EBG Structure for Low Frequency Applications

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***Abstract*—In this paper a multilayer electromagnetic band gap (EBG) structure is proposed as a size-reduced solution for application in Magnetic Resonance systems operating at around 300MHz. The reflection phase coefficient at normal and oblique incidence is studied, and the dispersion diagram is used to determine the TE and TM surface wave suppression band gap. The proposed EBG structure is designed to exhibit very small deviation in the resonant frequency versus angle of incidence and to exhibit a stop band gap related to the quadrature reflection phase criterion.**

***Index Terms*—Electromagnetic band gap structures, in-phase reflection band, surface wave suppression band gap.**

I. INTRODUCTION

The term metamaterial has been used to describe composite materials with features not readily available in nature. Electromagnetic band gap (EBG) structures [1]-[2] are broadly classified as metamaterials due to their unique band gap feature and high impedance properties. EBG structures exhibit useful properties, like the in-phase band gap reflection coefficient, which enable the design of low profile antennas [3], and the surface wave suppression band gap property which improves the antenna performance [1]. The reflection phase of the EBG surface varies continuously from 180^0 to -180^0 with frequency, and near the high impedance resonance, a plane wave is reflected in-phase ($+90^0$ to -90^0), instead of out of phase as on a PEC surface and thereby the EBG surface satisfies the PMC-like condition in this frequency band.

In the literature [4]-[5], EBG structures at low operating frequency are presented, but with either very large dimensions or complicated geometries, which are not feasible in practice. This paper focuses on a multilayer stacked EBG structure with considerably reduced dimensions relative to the structure in [4]. The structure is designed to be used instead of the PEC reflector of a shorted RF dipole coil for 7-Tesla [6] Magnetic Resonance tomography operating at 300MHz with the aim of improving the coil RF magnetic flux density (B_1) by suppressing the anti-phase surface currents on the reflector. In this application, the EBG size is the most limiting factor, since the cell dimensions are required to be far below the size of the coil element which has a length of about $0.25\ \lambda_{300\text{MHz}}$.

II. PROBLEM FORMULATION AND DESIGN SPECIFICATIONS

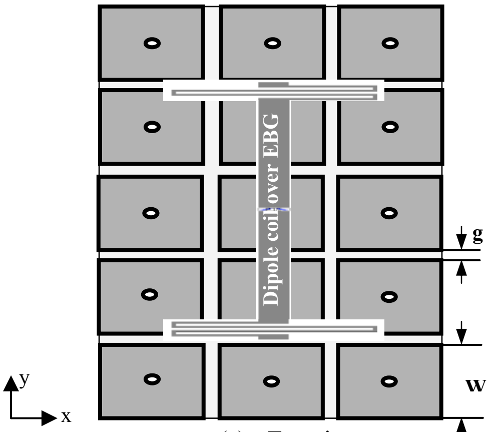
The modeled conventional mushroom-like EBG structure can be analytically for normal incidence by using the simple parallel LC resonant circuit [2]. When a plane wave illuminates the EBG surface at oblique incidence, the phase of the reflected field varies with the incident angle and the polarization state, and the structure is analyzed using the transmission line model [7]. In this model the reflection coefficient is related to the surface impedance of the EBG structure Z_s as shown in (1)-(2), where η_o is the free space wave impedance, θ is the incident angle, and Z_s expressed as the parallel combination of the grid and the metal backed slab impedances:

$$\Gamma^{TE} = \frac{Z_s^{TE}\cos\theta - \eta_0}{Z_s^{TE}\cos\theta + \eta_0} \tag{1}$$

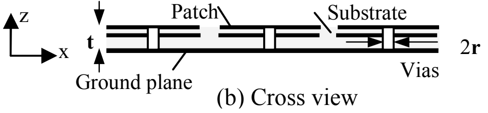
$$\Gamma^{TM} = \frac{Z_s^{TM} - \eta_0\cos\theta}{Z_s^{TM} + \eta_0\cos\theta} \tag{2}$$

These impedances for both TE and TM polarization, in the presence and absence of vias are described in [7]-[8].

In this paper, a stacked EBG structure is used, which consists of two arrays of metal patches stacked vertically and connected to a metal backed dielectric substrate by vertical metal-plated vias. The HFSS full wave simulator from Ansoft, based on FEM algorithm was used, where a unit cell of stacked EBG structure is surrounded by four walls of periodic boundary conditions (PBC) to model an infinite periodic structure. The geometry of the proposed stacked EBG design is shown in Fig. 1, where unit cells of two layers share the same boundary.



(a) Top view



(b) Cross view

Fig. 1. Stacked EBG design with unit cells of two layers sharing the same boundary. In an application, a dipole coil sits above the EBG structure in a height of approx. 20 mm.

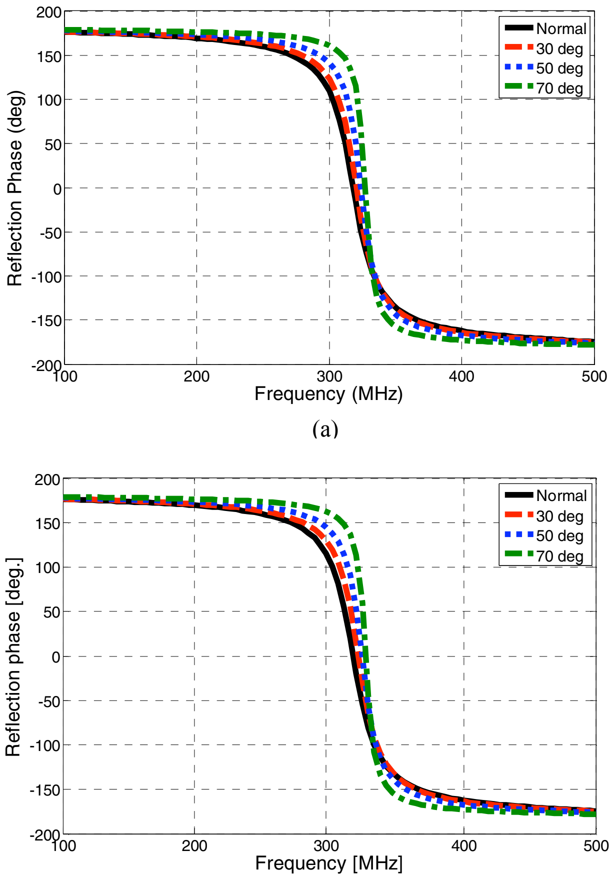
The electromagnetic properties of the EBG structures are characterized by five parameters, which are the patch width W, gap width g, dielectric constant ε_r, substrate thickness h, and vias radius r with the following design data:

$$W=0.072\,\lambda_{300\mathrm{MHz}},\ g=0.001\,\lambda_{300\mathrm{MHz}},\ t=0.014\,\lambda_{300\mathrm{MHz}},$$
$$\varepsilon_r=10.2,\ \text{and}\ r=0.00173\,\lambda_{300\mathrm{MHz}} \tag{3}$$

where λ_{300MHz} is the free-space wavelength at 300MHz, which is used as a reference length to define the physical dimensions of the analyzed structure. The spacing between the two layers of patches in the proposed structure was chosen to be 0.004 λ_{300MHz}. This stacked mushroom EBG structure has the advantage to operate at much lower frequency than the conventional mushroom EBG structure.

III. REFLECTION PHASE AND DISPERSION DIAGRAM

For a plane wave illuminating the stacked EBG surface based on the dimensions in (3) at normal incidence, the reflection phase is shown in the solid lines of Fig. 2. The MRI system frequency is in the frequency band where the reflection phase is in the range of $90^0 \pm 45^0$ [3] which is helpful for low profile antennas to achieve good return loss.



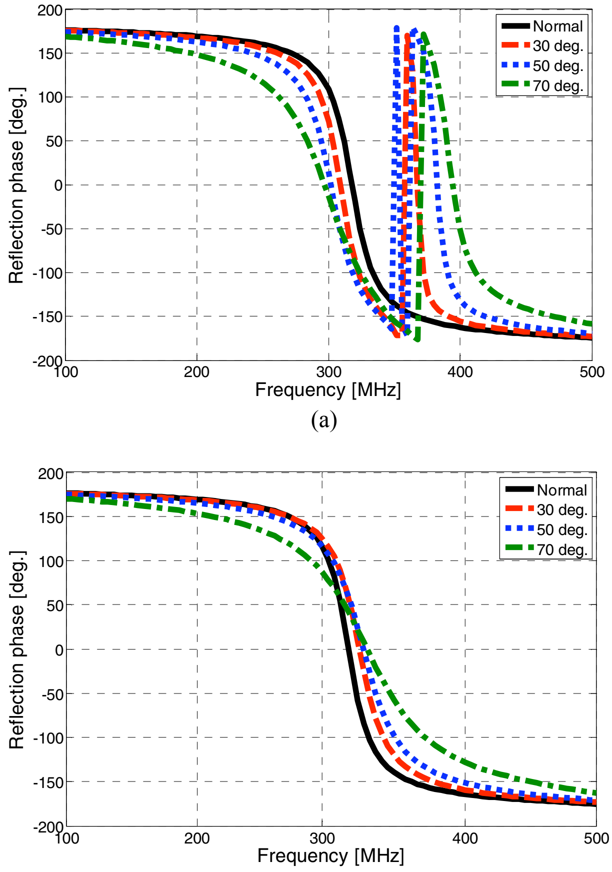
(a)

(b)

Fig. 2. Reflection phase characteristics of TE-polarized plane wave at oblique incidence on the proposed EBG structure: (a) with vias; (b) without vias.

For TE-polarized plane wave obliquely illuminating the stacked EBG structure in the presence of vias, the resonance frequency increases with the increase of the incidence angle, as shown in Fig. 2(a). The change in resonant frequency for angle of incidence varying from 0^0-70^0 was about 3%, which represents a stable resonance for the proposed dual layer EBG structure. In the absence of vias, the same effect is exhibited as shown in Fig. 2(b), because for TE-polarization, the electric field is always parallel to the EBG surface and the vias are not excited.

For TM-polarized plane wave obliquely illuminating the same structure with vias, dual resonance behavior is observed. This phenomenon has also been observed for the conventional mushroom-like EBG structure in [3], and [9]. In Fig. 3(a) the first frequency band of this behavior is lower than the in-phase frequency band at normal incidence, and is located inside the surface wave suppression band gap, while the second one is higher and outside the stop band gap, and the frequency separation between these two resonances increases as the incident angle increases. The presence of this second TM resonant mode [9] depends on the vias.



(a)

(b)

Fig. 3. Reflection phase characteristics of TM-polarized plane wave at oblique incidence on the proposed EBG structure: (a) dual resonant behavior in the presence of vias (b) single resonant behavior in the absence of vias.

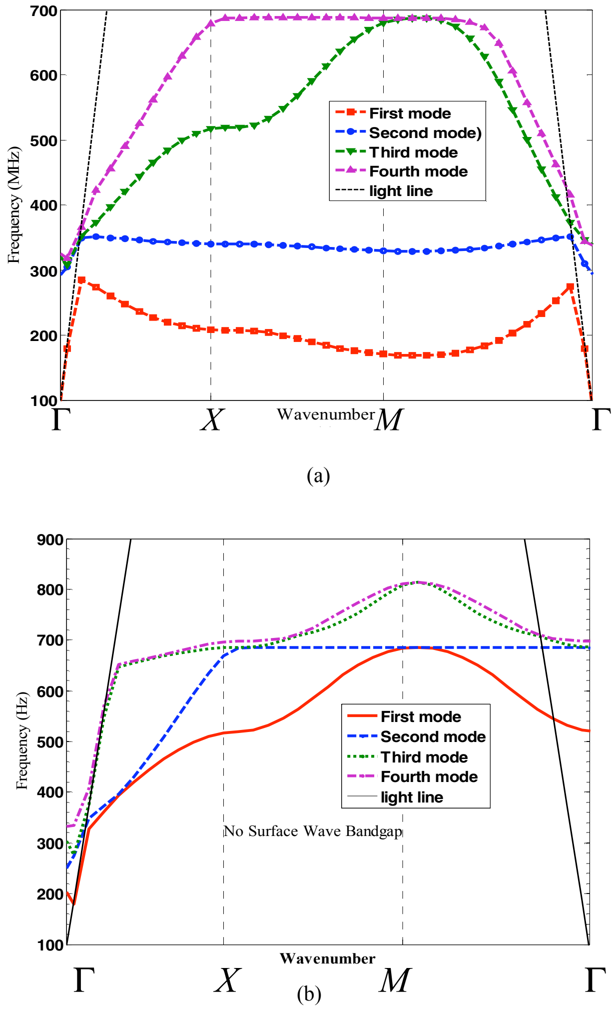


Fig. 4. Dispersion diagram of the proposed EBG structure: (a) when vias of radius 1.73mm is used; (b) In the absence of vias where no surface wave band gap is exist.

When there are no conducting vias in the structure, the dual resonant behavior disappears and the resonance frequency corresponding to zero degree reflection phase increases with the angle of the TM plane wave as shown in Fig.3 (b).

As shown in [8], the vias prevent a nonzero vertical electric field component to travel between the patch arrays and ground.

The dispersion diagram in Fig. 4(a) shows a stop band gap between the first two modes (TM mode and TE mode respectively) which is obtained in the frequency range (286 MHz - 325 MHz) very close to the frequency band where the proposed EBG structure shows a reflection phase in the range of $90^0 \pm 45^0$. The radius of the vias plays a role in determining the position of this surface wave suppression band gap and the radius could be adjusted to shift this stop band gap closer to the aforementioned quadrature reflection phase, and enable us to use this quadrature phase to identify the surface wave suppression band gap. In the absence of vias, as shown in Fig. 4(b), the stop band gap disappears, and the structure in this case is similar to a metal backed dielectric slab.

The stop band gap property of the EBG structure can be validated using an open air-filled microstrip transmission line which is loaded by the structure. The suitability of this approach was demonstrated recently [10] with a test cell using a microstrip of 195mm width and 40mm height over the ground plane which was loaded with a 3x5 unit cells EBG structure placed on the ground plane. In this experiment, measurements of the transmission scattering coefficient S_{21} showed very good agreement with the simulation results based on FDTD EMIRE XCcel.

The loaded microstrip experiment was simulated using our proposed EBG structure, and Fig.5 shows the transmission scattering coefficient $S_{21.}$

Due to the presence of vias, a number of stop band resonances appear across the observed bandwidth, and a stop band gap which matches our MRI operating frequency is clearly seen. Fig. 5 shows that our MRI operating frequency is located inside the stop band gap through which the surface waves are suppressed and also inside the qudrature frequency band (the shadow area) of the reflection phase coefficient which is very helpful for low profile wire antennas to achieve good return loss. This is also essential to ensure use of the proposed EBG structure for MRI applications. In the absence of vias, Fig. 5 shows that the stop band gap disappears in a similar manner as shown in Fig. 4 (b).

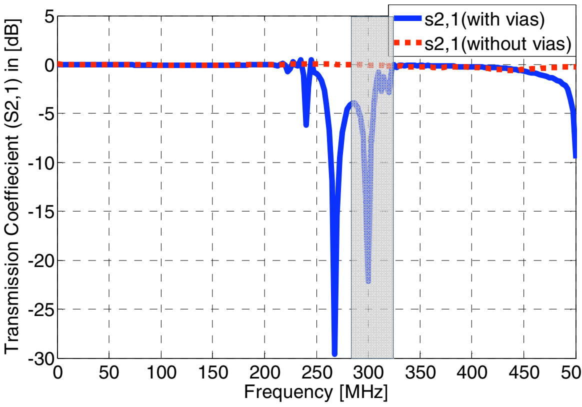


Fig. 5. FDTD simulation result of the transmission (S_{21}) scattering coefficient of the proposed EBG structure.

IV. CONCLUSION

A stacked mushroom EBG structure for an operating frequency of 300MHz and with electrically small size has been presented and the reflection phase and surface wave suppression band gap properties of the structure have been investigated. The proposed EBG structure exhibits very small deviation in the resonant frequency for angle of incidence varying from 0^0-70^0 (less than 3%), and exhibits a surface wave suppression band gap correlated to the quadrature reflection phase criterion in [3]. When a TM-polarized plane wave obliquely illuminates the proposed structure, a dual resonant behavior is observed, with a lower in-phase frequency band located inside the realized stop band gap (286MHz-325MHz). These properties make the proposed EBG structure a good candidate for a ground plane in a

7-Tesla Magnetic Resonance (MR) coil providing good suppression of anti-phase surface currents on the ground plane.

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