Analysis of Cylindrically Conformal Patch Antennas on Isoimpedance Anisotropic Substrates

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Abstract

We numerically investigate the performance of cylindrically conformal patch antennas on isoimpedance anisotropic substrates. These substrates are specifically designed to increase the effective (electrical) height without producing surface waves.

1 Introduction

'Transformation optics' (TO) techniques have received great attention in the electromagnetic community in recent years [1, 2] and many electromagnetic devices with new functionalities have been proposed using TO concepts [3]. With the rapid advance in fabrication technology, many such devices have become realizable at the prototype level [4].

One of the main challenges in patch antenna miniaturization is the trade-off between profile reduction and antenna performance (bandwidth, efficiency, etc.). Traditionally, high-dielectric substrates have been used to reduce the size of the patch and the profile of the substrate. However, high-dielectrics exacerbate surface waves, which can degrade the antenna performance significantly, including the bandwidth. Electromagnetic band gap (EBG) structures [6] and magneto-dielectric [7] substrates have been proposed to overcome the aforementioned problems. Recently, we have analyzed the performance of low-profile antennas on top of 'isoimpedance' anisotropic metamaterial substrates specifically designed (via TO) to modify the effective (electrical) height of the substrate [5] without affecting the substrate impedance. It was shown that such substrates can maintain basic antenna characteristics while reducing the overall antenna profile. In particular, such substrates effectively do not support surface waves which contributes to antenna performance [5]. The metamaterial blueprints and the antenna analysis considered in [5] were limited to planar geometries. In this paper, we extend such analysis for conformal patch antennas on cylindrical substrates and compare their performance against that of traditional dielectric substrates on such surfaces.

2 *'Isoimpedance'* Anisotropic Substrates

According to TO principles, a change in the metric of space can be mimicked by an 'equivalent' medium with anisotropic constitutive tensors. In other words, a electromagnetic problem in a (virtual) distorted space with ϵ and μ can be exactly represented by a problem in real space with constitutive parameters $[\epsilon] = \epsilon\,[\Lambda]$ and $[\mu] = \mu\,[\Lambda]$, where $[\Lambda]$ is the Jacobian of the metric transformation [1, 2]. Recently, this feature of Maxwell's equations has been exploited to design a host of electromagnetic devices such as electromagnetic cloaks, concentrators, polarization rotators, and waveguide transitions [1, 3, 4]. Recently, we explored this feature to design 'isoimpedance' anisotropic metamaterial substrates for low-profile antenna applications [5]. Such substrates can increase the effective (electrical) height of the substrate while keeping its impedance properties invariant. Thus, they are able to avoid excitation of surface waves and to provide a larger bandwidth compared to traditional (high-dielectric) substrates. The substrates are 'isoimpedance' to free-space if the condition $[\epsilon]/\epsilon_0 = [\mu]/\mu_0 = [\Lambda]$ is satisfied, with the tensor $[\Lambda]$ described below.

For conformal patch antennas on cylindrical surfaces (substrates), we derive the equivalent virtual geometry by applying the following transformation on the radial coordinate(ρ) in the region between the PEC

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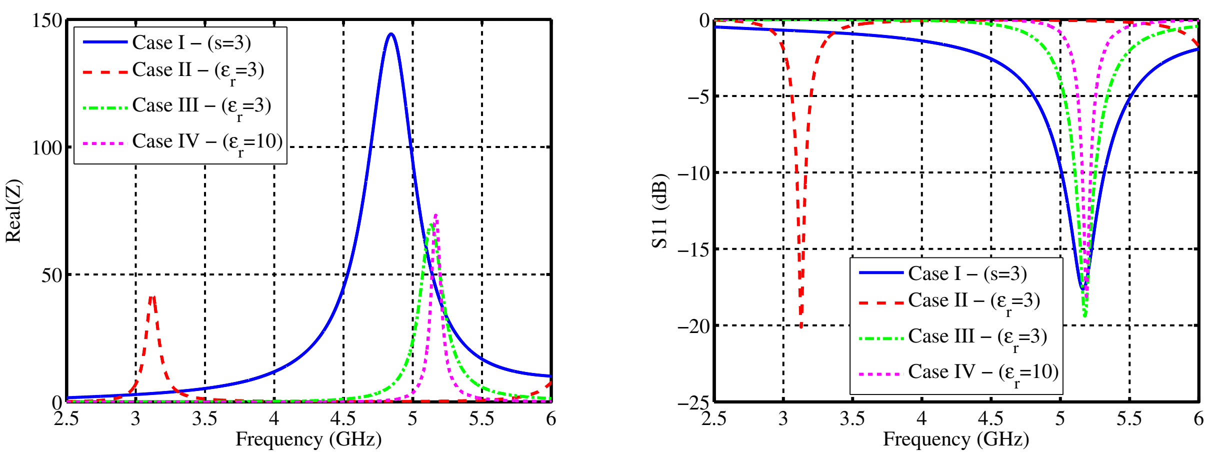
ground plane and the patch antenna:

$$\tilde{\rho} = \int_{\rho_0}^{\rho} s_\rho d\rho \quad \text{for} \quad \rho_0 \leq \rho \leq \rho_0 + h \tag{1}$$

where ρ_0 is the radius of the ground plane backing (inner PEC), h is the height (thickness) of the substrate, and s_ρ is the real factor that modifies the metric of space. According to the TO principles, the constitutive tensors (metamaterial blueprint) that mimic such transformation are given by $[\epsilon] = \epsilon\,[\Lambda]$ and $[\mu] = \mu\,[\Lambda]$ where $[\Lambda] = \text{diag}\,\{\tilde{\rho}/(s_\rho \rho),\ (s_\rho \rho)/\tilde{\rho},\ (s_\rho \tilde{\rho})/\rho\}$, in a cylindrical coordinate basis. Following the above discussion, the region between the PEC ground plane and patch can be equivalently 'squeezed' ($s_\rho < 1$) or 'stretched' ($s_\rho > 1$) depending on the choice of the s_ρ factor. A choice of $s_\rho > 1$ would yield an anisotropic media that will effectively mimics the effect of a thicker isotropic substrate with ϵ and μ.

3 Analysis and Numerical Results

The finite-difference time-domain (FDTD) method is employed for the analysis of the performance of cylindrically conformal patch antenna on such substrates. In order to reduce FDTD staircasing error and to fully conform with the geometry of the structure, a FDTD algorithm in 3-D cylindrical coordinates [8] is used. FDTD is a versatile method for the calculation of antenna characteristics where, for example, a wideband frequency response can be obtained with a single simulation. Moreover, complex material properties (i.e., anisotropy, inhomogeneity) are easily implemented. A Gaussian-derivative pulse of the form $V_s = \left(\frac{t-t_0}{\tau}\right) e^{-\left(\frac{t-t_o}{\tau}\right)^2}$ is used for the antenna excitation, and an efficient one-cell-gap model is implemented as a feed model [9]. In addition, the material properties at the substrate/air interface are averaged based on the proper field continuity conditions at the boundary.



(a) Real(Z)

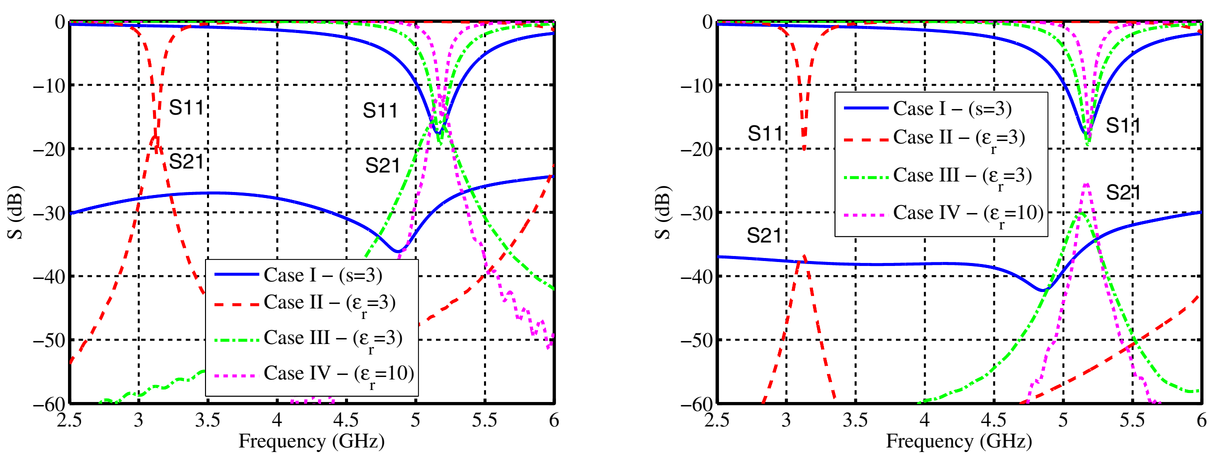
(b) S11

Figure 1: Real part of the input impedance and return loss for above mentioned four cases. The radius of the PEC cylinder is chosen as $\rho_0 = 20$ mm. (a) Real part of the input impedance and (b) return loss.

For comparison against traditional dielectric substrates, we also examine three other configurations. Namely, we consider: *Case I* with 'isoimpedance' anisotropic substrate, and length L_1 and width W_1; *Case II* with dielectric constant $\epsilon_r = 3$ and L_2, W_2; *Case III* with $\epsilon_r = 3$ and L_3, W_3; and *Case IV* with $\epsilon_r = 10$, and L_4, W_4. The set of patch dimensions is as follows: $L_1 = 25.64$ mm and $W_1 = 23.36$ mm, $L_2 = 25.64$ mm and $W_2 = 23.36$ mm, $L_3 = 16.58$ mm and $W_3 = 12.06$, and $L_4 = 9.06$ mm and $W_4 = 6.52$ mm, respectively. The substrate thickness is 1 mm for all cases. The antennas are backed by a cylindrical surface with 20 mm radius. In Case III and Case IV, the antenna dimensions are properly reduced in order to keep the resonant frequency same for (a). Note that patch size reduction is the main advantage of using high dielectric substrates.

Fig 1 shows the real part of input impedance and return loss for above mentioned four cases. As previously mentioned, the main advantage of using high-dielectric substrates is the size reduction of the patch. This can be easily seen from comparison of Case II against Cases III and IV. However, due to the increased surface waves at high-dielectric substrates, a much narrower bandwidth results. It is seen from Fig. 1 that the case with largest dielectric constant ($\epsilon_r = 10$) has the lowest bandwidth with about 1.2%. Notice that the isoimpedance substrate (Case I) has the largest bandwidth with about 6.0%. Case II and Case III have about 2.1% and 2.8% bandwidths, respectively.

To examine the effect of surface waves on the mutual coupling between array elements on such cylindrical substrates, we investigate the mutual coupling characteristics for the four configurations above in Fig 2. Since the anisotropic substrates are designed as isoimpedance, we expect less mutual coupling for Case I compared to the others. This is clearly observed from Fig 2. Notice also that, for the H-plane coupling there is a significant reduction in the mutual coupling; this is due to the cylindrical geometry and relatively small radius of the PEC cylinder. As we increase the radius, the mutual coupling is expected to increase in the H-plane and approach that of the E-plane.



(a) e-plane

(b) h-plane

Figure 2: Mutual coupling for above mentioned three cases. The distance between patches is chosen as $d = .5\lambda_{5.18\mathrm{GHz}}$ ($\lambda_{5.18\mathrm{GHz}}$ is the free space wavelength at the resonant frequency 5.18 GHz). (a) E-plane and (b) H-plane.

4 Conclusion

We have analyzed cylindrically conformal patch antennas on top of isoimpedance metamaterial substrates. These substrates consist of anisotropic tensors specifically designed to increase the effective (electric) height of the substrate without altering its (intrinsic) impedance properties. Antennas placed on top of such substrates have the same performance as on top of thicker, isotropic substrates. Therefore, such anisotropic substrates can in principle be used to reduce the antenna profile significantly without sacrificing the antenna performance, in contrast to conventional high-dielectric substrates which support (spurious) surface waves. The main limitation that exists in practice for the antenna performance stems from material response limitations, in particular losses and frequency dispersion. It is beyond the scope of this paper to examine fabrication issues. Suffice it to say that fabrication of such metamaterial substrates posses challenges similar as cloaking devices, for example [4].

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