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Patch antenna design based on 1D-EBG structures for high gain applications

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ABSTRACT

In this paper the band gap of one-dimensional electromagnetic band gap (1D-EBG) structures will be determined analytically using the dispersion diagram method. Next, we propose a 1D-EBG antenna design to improve the directivity at 3.5 GHz for WiMax applications. The primary goal of this endeavor is to validate the method and the directive EBG antenna's design at the resonant frequency 3.5 GHz with optimal adaptation and to demonstrate the effect of the dielectric substrates on increasing the directivity up to 20 dB. The proposed antenna with 1D-EBG shows 14 dBi enhancement in comparison to the conventional antenna without EBG and a very good adaptation is obtained. The design parameters of the antenna were optimized.

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1. INTRODUCTION

In recent years, the role of wireless communication technology is crucial in all sectors [1]. The antenna holds essential significance within a wireless communication system, and it serves as a vital element in applications such as energy harvesting, where its connection to a rectifier enables efficient operation [2]. The appearance of the microstrip patch antenna has opened up numerous options for antenna designing and manufacturing, it benefits include low cost and profile, and light weight, [3]-[5] therefore it is appropriate for today's applications. The major microstrip antenna drawbacks are limited bandwidth, gain and directivity. In contrast special attention has been paid to high directivity antennas, because of its ability to transmit information over a large distance. Therefore, high directivity microstrip patch antenna design is an important task. To improve the directivity of microstrip patch antennas several methods are described in literature such us a patch antenna design based on the fractal Sierpinski method maintained a small antenna dimension of 40 mm × 40 mm patch size resulting in a 10.9 dBi directivity at 3.866 GHz [6]. The fractal antenna in Koch Island described in [7] has a directivity of 13 dBi. Stacked patch antennas [8], [9] is an another approach for enhancing the directivity. In addition, antennas with high directivity include superstrates [10]-[13], metamaterials with zero index, filling curve of the Peano space [14], and materials with photonic band gap [15]. However, for obtaining a high directivity patch antenna, this paper provides the use of unidirectional one-dimensional electromagnetic band gap structures (1D-EBG).

The EBG resonator provides a significant means of increasing antenna directivity, called an EBG antenna [16]. The electromagnetic bandgap resonator antenna usually consists of an excitation source and two interfaces. The upper interface is usually one or more dielectric plates or a surface of metallic or dielectric rods, while the lower interface is a ground plane. In this paper we will study in more detail the electromagnetic properties of one-dimensional electromagnetic bandgap structures and their applications in directive antenna design. In section 2, we have established the dispersion diagram method to theoretically determine the band gap of the 1D EBG structure and to understand its operation. In section 3 we realized a design of 1D-EBG antenna, from which we replaced the plane of symmetry presented by the 1D EBG structure by a metallic plane, placing on the latter an excitation source (patch). The conclusion of this work will be discussed in section 4.

2. ANALYSIS AND CONFIGURATION OF THE EBG STRUCTURE

To facilitate the investigation of the solution of Maxwell's equations, the arrangement of the one dimensional EBG structure is established through the alternation of layers of dielectric material and air (refer to Figure 1(a)). In Figure 1(a), the diffraction of an incident electromagnetic wave with the EBG structure is depicted for two propagation directions: one in the positive direction (oz) and the other in the negative direction. The equation describing the electric field E in each dielectric layer, satisfying the wave (1), can be expressed as a second order differential as illustrated in (1).

$$\Delta\vec{E} + \frac{\omega^2.\varepsilon_r(x,y,z)}{c^2}\vec{E} = \vec{0} \tag{1}$$

The speed of light in vacuum is denoted as c, and the permittivity of the dielectric layer is represented as $\varepsilon r(x, y, z)$. When considering a one-dimensional periodicity model along the z axis and homogeneity in the xy plane, (1) is transformed into:

$$\frac{\partial^2 E(z)}{\partial z^2} + \frac{\omega^2.\varepsilon_r(z)}{c^2}E(z) = 0 \tag{2}$$

By considering a one-dimensional periodic network, the solution to (2) can be obtained effortlessly, taking into account the periodicity of the permittivity $\varepsilon r(z)$ with a period of L, as illustrated in Figure 1(b).

$Si\ 0 < z < d$:

$$\frac{\partial^2 E_d(z)}{\partial z^2} + \frac{\omega^2.\varepsilon_r(z)}{c^2}E_d(z) = 0 \tag{3}$$

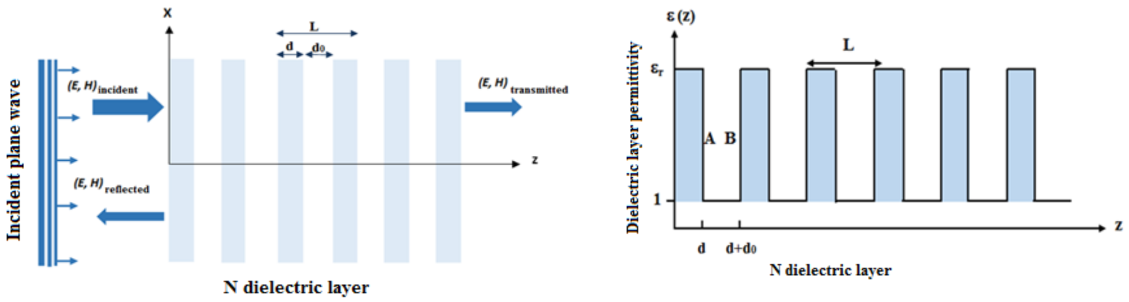
$Si\ d < z < d + d_0$:

$$\frac{\partial^2 E_{d0}(z)}{\partial z^2} + \frac{\omega^2}{c^2}E_{d0}(z) = 0 \tag{4}$$

The respective solutions to the differential (3) and (4) are given by:

$$E_d(z) = A\sin(\alpha z) + B\cos(\alpha z) \tag{5}$$

$$E_{d0}(z) = C\sin(\beta z) + D\cos(\beta z) \tag{6}$$



(a) (b)

Figure 1. 1D-EBG structure: (a) in interaction with plane waves and (b) periodic dielectric permittivity $\varepsilon r(z + L) = \varepsilon r(z)$

$$Avec\ \alpha = \frac{\omega\sqrt{\varepsilon_r}}{c}\ et\ \beta = \frac{\omega}{c}$$

By utilizing the property that the function $E(z)$ and its corresponding derivative $E'(z)$ remain continuous at the interface, such as at point A, we can leverage the Bloch-Floquet theorem [17], [18]. As a consequence, it can be asserted that any solution $E(z)$ which meets the wave (2) within a periodic structure can be expressed in:

$$E(z) = u(z)e^{jkz} \tag{7}$$

In which $u(z)$ is a periodic function exhibiting the identical period L as the distribution of permittivity, in other words $u(z + L) = u(z)$ and wave constant $k = 2\pi/\lambda$ applies. We show that the dispersion relation is in (8).

$$\cos(\alpha d)\cos(\beta d_0) - \sin(\alpha d)\sin(\beta d_0)\frac{\varepsilon_r+1}{2\sqrt{\varepsilon_r}} = \cos[k(d + d_0)] \tag{8}$$

The wave constant k can be expressed based on the dispersion (8).

$$k = \frac{1}{d+d_0} arcos\left[\cos(\alpha d)\cos(\beta d_0) - \sin(\alpha d)\sin(\beta d_0)\frac{\varepsilon_r+1}{2\sqrt{\varepsilon_r}}\right] \tag{9}$$

Figure 2(a) illustrates the frequency-dependent variation of the left-hand side of (10). It is observed that the left-hand side of the equation can exceed $+1$ or fall below -1, whereas the right-hand side always remains within the range of $-1\ to\ +1$. Figure 2(a) illustrate that if the left-hand side of the dispersion equation goes beyond ±1, there are frequency bands in which the reduced wave constant $kr = \frac{(d+d_0).k}{\pi}$ is undetermined as illustrated in Figure 2(b), in other words in these frequency bands no wave can propagate, we speak then of forbidden frequency bands. The one-dimensional periodic structure prevents electromagnetic waves from propagating within these frequency bands. It is necessary for an application with a well-defined frequency $f0$, for example in antenna design, to center the first band gap around the frequency $f0$, i.e., in this frequency the left-hand side of the dispersion equation has an extreme value, therefore (10) is used.

$$\frac{d(1^{er}membre)}{df}/f = f_0 = 0 \tag{10}$$

That is:

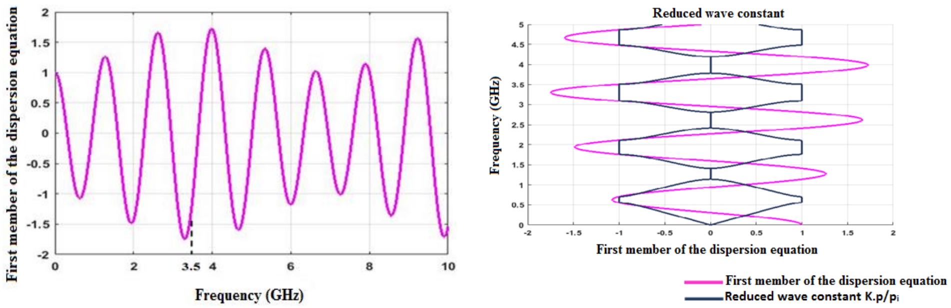
$$(\varepsilon_r + 3)\, sin(\alpha d)\, cos(\beta d_0) + (2\sqrt{\varepsilon_r} + \varepsilon_r + 1)\, cos(\alpha d)\, sin(\beta d_0) = 0 \tag{11}$$

This condition can be satisfied if.

$$\alpha d = \frac{\pi}{2}\ et\ \beta d_0 = \frac{\pi}{2} \tag{12}$$

Through expressions of $\alpha = \frac{\omega\sqrt{\varepsilon_r}}{c} et\ \beta = \frac{\omega}{c}$ we find.

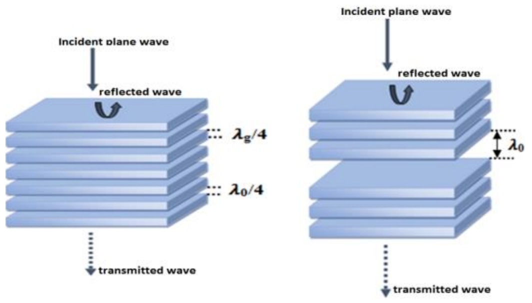
$$d = \frac{c}{4f_0\sqrt{\varepsilon_r}} = \frac{\lambda_g}{4}\ et\ d_0 = \frac{c}{4f_0} = \frac{\lambda_0}{4} \tag{13}$$



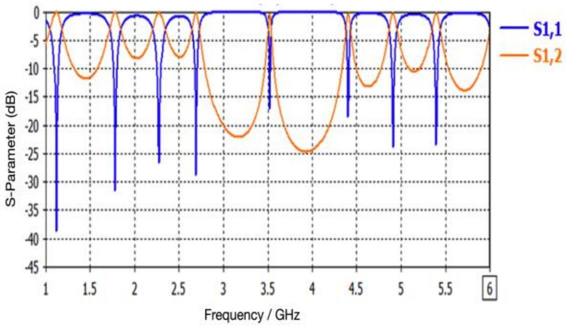
(a) (b)

Figure 2. Dispersion diagram: (a) first member of the dispersion equation for $\varepsilon_r = 10.2$ and (b) dispersion relation of a 1d periodic structure for $\varepsilon_r = 10.2$

With $\lambda 0$ represents the wavelength in vacuum corresponding to the center frequency $f0$ of the band gap and λg that in the dielectric, εr represents the relative permittivity of the dielectric material. In order to obtain band gaps around the frequency $f0$, to attain destructive interference of transmitted electromagnetic waves, it is necessary for the layers' thickness to match $\lambda/4$. The suggested EBG structure is composed with alternated layers of Neltec with relative permittivity $\varepsilon r = 2.6$ and other air layers. This structure is illustrated in Figure 3(a). If a $\lambda 0$ default which corresponds to the frequency of operation 3.5 GHz is formed in the EBG structure's center as shown in Figure 3(a), there is a narrow band of transmission created in the band gap's center as illustrated Figure 3(b). By observing Figure 3(b), it is evident that the transmission peak is located symmetrically in the band gap. This is due to the fact that the frequency of this peak is directly related to the periodicity defect between the plates.



(a)



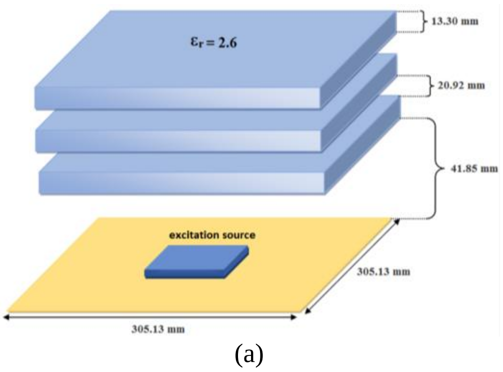
(b)

Figure 3. 1-D EBG structure: (a) periodic configuration and (b) transmission coefficient (orange curve) and reflection (blue curve) of the EBG structure with default

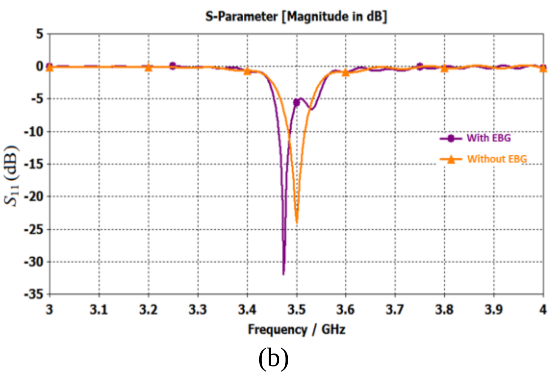
3. CONFIGURATION OF THE EBG ANTENNA

We can replace the symmetry plane shown in Figure 3(a) by a ground plane (or metal plane), as the electrical field mapping indicates that the tangent component of the E-field on this symmetry plane is cancelled [19]. Consequently, when the electric image theory is applied, the half-structure behavior over the ground plane becomes similar to the defected EBG structure. At the ground plane, an excitation source is positioned and the resulting antenna is named EBG antenna. It is composed by a ground plane with the patch of excitation positioned on the EBG structure symmetry plane in the center of the fault as defined by Thevenot *et al*. [20].

Figure 4(a) shows the EBG (1-D) antenna. It consists of three 13.30 mm thick dielectric layers of Neltec NY9260 placed at a distance of 41.85 mm from the ground plane and an excitation source. Figure 4(b) illustrates EBG 1-D antenna return loss, which indicates that the antenna with and without EBG is well adapted and covers the objective WiMax band. From Figures 5(a), Figure 5(b) and Figure 6(a), Figure 6(b) it becomes evident that the EBG structure improves the performance of the antenna in a very significant way in terms of the radiation becoming more directive. Table 1 presents a comparison between our study and various antennas discussed in the literature is summarized. We can notice that our technique used to increase the directivity is the best one.

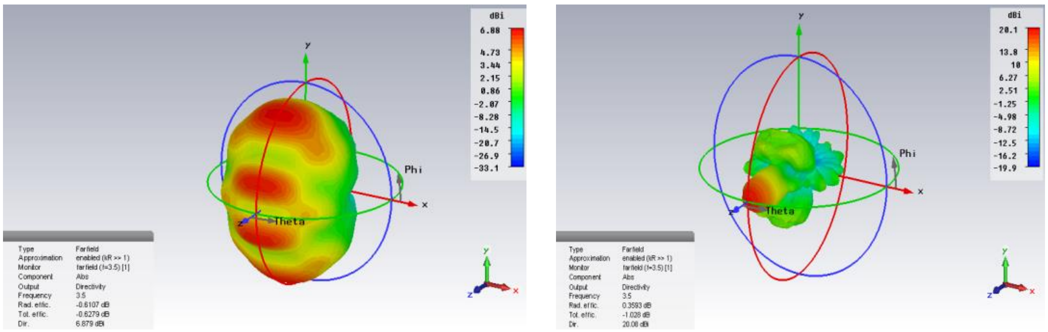


(a)



(b)

Figure 4. The proposed antenna: (a) EBG antenna design and (b) the antenna's reflection coefficient S11 with and without EBG



(a) (b)

Figure 5. 3D radiation pattern: (a) without EBG and (b) with EBG

(a) (b)

Figure 6. The radiation pattern of the dipole antenna with and without EBG is analyzed at 3.5 GHz in both the horizontal and vertical sections, considering two specific angles: (a) phi=0 and (b) phi=90

Table 1. Proposed antenna compared to existing reference antenna

References	Resonance frequency (GHz)	Directivity (dBi)	Reflection coefficient (dB)	Bandwidth (GHz)	Employed techniques
[21]	3.5	7.85	-25	–	Metasurface as superstrate
[22]	1.5	10.32	-22	–	Mpa loaded with npmms
	3.5	11.15			
	5	13.08			
	8.4	7.96		22.178-2.197	Circularly-polarized patch antenna
[23]	2.18	9.49	–	2.55-2.97	TModd-0 modes
[24]	2.6	15	–	5.76-5.84	Fabry-perot antenna with a nonuniform partially reflective surface
[25]	5.8	21.49	-25		
This work	3.5	20	-33	1D-EBG	1D-EBG

4. CONCLUSION

In this paper we have designed a planar 1D EBG antenna at the 3.5 GHz frequency for the WiMax bands. First, we developed a method to determine the band gap theoretically and understand their operation. Then we have realized a 1D EBG antenna design, from which we have replaced the symmetry plane presented by the 1D EBG structure by a metallic plane, arranging on it an excitation source (patch). The insertion of 1D EBG structures on top of the patch antenna results in a very interesting directivity increase of approx. 20 dB compared to the antenna without EBG structure which has a directivity of 6 dB.

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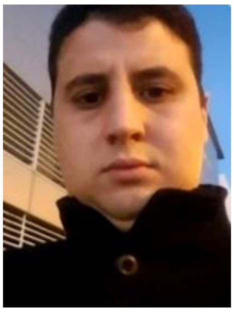

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