Directive Leaky-Wave Radiation from a Line Source in 2-D EBG Array of Scatterers

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Abstract

The directive radiation of dielectric EBG array of scatterers excited by a single line source is originally studied in terms of leaky waves. An extensive modal analysis of EBG waveguides composed by a finite number of periodic chains of 2-D circular rods is presented. The dispersion curves of the modes supported by periodic waveguides of different transversal dimensions are analyzed as a function of the normalized frequency. The analysis has shown that a multiplicity of bound and leaky modes can propagate in such a structure. In particular, the directive radiative features of the EBG structures in two different frequency regions can be properly described in terms of suitably excited dominant leaky modes. However, the presence of further spurious guided and higher-order leaky modes, which can be simultaneously excited by the source, needs to be carefully considered when a realistic truncated structure is considered. The final results are in a good agreement with those predicted by our modal analysis, which thus represents a valid approach to optimize the radiation features of these interesting EBG structures.

1 Introduction

The directive radiation from elementary sources embedded in Electromagnetic Band Gap (EBG) materials has been a topic of extreme interest in the last two decades [1-5]. EBG working in a complete bandgap region have been adopted as partially reflecting structures in highly directive Fabry-Perot cavity antennas [2,3]. Alternatively, EBG without any defect, also known as a lattice structure, has been used to focus the radiation at wavelengths that do not belong to the bandgap region. In both cases, the radiative features of the EBG structures have been investigated by recurring to the properties of the Band diagrams or the field patterns of the crystal modes of an infinite structure [1,4].
In this contribution, radiation from array of scatterers made by a finite number of periodic chains of two-dimensional (2-D) dielectric circular rods in free space is investigated with a different perspective. The relevant problem is studied in terms of leaky modes [6], excited by the adopted source, of a 2-D open waveguide, which is infinite along the longitudinal direction of propagation, but finite in the transverse direction. Following this approach, radiation in the half spaces surrounding the transversely limited lattice structure is rigorously taken into account and the radiative features of the structure are related to the properties of the involved leaky modes. Leaky-mode complex wavenumbers are obtained by using an ad-hoc self-contained rigorous formulation based on the Lattice Sums (LSs) technique [7], while the far fields of the infinite and truncated EBG waveguides excited by an electric line source are investigated by using CST microwave studio.

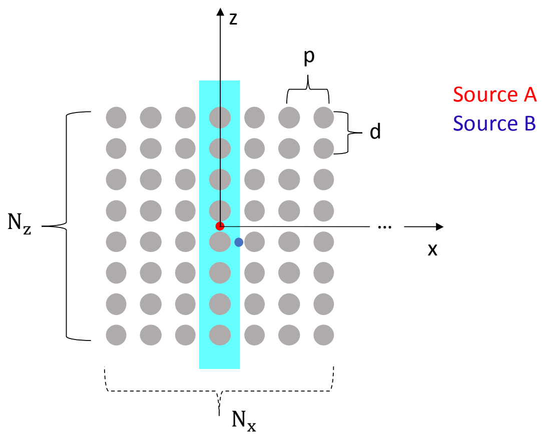


Figure 1. 2-D EBG open waveguide consisting of a finite number (N_z) of periodic chains of 2-D circular rods with radius r. The shadowed cyan region indicates the chosen one-dimensional unit cell. The period along x direction is p, while d is the distance between two nearest rods along the z-axis.

2 2-D EBG Waveguides Excited by an Electric Line Source

We analyze a 2-D EBG structure consisting of infinite (along y direction) dielectric circular rods, with radius r and dielectric permittivity ε_r=11.7 in a vacuum background. The structure is infinite along the x direction, with period p, and formed by a finite number N_z of cylinders along the z direction, spaced by a distance d, thus representing a 2-D open waveguide (see Fig. 1). The waveguide can be excited by an embedded electric line source parallel to the axes of the rods; only E_y, H_x, and H_z field components exist, corresponding to the TE-mode case. The source can be located either in position A or B within the unit cell (indicated as a shadowed cyan region in Fig.1), since it is

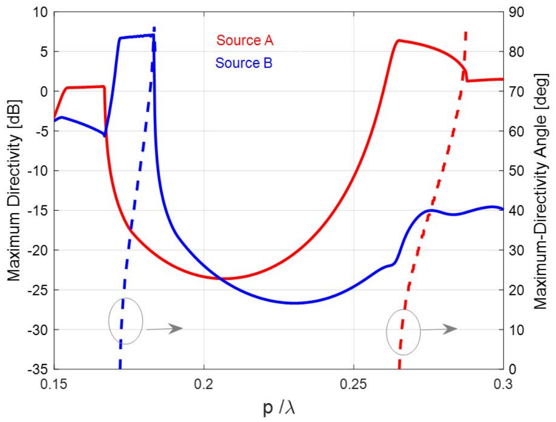


Figure 2. Plot of the directivity (solid line) and angle of radiation (dashed line) as a function of the normalized frequency $\boldsymbol{p/\lambda}$ for the infinite waveguide in Fig.1 with $\boldsymbol{N_z}$=**8**, *r*/*p*=0.35, and *d*/*p*=1. Results for source position A and B are indicated in red and blue, respectively.

known that different electromagnetic configurations, allowed by a square lattice at a given frequency, can be selectively excited by placing the feeding point in specific locations [5].

The total far field excited by the source is here obtained by simulating a single unit cell in a periodic environment with CST, and applying reciprocity [8]. A study of the directivity of the radiated field excited by an electric line source in position A or B (as indicated in Fig. 1), is performed and shown in Fig. 2. Two regions of high directivity, which also present a scan of the main radiated beam from broadside to endfire by increasing frequency, can be observed, with maximum directivity at broadside of 6.4 dB at p/λ =0.265 and 6.7 dB at p/λ =0.172, for the source in position A and B, respectively. We note that the directive radiative region at higher frequency corresponds to the lowest edge of the second band of the irreducible Brillouin zone of the square lattice of dielectric rods (i.e., of an EBG that is infinite along both *x* and *z* directions), which is typically considered as a good working point for the lattice structure to behave as a spatial filter and to focus the radiation [1,4,5].

3 Bound and Leaky Modes in 2-D EBG Waveguides

In this section, we will discuss the dispersion curves of the TE bound and leaky modes propagating along *x* direction in the 2-D EBG waveguide shown in Fig. 1, with the aim of finding leaky modes responsible for the directive radiation described in Fig. 2. Numerical results for different propagation regimes, obtained with the LSs technique extended to complex wavenumbers in [7], are described and reported in the Brillouin diagrams in Fig. 3. The periodicity allows us to express the field quantities, by means of Floquet's theorem, as a sum of an infinite number of space harmonics with complex propagation

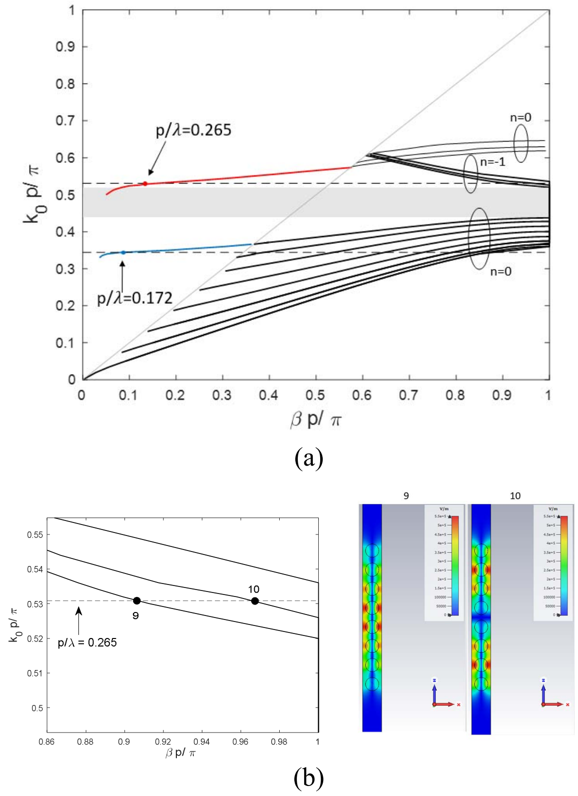
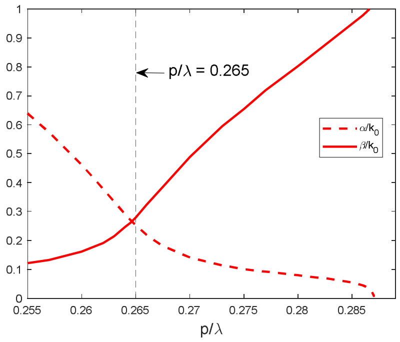


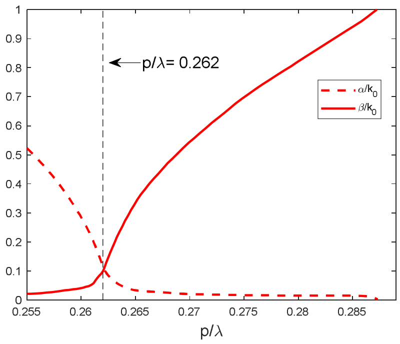
Figure 3. (a) Brillouin diagram for the n = 0 and n = −1 space harmonics of the TE bound and leaky modes of the structure studied in Fig. 2. Bound modes are indicated as black solid lines. Blue and red curves show lower and upper leaky modes, respectively, responsible for the regions of high directivity shown in Fig. 2. The gray solid line indicates the light line. (b) Intersection between p/λ=0.265 line and the first two backward bound modes. Modal configurations of these two modes are also shown.

wavenumbers $k_{xn}=\beta_n - j\alpha = \beta_0 + 2\pi n/p - j\alpha$, with n = 0, ±1, ±2,..[7,9]. The Brillouin diagram shows the dispersive behavior of the space harmonics as a plot of the normalized frequency k_0p/π versus the normalized phase constant $\beta p/\pi$, where β represents the phase constant along x of any particular space harmonic [9]. At low frequency, we observe eight fundamental guided modes, one for each of the eight periodic chains of the structure [10], the relevant phase constants (n = 0 harmonics) with positive group velocity are indicated as black solid lines. Between $0.44<k_0p/\pi<0.52$ a closed stopband regime for all bound modes is observed (see shadowed region in Fig. 3(a)) [9], where the modal wavenumber is complex; for $k_0p/\pi>0.52$ a second passband region occurs where the modal solutions are again proper and real (the n = −1 harmonics, with negative group velocities, of only the first three modes are indicated as black solid lines in Fig. 3(a)). At higher frequencies, eight higher-order TE guided modes also exist. Note, that the n = 0 harmonics with positive group velocities of only the first three modes are indicated as black solid lines in Fig. 3(a).

Each guided mode presents an improper or proper leaky-wave branch in the fast-wave region on the left of the light



(a)

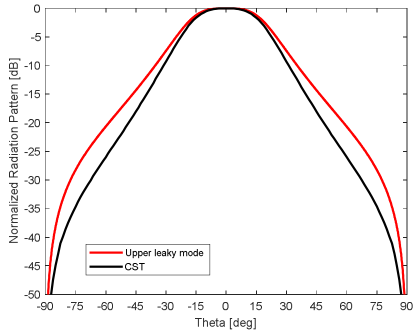


(b)

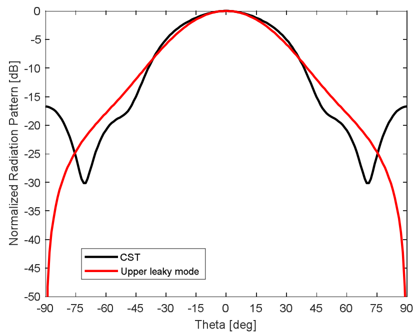
Figure 4. Normalized phase (n = 0 harmonic) and attenuation constants of the upper leaky mode vs. normalized frequency for: (a) $\boldsymbol{N_z = 8}$ and (b) $\boldsymbol{N_z = 16}$.

line (gray solid line) in Fig. 3(a), except for the low-order fundamental TE mode which has its cutoff at zero frequency. Only the two improper leaky-wave solutions (n = 0 harmonics), responsible for the main radiative regions reported in Fig.2, are shown in the Brillouin diagram in Fig. 3(a), indicated as solid blue and red lines. We observe that at p/λ=0.172, corresponding to the maximum directivity at broadside for the source in position B, in addition to the leaky mode in blue in Fig. 3(a) (lower leaky mode), up to seven lower-order guided modes can be excited, depending on the modal field configurations. This strong multimodal behavior makes this frequency region not suitable to be used for the design of a leaky-wave antenna, since strong spurious radiation from the lower-order guided modes at the edge truncation of the antenna would be observed. At p/λ=0.265, corresponding to the maximum directivity at broadside for the source in position A, only two bound modes in a backward propagation regime (modes indicated as number 9 and 10 in Fig. 3(b)) can be excited together with the leaky mode in red in Fig. 3(a) (upper leaky mode), since all the remaining bound modes are still in a stopband regime. However, the y-component of the electric modal fields of these two guided modes are shown in Fig. 3(b) and present a null of the field exactly in the section x=0, where the electric line source is placed. Hence, these guided modes cannot be excited by the source, thus making the upper leaky mode more suitable to be used for the design of a leaky-wave antenna.

In Fig. 4(a) the normalized phase β/k_0 (n=0 harmonic) and attenuation constants α/k_0 of the upper leaky mode of Fig. 3(a) are plotted as a function of the normalized frequency.



(a)



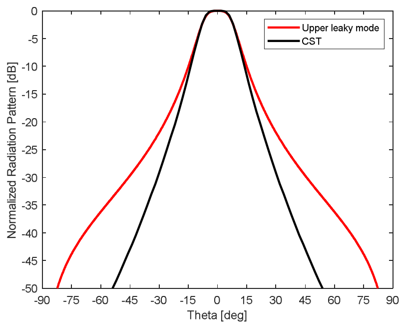
(b)

Figure 5. Normalized radiation pattern: comparison between leaky-wave and full-wave approach. $\boldsymbol{N_z = 8}$; (a) $\boldsymbol{N_x = \infty}$ and (b) $\boldsymbol{N_x = 5}$.

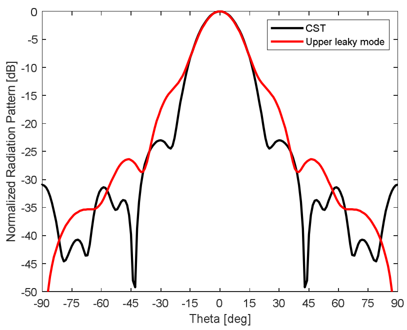
We observe that the frequency of maximum directivity at broadside is very close to the condition $\beta = \alpha$, as expected [6]. However, the value of the normalized attenuation constant is too high ($\alpha/k_0 \cong 0.252$) to give rise to directive radiated beams. In order to increase the directivity, the number of periodic chains has to be increased. In Fig. 4(b) the dispersion behavior of the upper leaky wave for a structure with 16 rows of cylinders is shown. Very low values of the attenuation constant are obtained at the broadside normalized frequency of p/λ =0.262 ($\alpha/k_0 \cong 0.114$), which are consistent with a directivity of 11.5 dB observed for the infinite structure excited by a line source in position A.

4 Comparisons between Leaky-Wave and Total Full-Wave Radiated Fields

In this section, the far-field radiation patterns are reported for the structure shown in Fig. 1 where transversal dimensions of N_z =8 and N_z =16, along z-axis, and infinite and truncated structures, along x-axis, are considered. For the infinite structure, comparisons are provided between the exact total normalized far field obtained by simulating a single unit cell in a periodic environment with CST, applying reciprocity, and the normalized leaky-wave far-field contribution due to the excited upper TE leaky mode. Results are shown in Figs. 5(a) and 6(a), for N_z=8 and 16, respectively. (Only angles, measured from the positive z axis, ranging from -90° to +90°, through 0°, are shown,



(a)



(b)

Figure 6. Normalized radiation pattern: comparison between leaky-wave and full-wave approach. $\boldsymbol{N_z = 16}$; (a) $\boldsymbol{N_x} = \infty$ and (b) $\boldsymbol{N_x = 13.}$

since the structure in Fig. 1 is symmetric with respect to the z=0 plane.)

The effect of truncating the structure along x direction is considered by comparing the exact normalized far field obtained with CST and the leaky-wave normalized far-field for an aperture with a finite length. In the latter case, the hypothesis that an ideal absorbing load is placed at the end of the aperture to avoid a reflected wave is made [6]. Results are shown in Figs. 5(b) and 6(b), for N_z =8 and N_z =16, respectively, where in each case the number N_x of cylinders along the longitudinal direction x is chosen in order to have a leaky-wave radiation efficiency of 90% [6]. A good agreement is observed in all cases for the main lobe between the total field and the TE leaky-wave field. We note that, for the case of Fig. 5(a), the half-power beamwidth (HPBW) is 40.8° and 37.2° for the leaky-wave and total full-wave field, respectively. In the finite length case of Fig. 5(b), HPBW values are 42.0° and 48.0°, respectively. The more directive case of Fig. 6 presents HPBW of 17.3° and 17.2° (infinite structure), respectively, and of 18.0° and 18.6° (truncated structure), respectively.

Due to the multimodal nature of the lattice structure, higher-order leaky modes (not reported here for brevity) could contribute to the representation of the total far field excited by the source in position A. In a future work, we aim at studying the radiation features obtained by considering both the upper and the higher-order leaky modes, weighed by the relevant excitation coefficients, in order to definitively improve the agreement between leaky-wave field and total field excited by a source embedded in such kind of dielectric EBG waveguides.

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