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Journal

IEEE Antennas and Propagation Society, AP-S International Symposium (Digest), 1

ISSN

1522-3965

ISBN

9781467304627

Authors

Guclu, C
Campione, S
Sedighy, SH
et al.

Publication Date

2012-12-10

DOI

10.1109/APS.2012.6348086

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Hiding and Absorbing the Power Emitted by a Dipole at the Interface of an Indefinite Medium

Caner Guclu, Salvatore Campione, Seyed Hassan Sedighy, and Filippo Capolino

Department of Electrical Engineering and Computer Science

University of California, Irvine,

Irvine, California 92697, USA

{cguclu; scampion; sedighis; f.capolino}@uci.edu

Abstract—The power emitted by a dipole at the interface between an indefinite (hyperbolic) medium and an isotropic medium is analyzed. The theoretical estimation is performed by using a transmission line method for time-harmonic fields in layered isotropic materials. The indefinite medium can be constructed in different ways; here we analyze, as an example, the case of alternating two subwavelength layers of isotropic materials. We compute the power spectrum of transverse electric and magnetic (TE and TM) waves and show that the power emitted by the dipole is mainly coupled into the indefinite medium underneath, opening up several application scenarios, such as innovative carpet cloaking implementations and super absorbers.

I. INTRODUCTION

An indefinite (hyperbolic) medium (IM) is an anisotropic medium characterized by permittivity and/or permeability tensors that provide with a different response, according to the polarization of the field, resulting in a hyperbolic-like dispersion diagram [1].

Figure 1. Dipole at the interface between an isotropic medium (up) and an IM (down): (a) homogeneous, (b) wire medium, and (c) periodic bi-layer structure representation.

One of the recent usages of IMs shows that such media allow for subwavelength focusing of the field, also useful for lensing applications [2-5]. The hyper-lens effect that the evanescent wave can be converted into the radiative wave has been confirmed in [6]. Very recently, there have been studies about the emission of a dipole in proximity of an IM. For example, in [7] the authors analyzed the dipole radiation fraction, comparing the results for real metal-dielectric multilayers as in Fig. 1(c) with those for a homogenized slab with parameters given by the effective medium approach as in Fig. 1(a), concluding that the latter gives overestimated rates. The spontaneous emission patterns of electric and magnetic dipoles on gold or silver metallic surfaces and a hyperbolic

metamaterial (HMM) surface were estimated using the dyadic Green's function technique in [8]. Experimental results in [9] proved that corrugated surfaces of HMMs result in a very low reflectance and ultimate dark appearance. Here, we focus on determining the power spectrum of TE/TM waves of a dipole at the interface between an IM and an isotropic medium, aiming at showing that most of the emitted power is coupled inside the IM.

II. POWER EMITTED BY A HORIZONTAL DIPOLE

We use the transmission line (TL) formalism to compute the power emitted by an elementary dipole just above or at the interface between free space and IM. Hyperbolic materials are a special case of uniaxially anisotropic materials (UAM), whose relative effective permittivity tensor is given as $\underline{\epsilon}_{down}$ (Fig. 1(a)), which is a diagonal matrix with entries $\epsilon_{xx} = \epsilon_{yy} = \epsilon_t$ and $\epsilon_{zz} = \epsilon_z$ (the axis of anisotropy is the z -axis). Two categories of waves can propagate in the UAM: ordinary and extraordinary waves, defined by the equations $k^2 / \epsilon_t = \omega^2 / c^2$ and $k_t^2 / \epsilon_z + k_z^2 / \epsilon_t = \omega^2 / c^2$, respectively, where k_z and k_t are the z and the transverse to z component of the wavenumber. Since the axis of anisotropy coincides with the z -axis, ordinary modes are TE_z modes (which are related to ϵ_t regardless of propagation direction) and extraordinary modes are TM_z modes (which will have a hyperbolic dispersion relation when either ϵ_z or ϵ_t is negative) inside the UAM. Here we consider the negative ϵ_z case for which, inside the IM, extraordinary waves can propagate for all k_t values, and ordinary waves can propagate only for $k_t < k_0 \sqrt{\epsilon_t}$.

Uniaxially anisotropic metamaterial can be designed by using a wire medium or stacking layers of alternating materials (as shown in Figs. 1(b) and 1(c), respectively). Provided that the periodicity of the designed metamaterial is subwavelength, it can be modeled as homogenized IM (Fig. 1(a)). In order to utilize the TL formalism, we implement the IM with infinitely periodic bi-layer structure of thickness d as in Fig. 1(c). The transverse elementary dipole located at the interface between free space ($\epsilon_{up} = 1$) and the IM, $J_d \hat{x} \delta(\mathbf{r})$, is represented as a shunt current generator in the TL formalism. This current generator is then loaded by the TE/TM admittances of the free

space (up) and of the IM (down). The power emitted by the dipole into any of these half spaces in TE or TM mode can be computed as (for instance)

$P_{\text{up}}(\omega) = |J_d|^2 / (8\pi) \int_0^{+\infty} p_{\text{up}}(\omega, k_t) dk_t$, where $p_{\text{up}}(\omega, k_t)$ is the upward power spectrum evaluated via TL theory. An analogous formula holds for the power into the IM, as a function of the downward power spectrum $p_{\text{down}}(\omega, k_t)$. Note that with this formula, one can calculate the spectral power of the TE/TM modes in either of the half spaces, independently.

TABLE I. HOMOGENIZED PERMITTIVITY VALUES.

Cases	ϵ_t	ϵ_z	$ \epsilon_t / \epsilon_z $
Case A	0.5	-5	0.1
Case B	2	-20	0.1

Figure 2. Dispersion relations when the bottom material is an IM for Case A and Case B.

As a comparison, we provide the power plots for two cases whose homogenized relative permittivity entries are provided in Table I. Case A (B) has ϵ_t smaller (larger) than 1, so that in the IM the propagating spectrum of TE waves is narrower (wider) than that of the free space (Fig. 2). In Fig. 3 the normalized (by k_0) spectral power of TE/TM waves in the $+z$ direction (up, $p_{\text{up}}^{\text{TE/TM}}/k_0$) and $-z$ direction (down, $p_{\text{down}}^{\text{TE/TM}}/k_0$) and total normalized spectral power in each direction ($p_{\text{up/down}}$) are plotted at the frequency of $\lambda_0 = 15d$. The power in the $+z$ direction is only present in the propagating spectrum ($k_t < k_0$); however, inside the IM, the TM waves carry power in the $-z$ direction for any k_t , and especially till $k_t \approx 10k_0$. This is the main reason why the power emitted by the dipole at the interface is mostly coupled to the IM. However, for Case B, one can also increase the spectrum of TE waves in the IM as a result of larger ϵ_t with respect to Case A. In Fig. 4 we show the ratio between the total power emitted by the dipole in $+z$ direction (up) and that in $-z$ direction (down) versus normalized wavelength λ_0/d . Larger ϵ_t yields to a decrease of $P_{\text{up}}/P_{\text{down}}$. As λ_0/d increases (subwavelength regime is satisfied [7]), the $P_{\text{up}}/P_{\text{down}}$ ratio tends to decrease. The absorption properties at IM surfaces can be used for efficient

absorbers, sensors, photodetectors, solar cells, and for hiding (concealing) small scatterers at the IM surface.

Figure 3. The normalized spectral power of TE/TM waves in the $+z$ direction (up) and $-z$ direction (down) and total normalized spectral power in each direction at $\lambda_0 = 15d$ for (a) Case A, and (b) Case B.

Figure 4. The total power emitted into free space (up) divided by the power emitted into the IM (down) versus λ_0/d .

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