Miniaturization of microstrip patch antenna for wireless applications by use of multilayered electromagnetic band gap substrate

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ABSTRACT - The effect of a two-layer, periodic, electromagnetic bandgap (EBG) substrate on the performance of a dual-polarization, square, patch antenna is investigated in this paper. The antenna is printed in a gap area of the uppermost surface of the EBG substrate, disturbing by its presence the periodicity and the symmetry of that surface. Finite difference, time domain methods have been used for the simulations and a prototype of the proposed structure has been made in our laboratory in order to verify the simulated results. The proposed antenna resonates at 2415*MHz* and it is 24% smaller in area than a square patch with the same type of feedlines and the very same resonance frequency, which is printed on an ordinary, reference substrate. By "ordinary" it is implied that the reference substrate is a stack of two layers having the same dielectric constant and thickness as those of the proposed two-layer, EBG substrate. The decrease in frequency is 45.2% with respect to a square patch of the same size on the reference substrate. Still, the bandwidth of the proposed antenna increases by 12%, despite the narrowband nature of the quarter-wavelength matching circuits at both inputs, and it presents higher isolation between the two ports.

1. INTRODUCTION

Strong interest in advanced materials and structures has been manifested in the recent years. Three principal categories of such materials have arisen and established. They are (a) the photonic crystals, (b) the electromagnetic band-gap (EBG) structures [2], and (c) the double-negative materials. The main characteristic of their typical structure is that a number of dielectric slabs interchange with metallic layers carrying various periodic patterns. Interest in this paper is focused on the second category mentioned above, namely that of EBG structures.

EBG surfaces have been integrated with patch antennas due to the ability of the former to suppress surface waves, when certain conditions are fulfilled [4-6]. This has been the first attempt to exploit the properties of an EBG surface for antenna design and optimization. Another very interesting property of EBG surfaces relates closely to the reflection phase, i.e. the phase of the reflected electric-field intensity at the reflecting surface, normalized by the phase of the incident electric-field intensity. It is well-known that a perfect electric conductor (PEC) presents reflection phase equal to 180^o when a plane wave is normally incident on it. In contrast to that phenomenon, the reflection phase of a perfect magnetic conductor (PMC), which does not exist in nature, is equal to 0^o. EBG structures have been known to function in a way that reminds of a PMC. Actually, the reflection phase of an EBG structure may vary with frequency from $+180^o$ to -180^o continuously and, because of that property, EBG surfaces can exhibit both PEC- and PMC-like behavior, albeit at different frequencies. Furthermore, the anisotropic characteristics of EBG structures have been studied [9] and applied to the design of microstrip, diplexer antennas and diplexer filters.

Dual-frequency, dual-polarization, patch antennas are often used in modern communication systems in order to enhance their capacity through frequency reuse. However, orthogonal, patch antennas, which are quite commonly used for the previously stated task, exhibit rather poor isolation between the ports (about 25*dB*). The latter characteristic inhibits the efforts to integrate directly a microstrip antenna with active, microwave components, which is desirable for the design of modern transceivers. Consequently, a low insertion-loss, band-pass filter has to be used before low-noise amplification in the receiver, which adds complexity to the overall design of the device. The anisotropic characteristics of an EBG structure are now well understood and it has been proven that such surfaces can operate in such way that the aforesaid band-pass filter is made redundant.

An EBG surface is presented in this paper, which (a) contributes to the miniaturization of a dual-polarization, square, patch antenna operating at 2.4*GHz* and (b) improves the isolation between the two ports. The aforesaid antenna is printed on top of that EBG structure, which comprises two layers, each one carrying a biperiodic array of circular patches. It is noteworthy that the whole structure has been made solely by use of TACONIC TLY-5 laminates of different height and by use of the proper adhesive, thus reducing drastically the cost required for such structures.

A prototype structure, i.e. antenna and EBG substrate, which meets the design specifications discussed in the following section, has been made in our laboratory.

Measured results have been compared with simulated results, thus providing safe ground for the proposed design methodology.

2. ANTENNA DESIGN AND CALCULATIONS

The initial design of the EBG substrate is shown in Fig. 1; it consists of two layers and the antenna is printed on the upper surface of the top layer (Fig. 1a). The bottom layer carries a biperiodic array of circular patches (Fig. 1b), which are all grounded by use of vias. The spacing between adjacent patches is δ and the radius of each patch is r_p; hence, the period of the aforesaid array is $r_p + d$ in both dimensions. Each via extends from the center of a metal circle to the underlying continuous ground plane. This design has emerged by execution of many simulations. The values of the parameters involved in this, initial, design have been determined by use of an iterative, optimization procedure and they are shown in Table 2.1. The top layer was printed on one-sided, TACONIC, TLY-5A laminate with height 31*mil* and (relative) dielectric constant $\varepsilon_r = 2.17$. The bottom layer was printed on two-sided, TACONIC, TLY-5 laminate with height 62*mil* and (relative) dielectric constant $\varepsilon_r = 2.21$.

S	W_p	r_p	Δ
3900 *mil*	1200 *mil*	256 *mil*	24 *mil*

Table 2.1: The values for the various parameters appearing in Fig. 1

The design presented above has been associated with reduction by about 9% of the resonating frequency of the square, patch antenna; this figure has been calculated by reference to a square, patch antenna, printed on an ordinary substrate and resonating at the same frequency. By “ordinary” it is meant that the substrate of the reference antenna is a stack of two layers of the same dielectric constant and thickness as those of the two-layer, EBG substrate. The aforesaid result has been considered as very poor and it could not justify in any way the increased complexity of the EBG substrate. Still, the isolation between the two ports of the antenna, because of the EBG substrate, has increased to approximately 40*dB* and this has been, at the time, some encouragement to proceed with modifications of the initial design.

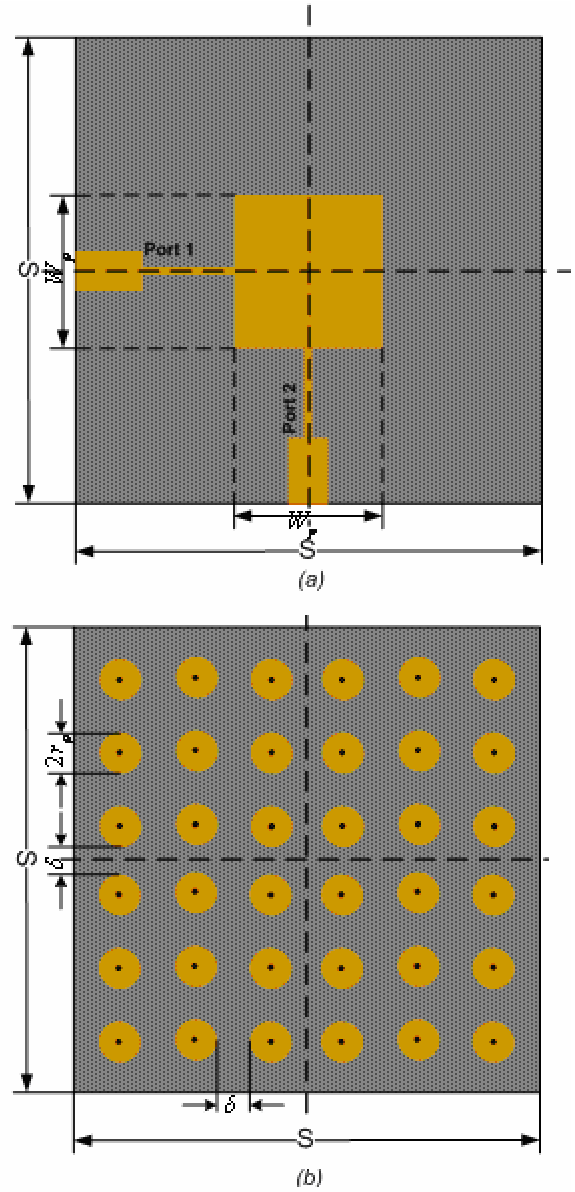


Figure 1: Initial design of top (a) and bottom (b) layers of EBG structure; the antenna is at the center of the top layer.

The first modification has been made by the addition of patches, identical to those of the bottom layer, to the upper surface of the top layer, around the antenna. Attention has been paid to the distance of those passive, radiating elements from the antenna, so as to inhibit significant coupling between the antenna and the patches nearest to it. A sensitivity analysis has shown that 140*mil* is the minimum distance which can be considered safe for that purpose. The patches of the top layer were identical to those of the bottom layer and they have been printed exactly above the latter. Four patches from the middle of the uppermost surface and four more patches, which happened to be close to the

50*Ohm* feedlines have been omitted to make space for the antenna and the matching circuits.

This first, modified design of the EBG structure, actually the top layer thereof, is shown in Fig. 2; simulations executed for this design have indicated that the decrease in the operating frequency could reach 15%, which is some advancement from the initial design. The matching circuits (quarter-wavelength transformers) in front of the ports have been adjusted to the new impedance displayed by the patch antenna at the feeding points. Although the width of the $\lambda_g/4$ line had changed, the same type of matching circuit has been used in every step of the road to the final design, so that comparisons could be made.

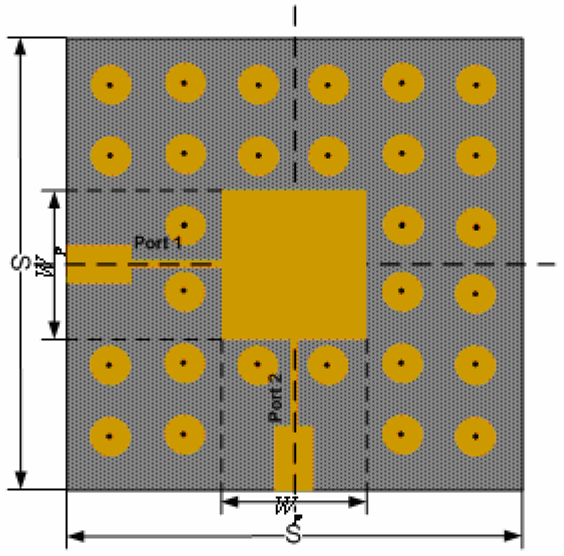


Figure 2: First, modified design of the top layer of the EBG structure; the bottom layer is as shown in Fig. 1(b).

Once the number of patches, their shape, and the overall design had been, more or less, established, attention has been focused on the relationship between the operating frequency of the antenna and the various parameters of the first, modified design (Figs. 1b and 2). Many simulations have been executed with varying values for the spacing δ and the radius r_p of the patches (Fig. 1b) and the results are shown in Figs. 3 and 4. It may be deduced from those figures that the appropriate values of δ and r_p for common resonating frequency of the square, patch antenna are $\delta = 24mil$ and $r_p = 256mil$; these values are expected to provide the optimal miniaturization condition. Still, these estimates have been obtained by interpolation and they have had to be verified by use of an electromagnetic simulator. Indeed, simulations executed for the first, modified design of Fig. 2 have shown that the reduction in the resonating frequency of the antenna is 24.3% with $\delta = 24mil$ and $r_p = 256mil$.

Although the degree of miniaturization that had been achieved at that point might have been considered as acceptable, intuition has been urging for further improvement. A reason for hope has been the simple fact that the miniaturization achieved as above could have been achieved by use of a single-layer antenna, like those proposed in previous research work [12]. Therefore, the need for a two-layer structure, loaded with arrays of patches had not been justified yet.

Still, it was evident that no better results could have been expected with that parameterization of the EBG structure. More detailed, geometrical analysis and a more complex, optimization algorithm, like the classic Powell optimizer [13,14] were needed for the task.

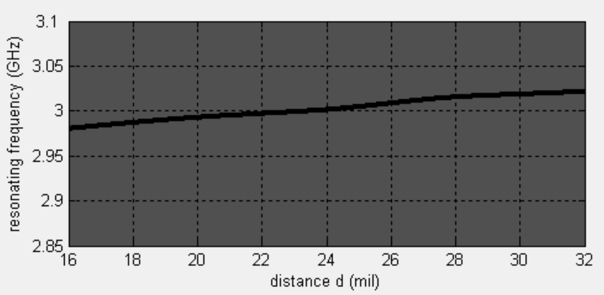


Figure 3: Effect of the spacing δ between adjacent patches of the EBG surface on the operating frequency of a square, patch antenna (1200mil side length)

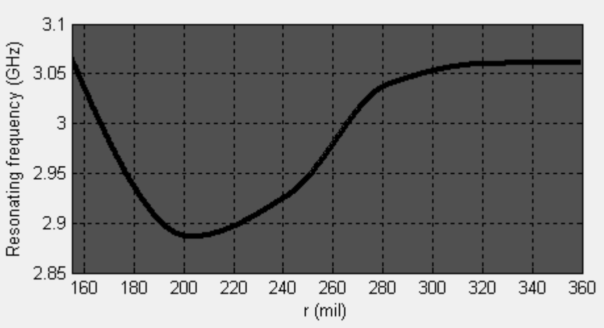


Figure 4: Effect of the radius r_p of circular patches of the EBG surface on the operating frequency of a square, patch antenna (1200mil side length)

The second modified design for the EBG structure is displayed in Fig. 5. The patches carried by both layers have been arranged in four groups. By application of an optimization algorithm, conditioned (a) for resonance in the neighborhood of 2.4*GHz,* (b) return loss at port 1 below -20*dB*, and (c) return loss at port 2 below -25*dB*, a possible set of values for the displayed parameters in

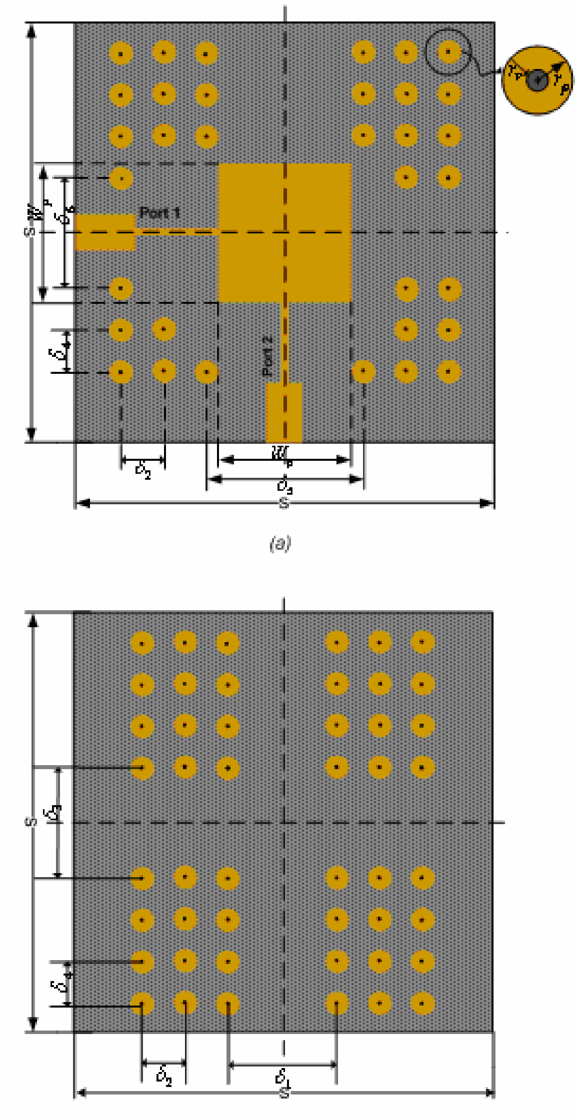
Fig. 5 is extracted. Those values are shown in Table 2.2. Prior to execution of the aforesaid optimization algorithm, certain concessions had had to be made in order to simplify somewhat the problem at hand. The main reason for those concessions has been the need for a structure that would be as simple as possible to manufacture. Hence, the following assumptions were made:

(a) All patches must have the same radius; changing the radius of the patches from layer to layer or even from one part to another in the same layer would increase the milling time of the structure with doubtful effect on the frequency reduction.
(b) The distance between adjacent patches in each one of the four groups displayed in Fig. 5 is the same in both layers.
(c) The dielectric constant of the laminates used and the height of the dielectric remained the same for all simulations.
(d) The number of patches on the upper surface of the bottom layer must be 48 and the patches must be arranged in four groups of 12 patches.
(e) Six patches must be omitted from the upper surface of the top layer to make space for the antenna and the matching circuits.

$\delta_1 = \delta_3$	618 *mil*
$\delta_2 = \delta_4$	382 *mil*
$\delta_5 = \delta_6$	596 *mil*
W_p	900 *mil*
r_v	16 *mil*
r_p	180 *mil*
S	3700 *mil*

Table 2.2: The values, obtained by calculations, for the various parameters that appear in Fig. 5; the square, patch antenna operates at $(2400 \pm 15)\,MHz$

Because the (somewhat stricter) condition applied to port 2 could not have been verified through the aforementioned arrangement of the patches, six more patches had had to be omitted, thus producing the design shown in Fig. 5(a). Simulated results for the S parameters and the radiation pattern, obtained by use of a time-domain algorithm, are displayed in Figs. 6 and 7, respectively. The antenna gain has been calculated around 5.62*dB* and the radiation efficiency exceeds *0.9*.



(a)

(b)

Figure 5: Second, modified design of top layer (a) and modified design of the bottom layer (b)

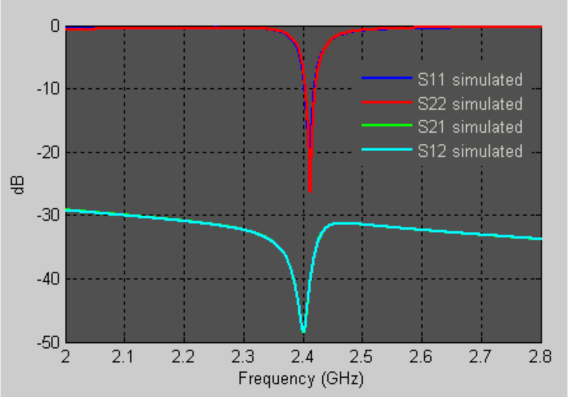


Figure 6: Simulations of S-parameters of square, patch antenna (900mil side length) on EBG substrate

Because of the slight asymmetry of the EBG structure and the difference in the matching circuits, the return loss at ports 1 and 2 is not exactly the same. Actually, it can be realized from Fig. 6 that port 2 is better matched than port 1. Furthermore, the minima of the S-parameters appear at frequencies differing by 6*MHz*. The transmission loss is practically the same for both ports.

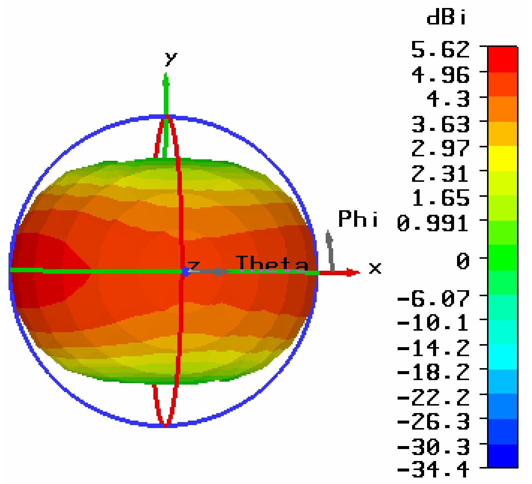


Figure 7: Radiation pattern of square, patch antenna (900mil side length) on EBG substrate

3. EXPERIMENTAL RESULTS

A prototype antenna (Fig. 8) has been made and measured in our laboratory. To bond the two laminates together a TACONIC, HT-1.5, bonding material has been inserted between them before pressing. The laminates have been milled and drilled by use of a T-Tech, QuickCircuit 5000 router and they have been pressed together by use of an LPKF Multipress press. The vias have been inserted manually by use of a T-Tech via kit. The S-parameters of the antenna have been measured on an HP-8714 network analyzer.

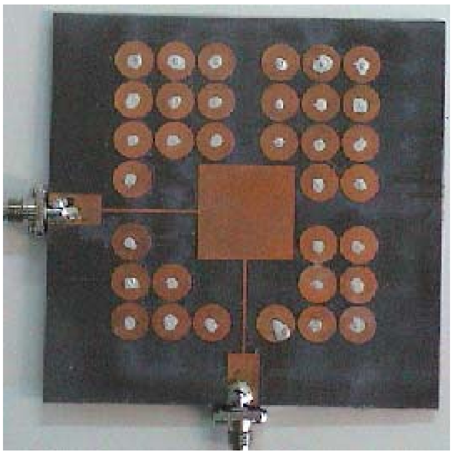


Figure 8: Prototype, square, patch antenna over EBG substrate

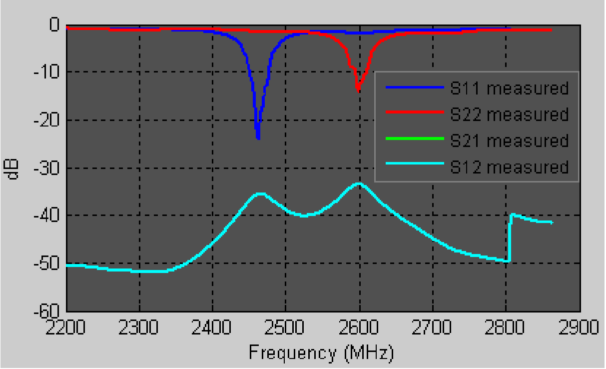


Figure 9: Measurements of S-parameters of square, patch antenna (900mil side length) on EBG substrate

The measurements are shown in Fig. 9. On the one hand, the return loss at port 1 is in accordance with the predicted results of Fig. 6; the minimum occurs at 2.434*GHz*, whereas the corresponding minimum of Fig. 6 occurs at 2.415*GHz*. The frequency shift of 19*MHz* between simulations and measurements may be justified partly by the number of mesh cells used and partly by the electromagnetic simulator, which is not optimized for periodic, multilayered structures. On the other hand, the return loss at port 2 appears offset by 200*MHz* because of anomalies of the uppermost surface of the top layer near that port, which have been inflicted during the milling process. The average thickness of the top layer near port 2 after milling has been found to be equal to 22*mil*, instead of 29*mil* average thickness near port 1, which operates as expected. Finally, the measured transmission loss is below -30*dB*, as predicted by the simulations.

4. CONCLUSIONS

A square, patch antenna on top of an EBG substrate has been designed and measured in this paper. The antenna resonates at 2.4*GHz*. The substrate provides significant miniaturization, better isolation between the ports of the antenna, and slightly increased bandwidth, all with respect to a similar antenna over an ordinary substrate.

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