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Radiation from a short vertical dipole in a metal-backed rod array

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Abstract

Based on an effective medium approach, we investigate the problem of radiation of a short vertical electric dipole embedded in a metal-backed dielectric rod array. We obtain the radiated electromagnetic field in the form of a Sommerfeld integral, and calculate the near and far electric fields for both lossless and lossy rod arrays. The characteristic equation for the guided modes is derived and solved. The guided modes are found to be slow waves and their propagation constants and modal distributions are extracted. All theoretical results are compared with full-wave simulations.

Keywords: Dielectric rod array; Effective medium theory; Radiation; Propagation

1. Introduction

A dielectric rod array – understood as a 2-D periodic structure formed by either infinite-length or finite-length cylindrical dielectric rods – has long been of interest because of its unique electromagnetic characteristics. It was used as a dielectric waveguide element in a phased array [1], as well as a photonic bandgap (PBG) structure [2]. More recently, arrays of negative permittivity rods have also received great attention due to their unusual potentials in manipulating the near-field in the nanoscale [3–8], in enhancing light-matter interactions [9–17], and in controlling the radiative heat transfer [18].

In a different research direction, a dielectric rod array may be used to represent a simple scaled forest model. For example, the dielectric constant of water at microwave frequencies (77-j10 at 2.5 GHz) is close to that of typical pine trees at HF/VHF frequencies (50-j15 at 50 MHz [19]). Based on this observation, a periodic array consisting of water-filled straws was introduced to represent a 1:50 scaled forest model in both measurements [20] and full-wave numerical simulations [21]. While modeling vegetation media as a periodic dielectric array is evidently a very rough approximation in areas where the vegetation is dominated by grass, this approach can provide relevant physical insights in other scenarios (e.g. areas with tall tree trunks), and we expect that for some kinds of aligned forest it can capture the main physical mechanisms of the electromagnetic wave propagation, in particular for long wavelengths.

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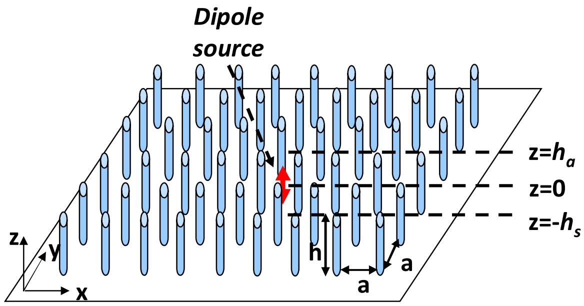

Fig. 1. A dielectric rod array setup.

Motivated by this application and with the aim to unveil the radiation and propagation mechanisms in a forest, here we investigate the radiation of an elementary short vertical dipole embedded within a metal-backed rod array from a theoretical viewpoint. The ground is supposed to model the electromagnetic response of the soil, and for simplicity here it is assumed to be a perfect electrical conductor (PEC). Our analysis is based on the effective medium model of metallic wire media developed in [22]. Analytical continuation arguments suggest that the same model may apply to ε-positive rod array as well. Using these ideas and techniques previously developed for metal wire arrays, we prove that the radiation fields can be expressed in the form of a Sommerfeld integral. Related problems were previously solved for perfectly conducting metal wire arrays [23,24]. Here we concentrate on dielectric rod arrays, aiming to understand the guided modes that are excited and the radiation mechanisms in this unique structure.

The article is organized as follows. In Section 2, the radiated fields are derived and written in the form of a Sommerfeld integral. In Section 3, the integral is evaluated numerically to generate near and far electric field data for both lossless and lossy dielectric rod arrays. The guided wave in the array is extracted and its propagation properties are highlighted. The results are compared with full-wave simulations. Section 4 summarizes our findings.

2. Theoretical model

Fig. 1 shows the geometry of the problem: a square array of dielectric rods is placed over a PEC ground plane. The rod height, rod radius, and the spacing between rods are h, r, and a, respectively. The source embedded inside the array is a vertical Hertzian dipole described by the current density $\vec{J}$ ($\vec{J} = j\omega p_e \delta(x, y, z)\hat{z}$, where p_e represents the electric dipole moment), and is placed at the height h_s above the PEC, and at a distance h_a below the air–slab interface. The permittivity of the rod and host medium are ε_m and ε_h, respectively, and the upper region is air.

Similar to the analysis of [23], first we define an intermediate normalized potential function Φ (which simply relates to the well-known magnetic vector potential A_z as $A_z = j\omega\mu_o p_e \Phi$), such that the electric field $\vec{E}$ in all space can be expressed as:

$$\frac{\vec{E}}{p_e} = \omega^2 \mu_o \Phi \hat{z} + \nabla \left(\frac{1}{\varepsilon_h (z)} \frac{\partial \Phi}{\partial z} \right) \tag{1}$$

The potential function Φ can be computed from its spectral domain counterpart $\tilde{\Phi}$. In [24], $\tilde{\Phi}$ for an unbounded dielectric rod array medium (formed by infinitely long dielectric wires) was found to be,

$$\tilde{\Phi} = \frac{1}{2\gamma_{qT}} C_{qT} e^{-\gamma_{qT}|z|} + \frac{1}{2\gamma_{TM}} C_{TM} e^{-\gamma_{TM}|z|} \tag{2}$$

where:

$$C_{qT} = \frac{\gamma_h^2 - \gamma_{TM}^2 + k_p^2}{\gamma_{qT}^2 - \gamma_{TM}^2} \tag{3.a}$$

$$C_{TM} = \frac{\gamma_h^2 - \gamma_{qT}^2 + k_p^2}{\gamma_{TM}^2 - \gamma_{qT}^2} \tag{3.b}$$