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EBG FREQUENCY RESPONSE TUNING USING AN ADJUSTABLE AIR-GAP

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Abstract—A new adjustable Electromagnetic Band-Gap (EBG) structure whose frequency response is controllable by adjusting spacer height is proposed. The finite difference time domain method is adopted for the simulations. Results show that the desired frequency response can be selected by adjusting the spacer height. The effects of the air-gap on the polarization dependent and conventional EBG structures have been investigated both theoretically and numerically. The agreement between the theoretical calculations and numerical results is reasonably good.

1. INTRODUCTION

In the recent years, EBG structures caught the attention of many researcher groups all over the world [1–5]. They have been widely applied in antenna engineering due to their interesting properties such as in-phase reflection, surface wave suppression, light weight, ease of fabrication and low fabrication cost. As mentioned in [6], the EBG structures, when are employed as an artificial magnetic conductor (AMC), are innately narrow band. The antenna bandwidth is much wider than the AMC bandwidth, which in turn restricts the antenna bandwidth. On the other hand, the resonant frequency of the EBG structures cannot be changed after construction. And thus, they cannot be employed as a ground plane for other antennas with different resonant frequencies.

To eliminate the aforementioned problems, different methods have been proposed in the literature whereby the EBG frequency response can be tuned over the entire frequency band of interest so that the same EBG structure can be utilized for several antennas.

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The frequency response of the EBG structure can be also altered by changing its dimensions. But the EBG patch width is unchangeable after construction. A substantial amount of methods on increasing the frequency agility of the EBG structures have been reported in the literature. These include the addition of varactor diodes between the metallic patches [7], micro-electro-mechanical system (MEMS) actuators [8, 9] and using ferrite substrates [10]. However, adding loading components such as varactor diodes and their attendant biasing circuits make the resultant EBG structure much more complicated than the conventional EBG structure. Furthermore, at higher microwave frequencies, the EBG dimensions are very small and it is difficult to settle the diodes between the patches. On the other hand, the high-quality ferrites cannot be employed as a substrate in microwave region [11]. In addition, the required external magnetic source makes it large and bulky.

In this paper, a novel tunable EBG structure has been proposed. A suitable method for tuning the resonant frequency is to insert an adjustable air-gap beneath the EBG substrate similar to those reported for the patch antennas [12, 13]. It can be also used to reduce the effective loss tangent of a lossy substrate [14]. Compared to the electrical tuning, the mechanical tuning has the following advantages: 1) It is more economical to use this mechanical tuning, rather than using electrical tuning, especially where a relatively large number of elements is used. 2) The air-gap idea is more general and is feasible to be used in any EBG structure with any arbitrary shaped patch. Nevertheless, in comparison with the electrical tuning methods, the obvious disadvantage of the proposed structure is that it is difficult to exactly control the height of air gap.

2. EBG CONFIGURATION

By using an air-gap beneath the dielectric substrate of the EBG structure, the permittivity and thickness of the substrate are changed. Compared to the same EBG structure without air-gap, the substrate permittivity is obviously smaller, while the substrate thickness is higher. As mentioned in [6], both changes increase the EBG bandwidth but they have opposite effects on the resonant frequency and thus, the dominant effect determines the value of the resonant frequency. When one uses a high permittivity substrate, the dominant effect is the relative permittivity resulting in an increase in the resonant frequency compared to the initial EBG structure. In contrast when one uses a low permittivity substrate, the dominant effect is the substrate thickness leading to decrease in the resonant frequency. Also, one can tune

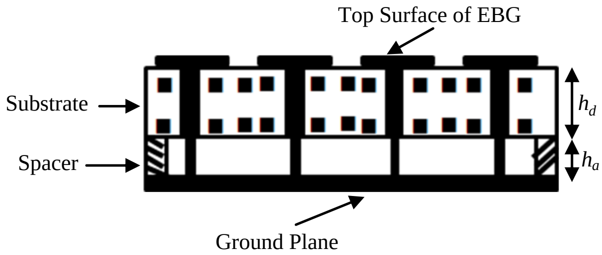

Figure 1. Geometry of proposed EBG structure.

the resonant frequency of the EBG structure by adjusting the air-gap thickness. The bandwidth of the EBG has also been improved partially due to the increase in the substrate thickness and partially due to the decrease in the equivalent dielectric constant. The configuration of the EBG structure with an additional air-gap is displayed in Figure 1. It is composed of a two-layer substrate: the top layer is the substrate of thickness h_d with dielectric constant ε_r, and the bottom layer is the air-gap of thickness h_a. One can model this two-layer substrate with an equivalent single layer substrate of thickness $h = h_a + h_d$ and an equivalent dielectric constant ε_{reff} given by [14]

$$\varepsilon_{reff} = \frac{\varepsilon_r(h_d + h_a)}{(h_d + h_a\varepsilon_r)} \tag{1}$$

At the following section, two familiar models have been investigated to characterize the proposed EBG structure.

3. ANALYTIC MODELS FOR THE PROPOSED EBG STRUCTURE

In this section, the proposed EBG structure has been fully characterized with lumped element and transmission line models [6]. When the periodicity is not very large compared to the substrate thickness, the Lumped element model is approximately valid for the EBG structures [6]. Consequently, the EBG structure can be modeled with equivalent lumped LC elements. The capacitance results from the gap between the adjacent patches and given by [6]:

$$C = \frac{W\varepsilon_0(1 + \varepsilon_{reff})}{\pi} \cosh^{-1}\left(\frac{W + g}{g}\right) \tag{2}$$

where W and g denote the patch and gap widths, respectively. It is also a simple matter to obtain the inductance part as a function of substrate parameters using the transmission line theory. Surface impedance [15] associated with this grounded two-layer substrate is:

$$Z_s = j\eta_d \frac{\eta_0 \tan\left(\frac{2\pi h_a}{\lambda_0}\right) + \eta_d \tan\left(\frac{2\pi h_d}{\lambda_d}\right)}{\eta_d - \eta_0 \tan\left(\frac{2\pi h_a}{\lambda_0}\right) \tan\left(\frac{2\pi h_d}{\lambda_d}\right)} \tag{3}$$

Since h_a, $h_d \ll \lambda$, the surface impedance becomes inductive and one can apply the small-angle approximation, so that the aforementioned inductor then becomes

$$L_{lump} = \mu \frac{(h_a + h_d)}{(1 - ((w/c)^2 h_a h_d \varepsilon_r))} \tag{4}$$

where subscript lump refers to the lumped element model. At the microwave frequencies, the second term in the denominator of Equation (4) is negligible compared to 1 and one can easily write $L_{lump} = \mu(h_a + h_d)$. Another approach is to use the transmission line model which was first proposed in [16]. The proposed EBG structure can be modeled with arrays of resonators, which are also loaded reactively, coupled by gap capacitors [16]. Its loading reactance results from the shorting pins and can be obtained, to good approximation,

$$L_{\text{TL}} = \frac{\mu_0 h(\ln\left(\frac{4h}{d}\right) + 0.5\left(\frac{d}{h}\right) - 0.75)}{2\pi} \tag{5}$$

where subscript TL refers to the transmission line model, h is the total thickness, consisting of h_a and h_d, and d is the average diameter of the bipartite via. One can follow the same procedure which was proposed in [16]. The transmission line can be successfully modeled either by a suspended microstrip line or a conductor-backed coplanar waveguide with an air-gap. It should be pointed out here that a suitable 2-D analysis is essential to obtain dispersion diagram of 2-D EBG structure. For a rectangular patch EBG surface, the surface wave band gap in the X direction does not coincide with that in the Y direction. This example clearly reveals that the 2-D analysis cannot be replaced by 1-D analysis.

4. ANALYTICAL AND NUMERICAL INVESTIGATION

Throughout this paper, simulations are carried out using a full-wave FDTD numerical method developed by the authors. The plane wave is normally launched in $-z$ direction to stimulate the EBG structure with an air-gap. A unit cell of the EBG structure with an air-gap is shown in Figure 2, where a metallic patch is placed on top of a two-layer substrate and conducting via is divided into two parts. The bottom part of the via has a lower diameter and is fixed while the top part is

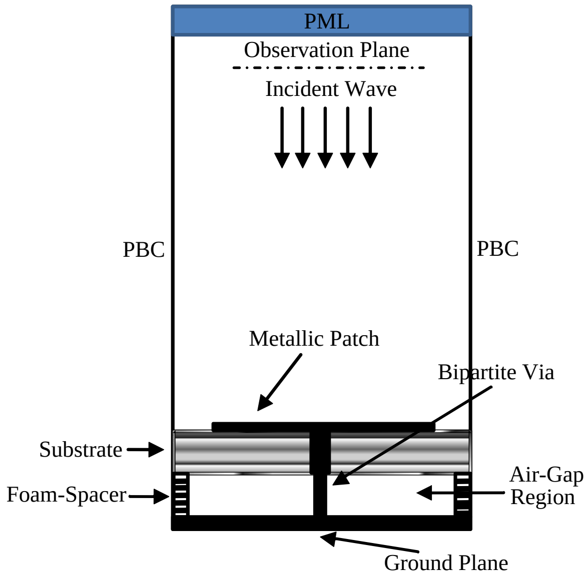

Figure 2. Unit cell geometry of an EBG structure with an air-gap.

soldered to the metallic patch and can go down freely by adjusting the spacer thickness. For simple construction, the upper part is perforated so that the lower part can go into the upper part by adjusting the spacer thickness. Periodic boundary conditions (PBCs) are put on four sides of the unit cell to realize an infinite EBG structure. The height of the observation plane is selected to be large enough, $0.5\lambda_{3\,\mathrm{GHz}}$ (where $\lambda_{3\,\mathrm{GHz}}$ is the free-space wavelength at 3 GHz), to ignore the effect of higher-order modes. The reflection phase of the EBG structure with an air-gap is then calculated as following [6]:

$$\varphi = \varphi_{\mathrm{EBG}} - \varphi_{\mathrm{PEC}} + 180 \tag{6}$$

where φ_{EBG} and φ_{PEC} are, respectively, reflected phases from the EBG and PEC surfaces at the observation plane. In this paper, both the rectangular and square patch EBG structures have been investigated. Since the bandwidth of the rectangular patch-EBG, in which the polarization sense of the reflected wave remains the same as the incident wave, is narrow, it has been investigated in more detail. For the example discussed here, the thickness of the dielectric substrate (h_d) is $0.04\lambda_{3\,\mathrm{GHz}}$, the patch width ($W$) is $0.16\lambda_{3\,\mathrm{GHz}}$, the patch length ($L$) is $0.24\lambda_{3\,\mathrm{GHz}}$, the relative permittivity of the substrate (ε_r) is 2.2, the grid-size is $0.005\lambda_{3\,\mathrm{GHz}}$, the gap width ($g$) is $0.02\lambda_{3\,\mathrm{GHz}}$, the computational domain size is $36 \times 52 \times 130$ cells and via radius is assumed to be infinitely thin in the simulations. Since a low

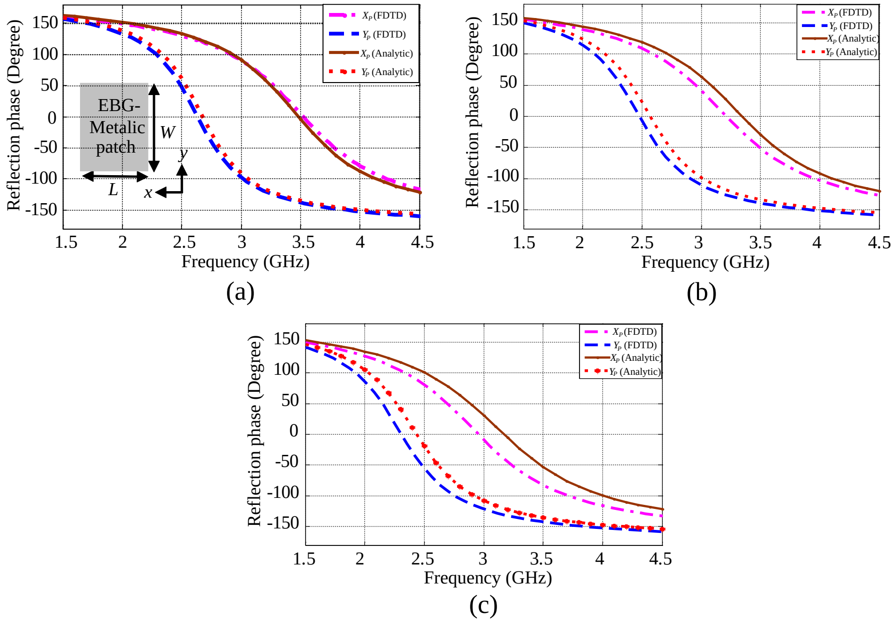

Figure 3. Comparison between theoretical and simulated reflection phase for different airgap thicknesses, (a) $h_a = 0$, (b) $h_a = 0.01\lambda_{3\,\mathrm{GHz}}$, (c) $h_a = 0.02\lambda_{3\,\mathrm{GHz}}$.

permittivity substrate is used, the substrate thickness plays a dominant role in determining the resonant frequency. Figure 3 presents the FDTD simulated reflection phase results for the x-polarized and y-polarized incident waves as compared with the analytical results. As can be seen, the agreement between the simulation and analytical results is quite good. The rectangular patch is also in the x-y plane with the length along the x-axis and width along the y-axis, as shown in Figure 3(a). It is known that when a right-hand circularly polarized (RHCP) plane wave impinges upon a PEC reflector, the polarization sense of the reflected plane wave is reversed [6]. This could be a serious problem in many applications. As demonstrated in [6], the rectangular-patch EBG reflector can be an attractive candidate in maintaining the same polarization sense. As a result, the polarization sense of the reflected plane wave remains the same as the incident wave at around the frequencies where the reflection phase difference between two orthogonal polarizations is around 180° [6]. To illustrate the polarization feature of the proposed rectangular patch EBG reflector, let us consider the previous rectangular patch EBG surface but on a high permittivity substrate, ($\varepsilon_r = 10.2$). The reflection phase difference in the x and y directions are shown for different air-gap

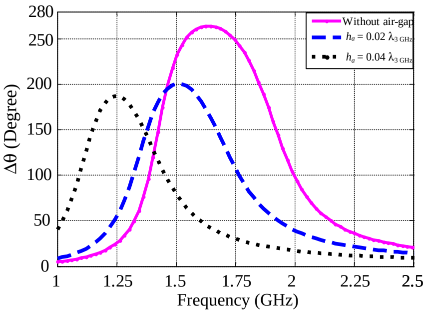

Figure 4. Reflection phase difference between x- and y-polarizations of the rectangular PDEBG surface.

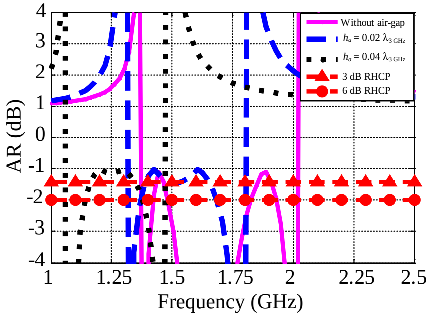

Figure 5. Simulated axial ratio of the reflected plane wave from the PDEBG reflector with different air-gap thicknesses.

thicknesses in Figure 4. Suppose that a right hand circularly polarized incident wave normally impinges upon this polarization dependent electromagnetic band-gap (PDEBG) structure. The axial ratio (AR) of the reflected wave [6] is shown for different air-gap thicknesses in Figure 5. As can be seen, the operating frequency of the PDEBG structure, in which the reflected wave is a right hand circularly polarized wave, can be tuned using adjustable air-gap. Moreover, the aforementioned PDEBG structure without air-gap has both separated and close operational band of frequencies. And thus, it can be used as a reflector for the desired dual frequency antenna. Closer inspection of Figures 4 and 5 also reveals a slight tuning of the EBG frequency response. To show this tuning effect more clearly, we consider the reflection phase of an EBG structure at the higher microwave frequencies. In addition, practical realization of other tuning methods is really hard at these frequencies. For this reason, we have simulated a proposed EBG structure with the following dimensions:

$$h_d = 0.04\lambda_{30\,\mathrm{GHz}}, \quad W = 0.24\lambda_{30\,\mathrm{GHz}}, \quad \varepsilon_r = 2.2, \quad g = 0.02\lambda_{30\,\mathrm{GHz}}.$$

Figure 6 shows the simulated reflection phase of the EBG structure with different values of h_a. As revealed in this figure, a tuning range of about 25.2% in resonant frequency and approximately 6% enhancement in the bandwidth are obtained as h_a changes from 0 to 0.4 mm. On the other hand, the EBG frequency response can be also changed when a piece of dielectric substrate of arbitrary permittivity is inserted in the air-gap region. Another approach is to load the superstrates of various thicknesses onto the EBG structure which decreases its resonant frequency. The frequency response of this structure can be tuned using different superstrate permittivities and thicknesses. Compared to the conventional EBG structure with the

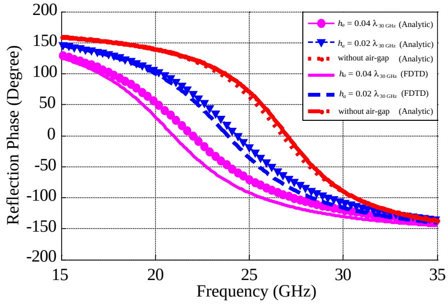

Figure 6. Simulated reflection phases of the proposed EBG structure with different air-gap thicknesses.

same height, its resonant frequency is somewhat higher but it has a tunable frequency response. In addition, its resonant frequency is much lower than that of the grounded dielectric slab.

5. CONCLUSION

A new tunable EBG structure was proposed in this paper. Compared to the electrical tuning methods, the proposed method is more economical and general. A bunch of numerical and theoretical studies has been carried out on the EBG structures with an air-gap to verify the tunability of the operational band. The agreement between the numerical and theoretical results is reasonably good.

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