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Dual stopband frequency selective surface by using half rings and slots

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ABSTRACT:

In this letter, a novel technique is proposed to design a dual stopband frequency selective surface (FSS) by combining a bandpass filter with its complementary structure in series. It displays flexibility to control the stopband frequencies which is the most attractive feature of this design. The proposed FSS filter is also very easy to fabricate, consisting of a single metal layer on a dielectric layer. A theoretical equivalent circuit model is proposed to characterize the structure. Explanation of the proposed filter response based on analysis of the equivalent circuit is discussed in detail. It is shown that the frequency response of the proposed FSS is almost the same for different incident angles.

Key words: FSS; dual band; ring; slot; complementary

1. Introduction

An FSS is formed by periodic arrays of usually metallic elements on a dielectric substrate. FSS`s have been the subject of intense investigations to applications on a large scale as the spatial microwave and optical filters for decades [1-2]. FSS structures have been employed in a variety of applications, such as radomes for reducing the radar cross section of an antenna system outside its frequency band of operation, or components in radar absorbing material (RAM) [3-4]. Decreasing loss in antennas and improving the radiated power are successfully realized by using these structures [5]. Various responses can be achieved by using different traditional FSS element shapes. The frequency responses of spatial filters can be influenced by the dielectric constant of the substrate and the incident angle of the wave.

If an aperture type FSS is created from a patch type FSS in such a way that the metal portions of the former are replaced by aperture portions of the latter, then the two FSS are said to be duals of one another. Babinet's principle can be applied to prove that the transmission coefficient for the complementary structure of one array equals to the reflection coefficient for the array [6]. The frequency response of the transmitted signal of the complementary FSS is not exactly the dual of the reflected signal of the FSS due to the loss in the dielectric substrate. A perfectly dual behaviour for the complementary screen of the proposed filter is expected if the loss of the dielectric substrate, as well as the effects of the metal thickness, is neglected [7]. Several types of design have been proposed to achieve a dual band filter. Gosper prefractals based on a hexagonal geometry display a dual bandstop frequency response [8]. A dual band FSS is built by cascading a metal loop shaped layer and its complementary in [9]. Cascading two layers of conducting patches with slots to design dual bandstop FSS is used in [10]. Left-handed structures and capacitive grids are used to design dual band FSS in [11]. The objective of this work is to use untraditional methodology to design dual bandstop spatial filters by using FSS periodic arrays composed of a bandpass and a bandstop element. The fabrication of the dual bandstop filter is significantly simplified by using a single metal layer on a dielectric substrate.

2. Filter design and simulation

A novel method is proposed in this letter to design dual stopband filters by making use of the duality behaviour of a structure and its complementary. A ring shape is used in the study to demonstrate how the proposed technique works. Arrays of rings are of interest as FSS for dichroic reflector antennas [12]. The equivalent circuit of the ring is an inductor L_s in series with the mutual capacitance of adjacent cells C_m. It works as a bandstop filter as shown in Fig. 1(a) [12]. The first step to design a desired dual stopband FSS is to design the constituting grid element. The ring resonator is designed on a 1.5 mm thick FR4 substrate with a dielectric constant of 4.3. The radius of the ring r_1, as shown in Fig. 1(a), is 9.5 mm; the width of the circumference of the ring w is 1 mm; the periodic constant P is 22 mm. The complementary of the ring structure, effectively a slot, works as a bandpass filter at approximately the same band. The equivalent circuit of the complementary structure is an inductor L_p in parallel with a capacitor C_p as shown in Fig. 1(b), where S is the aperture width and r_2 is the radius of the circular patch. The structure of the proposed filter is built up by using half of the ring and half of the slot, the complementary of the ring. It can be characterized that the structure is very simple and can be built by printing a single metal layer on a dielectric layer as shown in Fig. 2(a). The equivalent circuit of proposed resonator is based on connecting a parallel LC with a series LC in series as shown in Fig. 2(b). As shown in Fig. 2, L_1 and C_1 are the equivalent circuit components of half of the slot. L_2 and C_2 are the equivalent circuit components of half of the ring.

It is found in simulation that the resonant frequency of the ring is 3.15 GHz, while the resonant frequency of half of the ring is 0.13 GHz higher at 3.28 GHz as shown in Fig. 3. The resonant frequencies of the slot and half of the slot are 3 GHz and 2.96 GHz, respectively, as shown

The impedance of the parallel connection of *LC* at frequency *f* (ω=2π*f*) is:

$$Z_{pass} = \frac{j\omega L_1}{1-\omega^2 L_1 C_1} \quad (1)$$

It is infinite (open-circuit condition) when $\omega=\omega_0=1/\sqrt{L_1 C_1}$

The impedance of the series connection of *LC* is:

$$Z_{stop} = -j\frac{1-\omega^2 L_2 C_2}{\omega C_2} \quad (2)$$

The impedance of the dual stopband FSS resonator is:

$$Z_T = Z_{pass} + Z_{stop} = \frac{j\omega L_1}{1-\omega^2 L_1 C_1} - j\frac{1-\omega^2 L_2 C_2}{\omega C_2} \quad (3)$$

The first stopband frequency f_1, and second stopband frequency f_2 of the proposed dual stopband can be computed from solving (3):

$$f_{1,2}^2 = \left| \frac{(L_1C_1 + L_1C_2 + L_2C_2) \pm \sqrt{(L_1C_1 + L_1C_2 + L_2C_2)^2 + 4L_1C_1L_2C_2}}{8\pi^2 L_1C_1L_2C_2} \right| \quad (4)$$

At around f_0 (the resonant frequency of the bandpass structure), the magnitude of the impedance of the parallel *LC* is infinity or open circuit, so all energy is transmitted. In this design, the resonant frequencies of the parallel *LC* circuit and the series *LC* circuit are very close to each other. At $f < f_0$, the impedance of parallel *LC* circuit in (1) is inductive. This effective inductance, being in series connection with the series *LC* circuit, will lower the resonant frequency of the series circuit. It can be calculated from (4) that the impedance of the equivalent circuit is zero at the lower stopband frequency f_1 (< f_0). f_1 is found to be 2.36 GHz by simulation. Similarly, at

$f > f_0$, the impedance of parallel *LC* circuit in (1) is capacitive. This effective capacitance will increase the resonant frequency of the series *LC* circuit. It can be calculated from (4) that the impedance of the equivalent circuit is zero at the upper stopband frequency f_2 (> f_0). f_2 is found to be 3.36 GHz by simulation. The structure exhibits flexibility to control the stopband as well as the passband frequencies by changing the dimensions of either the rings or the slots or both. In Table 1, three cases are given to demonstrate how to control the frequency response of the dual stopband filter as illustrated in Fig. 4. Case A can be regarded as a reference to other cases. Both the stopband frequencies f_1 and f_2 can be changed by changing the ring dimensions (r_1 and w) as shown in case B, without changing the bandpass frequency f_0. Changing the dimensions of the complementary structure will shift both the stopband frequencies f_1 and f_2 and the passband frequency f_0 as illustrated in case C. The maximum attenuations at f_1 and f_2 are more than 50 dB in all cases. The 10 dB attenuation bandwidth for f_1 is 28% and for f_2 is 24%. The unit cell size of the proposed FSS is $0.17\boldsymbol{\lambda} \times 0.17\boldsymbol{\lambda}$, where $\boldsymbol{\lambda}$ is the wavelength at the passband frequency. The transmission coefficients of the dual stopband FSS with case A parameters were tested under various angle of incidence. It is observed in simulation that the resonant frequencies of the filter are not strongly sensitive to the angle of incidence (θ). This is especially valid for $-45 \le \theta \le 45$.

3. Measurement

A prototype of the proposed case A FSS has been fabricated and measured to validate the design. The size of the FSS prototype is 176×176 mm^2 and the whole structure consists of 8×8 elements. The measurement setup is illustrated in Fig. 5. Two horn antennas and a vector network analyser were used for the measurement.

The transmission coefficient S_{21} was measured at various angles of incidence. The measured frequency response of the proposed FSS shows a good agreement with the simulated result as shown in Fig. 6. The frequency response of the proposed structure is insensitive to the angle of incidence as also shown in Fig. 6. The maximum attenuations at f_1 and f_2 are around 35 dB and 45 dB, respectively. The insertion loss at f_0 is 0.6 dB. The minor discrepancies between the simulated and measured results can be attributed to errors occurred during the fabrication and measurement environment.

4. Conclusion

An untraditional methodology to design dual stopband FSS structure is proposed in this letter. The proposed filter is relatively easy to fabricate due to its simple structure consisting of a single metal layer on a dielectric layer. It is shown that the dual stopband filter can be built up by combining the structure of half a ring and its complementary. The proposed structure is tested under different incident wave angles to verify that the response is insensitive to the incident angle. It is also shown that the proposed structure is very flexible in changing the stopband and passband frequencies.

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Legends for Figures:

Fig. 1(a) Grid and equivalent circuit of the ring shape (bandstop filter) (E is the electric field)

Fig. 1(b) Grid and equivalent circuit of the complementary structure (bandpass filter)

Fig. 2 **(**a) The proposed structure of the dual bandstop filter

Fig. 2 **(**b) Equivalent circuit model of the proposed dual bandstop filter

Fig. 3 Transmission coefficient (S_{21}) of the whole and half structure of the bandstop resonator (ring shaped) and the bandpass filter resonator (C. is complementary)

Fig. 4 Simulated transmission coefficients of the proposed dual stopband filter in three cases

Fig. 5 The dual bandstop FSS measurement setup

Fig. 6 Measured transmission coefficients of the proposed dual stopband FSS with different angles of incidence (θ)

Explanatory titles for all tables

Table 1: Dimensions of the proposed filter in three cases (Unit: mm)

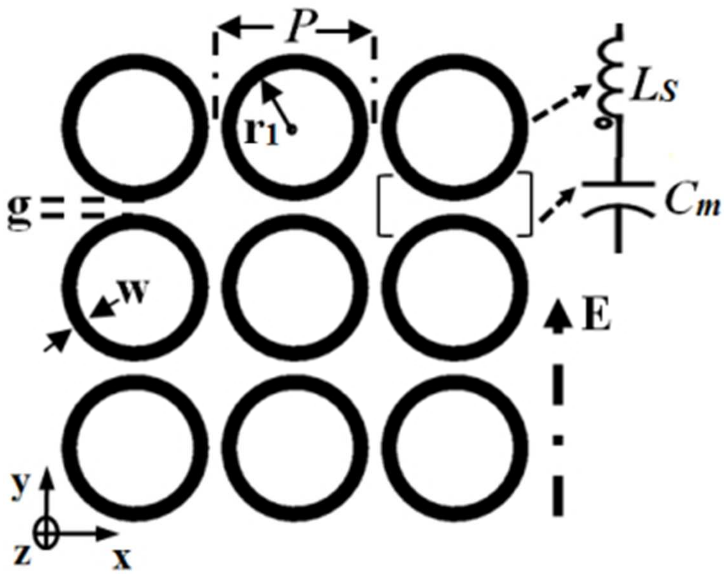

Fig. 1(a) Grid and equivalent circuit of the ring shape (bandstop filter) (E is the electric field)
41x33mm (220 x 220 DPI)

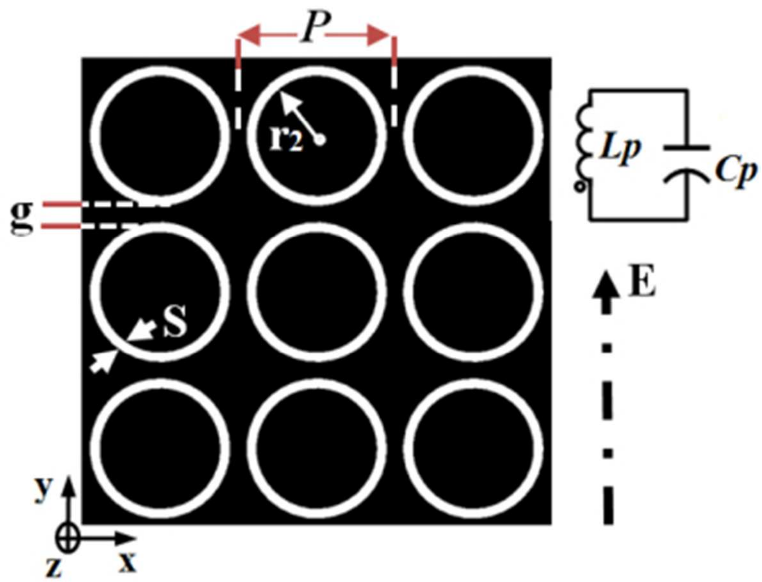

Fig. 1(b) Grid and equivalent circuit of the complementary structure (bandpass filter)
43x33mm (220 x 220 DPI)

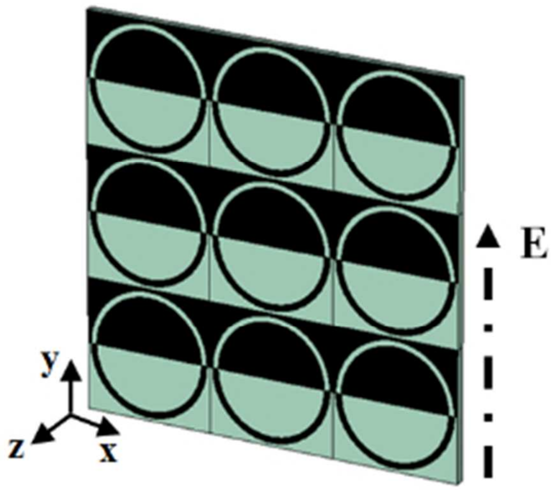

Fig. 2 (a) The proposed structure of the dual bandstop filter
32x28mm (220 x 220 DPI)

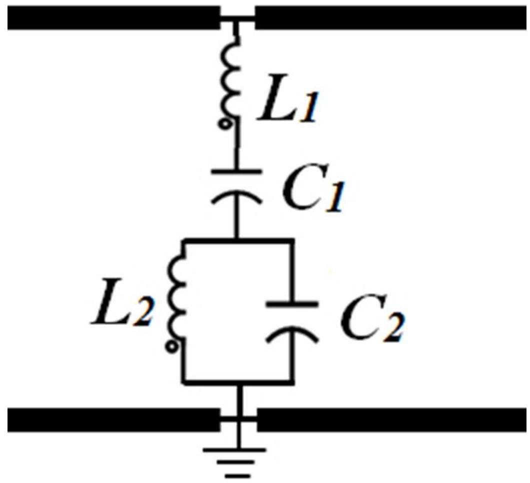

Fig. 2 (b) Equivalent circuit model of the proposed dual bandstop filter
68x68mm (96 x 96 DPI)

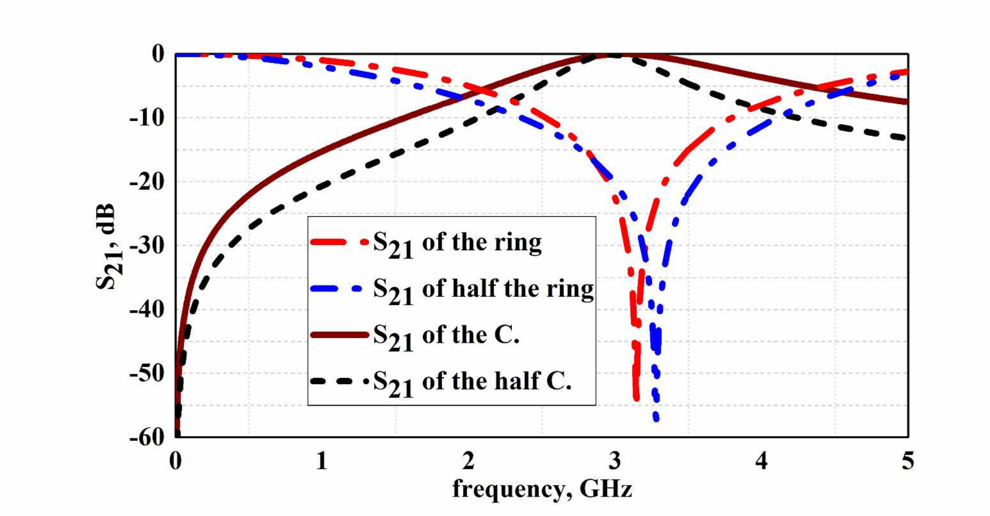

Fig. 3 Transmission coefficient (S21) of the whole and half structure of the bandstop resonator (ring shaped) and the bandpass filter resonator (C. is complementary)
292x152mm (300 x 300 DPI)

Table 1: Dimensions of the proposed filter in three cases (Unit: mm)

	Ring parameters		C. ring parameters	
Case	r_1	W	r_2	S
A	9.5	1	9.5	1
B	9	1.5	9.5	1
C	9.5	1.5	9	1

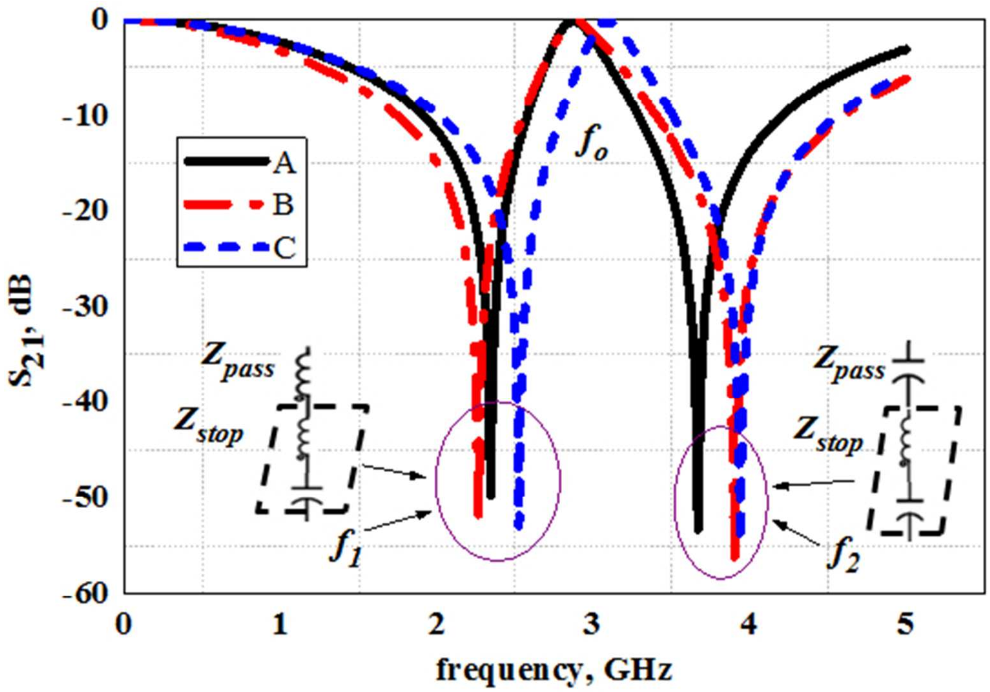

Fig. 4 Simulated transmission coefficients of the proposed dual stopband filter in three cases
145x100mm (96 x 96 DPI)

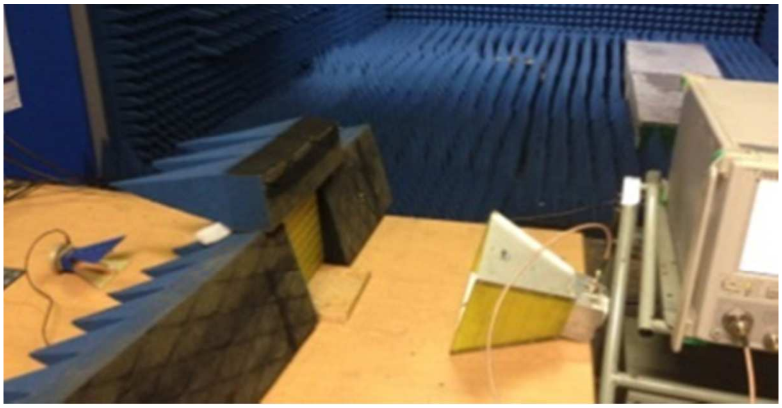

Fig. 5 The dual bandstop FSS measurement setup
182x133mm (54 x 38 DPI)

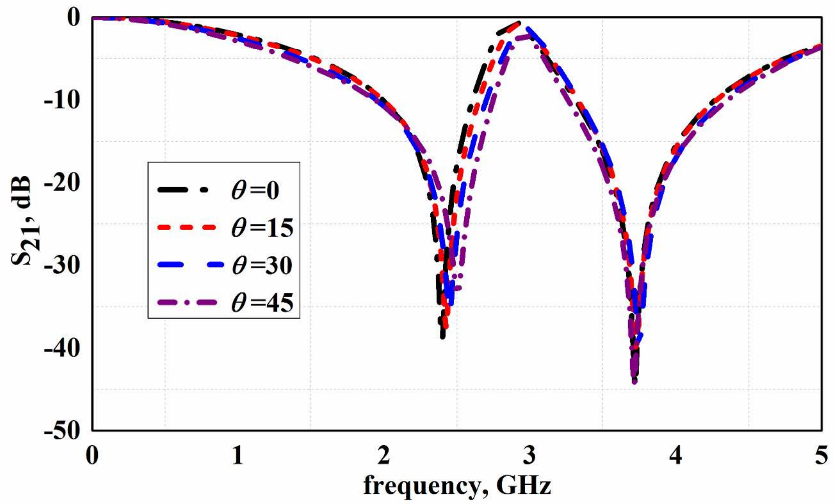

Fig. 6 Measured transmission coefficients of the proposed dual stopband FSS with different angles of incidence (θ)
279x177mm (300 x 300 DPI)