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A STUDY OF USING THE DOUBLE NEGATIVE STRUCTURE TO ENHANCE THE GAIN OF RECTANGULAR WAVEGUIDE ANTENNA ARRAYS

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Abstract—In this paper we propose a new method to enhance the gain of rectangular waveguide antenna arrays using the double negative medium (DNG) structure composed of strip wires (SW) and split ring resonators (SRR). The electromagnetic parameters of the DNG structure are retrieved and the rectangular waveguide antennas with and without the DNG structure are studied using numerical simulation method. The simulation results show that the DNG structure can congregate the radiation energy when the index of refraction approximates zero, since that the gain of the antenna arrays is enhanced and the radiation performance of the antenna arrays is effectively improved. Far-field radiation patterns are measured, which indicate that this method is effective to enhance the gain.

1. INTRODUCTION

In 1968 Veselago [1] studied the electrodynamics of substances with simultaneously negative values of dielectric permittivity (ε) and magnetic permeability (μ).In such a medium, the electric field, the magnetic field, and the propagation vector $\vec{k}$ form a left-handed triple. Because of this relationship, this medium has been named left-handed media (LHM). Recently, metamaterials with simultaneously negative values of dielectric permittivity and magnetic permeability have been discussed in many papers. In 1996 an array of metallic strip wires (SW) was shown to have plasma frequency in the microwave regime. When lower than the plasma frequency, this structure can produce an effective negative permittivity suffering relatively small losses [2]. Then, in 1999 an array composed of split ring resonators (SRR) was proposed that exhibited a negative magnetic permeability in the resonance region [3]. The first double negative medium (DNG) was proposed soon when these two structures were combined and it was shown that both the real part of the electric permittivity and the magnetic permeability were negative. The medium is, in effect, a spatial filter. Its properties suggest the possibility of using planar slab of such media as alternative to conventional curved lenses or reflectors for highly directive antennas [4]. Double negative media were widely used in the field of antenna excluding antenna arrays to effectively enhance the directivity of antenna [5–8].

The arrays of rectangular waveguide antenna had found wide application in communication and radar domain. In this paper, we present a new design of high-gain rectangular waveguide antenna arrays using the DNG structure. The properties of the DNG structure and the radiation characteristics of the antenna arrays are investigated by numerical method. The simulation results are given using Ansoft HFSS 3-D simulator which is based on the finite element method (FEM). Our studies demonstrate that the DNG structure can realize an effective index of refraction which approximates zero and congregate the radiation energy. Moreover, a great improvement of gain can be obtained by using the structure on the antenna arrays in comparison with the conventional ones.

2. CHARACTER ANALYSIS OF THE DOUBLE NEGATIVE STRUCTURE

The DNG structure which is studied in this paper is composed of SW and SRR. The sketch map is shown in Fig. 1. The structure uses the metallic strip wire to produce effectively negative permittivity. When

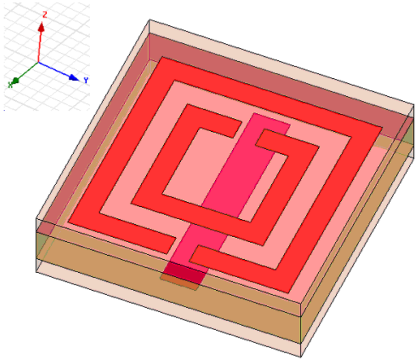


Figure 1. Structure of the DNG medium.

electric field E is parallel to SW, the dispersive character which is similar to plasma is shown as follow [2]:

$$\varepsilon_{\mathit{eff}} = 1 - \omega_p^2/\omega^2$$

where ω_p is the plasma frequency. From this equation, the effective permittivity is negative when the frequency of the propagating electromagnetic wave is below the plasma frequency.

The SRR structure considered here consists of two concentric square rings, with gaps on them and opposite to each other. SRR can result in an effective negative permeability over a particular frequency range. The effective permeability of the periodic structure composed of SRR has the well-known form [3]:

$$\mu_{\mathit{eff}}(\omega) = 1 - \frac{F\omega_0^2}{\omega^2 - \omega_0^2 - i\omega\Gamma}$$

where ω_0 is the resonant frequency, F is the fractional area of the unit cell occupied by the interior of the split ring and Γ is the dissipation factor.

It is well known that $\varepsilon_{\mathit{eff}}$ is negative when $\omega < \omega_p$, and μ_{eff} is negative when $\omega_0 < \omega < \omega_{mp}$ (magnetic plasma frequency). Overlaying these two frequency region, both the permittivity and permeability are simultaneously negative, thus the index of refraction may have a small value over a passband region.

From Snell's law, the refraction index of the media can be written as $n = \sqrt{\mu_r \varepsilon_r}$. In the region where both $\varepsilon_{\mathit{eff}}$ and μ_{eff} are simultaneously negative, the index of refraction is less than 1 and tends to become zero when the frequency of the electromagnetic wave is close to the plasma frequency ω_p (or ω_{mp}). The DNG structure can congregate the energy, so the emitted electromagnetic field can be concentrated around the normal of the slab, as is shown in Fig. 2. The length of the board is 60 mm and the width is 0.5 mm. The source is 3 mm apart from the board. An infinite metal plate is placed behind the source to increase the transmitted electric field. We apply the DNG structure to the antenna in order to congregate the incident field from the source.

The DNG structure is applied in the rectangular waveguide antenna array and its frequency is 12 GHz. The S parameter is retrieved using HFSS tools which are based on the finite element method. Each simulation model consists of a two-port waveguide formed by a pair of both perfect electric conductor (PEC) and perfect magnetic conductor (PMC) walls. The input wave is launched in free space toward the inside of waveguide at normal incidence from each

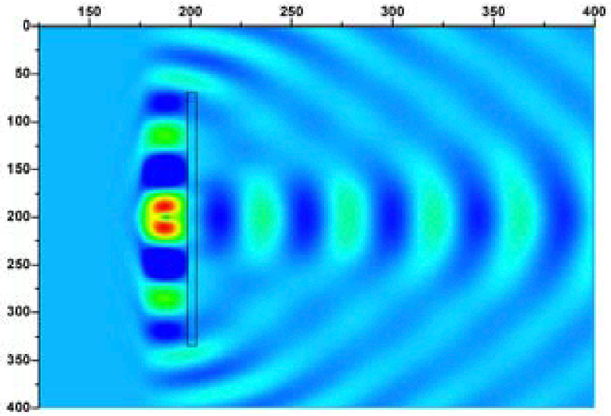
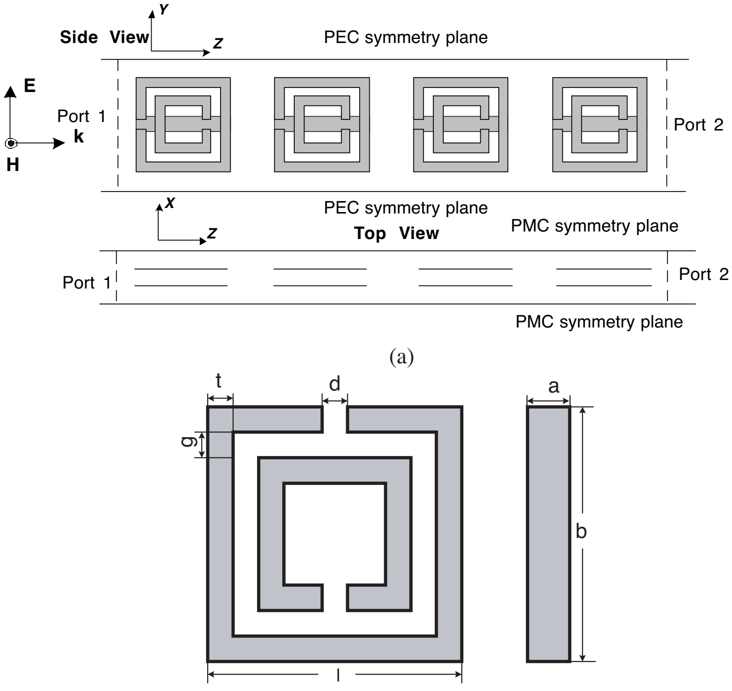


Figure 2. Example of how the DNG structure can be used to congregate the radiation energy.



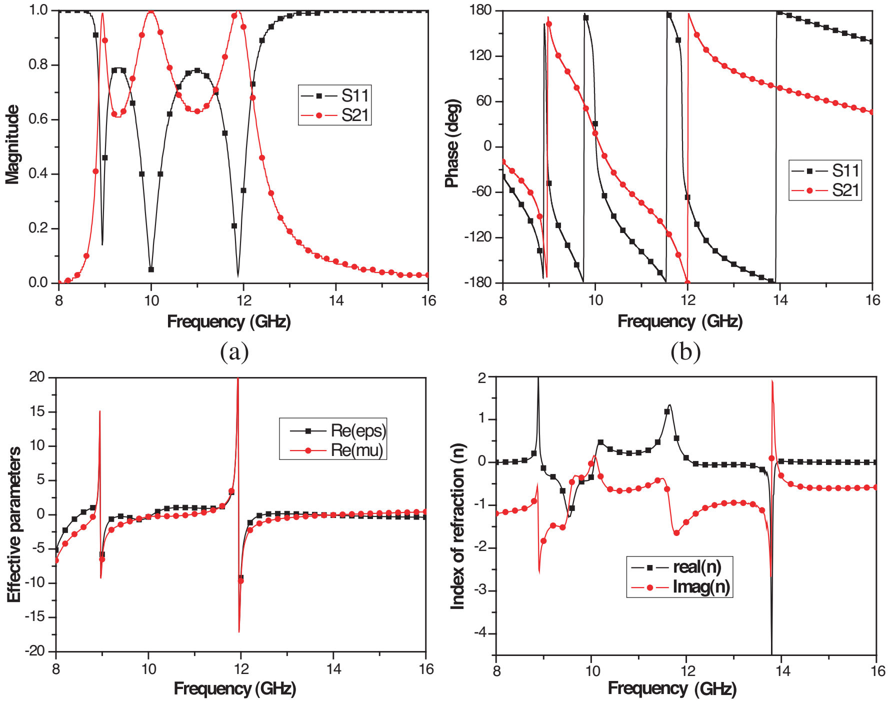
(a)

(b)

Figure 3. (a) DNG structure geometry, (b) dimensions of the DNG structure.

port. The waveguide is filled with a $\varepsilon_r = 2.65$ dielectric substrate. Four DNG structure units shown in Fig. 1 are centered in the waveguide along the z direction. The space between the SW and SRR is 0.5 mm. The space between the two PEC symmetry planes is 4 mm and between the two PMC symmetry is 1 mm. The z length of the waveguide is 19 mm. The geometry of the DNG structure is shown in Fig. 3(a). The dimensions of the structure shown in Fig. 3(b) are: $l = 3$ mm, $d = t = g = 0.3$ mm, $a = 0.5$ mm, $b = 3$ mm, the spacing between the DNG units is 5 mm.

The HFSS-predicted magnitude and phase of S parameters of the waveguide in the range of 8–16 GHz is plotted in Figs. 4(a) and (b).With the S-parameter data from the waveguide, we can retrieve the effective permittivity and permeability using modified Nicolson-Ross-Weir (NRW) approach [9] as shown in Figs. 4(c) and (d).



(a) (b)

(c) (d)

Figure 4. (a) Magnitude of the S parameters, (b) phase of the S parameters, (c) effective permittivity and permeability, (d) index of refraction.

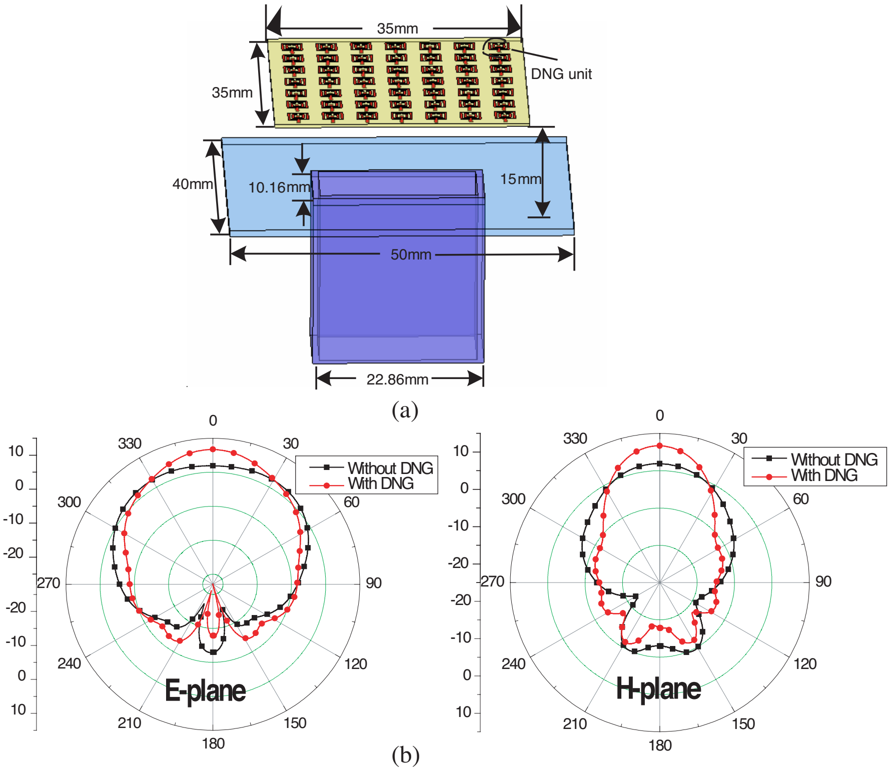
From Fig. 4, it is clear that resonance occurs at 12 GHz. The phase of S_{21} goes to zero and the magnitude approaches unity. The permittivity and permeability are simultaneously negative, and the real part of the refraction index tends towards zero. Because of this extraordinary property of the DNG structure, we can apply it to the antenna in order to congregate the incident radiation field of the antenna. The unit number of the antenna arrays could be reduced for the same gain, which has great significance of the minimization design of antenna arrays.

3. SIMULATION AND NUMERICAL RESULTS

3.1. The Single Rectangular Waveguide Antenna

As the foundation of the antenna arrays, it is significant to analyze the radiation properties of the single rectangular waveguide antenna. The simulation results are given using Ansoft's HFSS which is based on the finite element method (FEM). To simplify the theoretical study, the rectangular waveguide used is BJ-100 with the size 22.86 mm×10.16 mm. The frequency chosen for the antenna is 12 GHz and the size of metal ground is 40 mm×50 mm. The DNG structure is placed above the rectangular waveguide antenna so as to study its effect on the radiation characteristics as shown in Fig. 5(a). The structure is composed of 7×7 cells with the size 35 mm×35 mm. The thickness of the dielectric board is 0.5 mm and its relative permittivity is 2.65. The DNG structure is located at 15 mm from the antenna aperture.

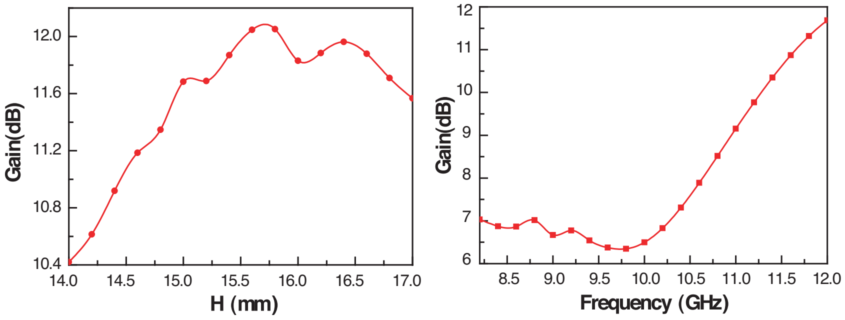
The simulation results of the rectangular waveguide antenna with and without DNG structure are shown in Fig. 5(b). The gain of antenna with DNG structure is enhanced from original 6.86 dB to 11.68 dB, while the backward is obviously restrained. As the foundation of the antenna design, it is necessary to analyze the effect of the spacing between the DNG structure and the antenna aperture. The curve of the gain with the variation of the spacing is shown in Fig. 6(a), while the curve of the gain with different operating frequency is shown in Fig. 6(b).Since the relatively permittivity and permeability are simultaneously negative at around 12 GHz, the antenna can get a more gain. When the spacing (H) is between 15 mm and 17 mm, all the gain is above 11.6 dB. Considering the computing time of numerical simulation, the spacing we choose is 15 mm.



(a)

(b)

Figure 5. (a) Rectangular waveguide antenna with DNG structure, (b) radiation patterns of the rectangular waveguide antenna.



(a)

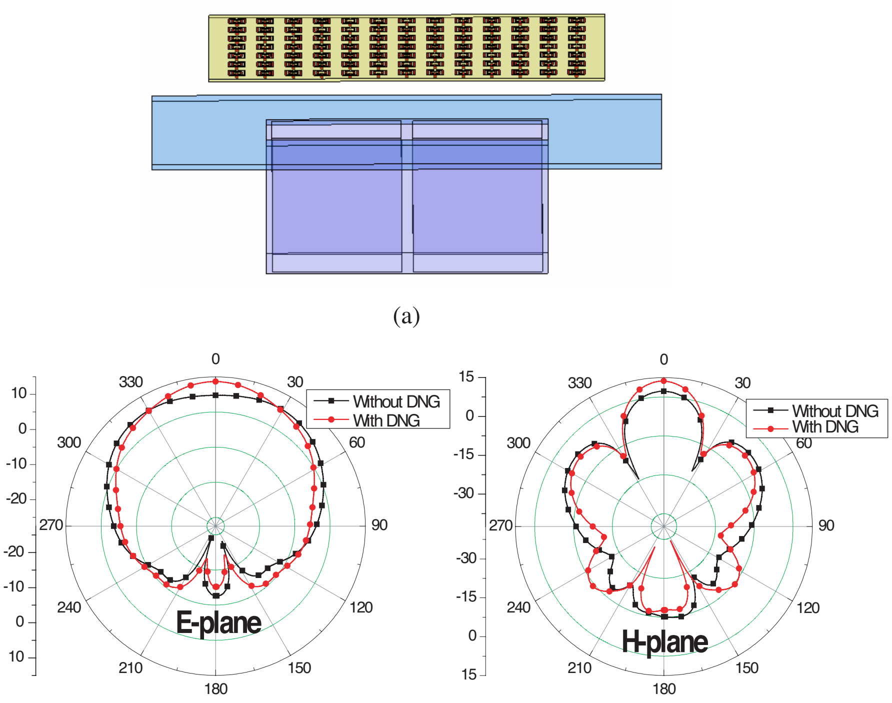
(b)

Figure 6. (a) Gain of the antenna with the variation of frequency, (b) gain of the antenna with different spacing.

3.2. Rectangular Antenna Arrays

3.2.1. Two Elements Array

A model of antenna array with two parallel elements along the H plane integrated with DNG structure is shown in Fig. 7(a). The dimension of the element in the array is the same as in the single rectangular waveguide antenna. The DNG structure is composed of 13×7 cells with the total size 68.4 mm×114 mm. The spacing between the structure and the antenna array is also 15 mm. The simulation results are shown in Fig. 7(b).



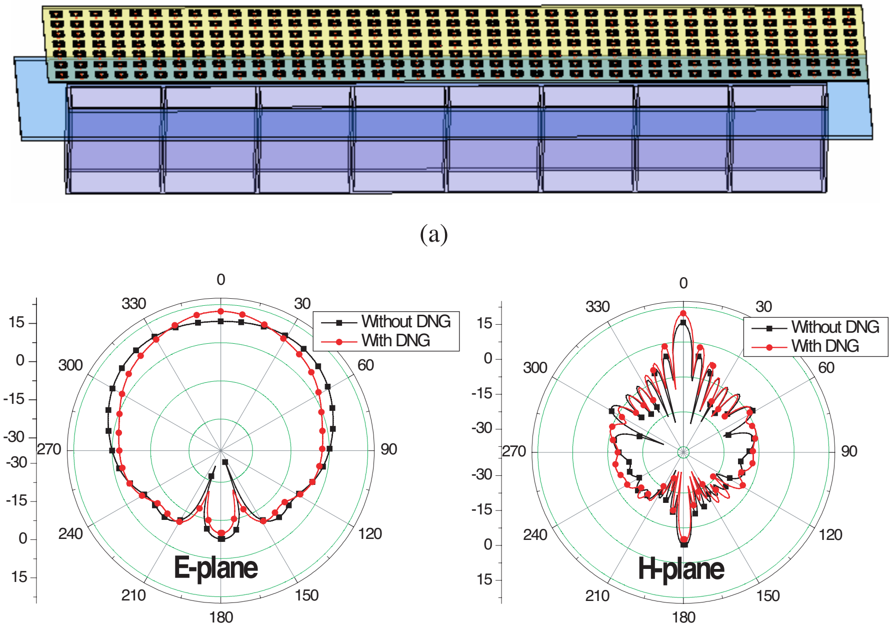
(a)

(b)

Figure 7. (a) Model of the two-element array integrated with the DNG structure, (b) radiation patterns of the two-element array.

3.2.2. Linear Array

We studied the linear array with eight waveguides along the H plane. The dimension of the elements is the same as the single rectangular waveguide antenna. The DNG structure is composed of 7 × 22 cells and the total size is 37 mm×113 mm. The model of the linear array integrated with the structure and the simulation result are respectively shown in Figs. 8(a) and (b).



(a)

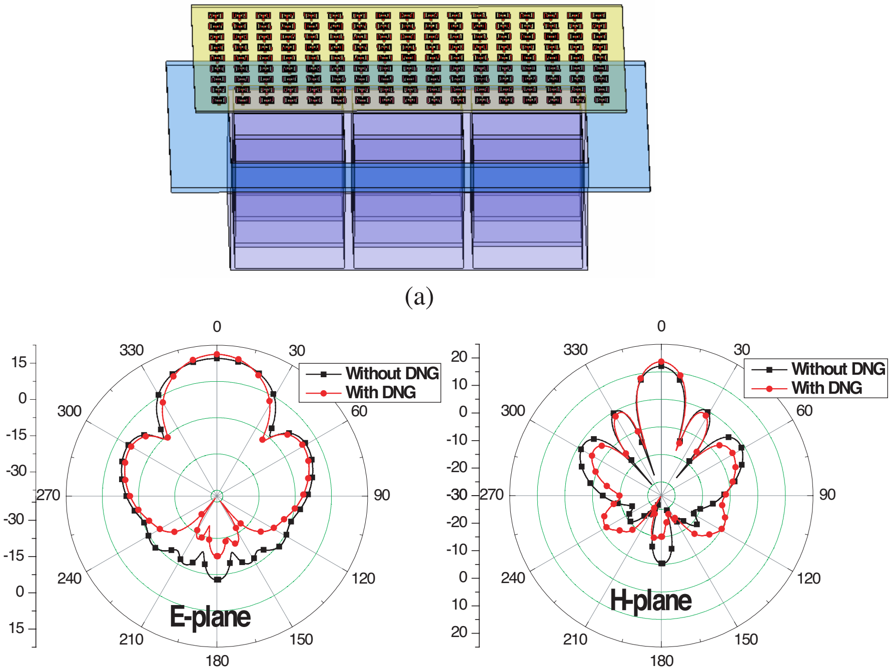
(b)

Figure 8. (a) Model of the linear array integrated with the DNG structure, (b) radiation patterns of the linear array.

3.2.3. Planar Array

In the model of 3×3 planar array, the dimension of the element is also the same as the single one. The DNG structure is composed of 17×9 cells with its total size 90 mm×50 mm. The model of the planar array is shown in Fig. 9(a) and the simulation results are shown in Fig. 9(b).

From the simulation results, we can see that the gain of the two-element antenna array increases from the original 9.7 dB to 13.65 dB, while that of the linear array is improved from 15.67 dB to 19.77 dB and from 16.9 dB to 18.66 dB for the planar array, respectively. Generally speaking, the gain of the rectangular waveguide array antenna with DNG structure has been obviously enhanced in comparison with that of conventional antenna without DNG structure. We believe that



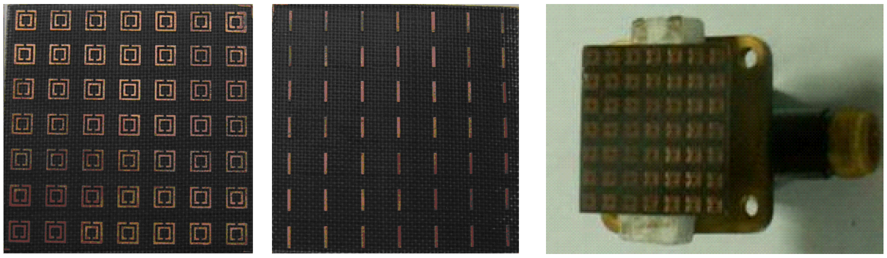
(a)

(b)

Figure 9. (a) Model of the planar array integrated with the DNG structure, (b) radiation patterns of the planar array.

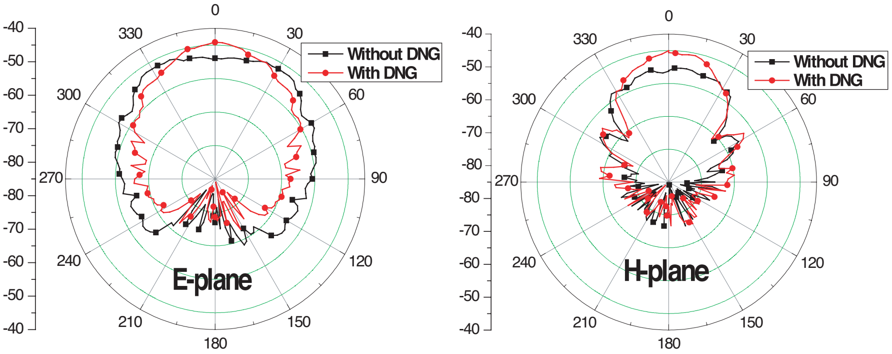
the improvement is owed to the DNG structure used on rectangular waveguide array antenna which can congregate the radiation energy. From Fig. 9, it is shown that the DNG structure can also decrease the backward radiation.

In order to prove the validity of the simulation results, a rectangular waveguide antenna with DNG structure is fabricated and measured. The photographs of the DNG structure and the antenna with the structure are shown in Fig. 10. Fig. 11 shows the radiation patterns of the rectangular waveguide antenna integrated with and without the DNG structure at 12 GHz. A comparison of the radiation patterns shows that the gain of the antenna with the DNG structure is enhanced about 5 dB and the backward radiation is somewhat restrained. The experimental results are consistent with the simulation conclusion, which indicates that this method is effective to enhance the gain of antenna.



(a) (b)

Figure 10. (a) Photograph of the DNG structure, (b) photograph of the antenna with the DNG structure.



(a) (b)

Figure 11. Measured radiation patterns of the rectangular waveguide antenna (a) E-plane, (b) H-plane.

4. CONCLUSION

A new method to enhance the gain of rectangular waveguide antenna arrays is presented in this paper. The principal characteristic of the proposed DNG structure is studied, and then the radiation performance of a rectangular waveguide antenna arrays with DNG structure are simulated using numerical method. The simulation results, which validate the theoretical analysis, show an effective enhancement in the antenna arrays gain in comparison with the conventional antenna arrays without the DNG structure, so the radiation performance of antenna arrays with the structure are remarkably improved. Finally, the practicability of this method is illustrated by an example of a single rectangular waveguide antenna. It is also expected that the DNG structure can be applied in various antennas to improve their radiation performance.

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