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# ENHANCEMENT OF RADIATION PROPERTIES OF A COMPACT PLANAR ANTENNA USING TRANSFORMATION MEDIA AS SUBSTRATES

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**Abstract**—In this paper we study the behavior of wave radiation of a horizontal electric dipole antenna with grounded metamaterial substrates formed by using coordinate transformation technology. From theoretical analysis and simulation results, we can find that such metamaterial substrates not only improve the directive emission but also enhance the radiation efficiency as the dipole antenna gets closer and closer to the metallic ground plane. We thus demonstrate that the transformation medium can offer a theoretical basis for designing a compact planar antenna with transformation media as substrates.

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## 1. INTRODUCTION

When a metal ground plane is used as antenna reflector, it should be placed at a distance of a quarter wavelength away from the horizontal antenna to achieve maximum power density efficiency [1]. In many applications, as the antenna approaches the metallic ground plane, its performance unavoidably becomes worse mainly due to the fact that the finite metallic reflector often supports surface waves and certain edge effects, and the out-of-phase image is formed, which degrades the radiation pattern of the antenna. Therefore, it has received much attention for many years in the antenna community. For example, in many applications of radio frequency identification (RFID) [2–9], metallic objects need to be tagged and identified. However, typical label-fabricated RFID tags do not work well when attached to metallic objects.

Currently, three methods can be used to solve the problem. The first is to design the structure of the antenna directly [7]. The second is to adopt a high impedance ground plane (HIGP) as the effective substrates to suppress the surface modes on a conventional metallic ground plane, which was firstly proposed by Sievenpiper [10], and has been studying by many researchers [11, 12] and now is widely used to data and voice transmission, such as cell-phone and GPS. When the mushroom-like HIGP operating at 2.45 GHz is used, the thickness of the high impedance surface $t$ is 2–3 mm. If let $t$ be smaller, then the bandwidth will decrease, at the same time, the resonance frequency will increase. The third is to use artificial materials called metamaterials as substrates to improve the radiation efficiency. In 1967, Veselago theoretically pioneered the conceptual materials with simultaneously negative permittivity and permeability [13], and the leading works of Pendry et al. [14, 15] and Shelby et al. [16] were reported in 1996, 1999, and 2001, respectively. Since then, the related research work has become a rapidly growing field [17, 18]. The metamaterials give rise to many peculiar electromagnetic phenomena and potential applications. Naturally, metamaterials have been applied to the area of antenna systems [19–22]. For instance, near-zero refractive index or epsilon-near-zero metamaterials can effectively improve the directivity of the antenna or tailor the radiation phase pattern [23].

At present, what should be the electromagnetic characteristic of the metamaterial substrates and how to design the very thin substrates are still concerned by many researchers all over the world. In the present paper, we would like to use the transformation medium concept [24, 25] to explorethe physical properties of a compact planar antenna with transformation media as substrates.

## 2. THEORETICAL ANALYSIS

When a horizontal electric dipole is close to the metallic ground plane, the electromagnetic wave is reflected almost entirely by the metallic surface, and this greatly degrades the radiation power. In order to improve the radiation power, the transformation media as substrates are studied in details.

Here consider a transformation from an original Cartesian space $(x, y, z)$ to a new Cartesian space $(x', y', z')$ characterized by $x' = x'(x, y, z)$, $y' = y'(x, y, z)$, and $z' = z'(x, y, z)$, the Jacobian tensor between the two coordinate systems can be written as:

$$\overline{\overline{J}} = \frac{\partial(x', y', z')}{\partial(x, y, z)} = \begin{pmatrix} \dfrac{\partial x'}{\partial x} & \dfrac{\partial x'}{\partial y} & \dfrac{\partial x'}{\partial z} \\ \dfrac{\partial y'}{\partial x} & \dfrac{\partial y'}{\partial y} & \dfrac{\partial y'}{\partial z} \\ \dfrac{\partial z'}{\partial x} & \dfrac{\partial z'}{\partial y} & \dfrac{\partial z'}{\partial z} \end{pmatrix}, \tag{1}$$

and the relative permittivity and permeability tensors $\overline{\overline{\varepsilon}}'_r$ and $\overline{\overline{\mu}}'_r$ in the new coordinate system can be expressed by the original tensors $\overline{\overline{\varepsilon}}_r$ and $\overline{\overline{\mu}}_r$ as:

$$\overline{\overline{\varepsilon}}'_r = \frac{\overline{\overline{J}} \cdot \overline{\overline{\varepsilon}}_r \cdot \overline{\overline{J}}^T}{\det(\overline{\overline{J}})} \quad \text{and} \quad \overline{\overline{\mu}}'_r = \frac{\overline{\overline{J}} \cdot \overline{\overline{\mu}}_r \cdot \overline{\overline{J}}^T}{\det(\overline{\overline{J}})}. \tag{2}$$

Let's consider the possible design of a very thin planar antenna using such principle to enhance the radiation power. The antenna far away from the metallic ground plane which is horizontally placed in free space (the left part of Figure 1) can be transformed to be a compact planar antenna which can be mounted on the metamaterials (the right part of Figure 1). And then they should have the similar radiation patterns simply due to the transformation theory [25]. Note that the metallic ground plane is considered as a perfect electric conductor (PEC) in the microwave frequency band. For convenience, we refer to the left and right parts of Figure 1 as case 1 and case 2, respectively. Thus the metamaterial substrates can be characterized by the constitutive parameters $\overline{\overline{\varepsilon}}'_r$ and $\overline{\overline{\mu}}'_r$:

$$\overline{\overline{\varepsilon}}'_r = \overline{\overline{\mu}}'_r = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & 1/a \end{pmatrix}, \tag{3}$$

where $a = h/t$ is the compression ratio, $h$ is the height of the dipole away from the PEC and $t$ denotes the thickness of the metamaterial substrates. This metamaterial characterized by Formula (3) is called the transformation medium.

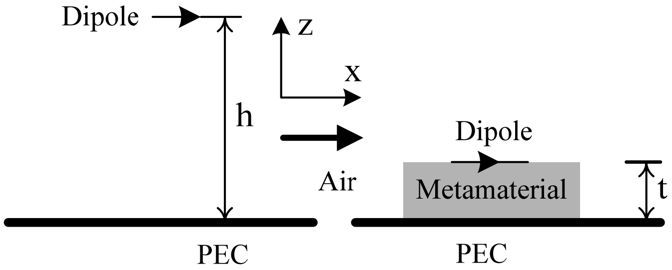


**Figure 1.** Cross section of a horizontal electric dipole placed away from the metal surface (left) and on the metamaterial surface (right), respectively.

Besides, for qualitative prediction of the radiation properties of the antenna constructed here, we employ an approximate analytical theory [26]. For $TE$ and $TM$ waves, the reflection coefficients for waves impinging on the 1D metamaterial substrates can be described respectively as:

$$R^{TE} = \frac{R_{01}^{TE} - \exp(i2tk_z^{TE})}{1 - R_{01}^{TE}\exp(i2tk_z^{TE})}, \tag{4}$$

$$R^{TM} = \frac{R_{01}^{TM} + \exp(i2tk_z^{TM})}{1 + R_{01}^{TM}\exp(i2tk_z^{TM})}, \tag{5}$$

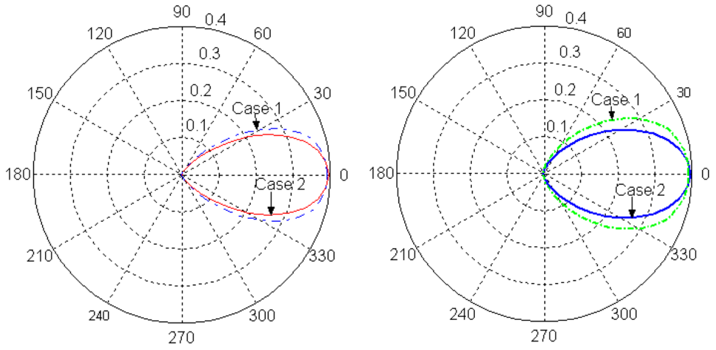
where $k_z^{TE} = \sqrt{\varepsilon_{rt}\mu_{rz} - \sin^2\theta}\sqrt{\mu_{rt}/\mu_{rz}}\omega/c$, $k_z^{TM} = \sqrt{\varepsilon_{rz}\mu_{rt} - \sin^2\theta}\times\sqrt{\varepsilon_{rt}/\varepsilon_{rz}}\omega/c$, $\varepsilon_{rz} = \mu_{rz} = 1/a$, $\varepsilon_{rt} = \mu_{rt} = a$, $c = 3\times10^8$ m/s, and the elements $R_{01}^{TE}$ and $R_{01}^{TM}$ have the following forms:

$$R_{01}^{TE} = \frac{1 - k_z^{TE}c/(\omega\mu_{rt}\cos\theta)}{1 + k_z^{TE}c/(\omega\mu_{rt}\cos\theta)}, \tag{6}$$

$$R_{01}^{TM} = \frac{1 - k_z^{TM}c/(\omega\varepsilon_{rt}\cos\theta)}{1 + k_z^{TM}c/(\omega\varepsilon_{rt}\cos\theta)}, \tag{7}$$

$$P_E = \left|1 + R^{TE}\right|^2 \quad \text{and} \quad P_H = \left|1 + R^{TM}\right|^2, \tag{8}$$

where $P_E$ and $P_H$ are proportional to the power density in the $E$ and $H$ planes respectively, therefore the radiation pattern can be characterized qualitatively by the quantities $P_E$ and $P_H$.



(a) (b)

**Figure 2.** Comparison of radiation patterns in the $E$ plane ($\phi = 0°$) (a) and $H$ plane ($\phi = 90°$) (b) between case 1 and case 2, respectively.

## 3. NUMERICAL RESULTS AND DISCUSSION

As a specific example, we explore the radiation efficiency of the constructed antenna. To simplify the analysis, we assume that the transformation medium is a linear and homogenous material with $\overline{\overline{\varepsilon}}'_r$ and $\overline{\overline{\mu}}'_r$ tensors in Formula (3). If $t$ is assumed to be 1 mm and $h$ is 10 mm, then the air medium is compressed 10 times in the $\hat{z}$ direction. Full-wave FDTD simulation using CST studio suite [27] is employed to verify the validity of transformation medium. During the simulating process, the input power is set up to be 1 W, the far-field pattern of the power density at 2.45 GHz in linear scale is measured at a radius of 1 m with respect to the center of a $\lambda/2$ dipole, the transverse size of the metamaterial substrates is $1\lambda \times 1\lambda$, and the transverse size of the metallic ground plane is $2\lambda \times 2\lambda$. Notice that the wavelength $\lambda$ is calculated in air at 2.45 GHz. The simulation results are shown in Figure 2. At the same time, the performance parameters are also shown in Tables 1 and 2 for convenient comparison. It is clearly seen that the radiation pattern of case 1 is very similar to that of case 2, and the results confirm that case 1 is approximately equivalent to case 2 from the theoretical point of view. To further illustrate the conclusion, we find that for case 1, the maximum radiation power density and directivity are $\sim$0.392 VA/m$^2$ which is $\sim$77% of the maximum radiation power density at $h = \lambda/4$ and 8.48 dBi, respectively, and for case 2, they are $\sim$0.396 VA/m$^2$ and 9.652 dBi, respectively.

The essential reason of the differences, as we understand, is presented as follows. Case 1 is equivalent to case 2 just when the $x$-$y$

**Table 1.** Comparison of performance parameters in the $E$ plane.

| Performance parameters | Case 1 | Case 2 |
|---|---|---|
| Main lobe | 0.392VA/m$^2$, 0° | 0.396VA/m$^2$, 0° |
| Angular width | 69.3° | 61.3° |
| Side lobe level | -24.1dB | -24.9dB |

**Table 2.** Comparison of performance parameters in the $H$ plane.

| Performance parameters | Case 1 | Case 2 |
|---|---|---|
| Main lobe | 0.392VA/m$^2$, 0° | 0.396VA/m$^2$, 0° |
| Angular width | 86.8° | 69.9° |
| Side lobe level | -24.8dB | -26.7dB |

**Table 3.** Performance parameters for case 1 when $h = 1\,\text{mm}$.

| Performance parameters | E plane | H plane |
|---|---|---|
| Main lobe | 0.005VA/m2, 0° | 0.005VA/m2, 0° |
| Angular width | 67.2° | 84.5° |
| Side lobe level | -23.4dB | -25.9dB |

plane is supposed to be infinity. However, in our actual simulation, the finite size of the $x$-$y$ plane and the edge effects are taken into account. Moreover, from Figure 2, the radiation direction of the maximum radiation power density appears in the $\hat{z}$ direction for the two cases.

Meanwhile, the radiation pattern for case 1 when $h = 1\,\text{mm}$ is also simulated (Figure 3). The performance parameters are shown in Table 3. This case is equivalent to case 2 when the metamaterial substrates are replaced by air. Compared with case 2 in Figure 2, it is concluded that the maximum radiation power density and directivity can be enhanced about $\sim$78-folds and $\sim$1.17 dBi respectively. Therefore, the transformation medium can enhance the radiation efficiency of the antenna when it is in the vicinity of the metallic ground plane. Note that the discrepancy between case 1 ($h = 1\,\text{mm}$) and case 2 in Figure 2 increases when the compression rate is increased or the transverse size of the transformation media is decreased, this is because the edge effects become more dominant.

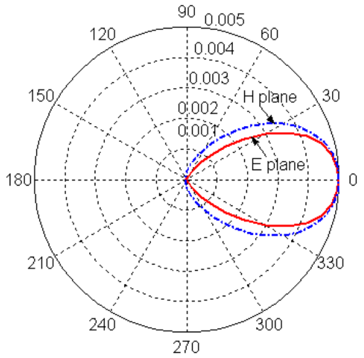
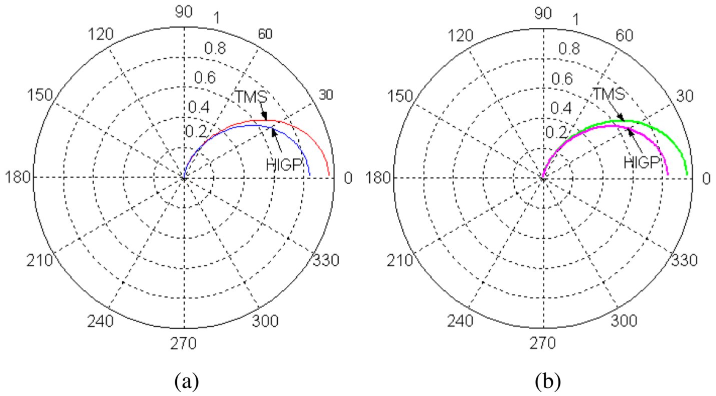


**Figure 3.** Radiation patterns in $E$ and $H$ planes for case 1 in which $h$ is 1 mm.



(a) (b)

**Figure 4.** Comparison of radiation patterns in $E$ (a) and $H$ (b) planes between TMS and HIGP.

Since the HIGP can be, to a certain extent, considered as an artificial magnetic conductor (AMC) [28], the image currents are in-phase and it can also enhance the radiation efficiency of the antenna mountable on metal plates. It is of interest to compare the radiation performance between the HIGP and transformation medium surface (TMS). For comparison, $\varepsilon_r'$ and $\mu_r'$ of the isotropic HIGP are chosen to 0.1 and 10, and $\overline{\overline{\varepsilon}}_r'$ and $\overline{\overline{\mu}}_r'$ of the transformation medium are also decided according to Formula (3) in which $a$ is 10. In addition, $h$ is equal to 1 mm and the other parameters are unchanged. Thus, the numerical results using the formula (8) are shown in Figure 4. We can see that there exists the similarity and the two cases offer better patterns. However, the radiation efficiency of the TMS is better than that of the HIGP. It should be mentioned that the theoretical results are also consistent with the CST simulation results on the whole.

## 4. CONCLUSION

In conclusion, a detailed investigation has been done on radiation patterns of a horizontal electric dipole with transformation media as antenna substrates. The results presented here show that it is possible to design the compact planar antenna with metamaterial substrates. The expected radiation pattern and efficiency enhancement can be achieved by choosing a suitable compression rate through which the fundamental characteristic of the metamaterial substrates can be determined. Hence the transformation medium concept is useful for designing this compact planar antenna which can be close to the metallic objects.

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