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High-Impedance Surfaces with Aperiodically-Ordered Textures

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Abstract — **This paper deals with a study of textured (mushroom-type) high-impedance substrates based on *aperiodic-tiling* geometries. In this connection, preliminary results from full-wave simulations are presented in order to explore possible applications as artificial-magnetic-conductor ground-planes for low-profile directive antennas.**

1 INTRODUCTION AND BACKGROUND

A textured high-impedance surface (HIS) is a kind of electromagnetic band-gap (EBG) structure exhibiting two important features: *i)* it can reflect electromagnetic waves with no phase reversal, thereby behaving as an *artificial magnetic conductor* (AMC), and *ii)* it can suppress the surface wave (SW) propagation within certain frequency ranges [1]. Both properties are highly desirable in ground planes for low-profile antennas, in order to improve the electrical and radiative responses. Over the past decade, the study and design of HIS ground-planes have been almost entirely restricted to *periodic* configurations, such as metal sheets covered with small bumps, corrugated metal slabs, mushroom-type surfaces, etc. The reader is referred to [2] for a collection of recent results and applications.

Recently, a new mushroom-type HIS configuration has been proposed [3], based on a *quasi-periodic* octagonal (Ammann-Beenker) tiling geometry. Such structure was found to exhibit a very interesting response, in terms of highly-directive radiation from a small dipole laid on it, and suppression of the transverse-electric SW over a broad frequency range.

In a series of ongoing investigations, as an attempt to better understand the underlying phenomenology and potentials, we have undertaken a preliminary parametric study of various HIS configurations with aperiodically-ordered mushroom-type textures, based on representative aperiodic tilings. Such geometries, intrinsically tied with the concept of "quasicrystals" in solid-state physics [4], are gaining a growing attention in many branches of science and technology [5]. In electromagnetics engineering, recent studies on EBG quasicrystals [7]–[13] have confirmed the possibility of obtaining effects and properties similar as those exhibited by periodic EBG structures, with potential advantages (e.g., larger bandgaps, lower and/or multiple frequencies of operation, higher isotropy, richer and more wavelength-selective defect states, easier achievement of phase-matching conditions) via a judicious exploitation of the additional degrees of freedom typically available in aperiodic structures. Interesting applications have been proposed to lasers [14], negative refraction and superlensing [15], nonlinear optical frequency conversion [16], wavelength-division multiplexing [17], enhanced transmission through subwavelength hole arrays [18], directive emission [19], etc.

In this paper, we consider two finite-size aperiodically-textured HIS ground-planes and, via full-wave simulations, we compare their responses in terms of the radiation (return loss and directivity) from a small dipole laid on them.

2 GEOMETRY AND RESULTS

We consider two aperiodic-tiling geometries:

- *Octagonal* (Ammann-Beenker), as in [3], made of square- and rhombus-shaped tiles, and characterized by 8-fold symmetry [4].
- *Dodecagonal*, made of square- and equilater-triangle-shaped tiles, and characterized by 12-fold symmetry [6].

The octagonal tiling is generated via a "cut-and-projection" algorithm [4], whereas the dodecagonal tiling is generated using the Stampfli substi-

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tution rules [6]. Starting from these tiling geometries, the corresponding HIS configurations are obtained by placing metallic patches shaped according to the tiles (suitably scaled so as to guarantee a constant spacing of 0.7 mm) on top of a 1.6 mm thick dielectric substrate with relative permittivity $\epsilon_r = 2.2$ (RT/duroid 5880) backed by a metallic ground plane. The metal patches are connected to the ground plane by metal vias of diameter 0.7 mm. It is important to emphasize that, in view of the aperiodicity, standard concepts and tools typically utilized for the study of periodic HIS configurations ("unit cell", band-structure, Brillouin zone, etc.) cannot be applied, with the consequent necessity of studying *finite-size* structures. In our examples, the structures are obtained by cutting a suitably-sized region of the tiling, preserving its center of local symmetry. Figures 1a,b show the top view of the two structures under analysis. Note that, in order to maintain the same spacing between the metal patches and a comparable number of patches, the patch side-lengths a_{patch} and the overall HIS sizes are slightly different for the two geometries (see Fig. 1 caption). The characteristic dimensions have been chosen as in [3], so as to allow direct comparison with our results (at least for the octagonal geometry), the total sizes being dictated by our current computational resource limitations.

For finite-size HIS structures, a common way of ascertaining the AMC behavior is to study the matching properties of a small dipole, laid parallel to the surface at a very close distance. For a flat metallic surface, it is well-known that the dipole will be short-circuited (out-of-phase image current), resulting in a very low radiation efficiency and in a return loss close to one. When the same dipole is laid on a HIS acting as an AMC, the image currents are in phase, so that the dipole can radiate much more efficiently, resulting in a low return-loss. In our study, we placed a 16mm–long dipole, parallel and very close (0.7 mm) to the surface (at its center of local symmetry), and computed via full-wave simulations the return loss spectra for the two configurations. Results are shown in Fig. 2. For both geometries, one observes some (more or less pronounced) dips in the return loss spectrum, corresponding to AMC-type behavior. In particular, for the octagonal HIS in Fig. 2a, the response reproduces fairly well the results observed in [3], with three main dips. A qualitatively similar behavior, with less pronounced and frequency-shifted dips, is observed for the dodecagonal HIS (Fig. 2b).

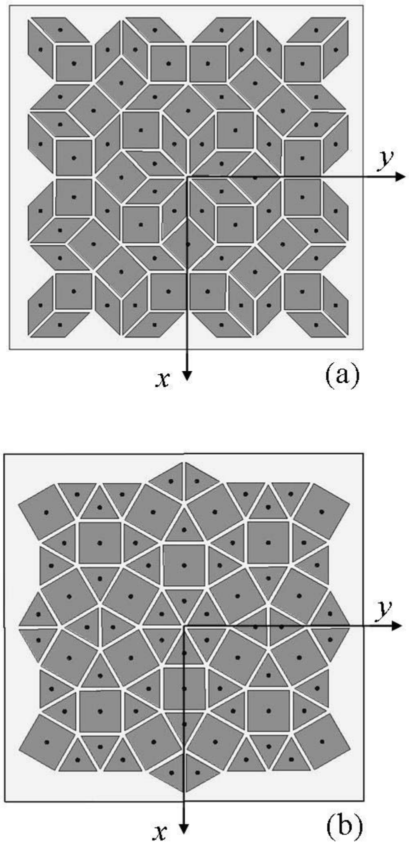

Figure 1: HIS geometry (top view). (a): Octagonal ($a_{square} = 7.6$ mm, $a_{rhombus} = 7.3$ mm, total size: 70×70 mm^2); (b): Dodecagonal ($a_{square} = 7.6$ mm, $a_{triangle} = 7.1$ mm, total size: 62×62 mm^2). Metal patches are laid with spacing 0.7 mm on a metal-backed dielectric substrate of thickness 1.6 mm and relative permittivity $\epsilon_r = 2.2$, and are connected to the ground plane by metallic vias with diameter 0.7 mm.

We then looked at the radiation patterns within the AMC bands. For a finite flat metal ground plane, SWs can propagate bound to the interface between metal and free space, and, when reaching a discontinuity (e.g., corner, edge), can radiate into free space. This typically results in the appearance of ripples in the forward direction, and a poor front-to-back ratio. Conversely, a HIS ground-plane can strongly suppress SWs, resulting in a smoother radiation pattern and a significant improvement of the front-to-back ratio. Figure 3 shows the most directive radiation patterns for the 16mm-long dipole laid on the two HIS ground planes, for comparable values of the voltage standing-wave ratio ($\lesssim 2$). One observes the expected lack of ripples and the almost complete absence of backward radiation. Again, these preliminary results confirm the high directivity observed in [3] for the case of

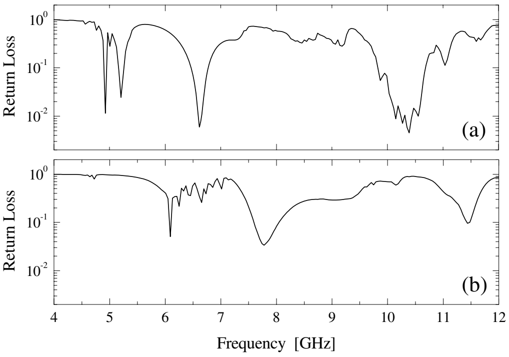

Figure 2: Return loss ($|S_{11}|^2$) of a 16mm–long dipole parallel to the HIS and placed above the center of local symmetry at a distance of 0.7 mm. (a): Octagonal; (b): Dodecagonal.

octagonal HIS (Fig. 3a), and extend them to the case of dodecagonal geometry (Fig. 3b).

3 CONCLUSIONS AND PERSPECTIVES

In this paper, we have been concerned with a preliminary study of the electromagnetic properties of finite-size HIS ground-planes based on aperiodically-ordered mushroom-type textures. We have considered two aperiodic-tiling (octagonal and dodecagonal) geometries, and compared their performance as ground-planes for low-profile directive antennas, in terms of return-loss and radiation pattern. Our results, based on full-wave simulations, confirm the possibility (already pointed out in [3], in connection with the octagonal geometry) of obtaining multiple AMC bands and directive radiation using aperiodically-ordered textures. However, a more comprehensive parametric study is still needed to assess their actual superiority as compared to the periodic counterparts. Also of interest, for future investigations, is a parametric study of the SW propagation, a deeper understanding of the role of the local order and symmetry properties, as well as the possible interpretation and parameterization of the directive radiation in terms of leaky waves.

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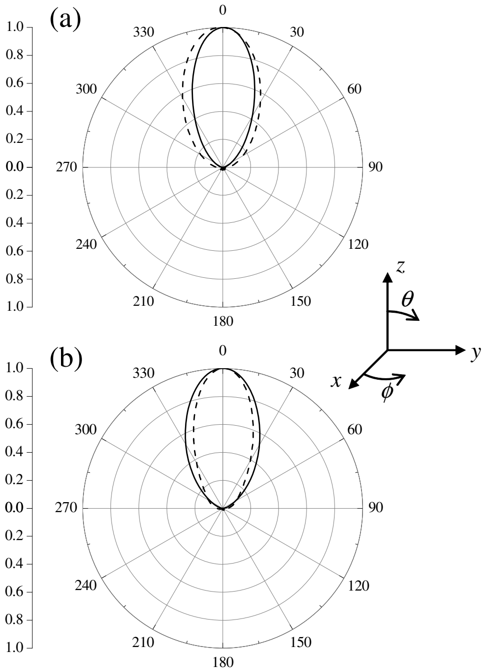

Figure 3: Radiation patterns (normalized to the peak directivity). (a): Octagonal (6.5GHz); (b): Dodecagonal (7.8 GHz). Solid curves: $\phi = 0°$ plane; dotted line: $\phi = 90°$ plane.

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