A FSS of hybrid combined elements for dual-band operations

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Abstract: This paper presents a novel design of frequency selective surface (FSS) with band-stop characteristics at dual frequency bands. The FSS element is a hybrid set consisting of four meander lines square loops and a criss-cross element, and can be implemented on a single-layer PCB substrate at low cost. It is found that the band-stop characteristics are valid for a relatively wide angular range of field incidence. Furthermore, structural parameters have been identified for the adjustment of flexible band separation. In this work, an equivalent circuit model is further developed to illustrate the electrical properties of band-stop as a space filter. The concept has been validated by considering a prototype at 6.3 and 8 GHz, where the simulation and measurement frequency responses are compared to exhibit the transmission characteristics of this FSS design.

Keywords: dual-band operation, frequency selective surface, hybrid combined elements

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

References

[1] B. A. Munk: Frequency Selective Surfaces: Theory and Design (Wiley, New York, 2000).
[2] B.-Q. Lin, et al.: “Design and simulation of a miniature thick-screen frequency selective surface radome,” IEEE Antennas Wireless Propag. Lett. 8 (2009) 1065 (DOI: 10.1109/LAWP.2009.2032251).
[3] Y. Rahmat-Samii and A. N. Tulintseff: “Diffraction analysis of frequency selective reflector antennas,” IEEE Trans. Antennas Propag. 41 (1993) 476 (DOI: 10.1109/8.220980).
[4] I. S. Syed, et al.: “A single-layer frequency-selective surface for ultrawideband electromagnetic shielding,” IEEE Trans. Electromagn. Compat. 56 (2014) 1404 (DOI: 10.1109/TEM.C.2014.2316288).
[5] H. Zhou, et al.: “A triband second-order frequency selective surface,” IEEE Antennas Wireless Propag. Lett. 10 (2011) 507 (DOI: 10.1109/LAWP.2011.2157074).
[6] X.-D. Hu, et al.: “A miniaturized dual-band frequency selective surface (FSS) with closed loop and its complementary pattern,” IEEE Antennas Wireless Propag. Lett. 8 (2009) 1374 (DOI: 10.1109/LAWP.2009.2039110).
1 Introduction

The frequency selective surface (FSS) has been widely employed as a space filter that may provide either band-pass or band-stop scattering characteristics for the practical applications of various electromagnetic (EM) scattering problems [1]. Typical examples include the formation of antenna radomes for low radar cross sections [2], the sub-reflectors of dual-reflector antenna systems to create additional spaces for the multiple feeds at different frequency bands [3], GSM frequency shielding [4], etc. The development trend of FSS tends to provide stable scattering characteristics for relatively wide angular ranges of EM field incidence at multiple frequency bands.

The proposed FSS design is a periodic structure of dual-band band-stop elements, which can be formed by using shorter periods for the lower frequencies at the high frequency band. It is noted that conventional approaches tends to implement the dual-band FSS on multi-layer PCB substrates, which will not only increase the manufacture cost, but also result in instability of scattering characteristics at high frequencies. Various structures of unit cells have also been proposed such as combining the same or complementary element patterns at different frequency bands into one element and implementing them on different layers [5, 6]. In such scenario, combined elements with overlapping square loops have been also investigated [7, 8]. Capacitive loadings have also been implemented to create dual frequency bands, and reduce the separate periods for the high frequency band [9]. This technique may implement the FSS on a single layer substrate, but will suffer from energy loss in the RF components. In addition, fractal or spiral elements are another options to achieve multiple resonant frequencies, but they are not able to resolve the issue of grating lobes caused by the over-sized periods at the highly separated frequency bands [10, 11].

The proposed FSS structure can be implemented on a single PCB substrate at low cost. The unit cell consists of criss-cross elements integrated with square loops
of folded meander lines for the dual-band operations. Not only the implementation complexity can be dramatically reduced, but also the periods of elements’ distribution can be properly controlled to avoid the occurrence of grating lobes. An example of design has been realized by simulation and validated by comparing the results with measurement data obtained from the corresponding prototype. The basic phenomena and feasibility are presented in the following studies.

2 The design concept and characteristic analysis

In the proposed improved FSS structure, every unit cell of elements is identical and consists of a metal criss-cross element and four square loops of metal strip lines. As illustrated by geometrical dimensions of unit cell and equivalent circuit in Fig. 1, each side of the square loops is equally subdivided into three segments, where the folded meander lines are implemented between two adjacent segments. To illustrate the design in Fig. 1, L1 is the side length of square loops and W1 is the width of metal loop lines, and S1, S2, S3 and D1 are used to describe the positions and the depth of the meander line grooves. For the low frequency elements, L2 is the length of criss-cross elements and W2 is their width of metal strips. Here S4 is the size of gap between the criss-cross elements and the square loops. D is the size of unit cell, and is also the period of FSS array. The values of these parameters for a design example to demonstrate the scattering characteristics are listed in Table I, and was realized on a PCB substrate where the FR4 substrate has a relative permittivity of 4.4, a loss tangent of 0.02 and a thickness of 1 mm. The periods are roughly 0.65 substrate wavelengths corresponding to 0.31 free space wavelengths at the low resonant frequency.

The scattering characteristics are shown in Fig. 2, where the commercial code HFSS was used to simulate its frequency responses when the structures of unit cells are employed to form an infinite periodic array illuminated by an incident plane waves. Two resonant frequencies near 6.3 and 8 GHz have been observed in the transmission coefficients to exhibit dual-band characteristics of band-stop space filter. In this case, the transmission coefficients are determined by the fundamental mode [12] of transmitted Floquet waves normalized with respect to the amplitude of incident plane wave.

| Parameter | L1 | L2 | S1 | S2 | S3 | S4 | W1 | W2 | D1 | D |
|-----------|----|----|----|----|----|----|----|----|----|---|
| Value     | 6  | 13.2| 1.2| 1.2| 0.3| 0.5| 0.3| 0.3| 0.9| 14.4 |

Fig. 1. The unit cell’s structure of the proposed FSS.
In particular, the transmitting frequency responses are simulated for the TE and TM cases in Fig. 2(a) and (b), respectively, where various angles of incidence along vertical plane are examined to illustrate the broad bandwidth and stability of frequency responses. Here the incident field’s two principal polarizations perpendicular and parallel to the plane of incidence have been examined for the incident plane waves, which are referred to “TE” and “TM” cases in Fig. 2 and afterward in the following analysis, respectively. In particular, for the TE cases, the resonant frequencies at the high frequency band remain relatively stable regardless of the changes of incident angles while that at the low frequency band experience slight downward frequency shifts by 0, 50, 100 and 100 MHz for the oblique incidences at 15, 30, 45 and 60 degrees. On the other hand, the occurrence of resonant frequencies remains very stable for the TM cases, where only the case of 60 degree incidence results in a 100 MHz upward shift. This stability of frequency responses make the FSS equipping with a broad bandwidth for practical applications. In this case, the valid bandwidths at −10 dB thresholds of transmission coefficients are 1.0 and 2.1 GHz in the cases of normal incidence, and 1.9 and 3.2 GHz at 60 degrees of oblique incidence in the TE mode. They are 0.5 and 1.3 GHz at 60 degrees of oblique incidence in the TM mode. In this case, the ratio of two resonance frequencies is roughly 1.27.

The resonance mechanism of frequency responses can be interpreted by considering an equivalent circuit as illustrated in Fig. 1. The folded meander lines are modeled by inductors while the gaps between two adjacent square loops, and between the square loops and criss-cross elements are modeled by capacitors. Thus the circuit model consists of a pair of parallel-connected L-C circuits and a pair of series-connected L-C circuits to result in two resonant frequencies. In this case, the equivalent capacitors and inductor can be expressed as

\[
C_p = \frac{1}{L_p\omega_p^2},
\]

\[
C_s = \frac{(\omega_p^2 - \omega_z^2)(\omega_p^2 - \omega_z^2)}{-L_p\omega_p^2\omega_z^2\omega_{z1}^2\omega_{z2}^2}.
\]

\[
L_s = \frac{(1 - \omega_z^2L_pC_p - \omega_z^2L_pC_s)}{C_s(1 - \omega_z^2L_pC_p\omega_z^2)}. 
\]
where $\omega_{z1}$, $\omega_{z2}$, $\omega_{p1}$, and $\omega_{p2}$ are the zeros and poles of the impedance of the equivalent circuit shown in Fig. 1, which are 6.3, 8.0, 0, 6.7 GHz, respectively. The resulted values of the parameters in (1)–(3) are found by $L_p = 52 \, \text{nH}$, $C_p = 10.5 \, \text{nF}$, $C_S = 0.42 \, \text{nF}$ and $L_S = 1.1 \, \text{pH}$. The frequency responses will be shown later in Fig. 4 for the comparisons between the simulated results and measurement data.

3 Experimental validation of the FSS

The proposed FSS structure of the example discussed above has been prototyped by using the geometrical parameters in Table I, which consists of $34 \times 34$ unit cells with a total size of $500 \times 500 \, \text{mm}^2$ where the FSS prototype and its unit cell are shown in Fig. 3. The transmission coefficients are measured by using two doubled ridged horn antennas placed on both sides of the FSS as a transmitting antenna (TXA) and a receiving antenna (RXA) to measure the $S_{21}$ by using Agilent N5227A vector network analyzer. Since the FSS operates at the fundamental modes at both frequency bands, the TXA and RXA are aligned along the line-of-sight direction when the FSS is absent. The distance between TXA and RXA is 5 m. Here both TE and TM cases are examined for various angles of incidence along the vertical plane.

Fig. 4 shows the comparisons between the results obtained from numerical simulation, measured data and equivalent circuit model in the case of normal incidence. In the experimental measurements, both TE and TM cases are considered, which should result in identical results because of the symmetrical structure of the proposed FSS. Here the simulated result was obtained from the first Floquet mode of an infinite array of the unit cells, and are used here as the reference to justify the transmitting characteristics obtained by the other three results. This simulation result was also used to find the equivalent circuit model previously discussed, which is therefore consistent very well with the simulation result. In this case, smooth curves have been obtained. On the other hand, the measurement results exhibit slight ripples in the frequency responses in Fig. 4, which are caused by the truncation diffractions arising from the finite size of FSS. Also the slight frequency shifts can be caused by the spherical waves radiated from the testing antennas to illuminate the FSS.
Finally, Fig. 5(a) and (b) shows the measured transmission coefficients for the TE and TM cases, respectively, at different incident angles. In this case, the two resonant frequencies for both TE and TM cases are consistent at nearly 6.2 and 7.9 GHz, respectively. Also, at different angles of incidence, the resonant frequencies remain relatively stable regardless of the incident angles. Similar to the observations in Fig. 4, ripples appear on the frequency responses, which are caused by the truncation diffractions due to the finite size of FSS.

4 Conclusion

This paper presents a design of dual-band FSS with band-stop transmitting characteristics by using a hybrid combined element consisting of criss-cross element and of folded meander lines square loops. The proposed FSS structure has advantages of low cost in implementation on a single-layer PCB substrate. In addition, the frequency responses remain relatively stable with respect to the angles of incidence. The scattering characteristics have been investigated and validated by performing numerical simulation and experimental measurements over a prototype. An equivalent circuit model has been also developed to exhibit the characteristics of frequency responses. Both numerical and experimental results agree very well to validate the design concepts. The stability of resonant frequencies makes the proposed FSS structure superior in the practical applications at low cost.

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