LETTER

Design of miniaturized dual-band frequency selective surface with spiral arrangement of meander lines

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Abstract A miniaturized dual-band frequency selective surface (FSS) is proposed in this letter. The FSS unit cell is composed of meander lines arranged spirally, and produces resonant frequencies of 1.42 GHz and 3.76 GHz with -3 dB bandwidths of 0.95 GHz and 0.49 GHz. The equivalent circuit model is introduced to explain the FSS performance. The meander lines at top and bottom layers are connected through copper vias to increase the equivalent inductance and capacitance of the FSS unit cell. The dimension of the unit cell is 10 mm, which is about 4.7% of the wavelength at the first resonant frequency. Simulation results show that the proposed FSS can work stably at resonant frequencies for both TE and TM polarizations while the incidence angle varies from 0 to 60 degree. A prototype of the FSS is fabricated and measured. The measurement results show reasonable agreement with the simulated results.

key words: frequency selective surface, miniaturized, dual-band

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Frequency selective surface (FSS) is a kind of two-dimensional periodic structure consists of metallic patches or apertures etched on a dielectric substrate [1], it has the characteristics of frequency selection and polarization selection of electromagnetic waves, so it is also called spatial filter. FSSs are widely analysed and applied in the microwave field, such as absorbers [2, 3, 4, 5, 6], antenna sub-reflectors [7, 8, 9], and polarization converter [10, 11, 12], in the past decades [13, 14]. The traditional FSSs have the dimension which is comparable with half a wavelength of the resonant frequency [1], which limits the practical applications. Miniaturization of FSSs can break the limits.

There have a great number of studies on miniaturized FSSs, such as closed loop and complementary structures [15, 16, 17, 18, 19], loading with passive lumped elements (capacitors and inductors) [20, 21, 22, 23],

coupling technology based on capacitive and inductive surfaces [24, 25, 26], and 2.5-D knitted structures [27, 28, 29]. A miniaturized FSS with double pass-band was designed in [15], which was based on the closed loop and its complementary pattern. Four FSSs were proposed based on the convoluted design in [16, 17, 18, 19]. These FSSs provided double stop-band response with the unit cell structures were printed on single layer of the substrate. In [20], a tunable, pass-band miniaturized-element FSS with an embedded bias network was proposed. In this design, two wire-grids are printed on opposite sides of a substrate and connected to each other with an array of varactors. The varactors are biased in parallel and thus are controlled individually. Three miniaturized FSSs incorporating 2.5-D structures have been reported in [27, 28, 29]. In these designs, vias are employed to connect the meander lines across two sides of a substrate to increase the capacitive coupling and the inductance.

In this letter, a miniaturized dual-band FSS unit with meander lines arranged spirally is proposed. The FSS unit consists of two metallic layers printed on each side of the substrate, and the top and bottom layers are connected by copper vias. At first, the equivalent circuit model (ECM) is introduced and analysed. Second, the full-wave simulations under different polarizations and angles of the incidence wave of the proposed FSS are calculated, the dimension of the unit can achieve 0.047 of the wavelength and the thickness is only 1 mm. Finally, a prototype of the proposed FSS is fabricated and measured. The results show the complete FSS based on the presented design has double band with transmission coefficient larger than -3 dB.

2. Unit cell design and simulation results

2.1 Design procedure

Fig. 1(a) shows the topology of the ECM of a dual-band FSS. The ECM is composed of two shunt serial LC resonators (L_1 - C_1 and L_2 - C_2) separated by a short transmission line Z_h with a parallel LC resonator (L_3 - C_3) in series. Z_h can be ignored in this design when the transmission line is very short. $Z_0=377\Omega$ is the wave impedance of the free space.

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Table 1. Equivalent circuit parameters of the ECM.

C_1	0.34pF	L_1	5.3nH
C_2	1.05pF	L_2	6.5nH
C_3	0.5pF	L_3	3.2nH

Fig. 1 Equivalent circuit model and Schematic view of the dual-band FSS unit cell. (a) Equivalent circuit model. (b) 3-D view. (c) Top layer of the FSS unit cell. (d) Bottom layer of the FSS unit cell.

The transmission coefficient of the proposed ECM can be calculated according to the theory of transmission lines as [30]

$$T(\omega) = \frac{2Z_{FSS}}{2Z_{FSS} + Z_0} \quad (1)$$

where Z_{FSS} is the equivalent impedance of the ECM. The resonant zero is produced while $Z_{FSS}=0 \Omega$, and the resonant pole is produced while $Z_{FSS}=\infty$.

According to the ECM presented in Fig. 1(a), Z_{FSS} can be obtained as

$$Z_{FSS} = \frac{Z_1 Z_2}{Z_1 + Z_2} \quad (2)$$

where

$$Z_1 = j\omega L_1 + \frac{1}{j\omega C_1} \quad (3)$$

Fig. 2 Transmission coefficient of the ECM and the proposed FSS.

$$Z_2 = j\omega L_2 + \frac{1}{j\omega C_2} + \frac{j\omega L_3}{1 - \omega^2 L_3 C_3} \quad (4)$$

It is obvious that three transmission zeros and two transmission poles can be introduced through the ECM. The first transmission zero f_{z1} can be obtained when $Z_1=0$

$$f_{z1} = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (5)$$

The first and second transmission poles can be obtained as

$$f_{p1} = \frac{1}{2\pi\sqrt{L_2 C_2}} \quad (6)$$

$$f_{p2} = \frac{1}{2\pi\sqrt{L_3 C_3}} \quad (7)$$

and the second transmission zero f_{z2} and the third transmission zero f_{z3} also can be obtained when $Z_2=0$, where

$$f_{z2} < f_{p1} \quad \text{and} \quad f_{z2} < f_{p2} \quad (8)$$

$$f_{z3} > f_{p1} \quad \text{and} \quad f_{z3} > f_{p2} \quad (9)$$

The parallel LC resonator (L_3 - C_3) is equivalent to an inductor and the serial LC resonator (L_2 - C_2) is equivalent to a capacitor at frequency f_{z2} . On the contrary, the parallel LC resonator (L_3 - C_3) is equivalent to a capacitor and the serial LC resonator (L_2 - C_2) is equivalent to an inductor at frequency f_{z3} .

The values of the lumped elements of the ECM are listed in Table 1. The transmission coefficient curve calculated by the ECM is shown in Fig. 2. It can be observed that the proposed ECM can produce dual-band

band-stop by the transmission zeros 1.42 GHz and 3.76 GHz, and produce dual-band band-pass by the transmission zeros 1.42 GHz, 3.76 GHz and 4.82 GHz, and the transmission poles are 2.34 GHz and 3.98 GHz respectively.

2.2 Description of the FSS unit cell

According the ECM, a dual-band FSS unit cell is proposed and the configuration is shown in Fig. 1(b). The FSS unit cell consists of two metallic layers printed on a FR-4 substrate ($\epsilon_r=4.4$ and $\tan\delta=0.02$) with thickness 1 mm. The top layer and bottom layer are connected by vias (Copper with $\sigma=5.8\times10^7$ S/m) as shown in Fig. 1(b). The top layer is composed of four structures S^1 arranged spirally, and the structure S^1 is composed of two U-shaped meander lines and one L-shaped meander line as shown in Fig. 1(c). The bottom layer is composed of four structures S^2 arranged spirally, and the structure S^2 is composed of three L-shaped meander lines as shown in Fig. 1(d).

Table II. Geometry parameters of the dual-band FSS.

Parameter	Value (mm)	Parameter	Value (mm)
p	10	l_1	4.85
l	9.6	l_2	1.1
h	1	l_3	5.65
g	0.2	l_4	4.85
d_1	0.3	l_5	1.15
d_2	0.4	w_1	0.5
w	0.3	w_2	1.3

The inductance L_1 is produced by the metallic strips of the top layer, and the capacitance C_1 is produced by the coupling between the metallic strips of the top layer. Similarly, L_2 and C_2 are used to describe the inductance and capacitance of the metallic strips of the bottom layer respectively. L_3 represents the inductance of the copper vias, and C_3 represents the coupling capacitance between the top and bottom layers. The values of L_1 and L_2 are proportional to the length of the metallic strips and inversely proportional to the width of the strips. The values of C_1 and C_2 are inversely proportional to the distance between metallic strips. The value of L_3 is proportional to the length of the via and inversely proportional to the diameter of the via, and the value of C_3 is inversely proportional to the distance between the top and bottom layers. The geometrical parameters of the FSS unit are listed in Table II.

2.3 Simulation results

The transmission coefficient of the proposed FSS is calculated by the full-wave simulation and compares with the one obtained by the ECM as shown in Fig. 2.

With the normal incident wave, it can be observed that the transmission zeros are 1.42 GHz, 3.76 GHz and 4.82 GHz, and the transmission poles are 2.34 GHz and 4.04 GHz, which are agree well with the ECM results.

Fig. 3 Transmission coefficients of the dual-band FSS with various incident angle. (a) TE polarization. (b) TM polarization.

Transmission coefficients of the proposed FSS with different incidence angles and polarizations are also shown in Fig. 3. It can be observed that the FSS resonates at 1.42 GHz, 3.76 GHz and 4.82 GHz with the normal incident wave for TE polarization (the electric-field component polarized along the y-axis) and TM polarization (the electric-field component polarized along the x-axis). The bandwidths of the dual-band band-stop are 0.95 GHz (from 0.88 GHz to 1.83 GHz) and 0.49 GHz (from 3.41 GHz to 3.90 GHz) with the transmission coefficient lower than -3 dB. The bandwidths of the dual-band band-pass are 1.58 GHz (from 1.84 GHz to 3.42 GHz) and 0.81 GHz (from 3.91 GHz to 4.72 GHz) with the transmission coefficient higher than -3 dB. While the incidence angle varies from 0 to 60 degree, the resonant frequencies are basically unchanged.

The bandwidths of the dual-band band-stop broaden as the incidence angle increases for TE polarization since the increased angle can lead to higher wave impedance for the TE polarization, as shown in Fig. 3(a). Conversely, the bandwidths narrow for TM polarization since the wave impedance is lower with the incidence angle increases, as shown in Fig. 3(b). In the meanwhile, the bandwidths of the dual-band band-pass narrow as the incidence angle increases for TE polarization and broaden for TM polarization. The simulations in Fig. 3 prove that the dual-band FSS is polarization-insensitive and angle-insensitive at incidence angle up to 60 degree. The dimension of each FSS unit cell is only $0.047\lambda_0 \times 0.047\lambda_0$, where λ_0 is the wavelength at 1.42 GHz in free space.

Fig. 4 Surface current distributions at two transmission-pole frequencies. (a) 2.42 GHz. (b) 4.04 GHz.

In order to further understand the working principle of the proposed dual-band FSS, the surface current distributions at the frequencies of the transmission poles are depicted in Fig. 4

As shown in Fig. 4(a), the surface current at 2.42 GHz focus on the metal lines printed on the top and bottom layers. The current flows in the direction of the arrows, which increases the equivalent inductor values of L_1 and L_2 effectively. The surface current at 4.04 GHz flows in the direction of the arrows as depicted in Fig. 4(b), which can also increase the equivalent inductor values of L_1 and L_2 .

3. Measurement results

The photograph of the fabricated FSS is shown in Fig. 5.

The dimension of the fabrication is $100\text{mm} \times 100\text{mm} \times 100\text{mm}$. Two broad-band horn antennas and a vector network analyser are used in the measurement.

Fig. 5 Fabricated prototype of the miniaturized dual-band FSS. (a) Top view. (b) Bottom view.

Fig. 6 Measurement results of transmission coefficients of the dual-band FSS with various incident angles. (a) TE polarization. (b) TM polarization.

The measured results for TE and TM polarizations under various incidence angles are plotted in Fig. 6 as well as compared with the simulated results. It can be observed that the transmission poles are stable under various incidence angles for both TE and TM polarizations, which are consistent with the full-wave simulations. For the normal incidence, the bandwidth of -

3 dB is over 0.95 GHz and 0.49 GHz. Furthermore, the measured results indicate that the frequency performance of the proposed FSS is stability for different polarizations because of the symmetric of the unit cell, and the performance also angular stability because of the miniaturized size of the unit cell.

To further demonstrate the performance of the proposed FSS, Table III gives the comparison of the characteristics between the proposed FSS design with other miniaturized FSSs in the published papers. It can be observed that the unit cell size of the proposed FSS is smaller compared with other similar structures, which demonstrates that the proposed FSS is a better miniaturized design.

Table III. Comparison with other FSSs in previous works.

FSS Structure	Substrate thickness (mm)	Dielectric constant (ϵ_r)	Band-stop	Unit cell size
Ref. [16]	1.6	4.4	Double	$0.08\lambda_0 \times 0.08\lambda_0$
Ref. [17]	0.8	4.4	Double	$0.065\lambda_0 \times 0.065\lambda_0$
Ref. [18]	1.6	4.4	Double	$0.052\lambda_0 \times 0.052\lambda_0$
Ref. [19]	0.5	2.65	Double	$0.075\lambda_0 \times 0.075\lambda_0$
Ref. [28]	1.6	4.4	Single	$0.063\lambda_0 \times 0.063\lambda_0$
Ref. [29]	2	2.2	Double	$0.072\lambda_0 \times 0.072\lambda_0$
Proposed structure	1	4.4	Double	$0.047\lambda_0 \times 0.047\lambda_0$

4. Conclusion

A meander lines structure for miniaturized dual-band FSS is proposed in this letter. The application of meander lines connected by vias miniaturizes the dimension of the FSS unit cell as $0.047\lambda_0 \times 0.047\lambda_0$. Three transmission zeroes and two transmission poles are achieved by two metallic layers printed on each side of the substrate. The resonant zeroes and poles can be adjusted by changing the length and width of the metallic stripes. According to the simulated and measured results, the proposed FSS has resonant stability, the stable bandwidths of the band-stop for various polarizations and incident angles.

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