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SPURIOUS MODES REDUCTION IN A PATCH ANTENNA USING AN EBG-BASED MICROSTRIP TRANSMISSION LINE FILTER

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Abstract—In this paper, a novel dual planar electromagnetic bandgap (DP-EBG) microstrip structure is investigated to suppress the spurious radiation of the patch antenna. It is demonstrated that the proposed structure achieves a ultra-wide stopband and excellent passband performance within a compact circuit area. Utilizing such special features, two units of the DP-EBG structure are employed in the feed line of patch antenna with the aim of suppressing harmonics and other spurious modes. The calculated and experimental results all verify that the application of this DP-EBG structure not only drastically diminishes spurious radiations of 2nd $\sim$ 6th harmonics in a broad frequency band, but also overcomes some shortages of other EBG microstrip antennas introduced in previous research such as large back radiation or beam squint. Besides that, by adjusting the separation between the DP-EBG structure constructed in the feed line and the patch's bottom edge in a moderate distance, the procedure for designing the EBG patch antenna working on a certain frequency with the goal of reducing spurious radiation is simplified.

1. INTRODUCTION

The active integrated antenna, which integrates active devices directly into the antenna platform, is prospective in communication systems for its simplification of the circuitry and downsizing of the transmission system [1], but this configuration easily generates spurious radiation at harmonic frequencies due to the inherent features of oscillation circuit. To overcome this problem, various methods have been developed to reduce the spurious harmonic radiation of patch antennas. In [2], a

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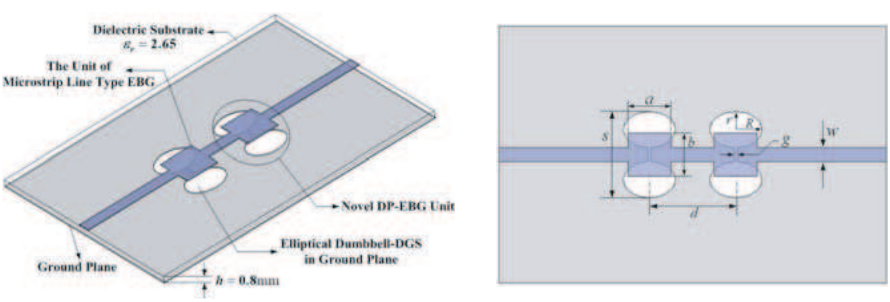
single microstrip antenna having two-dimensional EBG in the ground plane was proposed to suppress the second and third harmonics, but the backward radiation was serious at the dominant resonant frequency due to the presence of EBG circles in the ground. Sung and Kim [3] proposed two novel microstrip patch antennas using one-dimensional (1-D) EBG structures for both impedance matching and harmonic reduction. However, these EBG structures are only effective for suppressing the second harmonic radiation due to their narrow rejection frequency bandwidth, and a spurious resonance occurs around the second harmonic frequency for one patch antenna from the measured results, indicating that the effect of harmonic suppression is not very satisfying. Four pairs of split-ring resonators placed near both sides of the feed line with limited distance were proposed in [4] to eliminate the first and second harmonics. One lowpass filter with a circular head dumb-bell shaped DGS and an open microstrip stub was introduced in [5], and up to fourth harmonics were removed by employing this structure in the feed line of patch antenna. For the patch antenna with proximity coupled feeding line, the second and third harmonics were eliminated by adjusting the length of feed line and introducing one resonant cell [6]. A CPW-fed circular slot antenna with an arc-shaped slot inserted on the ground conductor was designed for achieving four-frequency band notch characteristic in the range of $2 \sim 10\,\mathrm{GHz}$ [7]. Some other structures such as the compact non-uniform transmission line transformers proposed in [8] may be expected to be used in the patch antenna to suppress harmonics and realize multi-band operation.

In this paper, we introduce a novel dual planar electromagnetic bandgap (DP-EBG) microstrip structure which is achieved with a combination of two one-dimensional (1-D) EBG structures, namely, an elliptical head dumbbell defected ground structure (DGS) and a microstrip line type EBG structure. The proposed DP-EBG structure works as a compact low-pass filter with ultra-wide stopband due to its intensive resonance effects. Then, two cells of this structure are utilized to the feed line of the microstrip patch antenna which resonates at 1.86 GHz. It should be noted that the feed network is very compact due to the small size of the given structure. Both numerical and measured results demonstrate that the proposed antenna obtains better performance than that of other designs in previous references in view of radiation patterns and the number of suppressed harmonic modes, indicating that the proposed DP-EBG structure is a more promising candidate in the active antenna system. Moreover, the simplification method for designing the EBG patch antenna operating at any certain frequency with the aim of reducing spurious modes is introduced in this work based on the comparison of experimental data between the proposed EBG antenna and the reference one.

2. NOVEL DP-EBG STRUCTURE DESIGN AND ANALYSIS

The typical microstrip line type EBG structure is constructed by periodic rectangular patches inserted in the microstrip line, such as the pattern on the top plane of the structure shown in Figure 1. It is simple to use this EBG structure for the design of microwave and millimeter-wave components, but this structure is not compact in physical size for low-frequency band applications since it is designed to satisfy the Bragg reflection condition [9]. In order to provide more evident stopband characteristic and decrease the circuit layout size, a rectangular head dumbbell defected ground structure (DGS) unit was proposed in [10]. The unit DGS circuit not only provides deeper stopband but also decreases the physical dimensions when compared with the microstrip line type EBG structure due to its highly-resonant characteristics. However, it is experimentally found that the passband performance of the DGS with only one or a few unit cells is not good [11]. Hence, if we superpose the microstrip line type EBG structure and the DGS section into a double-plane configuration, in which two types of EBG cells are strongly coupled to probably remove above mentioned shortages, this configuration may be expected to realize better stopband and low-pass band performance than that of any single type EBG structure.

Based on this idea, we propose a novel compact dual planar electromagnetic bandgap (DP-EBG) microstrip structure as shown in Figure 1, in which a microstrip line type EBG structure is overlapped



(a) (b)

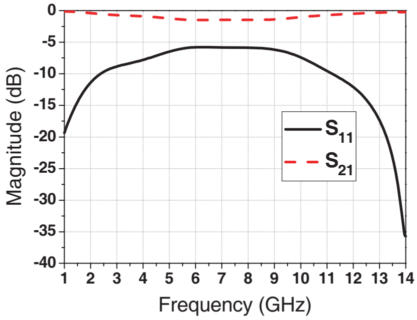
Figure 1. Schematic of the novel DP-EBG microstrip structure. (a) 3-D view. (b) Top View.

on an elliptical head dumbbell DGS. Each rectangular patch etched on the microstrip line together with its underlying DGS can be treated as one unit cell, so this novel DP-EBG structure shown in Figure 1 consists of two cells. We simulated one unit cell of the microstrip line type EBG on a complete ground and a common microstrip line on the ground with a elliptical head dumbbell DGS cell in addition to the proposed DP-EBG microstrip structure using a FR4 substrate with 0.8-mm thick and a dielectric constant of 2.65 by the full-wave simulator, Anosoft HFSS V.10.0. The line width w for all models is chosen to be 2.2 mm (equal to the width of microstrip 50 ohm line). The DP-EBG structure proposed in this paper is designed for 5.42 GHz resonant frequency of an elliptical head dumbbell DGS cell and 7 GHz Bragg condition of the microstrip line type EBG structure. Some correlative structural dimensions are calculated and shown in Table 1.

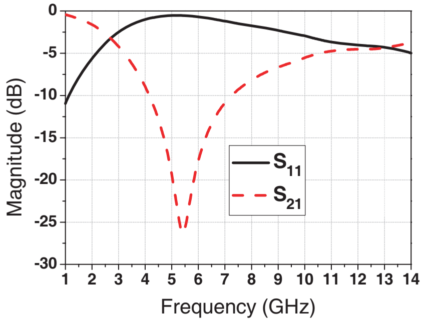
Figure 2 shows the calculated data of the single microstrip line type EBG cell and the single elliptical head dumbbell DGS cell. The single microstrip line type EBG cell shows flat transmission characteristics and very low insertion loss in the passband while the

Table 1. Novel DP-EBG microstrip structure specifications, where the axial ratio: R/r is assigned to be 10/7.

Parameters	d	a	b	R	r	g	s
Value (mm)	13.4	6.7	5	4	2.8	0.5	15.4

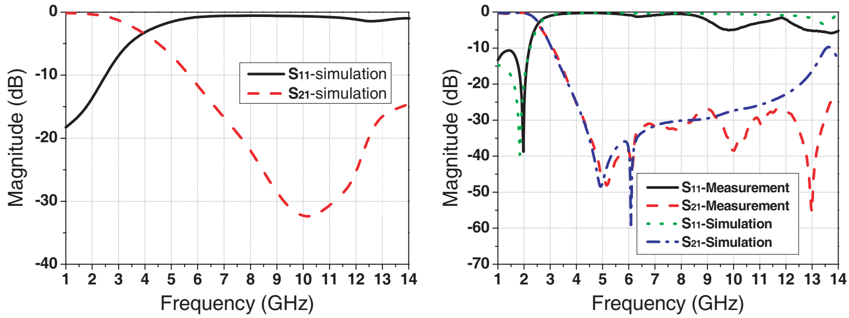


(a)



(b)

Figure 2. Simulated results of EBG cells: (a) single microstrip line type EBG cell and (b) single elliptical head dumbbell DGS cell.



(a) (b)

Figure 3. S-parameters of the proposed DP-EBG microstrip structure: (a) simulated results of one DP-EBG cell and (b) simulated and measured results of two DP-EBG cells.

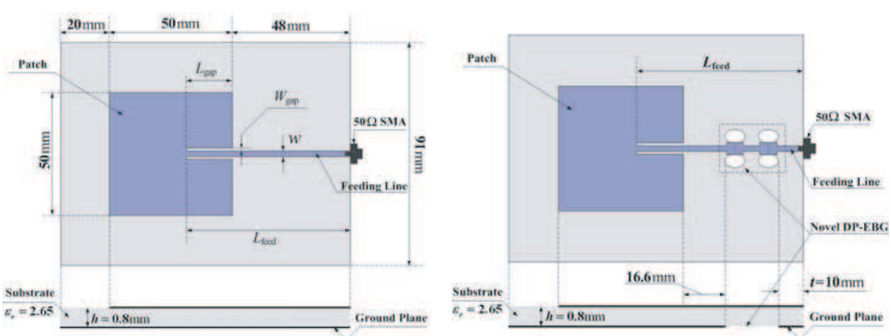
single DGS cell shows an attenuation pole location in the stopband, indicating that there is a highly-resonant behavior in the DGS. Figure 3 shows S-parameters of the proposed DP-EBG microstrip structure consisting of one cell and two cells, respectively (for the structure including two cells, the period d is kept equal to 13.4 mm). It is seen from these simulated data that the return loss in the lowpass band for the one-unit microstrip structure is not always below -10 dB, and its corresponding insertion loss is also a little higher than that of the DP-EBG structure including two cells. So we will adopt a microstrip line composed of two cells of the proposed DP-EBG structure as the feed line of the patch antenna to achieve good signal transmission over the dominant operating frequency band. Moreover, the proposed DP-EBG microstrip structure with two units is fabricated, and its measured S-parameters are also depicted in Figure 3(b). The measured data agree well with the simulation results except the difference occurring in the high frequency band which may be attributed to the variation of the actual dielectric constant and the loss tangent and fabrication tolerance. Regarding Figure 3(b), the most important feature of the proposed DP-EBG microstrip structure is about 20 dB stopband from 3.7 GHz to 14 GHz (over than 116%) in addition to the negligible insertion loss which is less than 0.5 dB throughout the passband. It is also noted that there are some attenuation pole locations in the stopband which are much deeper than that shown in Figure 2(b), meaning that the resonant behavior of the proposed DP-EBG structure is more intense than that of the single elliptical head dumbbell DGS cell. These favorable results are caused by the fact that the longitudinal resonant modes of the microstrip line type EBG structure and the transverse resonant modes of the elliptical head dumbbell DGS are strongly coupled through the DGS gap fields so that the passband and stopband characteristics are effectively improved by these multiple resonant modes. By virtue of the highly-resonant mechanism, this novel DP-EBG structure has relatively wider stopband characteristics and smaller required circuit size than that of Huang and Lee's DP-EBG structure proposed in [12, 13], which satisfies the Bragg reflection condition. Therefore, the proposed DP-EBG structure is essentially a new compact low-pass filter with ultra-wide stopband and can be effectively applied to various microstrip circuits to eliminate multiple spurious components.

3. APPLICATION OF THE NOVEL DP-EBG STRUCTURE IN MICROSTRIP ANTENNA

3.1. The Novel EBG Microstrip Antenna Design

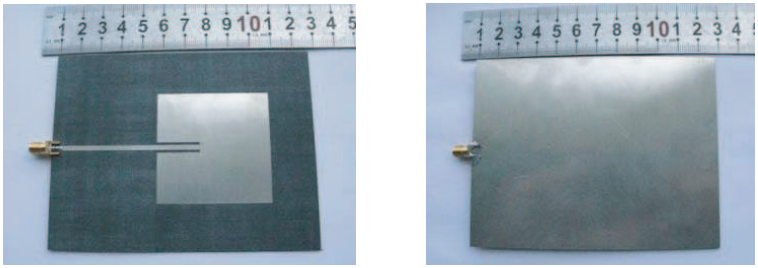
A normal microstrip patch antenna that serves as the reference antenna and operates at 1.83 GHz is designed firstly. Figure 4(a) shows the configuration of the reference antenna. A $50 \times 50\,\mathrm{mm}^2$ square patch is fabricated on the substrate with the physical size of $118 \times 91 \times 0.8\,\mathrm{mm}^3$ and relative permittivity of $\varepsilon_r = 2.65$. A 50 ohm microstrip feed line is used for antenna excitation. Inset cut with the length (L_{gap}) of 18.8 mm and the width (W_{gap}) of 1.2 mm is also adopted for a good impedance design for the reference antenna. Additionally, other structural parameters are evaluated and shown in Figure 4(a).

Then, the proposed DP-EBG structure shown in Figure 1 was constructed in the feed line of the microstrip patch antenna, as shown



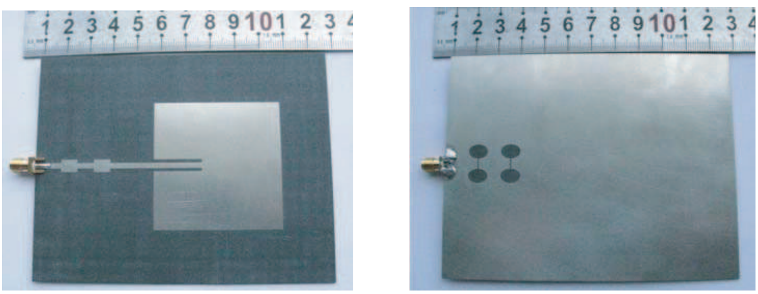
(a) (b)

Figure 4. Sketch of the printed antennas: (a) the reference patch antenna and (b) the proposed EBG patch antenna.



(a) (b)

Figure 5. Manufactured prototype of the reference patch antenna. (a) Top view. (b) Bottom view.



(a) (b)

Figure 6. Manufactured prototype of the proposed EBG patch antenna. (a) Top view. (b) Bottom view.

in Figure 4(b). Due to the small size of the cell compared with the free-space wavelength corresponding to the designed fundamental frequency, there are few changes in the size of the antenna employing the DP-EBG structure. It is apparent from the structure shown in Figure 4(b) that this novel EBG microstrip antenna has the same dimensions as that of the reference antenna except a modulated microstrip line on top of a ground plane etched with DGS cells.

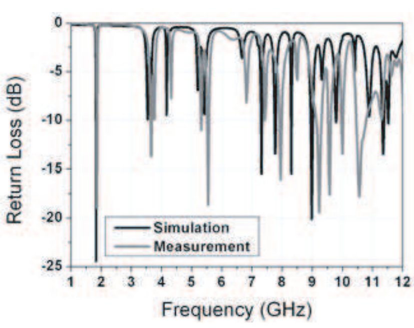
The above models are fabricated and measured experimentally to confirm the theoretical analysis. Figure 5 and Figure 6 show the manufactured prototypes of the reference antenna and the novel EBG microstrip antenna, respectively. All simulations are carried out by HFSS V.10. The reflection or transmission coefficients of all the fabricated prototypes are measured using an Anritsu ME7808A vector network analyzer while the radiation patterns are measured inside an anechoic chamber with an AV3635 antenna measurement system.

3.2. Simulation And Experimental Results

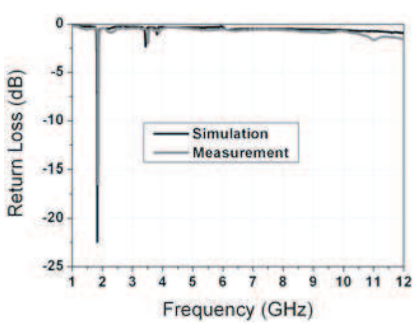
3.2.1. The Return Loss Properties

Figures 7(a) and (b) depict the simulated and measured reflection coefficients of the two antennas. Reasonable agreement is observed between the measurements and full-wave simulated data over the entire frequency span. The difference in the value of input return loss could be due to the number of sampling points taken while the slight shift in frequency could be attributed to the variation of the actual dielectric constant and the machining error. From the measured result shown in Figure 7(a), the dominant resonant frequency of the reference antenna is 1.86 GHz, slightly shifting from the simulated one, and its −10 dB bandwidth is about 16 MHz. The reference antenna also resonates at many harmonic frequencies along with other surface wave modes. For simplicity and comparison, the calculated and measured values of the fundamental frequency and other higher harmonic frequencies of the reference antenna are summarized in Table 2. However, for the EBG antenna, these harmonic resonances as well as other surface wave modes are totally suppressed within a wide frequency band as shown in Figure 7(b). It is also easily found by comparing the measured S_{11} of both antennas that the proposed EBG antenna has the same fundamental frequency (i.e., 1.86 GHz) as that of the reference antenna, and their bandwidths are well approximated to each other. Therefore, the proposed EBG antenna obtains a number of attractive features, including the following.

I. The operating frequency of the EBG antenna is not shifted away from the original resonance of the reference antenna, even though the patch sizes of the two antennas are identical. Unlike other



(a)



(b)

Figure 7. Calculated and measured return losses for (a) the reference antenna and (b) the proposed EBG antenna.

Table 2. Predicted and measured resonant frequencies of the reference patch antenna.

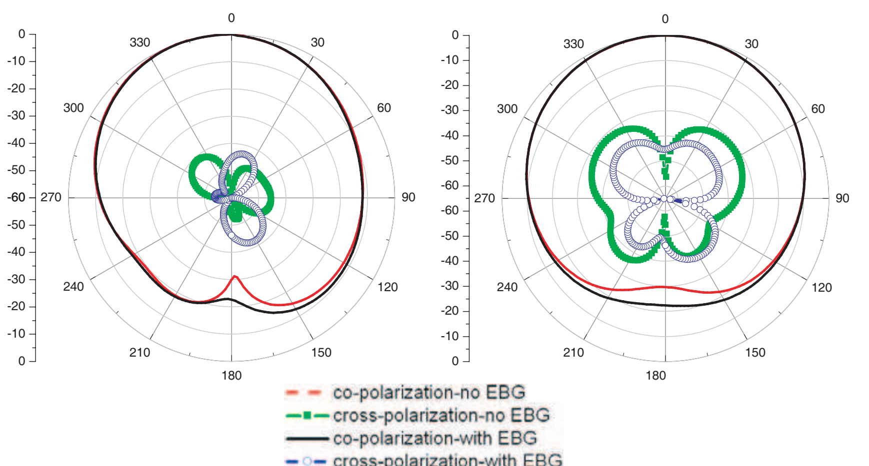
Resonant Frequency \ Frequency	Fundamental f_1	2nd Harmonic f_2	3rd Harmonic f_3	4th Harmonic f_4	5th Harmonic f_5	6th Harmonic f_6
Simulated Value (GHz)	1.83	3.65	5.43	7.32	**8.99**	10.89
Measured Value (GHz)	1.86	3.76	5.55	7.44	9.23	11.30

designs introduced in [2–6], where the fundamental frequencies of EBG antennas are always shifted more or less if they have the same patch size as that of the normal one. This character can be attributed to two reasons. Firstly, the low-pass characteristics of the feed line constructed with the proposed DP-EBG structure are so good that the propagation loss is small and can be comparable to that of a conventional microstrip line. On the other hand, the distance between the patch's bottom edge and the DP-EBG structure's top side is long enough (i.e., 16.6 mm, which is longer than 1/10 of the free space wavelength at 1.86 GHz), so the electromagnetic field in the vicinity of the patch is not disturbed by the DP-EBG structure, making the fundamental frequency of the EBG antenna stable. This concept is verified with the help of full-wave simulator HFSS, but the detailed process is not shown here. Based on the above reason, the design of any EBG patch antenna operating on a certain frequency with the aim of reducing spurious modes over a wide band can be simplified by using the method introduced in this paper since the patch size can be calculated by using the conventional evaluating procedure applied to the normal patch antenna and the fundamental frequency of the EBG antenna is only determined by its patch size and not affected by the EBG structure.

II. The proposed EBG antenna achieves the goal of notably diminishing resonances of 2nd $\sim$ 6th harmonics and other surface wave modes over a wide frequency range extending from 2 GHz up to 12 GHz, so the number of spurious modes suppressed by this proposed antenna is more than that of other designs in [2–7]. The slight discrepancies between the simulated and measured results, which are common, may give rise to some difficulties to suppress the harmonics exactly for the prototypes with narrow stopband, such as the structures proposed in [4]. But the proposed DP-EBG structure with relatively wide stopband can provide satisfactory allowance to reduce the harmonics even some discrepancies exist. Moreover, the total length of the two EBG units is about 21.4 mm, less than $\lambda_g/7$, where λ_g the free space wavelength at 1.86 GHz.

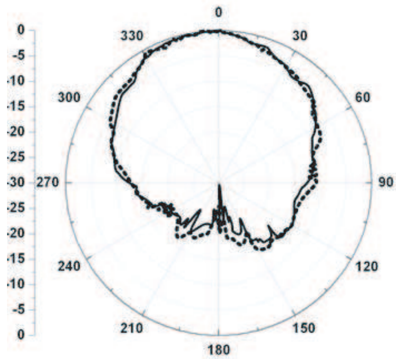
3.2.2. Radiation Patterns

Next, the radiation patterns at the fundamental frequency are simulated and measured for both antennas as depicted in Figure 8 and Figure 9. These power levels are normalized by the maximum level of the reference antenna at the dominant resonant frequency. The experimental co-polarization patterns agree well with simulated ones except slight discrepancies which can be attributed to the fabrication inaccuracy. It is easily seen from the measured results that both antennas have almost identical and quite stable co-polarization pattern characteristics in both plane at the fundamental frequency. The EBG antenna radiates broadside and maintains a cross-polarization level similar to that of the reference one, which is not presented here and remains below -20 dB in the E- and H-planes, respectively. The realized gain of the EBG antenna is similar to that of the reference antenna (i.e., 6.0 dB), satisfying the requirements for engineering applications. Unlike the EBG antennas introduced in [2, 3], where the back radiation at the designed frequency becomes especially large due to the presence of 2-D EBG lattice etched in the ground,



(a) (b)

Figure 8. Simulated radiation patterns for the reference antenna and the EBG antenna: (a) E-plane, (b) H-plane.



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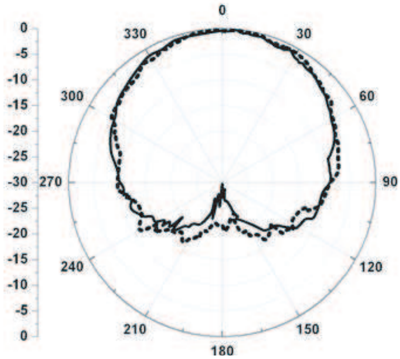

(b)

Figure 9. Measured co-polarization radiation patterns for the reference antenna (rigid line) and the EBG antenna (broken line) at the dominant resonant frequency: (a) E-plane, (b) H-plane.

there is no energy leaking in our designed EBG antenna because the DP-EBG structure constructed in the feed line cannot resonate effectively as an antenna and produces a negligible radiation loss at the operating frequency. Besides that, there is also no beam squint in the fundamental radiation pattern, which is different from the case presented in [3] where the DGS operating with some energy letting out is so close to the patch' bottom edge that its radiation disturbs the antenna's main radiation pattern. Therefore, this proposed EBG antenna in this paper obtains better radiation performance at the fundamental frequency in comparison with some designs in former references.

It is worth underlining that the DP-EBG structure also radiates through the holes on the ground plane in the frequency range 3 GHz–12 GHz even it makes little influence on the radiation pattern of the EBG patch antenna at the fundamental frequency, which can be read from Figure 9 that the level of the back radiation is only a little higher than that of the conventional patch antenna without a EBG structure. The proposed DP-EBG microstrip structure can be modeled with a equivalent circuit [14, 15] shown in Figure 10, where $j\mathbf{X}$ can be seen as the effective impedance of the modulated microstrip line and the parallel **LC** circuit represents the DGS, and the resistor **R** is necessary to explain the radiation loss. The four holes in the ground plane can be seen as a inductive FSS. When the FSS behaves as a pass-band filter, the impedance of the **LC** parallel tends to be infinite, and the energy does not flow across the transmission line leading to the nice S_{11} of the EBG antenna without high order resonances. However, part of the energy which does not flow throughout the transmission line is radiated through the holes behind the patch antenna. For this reason, even if the proposed design eliminates the additional resonances of a patch antenna, it is hard to avoid the problem that the patch antenna with the proposed DP-EBG structure radiates backward on higher order harmonics within the frequency range of 3 GHz–12 GHz. There are several techniques to reduce the level of back radiation deriving from the DGS such as the use of a shielding plane or a cavity. However, the shielding plane separated from the rear of the antenna by a foam dielectric promotes the generation of parallel plate modes, reducing the efficiency of the antenna. Adding a cavity to enclose the antenna can reduce back radiation without producing parallel plate mode, but its effective bandwidth is narrow besides the critical manufacturing issues. So a good choice is to put some thin electromagnetic absorbers with a wideband absorption performance such as the material introduced in [16] below the ground plane.

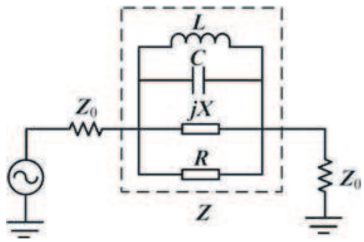

Figure 10. Equivalent circuit for the DP-EBG microstrip structure.

4. CONCLUSIONS

A patch antenna with a novel DP-EBG structure constructed in the feeding network has been studied in this work. The proposed DP-EBG microstrip structure, which yields good low-pass characteristics and ultra-wide stopband, is built up by a microstrip line type EBG structure overlapped on a elliptical head dumbbell DGS. It is demonstrated that the usage of this novel DP-EBG microstrip structure in the patch antenna leads to a perfect removal of up to sixth harmonics and other spurious resonances, which means that the number of spurious modes suppressed by this proposed antenna is more than that of other designs in former references, while the improvement in radiations at the fundamental frequency is also more significant than other designs given in previous research. Based on the low-pass characteristics of the proposed DP-EBG microstrip line and by modulating the separation between DP-EBG structure inserted in the feed line and the patch's bottom edge at a moderate distance (i.e., longer than $\lambda_g/10$), we realize the goal of making the fundamental frequency of the EBG antenna unchanged compared with the normal one even though the patch sizes of two antennas are identical. Therefore, the design of EBG patch antenna operating at any required certain frequency with the aim of reducing spurious modes can be simplified by using the method proposed in this paper since the patch size can be calculated through the conventional evaluating procedure applied to the normal patch antenna, and the fundamental frequency of the EBG antenna is only determined by its patch size and not affected by the EBG structure. Besides that, due to the small dimension of the DP-EBG structure, compact feed network is achieved. However, the microstrip line constructed with this DP-EBG structure works as a stop band filter, and part of the energy flows out from it passing through the holes in the ground plane. This problem will be solved by putting some thin electromagnetic absorbers below the DGS. Thereforethe proposed EBG antenna in this paper is quite effective for the suppression of spurious signals and may find applications in compact and low-cost active circuit system at microwave frequencies.

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