Efficient Finite-Difference Time-Domain Modeling of Integrated Antennas on Periodic Substrates

Dongying Li and Costas D. Sarris
The Edward S. Rogers Sr. Department of Electrical and Computer Engineering,
University of Toronto, Toronto, ON, Canada
E-mail: dongyingli@waves.utoronto.ca, cds@waves.utoronto.ca

Introduction

Periodic structures have been employed for a wide range of applications. In particular, electromagnetic bandgap (EBG) structure [1] substrates have been designed to enhance the performance of microwave circuits and antennas. Modeling techniques for the dispersion analysis of EBG substrates are well developed, by terminating the computational domain in periodic boundary conditions (PBCs). Yet, a problem worth studying is the interaction between periodic substrates and non-periodic objects, i.e., planar metallic structures above the substrates or localized sources. The non-periodic nature of the problem conventionally leads to large truncated structure modeling with high computational load.

Several ways have been proposed to solve this problem. In [2], the problem of microstrip lines on periodic substrates was efficiently solved using the array scanning method [3] combined with an integral equation formulation. In the context of the Finite-Difference Time-Domain (FDTD) method, the problem of localized sources has been addressed by connecting the array scanning method with FDTD implementations of PBCs, such as the sine-cosine method [4] or the spectral FDTD method [5], [6]. However, since PBCs periodically reproduce localized non-periodic boundary conditions, such as a metallic patch or a slot on a periodic substrate, their direct employment for the modeling of such geometries is prohibited.

In this paper, a modified version of an array-scanning based sine-cosine method is proposed, combining the PBCs with absorbing boundary conditions (ABCs). A practical way to numerically model EBG substrate based antennas and to calculate the far-field pattern using this method is discussed. One example of a conductor-backed folded slot antenna located on an EBG substrate (shown in Fig. 2 and studied in [7]) is presented. The simulation results demonstrate the accuracy and efficiency of the proposed approach.

Theory

The proposed method to model an EBG substrate integrated circuit, utilizing PBCs, is shown in Fig. 1. A combination of ABCs and PBCs is applied to terminate the computational domain in a stable manner. The proposed method effectively prevents the infinite reproduction of the conductors. The PBCs in the method are implemented by the sine-cosine method [8], which is suitable for wide-band applications. Both grids in the sine-cosine method are excited by identical modulated Gaussian pulses, which yields the response within the frequency range of interest in a single run.

While terminating the computational domain with the sine-cosine boundary con-
Figure 1: Combination of PBCs and ABCs ensures the structure to be simulated in the reduced computational domain.

Figure 2: The problem of a folded off-center fed slot antenna on a back-plated EBG substrate.

ditions, the array scanning method can be performed cancel the effect of all the periodic replicas of the original source and thus isolate the effect of the latter. For a two-dimensional periodic structure with lattice vector \( \vec{d} = d_x \hat{x} + d_y \hat{y} \), let \( \vec{E}_{array}(\vec{r}_0, \vec{k}, t) \) be the electric field for a point \( \vec{r}_0 \) determined by the sine-cosine boundary conditions, where \( \vec{k} \) is a Floquet wave vector within the irreducible Brillouin zone. The electric field at the point due to the non-periodic source can be found by [3]:

\[
\overline{E}_0(\vec{r}_0, t) = \frac{d_x d_y}{4 \pi^2} \int_{-\pi/d_x}^{\pi/d_x} \int_{-\pi/d_y}^{\pi/d_y} \overline{E}_{array}(\vec{r}_0, \vec{k}, t) dk_x dk_y. \tag{1}
\]

Practically, the integration is approximated by a finite summation with respect to discrete \( k_x \) and \( k_y \), and over discrete FDTD time steps \( t = m \Delta t \).

To use the method mentioned above for antenna simulations, the computational domain is set up as follows. Figs. 3 and 4 show two typical cases of a microstrip-fed patch antenna and a coaxial-fed slot antenna. In both situations, the computational domain is set up to enclose the entire antenna structure and the minimum number of unit cells of the periodic substrate covered by the antenna.

As mentioned above, the computational domain is excited by a wide-band Gabor pulse. For the microstrip-fed antenna of Fig. 3, the open boundaries are modeled by perfectly matched layers (PMLs). The excitation is applied directly under the microstrip line. For coaxial-fed antennas, since the feed line is not terminated at the boundary, PBCs can be implemented in both directions. The coaxial cable is modeled as a one-dimensional transmission line outside the computation domain, and the source is subsequently applied. Note that in Figs. 3 and 4, the plane of the patch/slot is terminated in PMLs; the PBCs are applied only at the substrate.

Finally, although not shown in the numerical example, the array scanning method can be used to calculate the far field patterns of EBG substrate based antennas. The methodology for that is straightforward. By replacing the electric field \( \overline{E}_{array} \) in (1) with the magnetic current \( \overline{J}_{array} \) determined by the surface equivalence theorem, the equivalent magnetic current \( \overline{J}_0 \) due to the non-periodic antenna under study is obtained. Then, by applying the conventional near-to-far field transformation the far field pattern of the antenna can be found.
Numerical Results

A conductor-backed folded slot antenna with a two-dimensional EBG substrate, introduced in [7], is simulated. The geometry of the folded slot is shown in Fig. 2. The gap width of the slot antenna is 0.6 mm in both the x– and the y–directions, as shown in Fig. 5. An off-center feed is provided by a coaxial cable with a characteristic impedance of 50 \( \Omega \). The metal sheet containing the slot antenna resides on a dielectric layer with thickness of 0.127 mm and relative permittivity of 2.2. The substrate includes a two-dimensional array of rectangular dielectric posts with relative permittivity of 10.2. The size of the dielectric posts is 4 x 8 x 4 x 8 x 54 mm and the periodicity of the EBG structure is 12 mm in both the x– and the y–directions. The entire structure is backed by a ground plane.

The modeling of the structure consisting of the slot antenna and 2 x 2 unit cells of the EBG substrate is set up as follows. The entire computational domain includes 40 x 40 x 125 Yee cells with a cell size of 0.6 x 0.6 x 0.127 mm. The EBG substrate is modeled by 20 Yee cells and the supporting substrate layer by one cell in the z–direction. The coaxial feed is modeled by a one-dimensional transmission line with a characteristic impedance of 50 \( \Omega \). The transmission line consists of 500 one-dimensional FDTD cells with the cell size of 0.6 mm. The computational domain is terminated in PBCs in both the x– and the y–directions and within the area of the EBG substrate, and by a 10-cell uniaxial PML elsewhere. A 1-20 GHz modulated Gaussian pulse is applied in the transmission line. The time step was set to 0.24 ps and 25000 time steps were run.

For the sine-cosine based array scanning method, the combination of 16 \( k_x \) points and 16 \( k_y \) points is uniformly sampled in the Brillouin zone and the calculation is performed in parallel on a grid server, within 1 hours 31 minutes. Fig. 6 shows the reflection coefficient at the antenna feed, compared to a finite structure simulation where the folded slot is located on an 8 x 8 array of the dielectric posts, which costs about 10 hours. Excellent agreement between the two results is observed, despite the significant computational savings obtained. The measured \( S_{11} \) from [7] is also plotted on Fig. 6, indicating the same resonance at 9.4 - 9.6 GHz.

Conclusions

The sine-cosine based array scanning method is modified to simulate integrated antennas above periodic substrates with FDTD. By means of periodic boundary conditions, the computational domain and the associated simulation cost can be
Figure 5: The geometry of the folded slot antenna.

Figure 6: The $S_{11}$ of the slot antenna from the proposed method and the truncated simulation, compared with the measured results from [7].

significantly reduced. The excellent performance and accuracy of the method have been demonstrated through an example of a slot antenna over an EBG substrate.

Acknowledgement

This work has been supported by the Natural Sciences and Engineering Research Council of Canada through a Strategic Grant.

References


