Computational Investigation and Design of Planar EBG Structures for Coupling Reduction in Antenna Applications

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Abstract — Performance of a planar EBG is assessed by means of a FEM analysis. The dispersion diagram reveals the existence of a nearly TEM mode that compromises the bandgap behavior, also affecting its coupling reduction performance. Alternative EBG designs without the presence of the nearly TEM mode are proposed and assessed.

I. INTRODUCTION

Electromagnetic bandgaps (EBGs) are periodic structures of great interest, mainly for use in microwave circuits, exhibiting frequency zones where surface wave propagation is prohibited [1]. Most EBG designs rely on extensive use of vertical metallic connections and vias [1]-[2], offering an efficient means to reduce antenna coupling. However, vias complicate fabrication, thus making planar EBGs without vias an interesting alternative [3]-[4]. These are easily fabricated but the absence of vias dictates the need for more elaborate designs to obtain bandgap zones.

With the aim to propose planar EBGs with wide bandgaps, we first reassess the behavior of the well-known cross-like EBG geometry [3] by means of a finite element analysis of the unit cell and the extraction of the dispersion diagram. By careful inspection of the dispersion curves, we note the existence of a mode that is very close to TEM, hence it is not a surface wave but a free-space propagating mode. The existence of this mode compromises the EBG behavior, since it allows significant coupling between cells, as it is clearly demonstrated in practical antenna simulations. New planar EBG structures are also proposed, with enhanced bandgap properties.

II. INVESTIGATION OF BANDGAP PROPERTIES

A 3D finite element (FEM) code with vector finite elements has been implemented to investigate the EBG dispersion diagrams. Only one cell (Fig. 1) is used in the computations, while periodic boundary conditions (PBC) at the cell sidewalls are imposed to account for periodicity. The domain is terminated with perfectly matched layers (PML) on top. The Galerkin formulation is

$$\int_{\Omega}\left(\nabla\times\mathbf{w}_i^*\cdot\mu_r^{-1}\nabla\times\mathbf{E}-k_0^2\mathbf{w}_i^*\cdot\varepsilon_r\mathbf{E}\right)dV=\oint_{\partial\Omega}\mathbf{w}_i^*\cdot\hat{\mathbf{n}}\times\nabla\times\mathbf{E}dS \quad (1)$$

where $\mathbf{w}_i$ are the basis functions and * denotes complex conjugate. The 3D solid modeler creates a consistent grid with respect to periodicity. Thus, we can define identical degrees of freedom on a pair of periodic surfaces and by use of the Bloch-Floquet theorem we can impose the PBC on the corresponding basis functions, i.e.

$$\mathbf{w}_{m'}=\exp\left(-j\mathbf{k}\cdot\mathbf{a}\right)\mathbf{w}_m,\mathbf{w}_{n'}=\exp\left(-j\mathbf{k}\cdot\mathbf{b}\right)\mathbf{w}_n, \quad (2)$$

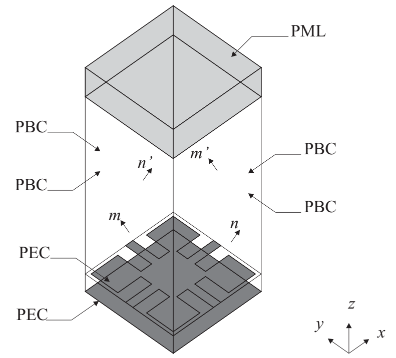

Fig. 1. Unit cell for the calculation of the dispersion diagrams.

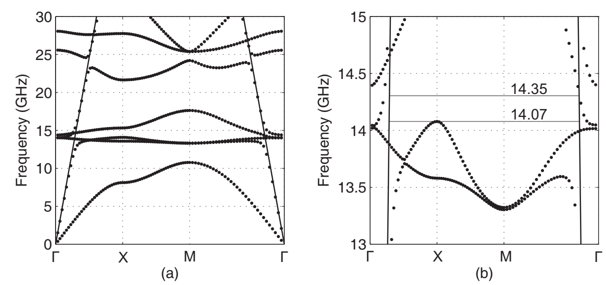

Fig. 2. Dispersion diagram of the cross-like EBG geometry (a) and zoom indicating a true bandgap from 14.07 GHz to 14.35 GHz (b).

where **a** and **b** are the cell vectors along the *x*- and *y*-direction and $(m-m')$, $(n-n')$ the associated pairs of degrees of freedom (Fig. 1). A generalized eigenvalue problem of the form $\mathbf{A}x=\lambda\mathbf{B}x$ is obtained and solved. The overall procedure is an extension of the method proposed in [5]. Other standard vector finite element and finite difference time domain (FDTD) codes, without the use of the Floquet-Bloch boundary conditions have also been implemented for the analysis of the full structures.

Using the developed FEM code, the dispersion diagram for the cross-like EBG is shown in Fig. 2(a). Although it is reported in [3] that there is a bandgap extending from 10.9 GHz to 13.5 GHz, the situation we observe here is quite different due to the existence of an eigenmode with its dispersion curve being very close to the light cone, indicating a TEM propagation mode. Hence, the presented bandgap only refers to substrate modes. The true bandgap of the structure is actually narrow, extending from 14.07 GHz to 14.35 GHz (Fig. 2 (b)).

To further investigate the effect of the nearly TEM eigenmode, we perform a simulated characterization process shown on Fig. 3, which aims at studying the propagation of TEM waves above the structure. Fig. 4 shows the resulting transmission coefficient, S_{21}, for multiple *n* unit cells. This is in perfect match with the bandgap predicted by the dispersion diagram.

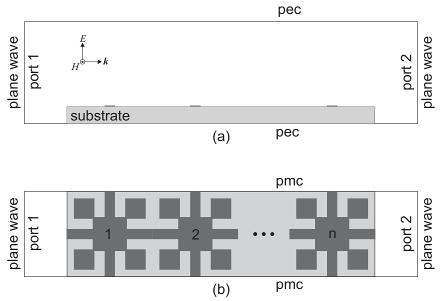

Fig. 3. EBG test geometry with n cells: (a) side view, (b) top view

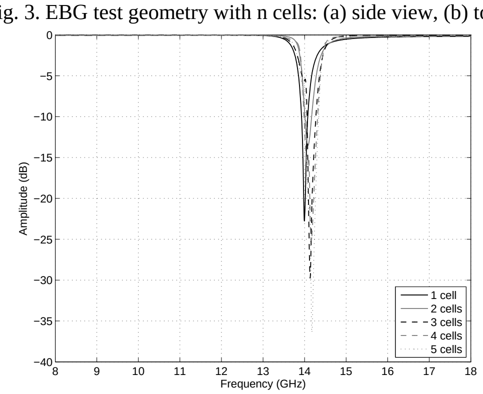

Fig. 4. Transmission coefficient for the test structure in Fig. 3 showing suppression for TEM waves only in a narrow zone close to 14 GHz.

III. INVESTIGATION OF MUTUAL COUPLING REDUCTION

Of particular interest concerning the application of an EBG is how it performs for antenna coupling reduction. Two E-plane coupled patch antennas on a substrate of ε_r = 10.2 and a thickness of 0.635 mm, separated or not by 4×3 EBG structures are considered (Fig. 5). The antennas have a size of 3.427×4.322mm, designed to oparate at 12.2 GHz, i.e. inside the bandgap according to [3]. Fig. 6 shows the reflection coefficient of an antenna and the two antennas before and after the insertion of the 4×3 EBG. The transmission coefficient is also shown. Clearly, there is no coupling reduction after the insertion of the EBG.

Next, the antennas are designed to operate at 14.1 GHz, i.e. inside the TEM-free bandgap. The antenna dimensions are 2.895×3.895mm. Fig. 7 shows the reflection and transmission coefficient for the two antennas before and after the insertion of the 4×3 EBG. Obviously, there is a significant coupling reduction, of about 9.3 dB. Far field calculations also show a slight directivity enhancement of 1.5 dB, being consistent with the presence of the bandgap.

Hence, when considering planar EBGs for coupling reduction applications, it is essential to enhance their bandgap characteristics. Toward this approach we propose here a new planar geometry, with an improved bandgap (Fig. 8). The main characteristic of this structure is the creative use of gaps and metal surfaces. It is expected that such structural features will exhibit clear inductive and capacitive behavior; hence, a variety of metal patches and capacitive gaps can be exploited to obtain a wideband behavior. For a structure with d_1 = 15 mm, d_2 = 10 mm, d_3 = 1 mm, d_4 = 11 mm and d_5 = 0.5 mm on FR4 substrate, the resulting dispersion diagram is shown in Fig. 8, indicating a clear wide bandgap from 5.74 GHz to 6.84 GHz.

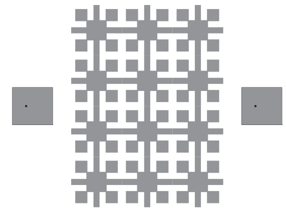

Fig 5. Geometry of two E-plane coupled patch antennas separated or not by a 4x3 periodic cross-EBG structure.

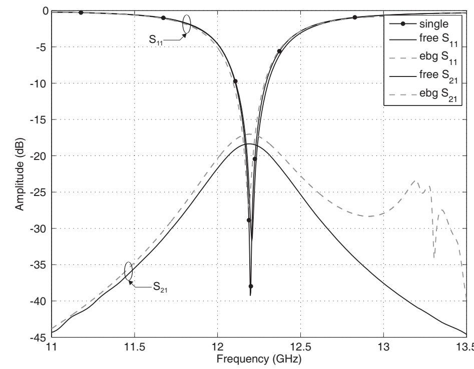

Fig 6. Reflection coefficients and coupling for E-plane coupled antennas operating at 12.2 GHz. No mutual coupling reduction is observed.

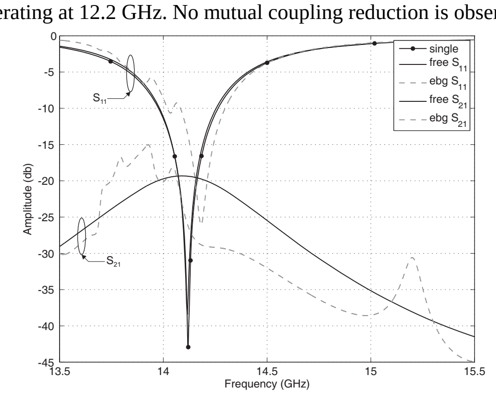

Fig 7. Reflection coefficients and coupling for E-plane coupled antennas operating at 14.1 GHz. Mutual coupling is considerably reduced.

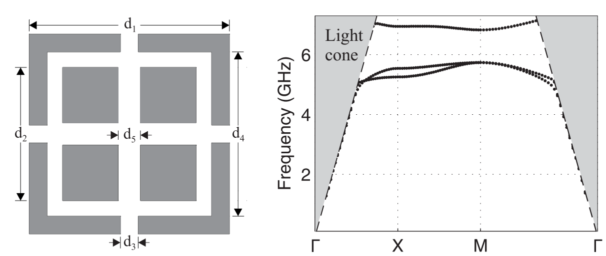

Fig. 8. The proposed uniplanar EBG structure and its dispersion diagram.

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