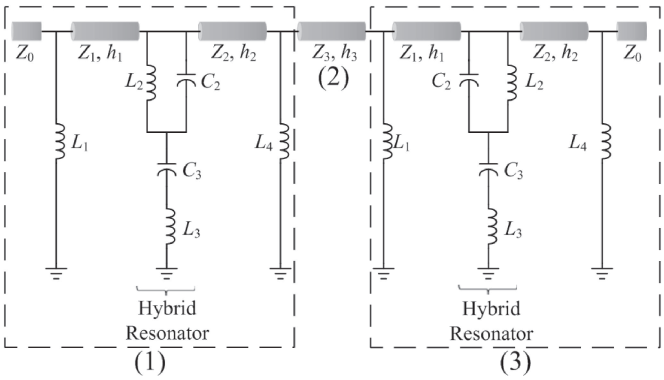

Fig. 2. The equivalent circuit model of the proposed FSS

3 Simulation and experimental verification

3.1 Simulation of a free-space MEFSS prototype

The design procedure described in Section II is performed for an MEFSS with a second-order bandpass response operating at 10 GHz with a fractional bandwidth of 18.7%. With this method, it is employed that a 0.762 mm thick dielectric substrate with the dielectric constant of $\varepsilon_r = 3.48$ and $\mu_r = 1$ (Rogers RT/Duroid 4350B). The FSSs are simulated using full-wave electromagnetic (EM) simulations in CST

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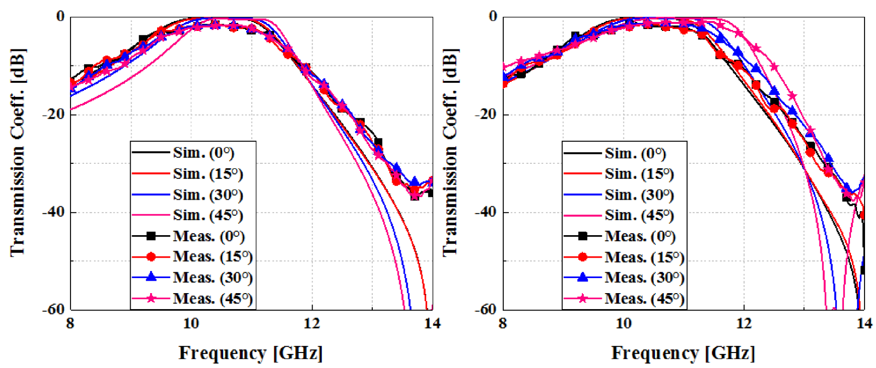
Microwave Studio (MWS) and the Agilent's Design Systems (ADS). The frequency responses in the normal incidence are obtained and shown in Fig. 4(b). The details of parameters are listed in Table I. Moreover, the frequency responses of this MEFSS under oblique incidence for both the transverse electric (TE) and transverse magnetic (TM) polarizations of incidence are also simulated and the results are shown in Fig. 3(a) and Fig. 3(b), respectively. The frequency responses of the structure are relatively stable to variations of incidence angle in the range of 0° to 45° and polarization state.

Table I. The parameters of the unit cell of proposed FSS studied in Fig. 1

Parameter	D_x	D_y	w	D_1	LL_1	W_1	LL_2
Value	6 mm	6 mm	0.2 mm	3.6 mm	2.8 mm	0.5 mm	1.5 mm
Parameter	W_2	$L_{1,4}$	L_2	L_3	C_2	C_3	$Z_{1,2}$
Value	0.1 mm	3.56 nH	8.85 nH	2.64 nH	0.062 pF	10.2 pF	202.1 Ω



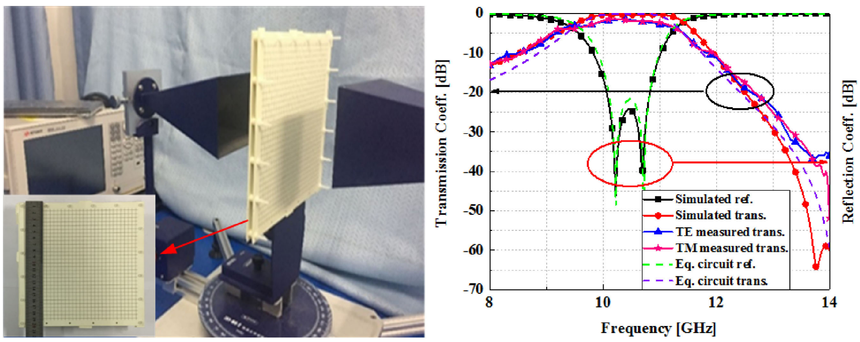
(a) TE polarization (b) TM polarization

Fig. 3. Simulated and measured transmission coefficients at various angles of incidence ranging from theta = 0° to 45°.

3.2 Experimental verification and measurement results

To experimentally verify the second-order MEFSS described in the previous section, a prototype is fabricated using the standard PCB lithography and tested using a free-space measurement setup. The photograph of one of the fabricated prototype is displayed in Fig. 4(a). The FSS layer with 30×30 elements, about $160 \times 160\,mm^2$, is fabricated on a 0.762-mm-thick dielectric substrate with permittivity of $\varepsilon_r = 3.48$ and loss tangent of 0.0037. As shown in Fig. 4(a), the two same structures are cascaded with the 6 mm airspace between the FSS structures. The structures are cascaded using Teflon spacers and screws to provide the air gap [11]. The nuts, screws, and spacers built in Teflon don't affect the measurement results, which is shown in Fig. 4(a). As shown in Fig. 4(a), two standard horn antennas were connected to the Agilent-E5063A vector network analyzer (VNA) are selected as the transmitting and receiving antennas. The horn antennas with 8–14 GHz operating bandwidths are identical, which entirely covers the operational bandwidth of the proposed FSS.

Fig. 4(b) depicts the comparisons between the results obtained from the full-wave EM simulation, equivalent circuit model and measured results in the case of normal incidence. A relatively good agreement between the measured and simulated results is achieved from this figure. Besides, Fig. 3(a) and (b) show the comparisons between the simulated and measured transmission coefficients for the TE and TM polarizations, respectively at different incident angles. As observed from this figure, the measurement results demonstrate that the designed FSS structure provides a quite stable frequency response in the 0° to 45° range as predicted. The main differences observed between the results obtained using the full-wave simulations and the measurement are mainly performed in the stop band of the FSS. These discrepancies are attributed to the fabrication complexity of the structure and the insensitivity of the response of the structure to alignment errors. The electromagnetic wave will leak from the gaps that exist between the edges of the FSS panel and the airspace also will affect the electromagnetic performance. Furthermore, the dielectric losses of the structure have an impact on the frequency response.



(a) (b)

Fig. 4. The photograph of the proposed FSS. (a) Top view of the fabricated FSS. (b) Measurement setup with cascaded structure.

4 Conclusion

In this letter, a novel miniaturized-element frequency selective surface with second-order bandpass frequency responses was presented for the 8–14 GHz. The proposed structure was based on modeling the FSS with an electromagnetic model. The model consists of sub-wavelength inductive wire grids and a hybrid resonator composing of a two-dimensional periodic arrangement of miniaturized Jerusalem slots etched into a ground plane. The electromagnetic and equivalent circuit model simulations were conducted. Finally, the validity of the proposed structure was experimentally demonstrated by a fabricated FSS test sample. The measurement results for normal incidence and for oblique angle of incidence demonstrate that the frequency responses of this structure are not sensitive to the angle of incidence ranging from theta = 0° to 45° at the center frequency of 10 GHz.

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