Progress In Electromagnetics Research M, Vol. 16, 159–169, 2011

DESIGN OF A PERFECT ELECTROMAGNETIC CONDUCTOR (PEMC) BOUNDARY BY USING PERIODIC PATCHES

H. M. El-Maghrabi

Housing and Building National Research Center, Giza, Egypt

A. M. Attiya

Electronics Research Institute, Giza, Egypt

E. A. Hashish

Faculty of Engineering
Cairo University, Giza, Egpyt

Abstract—Perfect electromagnetic conductor (PEMC) is a novel concept in electromagnetic fields of interesting properties and many potential applications. This paper introduces a new technique to design an artificial surface that has equivalent PEMC properties. The proposed PEMC boundary is based on a periodic structure composed of two conducting patches on a grounded dielectric slab. One of them is embedded inside the substrate and the other lies on the surface of the substrate. A conducting via is used to connect the two patches. In the resulting PEMC boundary, the polarization of the reflected wave is controlled by the tilting angle between the two patches.

1. INTRODUCTION

Lindell and Sihvola introduced a novel concept of a perfect electromagnetic boundary (PEMC) as a generalization for perfect electric (PEC) and the perfect magnetic (PMC) boundaries [1–7]. The electric and magnetic fields at this new boundary are related by [1]:

$$\mathbf{n} \times (\mathbf{H} + M\mathbf{E}) = 0 \tag{1a}$$

$$\mathbf{n} \cdot (\mathbf{D} - M\mathbf{B}) = 0 \tag{1b}$$

Received 22 November 2010, Accepted 6 January 2011, Scheduled 15 January 2011
Corresponding author: Ahmed M. Attiya (aattiya@ksu.edu.sa).

where **n** is the unit vector normal to the surface of the PEMC and M represents the admittance parameter of the PEMC in Ω^{-1}. In the limiting cases where $M \to \pm\infty$, the PEMC boundary corresponds to a PEC boundary where $\mathbf{n} \times \mathbf{E} = 0$ and $\mathbf{n} \cdot \mathbf{H} = 0$. On the other hand, at $M \to 0$, the PEMC boundary corresponds to a PMC boundary where $\mathbf{n} \times \mathbf{H} = 0$ and $\mathbf{n} \cdot \mathbf{E} = 0$. For a normally incident plane wave, Equation (1) can be rewritten as:

$$(\mathbf{H} + M\mathbf{E}) = 0 \tag{2}$$

which means that total **E** and **H** fields are related linearly through an equivalent admittance parameter M at the boundary. This property introduces polarization rotation in the reflected field with respect to the incident field as shown in Figure 1 [3]. The angle of this polarization rotation is related to the admittance parameter M as follows [7]:

$$\theta_p = 2\tan^{-1}(M\eta_0) \tag{3}$$

where η_0 is the characteristic impedance of the surrounding medium which is free space in the present case.

Different approaches are discussed to implement this PEMC boundary. Lindell and Sihvola introduced a structure composed of an array of conducting and ferrite cylinders embedded in a dielectric medium [2], as a tentative implementation of a PEMC boundary. To operate as a PEMC boundary, this structure must satisfy the conditions $\varepsilon_{zz} = \infty$ and $\mu_{zz} = \infty$, respectively, where z is the coordinate parallel to the axes of the rods and is also the normal direction on the PEMC boundary. To obtain this magnetic permeability, a static bias field H_0 is required to bias the ferrite rods. Another approach for implementing a PEMC boundary is introduced in [8, 9] by using a grounded ferrite slab. This ferrite slab introduces Faraday rotation which is equivalent to PEMC effect. However, this approach requires biasing magnetic field as the previous one.

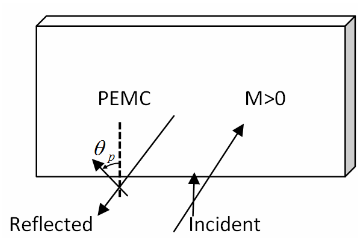


Figure 1. The polarization of reflected wave due to a PEMC boundary is rotated by an angle θ_p with respect to the polarization of the incident wave [6].

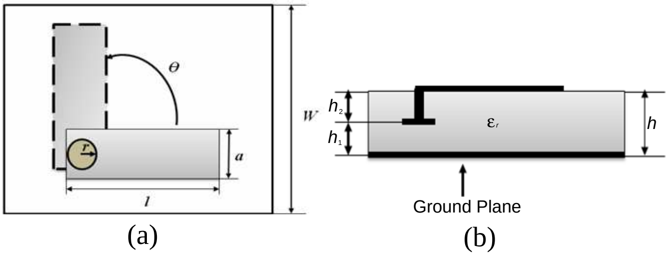


Figure 2. Geometry of a unit cell of the proposed PEMC surface. (a) Top view. (b) Side view.

On the other hand, extensive studies are presented for introducing orthogonal polarization rotating surfaces based on two cascaded reflecting surfaces [10–16]. As an example for these surfaces, periodic slots above a grounded dielectric slab where the slots are tilted by an angle 45 degrees with respect to the periodicity axes. In this paper we introduce a modification on polarization rotating reflected surfaces to realize a PEMC boundary. The proposed structure is composed of an array of two conducting patches as shown in Figure 2. One of them is embedded inside the substrate and the other lies on the surface of the substrate. A conducting via are used to connect the two patches. The polarization of the reflected plane wave is controlled by the tilting angle between the two patches. The basic idea of the proposed structure is to introduce a surface that produces co-polarized and cross-polarized field components of the same phase. By adjusting the amplitudes of the co-polarized and cross-polarized components, one can adjust the tilting angle of the reflected plane wave which is equivalent to adjusting the admittance parameter M of the proposed PEMC boundary. The advantage of the proposed configuration is that it does not require additional magnetic biasing like the case of the ferrite rods and the ferrite grounded slab. In the following section we show the basic parameters of the proposed structure and numerical simulations based on Ansoft HFSS ®. The present simulation is based on periodic boundary conditions to simulate an infinite periodic structure by using a single cell.

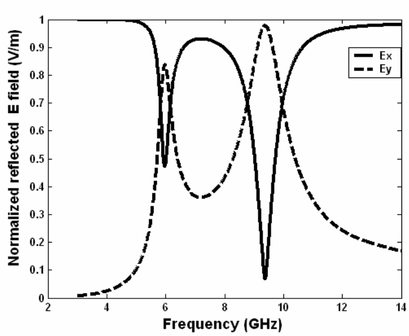
2. DESIGN OF A PEMC SURFACE

As discussed in the previous section the proposed structure is composed of two patches on a grounded dielectric slab. The suggested slab has a dielectric constant $\varepsilon_r = 3.38$ and total dielectric thickness $h = 2\,\mathrm{mm}$ where the embedded patch lies at thickness $h_1 = 1\,\mathrm{mm}$. For manufacturing purpose, this substrate is divided into two parts. The first part has the thickness $h_1 = 1\,\mathrm{mm}$ where a conducting sheet lies on its bottom surface. On the other hand, another dielectric super-strate of thickness $h_2 = 1\,\mathrm{mm}$ is etched on both sides with upper and the lower patches which are connected by using cylindrical vias. This super-strate is fixed on the lower substrate to form the complete structure. The patches are rectangular shape of length is $l = 8\,\mathrm{mm}$ and width $a = 3\,\mathrm{mm}$. The connecting via is a cylinder of radius $r = 1\,\mathrm{mm}$. These patches are arranged as an infinite periodic array of square cells with periodicity $W = 12\,\mathrm{mm}$. The tilting angle between the patches is adjusted to different values.

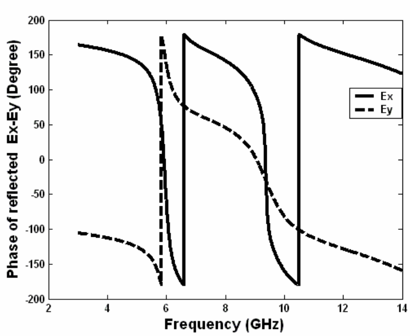
The basic idea of the present analysis is to excite the periodic unit cell by an x-linearly polarized plane wave and study the polarization of the reflected field. PEMC boundary corresponds to the case where the reflected field includes both x and y electric field components of the same phase. The tilting angle of the reflected field polarization in this case is $\theta_p = \tan^{-1}(E_{y\_ref}/E_{x\_ref})$. By using this polarization rotation angle in (3), it can be shown that normalized admittance parameter of the equivalent PEMC boundary is given by:

$$\eta_0 M = \tan(0.5 \tan^{-1}(E_{y\_ref}/E_{x\_ref})) \tag{4}$$

In the following section we present a parametric study to show the effect of the tilting angle between the patches on the center frequency of the resulting PEMC boundary and the corresponding admittance parameter.



(a)



(b)

Figure 3. Reflection coefficients of co-polarized and cross-polarized field components. The tilting angles between the patches $\theta = 90°$. (a) Amplitudes of reflection coefficients. (b) Phase of reflected coefficients.

3. RESULTS AND DISCUSSIONS

Figure 3 shows the amplitude and the phase of co-polarized and cross-polarized reflection coefficients for the proposed geometry. The tilting angle between the patches in this case is 90°. The incident field is normally incident x-polarized wave. It can be noted that the phase of the reflected co-polarized and cross-polarized components coincides in this case at frequency 9.35 GHz as shown in Figure 3(b). At this frequency the ratio of the cross-polarized component to the co-polarized component is found to be 14.6 as shown in Figure 3(b). This ratio correspond to a normalized equivalent admittance parameter $\eta_0 M = 0.934$.

By following similar simulations for different tilting angles we obtained the relation between the tilting angle and the PEMC operating frequency as shown in Figure 4. It can be noted that the PEMC operating frequency increases by increasing the tilting angle. Similarly, we obtained the relation between the tilting angle and normalized equivalent admittance parameter $\eta_0 M$ as shown in Figure 5. It can be noted that, the equivalent admittance parameters tends to be zero if the tilting angle vanishes. This is equivalent to equivalent PEC surface. By increasing the tilting angle between the two patches, the equivalent admittance parameters increases in nearly linear scheme as shown in Figure 5.

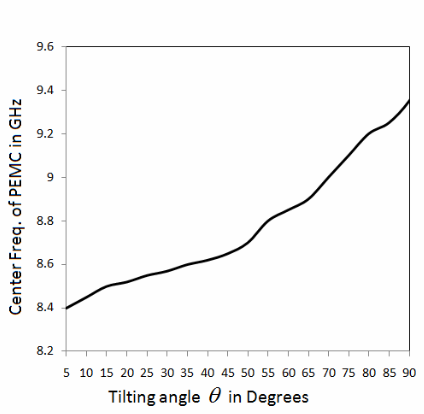


Figure 4. Center frequency of PEMC boundary as a function of the tilting angle between the two patches.

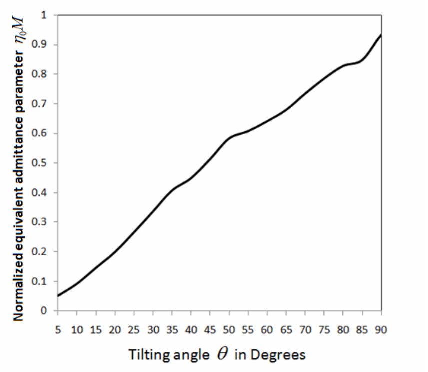
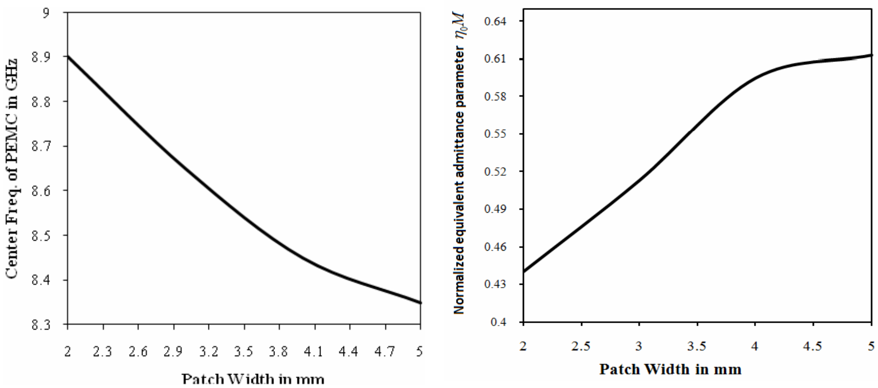


Figure 5. Normalized equivalent admittance parameter of PEMC boundary as a function of the tilting angle between the two patches.



(a) (b)

Figure 6. The effect of the patch width. (a) Center frequency of PEMC boundary as a function of the patch width. The tilting angles between the patches $\theta = 45°$. (b) Normalized equivalent admittance parameter of PEMC boundary as a function of the patch width. The tilting angles between the patches $\theta = 45°$.

Patch width plays an important role in determining the center frequency and equivalent admittance of the PEMC surface. To study the effect of the patch width, other parameters are the same as in the case of Figure 3 while the tilting angle between the patches is changed to be $\theta = 45°$. The patch width is changed from 2 mm to 5 mm. Figure 6(a) shows the center frequency of the equivalent PEMC surface for different patch widths. Figure 6(b) shows the corresponding normalized equivalent admittance parameter of the PEMC boundary surface as functions of the patch width. It can be noted that when the patch width is increased, the center frequency is decreased while the equivalent admittance increase. For large width, the admittance parameter starts to saturate.

To study the effect of the patch length, other parameters are the same as in the case of Figure 3 while the patch length is changed from 7 mm to 10 mm. The tilting angle between the patches is $\theta = 45°$. Figure 7(a) shows the center frequency of PEMC surface for different patch lengths. Figure 7(b) shows the normalized equivalent admittance parameter of PEMC boundary surface as functions of the patch length. It can be noted that by increasing the patch length is increased, both the center frequency and the equivalent admittance are decreased.

On the other hand, the cell size controls the coupling between the patches. Variation of the cell width affects the center frequency and admittance of the surface. The cell size is increased from 12 mm to

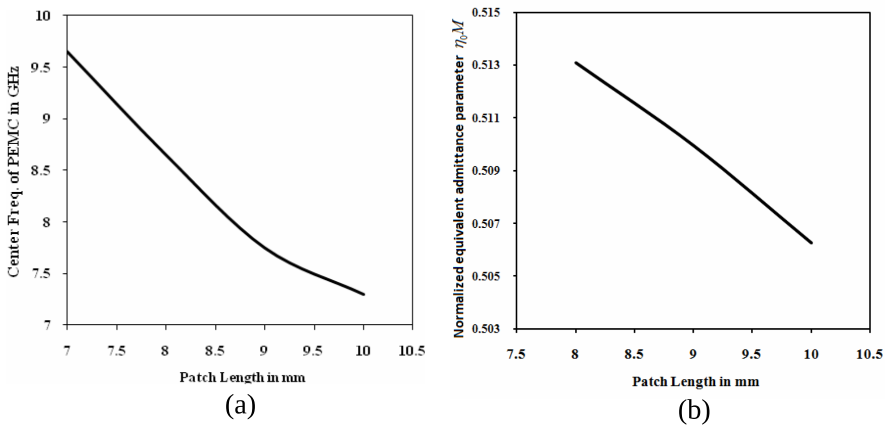


Figure 7. The effect of the patch length. (a) Center frequency of PEMC boundary as a function of the length of the patch. The tilting angles between the patches $\theta = 45°$. (b) Normalized equivalent admittance parameter of PEMC boundary as a function of the length of the patch. The tilting angles between the patches $\theta = 45°$.

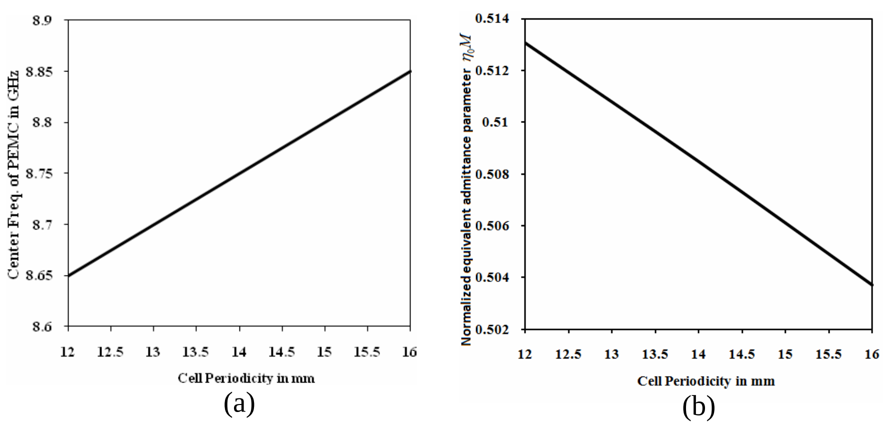
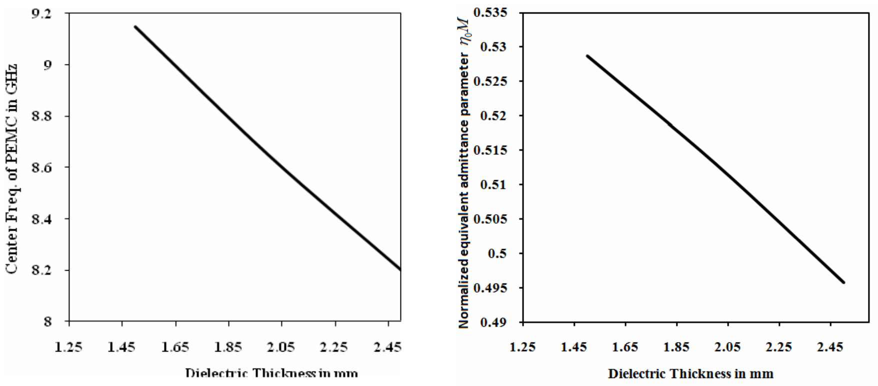


Figure 8. The effect of the cell periodicity. (a) Center frequency of PEMC boundary as a function of the cell periodicity. The tilting angles between the patches $\theta = 45°$. (b) Normalized equivalent admittance parameter of PEMC boundary as a function of the cell periodicity. The tilting angles between the patches $\theta = 45°$.

16 mm while the remaining parameters of the surface are kept constant as in Figure 3. Figure 8 shows the center frequency and normalized equivalent admittance parameter as functions of the cell size. It can



(a) (b)

Figure 9. The effect of the dielectric thickness. (a) Center frequency of PEMC boundary as a function of the dielectric thickness. The tilting angles between the patches $\theta = 45°$. (b) Normalized equivalent admittance parameter of PEMC boundary as a function of the dielectric thickness. The tilting angles between the patches $\theta = 45°$.

be noticed that the variation of the cell size has a moderate effect that is opposite effect to the variation of the patch width. As the cell width increases, the center frequency slightly increases while the admittance is slightly decreased.

Figure 9 shows the effect of the substrate thickness on the characteristics of the equivalent PEMC surface. The remaining parameters are kept constant as in Figure 3. It can be noted that by increasing the substrate thickness both the center frequency and admittance parameter are slightly decreased. The effect of the substrate dielectric constant is similar to the effect of the patch width. Finally, Figure 10 shows the effect of dielectric permittivity on the equivalent PEMC surface. It can be noted that by increasing the permittivity, the center frequency is decreased while the admittance is slightly increased.

From the above results it can be concluded that the introduced polarization rotation in the reflected field is mainly due to direct coupling between the two tilted patches through the connecting via. This tilting angle is mainly the main controlling parameter to produce cross-polarized component. This explains the nearly linear relation between the equivalent admittance parameter and the tilting angle shown in Figure 5. The other point that can be noted is that the equivalent PEMC boundary in the present structure is mainly due to a resonance behavior as it can be noted in Figure 3. This resonance

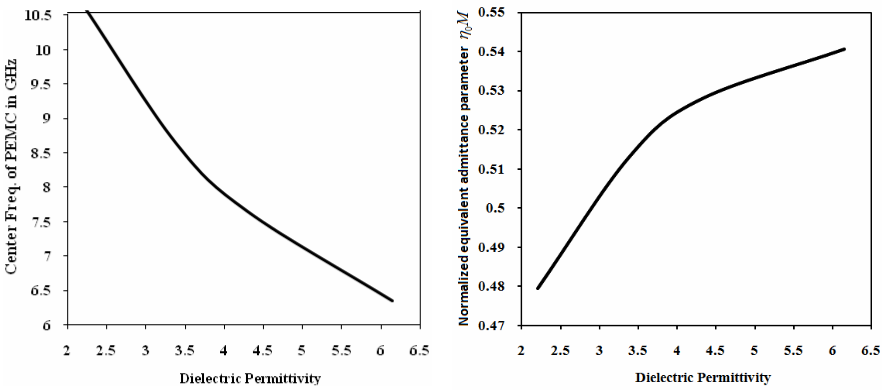


Figure 10. The effect of the dielectric permittivity. (a) Center frequency of PEMC boundary as a function of the dielectric permittivity. The tilting angles between the patches $\theta = 45°$. (b) Normalized equivalent admittance parameter of PEMC boundary as a function of the dielectric permittivity. The tilting angles between the patches $\theta = 45°$.

behavior depends on the effective electrical length of the combined two patches. This explains the decrease of center frequency of the equivalent PEMC surface by increasing the length of the patch as shown in Figure 7(a). On the other hand, by increasing the width of the patch, the fringing effect of the fields at the ends of the two patches would be increased. This effect results in increasing the effective electrical length and subsequently decreasing the center frequency of equivalent PEMC boundary as shown in Figure 6(a). In a similar way one can explain the effects of increasing the dielectric thickness and the dielectric constant on the center frequency of the equivalent PEMC boundary as shown in Figures 9(a) and 10(a) respectively. On the other hand, all these parameters have little effects on the resulting equivalent admittance compared with the effect of the tilting angle between the two patches. Finally, the radius of the connecting via is also studied as a separate parameter from $r = 0.25$ mm to $r = 1.25$ mm. However, we obtained very little effect on both the center frequency and the equivalent admittance parameter of the introduced PEMC boundary. It should be also noted that the present analysis is mainly based on normal incidence. It is expected that the value of the equivalent admittance parameter is depending also on the angle of incidence. This would be further investigated in a future research.

4. CONCLUSION

A new design for PEMC surface is introduced. This surface is based on a periodic structure composed of two conducting patches on a grounded dielectric slab. The two patches are tilted to each other by an angle θ. One of them is embedded inside the substrate and the other lies on the surface of the substrate. A conducting via are used to connect the two patches. The center frequency of the equivalent PEMC boundary and the corresponding equivalent admittance parameter are found to be nearly linearly proportional to the tilting angle between the patches. The present equivalent PEMC surface has the advantage of not using biasing magnetic field as the previously proposed configurations based on ferrite materials. It is also much simpler for fabrication. It is found when the patch width is increased, the center frequency and the admittance decrease. On the other hand, increasing the patch length decreases both the center frequency and the equivalent admittance. It is also found that by increasing the cell width the center frequency increase while the admittance decreased. When the substrate thickness is increased both the center frequency and admittance are decreased,. Finally, it is found that decreasing the substrate dielectric constant increases center frequency and decrease the surface equivalent admittance.

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