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A NOVEL BEAM SCANNING/DIRECTIVITY RECONFIGURABLE M-EBG ANTENNA ARRAY

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Abstract—In this paper, we introduce a new technique for an electronic beam scanning/directivity reconfigurable which can be carried out by using a joint array of Metallic Electromagnetic Band Gap (M-EBG) sectoral antennas. This study opens new avenues of research on M-EBG sectoral antennas by combining multiple radiating elements in an array. Usually M-EBG structures are designed in passive configurations to radiate fixed/shaped beams thanks to a specific radiating aperture at the surface of the M-EBG antenna. However by opting this new technique, we are able to control the radiating aperture, and therefore provide a tunable directivity/beam pattern. The objective of the paper is to propose a solution for M-EBG antennas in order to achieve Beam Scanning and Directivity reconfigurability. The main advantage of the proposed technique is that the array have negligible mutual coupling between the radiating elements, simplifying therefore the conception of the beam-forming network and the problems of constrained beam scanning. Another objective of the paper is to be able to achieve wide angle beam scanning $-/+58$ degrees. This method makes it possible to obtain in a simple way an agile M-EBG antenna without the need of the expensive active electronic components. Several results show the effectiveness and the capabilities of the proposed technique.

1. INTRODUCTION

Beam scanning and pattern reconfigurability have found a great demand in the fields of wireless communications, satellite communications, radar, etc. [1, 2]. These applications are generally covered by

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phased array antennas [3], where several elements are grouped together in a linear or planar spatial configuration. The radiated beam is determined by the vectors addition of the electromagnetic fields radiated by the individual elements. One of the main concerns of phased array antennas is the mutual coupling between the radiating elements [4]. The performances of phased array antennas are affected in many aspects. Firstly, the input impedance of each radiating element changes from its initial value due to the mutual coupling, this variation is unstable when we change the direction of the radiated beam. This phenomenon causes a mismatching between the output impedance of the beam-forming network and the input impedance of the elements at different given beam directions if the BFN is not properly designed. Secondly the array can radiate no power in certain angles; this phenomenon is called angle blindness [5]. One solution to overcome these limitations is to reduce the mutual coupling between the radiating elements [6].

Utilization of electromagnetic band-gap (EBG) structures is becoming attractive in the electromagnetic and antenna community. Several papers on agility and beam shaping using antennas based on band gap structures were presented [7, 8]. Others demonstrated that EBG structures can be used between the array elements to reduce the mutual coupling, a significant 8 dB reduction mutual coupling were noticed by [9].

The proposed structure is an array of M-EBG sectoral antenna. Previous M-EBG sectoral designs which were presented earlier in [10–12] can be used as an elementary radiating unit. The mutual coupling is minimized thanks to metallic walls between the elements. This issue is the main concern of this paper, is to be able to achieve Beam agility without being concerned of the mutual coupling between the elements.

This paper is divided in two parts. In the first one, a "Beam scanning M-EBG Antenna" is presented. The proposed structure is composed by an array of 6 M-EBG sectoral antennas. In the second part, "Directivity Reconfigurable M-EBG Antenna" is achieved by an array of 5 Sectoral M-EBG antennas in order to realize joint rectangular cavities. The antennas can be excited (ON state) or adapted to matched load (OFF STATE).

In both cases the same M-EBG sectoral antenna is used as an elementary radiating element. The different designs have been simulated thanks to CST 2006B, an FIT (Finite Integration Technique) based software.

2. BEAM SCANNING M-EBG ANTENNA DESIGN

2.1. Principle of the Beam Scanning M-EBG Antenna

Beam scanning is achieved through a joint array of M-EBG sectoral antenna in the horizontal plane. The scanning angle of the antenna main lobe is determined by the feeding network that provides appropriate amplitude and phase for each radiant element. Antenna elements are joined together and the width of each element is d. They are excited by a phase gradient φ. The phase shift applied to each element can create a wave front which is inclined at an angle of θ to the alignment of radiant elements (Fig. 1).

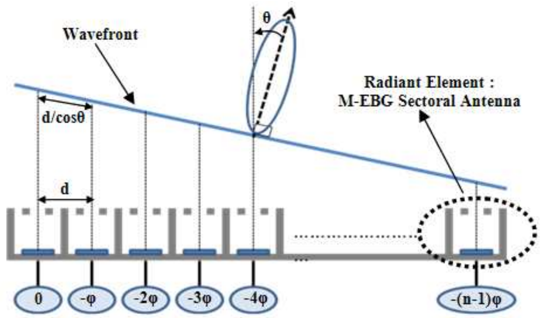

Figure 1. Schematic representation of the phased M-EBG sectoral antenna array.

The distribution circuit that generates the weights on the various radiant elements can be achieved by two different methods:

- One is to use active components (RF amplifiers for amplitude control and variable phase shifters for phase control); this technique is expensive and complicated.
- Another is to use beam-forming networks for a multiple-beam array. Multiple beamformers are either networks [13, 14] (Butler Matrix, Blass Matrix) or quasi-optical systems lens (Rotman lens).

The second method will be used. In this paper, we have chosen to discard this study and focus rather on the EBG array. We will try to present the missing parts in a future paper along with the designed feeding network. In this paper, the antennas are excited directly by feeding ports with the proper excitations.

2.2. Objective and Antenna Specifications

The aim of this work is to scan the beam in the horizontal plane. The radiation pattern should have a narrow angular width for the

Table 1. Beam scanning M-EBG antenna specifications.

WIMAX Frequency Band	5.47–5.725 GHz
Directivity	24 dBi
H-Plane radiation lobe and horizontal beamwidth	Electronic scanning beam to cover a sector greater than 55°
Polarization	Vertical

beam therefore a high directivity even with few radiant elements. We preferred the case of a scan beam over a given wide angular sector instead of a broad beam with low directivity. In this way, the antenna is agile and has significant performance advantages over current competing antenna technologies. In order to validate the design process, Table 1 summarizes the final antenna specifications.

We will now discuss in more detail the principle of beam scanning M-EBG antenna design, i.e., the choice of the basic radiant element.

2.3. Radiant Element: M-EBG Sectoral Antenna

The M-EBG sectoral antenna must meet two criteria:

- The width of the radiating element should be determined versus the value of the directivity. Furthermore the angle of the scan beam is imposed by the antenna specifications. In order to achieve high directivity without having grating lobes (especially for extreme beams), the width of the radiant element is set to $d \approx 0.7\lambda_0$ in order to obtain large scanning angle and to reject the apparition of grating lobes.
- The directivity of the elementary antenna must be around 15 dBi if we are looking for a directivity of 24 dBi for the array.

To design the elementary radiating antenna, we should follow the steps below:

1. Width $d = 0.7\lambda_0 = 37\,\mathrm{mm}$ at 5.7 GHz
2. We obtain a directivity D of 15 dBi when the element's length (L) is equal to 310 mm, as given by the Equation (1) in [15]:

$$L = \frac{D\lambda_0^2}{4\pi d} = 310\,\mathrm{mm} \tag{1}$$

   Although 310 mm are sufficient in theory to provide a directivity of 15 dB, a length of 400 mm is chosen to properly conserve the radiant energy into the resonant cavity to produce high directivity.

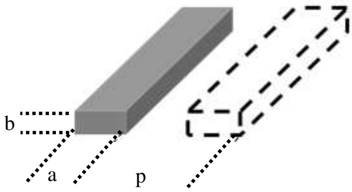

Figure 2. Geometry of the upper M-EBG structure.

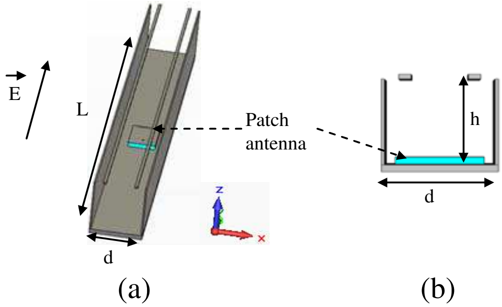

Figure 3. (a) Perspective and (b) inside views of the radiant element geometry: M-EBG sectoral antenna.

3. With regard to the upper M-EBG structure (Fig. 2), simple metallic rods can be used with $a = 4\,\text{mm} \times b = 2\,\text{mm}$, spaced by $p = 22\,\text{mm}$. The reflection coefficient of $r = 0.83e^{j91\pi/120}$ at the upper M-EBG layer is obtained by illuminating a unit cell with TM polarized wave (electric field parallel to metallic rods) [16].

The considered M-EBG has a good reflectivity required to achieve a directivity of 15 dBi. From the reflection coefficient of the periodic structure, the antenna cavity height (h) has been determined using the formula (2) [17, 18]

$$h = \frac{1}{2}\frac{c\left(\frac{1}{2} + \frac{\varphi_{\text{M-EBG}}}{2\pi}\right)}{\sqrt{f^2 - \frac{c^2}{4d^2}}} = 36\,\text{mm} \tag{2}$$

where: $\varphi_{\text{M-EBG}}$: is the reflection phase of the upper M-EBG structure, h: the antenna cavity height, d: the width of the radiant element.

Figure 3 gives the geometry of the elementary antenna. It is excited by a single patch ($19.5\,\text{mm} \times 28.5\,\text{mm}$) placed in the middle of the cavity above the ground plane (Fig. 3). The patch is fed by a coaxial probe in linear polarization (Fig. 3).

2.4. Elements Array Design

The final antenna geometry consists of combining several elementary antennas (M-EBG sectoral antenna (Fig. 3)) in a joint array in order to meet the best requirements in terms of directivity, coverage and radiation patterns. The following step is to determinate the required number of elementary antennas to meet with the desired specifications. By analyzing the Radiation pattern versus the number of elementary antennas, we conclude that 6 elements are needed if we are looking to

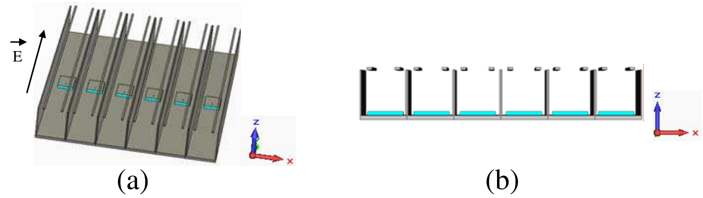

Figure 4. (a) Perspective and (b) inside views of the beam scanning M-EBG antenna.

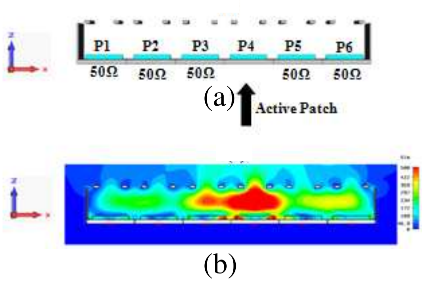

Figure 5. (a) multisource directive M-EBG antenna structure, (b) field distribution (E_y) in the horizontal plane inside the resonant cavity (only P_4 is fed).

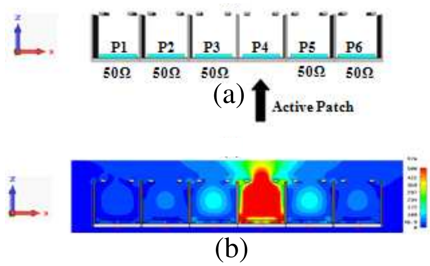

Figure 6. (a) Array of 6 M-EBG sectoral antennas, (b) field distribution (E_y) in the horizontal plane inside the resonant cavity (only P_4 is fed).

scan the beam in 5 different angles and to cover a sector greater than 55°. The beam scanning M-EBG antenna is shown in Fig. 4.

2.5. Inter-element Mutual Coupling and Comparison with the Multisource Directive M-EBG Antenna

In order to evaluate the mutual couplings versus the metallic walls, the final structure composed by the Array of 6 M-EBG sectoral elements (Fig. 4/Fig. 6(a)) is compared to a multisource directive M-EBG antenna (Fig. 5(a)). The difference of these two designs is the presence of walls. Indeed, apart that, they are similar. The patches are separated from each other by 37 mm ($0.7\lambda_0$) and they are all connected to a 50 Ω except for the patch number 4 (P_4) which is fed.

Without the walls (Fig. 5(a)), the field distribution (E_y) inside the cavity shows that a significant portion of the energy radiated by the active source (P_4) is received by the adjacent inactive sources (Fig. 5(b)) due to the fact that the patches are placed inside a resonant cavity. This mutual coupling has a substantial impact on the radiation pattern.

To overcome of this limitation, the solution is to prevent the energy created by the active patch to reach inactive patches close by. To do so, vertical metallic walls placed in the M-EBG sectoral antenna are used to force the tangential components of the electric field to vanish and thus inhibit the coupling effect between radiating elements [7] (Fig. 6(b)). In this case, the radiating elements are considered independent of each other, since the mutual coupling between them is drastically reduced.

The mutual coupling between two adjacent patches P_3 and P_4 for the array of M-EBG sectoral antennas (Fig. 6(a)) is shown in Fig. 7, compared to the multisource directive M-EBG antenna (Fig. 5(a)).

We conclude that the technique of using an array of M-EBG sectoral antennas can give interesting results. The mutual coupling between two adjacent elements is reduced by 16 dB; it passes from −8 dB to −24 dB at 5.6 GHz. In the following steps, we assume that the elements are isolated, a coupling level at −25 dB is way too negligible to impact the array synthesis.

2.6. Antenna Performances

The beam scanning M-EBG antenna has been simulated via the commercial software CST Microwave Studio, this software is based on a finite-integration-technique (FIT).

2.6.1. Directivity over Bandwidth

The simulation results are shown in Fig. 8. It gives the calculated directivity versus the frequency in two cases. In the first case only one element exists and the directivity is around 14.7 dBi. In the second case an array of 6 elements is simulated and the directivity is around

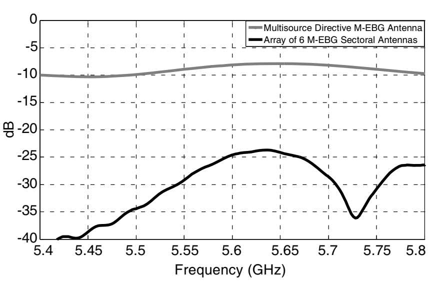

Figure 7. Mutual coupling between two adjacent patches obtained for each configuration.

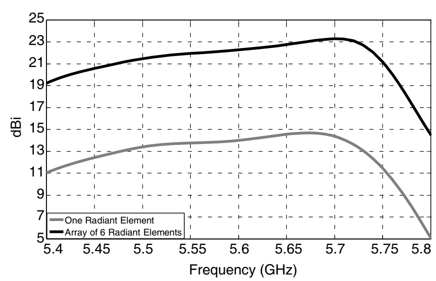

Figure 8. Directivity evolution for the two cases.

23.5 dBi at the frequency 5.69 GHz. We can notice that we have gained 8.5 dBi. The elements are fed with equi-amplitude and equi-phase excitations so we are looking to focus the beam at $\theta = 0°$ and $\varphi = 0°$.

2.6.2. Matching

The matching of the 6 radiating elements is presented in Fig. 9. The obtained matching of the elements are identical. This means that each the elements are isolated is considered, this is a natural consequence of a very low mutual coupling. The matching is less than -10 dB over the frequency range [5.6–5.725] GHz and varies between -1 and -10 dB at the beginning of frequency band.

2.6.3. Radiation Patterns in the Horizontal Plane (H Plane)

We have calculated the phase shift $\Delta\varphi$ between adjacent elements required to radiate five beams in different scanning angles. The different excitations applied at the different radiating elements are listed in Table 2.

We have simulated 5 different scan beam cases as depicted in

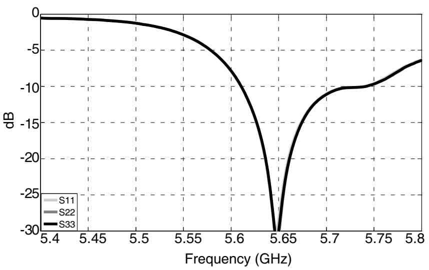

Figure 9. Matching of each radiant element.

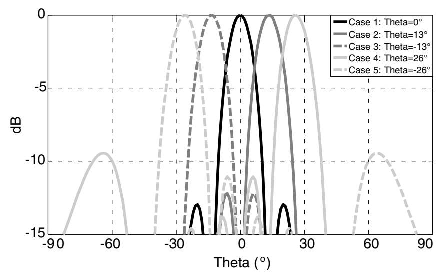

Figure 10. Radiation patterns in the H plane at 5.7 GHz.

Table 2. Weights applied to radiant elements for the five scanning beams.

Weights	Elements	1	2	3	4	5	6
Amplitude	All cases	1	1	1	1	1	1
Phase (deg)	Case 1	0	0	0	0	0	0
	Case 2	300	240	180	120	60	0
	Case 3	0	60	120	180	240	300
	Case 4	577.5	462	346.5	231	115.5	0
	Case 5	0	115.5	231	346.5	462	577.5

Table 2. For each case the radiation pattern is observed at 5.7 GHz in the horizontal plane (H plane), as depicted in Fig. 10.

The radiating patterns are satisfying. The main beam can be scanned approximately from $-30°$ to $30°$ in the H plane. Scanning angles are symmetrical about the axial beam. In fact, these scanning angles are $-13°/13°$, $0°$ and $-26°/26°$. We note that grating lobes appear for extreme beams (cases 4 and 5) with 10 dB lower than the main lobe because the radiating element is quite large ($d \approx 0.7\lambda_0$). The side lobes are only 13 dB below of the main lobe.

A Beam Scanning M-EBG antenna has been investigated. Next, the basic idea to design the reconfigurable antenna will be studied.

3. RECONFIGURABLE M-EBG ANTENNA DESIGN

3.1. Principle of the Proposed Idea

It is preferred that the M-EBG sectoral antennas are symmetric in X and Y directions, so the final array design have a square radiating aperture. Indeed, the directive radiation pattern of the square M-EBG antenna is due to the uniform circular electric field repartition in the resonant cavity. Metallic Walls deny the mutual couplings between the different resonance cavities. Walls positions and height should be optimized by the designer to meet with his specifications.

The objective is to control the repartition of energy inside the different resonance cavities. The array has N elements with N inputs that can be switched ON or OFF. The ON states means the antenna is excited therefore the antenna participates in the radiation pattern. The OFF state means that the antenna is inactive. These states are calculated versus a given directivity, a given beamwidth or a given shaped beam. Fig. 11 shows an example of a simple case where the ON sates (or N excited elementary units) are given versus the directivity we are looking at. The proposed technique is simple and easy to manage.

On the long terms what we are looking for is the following. A reconfigurable antenna which is able to switch the cells ON/OFF to jump from a directive beam in a given direction to another directive beam in another direction, or radiate shaped contour beams.

One or more radiating elements can be fed simultaneously, according to the radiation pattern form which one wants. The interesting part that makes this technique quite feasible is that the mutual coupling do not troubles the beam synthesis. An unexcited cell will be invisible in the entire radiation process. The array concept is slightly different from a classic beam scanning array or switched parasitic elements array where usually the ON/OFF states

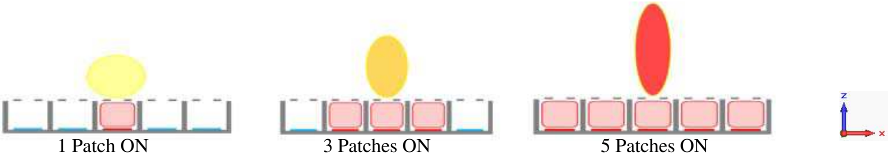

Figure 11. Principle of the directivity/beam reconfigurable M-EBG antenna.

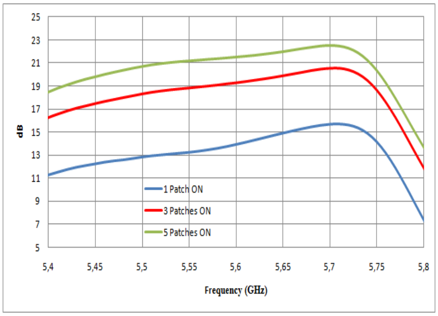

Figure 12. Directivity evolution for the three cases.

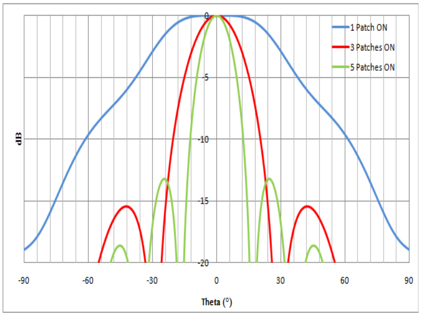

Figure 13. Radiation patterns in the H plane at 5.7 GHz.

are explained as Short-circuit/Open-circuit impedance behind the elements, and where all the cells participate in the radiation pattern.

For the sake of simplicity, I show next ON/OFF states to control the directivity. Indeed, in this study, we only consider an array of five M-EBG sectoral antennas instead of six in order to have a symmetric structure. The elements are fed symmetrically around the central cell.

3.2. Antenna Performances

In this paragraph, we present the performance of the final antenna design for three possible configurations. Firstly we excite only one active cell (ON) while the surrounding four cells are inactive or invisible (OFF). The second case consists of 3 active cells and 2 inactive cells. The last test case consists of all active cells (ON) as depicted in Fig. 11.

In the first case, the directivity is 15.7 dB (Fig. 12) and the beamwidth is 61° (calculated as angles where the directivity is -3 dB lower than the maximum directivity) (Fig. 13).

In the second case, the directivity is 20.5 dB (Fig. 12) and the beamwidth equals 24° (Fig. 13).

In the last case where all the cells are active (ON), the directivity reaches 22.5 dB (Fig. 12) and the beamwidth is around 14° (Fig. 13).

4. CONCLUSION

A novel reconfigurable M-EBG antenna structure with controllable beam and directivity has been proposed.

The paper discusses in the first part the proper technique to design the element antenna shape. Several antennas are aligned together in an array to perform beam scanning over a wide angle or shaping capabilities. M-EBG sectoral antennas enabled us to reach a good directivity with few elements; this is explained by the fact that the element alone has 15.7 dB. As we can see, we have successfully employed metallic walls to suppress the mutual coupling between the resonance cavities.

In the second part of the paper, M-EBG antennas were put together in joint array. This time, ON/OFF states allows controlling the shape of the radiation pattern. A performance study on the directivity was carried out by changing the excited antennas. This method makes it possible to obtain in a simple way an agile M-EBG antenna without the use of active electronic components.

This novel design provides more flexibility and can be used in military applications or commercials purposes.

The presented paper demonstrated a technique for a reconfigurable antenna that can achieve high directivity with few radiating elements. This work will be followed by numerous studies on different aspects of the proposed idea, such as the distribution circuit for the ON/OFF M-EBG array, the beam shaping techniques and M-EBG array associated with a parabolic reflector for space communications.

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