From a PEC Ground Plane to an EBG Surface: Understanding the Underlying Physics

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1. Introduction

Low profile antenna designs form extremely attractive solutions for wireless communications and mobile devices. [1] provides ample references for the existing state-of-the-art electromagnetic band-gap (EBG) structures. The challenge in these designs is to decouple the effect of the adjacent ground plane from the antenna itself. For example, when an electric dipole antenna is placed closely parallel to perfect electric conductor (PEC) ground plane due to the reverse image current (image theory), the antenna performance is severely compromised. In order to overcome this ground plane and antenna interaction, artificial complex ground planes such as electromagnetic band-gap (EBG) structures have been proposed. Due to their unique electromagnetic properties like in-phase reflection and surface wave suppression, EBG structures have garnered considerable research interest in the antenna design community. The focus of this work is to systematically evolve from PEC to EBG and try to understand the underlying physical mechanisms involved in the whole process. In order to analyze the features of EBG (mushroom-like) structures we utilize full wave electromagnetic simulators based on advanced numerical methods. These EBG (periodic) structures consist of patches connected to the PEC ground plane through vias. The EBG structures are characterized based on their reflection phase, dispersion diagrams and band-gaps. Some of the applications of these EBG surfaces include antenna substrate for surface wave mitigation and reflection/transmission surfaces for high gain antennas. Firstly, the reflection phase characterization of the PEC ground plane, via loaded PEC ground plane, patch loaded PEC ground plane and EBG surface is performed in that order. Next, the dispersion diagram characterization for patch loaded PEC ground plane and EBG surface is discussed to identify the stop band. Finally, an electric dipole is selected as a test antenna and placed close to PEC ground plane, patch loaded PEC ground plane and EBG surface and the antenna performance is evaluated.

2. Reflection Phase Characterization

Fig. 1 shows the evolution of the EBG surface from the PEC surface. In this analysis, the periodic structures (unit cell) are illuminated with plane wave incident at different angles for TE and TM polarizations. The reflection phase is obtained for various incident angles and different frequencies using HFSS. In Fig. 1, 'h' is the height of the plane at which the reflection phase is computed, 'd' is the distance between the vias and also the distance between the center of the patches, and 'g' is the gap between the edges of the patches. Reflection phase characteristics of the PEC ground plane, via loaded PEC ground plane, patch loaded PEC ground plane and EBG-Mushroom surface are presented. As a representative example, the 0° reflection phase for both TE and TM polarization for all the test cases.

Fig. 1(a) shows the reflection phase obtained from the PEC surface. It is observed that 0° phase contour for both TE and TM waves starts at $h = \lambda/4$ for normal incidence (as expected) and bends at higher frequencies. Fig. 1(b) shows the reflection phase obtained from the via loaded PEC surface. In this case, the height of the plane at which the reflection phase is computed is equal to the distance between the vias ($d = h$). For TE waves, 0° contour starts at $h = \lambda/4$ for normal incidence and bends at higher frequencies. For TM case, 0° contour starts at $h = \lambda/4$ for normal incidence and is angle independent at higher frequencies. Fig. 1(c) shows the reflection phase obtained from the patch loaded PEC surface. In this case, the height of the plane at which the reflection phase is computed is equal to the distance between the center of the patches (d = h) and twice the gap between the edges of the patches (g = h/2). For TE waves, 0° contour starts at h = λ/6 for normal incidence and it is not significantly dependent on incident angle at higher frequencies. For TM case, 0° contour starts at h = λ/6 and bends at higher frequencies. Fig. 1(d) shows the reflection phase obtained from the EBG surface. In this case, the height of the plane at which the reflection phase is computed is equal to the distance between the center of the patches (d = h) and twice the gap between the edges of the patches (g = h/2). For TE waves, 0° contour starts at h = λ/6 for normal incidence and it is not significantly dependent on incident angle at higher frequencies. For TM case, 0° contour starts at h = λ/6 for normal incidence and is angle independent at higher frequencies. It is clearly observed that for the EBG-Mushroom structure the 0° phase contour is nearly independent of the angle of incidence and polarization. This analysis shows that the EBG structure is most robust to different incident angles and polarizations. By altering the gap (g) and the distance (d), the 0° contour can be lowered. By properly adjusting the parameters (g, d), flattened reflection phase curves can be obtained for all angles of incidence.

3. Dispersion Diagram Characterization

The dimensions of the analyzed EBG structure are W = 0.10λ, g = 0.02λ, h = 0.04λ, ε_r = 2.94. The radius of the via in the EBG structure is 0.005λ. The free-space wavelength at 4 GHz, λ = 75 mm, is used as a reference length to define the physical dimensions of the EBG structure. In this implementation, a single unit of the EBG structure is simulated to model an infinite periodic structure using HFSS. The bandgap characterization for EBG [2] is shown in Fig. 2(c). According to the finite element model, the first mode follows the light line up to a certain frequency, where it suddenly becomes very flat. The second mode begins at a higher frequency, and continues upward with a slope of less than the speed of light in vacuum, which is indicated by a dotted line. The band gap is from 4 to 6 GHz for this particular structure. The band diagram for the patch loaded structure is also shown in Fig. 2(d). The second mode waves are unaffected by the absence of the vias, and appears similar to the EBG structure. However, the first mode is no longer terminated below the resonance frequency, as it was when the vias were present, and there is no band gap. The first mode curve continues upward with a slope of slightly less than the speed of light. Therefore, the presence of the vertical connecting vias is critical for the suppression of first mode surface waves, and the creation of a forbidden band. In order to characterize this band from reflection phase method, the unit cell for both EBG structure and patch loaded PEC surface was simulated. It was observed that both the reflection phase plots were identical for normal incidence (effect of vias not seen for normal incidence). The bandgap corresponds to reflection phase band from 45° to 135° [1]. Similar analysis has also been performed for Uniplanar Compact EBG (UC-EBG). This particular class of EBG does not consist of shorting vias.

4. Test Case: Electric dipole

Fig. 3(a) shows a comparison of a low-profile wire antenna design in free space, on substrate backed ground plane, on substrate with periodic patches and on an EBG surface. The dipole length is 0.32 λ and its radius is 0.005λ, where the reference frequency is 4 GHz (λ = 75 mm). The dipole is placed 0.06λ from the PEC surface, 0.02λ from the EBG top surface. A finite ground plane, having a 1λ × 1λ size, is used in the analysis. The dipole resonates at 5.6 GHz in free-space with -15 dB match. When placed over a substrate backed ground plane, the matching deteriorates to -5 dB at 5.2 GHz [3]. This is due to the reverse current image phenomenon where the radiation from the original dipole and image cancel each other resulting in poor matching. When the dipole is placed on substrate with periodic patches, the matching improves to -15 dB at 5 GHz. The best return loss of −38 dB at 5.35 GHz is achieved by the dipole antenna over the EBG ground plane. The reflection phase of the EBG surface varies with frequency from 180° to −180°. In a certain frequency band, the EBG surface successfully shields the effect of ground plane so that the dipole can radiate efficiently. The radiation patterns (not shown here) also validate the working of dipole over EBG.

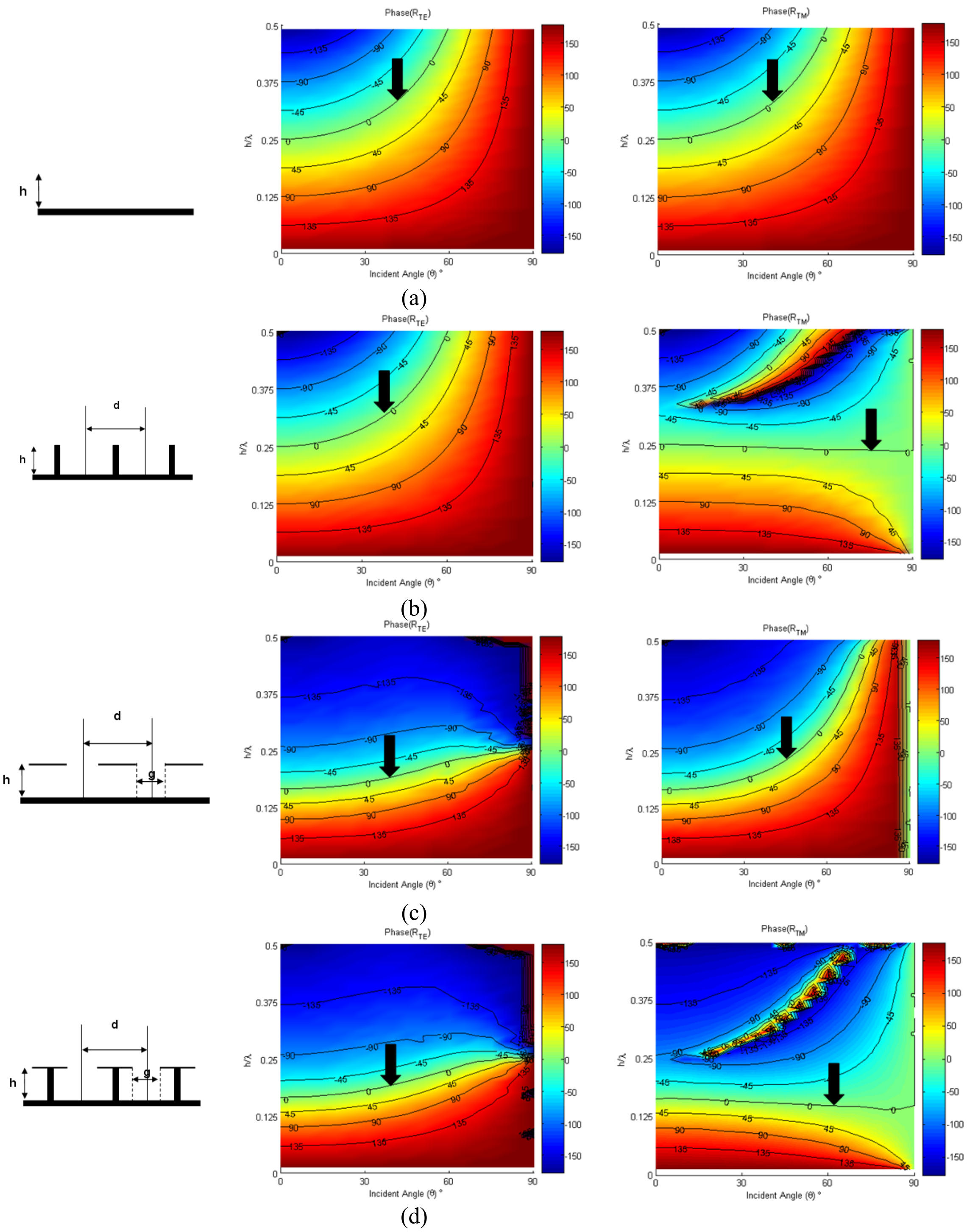

Figure 1: Reflection Phase for both TE (left figures) and TM (right figures) polarization waves for different angles of incidence (a) PEC surface (b) Via loaded PEC (c) Patch loaded PEC surface (d) EBG surface. Note the features of 0° and 90° phase curves versus angle of incidence.

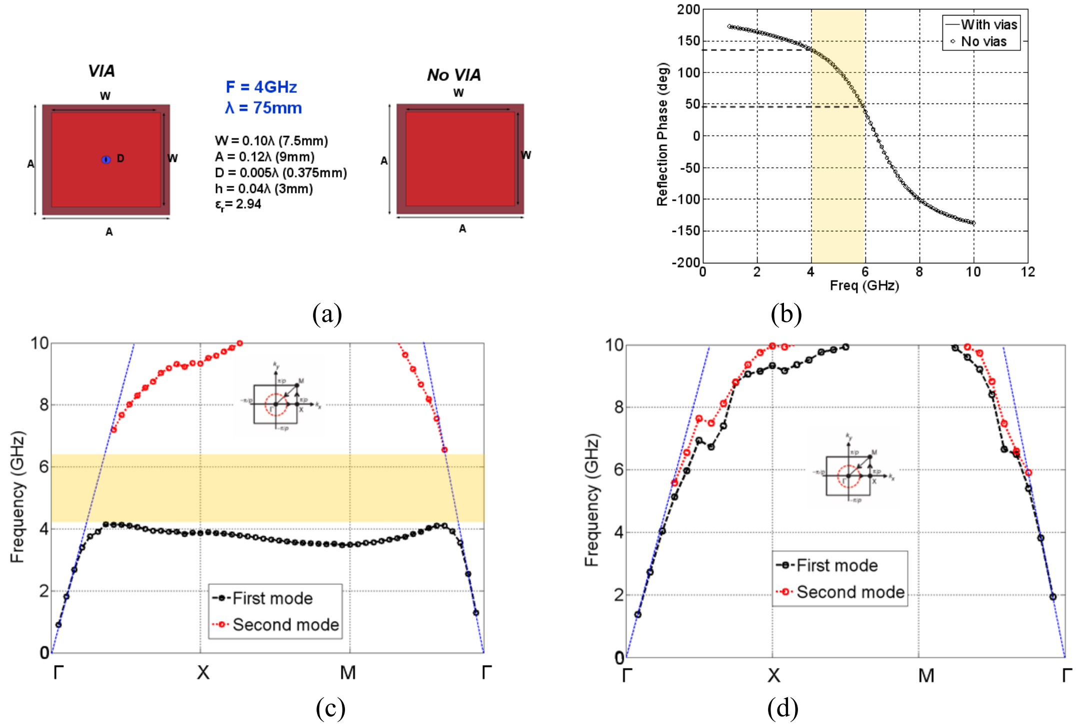

Figure 2: Comparison between EBG and periodic patch unit cell. (a) Dimensions. (b) Reflection phase for normal incidence. (c) Dispersion diagram for EBG (with via). (d) Dispersion diagram for periodic patch (without via).

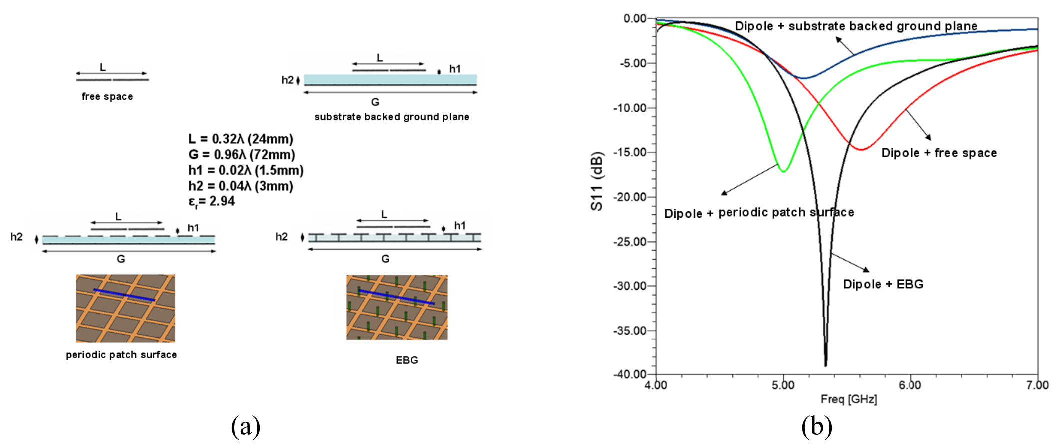

Figure 3: (a) Electric dipole placed horizontally in free space, on substrate backed ground plane, on substrate with periodic patches and on EBG surface. (b) Return loss characteristics for the dipole on different platforms. Note the best return loss is observed for the EBG structure.

References

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