O. Luukkonen, A. B. Yakovlev, C. R. Simovski, and S. A. Tretyakov. 2008. Comparative study of surface waves on high-impedance surfaces with and without vias. In: Proceedings of the 2008 IEEE AP-S International Symposium on Antennas and Propagation (AP-S 2008). San Diego, California, USA. 5-12 July 2008, paper s326p3, 4 pages.

Comparative Study of Surface Waves on High-Impedance Surfaces With and Without Vias

O. Luukkonen[1], A. B. Yakovlev[2], C. R. Simovski[1], and
S. A. Tretyakov[1]

[1] Department of Radio Science and Engineering/SMARAD Center of
Excellence, TKK Helsinki University of Technology, P.O. 3000,
FI-02015 TKK
[2] Department of Electrical Engineering, The University of Mississippi,
USA
E-mail: olli.luukkonen@tkk.fi

Introduction

High-impedance surfaces (HIS) are periodical electromagnetic structures whose extraordinary properties have made them appealing for many applications, such as reflectarrays, phase shifters, filters, and EBG ground planes. In this paper we concentrate on EBG properties and surface-wave phenomena on HIS structures. It is observed that high-impedance surfaces enable to create an electromagnetic band gap regardless of the period of surface. This helps to minimize the area needed for the EBG structure on a circuit board.

Recently, a simple and accurate analytical model for the HIS structure comprising an array of patches over a grounded dielectric slab was introduced [1]. By taking into consideration the effect of vias, the model can be used to analyze surfaces such as Sievenpiper's mushroom structure. The surface-wave properties of HIS structures have been studied before using transmission-line models [2] or effective medium models [3]. However, these methods fail in the analysis of surface-wave spectrum below the resonance frequency of the HIS with vias or are rather complicated. In this presentation, a simple model is used for a comparative study of surface waves on different types of high-impedance surfaces. The analytical results are compared to simulations done by using Ansoft's High Frequency Structure Simulator (HFSS) [4]. It is shown that despite the simplicity, the model accurately predicts even the backward surface waves on the HIS for the TM polarization and, therefore, can be used for the accurate analysis of surface-wave propagation on different HIS structures.

Analytical Model

The high-impedance surfaces shown in Figs. 1 (a) and (b) are modeled by (input) surface impedance Z_{inp} that connects the cell-averaged tangential fields at the grid plane. This restricts the model to be valid only for wavelengths larger than the period D of the structure ($\lambda > D$). The input surface impedance is a parallel connection of the surface impedance of the grounded dielectric slab at the grid plane, Z_{s}, and the averaged grid impedance of the capacitive grid, Z_{g}:

$$Z_{\mathrm{inp}}^{-1} = Z_{\mathrm{g}}^{-1} + Z_{\mathrm{s}}^{-1}. \tag{1}$$

The grid impedance is naturally dependent on the choice of the capacitive grid and,

for instance, for an array of rectangular patches an expression for Z_g is available in [1].

In the absence of vias the surface impedance of the grounded dielectric slab can be calculated simply, for instance, through the impedance transformation equations for transmission lines. The dyadic form of the surface impedance reads (see e.g. in [5]):

$$\overline{\overline{Z}}_\mathrm{s} = j\omega\mu \frac{\tan{(\gamma d)}}{\gamma} \left(\overline{\overline{I}}_\mathrm{t} - \frac{\mathbf{k}_\mathrm{t}\mathbf{k}_\mathrm{t}}{k^2} \right) \tag{2}$$

where μ is the absolute permeability of the substrate (in our case $\mu = \mu_0$), $\gamma = \sqrt{k^2 - k_\mathrm{t}^2}$, $k = k_0\sqrt{\varepsilon_\mathrm{r}}$ is the wave number in the substrate material, and $\mathbf{k}_\mathrm{t}$ is the tangential wave number component.

The vias are taken into account by treating the material slab as an uniaxial wire medium composed of infinitely long wires (as in [6]): The ground plane acts as one of the image planes and the capacitive grid is considered approximately to act as the other image plane. As the period of the wires is directly proportional to the period of the HIS (above we have restricted the model to low frequencies), the length of the wires is small compared to the wavelength, and the propagation of the surface waves is mainly perpendicular to the wires, a quasi-static model of the wire media can be used.

The surface impedance for a wire medium comprising thin perfectly conducting wires reads [5]:

$$Z_\mathrm{s}^\mathrm{TM} = j\omega\mu_0 \frac{\tan(\gamma_\mathrm{TM}h)}{\gamma_\mathrm{TM}} \frac{k^2 - \beta^2 - k_\mathrm{p}^2}{k^2 - k_\mathrm{p}^2} \tag{3}$$

where $k = k_0\sqrt{\varepsilon_\mathrm{r}}$ is the wave number in the host medium, ε_t is the relative permittivity for the fields along the transverse plane,

$$\gamma_\mathrm{TM} = \sqrt{\omega^2 \varepsilon_0 \varepsilon_\mathrm{t} \mu_0 - \frac{\varepsilon_\mathrm{t}}{\varepsilon_\mathrm{n}}\beta^2} \tag{4}$$

and

$$k_\mathrm{p} = \frac{1}{a\sqrt{\frac{1}{2\pi}\ln\frac{a^2}{4r_0(a - r_0)}}}. \tag{5}$$

Here, a is the period of the wires, r_0 is the radius of the wires, and ε_n is the relative permittivity for the fields normal to the slab,

$$\varepsilon_\mathrm{n} = \varepsilon_\mathrm{t}\left(1 - \frac{k_\mathrm{p}^2}{k_0{}^2\varepsilon_\mathrm{t}}\right). \tag{6}$$
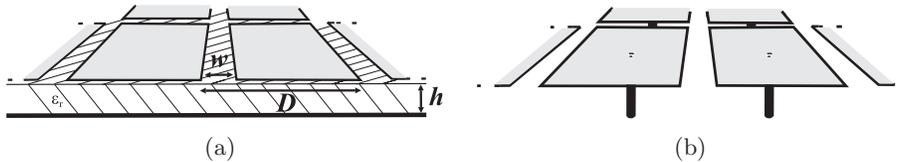

Figure 1: (a) A HIS without vias, where D is the period of the structure, w is the gap between the adjacent patches, h is the height of the substrate, and ε_r is the relative permittivity of the substrate. (b) A HIS with vias.

In the case when the vias are thin and vertically oriented, the relative permittivity for the fields along the transversal plane, ε_{t}, equals to the relative permittivity of the host medium, ε_{r}. In this case the transversal electric field components do not excite the vias and for the TE modes the expression (2) is still valid.

Results and Comparison

As an example, the dispersion behavior of surface waves on a high-impedance surface comprised of square patches over a grounded dielectric slab without and with vias is shown in Figs. 2 and 3, respectively. The solid lines are calculated using the analytical model described above and the simulation results by HFSS are denoted with squares. The dimensions of the HIS are the following: $D = 2\,\mathrm{mm}$, $h = 1\,\mathrm{mm}$, $w = 0.2\,\mathrm{mm}$, $\varepsilon_{\mathrm{r}} = 10.2$, and the radius of the vias is $0.05\,\mathrm{mm}$. The resonance frequency of the surface for normally incident plane waves is approximately $11.65\,\mathrm{GHz}$. The analytical results agree very well with the simulation results.
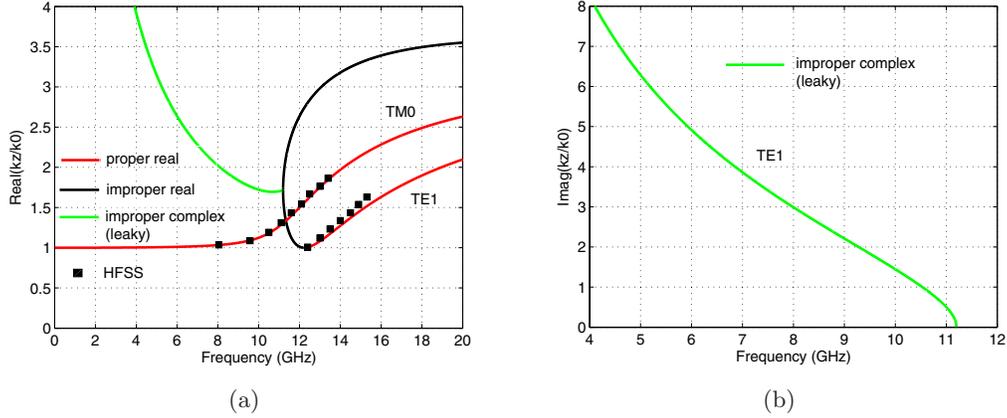

Figure 2: Color online. Dispersion behavior of surface waves on the HIS without vias. (a) The real part of the normalized propagation constant. (b) The imaginary part of the normalized propagation constant.
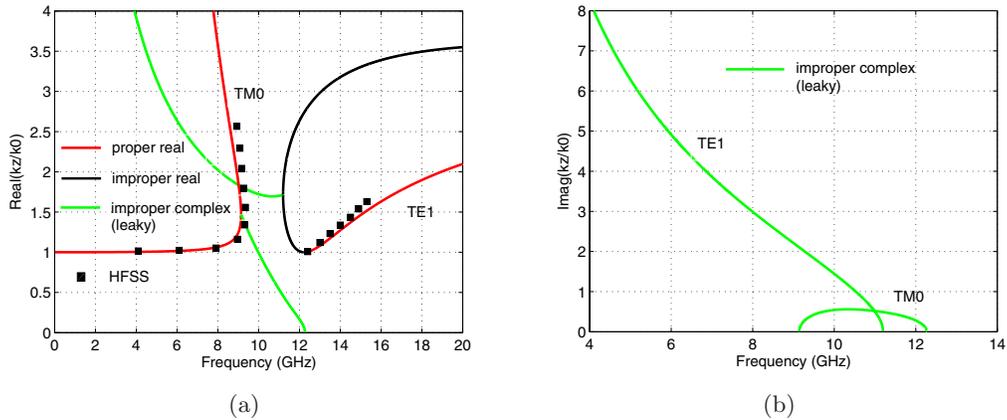

Figure 3: Color online. Dispersion behavior of surface waves on the HIS with vias. (a) The real part of the normalized propagation constant. (b) The imaginary part of the normalized propagation constant.

It can be seeing (Fig. 2 (a)) that in the absence of vias the analytical model predicts correctly the dispersion behavior and there is no band gap for the TE and TM surface waves. In the case when vias are presented (Fig. 3 (a)), the analytical model indeed predicts the band gap correctly. It is observed that at low frequencies the surface wave is a forward wave and it gradually transforms into a backward wave as the frequency increases (see also [2]). For the frequency band approximately from 8 GHz to 9 GHz we have two solutions for the TM0 mode: a forward- and a backward-wave solution. The TE1 mode is unaffected by the vias.

The backward-wave solution is due to the effective inductance of the thin metal vias. At low frequencies away from the resonance frequency of the surface the electromagnetic field weakly couples to the HIS structure. Therefore, the effective inductance due to the vias is minimal; only a forward-wave solution exists, and the TM0 mode solutions for the HIS with and without vias concur with each other. While moving closer to the resonance frequency of the HIS, the input impedance of the HIS changes and electromagnetic fields couple stronger to the structure and excite the vias. Because of this coupling, a backward-wave solution occurs, which creates a band gap between the TE and TM modes.

Conclusions

Comparative study of the surface waves on high-impedance surfaces has been presented. A simple analytical model for the HIS without vias is shown to predict accurately the surface-wave behavior. In the case of HIS structure with vias, it is shown that a simple model that treats the dielectric material with embedded vias as a uniaxial material is capable of predicting accurately the properties of forward and backward surface waves. The proposed analytical model can be effectively applied for the analysis of surface-wave behavior on different HIS structures.

References

[1] O. Luukkonen, C. Simovski, G. Granet, G. Goussetis, D. Lioubtchenko, A. Räisänen, and S. Tretyakov, "Simple and accurate analytical model of planar grids and high-impedance surfaces comprising metal strips or patches", available at: *http://arxiv.org/abs/0705.3548*.

[2] A. Grbic and G. V. Eleftheriades, "Dispersion analysis of a microstrip-based negative refractive index periodic structure," *IEEE Microwave and Wireless Components Letters*, vol. 13, no. 4, pp. 155–157, 2003.

[3] S. Clavijo, R. E. Díaz, and W. E. McKinzie, III, "High-impedance surfaces: An artificial magnetic conductor for a positive gain electrically small antennas," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 10, pp. 2678–2690, 2003.

[4] The homepage of Ansoft corporation, *www.ansoft.com*.

[5] S. A. Tretyakov, *Analytical Modeling in Applied Electromagnetics*, Artech House, Inc., Norwood, MA, 2003.

[6] O. Luukkonen, C. Simovski, A. Räisänen, and S. Tretyakov, "Propagation properties of a tunable impedance waveguide," available at: *http://arxiv.org/abs/0709.3160*.