Three-Dimensional Bandpass Frequency Selective Structures

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Abstract—Bandpass frequency-selective surfaces are very useful in many microwave applications. A traditional bandpass frequency-selective surface, consisting of a two-dimensional (2-D) periodical array of slots/apertures, is difficult to realize high selectivity, wide out-of-band rejection, and stable response under different angles of incidence. In this paper, a new class of three-dimensional (3-D) bandpass frequency selective structures (FSSs) based on an array of shielded microstrip lines are described, which can provide a number of transmission zeros/poles at desired frequencies and then exhibit high performance. A generalized equivalent circuit is also introduced to explain the operating principle of these high-performance bandpass FSSs.

I. INTRODUCTION

Bandpass frequency-selective surfaces have been widely used for many applications, such as antenna sub-reflectors, radomes, polarizer, and so on [1], [2]. It is highly desirable to realize a bandpass frequency-selective surface with high selectivity, wide out-of-band rejection, and stable response under different angles of incidence. However, a traditional bandpass frequency-selective surface, which consists of a two-dimensional (2-D) periodic array of slots/apertures etched out of a conducting layer, exhibits poor filtering characteristics, such as low selectivity and unstable angular response. Although cascading a number of these 2-D surfaces with dielectric spacers can improve the filtering performance [1], this will lead to a very thick frequency-selective surface, which is not desirable in practical applications. Consequently, several 2.5-D frequency-selective surfaces have been reported, such as patch-slot-patch structure [3], substrate integrated waveguide (SIW) based structure [4], [5], and so on. Most of the above-mentioned 2.5-D surfaces can introduce transmission zeros close to the passband, realizing high selectivity near the passband. Few designs can realize high selectivity together with wide out-of-band rejection characteristics.

Recently, a concept of 3-D frequency-selective structure (FSS) was reported in [6], where multiple transmission zeros/poles can be produced by a 3-D FSS with multimode resonators. Based on this concept, a number of 3-D FSSs based on a 2-D periodic array of shielded microstrip line resonators, were proposed in [7]-[10]. Because two quasi-TEM modes (air and substrate modes) are excited along the shielded microstrip line, transmission poles and zeros at desired frequencies can be realized by using resonances and couplings of the two modes. Unfortunately, the structures described in [6]-[8] exhibit only bandstop filtering response together with lowpass characteristics in lower frequencies.

In this paper, we first conduct a brief review of traditional 2-D bandpass FSSs with a focus on understanding their operating principles and identifying their advantages and limitations. After that, a generalized equivalent circuit is used to explain the operating principle of a new class of 3-D bandpass FSS. We also present several new bandpass FSS designs proposed by our research group.

II. 2-D BANDPASS FREQUENCY SELECTIVE SURFACES

A. Single-Layer Bandpass Frequency Selective Surface

A simple 2-D bandpass frequency-selective surface can be easily achieved by slots/apertures etched out of a conducting layer printing onto a dielectric substrate [1]. Fig. 1 shows a traditional 2-D bandpass frequency-selective surface, where a cross slot array has been etched out of a copper layer. As shown in Fig. 2, the cross slot array exhibits a bandpass response with a single transmission pole in the operating band and transmission zeros at infinity, which results in poor selectivity and narrow bandwidth. An equivalent circuit model shown in Fig. 2, containing a parallel LC resonator can be used to explain the operating principle of this surface. Since only one resonator is included in this structure, a transmission pole can be obtained at the resonant frequency of this LC resonator.

B. Double-Layer Bandpass Frequency Selective Surface

Fig. 3 shows the perspective and side views of a double-layer bandpass frequency-selective surface, which comprises two different layers separated by a substrate of dielectric constant ε_r and thickness d. The top and bottom layers are printed with 2-D periodic arrangements of double square
loops (DSLs) and gridded square loops (GSLs), respectively [2]. The frequency response of this frequency-selective surface is illustrated in Fig. 4, where a quasi-elliptic bandpass filtering response can be observed. In the two stopbands, three controllable transmission zeros are obtained, two of which are produced by the DSL array, realizing a sharp rejection skirt, and the third one is provided by the GSL array, widening the stopband at higher frequencies. In the passband, two transmission poles are produced by the DSL array, realizing a sharp rejection skirt, and three transmission zeros are achieved by the mutual coupling of resonators/modes.

III. 3-D BANDPASS FREQUENCY-SELECTIVE STRUCTURES

A. Operating Principle

Unlike 2-D frequency-selective surfaces, 3-D frequency-selective structures, employing a number of resonators and/or propagating modes, can easily realize a desired number of transmission zeros and poles at finite frequencies by controlling resonances of these resonators. Therefore, compared with 2-D surfaces, the filtering responses of 3-D FSSs, such as selectivity and out-of-band rejection, can be greatly improved. Fig. 5 shows a generalized equivalent circuit model of a 3-D FSS unit cell containing a number of resonators, where $R_{ai} (i = 1, 2, \ldots, N)$ are resonators linking the input and output ports, $R_{bj} (j = 1, 2, \ldots, N)$ and $R_{bk} (k = 1, 2, \ldots, N)$ are resonators only attaching to the input or output port, respectively. $R_{ai}$ can provide transmission zero/poles at their resonant frequencies, similar to the model in [9]. $R_{bj}$ and $R_{bk}$ can provide additional transmission zeros at desired frequencies, which can further improve the selectivity of a bandpass FSS. It should be noted that the single-layer 2-D surface shown in Fig. 1, including only one resonator, is actually the special case of this equivalent circuit model for 3-D FSSs, with only one transmission pole, and hence suffers from poor filtering performance.

Fig. 5. Generalized equivalent circuit model of a 3-D FSS with multiple resonators/modes.

B. Recent 3-D Bandpass FSS Design

Fig. 6 shows a unit cell of a 3-D bandpass FSS proposed in [10]. Each unit cell of this structure consists of a 2-D shielded microstrip line inserted into a waveguide. Due to this arrangement, a quasi-elliptic bandpass FSS with two transmission poles and two transmission zeros located near the passband can be realized, as shown in Fig. 7. The two transmission poles in the passband are produced by resonances of quasi-TEM mode (microstrip line resonator) and TE_{10} mode (waveguide resonator), respectively. The transmission zeros are provided by the mutual coupling between evanescent modes (or higher-order modes) in the waveguide and quasi-TEM mode along the microstrip line.

C. Bandpass FSS with Multiple Transmission Zeros

Fig. 8 shows a unit cell of a 3-D bandpass FSS with two transmission zeros, which is modified from the simple array of shielded microstrip lines described in [6]. Each unit cell of this FSS consists of a 2-D shielded microstrip line with...
shorting via to ground at its centre and a metallic plate inserted in the air region between the microstrip line and ground. As discussed in [6], when the E-field of an incident plane wave is perpendicular to the strip lines (TE polarization), two propagating paths, the air and substrate paths, are formed linking the input and output ports. Each path can be seen as a resonator $R_i$ ($i = 1, 2$), where air and substrate quasi-TEM modes are excited, respectively. At lower frequencies, most signals go from one port to the other through the air path, thus leading to a lowpass response. At higher frequencies, signals can pass through both paths. Because of the fact that the guided wavelength of the substrate mode is smaller than that of the air mode, the substrate resonator (or mode) will resonate first. When the phase difference between two signals along the substrate and air paths is 180 degrees at the output port, transmission zeros may then be produced.

**D. Wideband Bandpass FSS Design**

Fig. 10 shows an improved design of 3-D wideband bandpass FSS. In each unit cell of this structure, two microstrip lines are separated by a horizontally placed rectangular metallic bar. The top microstrip line is printed on a substrate with high dielectric constant ($\varepsilon_r^1$), while the bottom microstrip line is printed on a low dielectric constant substrate ($\varepsilon_r^2$). Furthermore, both of the two microstrip lines are shorted to ground by a centred shorting via hole, respectively. In addition, a long and thin metallic bar of rectangular shape is inserted in the air region, which is in contact with both microstrip lines.

It should be mentioned that in this structure, the substrate propagating path still exists. However, the air propagating path is blocked by the inserted metallic plate because signals coupled to the air path will be reflected by the inserted metallic plate. Compared with the structures in [6], this FSS has only one propagating path together with two reflecting paths, which can provide more resonances in the operating bands. Fig. 9 shows the simulated S-parameters of this bandpass FSS. At lower frequencies, signals can pass through the substrate path and a bandpass response with a transmission pole is realized around the resonant frequency ($f_{a1}$) of the microstrip line resonator. Moreover, the shorting microstrip line can provide one more resonance at $f_{a2}$, thus widening the bandwidth of its passband. The inserted metallic plate in the air region is employed to reflect signals carried by the air mode and produce two transmission zeros ($f_{b1}$ and $f_{c1}$) at higher frequencies.

Fig. 11 shows the simulated results of the wideband FSS, where a wide passband with four transmission poles can be observed. Similar to the structure in Fig. 8, the air propagating path is blocked by the inserted metallic bar and the substrate.
A new class of 3-D bandpass frequency-selective structures has been presented, which are basically made of a 2-D periodic array of shielded microstrip lines. When the E-field of an incident wave is perpendicular to the strips, multiple resonators are constructed in these FSSs. Several designs of 3-D bandpass FSSs have been described based on a generalized equivalent circuit model. Unlike many traditional 2-D FSSs, these 3-D FSSs can provide more transmission poles/zeros in the operating band, leading to high selectivity, stable angular response, wide out-of-band rejection and/or wide passband frequency range. Due to their superior features and performances, these proposed 3-D FSSs are expected to be very useful in many practical applications. Other relevant studies include design of dual-polarized 3D FSSs and ultra-wideband band-stop FSSs.

REFERENCES