Radiation Efficiency Enhancement of a Horizontal Dipole on an Electrically Thick Substrate by a PMC Ground Plane

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Abstract

A method for the enhancement of the radiation efficiency of horizontal electric radiators on grounded substrate at low-efficiency substrate thicknesses, corresponding to TM surface-wave cutoff frequencies, is presented. This method consists in placing a thin (high permittivity) dielectric slab between the initial slab and the ground plane so as to generate an equivalent perfect magnetic conductor (PMC) condition at the bottom of the main substrate. Full-wave simulation results have demonstrated an efficiency enhancement to 40% from a non-radiating dipole at the cutoff frequency of the second TM surface-wave mode. This method can be used to provide more design flexibility in high-efficiency planar antennas in the millimeter-wave regime, where the substrates are typically electrically very thick.

1 Introduction

Over the past decades, planar antennas spurred continued interest due to their low profile, low cost and compatibility with integrated circuits. At the same time, millimeter-wave technologies are gaining increased attention in wireless systems due to new bandwidth requirements and miniaturization constraints. However, the substrates are typically electrically thick at millimeter-wave frequencies, and therefore they may support several surface-waves, which is well-known to degrade the radiation efficiency of planar antennas.

Some studies showed that the efficiency is not a monotonic decreasing function of the substrate electrical thickness [1]-[3], but rather passes through local maxima and minima at the cutoff frequencies of TE and TM surface-wave modes, respectively. In [4], it is shown that this behavior occurs as the result of equivalent perfect electric conductor (PEC) and perfect magnetic conductor (PMC) characteristics at air-dielectric interface at the onset of the TE and TM surface-modes cutoffs, respectively.

In this paper, based on the analysis of [4], a method is proposed for the efficiency enhancement of planar antennas at the TM cutoffs, where it transforms the air-dielectric boundary condition from a PEC into PMC boundary. This is accomplished by inserting a high-permittivity dielectric slab between the initial slab and the ground plane.

2 Radiation Efficiency Behavior

The radiation efficiency η of a planar antenna without metallic and dielectric losses is [1]-[3]

$$\eta = \frac{P_{rad}}{P_{rad} + P_{sw}}, \tag{1}$$

where P_{rad} and P_{sw} are the radiated and surface-wave powers, respectively, which indicates that the efficiency is limited by the propagation of surface waves.

As the electrical thickness of the substrate, d/λ, increases, the number of surface modes increases, and therefore the

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total surface-mode power increases as well. However, the radiation efficiency does not decrease in trivial monotonic manner; but exhibits a damped oscillatory behavior for increasing substrate electrical thickness. In the case of a horizontal electric radiator on a grounded substrate, depicted in Fig. 1a, the maxima and minima of $\eta(d/\lambda)$ occur at the cutoff of the TE_z and TM_z surfaces modes, respectively [1]-[3].

This $\eta(d/\lambda)$ behavior may be explained using a transmission line model [6], as shown in Fig. 1b [4]. At the cutoff of the TE_z surface modes, $\beta_z d = (2m+1)\pi/2$ [$m \in \mathbb{N}$] (where β_z and d are the propagation constant along the z axis and the thickness of the substrate, respectively), the input impedance at the air-dielectric interface (Fig. 1a), $Z_{in} = jZ_c \tan(\beta_z d)$ (where Z_c is the characteristic impedance of the slab), tends to infinity. As a result, at the TE cutoff, the air-dielectric interface acts as an equivalent PMC (open) boundary. In contrast, at the TM_z cutoff, $\beta_z d = m\pi$, Z_{in} vanishes. As a result, at the TM modes cutoff, the air-dielectric interface becomes an equivalent PEC (short) boundary. In general, the transmission line model of Fig. 1b can be replaced by the equivalent system shown in Fig. 1c, which is formed by a pair of two electric dipoles *in free space*, the source dipole J_g and a dipole J_{sub} which takes into account the effect of the substrate. At the TE cutoff, where the air-dielectric interface represents an equivalent PMC boundary, the substrate equivalent dipole is in-phase with respect to the source while at the TM cut-off they are out-of-phase, corresponding to the phase values indicated in Fig. 1c for J_{sub}. This equivalent dipole pair clearly show that the radiated power, and therefore the efficiency, will tend to reach a maximum at the TE cutoff and a minimum at the TM cutoff, as demonstrated in [4].

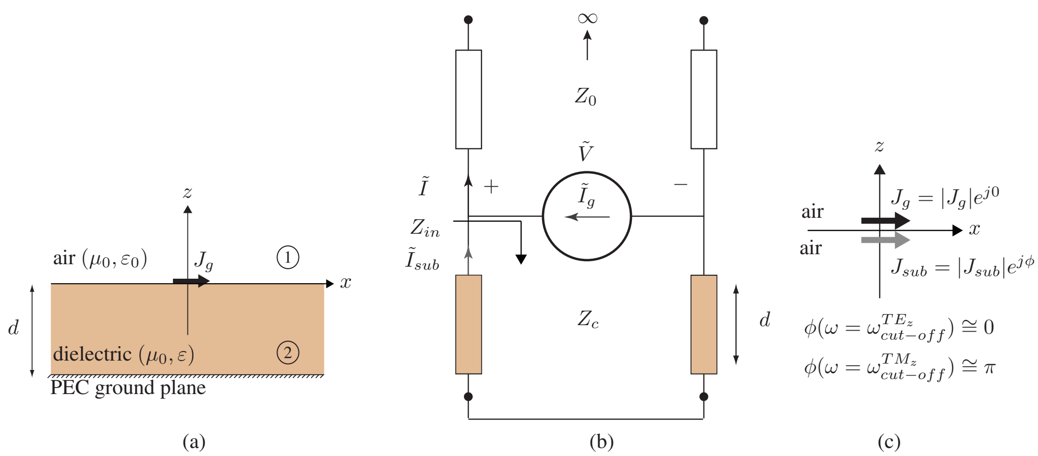


Figure 1: Horizontal electric dipole on a PEC-grounded dielectric slab. (a) Structure. (b) Transmission line model. (c) Equivalent free-space dipole pair formed by the source dipole J_g and the substrate equivalent dipole J_{sub}.

3 Radiation Efficiency Enhancement

Based on the explanation of Sec. 2, the radiation efficiency at the TM mode cutoffs may be enhanced by transforming the PEC boundary at the air-dielectric interface into a PMC boundary. In this case, the substrate equivalent dipole will be in-phase with respect to the source, and the radiated power and therefore the efficiency will be enhanced.

From the transmission line model of Fig. 1b, it is seen that if we substitute the PEC ground plane by a PMC ground plane, as shown in Fig. 2a, the input impedance of the equivalent transmission line model (Fig. 2b) is transformed from $Z_{in} = jZ_c \tan(\beta_z d)$ to $Z_{in} = jZ_c \cot(\beta_z d)$. Therefore, in opposite to the dielectric with a PEC ground plane, at the TE cut-off $Z_{in} = 0$ will correspond to a short while at the TM cut-off $Z_{in} \rightarrow \infty$ will correspond to an open. Consequently, the air-dielectric interface will become an equivalent PEC and PMC at the TE and TM cut-offs, respectively, and the substrate equivalent dipole will be out-of-phase and in-phase with respect to the source, respectively (Fig. 2c). This results in efficiency minima and maxima at the TE and TM cutoffs, respectively.

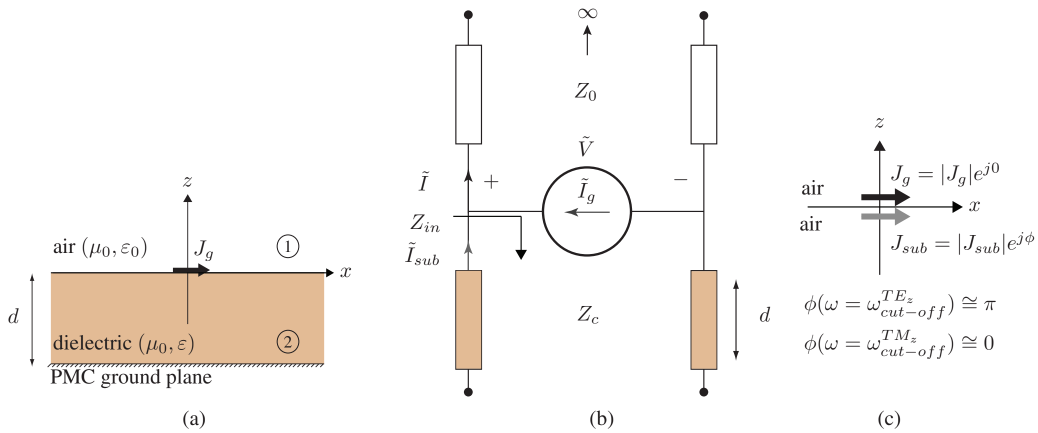


Figure 2: Horizontal electric dipole on a PMC-grounded dielectric slab. (a) Structure. (b) Transmission line model. (c) Equivalent free-space dipole pair formed by the source dipole J_g and the substrate equivalent dipole J_{sub}.

3.1 PMC Implementation

The aforementioned TM_z cutoff PMC boundary may be realized by a grounded dielectric substrate, as shown in Fig. 3a, with the thickness $d' = \lambda/(4\sqrt{\varepsilon_r' - 1})$ [5], where ε_r' is the dielectric constant of the slab and λ is the wavelength at the PMC frequency. This is the thickness for which the input impedance seen from the air-dielectric interface of the slab is infinite, corresponding to a PMC boundary [5]. The overall resulting structure is shown in Fig. 3b. Note that this configuration may lead, using a high-permittivity bottom substrate, to a much lower-profile and also potentially to a higher efficiency than the option of simply increasing the thickness of the initial substrate.

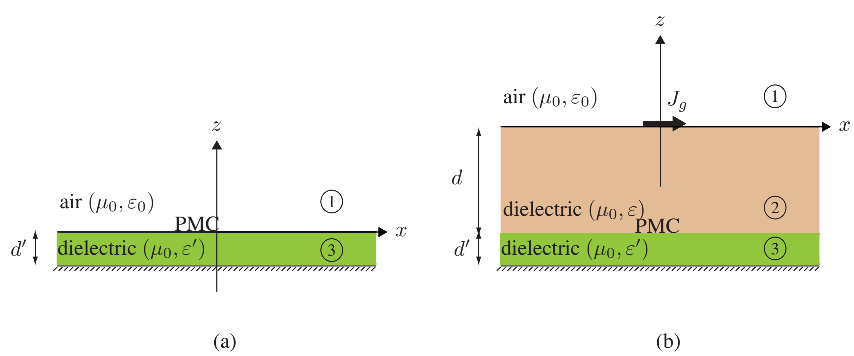
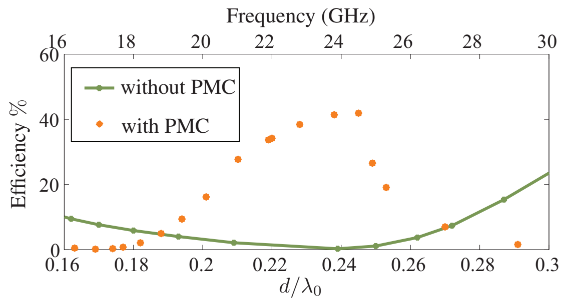


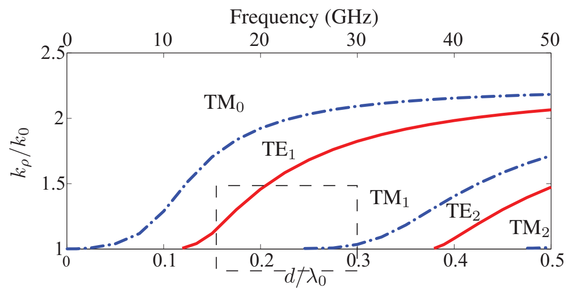
Figure 3: Proposed PMC boundary configuration for the enhancement of the radiation efficiency at the TM_z surface-wave cutoff frequencies. (a) $d' = \lambda/(4\sqrt{\varepsilon_r' - 1})$ dielectric slab PMC. (b) Overall structure, with the PMC boundary placed at the bottom of the initial dielectric slab.

3.2 Results

To demonstrate the proposed TM_z cutoff radiation efficiency enhancement scheme, a horizontal $\lambda/2$ dipole printed on a substrate with $d = 3$ mm and $\varepsilon_r = 5$ is full-wave simulated (using the software ADS Momentum). The resulting efficiency is plotted versus the substrate electrical thickness with the solid curve in Fig. 4a. A PMC boundary is designed at the cutoff of the TM_1 mode, namely at $f = 24$ GHz where the efficiency reaches a minimum, as shown in Fig. 4b. The PMC dielectric has a thickness of $d' = 0.835$ mm and a dielectric constant of $\varepsilon_r' = 15$. The efficiency of the corresponding PMC-backed structure is plotted versus the substrate electrical thickness with the dotted curve



(a)



(b)

Figure 4: Results. (a) Radiation efficiency η [Eq. (1)] versus substrate electrical thickness d for the initial slab with the PEC and the additional PMC slab at the TM_z surface-wave cutoff of the initial structure. (b) TM_z and TE_z surface modes.

in Fig. 4a. The enhancement of the radiation efficiency from a value in the order of 1% to around 40% clearly demonstrates the benefit of the proposed scheme.

4 Conclusion

A method for the enhancement of the radiation efficiency of horizontal electric radiators on grounded substrate at low-efficiency substrate thicknesses (TM surface-wave cutoff frequencies) has been presented. This method consists in placing a thin (high permittivity) dielectric slab between the initial slab and the ground plane so as to generate an equivalent perfect magnetic conductor (PMC) condition at the bottom of the main substrate. This method can be used to provide more design flexibility in high-efficiency planar antennas in the millimeter-wave regime, where the substrates are typically electrically very thick.

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