Directive Emission Obtained by Mu and Epsilon-Near-Zero Metamaterials

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Abstract. *In this work, we use Mu and Epsilon-Near-Zero (MENZ) metamaterials to realize the substrates that can modify the emission of an embedded line source. Simulation results show that the cylindrical waves emitted from the line source can be perfectly converted to plane wave through the MENZ metamaterial slab with planar exit face. Hence the line source together with the metamaterial slab constructs a high directive slab antenna. The directive radiation pattern of the MENZ metamaterial-assisted slab antenna is independent on the thickness of the slab, the position of the line source, and the shape of the entrance face of the slab, but the slab with grooved entrance side will result in stronger far-field intensity. We also show that the MENZ metamaterials can be applied to the design of antenna array. Moreover, compared with the high directive slab antenna obtained by coordinate transformation approach, the MENZ metamaterial-assisted antenna is more preferable.*

Keywords

Electromagnetic wave, finite element method, Mu and Epsilon-Near-Zero Metamaterials, slab antenna.

1. Introduction

The growth of interest in metamaterials has recently led not only to novel and interesting theoretical possibilities for microwave, infrared, and optical applications but also to several conceptual advancements in the fundamentals of the electromagnetic theory. Limits that were considered insurmountable in conventional setups have indeed been shown to be, at least potentially, surpassed when special materials are employed [1]. Examples of these achievements, such as perfect lens, electromagnetic cloak, tunneling effect, directive emission and so on, have been proven theoretically and, in part, experimentally in the recent technical literatures [2-12].

The most exciting applications can be envisaged for electromagnetic cloaks working in the visible part of the spectrum. Cloaking with metamaterials that enable the creation of volumes with zero electromagnetic fields inside a device composed of such materials. Cloaking techniques rely on the transformation of coordinates, e.g., a point in the electromagnetic space is transformed into a sphere in the physical space, thus leading to the creation of a spherical volume where electromagnetic fields do not exist, but are instead guided around this volume [6]. Based on the coordinate transformation theory, other novel devices, such as the EM concentrators [13], electromagnetic-wave rotators [14], hyperlens [15], optical sensor and power divider [16] were also investigated. These rapid progresses make the coordinate transformation approach a hot topic in electromagnetics and imply very important future applications [17]. Recently, Zhang et al. [18] proposed the method of utilizing coordinate transformation to obtain directive emission. Yang [19] proposed an approach to design multibeam antennas using the finite embedded optical transformation. However, fabrication of the antenna based on the coordinate transformation approach can hardly be achieved, since the metamaterials with complex space variant dielectric properties are very difficult to realize.

In this paper, we propose an approach to design the high directive antennas using the MENZ metamaterials. At first, the simulation model is presented, and the impacts of dielectric properties of the MENZ metamaterials on the performance of the designed antenna are simulated and analyzed. Then, influences of the thickness, the position of the line source and the surface shape of the slab on the radiation pattern of the antenna are investigated in detail. At last, we show the application of the MENZ metamaterials in the design of antenna array using line source excitations. Due to MENZ metamaterials may be found naturally at infrared and optical frequencies [20], comparing with coordinate transformation approach, the fabrication of high directive antenna based on MENZ metamaterials is more preferable.

2. Simulation Model

Fig.1 shows the simulating model. Light grey region denotes the MENZ metamaterial slab. In all the following simulations, the length l of the slab is 1m and a transverse-electric (TE) polarized line source located at the right side of the slab is used to excite the electromagnetic wave at 2 GHz. The computational domain is surrounded by the perfectly matched layer (PML) which is used to simulate the absorbing boundary conditions. The permittivity and permeability of the MENZ metamaterial are denoted as ε_z and μ_z, respectively. The impact of ε_z and μ_z on the directivity of the slab antenna was investigated. The normalized far-field is shown in Fig. 2. It indicates that decreasing the values of ε_z and μ_z will results in an improvement of the directivity of the of the slab antenna. When ε_z and μ_z are less than 10^{-3}, the variation of the far-field becomes stable. Therefore, in this study, we use $\varepsilon_z = \mu_z = 10^{-4}$ for simulating the MENZ metamaterial-assisted slab antenna. The simulation is performed using the finite-element software COMSOL MULTIPHYSICS.

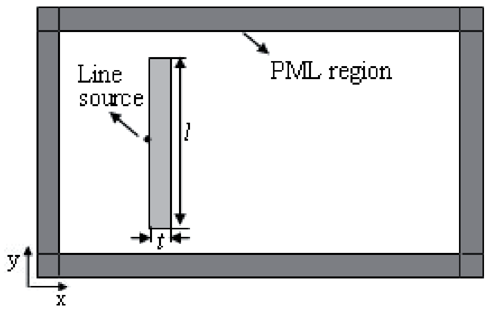

Fig. 1. Simulating model of the MENZ metamaterial-assisted slab antenna.

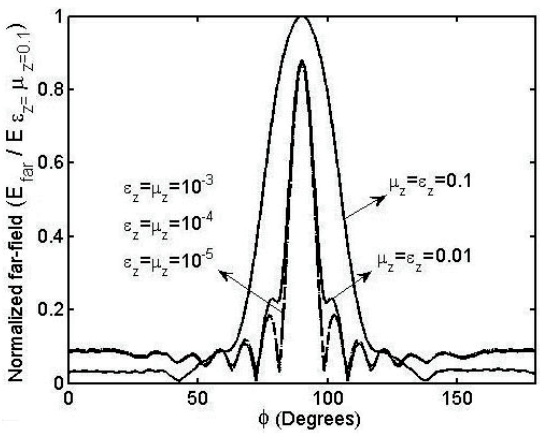

Fig. 2. Normalized far-field of the MENZ metamaterial-assisted slab antenna for different values of ε_z and μ_z. All curves are normalized to the far-field intensity of the antenna when $\varepsilon_z = \mu_z = 0.1$.

3. Numerical Results and Discussion

3.1 Performance of the MENZ Metamaterial-Assisted Slab Antenna

Fig. 3 (a) shows the near-field distribution of the slab antenna, of which the thickness t is 0.1 m, and the line source is located at the center of the left boundary. As the thickness of the slab is reduced to 0.02 m, the near-field distribution remains similar as shown in Fig. 3(b). Fig. 3(c) and 3(d) show that when the line source is scanned along the entrance side of the slab, the near-field distribution is exactly the same.

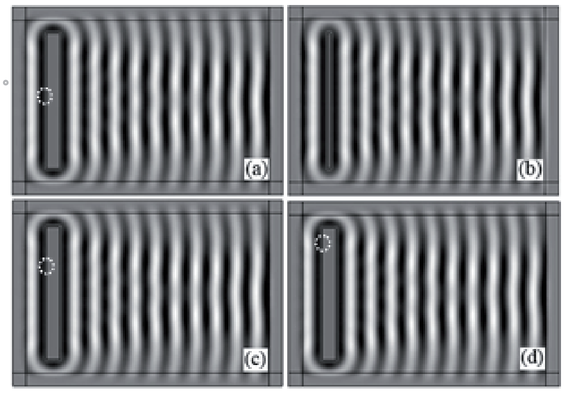

Fig. 3. Ez distribution when the antenna is excited by z-polarized TE wave. **(a)** t=0.1 m and the line source is located at the center of the entrance side of the slab. **(b)** t=0.02 m and the line source is located at the center of the entrance side of the slab. **(c)** t=0.1 m and the line source is located 0.2 m away from the center. **(d)** t=0.1 m and the line source is located 0.4 m away from the center. The zone delimited by the dotted line denotes to the position of the line source.

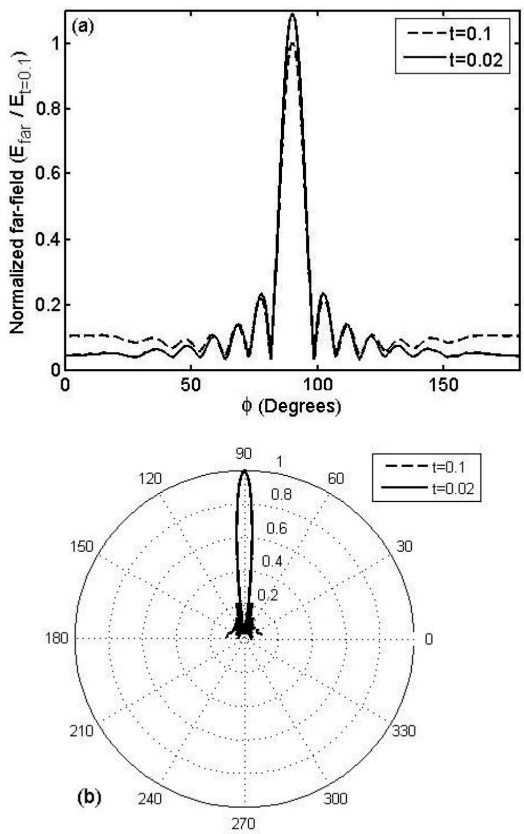

Fig. 4. **(a)** Normalized far-field for the antenna with the slab in different thickness. All curves are normalized to the far-field intensity of the antenna with the slab in the thickness of 0.1 m. **(b)** Directivity patterns.

The influences of the thickness of the slab on the normalized far-field intensity and the directivity patterns of the antenna are shown in Fig. 4. From Fig. 4(a), we find that the thin slab can give rise to stronger far-field intensity than that of the thick slab. Fig. 4(b) shows that the directivity of the antenna is independent on the thickness of the slab. This is in good agreement with literature results shown in Ref.[18], where coordinate transformation method is applied to design the slab antenna with high directive emission. Besides, we find that the position of the line source doesn't have any influence on the normalized far-field intensity and the directivity of the antenna as long as it is located along the entrance side of the slab. Therefore, the design of slab antenna based on MENZ metamaterials becomes very flexible, as it does not have thickness restriction and line source position restriction.

3.2 Impact of Surface Shape of Slab on the Performance of Antenna

The previous section shows the effectiveness of the application of MENZ metamaterials in the design of high directive antenna. To understand the response of the MENZ slab to line source excitation, the performance of the antenna with more complex slab structure is studied. Fig. 5(a) and 5(b) show the near-field distribution for the structure in which the entrance face of the slab is curved with grooves in the shape of semicircle and rectangular, respectively. The line source is positioned at the center of the groove. From these figures, we can clearly observe that the cylindrical waves emitted from the line sources at the entrance side with different surface shape are transformed perfectly to plane waves at the exit side, that is, the phase pattern at the exit side of the MENZ slab is independent on the surface shape of the entrance side. When the cylindrical wave emitted from the line source transmitted through a MENZ slab with concave exit face, the near-field distribution is shown in Fig. 5(c). When illuminated by plane wave, the response of such structure is shown in Fig. 5(d). It is seen that the wave front of an incident arbitrary wave at the output region can be tailored by the exit face shape of the MENZ slab. This phenomenon can be elucidated as follows.

When electromagnetic waves propagate in homogeneous and passive medium, wave vector is $k = \omega(\varepsilon\mu)^{1/2} = 2\pi/\lambda = \omega/v$. If ε and μ approach zero, then, λ and v approach infinite. The wavelength λ in such MENZ metamaterials is extremely large compared to the free-space wavelength λ_0. If somehow we manage to couple electromagnetic energy into the slab made of such material, the phase front at the exit side should conform to the shape of the exit face, since there is essentially no phase variation in the wave propagation inside the material. This implies that, in principle, with the use of such MENZ metamaterials, we can manipulate a given impinging phase front and transform its phase distribution into a desired shape by properly tailoring the exit side of the slab [1]. This may have important applications in wireless communications and radar technology.

The normalized far-field intensity for the antenna of which the entrance face of the slab is curved with groove in different shape is compared with that of the antenna with planar slab, as shown in Fig. 6. It indicates that the far-field intensity of the antenna can be strengthened by changing the surface shape of the entrance side of the MENZ slab. It is worth noting that when the entrance face of the slab is curved with groove in the shape of a semicircle or rectangular, the far-field intensity is more than two times that the antenna with planar surface. Therefore, we can conclude that although the phase pattern in the output region of the slab is independent on the shape of the entrance face, grooved entrance face will result in stronger far-field intensity. The mechanism of this phenomenon is not understood and remains the subject of our future work.

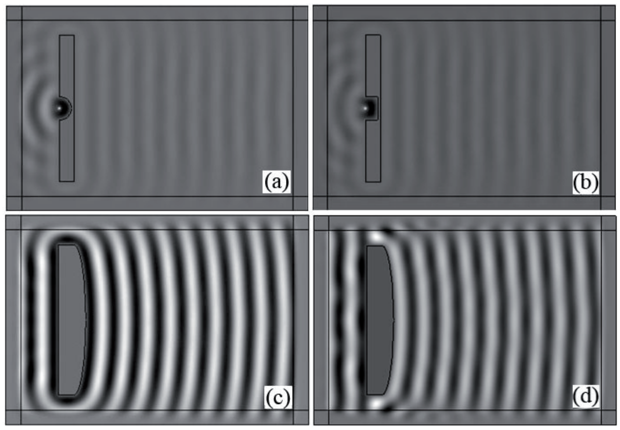

Fig. 5. Ez distribution of the antenna. **(a)** The entrance face is curved with a groove in the shape of a semicircle with radius r=0.08 m. **(b)** The entrance face is curved with a groove in the shape of a rectangular in the size of 0.08 m x 0.16 m. **(c)** The slab with a concave exit face excited by a line source. **(d)** The slab with a concave exit face illuminated by plane wave.

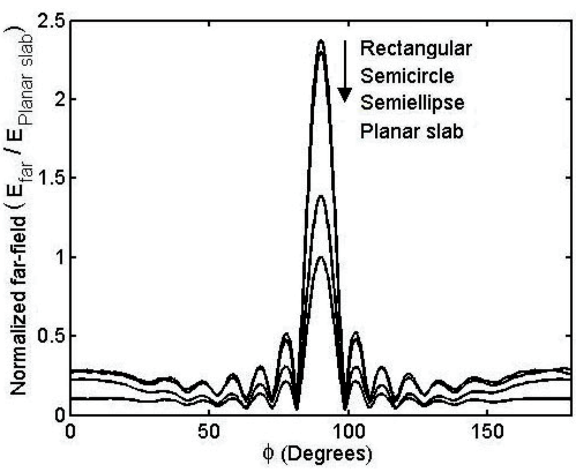

Fig. 6. Normalized far-field for the antenna of which the entrance face of the slab is in different shape. All curves are normalized to the far-field intensity of the antenna with planar slab.

3.3 Antenna Array Based on MENZ Metamaterials

In order to further explore the application of MENZ metamaterials in antenna technology, we analyzed the radiation pattern of the slab antenna arrays. We suppose that the excitation current of the slab antenna is I, and the excitation current of each line source of the slab antenna arrays with two, three,…, and N elements is $I/\sqrt{2}$, $I/\sqrt{3}$,…, and $I/\sqrt{N}$. In this study, the antenna arrays with at most four elements are simulated. The near-field distributions are shown in Fig. 7. The distance between two adjacent line sources is 1.2λ. It can be seen that cylinder wave emitted from the line source or line source arrays can be transformed perfectly to plane wave at the exit side of the slab, that is, wave pattern in the output region is independent on the number of excitations at the entrance side. Corresponding normalized far-field of the antenna arrays is shown in Fig. 8. It indicates that far-field intensity of the antenna with N line source is about $\sqrt{N}$ times that of the slab antenna with a single line source. This is in good agreement with the antenna array theory [21]. It shows that the MENZ metamaterials can also be applied in the design of antenna array.

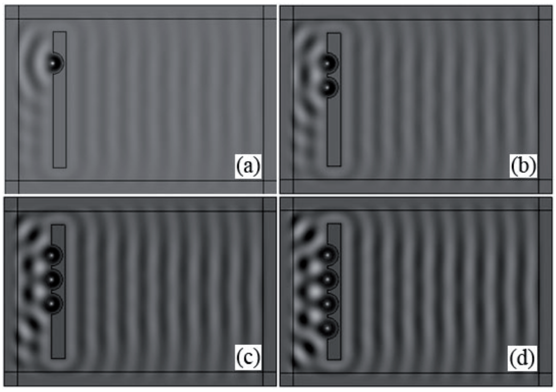

Fig. 7. Ez distribution of the slab antenna and antenna arrays. (a), (b), (c) and (d) correspond to Ez distributions of the slab antenna with one line source, two, three and four line sources, respectively.

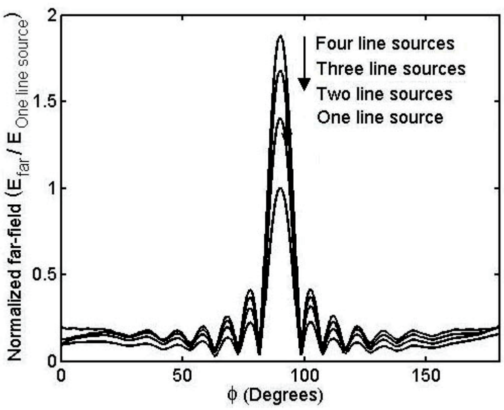

Fig. 8. Normalized far-field for the slab antenna, and antenna arrays. All curves are normalized to the far-field intensity of the slab antenna with one line source.

4. Conclusions

In this work, the application of the MENZ metamaterials in the design of high directive slab antenna is proposed. The performance of the MENZ metamaterial-assisted slab antenna is simulated and analyzed in detail. Results show that the directivity pattern of the designed antenna is independent on the thickness of the slab, the location of the line source, and the shape of the entrance face of the slab. The far-field intensity of the antenna can be greatly strengthened by curving the entrance face of the cavity with small rectangular groove. In addition, we show that the MENZ metamaterials can also be applied to the design of antenna array. The antenna based on the MENZ metamaterials may have important applications in wireless communications and radar technology.

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