Analysis and Design of a Cylindrical EBG based directive antenna

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Abstract—In this paper, a cylindrical electromagnetic bandgap (CEBG) structure composed of infinite metallic wires is analyzed, designed and used as a model to develop a new reconfigurable directive antenna. This structure is circularly and radially periodic, and it is excited at its center using an omnidirectional source. The analysis is based on calculating the transmission and reflection coefficients of a single cylindrical frequency selective surface (FSS) and then, considering only the fundamental mode interaction, deducing the frequency response of the CEBG structure composed of multiple cylindrical FSSs. For this structure, new analytical formulas are derived, and their accuracy is assessed compared to those obtained by the finite-difference time-domain method. As in rectangularly periodic structure case, the frequency response of the CEBG structure exhibits pass-bands and bandgaps, and it is possible to obtain directive beams by introducing defects in the periodic structure. Using this concept, a new antenna was developed to obtain a controllable directive beam. An antenna prototype, without control, was designed, fabricated, and tested. An excellent agreement was obtained between theory and experiment for both return loss and radiation patterns.

Index Terms—Cylindrical structures, directive antennas, electromagnetic bandgap (EBG) materials, periodic structures.

I. INTRODUCTION

RECENTLY, photonic bandgap (PBG) materials [1], [2] have drawn significant attention in physics and engineering due to their analogy to semiconductor crystals, where electron bandgaps can be found. In microwave and antenna domains, they are known as electromagnetic bandgap (EBG) structures. EBG materials are periodic structures characterized by the forbidden propagation of electromagnetic waves whose frequencies belong to frequency bandgaps, and also characterized by the ability to open localized electromagnetic modes inside the forbidden frequency bandgap by introducing defects into the periodical structures. EBG structures, rectangularly periodic, have been used in several applications, such as suppressing surfaces waves [3], designing directive antennas with a single feed [4], [5], and creating a controllable beam [6], [7]. In this paper, a new concept of circularly and radially

periodic structures, i.e., cylindrical EBG (CEBG) structures, is investigated in order to demonstrate the advantage of their circular symmetry, which can allow a reconfigurable directive beam over 360° range.

It is known that the transmission and reflection characteristics of periodic structures, composed of multiple layers of planar frequency selective surfaces (FSSs), can be obtained using the cascading scattering matrix method [8]. This method is inspired from that of cascading networks in the circuit theory, and it reduces considerably computing time compared to the conventional ones that calculate the overall scattering from the structure. The cascading approach is well suited to the design process because it is possible to evaluate the effect of any changing in one layer or in the period without repeating the entire computing process. The same approach may be applied to CEBG structures by calculating the transmission and reflection characteristics of a single cylindrical FSS. Cylindrical FSSs have been studied by several investigators [9]–[12]. One of the principal objectives was to calculate scattered fields of cylindrical surface using Floquet harmonics. In [9], both internal line source excitation and plane wave excitation were considered. In [10], a numerical technique based on the Conjugate Gradient with Fast Fourier Transform was used. In [11], [12], the cylindrical FSS has been used as a waveguide, and the propagation constant has been studied. However, from these contributions, the transmission and reflection coefficients of the cylindrical FSS have not been calculated yet. The challenge in this structure is the existing of multiple reflections between the cylindrical FSS and its center.

This paper presents the design of a new reconfigurable directive antenna using a simple but efficient model based on CEBG structures and a cascading approach. The problem of the characterization of a single cylindrical FSS is resolved and the multiple reflections of cylindrical waves between cylindrical FSSs are developed for the first time. In this work, the periodic structures are composed of infinite metallic wires and only the fundamental mode interaction between cylindrical layers is considered. The proposed approach is well suited for the design process of the proposed antenna. An equivalent network approach for circular cylindrical FSSs which considers multiple modes interactions can be found in [13], but it is more time consuming that the present approach. Using the CEBG structure model, an application for creating a controllable beam over 360° range is proposed. The concept of controllable beam with reconfigurable EBG structures has been proposed in [6], [7], where the authors have proposed to commute between continuous and discontinuous wire structures for reconfiguring
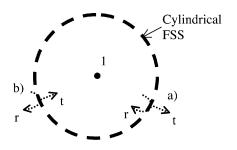
Fig. 1. Characteristics of a cylindrical FSS: (a) reflection and transmission coefficients for a cylindrical wave coming from inside to outside, (b) reflection and transmission coefficients for a cylindrical wave coming from outside to inside.
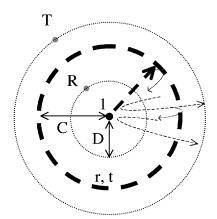

Fig. 2. Cylindrical FSS illuminated by a cylindrical wave coming from the center. Multiple reflections between the center and the surface lead to the coefficients T and R.

the radiation patterns of an antenna. Indeed, these two structures behave differently at low frequencies, by presenting a pass-band and a stop-band for discontinuous and continuous wires cases, respectively. To obtain the commutation, the authors have placed periodically diodes in the broken wires. When the diodes are switched on, the structure behaves as a continuous wire medium, if the impedance of the diodes are neglected, whereas when the diodes are switched off, the structure behaves as a discontinuous wire medium. We have recently presented an analysis of the band structure of the discontinuous wire medium for different wire diameters and lengths in [14]. In [6], [7], EBG structures with rectangular mesh have been used. However, EBG structures with rectangular mesh present a major drawback: they do not make possible to obtain a beam turning on $360°$ with any angle of direction and any step. Cylindrical EBG structures allow to overcome this drawback.

In the next section, new formulas to extract the transmission and reflection coefficients of a single cylindrical FSS are outlined, completing our previous work [15]. Then, in Section III, we develop an iterative formulation to handle multilayered CEBG structures. The approach is validated using finite-difference time-domain (FDTD) method. As an application, a new reconfigurable directive antenna, based on CEBG structures with defects, is described in Section IV. Finally, in Section V, an antenna prototype is designed, fabricated and tested. The fabricated antenna does not have a control yet in order to test first the directivity characteristic of CEBG structures with defects. Both theoretical and experimental results are presented and discussed, which demonstrate the accuracy and usefulness of the present approach.

II. CHARACTERIZATION OF A SINGLE CYLINDRICAL FSS

In this section, the transmission and reflection coefficients of a single cylindrical FSS are calculated. These coefficients can not be directly obtained as in the planar case because of the multiple reflections between the cylindrical FSS and its center. It is clear that, for a current line source or no object in the center, the reflection coefficient at the center is equal to 1. Now, let us consider the transmission (t) and reflection (r) coefficients of the cylindrical FSS as shown in Fig. 1. Using the principle of reciprocity, these coefficients are the same whatever the structure is illuminated by a cylindrical wave coming from inside or from outside. To study these coefficients, we consider an incident cylindrical wave coming from the center as shown in Fig. 2.

Calculating the normalized fields at points outside and inside the cylindrical cavity leads to the coefficients T and R as illustrated in Fig. 2. In Section II-A, analytical relations between (t, r) and (T, R) coefficients are developed, and in Section II-B, the coefficients T and R are calculated for the particular case of a single surface composed of metallic wires.

A. Extraction of the Reflection and Transmission Coefficients

Using the multiple reflections between the cylindrical FSS and its center as shown in Fig. 2, the coefficient T can be expressed as a function of t and r

$$T = t \sum_{n=0}^{\infty} r^n e^{-jn2\eta_0(kC)}$$
$$= \frac{t}{1 - re^{-j2\eta_0(kC)}} \qquad (1)$$

where k is the free space wave number, C is the radius of the cylinder and $\eta_0(x)$ is the phase of the cylindrical wave

$$\eta_0(x) = arctan\left(\frac{N_0(x)}{J_0(x)}\right) \qquad (2)$$

where $J_0(x)$ and $N_0(x)$ are the first and second kind Bessel functions of zero order.

To obtain R, an observation point at the distance D $(D < C)$ from the center is considered. Referring to Fig. 2, R can be expressed as a function of t and r

$$R = \frac{1 + re^{-j2\eta_0(kC)+j2\eta_0(kD)}}{1 - re^{-j2\eta_0(kC)}}. \qquad (3)$$

From (1) and (3), one can show that t and r can be expressed as

$$t = \frac{1 + e^{j2\eta_0(kD)}}{R + e^{j2\eta_0(kD)}} T \qquad (4)$$

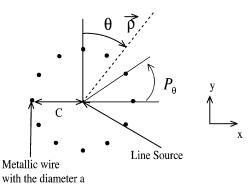$$r = \frac{R - 1}{R + e^{j2\eta_0(kD)}} e^{j2\eta_0(kC)}. \qquad (5)$$

Fig. 3. Periodic cylindrical structure made of infinite long metallic wires and illuminated by a TM cylindrical wave coming from the center.

B. Calculation of the Scattered Field

In this section, we present a simple method to calculate T and R coefficients for a single cylindrical FSS composed of infinite long metallic wires as illustrated in Fig. 3. The parameters of this structure are the diameter of the wires a, the radius C, and the angular period P_θ. We also denote by P_t ($P_t = P_\theta C$) the transversal period and by N ($N = 360/P_\theta$) the number of wires.

The structure is illuminated by an infinite line source, with a TM cylindrical wave. The transverse electric field $E(\overrightarrow{\rho})$ is a function of the frequency and the position $\overrightarrow{\rho}$ from the center. According to [16], this transverse field is equal to the incident field plus the field scattered by the wires. Thus, $E(\overrightarrow{\rho})$ can be written as

$$E(\overrightarrow{\rho}) = E_{\text{inc}}(\overrightarrow{\rho}) + \sum_{n=0}^{N-1} K_n E_{sn}(\overrightarrow{\rho}) \qquad (6)$$

where $E_{\text{inc}}(\overrightarrow{\rho}) = H_0^2(k\|\overrightarrow{\rho}\|)$, H_0^2 is the Hankel function of the second kind and of zero order, and E_{sn} is the scattered field by the wire n ($n = 0, \ldots, N-1$). K_n are unknown coefficients due to the interactions between the wires. Because of the symmetry of the structure, the coefficients K_n are all identical, i.e., $K_n = K$, and we can write

$$\sum_{n=0}^{N-1} K_n E_{sn}(\overrightarrow{\rho}) = K \sum_{n=0}^{N-1} E_{sn}(\overrightarrow{\rho}). \qquad (7)$$

For a small wire diameter a, the scattered fields E_{sn} can be written in terms of the Hankel function H_0^2 as

$$E_{sn}(\overrightarrow{\rho}) = H_0^2\left(k\sqrt{C^2+\|\overrightarrow{\rho}\|^2-2C\|\overrightarrow{\rho}\|\cos\left(\frac{n2\pi}{N}-\theta\right)}\right)$$
$$n = 0, \ldots, N-1. \qquad (8)$$

K is obtained by imposing $E(\overrightarrow{\rho_s}) = 0$ on the wire surface, for the case of wire $n = 0$: $\overrightarrow{\rho_s} = C\overrightarrow{y} + \overrightarrow{ds}$, where $\overrightarrow{ds}$ is the vector defined by the center of the wire $n = 0$ and a point on the surface of this wire.

The equation $E(\overrightarrow{\rho_s}) = 0$ must be satisfied at all points of the surface of the wire $n = 0$. As a good approximation for a small wire diameter, $\overrightarrow{ds}$ is neglected in the expressions of

$E_{\text{inc}}(\overrightarrow{\rho_s})$ and $E_{sn}(\overrightarrow{\rho_s})$ ($n = 1 \ldots N-1$). Since $E_{s0}(\overrightarrow{\rho_s})$ does not depend on the angle defined by the vector $\overrightarrow{ds}$, then the point $C\overrightarrow{y} + a/2\overrightarrow{y}$ can be included in the E_{s0} expression. Finally, K is obtained by the following relation:

$$K = -\frac{E_{\text{inc}}(C\overrightarrow{y})}{E_{s0}\left(\left(C+\frac{a}{2}\right)\overrightarrow{y}\right) + \sum_{n=1}^{N-1} E_{sn}(C\overrightarrow{y})}. \qquad (9)$$

The variable T is defined as the radiated transverse electric field outside the cavity normalized by the radiated field of the source with the cylindrical surface not present, and R is the transverse electric field inside the cavity at the distance D ($D < C$) from the center normalized by the radiated field of the source with the cylindrical surface not present, then we can write

$$T = \frac{E(\overrightarrow{\rho})}{E_{\text{inc}}(\overrightarrow{\rho})}, \quad \|\overrightarrow{\rho}\| > C + P_t \qquad (10)$$

$$R = \frac{E(\overrightarrow{\rho})}{E_{\text{inc}}(\overrightarrow{\rho})}, \quad \|\overrightarrow{\rho}\| = D < C - P_t. \qquad (11)$$

Here we can note that, after numerical studies, a minimum distance of approximately P_t, the transversal period, must be respected between the observation point and the surface to avoid non propagating waves. In this case, it can be seen that the coefficient $|T|$ does not depend on the position of the observation point as long as it is far enough from the surface, i.e., $\|\overrightarrow{\rho}\| > C + P_t$.

To validate the accuracy of the above expressions, the structure shown in Fig. 3 has been simulated using the FDTD method. The source is an infinite line current source and the wires are modeled using Holland *et al.* thin wire formalism [17]. The T and R coefficients are obtained with the FDTD method by carrying out two simulations: one with the structure and another without the structure for the normalization. Numerical results based on this current analysis and the FDTD simulations for $|T|$ are plotted in Fig. 4. A good agreement is observed between the results obtained by the current method and those computed by the FDTD method. The reason of a strength of $|T|$ greater than one is that the cavity modifies the matching of the line source, which is not initially matched to free space, and then the power supplied outside the cavity, at resonance, is greater than the power supplied by the line source alone. However, according to the energy conservation principle, the strengths of $|t|$ and $|r|$ are always smaller than one, as it is shown in the next section.

C. Cylindrical FSS

The extraction of the reflection and transmission coefficients for different cylindrical FSSs allows an interesting analysis presented in this section. For instance, we consider the following case: $C = 45$ mm, $P_\theta = 30°$ and $a = 1.5$ mm. The transversal period is $P_t = \pi/6 \times 45$ mm. Fig. 5 shows $|t|$ and $|r|$ coefficients obtained with the proposed extraction method [using (4) and (5)].

The characteristics $|t|$ and $|r|$ of a second structure with the parameters $C = 90$ mm, $P_\theta = 15°$ and $a = 1.5$ mm were computed. This structure has the same transversal period as the
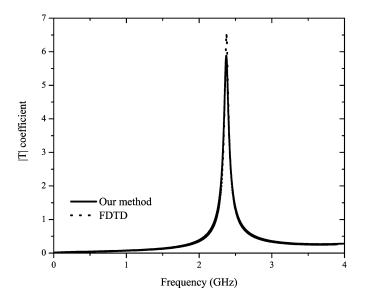
Fig. 4.   Transmission coefficient $|T|$ of a single cylindrical FSS ($a = 1.5$ mm, $P_\theta = 30°$, $C = 45$ mm).

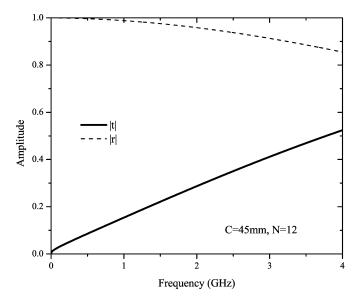Fig. 6.   Coefficients $|t|$ and $|r|$ of a single cylindrical FSS ($a = 1.5$ mm, $P_\theta = 15°$, $C = 90$ mm).

Fig. 5.   Coefficients $|t|$ and $|r|$ of a single cylindrical FSS ($a = 1.5$ mm, $P_\theta = 30°$, $C = 45$ mm).

previous structure ($P_t = \pi/3 \times 90$ mm). Fig. 6 shows the coefficients $|t|$ and $|r|$ of this case. We can observe that the coefficients $|t|$ and $|r|$ are similar to the previous ones shown in Fig. 5, and the phases of t and r (not shown here) are also similar to the previous ones. This observation can be verified with other structures, and it can be conclude that when the transversal period is constant, the structure has the same t and r coefficients. EBG structures composed of planar FSSs use usually surfaces with the same characteristics. Therefore, it is possible to apply the
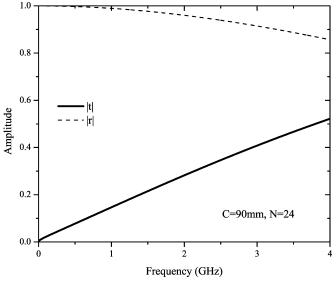
same design for CEBG structures using cylindrical FSSs with the same transversal period.

III. MULTILAYERED CYLINDRICAL STRUCTURES

In this section, a new analytical iterative formulation is developed to handle cylindrical multilayered structures. A CEBG structure composed of multiple layers of cylindrical FSSs of metallic wires as shown in Fig. 7 is considered. The cylindrical surfaces are periodically spaced with the period P_r and have the same transversal period P_t, and accordingly the same transmission and reflection coefficients. The transversal period is kept constant by modifying adequately the angular period of each layer $(P_{\theta 1}, P_{\theta 2}, \ldots)$.

Using multiple reflections and considering single-mode interactions between layers, one can show that the transmission and reflection coefficients of the CEBG structure composed of n layers of cylindrical FSSs can be written as in (12) and (13), shown at the bottom of page. The transmission (t_n) and reflection (r_n) coefficients of a multilayered structures composed of n layers of cylindrical FSSs are functions of the coefficients of the structure composed of $n - 1$ layers. To our knowledge, this is the first time that analytical relations of the multiple reflections of cylindrical waves in radially periodic structures are presented. These relations are an extension to the cylindrical case of formulas for multi-sections transmission lines [18]. Taking into account the multiple reflections with the center, we obtain the coefficient T_n

$$T_n = \frac{t_n}{1 - r_n e^{-j2\eta_0(kC)}}. \tag{14}$$

$$t_n = \frac{t_{n-1} t}{1 - r_{n-1} r e^{-j2\eta_0(k(C+(n-1)P_r)) + j2\eta_0(k(C+(n-2)P_r))}} \tag{12}$$

$$r_n = r_{n-1} + \frac{t_{n-1}^2 r e^{-j2\eta_0(k(C+(n-1)P_r)) + j2\eta_0(kC)}}{1 - r_{n-1} r e^{-j2\eta_0(k(C+(n-1)P_r)) + j2\eta_0(k(C+(n-2)P_r))}}. \tag{13}$$

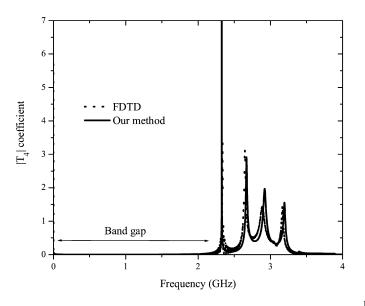Fig. 7.   CEBG structure composed of multiple layers of cylindrical FSSs.

Fig. 9.   Geometry of the CEBG structure with defects ($n = 4$, $C = P_r = 45$ mm, $P_{\theta 1} = 30°$).

Fig. 8.   Coefficient $|T_n|$ of a CEBG structure made of four layers ($n = 4$).

Fig. 10.   Simulated radiation patterns in the H-plane at 2 GHz for different number of layers of the CEBG structure with defects consisting of removed wires.

As an example, the coefficient $|T_4|$ of the structure shown in Fig. 7, with the parameters $C = P_r = 45$ mm, $P_{\theta 1} = 30°$ and $a = 1.5$ mm is computed by the proposed approach and the FDTD method. Fig. 8 shows a comparison between both results. A good agreement is observed between the predicted results by our approach and those obtained using the FDTD method. The advantage of our proposed approach is that the computational time is considerably reduced compared to the FDTD method, which makes the design easier. From curves presented in Fig. 8, one can note that there is a first bandgap, where the value of $|T_4|$ is very low, and a passband, where the number of peaks is correlated with the number of cylindrical layers. The positions of the bandgap and the passband can be controlled by modifying the geometric parameters of the structure: C, P_t, P_r and a. For the application presented in the next section, the end of the bandgap is positioned at 2 GHz.
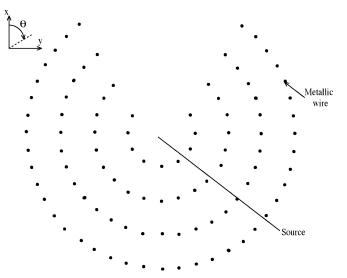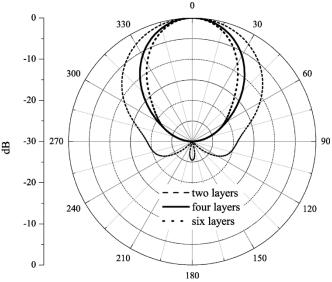
IV. APPLICATION TO RECONFIGURABLE DIRECTIVE ANTENNAS

The radiation pattern of CEBG structures, excited at their center, is omnidirectional as long as $P_t/\lambda < 0.5$. To modify their radiation pattern, defects are introduced in the proposed structures. To demonstrate this approach, we consider the CEBG structure with defects, as illustrated in Fig. 9. In this example, defects consist of removing multiple wires: 3 wires are removed from the first layer, 5 from the second, 7 from the third, and so on.

For this case, numerical simulations using the FDTD method were carried out. Fig. 10 shows the radiation patterns in the H-plane of the CEBG structures with defects, for different number of layers, at 2 GHz (this frequency is located at the end of the bandgap). From these curves, it can be seen that
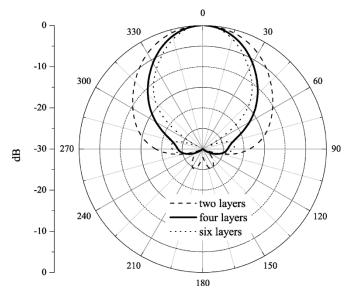
Fig. 11.   Simulated radiation patterns in the H-plane at 2 GHz for different number of layers of the CEBG structure with defects consisting of discontinuous wires.

Fig. 12.   Side view of the CEBG antenna (dimensions in millimeters).

the directivity increases with the number of layers. The directivity is due to the electromagnetic wave modes opened by the defects in their direction and the electromagnetic waves forbidden in other directions caused by the existing bandgap. If we replace the continuous wires by discontinuous ones with diodes, where diodes are off for the removed wires and on for the remaining wires, we can note that the CEBG structure can allow an electronically sweeping of the antenna beam and reconfiguration of its radiation pattern over 360° range. With this features it is possible to design reconfigurable antennas. These reconfigurable antennas have a potential application in mobile communications, and they can be used at the base station for reducing interferences and fading.

We consider now that the removed wires are replaced by discontinuous wires. The finite wires are 12 mm length and the vertical distance between two wires is 3 mm. Fig. 11 shows the radiation patterns in the H-plane of the CEBG structures with defects consisting of discontinuous wires, for different number of layers, at 2 GHz. From this figure, it can be seen that the structures with discontinuous wires present the same desired radiation characteristic, i.e., a single directive beam, than those of the structures with removed wires.

As an example, an antenna made of a CEBG structure with defects (wires removed) is considered and studied in the next section.

V. EXPERIMENTAL RESULTS

A CEBG antenna prototype has been simulated with the FDTD method and fabricated to validate the proposed concept. The geometry of the CEBG illustrated in Fig. 9 is used. Fig. 12 shows a side view of this antenna. It consists of a monopole, as an excitation source, a ground plane, and a four-layer CEBG structure made of metallic wires (see Fig. 9).

In the FDTD simulations, the ground plane is considered infinite. The monopole has the same diameter as the parasitic wires,
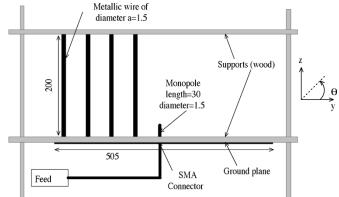

Fig. 13.   Photograph of the fabricated CEBG antenna.

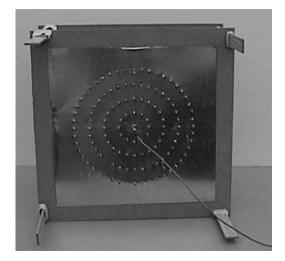Fig. 14.   Photograph of the fabricated CEBG antenna showing the connection and the ground plane.

and its length has been optimized to obtain matched impedance at 2 GHz. Figs. 13 and 14 show photographs of the fabricated CEBG antenna. The simulated and measured return loss of the antenna are shown in Fig. 15. A good agreement is obtained between theoretical and measured results. From the measured
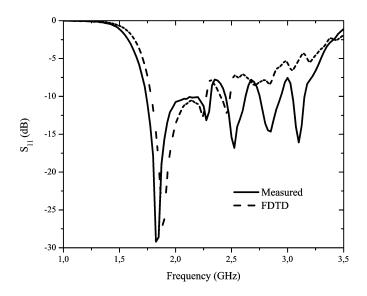
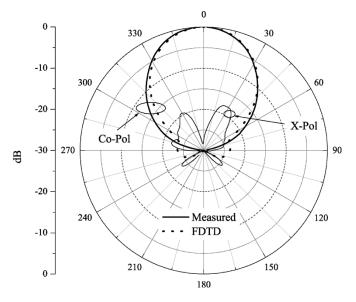Fig. 15.   Measured and simulated return loss of the proposed CEBG antenna.

Fig. 17.   Simulated and measured radiation patterns in the E-plane at 1.77 GHz (simulated and measured X-pol are lower than −30 dB).

Fig. 16.   Simulated and measured radiation patterns in the H-plane at 1.77 GHz (simulated X-pol is lower than −30 dB).

Fig. 18.   Simulated and measured radiation patterns in the H-plane at 2.17 GHz (simulated X-pol is lower than −30 dB).

curve, a bandwidth $(S_{11} < -10 \text{ dB})$ from 1.74 to 2.31 GHz (a fractional bandwidth of 28%) is achieved, which is enough to cover the DCS, PCS, and UMTS bands (1.77–2.17 GHz). This CEBG antenna can find application for mobile communication base stations.

A further study of the CEBG antenna has focused on its radiation performance. The radiation patterns of the proposed antenna were measured in an anechoic chamber located at INRS, in Montreal. For comparison, numerical simulations for radiation patterns were also carried out using the FDTD method. The measured and simulated patterns are shown in Figs. 16–19. With reference to these curves, a good agreement between predictions and measured data can be observed. The half-power beam widths in the H-plane are 47.8° and 37.9° at 1.77 and 2.17 GHz, respectively. In the E-plane, the half-power beam widths are 36.3° and 29.9° at 1.77 and 2.17 GHz, respectively. The values of the maximum radiation in the cross polarization
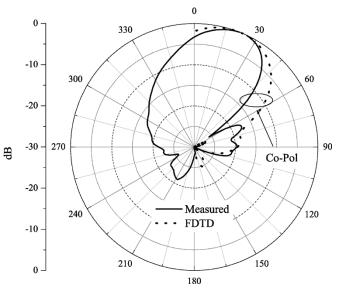
are −18 dB and −20.5 dB at 1.77 and 2.17 GHz, respectively. Note that in the E-plane the beam is slightly tilted. The angles of the tilt are 23.4° at 1.77 GHz and 19.8° at 2.17 GHz. To explain the beam tilting, Fig. 20 presents the simulated radiation patterns in the E-plane of the CEBG antenna and of the monopole alone. From these curves, it can be seen that the beam tilting is essentially due to the monopole. Future work will concentrate on the examination of other sources that have a maximum radiation in the horizontal (e.g., a dipole antenna). The measured gains of the CEBG antenna are 12.2 and 15.8 dB at 1.77 and 2.17 GHz, respectively.

These measurements of CEBG antenna are unique and very positives. With such features, these antennas are suitable for wireless communication systems operating at 2 GHz, specially at the base station, where more gain is needed.

Fig. 19. Simulated and measured radiation patterns in the E-plane at 2.17 GHz (simulated and measured X-pol are lower than −30 dB).

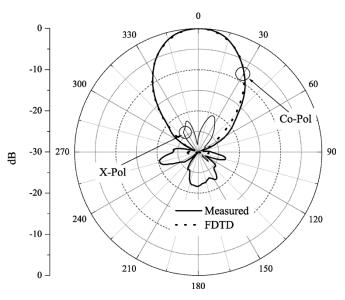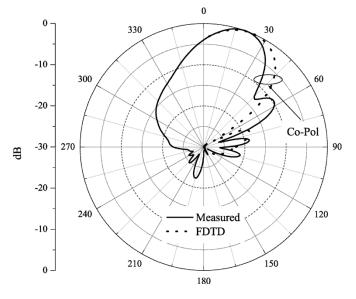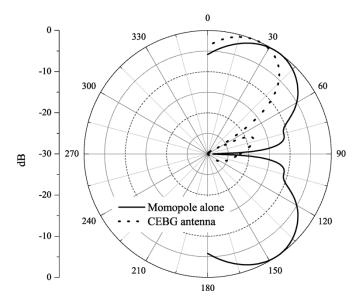Fig. 20. Simulated Co-pol radiation patterns in the E-plane, at 2.17 GHz, of the monopole alone and the CEBG antenna.

VI. CONCLUSION

This paper has presented the design of a new reconfigurable directive antenna by incorporating Cylindrical EBG structures composed of metallic wires. For this, a simple but efficient analysis of these periodic structures has been proposed. First, the transmission and reflection coefficients of a single cylindrical FSS have been extracted, and then, considering only fundamental mode interaction between layers, iterative relationships to handle multilayered Cylindrical EBG structures have been also developed and described. The obtained results by the proposed method have been successfully compared with that obtained using the FDTD method. Using the CEBG structures model, a prototype of a new directive antenna, without control, was designed, built and tested. This antenna offers a bandwidth of 28% and a gain between 12 and 16 dB, which

are enough for wireless applications, such as DCS, PCS, and UMTS.

The proposed CEBG antenna has several advantages, such as easy fabrication and a single feed, which can reduce complexity compared to feeding networks used in conventional antenna arrays. In addition, the gain can be increased by adding other layers and different types of exciting source can be used. Finally, due to the circular symmetry of the structure, it is possible to obtain a controllable radiation pattern over 360° range by incorporating in the structure active components, such as diodes.

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