Artificial high-impedance surfaces: Theoretical analysis for oblique incidence

C.R. Simovski[1], S.A. Tretyakov[2] and P. de Maagt[3]

[1]Physics Department, St. Petersburg Institute for Fine Mechanics and Optics, 197101, Sablinskaya 14, St. Petersburg, Russia, simovsky@phd.ifmo.ru
[2]Radio Laboratory, Helsinki University of Technology, P.O. 3000, FIN-02015 HUT, Finland, sergei.tretyakov@hut.fi
[3]European Space Research and Technology Centre (ESTEC), European Space Agency (ESA), PO Box 299, 2200 AG Noordwijk, The Netherlands. Peter.de.Maagt@esa.int

1 Introduction

Patch antennas and other printed circuit antennas are widely used in the microwave domain. From a performance point of view the height of the radiating element over the ground generally needs to be small compared to the wavelength in free space. If the antenna is separated from the ground plane by a dielectric layer, its performance can be poor because a considerable part of the radiated power can be lost due to the excitation of surface waves in the substrate. Recently, it has been proposed to replace conventional dielectric substrates with so-called high-impedance surfaces (HIS) to obtain a metal-backed substrate that potentially offers constructive interaction with the antenna [1, 2, 3]. These surfaces are basically periodical structures of planar conducting patches separated by the slots or complimentary arrays of slots in metal planes. For arrays of patches positioned in close proximity to a solid metal plane as in [1], periodically positioned metal pins are introduced to prevent electromagnetic waves from propagating inside the substrate. Because of the specific geometry, this structure is sometimes referred to as *mushroom* array. Suggested applications in antennas and microwave filters [2] also utilize the existing stop bands for waves propagating along these surfaces.

In this paper we report our results on analytical modeling and experimental investigations of mushroom surfaces excited by obliquely incident plane waves. The geometry of the problem is illustrated by Figure 1. The results show the role of vias connectors leading to stable reflection properties for all incidence angles for the TM polarization when the pins are excited. Furthermore, we look at novel geometries of the patch array [4] that improve the main characteristics of HIS, potentially increasing the bandwidth and providing a more stable frequency dependence of the surface impedance versus the angle of incidence. Our approach is an extension of the analytical dynamic model of mushroom arrays [5]. The analytical results are compared with experimental data.

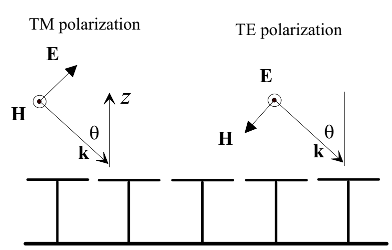

Figure 1: TM and TE plane waves incident on a mushroom layer.

2 Analytical model

Let us first consider a planar array of patches in free space. If the grid period is smaller than the wavelength, its electromagnetic properties can be described in terms of the grid impedance Z_{grid} which connects the averaged electric field in the grid plane and the averaged current density: $\langle E\rangle = Z_g\langle J\rangle$. Consider a self-resonant grid modeled by Z_g positioned on the interface of a metal-backed dielectric substrate which is periodically perforated by metal pins. The surface (input) impedance of the whole structure Z_i is the parallel connection of Z_g and the equivalent surface impedance of the substrate:

$$Z_i = \frac{Z_g Z_s}{Z_g + Z_s}. \tag{1}$$

This transmission-line approach was successfully confirmed in [5], where the full-wave interaction with the ground was taken into account and it was shown that the corrections are small for practical cases. In the theory of self-resonant grids [6] it was proven that if the cell size is small compared to the wavelength, the grid impedance (for normal incidence) is close to that of the series LC-circuit, where L and C are the parameters of a unit cell of the grid. We introduce impedances normalized to the free space impedance $\eta = 120\pi$ Ohm and write

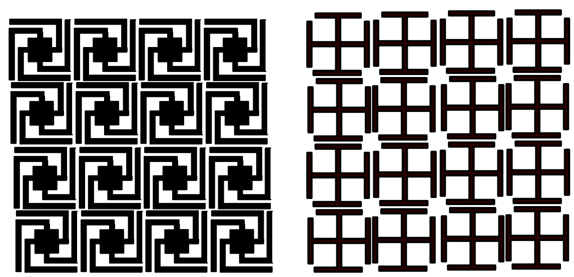

Figure 2: Self-resonant grids of planar metal particles. Left: array of spiral-shaped patches. Right: array of Jerusalem crosses.

$$Z_g^{\text{norm}} = j\frac{\omega L}{\eta}\left(1 - \frac{\omega_0^2}{\omega^2}\right), \tag{2}$$

where $\omega_0 = (LC)^{-1/2}$ is the grid self-resonance frequency. Examples of self-resonant grids are presented in Fig. 2. The normalized grid impedance for the TE-incidence can be calculated as $Z_g^{TE} = Z_g^{\text{norm}}/\cos^2\theta$ and for TM-incidence one has $Z_g^{TM} = Z_g^{\text{norm}}$.

For the TE-incidence Z_s is not affected by pins, and we obtain,

$$Z_s^{TE} = \frac{j}{\sqrt{\epsilon}}\tan k_{zd}H, \tag{3}$$

where $k_{zd} = \omega\sqrt{\epsilon - \sin^2\theta}\sqrt{\epsilon_0\mu_0}$, and H is the substrate thickness. For the TM-case it can be approximately treated as the normalized surface impedance of a thin metal-baked layer of a *wire medium.* The wire medium can be considered as a multi-wire TEM transmission line. It was recently shown [7] that TM-polarized incident field excites two eigenwaves in wire media. One is the TM-mode that has a stop band at low frequencies. In our case that wave exponentially decays inside the substrate, and we assume that its influence can be neglected. The only relevant solution is the

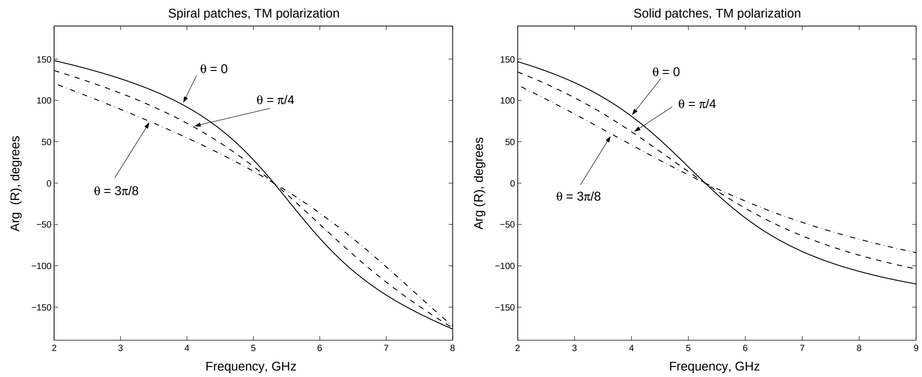

Figure 3: Frequency dependencies of the reflection coefficient phase for a structure with SSP (left part) and usual metal patches (right part).

TEM wave. Its propagation factor has two components: the normal to the interface component is equal to the wavenumber in the dielectric matrix $k_d = \omega\sqrt{\epsilon\epsilon_0\mu_0}$, and the tangential component equals to that of the incident wave vector. So, the substrate is a transmission line with the energy propagating strictly along z, and its surface impedance does not depend on the incidence angle: $Z_s^{TM} \approx j\tan(k_d H)/\sqrt{\epsilon}$. The reflection coefficient can be easily found when one has obtained Z_i:

$$R^{TE} = \frac{Z_i^{TE}\cos\theta - 1}{Z_i^{TE}\cos\theta + 1}, \qquad R^{TM} = \frac{Z_i^{TM} - \cos\theta}{Z_i^{TM} + \cos\theta}. \tag{4}$$

As an example we have considered the structure [4] shown on the left of Fig. 2. To calculate L in $Z_g^{\rm norm}$ we have used analytical models with tabulated functions from [8]. To calculate C we have considered the spiral-shaped patches as pieces of a wire mesh and applied the known averaged boundary conditions to find the effective capacitance of a piece of mesh. This approach is widely used in the theory of low-frequency wire antennas with capacitive loading on the ends. We have compared this self-resonant grid with arrays of simple patches used in mushroom structures. A simple patch array has a capacitive impedance $Z_g = 1/j\omega C$. The grid impedance of the self-resonant grid contains an inductive part $Z_g = j\omega L + 1/j\omega C$, but its capacitance is smaller.

3 Results and discussion

In Fig. 3 we compare the frequency dependencies of the reflection coefficient phase $\arg\{R^{TM}\}$ for a structure with SSP (left part) and a MS (right part). The main conclusion is that in case of the TM polarized incidence the input surface impedance seen by the incident wave is no changed much if the incidence angle is changed, due to the presence of vias connectors. In particular, the resonance frequency where the surface behaves as the magnetic wall is practically independent from the incidence angle. For the TE-case the dynamics of the frequency plots of the reflection phase (with respect to the incidence angle) is the same for the structure with SSP and the MS. The resonance frequency increases with increasing θ.

To validate our theory we have made experiments with a sample of a SSP structure. The main parameters were as follows: substrate thickness $H = 6.1$ mm, permittivity

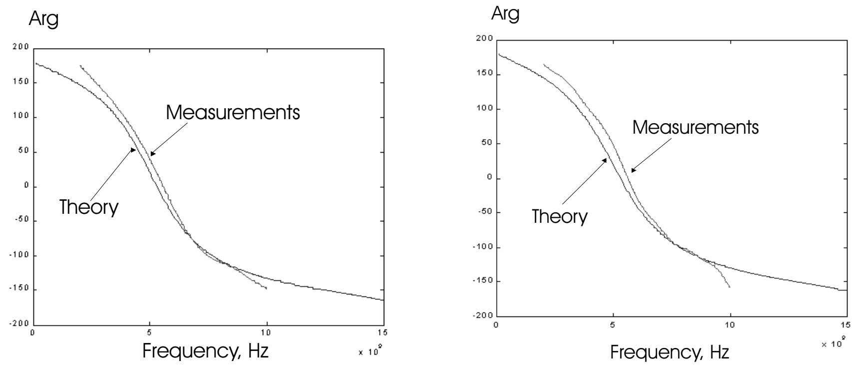

Figure 4: Frequency dependencies of the reflection coefficient phase for a structure with SSP. Left part: normal incidence. Right part: $\theta = 20^o$.

$\epsilon = 2.17$, the array period $D = 4.2$ mm, the strip width $w = 0.3$ mm, the central metal bit size $\Delta = 1.5$ mm. In Fig. 4 we present the results of comparison between the theory and the measurements for the TM-incidence.

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