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Gain Enhancement of a Microstrip Patch Antenna Using a Cylindrical Electromagnetic Crystal Substrate

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***Abstract*— In this paper, the performance of a circular microstrip patch antenna is improved using a new cylindrical Electromagnetic Bandgap (EBG) substrate. The microstrip patch antenna is fed by a coaxial probe and is integrated within a cylindrical electromagnetic bandgap substrate, based on the mushroom-like substrate, to increase the antenna gain. The cylindrical electromagnetic bandgap structure is a combination of two periodic structures with different periods. One is made of metallic rings and the other of grounding vias, which are disposed such as to form a radially and circularly periodic structure. A parametric analysis using a full-wave method was carried out in order to design the EBG structure. With the proposed concept, an antenna prototype was fabricated and tested. The radiation patterns and return loss obtained from measurements show a good impedance matching and a gain enhancement of the proposed antenna.**

***Index Terms*— Electromagnetic bandgap materials, cylindrical structures, integration, microstrip patch antennas.**

I. INTRODUCTION

MICROSTRIP patch antennas offer an attractive solution to compact, conformal and low-cost designs of many wireless application systems [1]. It is known that the gain of a single patch antenna is generally low.

The gain of patch antennas can be increased by using multiple patches connected to an array or by reducing the surface wave which can create ripples in the radiation pattern. Several methods have been proposed to reduce the effects of surface waves [2-8]. One approach suggested is the synthesized substrate that lowers the effective dielectric constant of the substrate either under or around the patch [2-3]. Other approaches are to use parasitics elements [4-5] or to use a reduced surface-wave antenna [6-8]. Electromagnetic band-gap (EBG) structures, also known as photonic crystals [9], are also used to improve the antenna performance [10-16]. These structures have the ability to open a bandgap, which is a frequency range for which the propagation of electromagnetic waves is forbidden. By surrounding a patch antenna with a square-lattice of small metal pads with grounding vias, also called mushroom-like structure, a substantial suppression of surface waves excited in the dielectric substrate has been observed, which improves the antenna gain or effective radiated power [11]. Reduction of mutual coupling and co-site interference are other benefits of these EBG antennas [14].

In [15,16], a circularly periodic EBG substrate has been designed in order to enhance the performance of printed dipoles antennas and microstrip slot antennas. The advantage of the circularly symmetric geometries is that a surface wave generated by a source located at the center experiences the same bandgap effect in all radial directions.

In this paper, a new circularly periodic EBG substrate is introduced to increase the gain of a circular microstrip antenna. The proposed EBG substrate is based on the mushroom-like structure and is constructed as a combination of two periodic structures. One periodic structure is composed of metal rings and the other is constituted of vertical metal vias, which are disposed such as to form a radially and circularly periodic structures. A strip-type ringed Artificial Magnetic Conductor (AMC) has been proposed in [17] to improve the performance of a circular patch antenna. However, the disposition of the vias proposed in this paper is different from the configuration proposed in [17]. The disposition of the vias is based on our previous analysis on metallic cylindrical EBG structures [18], where the transversal period is constant for all cylindrical layers.

The dielectric substrate considered in this paper has such a thickness that only the TM_0 mode is in propagation. The design of the cylindrical EBG substrate is based on a parametrical study, where the metal rings and the metal vias are disposed independently.

The remainder of the paper is organized as follows. Section II provides the analysis and design of the proposed circular patch antenna integrated on a cylindrical EBG substrate. In Section III, the distribution of the field at the surface of the substrate is studied. To validate the proposed concept, Section IV gives experimental results from a conventional patch antenna and a patch antenna with an EBG substrate. The results demonstrate that an enhancement of the gain of $2.9\ dB$ is obtained thanks to the cylindrical EBG substrate without modifying significantly the matching of the patch antenna. Finally, concluding remarks are given in Section V.

II. ANALYSIS AND DESIGN

In this section, a circular microstrip patch antenna and its cylindrical EBG substrate are designed by using a Finite Element method (HFSS-Ansoft). In the simulation process, convergence and minimization of numerical errors were obtained by ensuring that the mesh was sufficiently fine. In

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Subsection A, the patch antenna is designed to operate at an arbitrary chosen frequency. Then, in Subsection B, the EBG substrate is designed to increase the gain of the patch antenna at its operating frequency.

A. Circular microstrip patch antenna

This subsection describes the patch-antenna configuration that is selected to perform the comparison between using a normal substrate and a cylindrical EBG substrate. The antenna is shown in Fig. 1. The patch antenna is circular with a radius of $b = 20\ mm$ and is printed on a substrate with a relative permittivity of $\varepsilon_r = 2.55$ and a thickness of $h = 3.2\ mm$. The patch is fed by a probe with a radius of $0.5\ mm$ placed $6\ mm$ from the center of the patch. The feed location was optimized to give good impedance matching. The size of the substrate is $180\ mm \times 180\ mm$. The antenna resonates at $2.6\ GHz$.

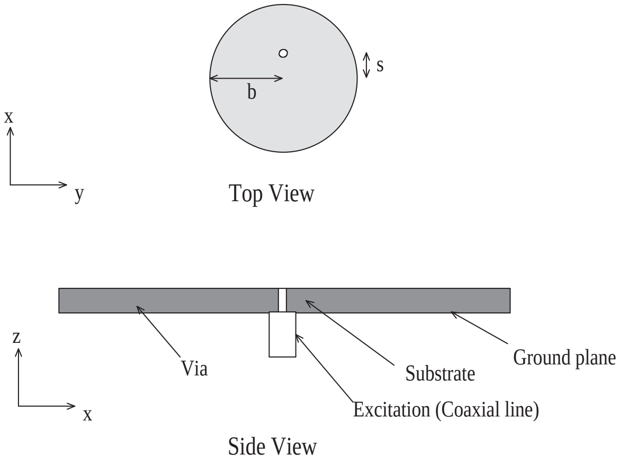

Fig. 1. Circular patch antenna using a coaxial probe excitation.

The TM_0 surface mode always exists in such a structure. However, the cutoff frequency for the first TE_1 surface mode is

$$f_c = \frac{c}{4h\sqrt{\varepsilon_r - 1}} \tag{1}$$

where c is the speed of the light. With the current configuration, one has $f_c = 18.8\ GHz$, which is larger than our operating frequency. Then, only the TM_0 surface mode is propagating.

The maximum gain of the patch antenna is around $6\ dB$. The gain of this antenna is increased using a cylindrical EBG substrate, which is described in the next subsection.

B. Patch antenna surrounded by a cylindrical EBG substrate

While the previous subsection has defined the patch-antenna configuration, the design of the EBG substrate is now presented. Figure 2 shows the schematic of the proposed patch antenna surrounded by a cylindrical structure composed of metal rings and grounding vias.

The concentric rings of strips are etched on the same plane than the patch antenna, with the distance g from one to another, and with a radial period P_{r1}. The first metal ring starts at the radius $b + g$ so that the beginnings of the strips are $b + g + (n - 1)P_{r1}$. The vias have the radius a, and they are disposed with the same transversal period P_t and the same radial period P_{r2}.

In this work, an optimization using Finite Element method was carried out in order to maximize the gain of the antenna. The following parameters are fixed: $2a = g = 2mm$. The remaining parameters P_{r1} and P_{r2} were optimized. Three concentric rings and three circularly periodic structures of vias are considered. According to numerical results (not shown here), the gain is not sufficiently increased when only one

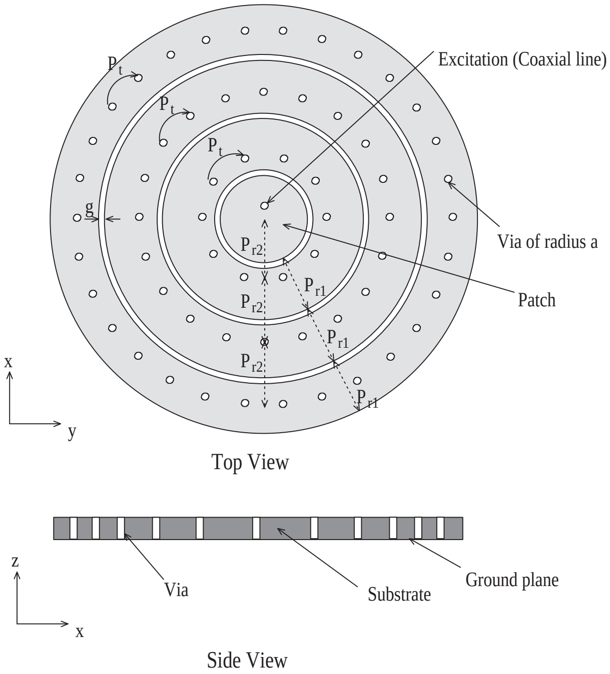

Fig. 2. Patch incorporated with the cylindrical EBG substrate.

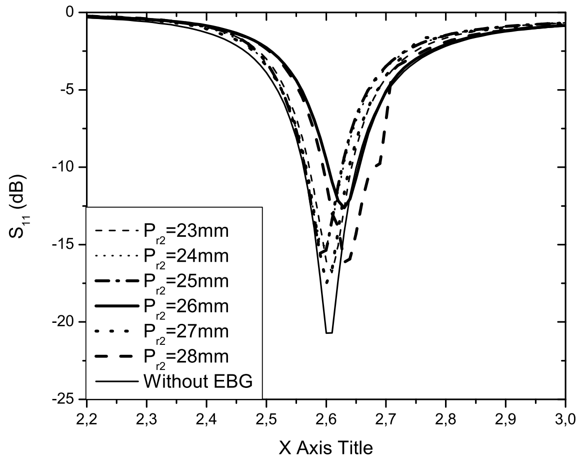

Fig. 3. Simulated return loss of the EBG antenna for different values of P_{r2}. $P_{r1} = 23mm$, $2a = g = 2mm$.

or two layers are used.

Figures 3 and 4 show the simulated return loss and the simulated gain of the EBG antenna for different values of P_{r2}, with $P_{r1} = 23mm$. Figures 5 and 6 show the simulated return losses and the simulated gain at broadside of the EBG antenna for different values of P_{r1}, with $P_{r2} = 26mm$. From Figs. 3 and 5, it is observed that the antenna resonates around 2.6 GHz, for all cases. Although the existence of the EBG structure has some effects on the impedance matching of the antennas, all the antennas still have better than -10 dB matches, for more than 3% bandwidth.

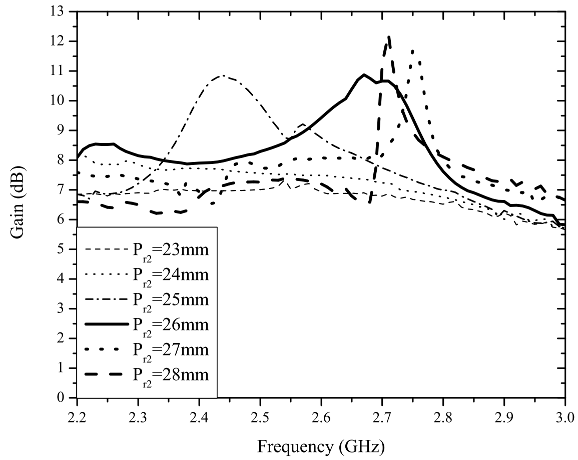

Fig. 4. Simulated gain of the EBG antenna for different values of P_{r2}. $P_{r1} = 23mm$, $2a = g = 2mm$.

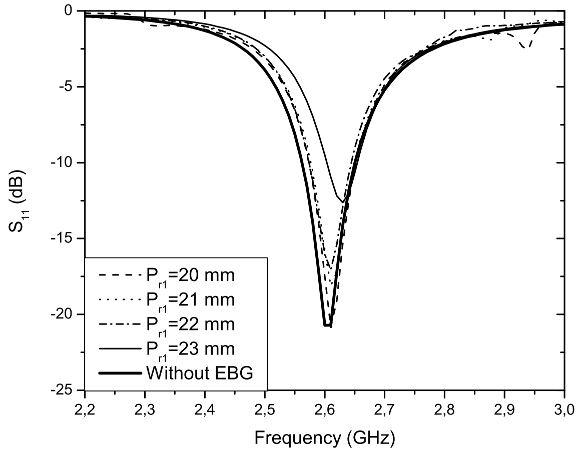

Fig. 5. Simulated return loss of the EBG antenna for different values of P_{r1}. $P_{r2} = 26mm$, $2a = g = 2mm$.

Here it should be noted that, during the gain optimization, we looked for an enhancement of the gain in a sufficiently large frequency band around the operating frequency to avoid a resonance effect at only one frequency.

From Figs. 4 and 6, the maximum gain at the frequency 2.6 GHz is obtained for the following case: $P_{r1} = 23mm$ and $P_{r2} = 26mm$. From this, a radial period between the vias of $P_{r2} \approx \lambda_0/4$ and a radial period between the rings a little smaller than $\lambda_0/4$ are required. One can note that the EBG substrate is not a periodic structure, because the parameters P_{r1} and P_{r2} are different. However they have close values. In order to analyze the contribution of the EBG substrate to the reduction of the surface wave, the distribution of the field at the surface of the substrate, with and without the EBG structure, is studied in the next section.

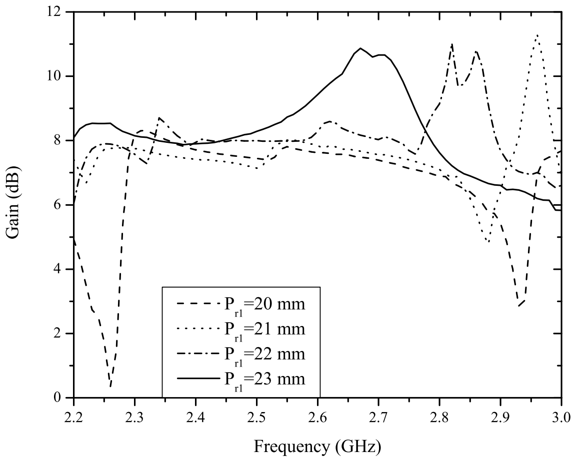

Fig. 6. Simulated gain of the EBG antenna for different values of P_{r1}. $P_{r2} = 26mm$, $2a = g = 2mm$, $s = 6mm$.

III. ANALYSIS OF THE FIELD AT THE INTERFACE BETWEEN AIR AND THE EBG SUBSTRATE

Here we can note that the previous results for the EBG antenna were validated with a home-made Finite Difference Time Domain (FDTD) code. The code was also used to compute the distribution of the transverse Electric field at the air-substrate interface of the patch antenna and of the optimized EBG antenna. The substrate is considered now of infinite extent in the plane of the patch. In the FDTD simulations, the spatial mesh sizes used are $\triangle_x = \triangle_y = 2$ mm and $\triangle_z = 0.8$ mm.

Figure 7 shows the distribution of the transverse field at the surface of the substrate of the patch antenna alone and of the EBG antenna for an observation point positioned in the x-axis. In the FDTD computation, the observation point is at the cell above the substrate. From Fig. 7, it can be noted that at large distances, without the EBG structure, the field decays nearly as a surfaces wave field (the surfaces wave field decays as $1/\sqrt{\rho}$, where ρ is the horizontal distance away from the axis of the antenna). With the EBG structure, at large distances, the field decays as a lateral field (the lateral field decays as $1/\rho^2$). From this, it can be concluded that the EBG structure has reduced the surface wave.

It can be also noted that the surface wave of the patch antenna alone is already small compared to the direct source field. From this, the gain enhancement of the EBG antenna is not only due to the reduction of the surface wave but it is mainly due to the coupling between the patch antenna and the EBG structure.

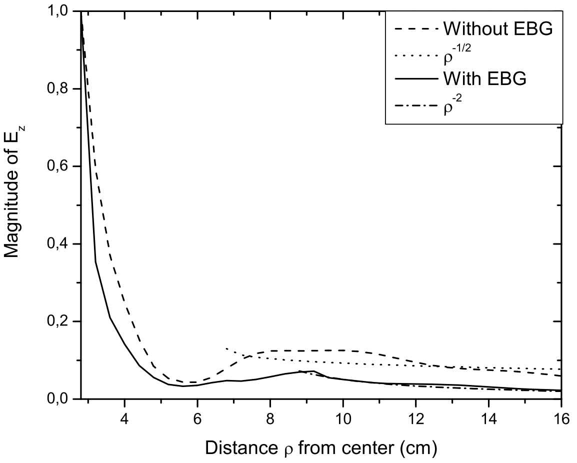

Fig. 7. Simulated normalized magnitude $|E_z|$ *vs.* the distance ρ at the surface of the antenna substrate.

IV. EXPERIMENTAL RESULTS

To confirm the proposed design concept, a prototype was fabricated and measured. The antenna design started from a reference circular patch antenna on a 3.2 mm thick Taconic substrate with $\varepsilon = 2.55$. The patch antenna is fed via a coaxial line probe. The radius of the patch is $b = 20$ mm and the excitation is at the distance 6 mm from the center. Meanwhile, the EBG patch has the same dimensions with the reference antenna, except for the surrounding EBG structure. The EBG ring pads are 21 mm large with 2 mm gaps, and the grounding via has a radius of 1 mm. Fig. 8 shows the photographs of the fabricated EBG patch antenna. The total width of the antenna substrate is 180 mm.

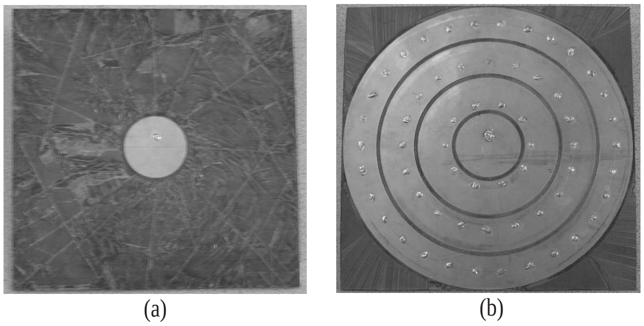
(a) (b)

Fig. 8. Photographs of the circular patch antenna (a) with classical substrate (b) incorporated with a cylindrical EBG substrate.

Figure 9 shows the measured input return loss of the two antennas. One can note that the EBG structure modifies slightly the impedance matching of the antenna. The EBG antenna is matched ($S_{11} < -10$ dB) from 2.56 GHz to 2.64 GHz, which represents a fractional bandwidth of 3%.

Figure 10 shows the measured gain for the two antennas. From these curves, the results obtained in the previous analysis are confirmed. The EBG structure allows to increase the gain of the patch antenna around the operating frequency. In the matching band of the EBG antenna the gain vary from 8.1 dB to 9 dB, whereas in the same band, the gain of the patch antenna alone varies from 6.2 to 6.4 dB. Then in the matching band, the gain enhancement varies from 1.9 dB to 2.6 dB. The maximum gain of the EBG antenna is 9.33 dB, which is achieved at 2.65 GHz. At this frequency, the return loss is -9 dB, and the gain enhancement is 2.9 dB.

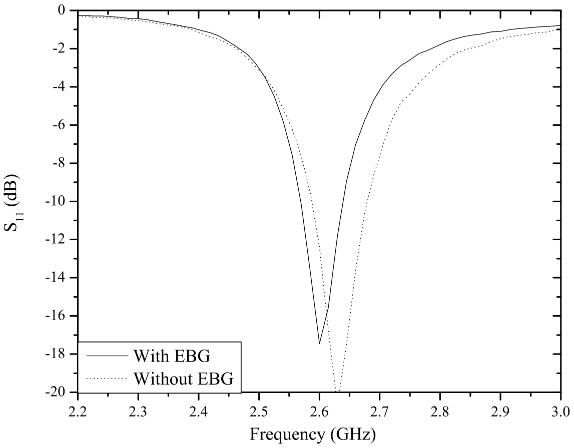

Fig. 9. Measured return loss for patch antennas with classical ground plane or with EBG substrate.

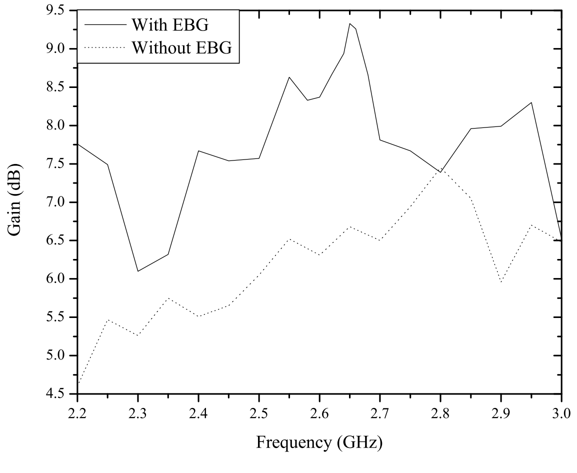

Fig. 10. Measured gain *vs.* frequency for cylindrical path antennas with classical ground plane or with EBG substrate.

Figures 11 and 12 show the measured H- and E- plane radiation patterns of the two patch antennas at 2.6 GHz, including both co- and cross-polarization patterns. From both E- and H-plane measurements, the EBG patch has reduced radiation power along the dielectric substrate (90° from broadside). The front-to-back ratio has also improved.

It can be noted that the slight differences between measured and simulated results for the resonant frequency and gain are due to fabrication tolerances.

The design technique has been also tested for a circular antenna operating at another frequency, giving good simulation and experimental results. For this antenna, three rings of vias and strips were also used and the two periods of the EBG structure were optimized with the same method as described in this paper.

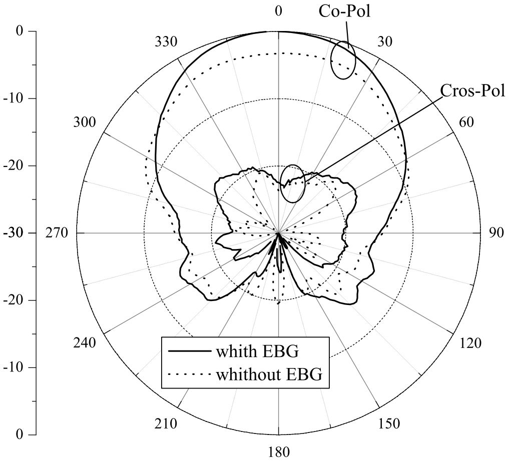

Fig. 11. Measured radiation patterns in the E-plane at 2.6 GHz, with and without EBG structure, in Co- and Cros-Pol.

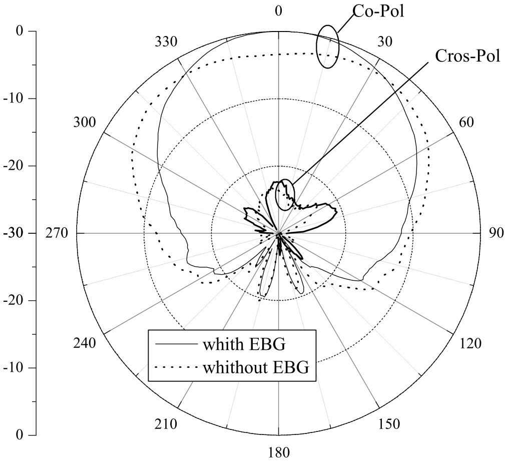

Fig. 12. Measured radiation patterns in the H-plane at 2.6 GHz, with and without EBG structure, in Co- and Cros-Pol

V. CONCLUSION

In this paper, a novel technique for the gain enhancement of micro-strip patch antennas using a cylindrical EBG structure has been proposed and demonstrated. The EBG structure is based on the mushroom-like structure with a circular symmetry. It is composed of a periodic structure of metallic rings and of a periodic structure of vias. The periods of these two structures have been optimized using a full-wave method to maximize the antenna gain. The new substrate reduces the surface wave, but the gain enhancement is mainly due to the coupling between the patch and the EBG structure. To validate the proposed concept, experimental results have been presented, showing that a gain enhancement of $2.9\ dB$ is achieved with the new substrate.

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