Wideband Bandpass Frequency Selective Structure Based on Periodic Array of Multi-Layer Strip Lines

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Abstract

A three-dimensional bandpass frequency selective structure (FSS), consisting of a 2D periodic array of two vertically placed microstrip lines and one inserted metallic bar, is presented to realize wideband filtering response. Through analyzing the propagation characteristic, it is obtained that two substrate modes and one air mode are excited in each unit cell of the shielded microstrip-line structures. By establishing the equivalent circuited model of the proposed FSS, we observe that the wide passband with four transmission poles is produced by four substrate-mode resonators. Moreover, two air-mode resonators are formed to provide the transmission zeros in upper stopband, thus improving the selectivity of the proposed FSS. A prototype of the proposed FSS is fabricated and tested. The measured 3-dB fractional bandwidth is 60% from 5.3 to 9.8 GHz. Measured results show that this FSS exhibits stable wideband filtering response under a large variation of incident angle.

1. Introduction

It is well known that a frequency selective surface with wideband bandpass characteristic is desirable in many applications [1]. Unfortunately, a conventional bandpass frequency selective surface consisting of 1- or 2-D single-layer array has a limited bandwidth. In order to obtain a wideband and stable bandpass filtering response, dielectric slabs are usually added on both sides of the periodic array or between these cascaded arrays. However, the relative permittivity of these dielectric slabs should be chosen to be rather low and their thicknesses are around $\lambda_g/4$ (λ_g is the guided wavelength) [1]. Resultantly, the thickness of the whole structure can be very large when a number of periodic arrays are cascaded together. New structures were then proposed to design low-profile multilayered frequency selective surfaces [2, 3] by cascading multiple layers with non-resonant elements printed on thin dielectric substrates. The angular stability of frequency response and the operating bandwidth can then be improved due to the sub-wavelength unit cell size and high-order filtering characteristics respectively.

Recently, 3D frequency selective structures (FSS) with multimode cavities/resonators were demonstrated to obtain multiple transmission zeros/poles at finite frequencies [4-7]. Compared to 2D and multilayered surfaces, 3D FSSs of high filtering performance can be easily achieved by introducing transmission zeros/poles at desired frequencies. In [4-6], several 3D FSS designs based on a simple 2D array of shielded microstrip lines were presented to achieve quasi-elliptic responses. Transmission poles and zeros were realized by resonances and couplings of two quasi-TEM modes (substrate and air modes) excited in the shielded microstrip lines. In addition, a new design of 3D bandpass FSS with wideband responses were presented in [7]. Results show that this design can exhibit 3-dB bandwidths of 66.6%. However, it is obvious that this design is difficult to fabricate and will suffer from unstable angular response under a large oblique incidence due to their large unit cell size.

In this paper, a novel 3D bandpass FSS with wideband filtering performance is presented, which is the extended study of the 3D FSS based on shielded microstrip lines in [4, 5]. In each unit cell of the proposed structure, multiple resonators are constructed by using two microstrip-line structures printed on two different substrates and separated by a thin and narrow metal bar, thus leading to a wideband bandpass response with multiple transmission poles and zeros. With the help of the established equivalent circuit model, the resonant characteristic of each resonator in the proposed FSS are given. Measured results are in good agreement with the simulated ones.

2. Description of the Structure

Fig. 1(a) shows the perspective view of the proposed wideband FSS, which is composed of a 2D periodic array of two vertical microstrip-line structures and one inserted metallic bar. Figs. 1(b) and (c) illustrate the front and side views of a unit cell. It is seen that two shielded parallel microstrip lines of the same width *w*, named as

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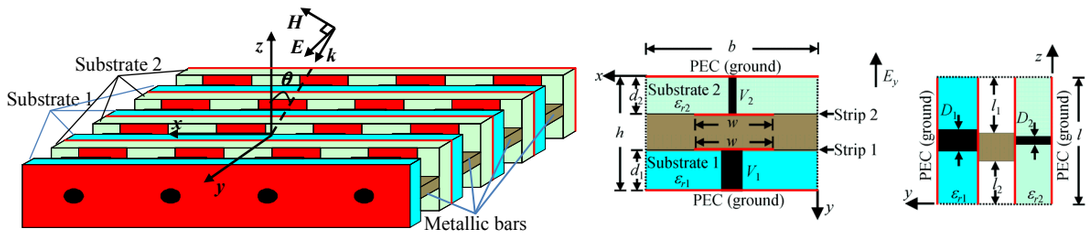
strips 1 and 2, are printed on two different substrates 1 and 2 respectively. These two microstrip lines are shorted to ground (PEC) by two centered via holes V_1 and V_2 respectively. In addition, a thin metallic bar is inserted into the air gap between substrates 1 and 2, which is in contact with both two microstrip lines. The air gap is consequently divided into two parts with lengths l_1 and l_2 by the metallic bar, as shown in Fig. 1(c). It should be mentioned that the line width of the two microstrip lines are set to be the same to simply the analysis and design procedure, though it may not be necessary. In order to obtain a wideband filtering response with multiple resonances, the dielectric constant of substrate 1 should be much higher than that of substrate 2 ($\varepsilon_{r1} > \varepsilon_{r2}$). This is because the guided wavelength in substrate 1 is shorter than that in substrate 2. Then, resonators along strip 1 will resonate at lower frequencies and resonators along strip 2 operate at higher frequencies, thus leading to multiple resonances.

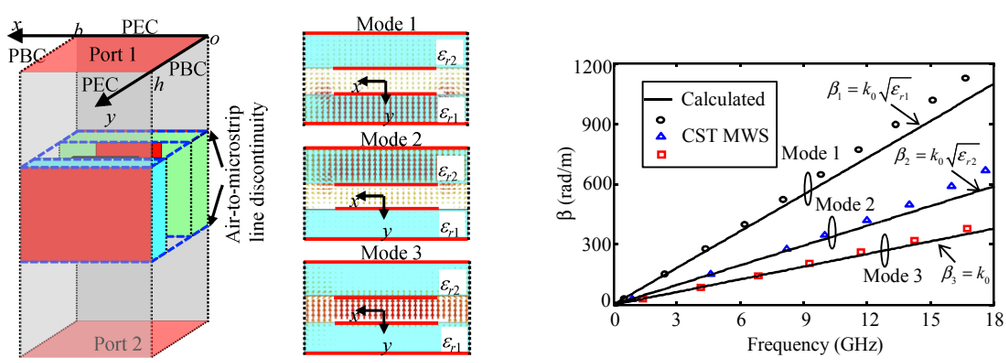


(a) Perspective view of the FSS (b) Top view of a unit cell (c) Side view of a unit cell

Fig. 1. Illustration of the proposed wideband FSS and its unit cell.

3. Propagation Characteristics

In order to explain the operating principle, it is worth mentioning a simplified unit cell shown in Fig. 2(a). It is seen that this simplified unit cell has the same topology as our proposed structure except the inserted metallic bar and two via holes. Moreover, it can be seen as an improved structure from the one presented in [4], which has only one shielded microstrip line printed on a substrate in each unit cell. According to the discussions in [4, 8], multiple quasi-TEM modes can propagate through the structure when the electric field of an incident plane wave are perpendicular to the strip. Based on this, the electric field distributions of the first three propagation modes in the simplified unit cell are illustrated in Fig. 2(a). Furthermore, the comparison of the calculated propagation constants of the three modes and those obtained from CST Microwave Studio (CST-MWS) are shown in Fig. 2(b). From these two figures, we can obtain: i) These three propagation modes are all quasi-TEM modes, which can propagate through the simplified structure between 0 and 18 GHz. ii) The first two modes are substrate quasi-TEM modes concentrated in substrates 1 and 2, respectively. The third mode is the air quasi-TEM mode, which mainly lies in the middle air gap between these two substrates. iii) Three different propagation paths are constructed to transmit these excited modes. Furthermore, the propagation constants of these three modes are different due to different dielectric constants in three paths (substrate 1, substrate 2, and the middle air gap).

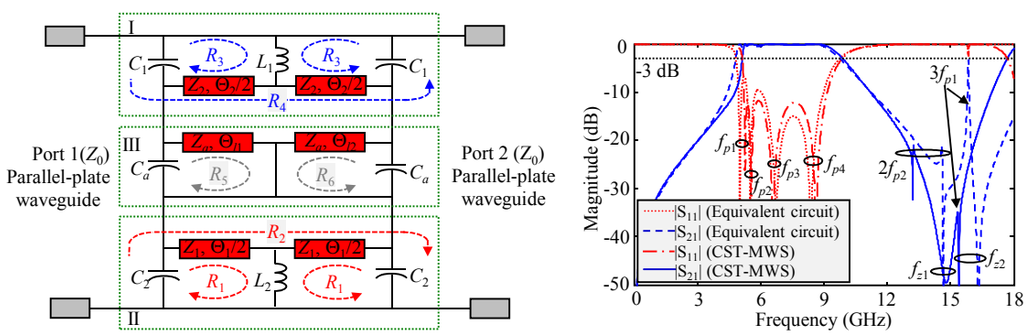


(a) Electric field distributions (b) Dispersion diagram

Fig. 2. Electric field distributions and dispersion diagram of the first three modes of the simplified structure using CST-MWS (b = 6.0 mm, h = 3.95 mm, w = 4.0 mm, l = 10 mm, l_1 = 4.5 mm, l_2 = 4.05 mm, D_1 = 2.3 mm, D_2 = 0.54 mm, ε_{r1} = 11.2, d_1 = 1.27 mm, ε_{r2} = 3.0, d_2 = 1.524 mm).

4. Equivalent Circuit Model Analysis

Compared to the simplified structure shown in Fig. 2, a thin metallic bar is inserted in the air gap of our proposed FSS, which is also in contact with strips 1 and 2. Therefore, the air propagation path is completely blocked by the inserted metallic bar, which means the air mode cannot propagate through the FSS, though it may still be excited. On the other hand, the two substrate propagation paths still exist because only two via holes are introduced in the two substrate regions, thus leading to propagation of two substrate modes. Based on these understandings, an equivalent circuit model is established in Fig. 3(a) for the proposed FSS. The air-to-microstrip line discontinuities between the free-space region and different paths (substrates 1, 2, and the middle air gap) of the FSS are presented by C_1, C_2, and C_a. The transmission lines (Z_1, Θ_1), (Z_2, Θ_2), and (Z_a, $\Theta_{l1} + \Theta_{l2}$) denote three propagation paths. L_1 and L_2 denote the inductances of via holes V_1 and V_2, respectively. It is noted that the air path is divided into two separate sections (Z_a, Θ_{l1}) and (Z_a, Θ_{l2}) by the inserted metallic bar. In the equivalent circuit model, an idea short-circuited line is added between (Z_a, Θ_{l1}) and (Z_a, Θ_{l2}) to denote the inserted metallic bar. Fig. 3(b) compares the simulated S-parameter results of the proposed structure from CST-MWS and those obtained from equivalent circuit model, where a good agreement can be observed. The circuit parameters are extracted by following the procedures described in [5]. It is seen that wideband bandpass filtering responses can be achieved in both results. Four transmission poles provided by four microstrip resonators are realized around frequencies f_{p1}, f_{p2}, f_{p3}, and f_{p4}, respectively. Furthermore, two high-order harmonics at $2f_{p2}$ and $3f_{p3}$, are suppressed by two transmission zeros (f_{z1} and f_{z2}) provided by the inserted metallic bar. It is also concluded that the former two transmission poles in the passband are provided by resonators R_1 and R_2 in the substrate 1, while the transmission poles at f_{p3} and f_{p4} are produced by resonators R_3 and R_4 in the substrate 2. The transmission zeros above the passband are achieved by the resonances of the short-circuited air resonators R_5 and R_6 formed in the blocked air path, thus increasing the selectivity of the structure.



(a) Equivalent circuit model (b) Simulated results

Fig. 3. Simulated S-parameter results of the proposed wideband FSS using CST MWS under the normal incidence (b = 6.0 mm, h = 3.95mm, w = 4.0mm, l = 10mm, l_1 = 4.5mm, l_2 = 4.05mm, D_1 = 2.3mm, D_2 = 0.54mm, ε_{r1} = 11.2, d_1 = 1.27mm, ε_{r2} = 3.0, d_2 = 1.524mm; Circuit parameters: Z_1 = 26.39Ω, Z_2 = 58.5Ω, Z_a = 78.2Ω, Z_0 = 248Ω, L_1 = 0.06nH, L_2 = 0.36nH, C_1 = 0.2pF, C_a = 0.01pF, C_2 = 0.04pF, $\Theta_1 = \pi$@14.2GHz, $\Theta_2 = \pi$@5.9GHz, $\Theta_{l1} = \pi/2$@15.35GHz, $\Theta_{l2} = \pi/2$@17.19GHz).

5. Implementation and Measurement

A prototype of the proposed FSS is fabricated to validate our concept. In the fabrication, two Rogers substrates with different dielectric constants are used: substrate 1 is Rogers 3010 (ε_{r1} = 11.2, d_1 = 1.27 mm, tanδ_1 =0.0022) and substrate 2 is Rogers 4230 (ε_{r2} = 3.0, d_2 = 1.524 mm, tanδ_2= 0.0023). Fig. 4 shows the photograph of the fabricated FSS, which has 42×28 unit cells. The overall size of the fabricated FSS is approximately 168 mm×168 mm. Both reflection and transmission measurements were carried out in an anechoic chamber. Fig. 5(a) shows the simulated and measured S-parameter results of the fabricated FSS under normal incidence, where wideband performance can be observed. It is noted that the first and second transmission poles are combined together in the measured reflection coefficient, thus leading to three transmission poles observed in the passband. Due to such a small discrepancy the measured 3-dB fractional bandwidth of the passband is 60%, which is therefore slightly narrower than the simulated 63%. Furthermore, the filtering performance of the proposed FSS under different incident angles is illustrated in Fig. 5(b). It is also noted that the dimensions ($l \times b \times h$) of each unit cell is $0.25\lambda_0 \times 0.15\lambda_0 \times 0.1\lambda_0$, where λ_0 is the free-space wavelength at the center frequency of 7.5 GHz. Owing to the small unit-cell size, the designed FSS can therefore achieve very stable bandpass filtering response for incident angles up to 30º.

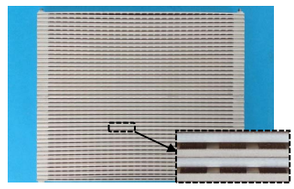
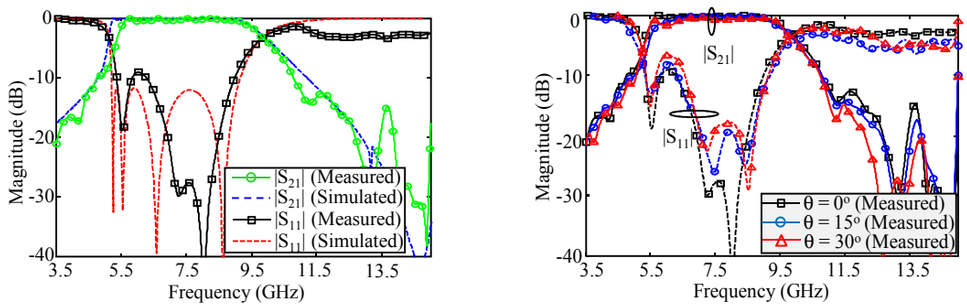


Fig. 4. Photograph of the fabricated FSS and its assembly details.



(a) Normal incidence (b) Oblique incidences

Fig. 5. Simulated and measured S parameters of the fabricated FSS under oblique incidences.

6. Conclusion

In this paper, a 3-D bandpass frequency selective surface with wideband response has been presented, which is composed of an array of vertically placed microstrip lines printed on two different substrates and a number of thin and narrow metallic bars inserted between them. The propagation characteristic has been analyzed and an equivalent circuit model has been established to explain its resonance characteristics of the proposed FSS. Utilizing the multiple resonators constructed through the microstrip lines, the proposed FSS has been experimentally verified to exhibit a wideband bandpass performance with up to 60% fractional bandwidth and stable angular response under a large variation of the incident angle.

References

1. B. A. Munk, *Frequency Selective Surfaces: Theory and Design*. John Wiley & Sons Inc., 2000.

2. N. Behdad and M. Al-Joumayly, "A generalized synthesis procedure for low-profile frequency selective surfaces with odd-order band-pass responses," *IEEE Trans. Antennas Propag.*, vol. 58, no. 7, pp. 2460-2464, 2010.

3. H. Zhou, S.-B. Qu, J.-F. Wang, B.-Q. Lin, H. Ma, Z. Xu, P. Bai, and W.-D. Peng, "Ultra-wideband frequency selective surface," *Electron. Lett.*, vol. 48, no. 1, pp. 11-13, 2012.

4. A. K. Rashid and Z. Shen, "A novel band-reject frequency selective surface with pseudo-elliptic response," *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1220-1226, 2010.

5. B. Li and Z. Shen, "Three-dimensional bandpass frequency selective structures with multiple transmission zeros," *IEEE Trans. Microwave Theory Tech.*, vol. 61, no. 10, pp. 3678-3589, 2013.

6. B. Li and Z. Shen, "Three-dimensional dual-polarized bandpass frequency selective structures with wide out-of-band rejection," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 130-137, 2014.

7. C. Pelletti, G. Bianconi, R. Mittra, and Z. Shen, "Frequency selective surface with wideband quasi-elliptic bandpass response," *Electron. Lett.*, vol. 49, no. 17, pp. 1052-1053, 2013.

8. A. K. Rashid, Z. Shen, and S. Aditya, "Wideband microwave absorber based on a two-dimensional period array of microwave lines," *IEEE Trans. Antennas Propag.*, vol. 58, no. 12, pp. 3913-3922, 2010.