Design of a Non-uniform High Impedance Surface for a Low Profile Antenna

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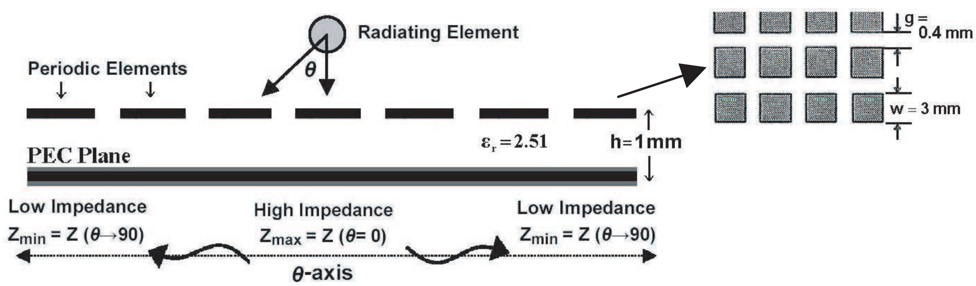
Abstract—Two Non-Uniform High Impedance Surfaces (NU-HIS or tapered HIS) are proposed against a Uniform HIS (U-HIS). All surfaces are one dimensional (1D) and made of parallel wires with a length a little less than $\lambda/2$ around the resonance frequency. To show the effect of the surfaces, a half wavelength dipole antenna is placed over four different surfaces, PEC, U-HIS, NU-HIS, and modified NU-HIS (MNU-HIS) while the dipole height is fixed and very close to the surface. These four EM problems are analyzed numerically by the method of moments (MoM), and the results are compared. It is concluded that MNU-HIS yields more bandwidth than NU-HIS, and also, NU-HIS yields more bandwidth than U-HIS, while overall structures in all cases have identical volumes and nearly identical gains. This effect is attributed to the decrease of sensitivity to the angle of incidence by applying non-uniformity.

1. Introduction

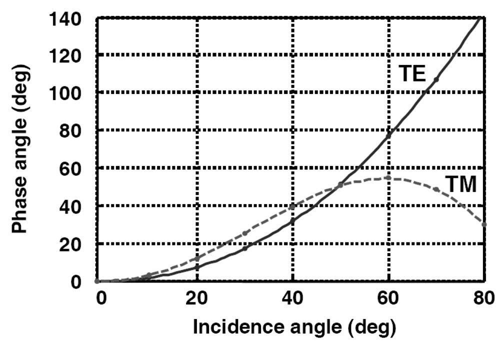
It is well known that a high impedance surface or specifically a hypothetical perfect magnetic conductor may be very useful in a large variety of microwave and antennas applications. Recently, electromagnetic bandgap (EBG) structures have been widely studied for their behavior as High Impedance Surface (HIS) or Artificial Magnetic Conductor (AMC). Principally, they show stop band frequencies in which the tangential magnetic fields are considerably reduced. AMC is a special member of HIS family, which is designed to imitate the behavior of a perfect magnetic conductor (PMC). In fact, the AMC condition is characterized by the frequencies where the phase of the reflection coefficient is zero, i.e., $\Gamma = +1$ [1]. In contrast, a HIS may deviate a little from this condition, sometimes yielding more flexibility in antenna design. For example, in [2], the mushroom structure played the role of a ground plane for a dipole antenna a little upper than its resonance or AMC condition. Besides, in [3] the behavior of the same structure as a reactive impedance surface (RIS) was introduced, and the idea was applied to patch and dipole antennas. Repeatedly, it has been shown that HIS structures improve antenna performance and reduce the effects of surface waves. The latter feature yields better antenna radiation pattern and less coupling between elements of an array [2, 4]. So far, some 3D [5] and 2D [1, 3] structures have been proposed to realize HISs. Current realizations of 2D HISs are based on a planar FSS at the interface of a metal-backed dielectric slab with or without vertical vias [6]. This configuration is desirable because it is low-cost and easy to integrate in practice [7]. There is a problem with most of proposed HISs, however. In fact, the shift of the resonant frequency versus the incidence angle affects the performance of most well known HISs [8, 9]. To clarify this flaw, the behavior of a typical mushroom structure for different angles of incidence is presented in Fig. 1.

The curve has been obtained by Ansoft's Designer software, which is an electromagnetic solver based on MoM (equipped with Periodic MoM, PMM [1]). Generally, if the frequency bandwidth of low-profile antennas, placed near a typical HIS is within the resonance band of HIS, a significant improvement in the radiation efficiency is expected, compared to the conventional cases using PEC ground plane. However, the improvement is not always as much as desired [10]. An explanation for this behavior is that the high-impedance surface does not exhibit uniform surface impedance with respect to the different spatial harmonics radiated by an antenna, as depicted in Fig. 1. For instance, it is known that electrically small horizontal antennas radiate a large angular spectrum of TE and TM-polarized plane waves. As a result, the resonant frequency at which the effect of the magnetic wall is observed depends on the incidence angle; Therefore, the total interaction between the antenna and the HIS will be a summation of constructive and destructive effects [6].

References [1, 6, 7, 9, 11] are examples of the works concentrating completely on designing angularly stable HISs or AMCs. In all of these cases, the basic cell shape is changed and optimized, while the cell size is fixed throughout the structure (uniformly periodic structures). In the present work, we seek angular stability for HIS in order to improve antenna radiation near the surface. This is done by applying non-uniformity to a uniform HIS. Two 1D NU-HISs made of parallel wires are proposed, and their behaviors are compared with that of the uniform version (U-HIS). Then, the performance of a half wavelength dipole very close to all of these surfaces



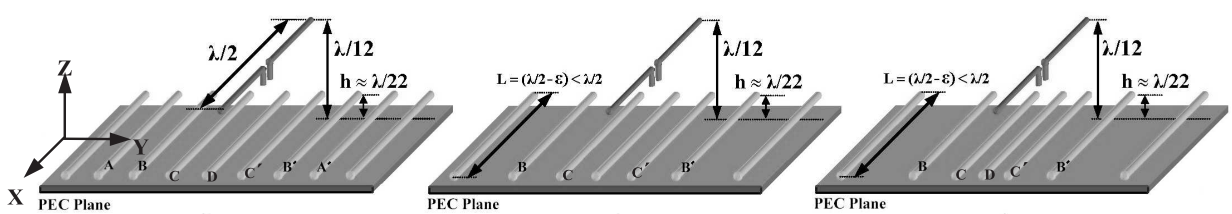
(a)



(b)

Figure 1: Behavior of a typical mushroom structure in different angles of incidence, $f = 18.55\,\mathrm{GHz}$, a) front view, cross section, and the relevant dimensions, b) phase of reflection coefficient versus angle of incidence obtained by Ansoft's Designer software.

is investigated. During the process, as shown in Fig. 2, the dipole length and radius ($\approx 0.45\lambda$ & $\lambda/220$), the spacing of side elements from center ($\approx 0.23\lambda$), and the spacing of dipole from the lower section of the planes (PEC planes) ($\approx \lambda/12$) are kept fixed for better understanding of the influence of the surfaces alone. Because the structures are composed of wires, NEC software (NEC Win Pro. V 1.1), which is an electromagnetic solver based on MoM, is used for analysis.



(a) (b) (c)

Figure 2: The geometry of the dipole antenna located over a) U-HIS, b) NU-HIS, and c) MNU-HIS.

2. The Main Idea, Explanation and Verification

The underlying basis for the idea in this paper returns to an important clue from this equation [12]:

$$\frac{X}{\eta_0} = F(p, w, \lambda) = \frac{p\cos\theta}{\lambda}\left[\ln\left(\cos ec(\frac{\pi w}{2p})\right) + G(p, w, \lambda, \theta)\right] \tag{1}$$

where η_0 and λ are free space wave impedance and wavelength respectively. Also, G is a correction term for large angles of incidence. The equation gives the surface impedance of parallel strips facing a TE plane wave as depicted in Fig. 3. Ignoring G in (1), the clue is that when w and λ are fixed, X can be kept stable by a proper increase of p against the increase of θ. In other words, by gradually increasing p from center elements to the side ones (applying tapering), more angular stability is achievable. Note that the same effect is also attained by gradually decreasing w. But there are three problems in using such an idea. Firstly, as in Fig. 2, we have

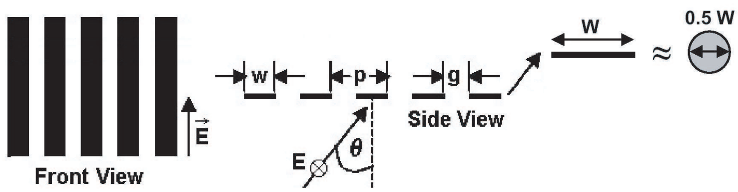


Figure 3: Front and side view of parallel metal strips (or equivalently wires) facing a TE plane wave impinging in different angles of incidence.

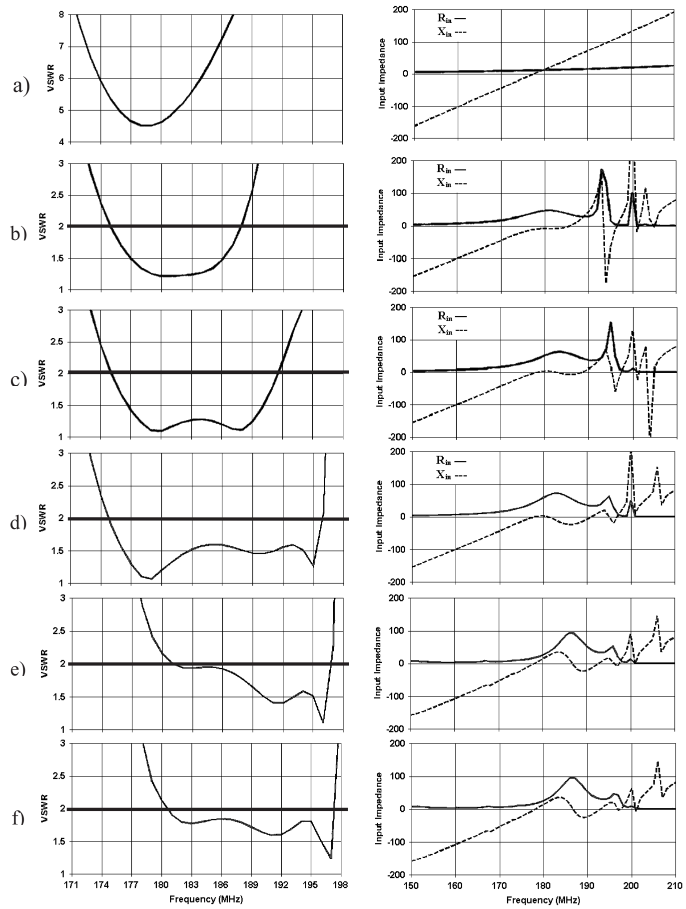


Figure 4: VSWR and input impedance of the dipole located over a) PEC ground plane, b) U-HIS, c) NU-HIS, d) MNU-HIS, e) MNU-HIS with finite wire ground plane, and f) the last design after a little tuning the dipole length and radius of side wires.

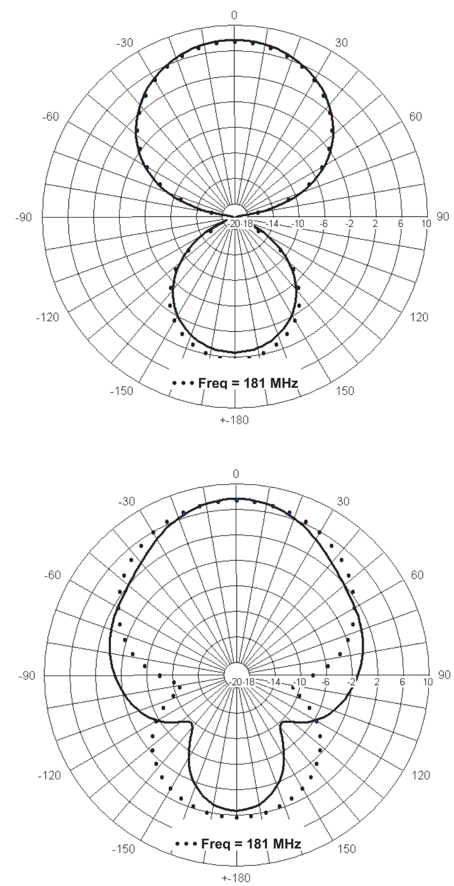


Figure 5: Gain (dB) for Fig. 2 (c), while the infinite PEC plane is replaced by the finite wire ground plane, a) E-plane, b) H-plane.

used parallel wires instead of strips; Secondly, (1) is not correct when the structure is placed near the PEC plane; Thirdly, in Fig. 3, the length of strips are infinite while those of this work are finite ($\approx \lambda/2$). The first problem is solved considering the nearly equivalent scattering properties of strip and wire as depicted in Fig. 3 and stated in [6]. As for the second, it can be said that because here we need the general (not exact) effect of tapering on X, we can foresee that even in the present condition the general behavior in (1) remains true. Finally, as for the third, it is reminded from transmission line theory that a $n\lambda/2$ slice of a transmission line represents an infinite line because the input impedance of such a line equals the load impedance. Fortunately, our numerical investigations have confirmed the correctness of the approximations and predictions above, at least for our proposed structures.

To study the effect of the idea, a half wavelength dipole antenna is numerically analyzed (by NEC) placed over four different surfaces, PEC, U-HIS, and NU-HIS, and modified NU-HIS (MNU-HIS) while the dipole

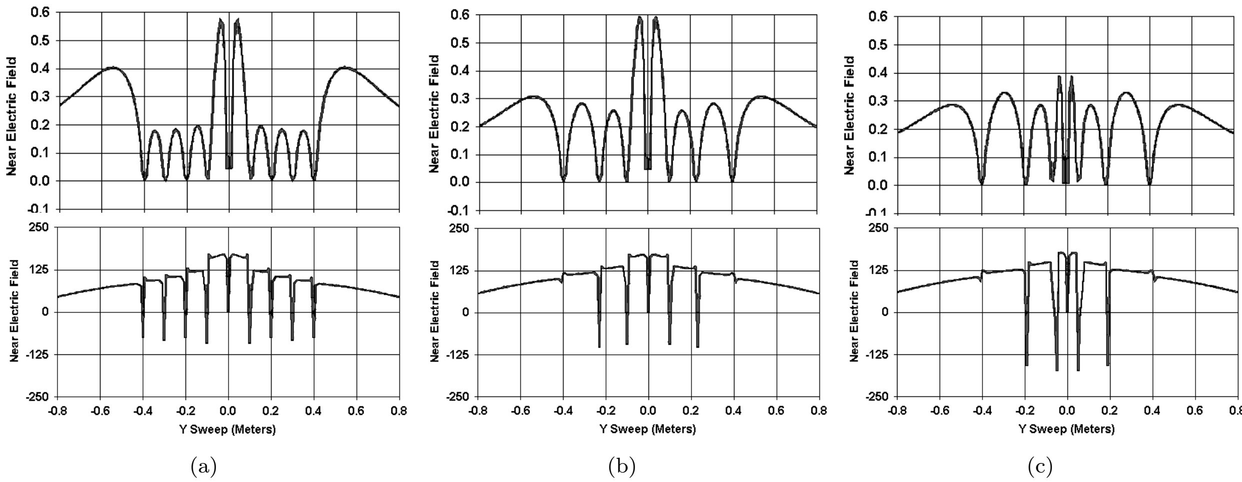


Figure 6: Near electric fields on the high impedance surfaces along Y-axis, excited by the dipole in Fig. 2, $X = 0$, $Z = 7.5\,\mathrm{cm}$, $f = 184\,\mathrm{MHz}$, a) U-HIS (a), b) NU-HIS (b), and c) MNU-HIS (c) (upper row for amplitude and lower for phase of the fields).

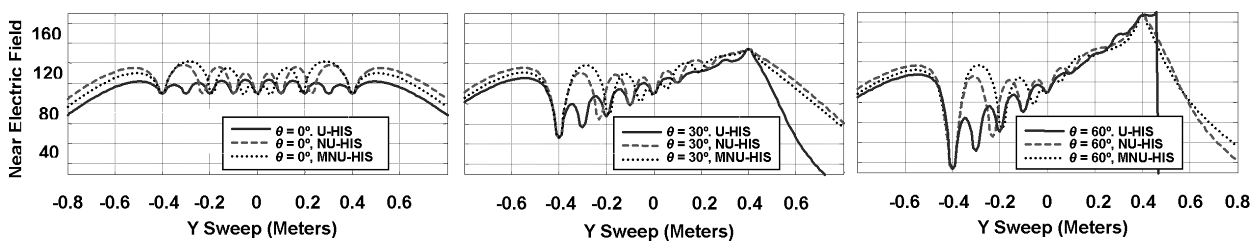


Figure 7: Phase of near electric fields excited by TE plane wave (in Fig. 2, E_X) on the high impedance surfaces, along Y-axis, $X = 0$, $Z = 7.5\,\mathrm{cm}$, $f = 184\,\mathrm{MHz}$.

height is fixed and very close to the surface. The proposed HISs are shown in Fig. 2 in which the dipole and the parasitic wires radii are 1 mm and 8 mm, respectively. As in Fig. 4 (a), for the dipole near the PEC plane without any parasitic wires, there is no resonance in Z_{in}. As a result, the VSWR is very poor. Deploying uniformly-placed wires ($\approx \lambda/17.5$) close to the PEC plane ($\approx \lambda/22$), as in Fig. 2 (a), a U-HIS is formed. As a result, the VSWR of the dipole will improve very much as in Fig. 4 (b). The bandwidth on VSWR (< 2, $Z_0 = 50$) is 6.3%. The curves are very similar to those in [2] and [3]. Now the non-uniformity idea emerging from (1) is applied by removing the two wires A and A' in Fig. 2 (a) and properly shifting the positions of B and B' sidewards. The best result rendering the most bandwidth is a Non-Uniform HIS (tapered HIS) shown in Fig.2 (b). Here the spacing BC is about $\lambda/13.5$. Fig. 4 (c) shows the VSWR and Z_{in} of this surface. As observed, the bandwidth increases form 6.3% to 9.3%. In the second step, considering the same point emerging from (1), it seems that also by making the center elements, C, D and C' a little denser the bandwidth may become better. Thus, using a simple optimization procedure, the spacing CD and simultaneously BC are adjusted in order to optimize the bandwidth on VSWR. The result is referred to as MNU-HIS and is shown in Fig. 2 (c). The spacing BC and CD are about $\lambda/13$ and $\lambda/29$ respectively. Fig. 4 (d) shows the related VSWR and Z_{in}. As seen, the bandwidth increases from 9.3% to 11.33%. Note that in all of these cases, the overall gain is nearly identical ($\approx 9\,\mathrm{dB}$) while the overall structure volume is fixed (not including the PEC plane, $0.45\lambda \times 0.45\lambda \times \lambda/12$).

Up to this point, all of the presented designs used an infinite PEC plane. In the next step, this ideal plane is modeled in NEC as a real finite plane ($x \approx 0.45\lambda$ & $y \approx 0.63\lambda$). Therefore, the overall structure volume is ($0.45\lambda \times 0.63\lambda \times \lambda/12$). The corresponding VSWR and Z_{in} are shown in Fig. 4 (e). As obvious, due to cutting the plane, the bandwidth deteriorates to 7.95%. To remove this descent, the radius of the side elements is tuned a little. In fact, from (1), it is deduced that gradually reducing the radius is an alternative means of improving angular stability of the surface. This tuning is done simultaneously with a little tuning of the dipole length. After tuning, the best side elements radius is 7 mm (formerly 8 mm) and dipole length is 79.6 cm (formerly fixed at 80 cm). The improved result shows 9.45% bandwidth as in Fig. 4 (f). The relevant gains in E and H-planes are depicted in Fig. 5. To give better understanding of the behavior of the surfaces, phase and amplitude of near fields excited by the dipole on the surfaces are presented in Fig. 6. In addition, the phases of near fields (on the surfaces) exited by a TE plane wave in different angles of incidence are rendered in Fig. 7. As deduced from Fig. 6, both the amplitude and phase become more stable as a result of imposing non-uniformity. In other words, in MNU-HIS the element right under the dipole and those on sides are illuminated much the same by the dipole. This is an implication for angular stability of the surface. Note that from apertures theory it is known that uniform phase and amplitude is an ideal condition yielding maximum performance. Fig. 7 is also a good indicator of angular stability of the surfaces. As observed, the phase of near fields on NUM-HIS withstands the most against increase of incidence angle. It can be concluded that the more the surface is angularly stable, the more bandwidth it renders near the dipole antenna. In other words, angular stability of the HIS, obtained through non-uniformity, improves the antenna performance.

3. Conclusion

The paper studies the effects of applying non-uniformity to a 1D uniform HIS. The proposed surfaces are made of parallel wires placed uniformly (U-HIS) or non-uniformly (NU-HIS) over a PEC ground plane. To show the effect of imposing non-uniformity, a half wavelength dipole antenna is numerically analyzed by MoM in the close vicinity of four different ground planes, PEC, U-HIS, NU-HIS, and modified NU-HIS (MNU-HIS), while the dipole height and length are kept fixed. Comparison of the results shows that MNU-HIS yields more bandwidth than NU-HIS, and also, NU-HIS yields more bandwidth than U-HIS, while all cases have identical volume and nearly identical gain. This effect is attributed to the improvement of angular stability of the surfaces caused by applying an apt non-uniformity.

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