Rigorous Analysis of Dipole Source Radiation in Cylindrical Bandgap Structures with Defects

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1. Introduction

Periodic dielectric or metallic structures are a subject of continuing interests because of their wide use for practical devices in microwaves and optical waves. Various analytical or numerical techniques have been developed over the years to formulate the electromagnetic scattering from the periodic arrays. However, the previous pertinent efforts have been mostly concerned with the planar periodic arrays. An alternative of the planar configuration is a cylindrical array formed by circular rods periodically distributed on a circular surface. The cylindrical periodic systems referred to as cylindrical electromagnetic bandgap (EBG) structures are being used to the designs of directive antennas, multi-beam or beam-switching antennas [1]. Recently, V. Jandieri and K. Yasumoto have proposed a rigorous semi-analytical approach successfully applied to the analysis of electromagnetic scattering and radiation in cylindrical periodic and bandgap structures [2-4].

In this paper, we generalize the proposed method to the analysis of electromagnetic radiation from a dipole source located inside the cylindrical EBG structures with defects, where the defects are introduced by removing the particular circular rods from each circular ring. Breaking the periodicity of the structure, the radiated energy is allowed to propagate through the defects in some particular direction and is forbidden in the opposite direction by the existing bandgap. The method could be applied to various configurations of the cylindrical EBG structures with defects and allows us to consider different types and locations of the sources. Discussions are given from the viewpoint of flexible design directive beam forming characteristics.

2. Formulation of the Problem

Cross sectional view of N-layered cylindrical arrays of circular rods located in a homogeneous background medium with material constants ε_0 and μ_0 is shown in Fig. 1. The z dependence of all field components is given as $\exp(i\xi z)$, where ξ is the propagation constant along the z-axis. The problem is formulated by employing electric E_z and magnetic $\hat{H}_z = (\mu_0/\varepsilon_0)^{1/2} H_z$ fields as the leading fields. The M circular rods of radius r_ν and the material constants ε_ν and μ_ν are symmetrically distributed on each of N-layered cylindrical surfaces with radii R_ν $(\nu = 1, 2, 3, \cdots, N)$ as illustrated in Fig.1. The total field in the (ν)-th region is expressed in the matrix form as follows:

$$\begin{bmatrix} E_z^{(\nu)} \\ \hat{H}_z^{(\nu)} \end{bmatrix} = \begin{bmatrix} \mathbf{\Phi}^T & \mathbf{0} \\ \mathbf{0} & \mathbf{\Phi}^T \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{b}^{e(\nu)} \\ \boldsymbol{b}^{h(\nu)} \end{bmatrix} + \begin{bmatrix} \mathbf{\Psi}^T & \mathbf{0} \\ \mathbf{0} & \mathbf{\Psi}^T \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{c}^{e(\nu)} \\ \boldsymbol{c}^{h(\nu)} \end{bmatrix} \tag{1}$$

with

$$\mathbf{\Phi} = [J_m(\kappa\rho)\exp(im\varphi)]\,; \quad \mathbf{\Psi} = [H_m^{(1)}(\kappa\rho)\exp(im\varphi)] \tag{2}$$

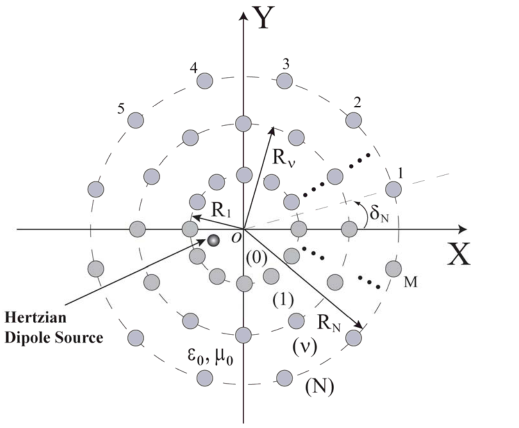

Figure 1: Cross-sectional view of N-layered cylindrical EBG structure formed by M circular rods with radius r_ν periodically distributed on each of N layer. Excitation by a Hertzian dipole source placed in the innermost region (0) is considered.

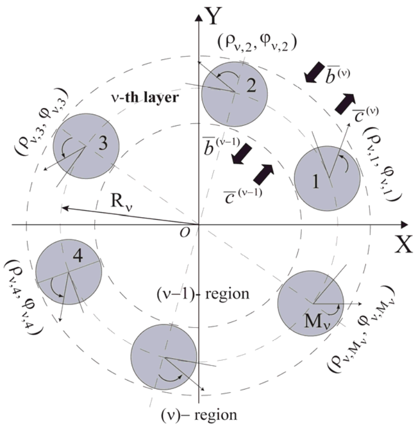

Figure 2: Schematic view of scattering process through the ν -th layer of the cylindrical arrays and local coordinate systems attached to each of M circular rods. $\overline{\boldsymbol{b}}^{(\nu)}$ and $\overline{\boldsymbol{c}}^{(\nu)}$ are the amplitude vectors of *incoming* and *outgoing* cylindrical waves.

where $\kappa=\sqrt{k_0^2-\xi^2}$, J_m and $H_m^{(1)}$ are Bessel and Hankel functions of the m-th order, respectively, $\overline{\boldsymbol{b}}^{(\nu)}, \overline{\boldsymbol{b}}^{(\nu-1)}$ and $\overline{\boldsymbol{c}}^{(\nu)}, \overline{\boldsymbol{c}}^{(\nu-1)}$ are the scattering amplitudes of the *incoming* and *outgoing* cylindrical waves on the ν -th layer and $\nu-1$ -th layer, respectively (Fig.2) and T" denotes the transpose of the indicated vectors. Following the same analytical procedure as presented in [2-4], the reflection $\overline{\mathbf{R}}_{\nu,\nu-1}(\xi)$, $\overline{\mathbf{R}}_{\nu-1,\nu}(\xi)$ and transmission $\overline{\mathbf{F}}_{\nu-1,\nu}(\xi)$, $\overline{\mathbf{F}}_{\nu,\nu-1}(\xi)$ matrices of ν -th cylindrical layer in the spectral domain are rigorously defined. We have omitted in the paper the detail calculation procedure due to the limited space, however, the interested readers can refer to the published papers [2-4].

3. Excitation by Hertzian Dipole

Let us consider that Hertzian dipole source located in the innermost (0) region at $(d_s, \phi_s, 0)$ is directed in z direction. Using the Fourier integral representation, the source field in the local coordinate (ρ_s, φ_s, z) is given as:

$$E_z^i=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{E}_z^i(\rho_s,\xi)\exp(i\xi z)d\xi, \quad H_z^i=0 \tag{3}$$

$$\tilde{E}_z^i(\rho_s,\xi)=-\frac{\omega\mu_0 I\ell}{4}\frac{\kappa^2}{k^2}H_0^{(1)}(\kappa\rho_s) \tag{4}$$

where $I\ell$ is the current moment of the electric dipole. The source field in the spectral domain is expressed in the global coordinate system (ρ,φ) as follows:

$$\tilde{E}_z^i(\rho,\varphi,\xi)=-\frac{\omega\mu_0 I\ell}{4}\frac{\kappa^2}{k^2}\mathbf{\Psi}^T\cdot\boldsymbol{s}^e \;; \qquad \boldsymbol{s}^e=[J_m(\kappa d_s)\exp(-im\phi_s)] \tag{5}$$

where $\{s_m^e(\xi)\}$ is the spectral amplitude of the source field. After straightforward mathematical manipulations, the transmitted fields $E_z^{t(N)}$ and $\hat{H}_z^{t(N)}$ in the far-zone are rigorously defined.

4. Numerical Analysis and Discussions

For the numerical analysis, we consider two different configurations of three-layered (N=3) cylindrical EBG structures composed of identical circular rods of perfect conductor with $r_{1,j}=r_{2,j}=r_{3,j}=0.15R_1$ as shown in Fig.3. The original three layered structure is formed by $M_1=8$, $M_2=2M_1=16$ and $M_3=3M_1=24$ circular rods periodically distributed on three circular rings with radii R_1, $R_2=2R_1$ and $R_3=3R_1$. Thus between the radii of the (ν)-th circular ring R_ν and the number of circular rods M_ν located on the (ν)-th circular ring, the following relation is fulfilled: $R_1/M_1=R_2/M_2=R_3/M_3$. The defects were introduced by removing two, three and four rods (Fig.3*a*) and three, five and seven rods from the 1st, 2nd and 3rd circular layers (Fig.3*b*), respectively. The missing rods are indicated by the hollow circles. The dipole source is located at a distance d_S along the y-axis $(\varphi_S = 90^0)$. After confirming the convergence of the solutions, the radiation patterns in both *H*-plane and *E*-plane are plotted in Fig.4 to Fig.7.

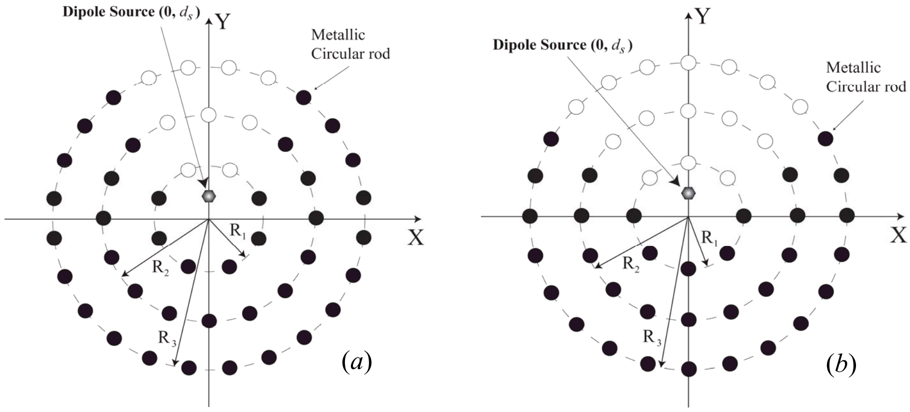

Figure 3: Cross-sectional view of two different configurations of three layered cylindrical EBG structure with defects composed of perfect conductor circular rods. Dipole source is located in the innermost region at a distance d_S from the global origin.

Figures 4 and 6 show the radiation patterns for three different normalized excitation frequencies R_1/λ in both principle *H*-plane and *E*-plane for EBG configurations illustrated in Fig 3*a* and 3*b*, respectively. The dipole source is located at the origin $d_S = 0$ of the cylindrical EBG structures. The radiation patterns in the *H*-plane for both bandgap configurations demonstrate that by increasing the excitation frequencies R_1/λ the bandwidth of the radiation patterns decrease and at $R_1/\lambda=0.5$ the flow of electromagnetic energy is strongly directed in the forward direction, where the defects are created. On the contrary, in the principle *E*-plane the increase of the excitation frequency leads to the increase of the bandwidth of the radiation pattern and at $R_1/\lambda=0.5$ the pattern is no longer directed in the vertical direction as it was observed at $R_1/\lambda=0.2; 0.35$. Next, we investigate the effect of the location of a dipole source on the radiation characteristics. The radiation patterns are calculated for three different locations of the source with $d_S=0$ (blue line), $d_S=0.4R_1$ (red line) and $d_S=0.7R_1$ (black line) and compared in Figures 5 and 7 for both configurations of cylindrical EBG structures. The excitation frequency is chosen to be the same $R_1/\lambda=0.5$ for both EBG configurations. From Figures 5 and 7 it follows that the directivity of radiation is very sensitive to the source location and strongly depends on the profiles of the defects. For the configuration of Fig.3(a), the beamwidth for the *H*-plane in the forward direction is getting narrower (black line) when the line source is placed close to the first circular ring $d_S=0.7R_1$ (Fig.5). The radiation patterns in Fig.7 for *H*-plane are quite different from those in Fig.5. The pattern for $d_S=0$ (solid line) with a narrow single beam in the forward direction is substantially deformed as the dipole source approaches the first circular ring of the structure as indicated by $d_S=0.4R_1$ (red line) and $d_S=0.7R_1$ (black line). The flow of electromagnetic energy is not directed in the forward direction. This could be explained by the fact that the elevation angle between the dipole source and the cylindrical EBG structure of Fig.3(*b*) is getting smaller and the EBG structure cannot form the directive beam in the forward direction. Quite different profiles in the radiation patterns are observed in the *E*-plane for both configuration of cylindrical EBG structure. There appear the strong sidelobes when the dipole source is located at some distance from the global origin $d_S \neq 0$. Our numerical analyses have shown that in order to obtain the directive beams in the *E*-plane in the vertical direction, where the defects are created, the lower excitation frequencies should be considered. Finally, we should mention that for the cylindrical EBG structures shown in Fig.3, our calculation confirmed that the effect of the number of the layers is prominent at N=3 and no noticeable changes in the radiation patterns are observed for the further increase of layers.

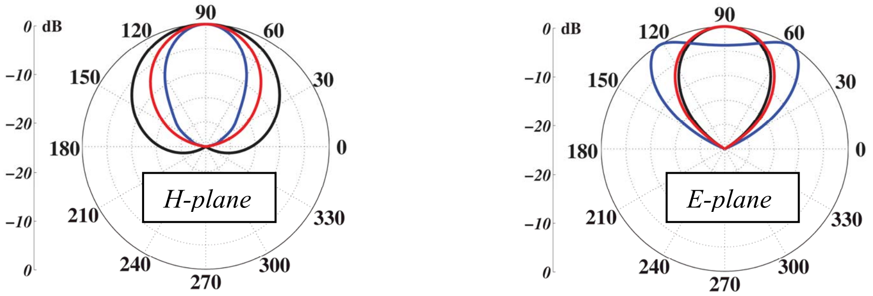

Figure 4: Radiation patterns of a dipole source for three different normalized frequency parameter R_1 / λ : $R_1 / \lambda = 0.2$ (black line), $R_1 / \lambda = 0.35$ (red line), $R_1 / \lambda = 0.5$ (blue line) of 3-layered cylindrical EBG structure shown in Fig.3*(a)*. Dipole source is located at the origin of the structure $d_s = 0$. Other parameters are the same as those presented in Fig.3(*a*).

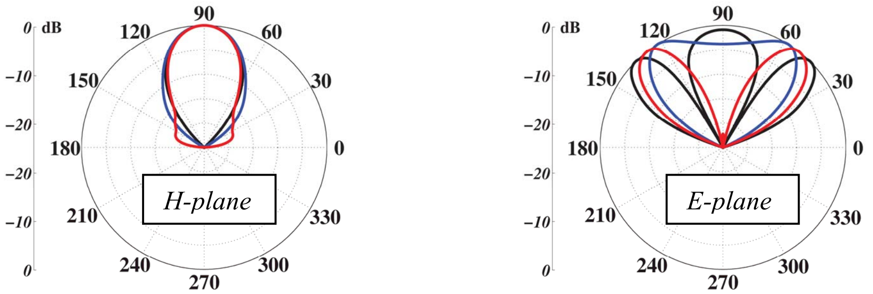

Figure 5: Radiation patterns for three different positions of a dipole source: $d_s = 0$ (blue line); $d_s = 0.4R_1$ (red line) and $d_s = 0.7R_1$ (black line) located inside the three-layered cylindrical EBG structure shown in Fig.3*(a)* at $R_1 / \lambda = 0.5$.

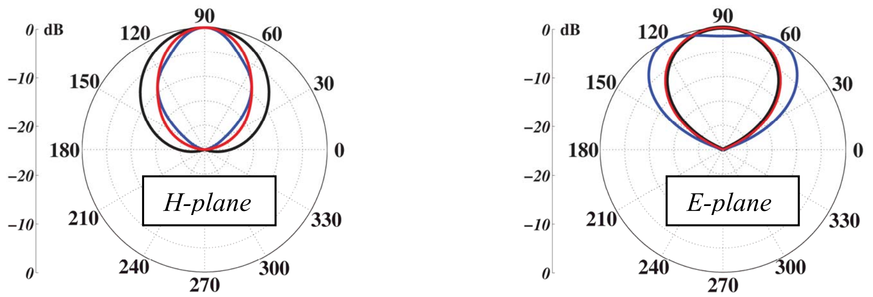

Figure 6: The same as in Fig.4 but for the cylindrical EBG structure shown in Fig.3(*b*).

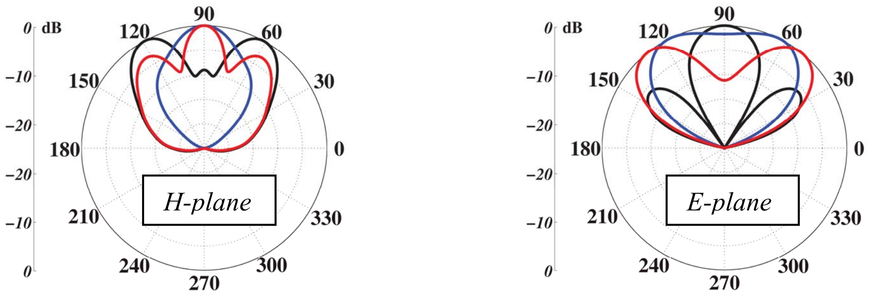

Figure 7: The same as in Fig.5 but for the cylindrical EBG structure shown in Fig.3(*b*).

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