

Enhanced Bandwidth Artificial Magnetic Ground Plane for Low-Profile Antennas

Leila Yousefi, Baharak Mohajer-Iravani, and Omar M. Ramahi

Abstract—In this letter, it is shown that using magneto-dielectric materials as substrate can increase the in-phase reflection bandwidth of electromagnetic bandgap (EBG) structures. To show this, a compact wideband EBG structure is designed and simulated. The numerical results show that this EBG has an in-phase reflection bandwidth of 70% which is several times greater than a conventional EBG resonating at the same frequency. Additionally, the new EBG surface has a smaller cell size, an important feature in the design of small antennas. As a demonstration of the effectiveness of the new structure, a low-profile unidirectional spiral antenna is designed to operate from 8 to 18 GHz. The improvement in the voltage standing wave ratio (VSWR) and gain of this antenna is presented while comparison is made to the case when using conventional EBG surface.

Index Terms—Electromagnetic band-gap (EBG) structure, magneto-dielectric materials, perfect magnetic conductor (PMC).

I. INTRODUCTION

RECENTLY, magneto-dielectric materials have become the focus of several studies because of their potential to improve the radiation characteristics of antennas [1], [2]. In [1], it was analytically shown that using materials with high but comparable permeability and permittivity results in wideband miniaturized antennas, while materials with only high permittivity result in miniaturized but narrowband antennas. In [2], it was demonstrated that using such substrates in woodpile EBG structures leads to an increase in its bandgap. In [3], a wideband artificial magnetic conductor (AMC) ground plane was designed using barium-cobalt hexaferrite material to work in the UHF frequency band. Although natural materials with high permeability in the microwave regime are rare, the possibility to create artificial magnetism at microwave frequencies by using engineered structures [4], [5] is promising.

In this work, a novel application for magneto-dielectric materials is introduced. Materials with permeability higher than one are used to increase the in-phase reflection bandwidth of the mushroom-type EBGs, and the designed EBG structure is used to implement a low-profile wideband antenna.

Electromagnetic bandgap (EBG) structures have been shown to emulate good magnetic conductors, or high-impedance surfaces, in their in-phase reflection bandwidth when used as

ground plane in the design of low-profile antennas [6]. Most EBG structures, however, have desirable properties over a narrow frequency range, thus limiting their application in the design of low-profile wideband antennas.

In [7] and [8], EBG structures were used as a ground plane to implement low-profile spiral antennas, but in these works the frequency independent behavior of the spiral antenna was limited by the relatively narrow in-phase reflection bandwidth of the EBG surface.

In this work, first using the simple circuit models originally introduced in [9], It is shown that using materials with permeability higher than one, as the substrate of mushroom-type EBGs, results in wider in-phase reflection bandwidth. The idea is then verified using incident plane wave analysis for EBG designs with different values of permeability. Finally, in Section III, the performance of the designed EBG used as the ground plane to implement low-profile wideband antennas is presented.

II. PROBLEM FORMULATION AND DESIGN SPECIFICATIONS

The surface impedance is defined as the ratio of the tangential component of the electric field to the tangential component of the magnetic field at the surface. Using the transmission line model for the normal incidence of plane waves, the reflection coefficient for the electric field is defined as

$$\Gamma = \frac{Z_s - \eta_0}{Z_s + \eta_0} \quad (1)$$

where Z_s is the surface impedance of the reflector and η_0 is the wave impedance in air. An EBG structure acts as a high impedance surface in its in-phase reflection bandwidth thus emulating a PMC surface.

The mushroom structure, first introduced in [9] and shown in Fig. 1, emulates a high impedance surface (HIS) in its in-phase reflection bandwidth. For normal incidence, the surface impedance of a mushroom EBG can be modeled as an inductor in parallel with a capacitor. The capacitance is equal to [10]

$$C = \frac{D\epsilon_0(\epsilon_r + 1)}{\pi} \ln\left(\frac{2D}{\pi g}\right) \quad (2)$$

where D is the grid period and g is the gap between the patches (see Fig. 1). The inductance part is due to the metal backed substrate of thickness h and can be calculated using transmission lines theory. A metal backed slab of thickness h can be modeled as a shorted transmission line leading to a surface impedance of

$$Z_s = j\eta \tan(\beta h) \quad (3)$$

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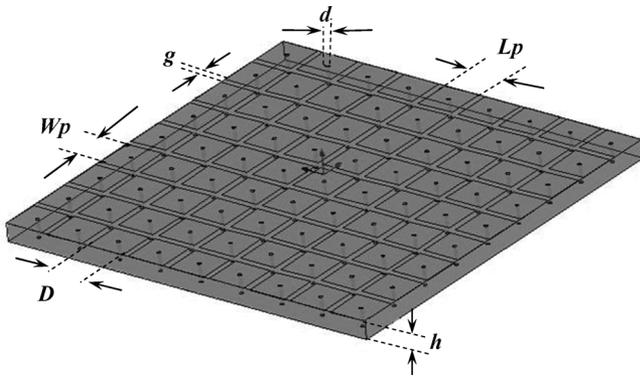


Fig. 1. Schematic showing the mushroom EBG structure.

where η and β are the wave impedance and phase constant in the slab, respectively. When $h \ll \lambda$, the aforementioned impedance becomes inductive and can be approximated as $Z_s = j\omega L$, where L is given by

$$L = \mu_0 \mu_r h \quad (4)$$

It was demonstrated in [11] that the LC circuit model leads to significant error only in the case when the grid period D is very large compared to the substrate height h . The usable bandwidth of an EBG, when operating as an AMC, has been considered to be the frequencies over which the phase of the reflection coefficient is bounded by ± 45 degrees. It is well known, that this in-phase reflection bandwidth for a parallel LC circuit is proportional to $\sqrt{L/C}$, while the resonance frequency is proportional to $1/\sqrt{LC}$. In this work, we use magneto-dielectric materials where the relative permeability, μ_r is greater than one to increase L and, thus, to increase the in-phase reflection bandwidth. The increase in L , for a specific resonance frequency, has the added advantage of reducing the size of the patch as smaller capacitance would be needed to achieve the same resonant frequency. Therefore, the in-phase reflection bandwidth increases more due to the reduced C .

To verify the idea, a mushroom EBG with substrate of permeability higher than one is designed and compared with a conventional EBG. To see the effect of permeability, new structures with the following dimensions $W_p = L_p = 0.5$ mm, $g = 0.15$ mm, $D = L_p + g = W_p + g = 0.65$ mm, $h = 1.57$ mm, $d = 0.1$ mm, $\epsilon_r = 2.51$, and with different values of permeability (μ_r) varying from 1–9 are considered. In [4] and [5], magnetic loss tangent, $\tan\delta_m$, of about 0.01 is achieved for engineered magnetic materials. In this work $\tan\delta_m = 0.01$ is assumed to model the loss in the designs with permeability higher than one. The structures are simulated with Ansoft HFSS using plane wave excitation with normal incidence. The simulation setup is the same as used in [6] and is shown in Fig. 2. The simulation results for different value of permeability are summarized in Table I. This table illustrates the in-phase reflection bandwidth (the range of frequencies in which reflection phase is bounded by ± 45 degrees) as well as the center frequency corresponding to a reflected phase of zero. As shown in this table, the in-phase reflection bandwidth increases as the permeability increases. For comparison, Fig. 3 shows the results of the simulation where the reflection wave phase is presented as a function of

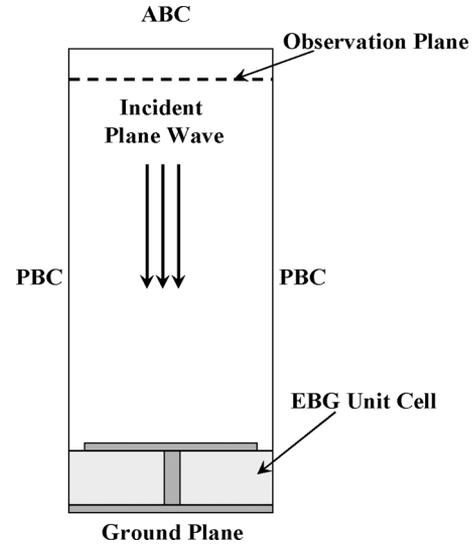


Fig. 2. Incident plane wave simulation setup where a periodic boundary condition (PBC) is placed around the cell to model an infinite EBG surface.

TABLE I
SIMULATION RESULTS FOR EBG WITH DIFFERENT PERMEABILITY

μ	In-phase Reflection Bandwidth (GHz)	Center Frequency (GHz)	Percentage Bandwidth
1	22 - 30	25.9	% 30.9
3	11.3 - 19	15	% 51.3
6	7.1 - 14.6	10.65	% 70.4
9	5.4 - 12.7	8.7	% 83.9

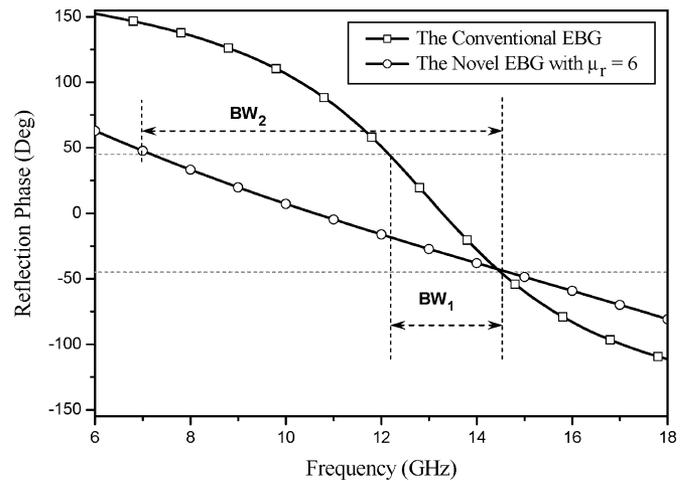


Fig. 3. Phase of the reflected plane wave for the EBG structure with $\mu_r = 6.0$ and for the conventional EBG introduced in [12].

frequency for EBG structure with $\mu_r = 6$ as well as the results for a conventional EBG. For the conventional EBG, we used the structure introduced, simulated and experimentally tested in [12] with the following dimensions: $W_p = L_p = 2.44$ mm, $g = 0.15$ mm, $D = 2.59$ mm, $h = 1.57$ mm, $d = 0.25$ mm, $\mu_r = 1$, and $\epsilon_r = 2.51$. The results presented in this figure show that the EBG with $\mu_r = 6$ has an in-phase reflection bandwidth of 70%, while the in-phase reflection bandwidth for the conventional EBG is only 18%.

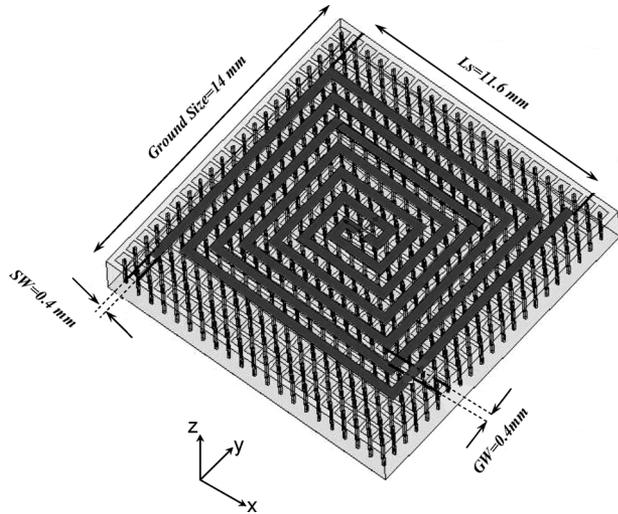


Fig. 4. Schematic of the low-profile spiral antenna above the EBG surface.

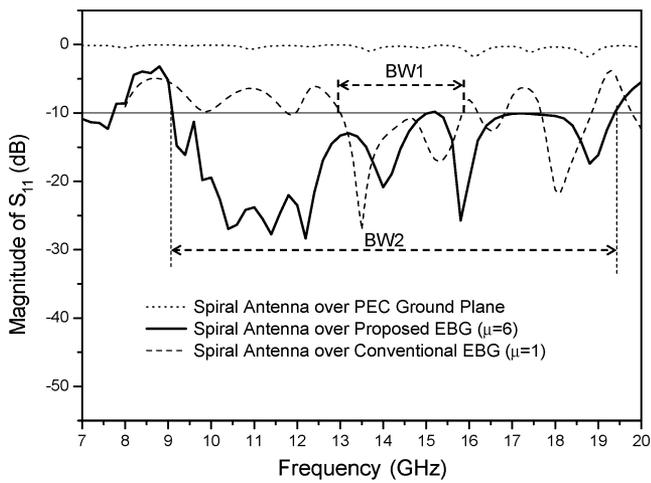


Fig. 5. Return loss of the spiral antenna on different ground planes.

III. LOW PROFILE SPIRAL ANTENNA USING THE DESIGNED EBG AS AN AMC GROUND PLANE

The idea of using an EBG structure as a ground plane to mimic the behavior of a PMC surface was first introduced in [9]. Guided by image theory, the previous findings in [9] and the EBG designed in this work using magneto-dielectric material, we designed a printed square spiral antenna to radiate effectively over the frequency range of 8 to 18 GHz.

The structure and dimensions of the spiral over the EBG surface are illustrated and provided in Fig. 4. The strip width of the spiral and the gap between the arms are set to 0.4 mm. The side length of the spiral is 11.6 mm which is equivalent to one third of the wavelength at the lowest frequency of 8 GHz.

The spiral antenna over the finite EBG surface is simulated using Ansoft HFSS and the results are illustrated in Figs. 5 and 6.

The finite EBG surface (14×14 mm) covered an area approximately equal to the footprint of the antenna. Fig. 5 shows the return loss of the low-profile spiral antenna when placed at a distance of only 0.2 mm, ($\lambda/105$ at the center frequency f_c of

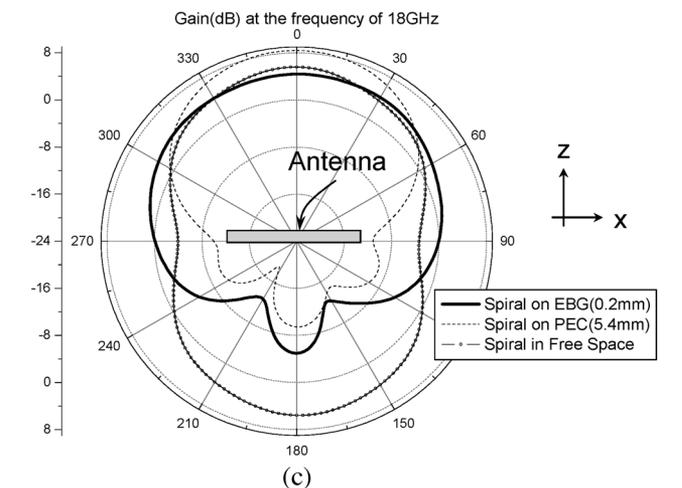
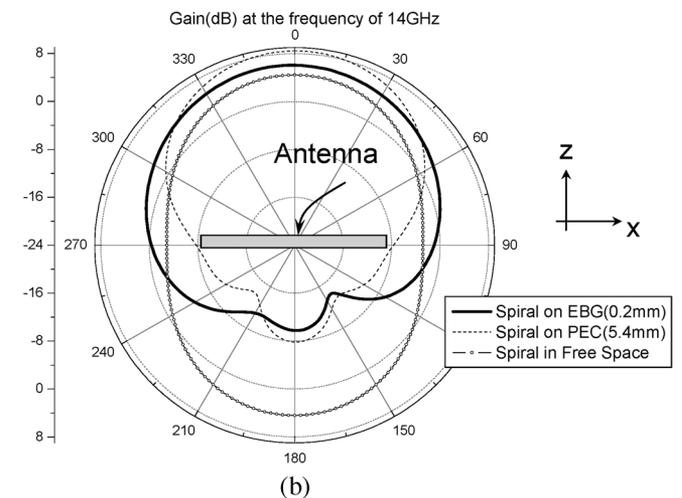
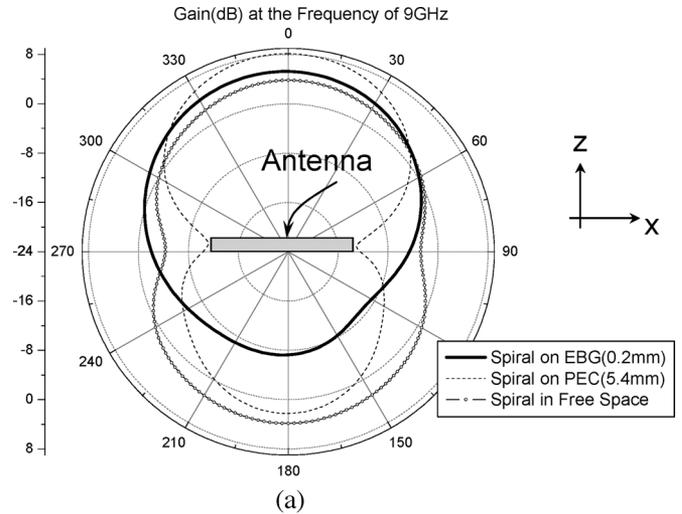


Fig. 6. Gain of the spiral antenna when placed in free space, over a PEC surface, and over the designed EBG surface. (a) 9 GHz. (b) 14 GHz. (c) 18 GHz.

14 GHz), above the designed EBG ground plane. For comparison and for a perspective on the low-profile antenna, we show in this figure the return loss for the same antenna when placed 0.2 mm (equivalent to $\lambda/105$ at f_c) above a PEC ground plane, and when placed at the same distance above the conventional EBG (with $\mu_r = 1$). As shown in Fig. 5, the new low-profile antenna has a bandwidth (VSWR < 2 : 1) of 9–19 GHz,

while the antenna over conventional EBG has a bandwidth of only 13–16 GHz. The achieved bandwidth for the designed low-profile antenna is even wider than the in-phase reflection bandwidth of the EBG. The 1 GHz upward shift in the bandwidth of the antenna is attributed to the near field interaction between the antenna and the EBG. A similar shift was observed for the dipole antenna in [6]. The gain of the antenna in the x-z plane is shown in Fig. 6 for different frequencies. The new design is compared to the same spiral antenna when placed 5.4 mm ($\lambda/4$ at f_c) above a PEC ground plane with the same size of the EBG ground plane (14×14 mm) and when suspended in free space. The comparison presented in Fig. 6 shows that the gain of the low-profile antenna, at the center frequency of 14 GHz is about 6.2 dB that is 1.6 dB higher than the spiral in free space, and it has a front to back ratio of 16 dB. Furthermore, the low-profile antenna shows an improved front to back ratio [see Fig. 6(a)]. However, when compared to the antenna backed by a PEC at $\lambda/4$, we observe a 2 dB decrease in the gain. This can be attributed to the magnetic loss of the material.

IV. CONCLUSION

Using a simple circuit model for mushroom-type EBG structures, it was shown that magneto-dielectric materials when used as a substrate can increase the in-phase reflection bandwidth of these structures. Using this fact, a compact wideband EBG structure was proposed and was shown to have an in-phase reflection bandwidth of 70% while having a cell size less than 0.25 of a conventional EBG resonating at the same center frequency. To evaluate the efficiency of the designed EBG when working as the ground plane of wideband antennas, a spiral antenna was designed to radiate effectively over the frequency range of 8–18 GHz coinciding with the in-phase reflection bandwidth of the EBG structure. A low-profile spiral antenna was implemented by placing the spiral antenna at a distance of 0.2 mm

($\lambda/105$ at f_c) above the proposed EBG. Simulation results show that the low-profile spiral antenna has a 2:1 VSWR over the frequency range of 9–19 GHz. The gain of the low-profile antenna at the center frequency of 14 GHz is 6.2 dB with a front to back ratio of 16 dB.

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