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3D Directive Radiation from a Horizontal Dipole Embedded in a Homogenized Grounded Wire-Medium Slab

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Abstract

Radiation features of an elemental electric dipole source embedded inside a grounded wire-medium slab are investigated. A homogenous model is adopted which takes into account both anisotropy and spatial dispersion of the metamaterial medium in the long wavelength limit. An equivalent transverse network is derived for plane waves TE and TM with respect to the wires' axis, coupled by a four-port network associated with the air-slab interface, and the far-field pattern is then derived via the reciprocity theorem. Numerical results are provided which show the possibility of achieving a narrow azimuthally symmetric pencil beam at broadside by properly choosing the physical and geometrical parameters of the structure. MoM results for the wire medium, not shown in this summary, confirm the phenomenology observed with the homogenous model.

Introduction

The possibility of achieving directive radiation from simple sources by employing planar layered structures made of artificial materials has been studied by several research groups, from the early investigations by Gupta [1] to more recent ones stimulated by the advent of electronic band-gap materials and of metamaterials [2-4].

In [5], a low-permittivity homogeneous and isotropic metamaterial grounded slab with a plasma-like effective permittivity has been considered, excited by an infinite electric line source. This metamaterial can model a grounded wire-medium slab, in the limit of large wavelength with respect to the wires' spacing, excited by an electric line source parallel to the wires' axis. In such a 2D configuration a purely TE_z field is radiated; in [5], conditions for maximizing the radiation at broadside and for achieving high broadside directivity have been derived and they have been shown to be related to the excitation of a weakly-

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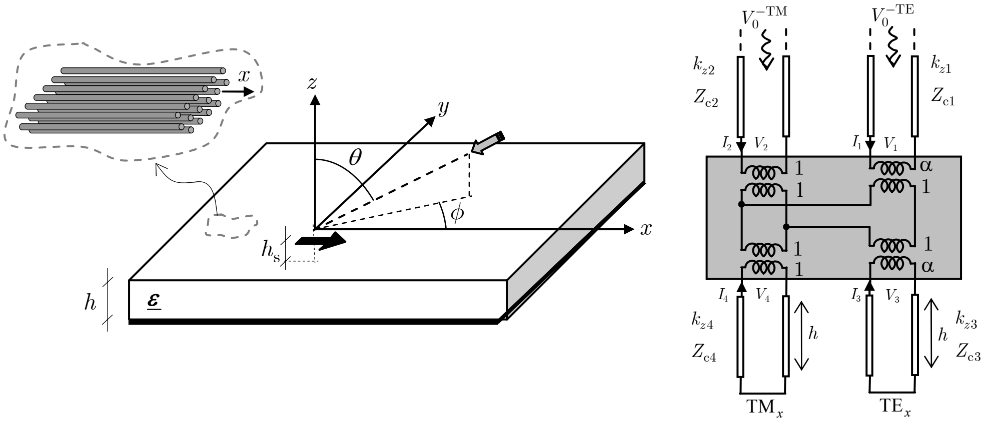
attenuated dominant TE leaky mode supported by the grounded metamaterial slab.

In this paper we extend the analysis of [5] by considering as an excitation an elemental horizontal electric *dipole* parallel to the wires' axis (see Fig. 1(a)). In this case the problem is 3D, the excited field is not purely TE, and the medium cannot be considered isotropic anymore. Moreover, as shown in [6], a homogeneous model of the wire medium has to take into account not only anisotropy but also *spatial dispersion* at any frequency. A transverse-network representation of the structure is derived here by adopting a spatially-dispersive dyadic permittivity and decomposing the spectral field into its TE$_x$ and TM$_x$ parts; the transverse network is then employed to calculate the 3D radiation pattern of the horizontal dipole via reciprocity theorem. Numerical results on a specific structure illustrate the possibility of achieving narrow azimuthally symmetric pencil beams at broadside.



(a) (b)

Fig. 1 – (a) Grounded wire-medium slab excited by a horizontal electric dipole with the relevant physical and geometrical parameters; also shown is a uniform plane wave incident from the direction (θ, ϕ) used in the calculation of the radiated far field based on the reciprocity theorem. (b) Transverse-network model for the problem of plane-wave incidence shown in (a).

Far-Field Calculation and Transverse Equivalent Network

The problem of calculating the far field radiated in an arbitrary direction (θ, ϕ) by a horizontal dipole embedded inside a wire-medium slab can be reduced, by means of the reciprocity theorem, to that of calculating the electric field produced at the source location by a plane wave impinging on the grounded slab from the same direction [7]. In order to solve the latter problem, the grounded wire-medium slab is modeled here as a homogeneous non-magnetic slab of thickness h (see Fig. 1(a)) with a spectral dyadic permittivity

$$\underline{\boldsymbol{\varepsilon}} = \varepsilon_0 \varepsilon_{\mathrm{r}} \left[\boldsymbol{x}_0 \boldsymbol{x}_0 \left(1 - \frac{k_{\mathrm{p}}^2}{k_0^2 - k_x^2} \right) + \boldsymbol{y}_0 \boldsymbol{y}_0 + \boldsymbol{z}_0 \boldsymbol{z}_0 \right] \tag{1}$$

where $k_{\mathrm{p}} = 2\pi f_{\mathrm{p}} / c$ is the plasma wavenumber, $k_0 = 2\pi f / c$ is the free-space wavenumber, and ε_{r} is the relative permittivity of the background medium inside which the wires are embedded. The homogenized wire medium is thus uniaxial and the dependence on k_0 and k_x in (1) indicates the presence of both temporal and spatial dispersion, respectively.

The field can be decomposed into its TE$_x$ and TM$_x$ parts, which correspond to ordinary and extraordinary waves, respectively, inside the slab medium. The TE$_x$/TM$_x$ fields can in turn be associated with equivalent transmission lines along the vertical z axis, following the same procedure as in [8]. It should be noted that, for the considered spatially-dispersive uniaxial medium, the effective refraction indexes of both the ordinary and extraordinary waves are independent of their propagation directions and are equal to $n_{\mathrm{o}} = 1$ and $n_{\mathrm{e}} = \sqrt{1 - k_{\mathrm{p}}^2 / k_0^2}$, respectively.

The air-slab interface is represented by a four-port network as in [8], and the complete transverse equivalent network for the problem is shown in Fig. 1(b), where the network parameters are

$$k_{z1} = k_{z2} = k_{z3} = k_0 \cos\theta \, , \, k_{z4} = k_0 \sqrt{n_{\mathrm{e}}^2 - \sin^2\theta}$$

$$Z_{\mathrm{c}i} = \frac{\eta_0 k_{zi}}{k_0} \frac{1}{(1 - \cos^2\phi \sin^2\theta)}, \quad (i = 1, 3) \tag{2}$$

$$Z_{\mathrm{c}i} = \frac{\eta_0 k_0}{k_{zi}} \left(1 - \cos^2\phi \sin^2\theta\right), \quad (i = 2, 4)$$

and the coupling parameter α in the four-port network depends on the incidence angle of the impinging plane wave as

$$\alpha = \frac{\left(\varepsilon_{\mathrm{r}}^2 - 1\right) \sin^2\theta \cos\phi \sin\phi}{\left(1 - \sin^2\theta \cos^2\phi\right)\left(\varepsilon_{\mathrm{r}}^2 - \sin^2\theta \cos^2\phi\right)} \tag{3}$$

being equal to zero for incidence in the principal (E and H) planes, or for any incidence angle when $\varepsilon_{\mathrm{r}} = 1$. The TE/TM electric field can be obtained from the TE/TM voltages; the total electric field at the source location is then found by summing the TE and TM components.

Numerical Results

In Fig. 2 radiation patterns in the principal planes $\phi = 0^\circ$, $\phi = 90^\circ$, and in the $\phi = 45^\circ$ plane are presented for a structure as in Fig. 1(a) with $f_{\mathrm{p}} = 20$ GHz, $h = 60$ mm, $h_{\mathrm{s}} = h / 2$ excited by a horizontal electric dipole placed in the middle of the slab. The results have been calculated at the optimum frequency

$f = f_{\mathrm{opt}} = 20.155\ \mathrm{GHz}$, for which the broadside power density of the corresponding 2D problem involving a line source is maximum, according to the analysis presented in [5]. It can be observed that the radiation patterns in the shown elevation planes are almost identical, which confirms the possibility of obtaining an azimuthally symmetric 3D highly-directive beam pointing at broadside by exciting the considered wire-medium slab with a simple finite source.

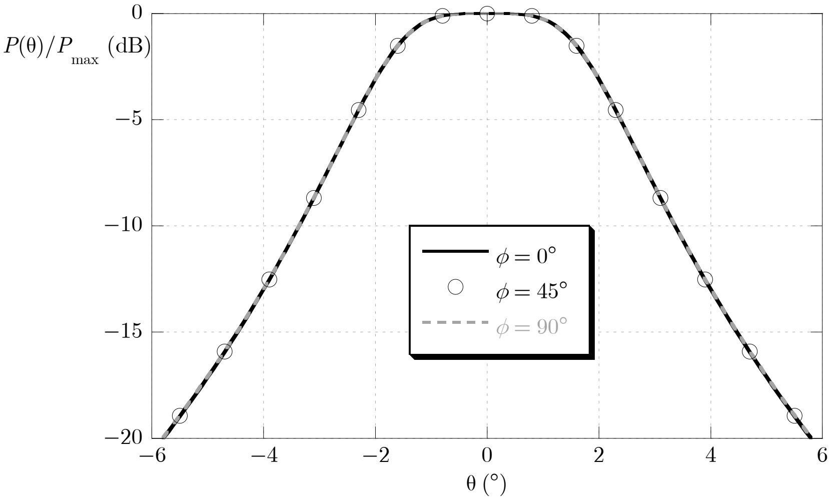


Fig. 2 – Normalized radiation patterns for a horizontal electric dipole embedded in a grounded wire-medium slab. *Parameters*: $f_{\mathrm{p}} = 20\ \mathrm{GHz}$, $h = 60\ \mathrm{mm}$, $h_{\mathrm{s}} = h/2$, $f = 20.155\ \mathrm{GHz}$.

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