Design of Low-Profile High-Gain EBG Resonator Antennas using a Genetic Algorithm

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***Abstract*— In this paper, we present a method to enhance the gain of electromagnetic band-gap (EBG) resonator antennas composed of a single-substrate frequency-selective-surface (FSS) using a genetic algorithm. In our method, the gain enhancement is realised by optimising the metallic patterns etched on the two surfaces of the FSS layer, using a Genetic Algorithm, and hence increasing the quality factor (Q-factor) of the EBG resonant cavity. The method is demonstrated using an example design and a prototype single layer EBG resonator antenna that achieves a gain of over 21 dB, which is normally reached only by a multilayer EBG antenna if the metallic patterns are not optimised.**

***Key words* - Electromagnetic band-gap, genetic algorithm, resonator antenna, high directivity, high gain**

I. INTRODUCTION

Electromagnetic band gap (EBG), or photonic band gap (PBG), structures have been of immense research interest within the antenna field because of their potential abilities to improve characteristics of antennas, such as reducing the size, enhancing the gain and radiation efficiency, etc. Among them, EBG resonator antennas are practically useful to enhance the gain of a planar antenna and easy to implement [1-5]. In these antennas an EBG material is placed above a metallic ground plane containing a small antenna, to form a resonant cavity, and hence the gain of the small antenna can be enhanced. It is found that the gain of EBG resonator antennas increases with the quality factor Q (Q-factor) of the resonant cavity [5]. Therefore, one of methods to further enhance the gain of the EBG antenna is to increase the Q-factor of the resonant cavity. This has been carried out before by increasing the number of dielectric EBG layers [2-4] or using EBG material of high permittivity, but the cost is the increase of the antenna height or the need of expensive materials. Another method for EBG antennas to achieve a high gain is to use a metallic grid [6] instead of dielectric EBG layers, which allows the reduction of the height of the EBG antenna [6].

In this paper, we propose another method to increase the Q-factor of a frequency-selective-surface (FSS) based EBG resonant cavity, and hence the gain of the related EBG resonator antenna, without increasing the number of layers or the height of the antenna. As we know, a resonant cavity composed of EBG material of high permittivity has a higher Q-factor than that of a low permittivity. However, materials with high permittivity such as Alumina generally cost more compared with those with low permittivity. Here we apply a genetic algorithm (GA) to optimise the Q-factor of an EBG resonant cavity so that a high Q-factor, which is normally obtained with a multilayer EBG material or material with high permittivity, can be achieved in an EBG resonant cavity that is composed of a single superstrate of low permittivity.

II. DESIGN PROCESS

Fig. 1(a) shows a dielectric EBG resonator antenna that is excited by a printed patch antenna. The superstrate is a FSS layer where two different periodic metallic patterns are printed on the two surfaces. Here the FSS layer works as an EBG structure and forms a resonant cavity together with a ground plane. The Q-factor of the resonant cavity determines the gain of the EBG resonator antenna [5]. The material considered for the FSS layer can be any standard low-cost material that has a low dielectric constant, such as FR4/Epoxy. To analyse such an EBG resonator antenna, we first apply 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 EBG resonator antenna. For this periodic EBG structure, the analysis can be reduced to that of a single cell by applying the periodic boundary conditions (PBC). Fig. 1(b) shows the configuration we analysed, which is composed of a single cell and its image. Since the gain of the EBG resonator antenna increases with the Q-factor and the Q-factor can be approximately evaluated by the 3-dB bandwidth of the transmission coefficient (S_{21}) [5] in a high Q resonant cavity according to,

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$$Q = \frac{f_r}{\Delta f_{-3dB}} \qquad (1)$$

where f_r is the resonant frequency, we can optimise the 3-dB bandwidth of the S_{21} to enhance the Q-factor of the structure in Fig. 1(b). Our method is to optimise the periodic metallic patterns printed on both sides of the EBG layer so that the EBG layer can exhibit the property of that of a higher dielectric constant.

A finite-difference time-domain (FDTD) method with periodic boundary conditions (PBCs) and uniaxial perfect matched layer (UPML) was applied in [7] for the characterisation of periodic structures. We use the same FDTD method to calculate the transmission coefficient of the structure in Fig. 1(b). A microgenetic algorithm (MGA) is then employed to optimise the two metallic patterns on both sides of the FSS layer so that a relatively high effective permittivity can be achieved and hence a high Q-factor and a high gain (or high directivity) of the EBG antenna are obtained. The MGA has the advantages of requiring only a small population for each generation, and achieving a near-optimal solution in a limited generation base. For applications in this work, the maximum number of generations required by the MGA is 300, the maximum population size is 5, the maximum number of bits of chromosomes is 256, and the maximum number of optimisation parameters is 20. The combination of the FDTD method and the GA algorithm is described in [7].

The EBG resonator antenna in this paper is designed to operate at 12.15 GHz. The distance between the superstrate and the ground should be about a half wavelength, and hence the distance between the unit cell and its image is 24 mm, as shown in Fig. 1(b). Normal incidence is assumed in the calculation of the transmission coefficient so that the main beam of the EBG resonator antenna is located in the broadside direction. Each side of the square unit cell is 6 mm long. In this design, the FSS layer uses the FR4/Epoxy material that has a dielectric constant of 4.4 and a thickness of 3.2 mm. In the optimisation, the top and bottom surfaces of the unit cell are divided into two 12×12 grids respectively. The grids are then encoded into a binary code. We let the grids be symmetrical to x- and y-axis. This reduces the complexity of the optimisation and makes it efficient. The minimum 3-dB bandwidth of the transmission coefficient is selected as the fitness goal. This will give rise to the maximum directivity of the corresponding EBG antenna.

Based on (1), the optimisation of the Q-factor can be carried out through that of the 3-dB bandwidth of the transmission coefficient S_{21}. For this purpose, we set the maximum of the transmission coefficient at 12.15 GHz. Our fitness goal was to achieve 10dB less transmission at frequencies 800 MHz from centre, i.e. 11.35 GHz and 12.95 GHz. Then we attempted two harder fitness goals, -15 dB and -20 dB transmissions at the same two frequencies. Finally, reasonable results are obtained in the fitness goal of -15 dB transmission at the two frequencies.

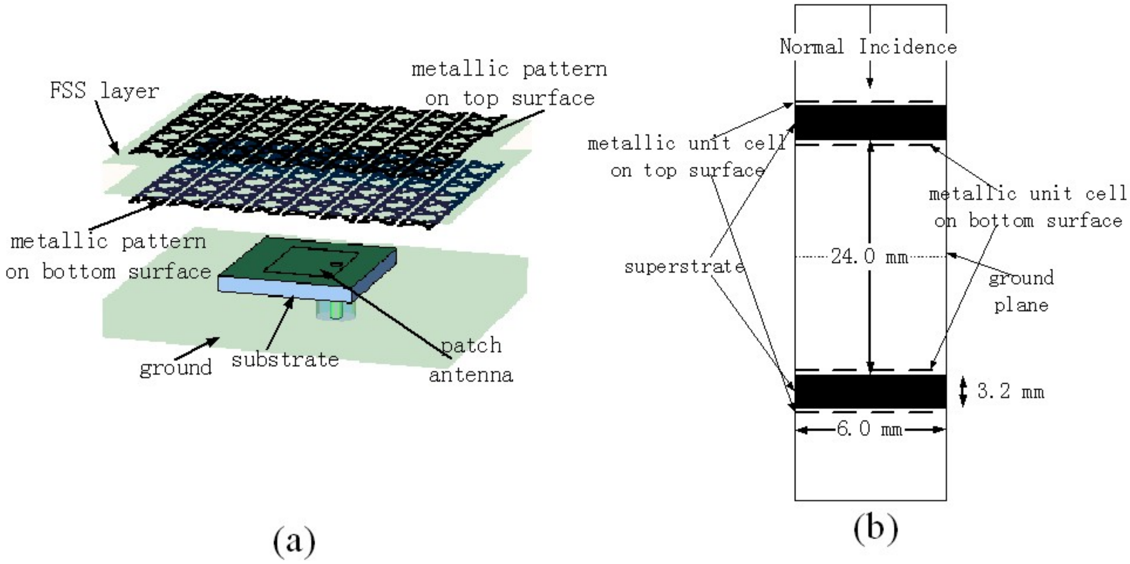

Figure 1 (a) Configuration of the proposed EBG resonator antenna
(b) Configuration and dimensions of a unit cell for FDTD-MGA optimization

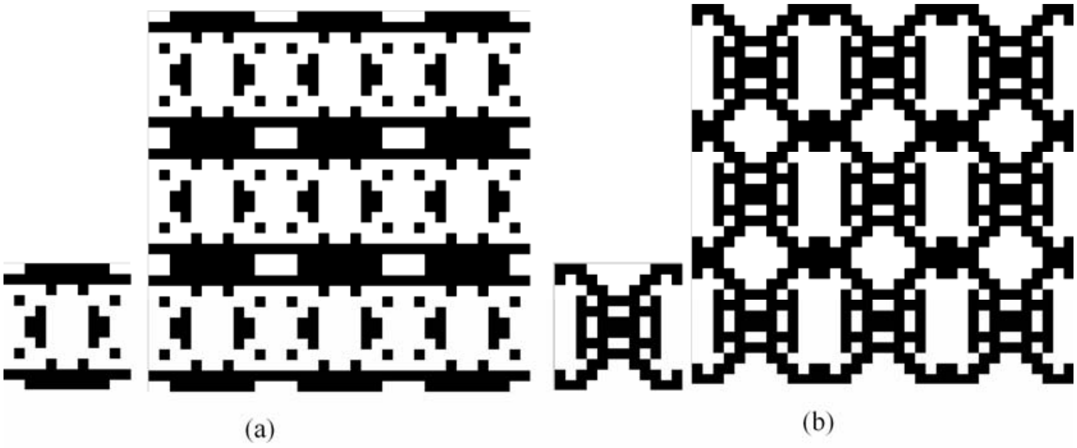

Figure 2 (a) Optimal Geometry of the unit cell and a 3×3 cell array on the top surface
(b) Optimal geometry of the unit cell and a 3×3 cell array on the bottom surface

III. RESULTS

The metallic patterns for the top and bottom surfaces (of a unit cell), obtained after optimisation for the fitness goal, are shown in Fig. 2. The transmission coefficient for the final antenna design is shown in Fig. 3. The value of the Q-factor based on the 3-dB bandwidth of the transmission is about 53.3. It is interesting to note that, in order to obtain a Q-factor of 53.3 without any printed metal patterns, one needs material with a dielectric constant of about 40. The transmission coefficient for the EBG cavity with a dielectric constant 40 and without any printed metal is also plotted in Fig. 3, for comparison. Further optimization with more stringent fitness goals does not increase the Q-factor of the EBG structure significantly.

We considered an EBG resonator antenna with a single optimised FSS layer, with dimensions of 150×150×3.2 mm^3 ($6\lambda_0\times6\lambda_0$ at 12 GHz), and it includes 25×25 unit cells. From our simulations we realised that the gain of the EBG resonator will not increase significantly with further increase of the size of the FSS layer. The distance between the lower surface of the FSS layer and the ground is 12 mm. The EBG antenna is excited by a rectangular patch antenna. The top view of the fabricated prototype of the EBG antenna is shown in Fig. 4. The input matching has been measured and shown in Fig. 5. As can be seen, the input matching bandwidth, determined by -10 dB of S_{11}, is 11.8 - 13.7 GHz. This antenna was then measured in our spherical near-field range for radiation patterns and the gain. Fig. 6 shows the measured E and H plane radiation patterns at 12.15 GHz, which exhibit high directivity. The 3-dB beamwidth is about 11° in E plane and 12° in H plane. The level of sidelobes is below -19 dB. The measured gain and directivity of the antenna are shown in Fig. 7. As we can see that the maximums of the gain and the directivity are at 12 GHz and 22.15 dB and 22.61 dB respectively. It is interesting to see that there is a beam squint between E-plane and H-plane. The reason is that the structure of the patch antenna is only symmetrical to y-axis, which leads to the symmetrical radiation pattern of the patch antenna in H plane while the asymmetrical pattern in E plane. Actually the maximum of the radiation in E plane is not located in the broadside of the patch antenna.

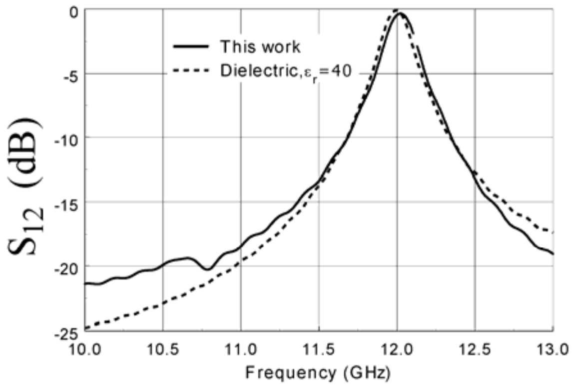

Figure 3 Simulated transmission coefficients from our FDTD code and CST Microwave Studio

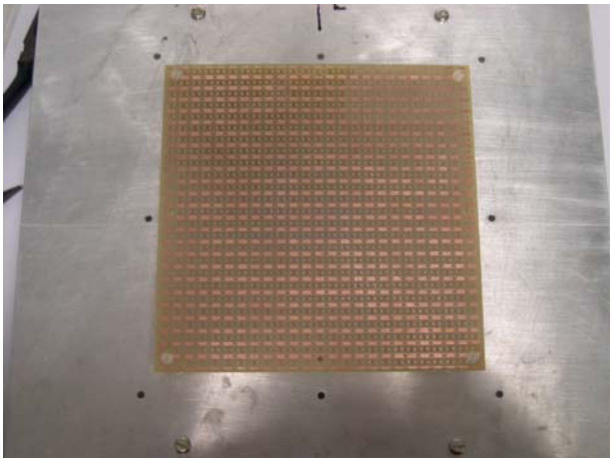

Figure 4 Prototype of the designed EBG resonator antenna

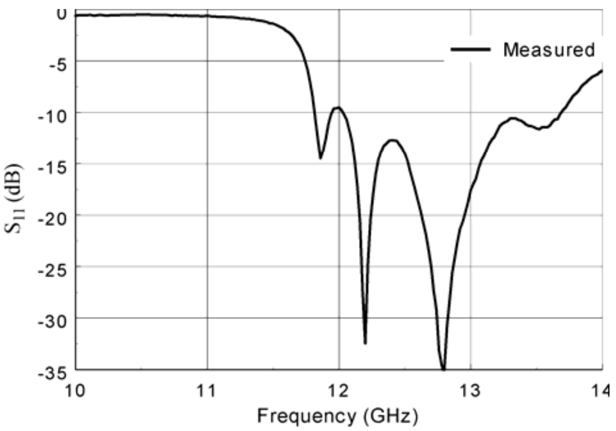

Figure 5 Measured return-loss of the designed EBG resonator antenna

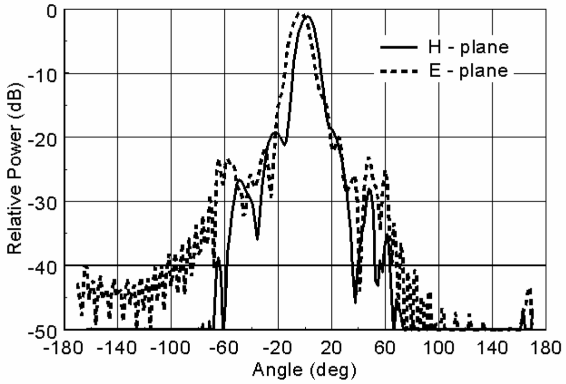

Figure 6 Measured radiation patterns for the designed EBG resonator antenna

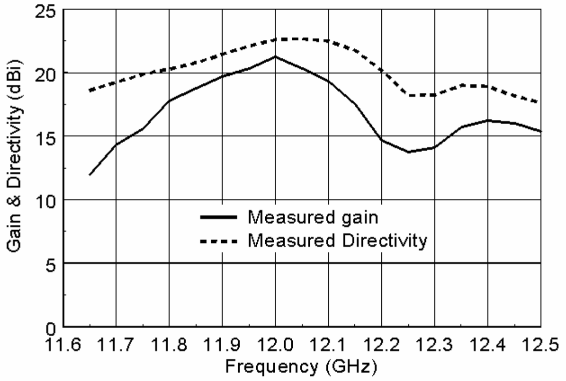

Figure 7 Measured gain and directivity for the designed EBG resonator antenna

IV. CONCLUSIONS

The gain of the EBG resonator antenna, composed of a double-sided FSS layer, a patch antenna and a ground plane, was successfully enhanced through optimising the Q-factor of the related EBG cavity. A microgenetic algorithm, integrated to the FDTD method, was employed to perform this optimisation. The gain normally obtained with multilayer EBG resonator antennas can be achieved by an EBG resonator antenna using a single superstrate with optimised double-sided printed patterns, significantly reducing the height of the standard high-gain dielectric EBG resonator antennas.

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