TRANSMISSION PHASE CHARACTERIZATIONS OF METAMATERIAL COVERS FOR ANTENNA APPLICATION

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Abstract—Metamaterial covers exhibit inimitable electromagnetic properties which make them popular in antenna engineering. A traditional metamaterial cover has an identical transmission phase for a normally incident plane wave regardless of its polarization state. The purpose of this research is to show the possibility of using a polarization dependent metamaterial cover to change the polarization state of the incident plane wave. Novel polarization-dependent metamaterial (PDMTM) covers, whose transmission phases for two principal polarizations are different, are presented. A full-wave FDTD numerical technique developed by the authors is adopted for the simulations.

1. INTRODUCTION

Due to their interesting features, metamaterial covers have been widely used in antenna engineering [1–5]. Two important features of metamaterial covers are increasing of the transmission rate and control of the direction of the transmission which enable one to design directive antennas. However, a considerable part of research at microwave frequencies is focused on isotropic metamaterial covers that are independent on polarization states. Polarization-dependent surfaces have recently found useful applications in changing the polarization state of the incident wave [6–9]. For a traditional metamaterial cover, the transmission phase remains the same regardless of the x- or y-polarization state of the incident plane wave. In contrast, the transmission phase of a PDMTM cover is a function of both frequency and polarization state. Hence, when a PDMTM cover is employed

as a director, the polarization state of the transmitted wave is fully characterized by the transmission phase difference between the x- and y-polarizations and the polarization state of the incident wave. And thus a proper phase difference between x- and y-polarized waves leads to a desired change in the polarization state of the transmitted wave.

Directive circularly polarized antennas are widely used in satellite communication systems. To obtain directive circularly polarized antenna, various types of metamaterial antenna have been proposed in the literature [10–13]. It was demonstrated in [10, 11] that the directive circularly polarized antenna can be realized by metamaterial antenna with a circular feed. A major limitation of this method is inability to tune mechanically. In other words, the polarization state of the antenna is only determined by the feed mechanism. Directive circularly polarized antenna can be also realized using either metallic wire polarizer [12] or meander line polarizer [13] stacked on the top of the one-layer metamaterial cover.

In this paper, instead of using meander line or metallic wire polarizer, the geometry of the metamaterial cover is changed to provide circular polarization. Consequently, the second layer (polarizer layer) can be replaced with another metamaterial cover layer, which in turn results in higher directivity. Moreover, in contrast to the previous directive circularly polarized antennas [10–13], polarization state of the directive antennas using our proposed metamaterial cover can be mechanically changed regardless of the feed mechanism. In this paper a useful guideline has been established as how to use the magnitude and phase of the transmission coefficient to identify the operational frequency band of the directive circularly polarized antennas based on polarization dependent metamaterial covers.

2. POLARIZATION DEPENDENT METAMATERIAL COVER DESIGNS

As a starting point, we consider a two-layer metallic grid placed on top of the patch antenna backed by a ground plane. A schematic of the metamaterial cover with square holes is shown in Figure 1. The simulations have been carried out to examine the transmission characteristic of the metamaterial cover, without the ground plane and without the antenna, using FDTD code developed by the authors. Figure 2 shows an effective unit cell model of the metamaterial cover which takes into account the image effect of the ground plane. This unit cell is a convenient method of computing of the transmission coefficient of a two layer metamaterial cover placed on top of the patch antenna backed by a ground plane. The normalization in the
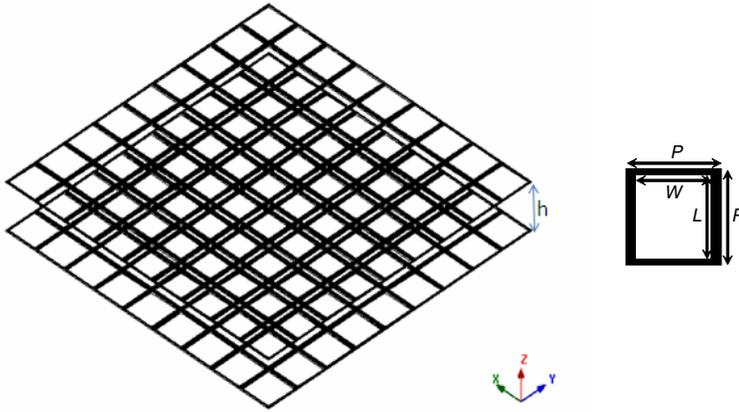
Figure 1. Schematic view of two layer metamaterial cover together with its unit cell.
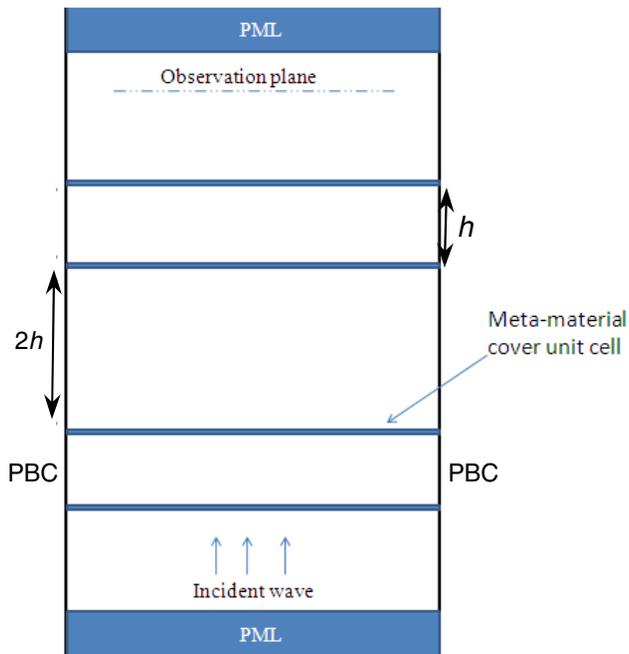
Figure 2. FDTD model for metamaterial cover analysis.

code consists of choosing the peak magnitude of the transmission coefficient to be unity. Therefore, the magnitude of the transmitted field from the metamaterial cover has been normalized to that without the metamaterial cover. We have used the same methodology applied in the measurements [2]. The periodic boundary conditions (PBCs) have been also applied to model an infinite periodic replication. When a plane wave normally impinges upon a metamaterial cover, the phase and magnitude of the transmitted wave change with frequency. In order to illustrate the polarization feature of the PDMTM cover, we assume that a left-hand circularly polarized (LHCP) wave, namely, $E^i = \overrightarrow{a_x}e^{-jkz} + j\overrightarrow{a_y}e^{-jkz}$ where k is the free-space wavenumber, is normally impinged upon a director placed in X-Y plane. The field transmitted through the director can be easily calculated from the following equation:

$$E^t = e^{-jkz}e^{j\theta_x}(\overrightarrow{a_x} + j\overrightarrow{a_y}e^{j(\theta_y-\theta_x)}) \tag{1}$$

The above field can be decomposed into two circularly polarized components

$$E^t = e^{-jkz}e^{j\theta x}\left[\overrightarrow{e_r}\left(\frac{1-e^{j(\theta_y-\theta_x)}}{\sqrt{2}}\right) + \overrightarrow{e_l}\left(\frac{1+e^{j(\theta_y-\theta_x)}}{\sqrt{2}}\right)\right] \tag{2}$$

where

$$\vec{e_l} = \frac{(\overrightarrow{a_x} + j\overrightarrow{a_y})}{\sqrt{2}}, \quad \overrightarrow{e_r} = \frac{(\overrightarrow{a_x} - j\overrightarrow{a_y})}{\sqrt{2}}$$

and θ_x and θ_y denote the transmission phases for the x- and y-polarized waves, respectively. For a traditional metamaterial cover $(\theta_y - \theta_x = 0)$, the transmitted wave is purely LHCP and thus the polarization sense does not change. In order to change the polarization state of the antenna, the PDMTM cover can be used as a director. At a certain frequency where phase difference is $180°$ and transmission is considerable, the transmitted wave is purely right-hand circularly polarized (RHCP). The left-hand circularly polarized incident wave can be also converted to the linearly polarized (LP) wave where the phase difference is $90°$ and the transmission is also considerable. One can follow the same procedure for the linearly polarized incident wave, $E^i = \overrightarrow{a_x}e^{-jkz} + \overrightarrow{a_y}e^{-jkz}$, so that the transmitted field then becomes:

$$E^t = \overrightarrow{a_x}e^{-j(kz-\theta_x)} + \overrightarrow{a_y}e^{-j(kz-\theta_y)}$$

$$= e^{-jkz}e^{j\theta x}\left[\overrightarrow{e_r}\left(\frac{1+e^{j(\theta_y-\theta_x+\pi/2)}}{\sqrt{2}}\right) + \overrightarrow{e_l}\left(\frac{1-e^{j(\theta_y-\theta_x+\pi/2)}}{\sqrt{2}}\right)\right] \tag{3}$$

Consequently the radiation mechanism of the linearly polarized antenna with metamaterial cover is conceptually described by

Equation (3). For an isotropic metamaterial cover, the phase difference between two orthogonal polarizations is zero and thus the polarization state does not change. An interesting feature of the PDMTM covers can be revealed by a closer investigation. When a PDMTM cover with 90° transmission phase difference is used as a director, the polarization state of the transmitted wave becomes LHCP. Moreover, when the phase difference is −90° the polarization state of the transmitted wave is RHCP. Consequently we can easily switch between LHCP and RHCP using a rotatory cover, which can be rotated smoothly with a 90° steps. Based on above discussion, one can conclude that the metamaterial cover can be used as a changing polarization plane. The operational frequency band of an antenna with PDMTM cover is defined as the frequency region within which the magnitudes of the transmission coefficients for both x- and y-polarized waves are close to their maximum values and transmission phase difference is desired. This interesting feature has been realized by changing the unit cell geometry, such as cutting rectangular holes instead of square holes and changing the relative height difference between the x- and y-directed strips of each layer.

3. RECTANGULAR HOLE METAMATERIAL COVER

The traditional metamaterial cover uses symmetric square holes so that its transmission phase for normal incidence remains the same regardless of the x- or y-polarization state of the incident plane wave. Therefore, the logical thought is to replace the square holes by rectangular ones. First, the design parameters of the metamaterial cover are selected
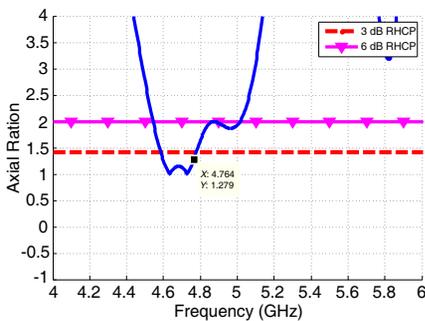
Figure 3. Axial ratio of the transmitted plane wave from the rectangular hole metamaterial cover.
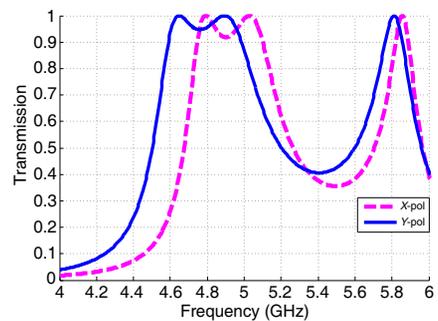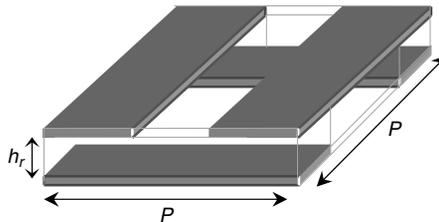
Figure 4. FDTD simulated transmission of the rectangular hole metamaterial cover.

to have a reasonable transmission at a specified frequency. The effect of different design parameters of the metamaterial cover on the magnitude of the transmission coefficient can be found in [4]. After the successful design of the isotropic metamaterial cover, the width or/and length of the square holes are changed to obtain both the desired transmission phase difference and the maximum transmission within the specified frequency band. When the hole width is increased, the plasma frequencies [2] shift down to the lower frequencies. Thus, by adjusting the width and length of the rectangular hole, the polarization sense of the transmitted wave can be changed. An example design for these parameters is as follows: $h = 24.5\,\text{mm}$, $P = 20.5\,\text{mm}$, $L = 17.5\,\text{mm}$, $W = 16.5\,\text{mm}$. For a linearly polarized antenna, namely $E^i = \vec{a_x}e^{-jkz} + \vec{a_y}e^{-jkz}$, the axial ratio of the transmitted wave is plotted in Figure 3. Also, Figure 4 shows the transmission curve for both x- and y-polarized incident plane waves. The frequency band inside which the axial ratio of the RHCP transmitted wave is below $6\,\text{dB}$ and the magnitudes of the transmission coefficients for both the x- and y-polarized incident waves are more than 90% ranges from $4.75\,\text{GHz}$ to $5\,\text{GHz}$ (5.12%).
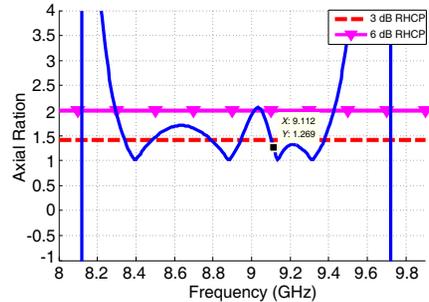
4. METAMATERIAL COVER WITH NONPLANAR STRIPS

Another approach to realize PDMTM covers is to add space between the x- and y-directed strips of each layer, as shown in Figure 5. For a traditional metamaterial cover, the x-directed strip is located on the same plane as the y-directed strip. For the nonplanar case discussed here the dimensions are chosen as follows: $L = W = 13.5\,\text{mm}$, $P = 18.5\,\text{mm}$, $h = 27.5\,\text{mm}$, $h_{r1} = 3.5\,\text{mm}$, and $h_{r2} = 7\,\text{mm}$, where h_{r1} denotes the relative height between the x- and y-directed strips of the first layer and h_{r2} denotes the same height for the second layer. Figure 6 shows the magnitudes of the transmission coefficients for both x- and y-polarized waves. The axial ratio of the wave radiated

Figure 5. A unit cell of metamaterial cover with offset strips.
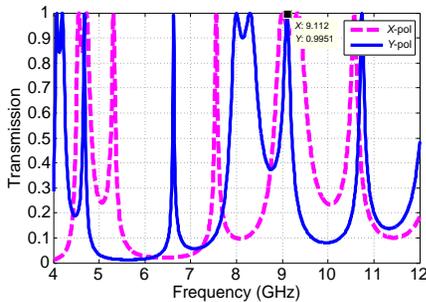
Figure 6. FDTD simulated transmission of the metamaterial cover with offset strips.

Figure 7. Axial ratio of the transmitted plane wave from the metamaterial cover with nonplanar strips.

from linearly polarized antenna is also plotted in Figure 7. It can be seen from Figures 6–7, that the operating frequency of the proposed structure is around 9.1 GHz where the metamaterial cover has both the desired transmission phase difference and the remarkable transmission.

The FDTD simulated results presented in this paper confirm the concepts of the proposed approach to control both the direction and the polarization of the transmitted wave. The authors believe that the proposed cover can find many applications in the broad electromagnetic areas such as antenna engineering and optical sources. However, a rigorous characterization should take into account the complex interactions between the antenna and the metamaterial cover, such as finite size of the ground plane and the antenna height. Consequently, it is indispensable to use full wave analysis method, such as the finite difference time domain (FDTD), in the antenna designs in order to obtain accurate results.

5. CONCLUSION

In this paper, the possibility of having both polarization diversity and directive emission has been investigated. Two novel polarization dependent metamaterial covers have been presented, including rectangular-hole metamaterial cover, and metamaterial cover with offset strips. The transmission phases were simulated using the FDTD method, and the phase difference between the x- and y-polarized incident plane waves was recorded as a function of frequency. It was illustrated that the proposed PDMTM covers can not only increase the transmission rate, but also at the same time can provide reconfigurable

polarizations. The directive circularly polarized antenna can be easily designed based on the engineering guidelines presented in this paper.

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