Mutual Coupling Reduction in Patch Antenna Arrays by Using a Planar EBG Structure and a Multilayer Dielectric Substrate

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***Abstract*—Periodic structures can help in the reduction of mutual coupling by using their capability of suppressing surface waves propagation in a given frequency range. The purpose of this work is to show the viability of using a planar electromagnetic band gap (EBG) structure based on a truncated frequency selective surface (FSS) grounded slab to this aim. The goal is to use it in patch antenna arrays, keeping both the element separation smaller than λ_0 for grating lobes avoidance (assuming broadside case) and the patch antenna size large enough to have a good antenna directivity. To this aim, a multilayer dielectric substrate composed of high and low permittivity layers is convenient. This allows the use of a planar EBG structure made of small elements printed on the high permittivity material and, at the same time, the low permittivity layer helps the bandwidth and the directivity of the antenna to be increased. The EBG structure was designed under these premises and optimized for the particular application via an external optimization algorithm based on evolutionary computation: ant colony optimization (ACO). The mutual coupling reduction has been measured and it is larger than 10 dB with a completely planar structure.**

***Index Terms*—Ant colony optimization (ACO), electromagnetic band gap (EBG), multilayer substrate, mutual coupling, patch antenna array, periodic structure.**

I. Introduction

MUTUAL coupling reduction in arrays has deserved much attention from antenna designers. This coupling becomes especially critical in arrays of patch antennas where coupling comes from two paths [1], [2]. The first one is due to the free space radiation which is present in all types of array antennas. The second path arises from surface waves and it constitutes a very important factor in patch antennas. In this type of antennas, surface waves are strongly excited in E-plane when the antenna is operated in the fundamental mode (TM_{10} for rectangular patches). In this mode, the field distribution inevitably excites the first propagating mode of surface waves (TM_0) in E plane, given that this mode has no cutoff frequency [3], [4]. Moreover, the use of thick or high permittivity substrates increases that excitation.

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Periodic structures as electromagnetic band gap (EBG) have the ability of suppressing surface waves propagation in a frequency band. Consequently, their use in mutual coupling reduction for printed antennas is straightforward. However, for the particular case of patch antennas, the reduction of mutual coupling by means of a periodic structure becomes particularly challenging when grating lobes must be avoided. The patch antenna has a size of approximately $0.5\lambda_{\epsilon_r}$ and, unless high permittivity materials are used, the space between the edges of two neighboring patches, even in the best scenario (broadside case), is very small under the no grating lobes constraint. This is the reason why most of the proposals that can be found in the literature use a high permittivity dielectric as antenna substrate. Even in these cases, the number of periods of the EBG that can be placed between the array elements is modest.

Some of these previous works are devoted to EBGs that include vias to the ground plane, i.e., non completely planar, as it is the case of [5]–[7]. All of them use thin high permittivity substrates and both the periodic structure and the patch antenna are printed on the same layer. There are other works that are based on completely planar EBGs without vias or pins, which also make use of high permittivity dielectric materials but thicker than in the via cases. Here again, the antenna and EBG are in the same layer and the electrically thick high permittivity substrate does not allow the antenna feeding by means of a simple coaxial probe [8]. Based on the same idea, other examples for different types of printed antennas such as dipoles with [9] or without [10] a ground plane, have been presented. In these latter cases the space is not as limited as in the patch antenna case. Finally, the use of three-dimensional dielectric EBG (woodpile type) has been proven to be useful for mutual coupling reduction in printed dipoles [11].

The few examples in which planar EBGs with or without via holes to the ground plane are used to reduce mutual coupling between patch antennas have some common aspects. The first one is that patch antenna becomes small due to the high permittivity material and consequently with low directivity. The second one is that, either antenna is narrow band if the substrate is thin [12], [3], or for thicker substrates it requires feed techniques different from the conventional feeding probe. Moreover, the fact that both the patch antenna and EBG share the same layer makes the distance between them critical, as a too short distance can negatively influence the antenna matching due to reactive coupling [8]. Also, the high permittivity materials excite strong surface waves.

The purpose of this work is to provide another approach in the mutual coupling reduction for patch antennas by using com-

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pletely planar EBGs. In this study, the common properties of patch antennas are assumed. These include: easy and efficient feeding by a coaxial probe (very difficult with thick high permittivity substrates) and medium directivity given by its size (which also needs a low permittivity substrate). A solution for mutual coupling reduction with such features has not yet been presented in the literature. One of the key aspects for this design is the use of a multilayer dielectric substrate [13]. With the combination of high permittivity and low permittivity dielectric layers, we can print the patch antenna and the EBG in different substrates (the EBG on the high permittivity material for the sake of compactness and the antenna on the low permittivity one). The advantages of this configuration will be further discussed in the manuscript.

A basic type of planar EBG, made of metallic patches printed on a grounded dielectric substrate, is the proposed periodic structure to be used for mutual coupling reduction. These structures have demonstrated to behave as artificial magnetic conductor (AMC) over a frequency range [14], and also to possess bandgaps for surface waves [15], [16], i.e., EBG behavior, in another frequency band. Moreover, they are completely planar, which is an advantage from the point of view of manufacturing when compared to others that include vias [17], [6], [18], [7]. The geometry we propose is the simplest EBG structure based on FSS, and has not been used before for the described application. Other more sophisticated geometries also based on FSS have been used to suppress surface waves [19], i.e., as EBG, but in a non-grounded version.

The paper is organized as follows. The initial design of both the antenna and the planar EBG structure in a multilayer dielectric structure is presented in Section II. Section III includes the optimization of the EBG structure for the particular application, i.e., including the two antennas and considering a limited number of periods. This optimization is performed by using an evolutionary algorithm based on Ant colony optimization (ACO) [20] that we have developed. Also in the same Section III, an investigation on the reduction of the number of elements used in the EBG structure to make it as compact as possible, is carried out. The section includes a final subsection with a study of the validity of the proposed scheme when the distance between patches is reduced down to $0.5\lambda_0$, with the purpose of extending the work from the initial broadside case to a general phased array. Finally, in Section IV an array of two patch antennas including some of the designed EBG structures is manufactured and measured for the evaluation of mutual coupling.

II. Initial Design

In this section the parameters of the reference antenna as well as the ones of the EBG will be fixed. The EBG structure will be made of rectangular metallic elements (patch type) based on [16] whose size to suppress surface wave propagation, is related to (usually smaller than) $0.5\lambda_{\epsilon_r}$. Therefore, as the unit cell of this EBG is not very compact, a high permittivity material is needed to reduce its size. A material with $\epsilon_r \simeq 10$ and a 2.54 mm thickness is selected.

On the other hand, the purpose of this work is to provide a solution with patch antennas with a reasonable bandwidth as

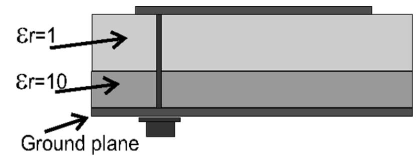

Fig. 1. Proposed multilayer squared patch antenna. Side: 35 mm. Feeding probe position: 3.5 mm from the edge.

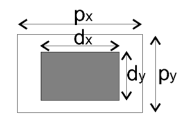

Fig. 2. Unit cell of the periodic structure.

well as a moderate directivity. These antenna characteristics are not possible when patch antennas are printed in thin high permittivity materials [3]. Hence, a solution is to use a multilayer dielectric structure including this thin high permittivity material but also another thicker layer of a low permittivity material ($\epsilon_r \simeq 1$ with 6 mm thickness). The antenna will be printed on top of this multilayer substrate as Fig. 1 shows. Antenna dimensions are provided in the figure caption assuming a work frequency of 3 GHz.

With this multilayer design, the EBG structure and the patch antenna can be placed in different layers. This is a fundamental aspect of this work as, on one hand, this allows EBG unit cell size to be considerably smaller than patch antenna size ffwithout sacrificing antenna performance. On the other hand, the EBG can be placed closer to the patch antenna when compared to designs in which antenna and EBG share the same layer.

The EBG unit cell is shown in Fig. 2. According to [16] the lower cutoff frequency of this structure to behave as an EBG is related to the periodicity in the direction of propagation (E-plane), being $\approx 0.5\lambda_g$. This λ_g is given by the effective permittivity in the above described multilayer dielectric substrate. Initially assuming a square unit cell, dimensions have been calculated in an approximate way considering that over the high permittivity material, $\lambda_{\epsilon_r}/2 \approx 15.6$ mm and taken the effective permittivity concept into account. With these considerations we choose $d_x = d_y = 15$ mm and $p_x = p_y = 25$ mm. Fig. 3 shows the dispersion diagram of the EBG in the E-plane (x) direction. Horizontal axis represents the normalized k_x propagation constant. The first bandgap includes the frequency band of interest (3 GHz), as expected.

These initial dimensions are also used to estimate how many unit cells of the truncated EBG can be placed between two patch antennas. With such dimensions and the ones from the antenna in Fig. 1 and keeping the distance between patch antennas smaller than λ_0 (at 3 GHz), only two elements of this structure can be included in E-plane. This is a strong limitation, as in any filtering structure, the larger the number of elements, the better the performance and the filtering. In H-plane there is, in principle, no constraint.

III. Mutual Coupling Reduction

Fig. 4 shows the top view of the two-element array in the multilayer dielectric substrate. Both antennas have the dimensions described in Section II. The separation between edges has been

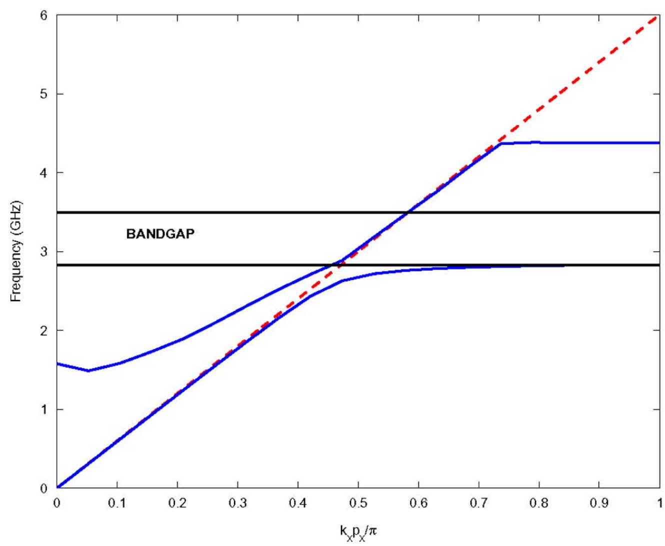

Fig. 3. Dispersion diagram of the EBG with $d_x = d_y = 15$ mm and $p_x = p_y = 25$ mm (represented in E-plane direction).

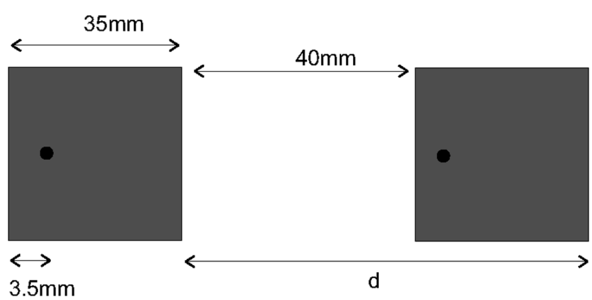

Fig. 4. Top view of a two-element array in a multilayer dielectric substrate (not shown) for mutual coupling evaluation.

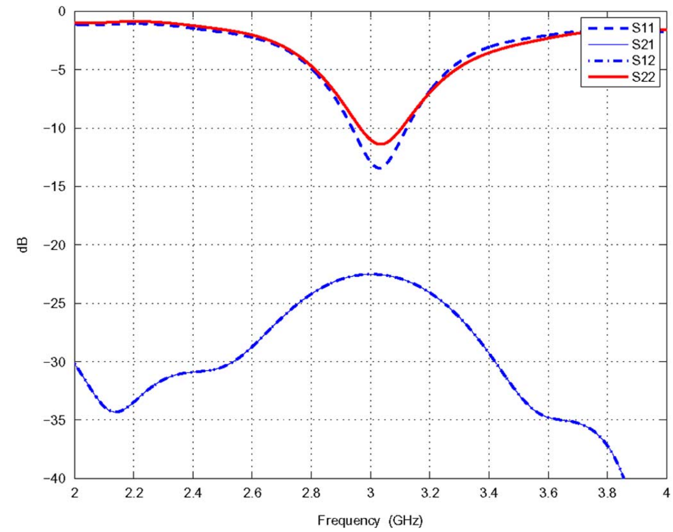

Fig. 5. Simulated mutual coupling between antennas in Fig. 4 and input impedance of both antennas.

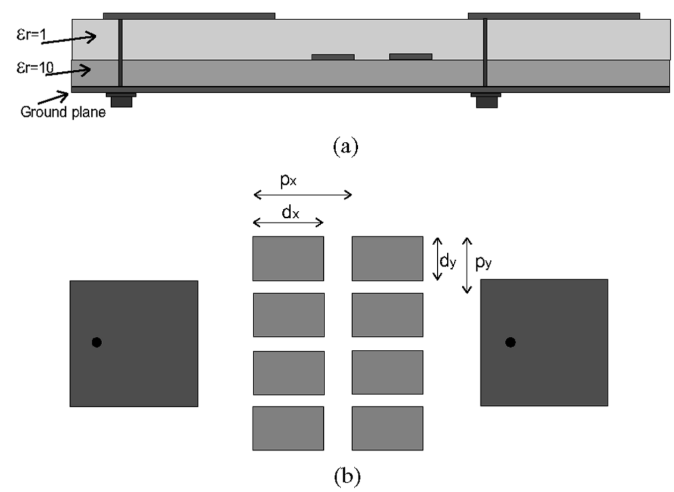

Fig. 6. Array of two patches in a multilayer dielectric substrate including a planar EBG structure.

chosen to be 40 mm and the total separation between elements is $d = 75$ mm which is $0.75\lambda_0$. Ground plane size is 130 mm.

The initial mutual coupling in E-plane is presented in Fig. 5. In the frequency band where the antenna is matched (with a S_{11} smaller than -10 dB) the maximum coupling level is -23 dB. Parameters S_{11} and S_{22} are not identical because the structure is not symmetrical. Simulations were carried out with *CST Microwave Studio*.

Initially, the EBG structure is forced to be placed out of the volume defined by each antenna but not necessarily laterally separated from them. The proposed design is shown in Fig. 6. The finite EBG has two elements in E-plane direction and four elements in H-plane direction.

The initial EBG structure, i.e., the one with $d_x = d_y = 15$ mm and $p_x = p_y = 25$ mm has been placed between the antennas. With this structure, a considerable reduction of the mutual coupling is achieved, as it is shown in Fig. 7. Particularly, the maximum mutual coupling in the useful frequency band now is -29 dB, therefore 6 dB below the case without the EBG structure (Fig. 5). Moreover, the S_{11} and S_{22} parameters have decreased with the addition of the EBG, thus having a better antenna efficiency.

A. *Ant Colony Algorithm*

This subsection describes the optimization process in the design of the EBG structure. Even if with the designed EBG a reduction in the mutual coupling by 6 dB is already achieved, the dimensions of the EBG structure: d_x, d_y, p_x, and p_y will be optimized in order to try to further reduce the mutual coupling. The only constraint is the space, as the EBG structure has to be placed with minimum overlapping with both patch antennas. This optimization is performed using the eight-element periodic structure shown in Fig. 6 for this particular application, i.e., the whole problem will be analyzed. An evolutionary algorithm based on ACO [21], [22] has been used for this purpose.

This algorithm family uses the behavior of ants when they are looking for food and they store that food in their nests. In that task ants are able to find the shortest path from the food to their nests by using pheromone that they give off as they move. This pheromone helps new ants to choose short paths.

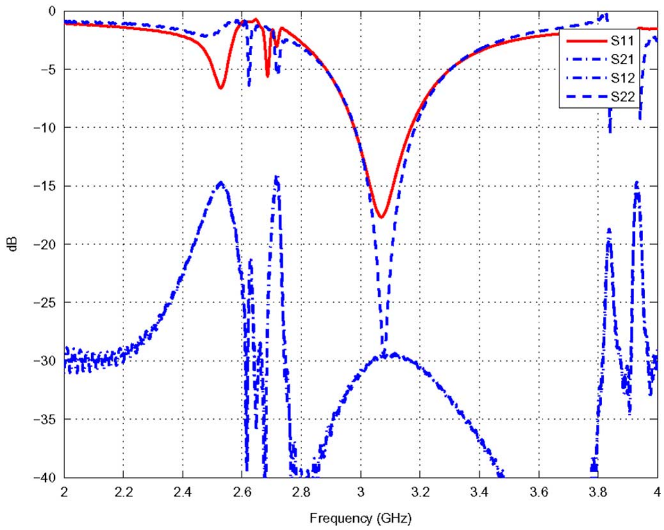

Fig. 7. Simulated mutual coupling and matching for the structure described in Fig. 6 with $d_x = d_y = 15$ mm and $p_x = p_y = 25$ mm.

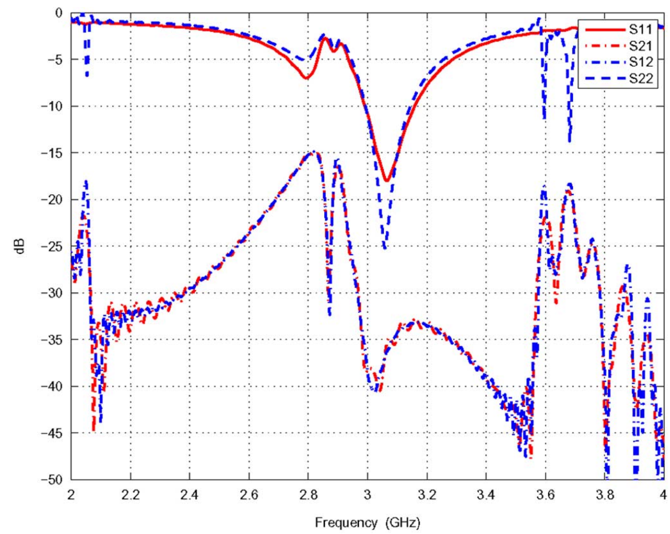

Fig. 8. Simulated mutual coupling and matching for the structure described in Fig. 6 with $d_x = 13$ mm, $d_y = 22$ mm, $p_x = 20$ mm, and $p_y = 35$ mm.

The space of possible solutions or search space will be divided into nodes that in this algorithm implementation are solutions. The algorithm makes a population-based search and also a probabilistic search, as the movements of ants in the space of solutions are determined by probability. That probability is a function of the pheromone level of the neighbor nodes and also of the "desirability" or goodness of the solution represented by those nodes. These types of algorithms have been successfully used by the authors in other electromagnetic problems [23], [24].

In our particular implementation, *ants* are solutions to the problem, i.e., vectors of four real numbers representing the four parameters of the unit cell to find out. The minimum variation, or step, is 1 mm. The probability of moving to another node is given by the most extended decision criterium proposed by [21] and described as

$$p_{i,j}(t) = \frac{[\tau_j(t)]^\alpha \cdot [\eta_j]^\beta}{\sum_{l\in\theta_i}[\tau_l(t)]^\alpha \cdot [\eta_l]^\beta}. \tag{1}$$

Where $p_{i,j}$ is the probability of node j to be chosen at iteration t being at node $i, \tau_j(t)$ represents the pheromone concentration associated with node j at iteration t, η_j is the desirability of node j, α controls the importance of pheromone concentration in the decision process whilst β does the same with the desirability, and θ_i is the set of nodes l available at decision point i.

The desirability η_j is a function that depends on the optimization goal. This function has to be evaluated at each node j for each ant. Its role is equivalent to the one of the "fitness" function in other algorithms. In this case, that desirability is the mutual coupling level in the desired frequency band. That mutual coupling is calculated by running a simulation of the complete structure of Fig. 6 with the parameters d_x, d_y, p_x and p_y of each node.

The function τ_j controls the change in the pheromone level in nodes with time. This includes the increment when ants visit that node but also the evaporation with time to avoid stagnation. The τ_j function can be implemented in different ways. In our case, we use

$$\tau_j(t+1) = \tau_j(t) + \Delta\tau_j(t) - d(t) \tag{2}$$

where $\Delta\tau_j(t)$ is the pheromone addition on node j, and $d(t)$ is the pheromone persistence

$$d(t) = \begin{cases} \rho & \text{if mod}\left(\frac{t}{\gamma}\right) = 0 \\ 0 & \text{if mod}\left(\frac{t}{\gamma}\right) \neq 0 \end{cases} \tag{3}$$

where γ is the period of pheromone elimination, and ρ is the coefficient of pheromone elimination by period.

All the algorithm parameters ($\gamma = 20, \rho = 1, \alpha = 30, \beta = 2$) have been chosen heuristically following some criteria given in [21].

The algorithm was developed in MATLAB and uses CST software as analysis tool to calculate mutual coupling level. For each ant we calculate the desirability of all the neighbor nodes (in this case eight nodes by changing one by one the values of the vector elements (four) increasing or decreasing them by the given step) as well as the pheromone level, and compute the probabilities of each node to make a probabilistic decision that determines the next node to which that ant moves.

After several iterations, the obtained dimensions are $d_x = 13$ mm, $d_y = 22$ mm, $p_x = 20$ mm, and $p_y = 35$ mm.

B. Results

The performance of the optimized EBG in terms of mutual coupling reduction is shown in Fig. 8. Here the mutual coupling level is under -35 dB over the entire operating band of the antenna. This means a 6 dB reduction compared to the initial EBG structure and approximately 12 dB compared to the case without EBG. Moreover, the S_{12} parameter shows a clear

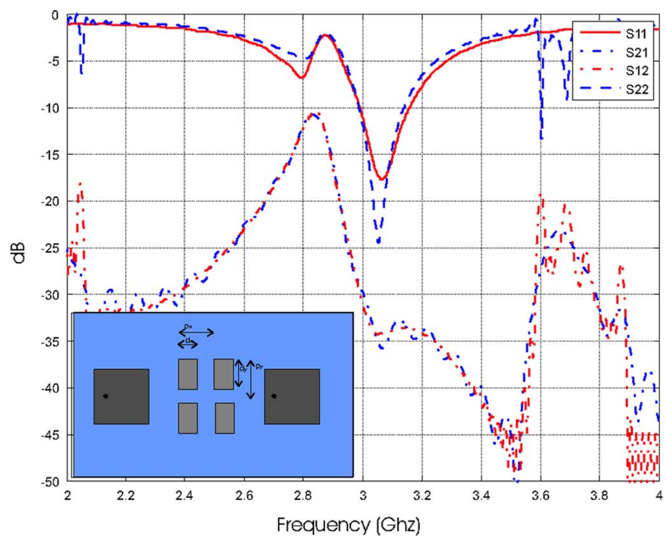

Fig. 9. Simulated mutual coupling and matching for the structure in the inset (EBG with only four elements).

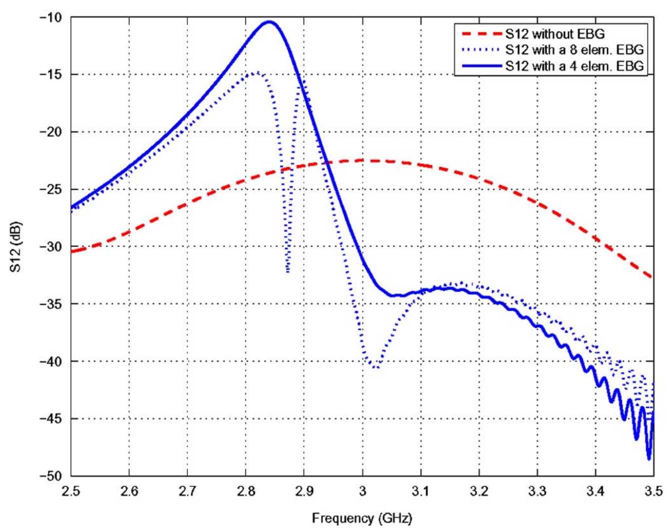

Fig. 10. Simulated mutual coupling comparison for the three studied cases: without EBG, with an eight-element EBG, and with a four-element EBG.

forbidden band that coincides with the antenna work frequency. Also, the matching of the antennas is excellent.

C. Reduction of the Number of Elements

In the optimized EBG, the elements are rectangular when compared to the initial squared ones. Furthermore, the number of elements in H-plane is four but two of them (the ones in the extremes) seem to be out of the area between patches. Consequently, the suppression of those four elements, as shown in the inset of Fig. 9, has been investigated. Simulation results for this new case are the ones in Fig. 9. The mutual coupling reduction is still very significant and it is close to the eight-element case. To have a better comparison, Fig. 10 includes the comparison of the initial case without EBG with the cases with EBGs having four and eight elements. The maximum level of mutual coupling in the frequency band in which the antenna return losses are under -10 dB is approximately the same in both EBG cases. However, in the eight-element EBG example, there is a narrow frequency band inside the bandwidth that has a lower mutual coupling level (by 5 dB) whereas for the four-element EBG this does not exist.

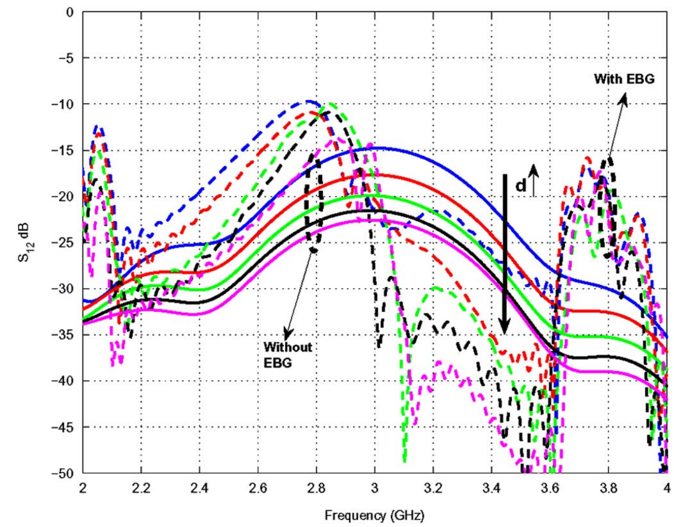

Fig. 11. Simulated mutual coupling as a function of the patch separation with (dashed lines) and without (solid lines) EBG. Distance d is increased by a step of $0.05\lambda_0$ from $0.5\lambda_0$ to $0.7\lambda_0$. EBG dimensions are the same for all curves ($d_x = 13$ mm, $d_y = 22$ mm, $p_x = 20$ mm, and $p_y = 35$ mm).

D. Distance Effect

The initial mutual coupling of -25 dB is already low due to the distance between patch antennas and the dielectric configuration. In this subsection, the effect of approaching the patch antennas while keeping the same optimized EBG inside, is checked. The reduction in the separation between patch antennas would allow the use of the proposed design also in non-broadside arrays including those for scanning purposes, at least within an angular range.

As previously mentioned, an advantage of the proposed scheme is that the EBG is not placed in the same layer as the patch antennas. This allows to approach the EBG to the antennas as much as desired (even overlapping the patch area).

From the initial $0.75\lambda_0$ separation, the patch antennas have been approached down to a final distance d of $0.5\lambda_0$. The mutual coupling variation with a step of $0.05\lambda_0$ in d, is presented in Fig. 11 for cases with and without EBG. By including the same EBG than in Fig. 8, the mutual coupling is always reduced independently of the distance between patch antennas. However, the frequency range where the coupling reduction occurs as well as its level, change depending on the distance.

Fig. 12 shows the effect of approaching the patch antennas in terms of matching. The antenna resonance frequency moves towards higher frequencies when the EBG approaches, probably as a consequence of the reduction on the fringing fields due to the EBG proximity. Also, the matching in one of the patches becomes worse. This could limit the EBG application for small element separation, as in the final array, the patches will have EBG elements at both sides.

IV. Experimental Results

To validate the previous conclusions, some prototypes have been manufactured and measured. Fig. 13 shows a photograph

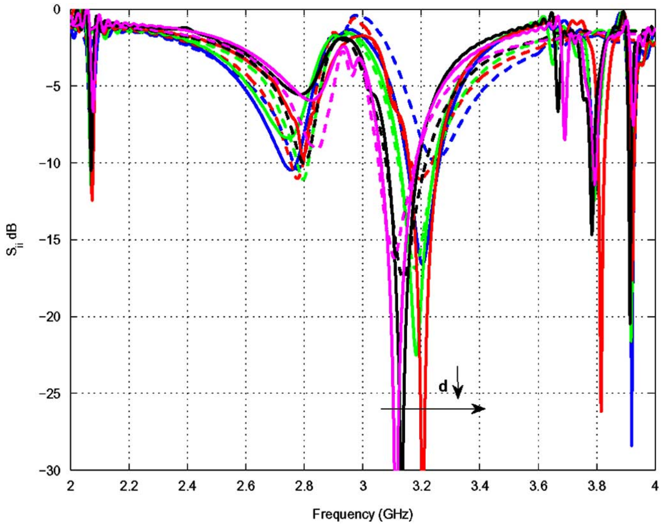

Fig. 12. Simulated antenna matching as a function of the patch separation d with EBG. Solid and dashed lines correspond respectively to each one of the patches. Distance d is decreased by a step of $0.05\lambda_0$ from $0.7\lambda_0$ to $0.5\lambda_0$.

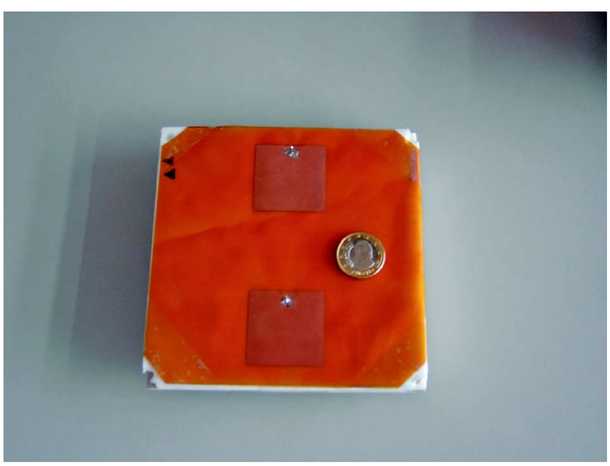

Fig. 13. Manufactured demonstrator of a two-element multilayer array.

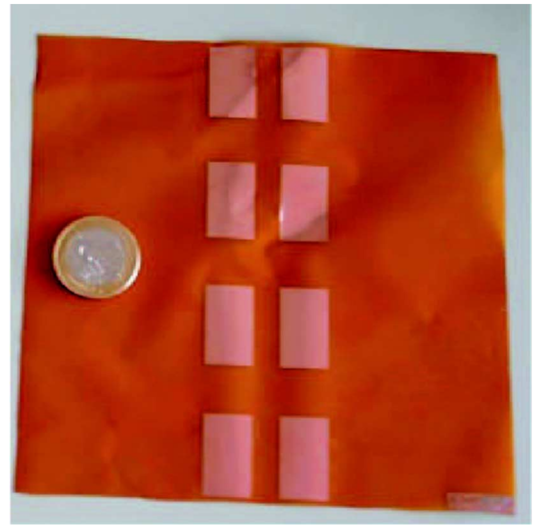

Fig. 14. Planar periodic structure with eight elements.

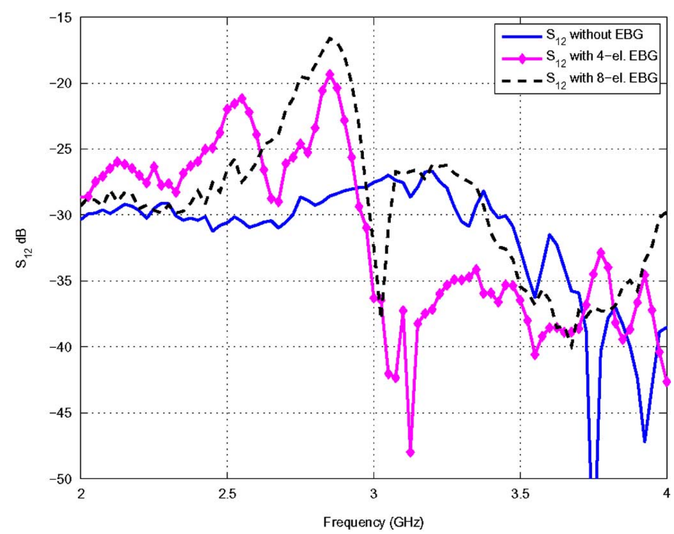

Fig. 15. Measured prototype without EBG and with two different EBG (with four and eight elements, respectively). Distance between edges of patch antennas is 45 mm and parameters of the EBG are $d_x = 15$ mm, $d_y = 22$ mm, and $p_x = 22$ mm, $p_y = 35$ mm.

of the array of two patch antennas in a multilayer substrate and Fig. 14 shows the planar truncated EBG with eight elements. The dimensions of antennas and periodic structures are the optimized ones described in simulations except for d_x, which in the final prototype (the one in Fig. 14) is 15 mm. The reason for this change is the uncertainty of the dielectric constant provided by the dielectric manufacturer. That dielectric constant was the one used in the simulations, however it does not exactly coincide with the one presented by the material, as reported also by other authors [9].

After a sensitivity analysis of the four parameters of the EBG structure for this particular application, the parameter d_x was demonstrated to be the most critical one. Therefore, only that parameter d_x needed to be tuned to fit with the actual permittivity. The separation between antennas was also increased to 45 mm due to the larger EBG size. With the new distance, the inter-element separation is $0.8\lambda_0$.

Fig. 15 includes the measurements of the final prototype without EBG and with both an eight- and a four-element EBG. The initial coupling is about -27 dB and the eight-element EBG creates a narrow dip in the mutual coupling inside the antenna bandwidth. In that band, the mutual coupling goes below -35 dB. Also, in the same figure, the measurements with the four-element structure have been plotted. A clear mutual coupling reduction is achieved for this case.

The comparison between simulated and measured mutual coupling is presented in Fig. 16.

Finally, Fig. 17 contains the comparison of the initial demonstrator without EBG and the one including the four-element EBG. In the figure, the -10 dB bandwidth of the antenna with the EBG is indicated. In most of the bandwidth, the mutual coupling is strongly reduced by more than 10 dB. Furthermore, this structure is more compact than the initial one with eight elements.

Experimental results confirm that the use of the truncated EBG is very close to the patch antenna ,but in a different layer

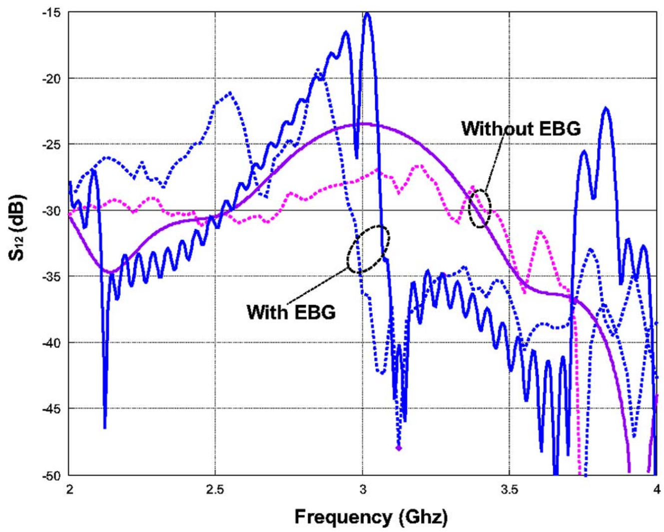

Fig. 16. Comparison of the simulated (solid lines) and measured (dotted lines) mutual coupling without EBG and with the four-element EBG.

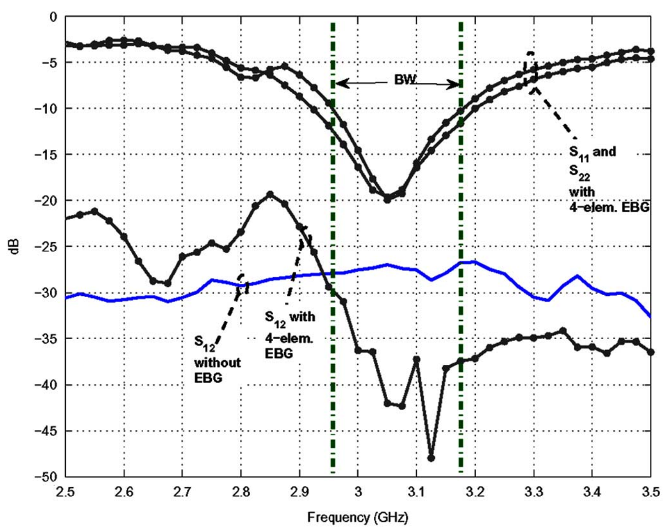

Fig. 17. Comparison of the measured mutual coupling without EBG and with the four-element EBG.

does not affect the antenna matching as it does when it is placed in the same layer.

V. Conclusion

The use of a planar EBGs printed on grounded multilayer dielectric substrate without vias to reduce mutual coupling in patch antenna arrays has been investigated.

These planar EBG structures were aimed at suppressing surface waves in the antenna operation frequency. The reduction in the number of elements has been investigated. The final truncated EBG has only two unit cells in the direction of interest but still produces the intended surface wave suppression.

The structure dimensions have been optimized. To this aim an evolutionary algorithm has been used. The key point in this optimization is the fact that it has been performed for the complete problem, i.e., the finite EBG in the particular application (inside a two-element patch antenna array) with a full wave simulator as analysis tool.

Antenna prototypes have been manufactured and measured to validate and confirm the simulation results. Small adjustments in the dimensions have been necessary due to the material tolerances. Experimental results show that the four-element structure behaves better than the eight-element case, albeit indicated otherwise by simulations, which indeed is good for the work purpose, as the EBG is smaller. Mutual coupling is reduced by more that 10 dB. Furthermore, for narrower frequency bands that reduction is larger than 15 dB.

The key aspect of the proposed design is the use of the mutilayer dielectric substrate with a high permittivity material where the EBG is printed and a low permittivity material where the patch antennas are printed. This design provides several advantages. The first one is the possibility of reducing the distance between patches up to $0.5\lambda_0$ due to the fact that the EBG and the patch antennas are located in different layers. The second one is that the patch antennas have a moderate directivity (derived from their size, as the patch effective permittivity is approximately 2 in this particular design) in front of solutions based on patches printed on high permittivity substrates. This relative large patch size also helps in the antenna feeding with a conventional coaxial probe. Finally, the proposed solution is completely planar, i.e., cheap and easy to manufacture.

An extension of this work to conformal patch arrays is apparently possible and constitutes one of the future research lines. Also, the use of other more compact planar EBG geometries (with the purpose of including more unit cells in E-plane) in the same configuration, is feasible.

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