A CLASS OF HIGH-GAIN LOW-PROFILE RESONANT CAVITY ANTENNAS BASED ON A SINGLE LAYER METAMATERIAL SUPERSTRATE

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ABSTRACT

This paper presents our recent achievements on the study of high-gain low-profile electromagnetic band-gap (EBG) resonator antennas (EBGRA) using our newly-developed GA-FDTD method. We first introduce the EBGRAs of dual-polarisation, circular-polarisation and single-polarisation applications. Then a class of more versatile EBGRAs based on a single thinner metamaterial layer is presented. Thirdly, an EBGRA, with a low-profile, a height of a quarter wavelength between the metamaterial layer and the ground, and still a high gain, is presented. Finally, we give the result of our recent study on the short-range scanning EBGRA.

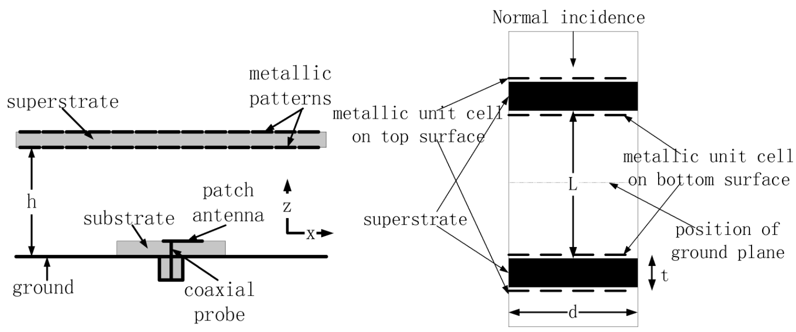
INTRODUCTION

Metamaterials have attracted much attention among researchers in the antenna area. One of important applications is to apply metamaterial covers as superstrates to enhance the gain of small antennas. Recently, we developed a novel method [1] to design high-gain resonant cavity antennas. Based on the method, the design of these antennas is transformed to that of the high Q-factor resonant cavity. Applying our in-house GA-FDTD code, which combines the finite-difference time-domain (FDTD) method with a genetic algorithm (GA), EBGRAs with high gain and low profile can be achieved.

In this paper, we present four of our recently developed high-gain low-profile EBGRAs [2-5]. The basic configuration of them is shown in Fig. 1(a), which is composed of a single-layer superstrate and a ground plane and excited by a small patch antenna. The superstrate is a frequency-selective-surface (FSS) based EBG structure, made up of FR4/Epoxy material that has a low dielectric constant of 4.4, and loaded with periodic metallic patterns on its two sides. These antennas have advantages of high gain, low profile, low cost and ease of fabrication and mounting.

HIGH-GAIN LOW-PROFILE DUAL-POLARISATION, CIRCULAR-POLARISATION AND SINGLE-POLARISATION EBGRAS

To analyse an EBGRA shown in Fig. 1(a), we apply the image theory to remove the ground. The cavity composed of the FSS layer and its image will resonate at the same frequency as that of the EBGRA. Considering the periodicity of the EBG structure, the periodic boundary condition (PBC) is applied so that the analysis of the EBGRA can be reduced to that of a single cell. Fig. 1(b) shows the configuration we analysed, which is composed of a single cell and its image and surrounded by four periodic boundaries.



(a) (b)

Fig. 1 (a) Geometry of the EBGRA
(b) Analysed and optimised cavity

The FDTD method with periodic boundary conditions and uniaxial perfect matched layer (UPML) was implemented [1] to characterise the cavity and calculate the transmission coefficient (S_{21}) and Q-factor of the cavity. The GA is used to optimise the Q-factor so that it is as high as possible. A high Q-factor cavity leads to a high directivity EBGRA.

For the designed antenna with dual- and circular-polarization applications, the operating frequency is *12.0 GHz*. The parameter *h* is *12.0 mm* (about $0.5\lambda_0$ at *12.0 GHz*) and the thickness (*t*) of the superstrate *is 3.2 mm* (about $0.25\lambda_g$ at *12.0 GHz*). The side length of the periodic square unit cell is *6.0 mm* (about $0.25\lambda_0$ at *12.0 GHz*). The two different metallic patterns on the two surfaces of the superstrate are symmetrical to its x- and y-axes as well as its two diagonals. By optimising the metallic patterns, the cavity in Fig. 1(b) will resonate at *12.0 GHz* with a high Q-factor. Using the optimised metallic patterns to construct the superstrate, a high-gain EBGRA is obtained. For the antenna with single-polarization application, it works at the same frequency band and has the same dimensions. However, the metallic patterns are only symmetrical to its x- and y-axes. The optimised metallic patterns for dual-, circular- and single-polarization applications are shown in Fig. 2, 3, and 4, respectively. When constructing the EBGRAs, all superstrates have the same size of $150\times150\times3.2$ mm^3 ($6.0\lambda_0\times6.0\lambda_0\times0.25\lambda_g$), which includes 25×25 unit cells. The simulated radiation patterns for dual- and circular-polarization applications and measured ones for the single-polarization application are also plotted in Fig. 2, 3, and 4. The calculated maximum directivities for the dual- and circular-polarization applications and the measured maximum gain for the single-polarization application are *23.41 dBi*, *21.64 dBi*, and *21.25 dBi*, respectively.

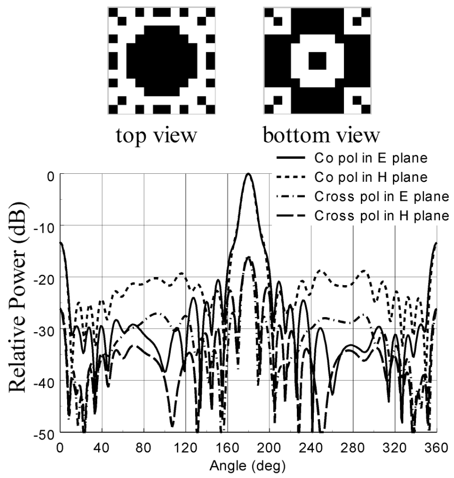


Fig. 2 Optimised metallic patterns for DP application and simulated radiation patterns

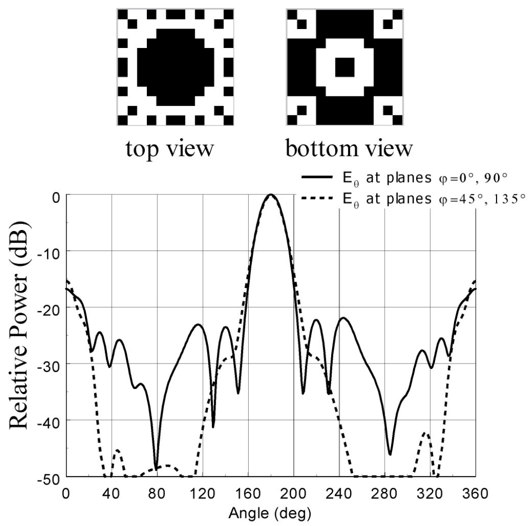


Fig. 3 Optimised metallic patterns for CP application and simulated radiation patterns

HIGH-GAIN LOW-PROFILE EBGRAS BASED ON A SINGLE THINNER DIELECTRIC LAYER

In the above EBGRAs, the thickness of the superstrate is approximately a quarter guide-wavelength. In practice, if the operating frequency is not *12.0 GHz*, the thickness of the superstrate will change and not be available directly in commercial products. One has to have it fabricated. This will increase the cost. Furthermore, if the operating frequency of the antenna and the dielectric constant of the superstrate are lower, the thickness of the superstrate will be very large, significantly increasing the weight of the antenna. It is found that the metallic grid has been utilised to form the EBG structure and enhance the gain of small antennas. A very thin superstrate with a low permittivity and periodic metallic patterns is expected to have the similar behaviour to the metallic grid. After study on the effects of the thickness of the supertrate on the performance of the EBGRA operating at *12.0 GHz*, we achieved good results using a superstrate of the FR4/Epoxy material, which has a thickness of *0.8 mm* (about 1/16 λ_g) and is the standard value of the commercial FR4/Epoxy products. The

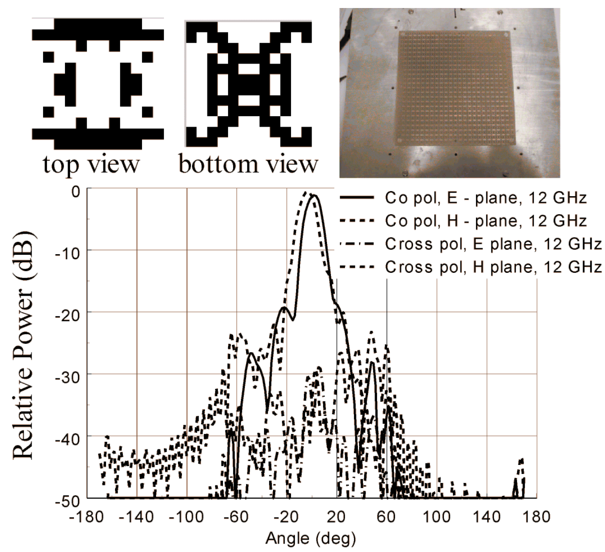


Fig. 4 Optimised metallic patterns for SP application and measured radiation patterns

geometry of the EBGRA and the dimensions of the cavity are the same as above. The optimised metallic patterns and the simulated radiation patterns are plotted in Fig. 5. The maximum simulated directivity is *22.52 dBi*.

A HIGH-GAIN ULTRA-LOW-PROFILE SINGLE-LAYER EBGRA

In the above EBGRAs, the distance (h) between the superstrate and the ground is about $0.5\ \lambda_0$. The ground is a perfect electric conductor (PEC) that reflects the fields out-of-phase. If one could use a perfect magnetic conductor (PMC) as the ground, the reflection would be in-phase, and hence the parameter h could be further reduced to $0.25\ \lambda_0$, reducing half of the height of the superstrate. Recently developed artificial magnetic conductor (AMC), one of metamaterials, is studied for this application. However, from our study, if using an AMC to replace a PEC, the radiation pattern of the small antenna will be changed and might not form an expected pencil beam above the superstrate. By loading periodic metallic patterns on one or both sides of a dielectric superstrate, the properties of the dielectric layer will be changed a lot. If such a superstrate has a thickness of $0.25\ \lambda_g$ and a height of $0.25\ \lambda_0$ above a PEC ground plane, a resonant mode is possible for the use of resonant cavity antennas. Here we give an example. The operating frequency of the EBGRA is *12.0 GHz*. The parameter h is *6.0 mm* (about $0.25\lambda_0$ at *12.0 GHz*) and the thickness (t) of the superstrate *is 3.2 mm* (about $0.25\lambda_g$ at *12.0 GHz*). The side length of the periodic square unit cell is *6.0 mm* (about $0.25\lambda_0$ at *12.0 GHz*). The two different metallic patterns are two square metallic patches with side lengths of *5.5 mm* and *1.5 mm* respectively. In the simulation of the antenna, the superstrate has a size of $90\times90\ mm^2$ ($3.6\lambda_0\times3.6\lambda_0$). The theoretical radiation patterns are plotted in Fig. 6 and the simulated maximum directivity is *17.46 dBi*.

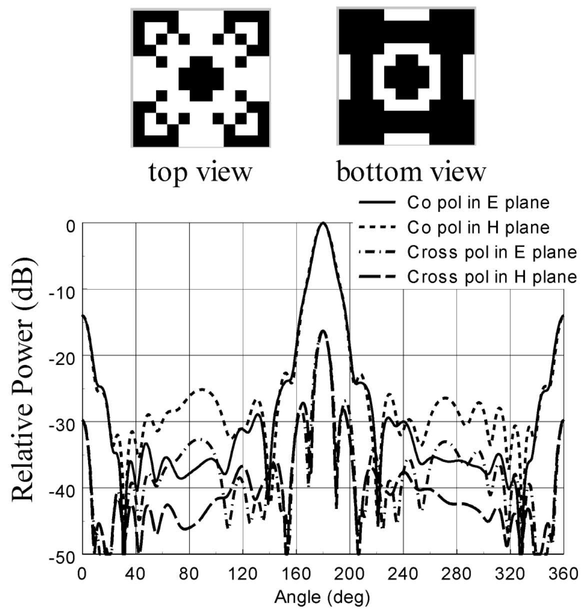


Fig. 5 Optimised metallic patterns and measured radiation patterns

A SCANNING EBGRA

Phased arrays have been extensively applied in the radio direction-finding and radar systems. As one class of phased arrays, the frequency-scanning array has the advantages of simplicity, low cost and ease of implementation. Previously a frequency-scanning array needs a lot of antenna elements that are placed on a surface, with an appropriate distance each other. Changing the frequency will result in a phase difference in each two adjacent antenna elements, and hence leads to the main beam to deviate the broadside of the antenna. If applying the metamterial as a superstrate to enhance the gain of a frequency-scanning array, the number of the antenna elements can be significantly reduced. However, due to the resonant property of the EBGRA, the radiation bandwidth of the antenna will be reduced and the direction of the main beam will deviate the original one when without the superstrate. For example, if the metamaterial superstrate is designed to make the main beam in the broadside of the antenna, when applying it to a frequency-scanning array, the scanning range will be reduced. Here we will use the EBGRA of single polarisation presented above to study the frequency-scanning characteristic of the EBGRA.

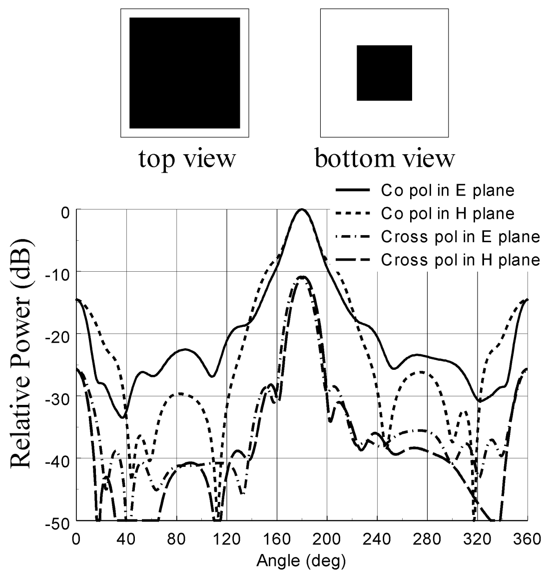


Fig. 6 Metallic patterns and measured radiation patterns

The EBGRA has the similar structure to that shown in Fig. 1(a), except that two feed antenna elements instead of one in Fig. 1(a) are used to excite the antenna. In our FDTD simulation, the two elements are aligned along x-axis, both xpolarised and fed using a serial feedline. Although the space distance of them is $0.5\lambda_0$, in order to result in a large beam scanning-range, the length of the feedline (*d*) between them is set to $9.0\ \lambda_0$. At the designing frequency of the EBGRA, *11.8 GHz* in this case, due to the two sources in-phase, the main beam is located in the broadside direction. The beam moving to the right and left sides is determined by the operating frequency higher or lower than the designing frequency. Table 1 shows our simulated results. It can be seen that the scanning-range is *–2.1°-11.0°* within the frequency range of *11.2-12.2 GHz*, while it is *–18.1°-30.5°* within the same frequency range if without the metamaterial cover. The directivity is within the range of *13.77-22.79 dBi*, while it is *9.55-10.61 dBi* within the same frequency range if without the metamaterial cover. Note that the frequency of the beam at the broadside is not the designing frequency of the metamaterial cover. The reason is that the designing frequency of the metamaterial cover is different from that of the frequency-scanning EBGRA. When the frequency is above the designing frequency of an EBGRA (*12.0 GHz*), the radiation pattern will deteriorate. We can only utilise the frequency range below *12.0 GHz* to carry out the beam scanning. Therefore, the designing frequency of the frequency-scanning EBGRA is chosen below *12.0 GHz* so that radiation patterns are reasonable in the scanning-range. However, we found from our simulations that due to strong resonance, the beam at *12.2 GHz* cannot deviate much the direction of the broadside, only *2.1°* in our case. Therefore, the designing frequency of the frequency-scanning EBGRA can be the same as that of the metamaterial cover. The short scanning-range achieved by an EBGRA is about *0.0° - 11.0°* using the frequency range below the designing frequency.

f_0 (GHz)	With MS		Without MS	
	θ	Directivity	θ	Directivity
11.2	11.2°	13.77 dB	30.5°	9.55 dB
11.3	7.4°	16.33 dB	24.2°	9.93 dB
11.4	7.0°	16.46 dB	18.9°	10.27 dB
11.5	4.3°	18.25 dB	14.4°	10.33 dB
11.6	1.7°	19.30 dB	9.8°	10.31 dB
11.7	0.8°	19.11 dB	4.5°	10.29 dB
11.8	0.2°	20.82 dB	0.3°	10.32 dB
11.9	-0.6°	22.33 dB	-4.3°	10.44 dB
12.0	-0.9°	22.79 dB	-8.9°	10.55 dB
12.1	-1.5°	22.10 dB	-13.2°	10.61 dB
12.2	-2.1°	19.54 dB	-18.1°	10.49 dB

Table 1 Simulated results of the frequency-scanning EBGRA
(θ is the direction angle of the beam, MS denotes the metamaterial superstrate)

CONCLUSION

In this paper, several designs of high-gain low-profile EBGRAs with different applications have been presented. These EBGRAs are composed of a single metamaterial layer based on an FR4/Epoxy superstrate that has a dielectric of *4.4*. Different applications, such as dual-polarization, circular-polarization and single-polarization operations, and short-range scanning, are successfully implemented in those presented EBGRAs. Good agreement between theoretical and experimental results has been obtained. The advantages of low cost, structure simplicity and ease of fabrication and mounting make them attractive for wireless applications.

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