Highly Directive Leaky-Wave Radiation in 2-D Dielectric Photonic Crystals

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***Abstract*—A comparative study of the directive radiation obtained from two kinds of 2-D photonic crystal structures excited by an electric source is presented in this letter. These structures consist of a stack of periodic chains of dielectric cylinders in free space or of circular voids in dielectric media. On the basis of an in-depth description of the physical phenomena underlying the Bloch transverse-electric modal field configurations of such structures, a set of design rules to achieve highly directive leaky-wave radiation is obtained. An analysis of the two types of structures shows that it is preferable to consider holey lattices to achieve more directive radiation, obtained by the excitation of a weakly attenuated fundamental leaky mode. Indeed, radiators consisting of an integer number of periodic chains of voids drilled in a dielectric medium over a metal plate show directivity at broadside approximately 6 dB higher than in the dielectric cylinder case. This class of holey lattices can be used to design highly directive leaky-wave antennas, with significant advantages of easy manufacturing, design simplicity, and low complexity.**

***Index Terms*—Electromagnetic band-gap (EBG) structures, leaky waves, leaky-wave antennas (LWAs), periodic structures, photonic crystals (PCs).**

I. Introduction

DIRECTIVE radiation by elementary sources in 2-D photonic crystals (PCs) [1], also classified under the broad terminology of electromagnetic band-gap (EBG) structures [2], has been investigated in lattices formed by both dielectric and metallic cylinders [3], [4], [5], [6], [7], [8], [9]. The focused emission from a dielectric PC was initially provided by using geometric-optics considerations [4] in the case of embedded sources operating at the lowest edge of the air band. A parametric analysis of the obtainable directivity was reported for different lattice geometries in [10] and compared to that of Fabry–Pérot cavity antennas realized with the same technology. Then a leaky-wave formalism was used to explain the radiative phenomenology, mainly when homogenized structures were considered [11], [12], but also in PCs and quasicrystals [13], [14]. Recently, the radiation mechanism of 2-D dielectric lattices has been thoroughly examined in terms of leaky waves [15], showing that a joined procedure based both on the analysis of the band diagrams of the Bloch waves propagating in the 2-D PCs and the leaky-wave investigation of transversely limited open periodic waveguides provides an interesting perspective for effective antenna design.

In this letter, leaky-wave radiation from dielectric rod PCs (DRPCs) as well as holey PCs (HPCs), made by 2-D periodic lattices of circular dielectric rods in free space and air columns drilled in a dielectric hosting medium, respectively, is considered. For the first time, a list of practical design rules for the design of highly directive PC leaky-wave antennas (PCLWAs) bisected by a metal plate are provided. Furthermore, the bisected HPC waveguides are individuated as the best candidate to achieve high directive radiation, with performance 6 dB higher than those based on DRPCs. Finally, a 3-D realistic configuration of holey PCLWA, fed by a standard coaxial cable, is designed and simulated showing good matching at the operating frequency and a very good agreement with the adopted leaky-wave model.

This letter is organized as follows. Section II gives design guidelines based on the dispersion-band diagrams and the field plots of the Bloch modes in infinite 2-D PCs, whereas Section III presents the radiative features and the modal field symmetries of DRPC and HPC open waveguides. In Section IV the directivity of metal-bisected PCLWAs is investigated and the design of a 3-D holey PCLWA is presented. Finally, Section V concludes this letter.

II. Gap Maps and Field Plots for a Square Lattice of Circular Dielectric Rods and Air Columns

Directive radiation by elementary sources embedded in PCLWAs is related to the presence of a band-gap between dielectric and air bands in the corresponding 2-D PC lattices and it is observed at the *lower edge* of the air band [3], [4], [5], [15]. Hence a preliminary Bloch-wave analysis of the DRPC and HPC 2-D lattices is needed to fix geometrical and physical parameters of the PCLWA. Gap maps in terms of normalized frequency versus r/p ratio, where r is the radius of the cylinder and p is the period of the structure, are obtained by using the eigenmode solver of CST Microwave Studio [16] and are shown for typical dielectric permittivities in Fig. 1(a) and (c) for the case of DRPCs and HPCs, respectively. (The case of electric

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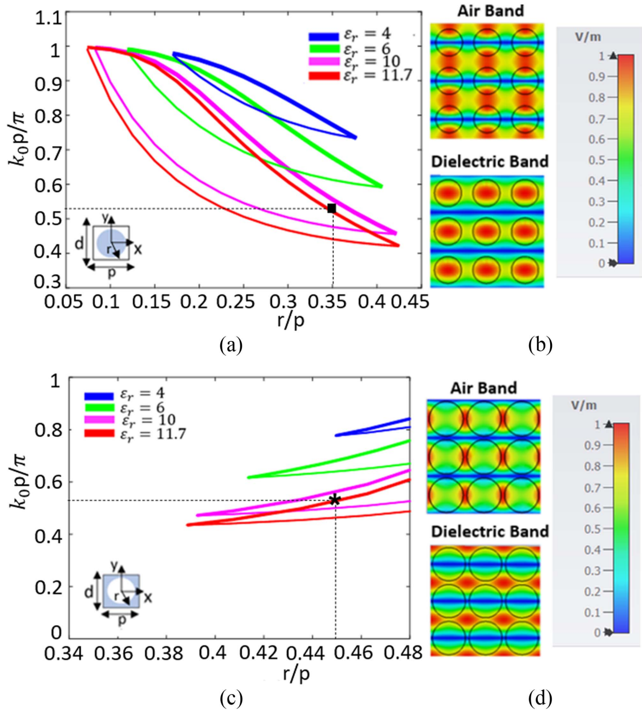


Fig. 1. Gap maps for TE Bloch modes, with respect to the x- and y-directions, in terms of normalized frequencies at the *lower edge* of the air band (thick lines) and at the higher edge of the dielectric band (thin lines) as a function of r/p for different values of dielectric permittivities for a square lattice ($d = p$) of (a) circular dielectric rods and (c) air columns. r is a radius of the cylinder, p is a period of the structure, and k_0 the free-space wavenumber. The two black markers indicate the chosen operating frequencies and the relevant lattice parameters. The magnitude of the z-component of the electric Bloch modal fields E_z at the air band and at the dielectric band for the two types of lattices are shown in (b) and (d), respectively.

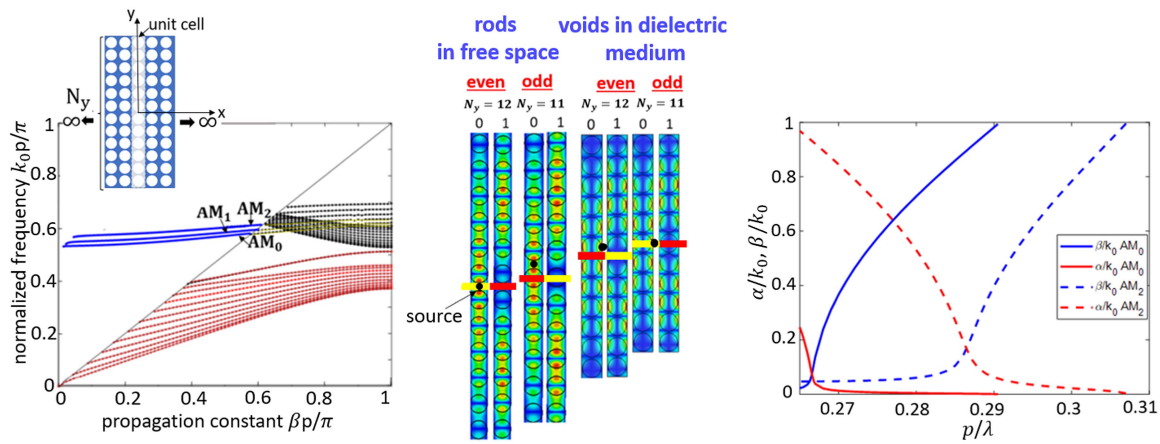
field aligned with the cylinder axis z, which corresponds to TE Bloch modes with respect to the x- and y-directions, is here considered.) The band-gap can be obtained for all the considered permittivities, by properly choosing the ratio r/p. Even if wide bandwidths are associated to the DRPC [1], the presence of narrower bandwidths, as occurs for the HPC, is anyhow sufficient to obtain highly directive radiation at broadside, as will be shown in Sections III and IV. The TE Bloch modal field configurations of the air and dielectric bands are shown in Fig. 1(b) and (d) for the two kinds of 2-D lattices. It can be observed that in the air bands the magnitude of the electric field presents a null exactly in the middle of the dielectric cylinders or in the dielectric region between two voids, for the DRPCs and HPCs, respectively.

III. Modal Field Symmetries and Directive Radiation in Open Waveguides Composed by Periodic Chains of Dielectric Rods and Air Columns

Once the geometrical and physical parameters of the 2-D lattices have been chosen to allow for a total band gap, an open waveguide composed by a stack of N_y infinite periodic chains [17] of dielectric cylinders or voids has been considered as a basic model of PCLWA [e.g., see the HPC open waveguide unit cell shown in the inset of Fig. 2(a), formed by $N_y = 12$ circular voids in the transverse y-direction]. Here, adopting the leaky-wave approach proposed in [15] and using the tailored numerical procedure developed in [18], the directive features of such kind of radiators have been investigated. A complete analysis, including structures with lossless dielectric rods in free space as well as the dual configuration consisting of circular voids in a hosting lossless dielectric medium, where both even and odd number of rods or voids are considered, is performed. The holey open waveguide in the inset of Fig. 2(a) is considered in the proposed design. The relevant parameters are chosen by fixing the normalized frequency $k_0p/\pi \cong 0.52$ at the lower edge of the 2-D lattice air band [e.g., $\varepsilon_r = 11.7$ and $r/p = 0.45$, as indicated by the black star in Fig. 1(c)]. In Fig. 2(a) the relevant Brillouin diagram for TE modes is shown. Twelve forward dielectric modes (the same classification in dielectric and air modes used for 2-D lattices [1] in Section II is kept for the open waveguide structure), one for each periodic chain, are observed at low frequencies (red-dotted curves), the twelfth being a plasmonic mode with modal field highly confined between the free space and the dielectric medium. At higher frequencies forward air modes (AMs) [the first three, i.e., AM_0, AM_1, and AM_2, highlighted in yellow in Fig. 2(a)] and backward dielectric modes (black-dotted curves) are present. All modes, except the lower order dominant dielectric mode, in the Brillouin diagram have their improper (forward) or proper (backward) leaky branch; however, only the AM_0, AM_1, and AM_2 improper leaky modes are shown here (blue solid lines), since they can be of interest in the description of the directive radiative features of the proposed PCLWAs, with the leaky AM_0 radiating at broadside at the lower edge of the HPC air band.

In Fig. 2(b), the magnitude of the unit-cell modal electric fields $|E_z|$ of the first two lower order TE air modes are shown for all the possible open waveguide configurations (i.e., even and odd numbers of rods and voids within the unit cell). We observe that the PMC or PEC symmetries of the first air-mode field in the open waveguides [see the thick yellow and red lines, respectively, in the bisection planes of the unit cells for the AM_0 and also AM_1 fields in Fig. 2(b)] are imposed by the air-band Bloch modal fields of the 2-D PCs, shown in Fig. 1(b) and (d). In particular, when an even (odd) number of dielectric rods forms the open waveguide unit cell, with the relevant bisection plane placed in the middle of an air space (a dielectric rod), the fundamental AM_0 in Fig. 2(b) shows a PMC (PEC) bisection symmetry. This is in agreement with the position of the minimum and maximum of the air-band fields $|E_z|$ in the 2-D DRPC, which lies in the horizontal central plane of a cylinder and in the center of a vertical air space between two rods, respectively, see Fig. 1(b). Conversely, the fundamental AM_0 of the HPC open waveguide in Fig. 2(b) naturally results in PEC and PMC bisection symmetries for even and odd voids, respectively, in agreement with the 2-D HPC air-mode fields shown in Fig. 1(d).

By placing an electric line source in the PMC bisection planes or slightly above the PEC bisection planes, where maxima of the electric fields of the leaky AM_0 are present for the different geometries investigated [see the black dots for the four different cases in Fig. 2(b)], only the leaky AM_0 is excited [15] and directive radiation with two beams at both sides of the open waveguide can be obtained. In Fig. 3, the maximum directivities at broadside evaluated with the same formulation adopted in [15] are shown for the dielectric rod [parameters are chosen by fixing $k_0p/\pi \cong 0.52$ at the lower edge of the 2-D PC air band for $\varepsilon_r = 11.7$, as shown by the marker in Fig. 1(a)] and holey nonbisected structures. The maximum directivity increases in all cases, with the holey structure presenting slightly higher



(a) (b) (c)

Fig. 2. (a) Brillouin diagram for the TE modes of an open waveguide with $N_y = 12$ periodic chains of air columns (see the inset), with $r/p = 0.45$ and $\varepsilon_r = 11.7$. The forward (bound) dielectric modes at lower frequencies are indicated with red dotted lines, while the corresponding backward modes at higher frequencies as black dotted lines. The first three forward air modes are indicated with yellow-dotted (bound modes) and blue solid (improper leaky modes) lines. (b) $|E_z|$ fields of the first two TE air modes, i.e., AM_0 and AM_1, for even and odd numbers N_y of periodic chains of dielectric rods and air columns; $\beta p/\pi = 1$. The PMC (PEC) symmetry at the unit-cell bisection plane is indicated with a thick yellow (red) line. The position of the electric line source in the two types of structures is shown with a black dot in the AM_0 field plots. The same scale of the amplitudes adopted in Fig. 1 is used here. (c) Dispersion diagrams for the TE leaky AM_0 and AM_2. Normalized phase (attenuation) constants β/k_0 (α/k_0) are shown in blue (red) solid and dashed lines, respectively.

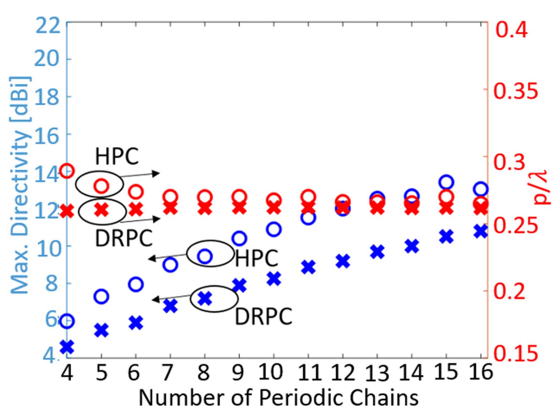


Fig. 3. Maximum directivity at broadside and the normalized frequency at which it is obtained, as a function of the number of periodic chains N_y: comparison between the DRPC (cross markers) and HPC (circle markers) structures. The r/p ratio for the DRPC structure is $r/p = 0.35$ and for HPC $r/p = 0.45$; $\varepsilon_r = 11.7$. The electric line source is positioned, as shown in Fig. 2(b).

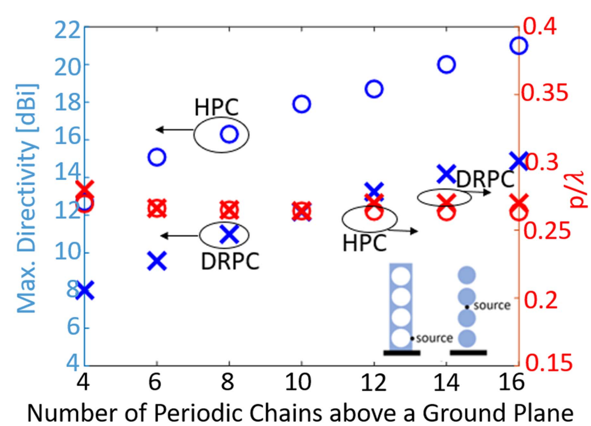


Fig. 4. Maximum directivity at broadside and the normalized frequency at which it is obtained, as a function of the number of periodic chains over a metal plate: comparison between the DRPC (cross markers) and HPC (circle markers) structures. Geometrical and dielectric parameters are the same as in Fig. 3. The position of the line source is indicated in the inset for the case of four cylinders over a metal plate.

directivities of about 2 dB, while the normalized frequency at which it is obtained remains quite stable, by increasing the number of periodic chains N_y.

IV. Highly Directive Bisected PCLWAs

A convenient LWA design based on PCs can be realized by bisecting the open waveguide described in Section III with a metal plate, in order to have a single radiated beam [8], [20]. Unit cells of the open waveguides with an even number of rods or voids, for the practical purpose of not cutting a cylinder in the bisection plane, are here considered [see the case of four rods (voids) over a metal plate in the inset of Fig. 4]. In the case of dielectric cylinders, the bisected structure selects odd modes numbered as, e.g., AM_1, AM_3,..., whereas the fundamental, i.e., AM_0, mode cannot be supported by this geometry [only the symmetries indicated by the red lines in Fig. 2(b) can be selected]. The main drawback of this configuration is that the lower order leaky air mode that can be excited in the bisected structure is the leaky AM_1, which is not the one for which the DRPC and the original open waveguide have been optimized, i.e., the leaky AM_0 [15]. In fact, the leaky AM_1 presents at broadside frequency, where phase and attenuation constants equal each other, higher values of the attenuation constant, with respect to the leaky AM_0, as can be inspected by comparing [15, Fig. 9(b)] with [20, Fig. 2] for the same DRPC open waveguide with $N_y = 16$ rods. As a result, the bisected PCLWA working on this leaky AM_1 shows moderate directivity [20]. Conversely, the HPC open waveguide with an even number of voids presents a PEC symmetry for the modes numbered with an even index, e.g., AM_0, AM_2,... Hence, the lower order leaky mode of the relevant

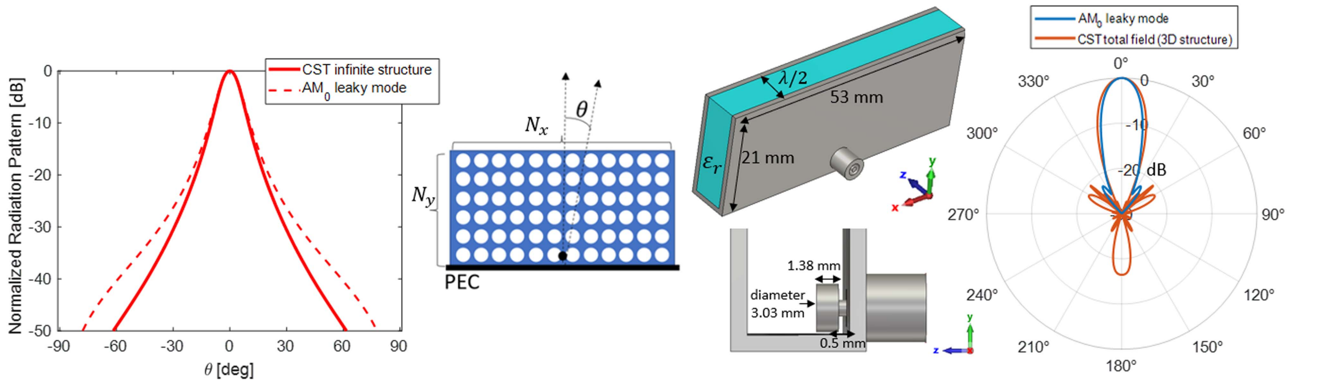


Fig. 5. (a) Normalized radiation patterns for the infinite bisected holey PCLWA composed by $N_y = 6$ periodic chains of air columns in a dielectric slab placed above a ground-plane and excited by an electric line source. Comparison between the TE AM_0 leaky mode and CST total far-field is shown in dashed and solid red lines, respectively. (b) Illustrations and details of the 3-D truncated structure and its coaxial cable feeder. (c) Comparison between the polar diagram of the leaky AM_0 and of the 3-D truncated structure sized to operate at $f = 24$ GHz ($p/\lambda = 0.2663$).

bisected structure will be the leaky AM_0, i.e., that responsible of the highest directivity at the lower edge of the HPC air band. This peculiar difference in the modal field configurations between the considered dual PC structures, i.e., the DRPC and HPC waveguides, leads to significantly different directivities in the corresponding metal-bisected PCLWAs. This important result can be vividly observed in Fig. 4, where the maximum directivities are evaluated taking into account that the antenna radiates only in the upper halfspace. In the case of bisected HPC structures, the maximum directivity is approximately 6 dB higher than that of the corresponding DRPC configurations with the same number of periodic chains, dramatically increasing the small differences already observed in the nonbisected open-waveguide configurations in Fig. 3. It is important also to note that the chosen parameters for the dielectric and holey structures allow for a fair comparison of the radiative antenna features, since a fixed operating normalized frequency, at which maximum directivity at broadside is observed, of around $p/\lambda = 0.26$ is obtained in both PCs independently of the number of periodic chains.

We consider now a bisected HPC structure consisting of $N_y = 6$ periodic chains of air columns drilled in a grounded dielectric slab with the unit-cell parameters selected in Section III. In Fig. 2(c) the normalized phase and attenuation constants, β/k_0 and α/k_0, respectively, of the improper TE leaky AM_0 and AM_2, producing forward kind of radiation [21], [22], are shown. At broadside normalized frequency [23] $p/\lambda = 0.2665$ for the leaky AM_0, where $\beta/k_0 \simeq \alpha/k_0 = 0.07$, the leaky AM_2 shows a considerably high attenuation constant and its contribution to the excited field would mainly be reactive. A very good agreement between the total field obtained in CST and the leaky AM_0 can be observed in Fig. 5(a) at normalized frequency corresponding to the maximum directivity condition $p/\lambda = 0.2663$ ($\beta/k_0 \simeq 0.05$, $\alpha/k_0 \simeq 0.11$) [23] for the infinite structure (here a directivity of about 15.1 dBi is obtained), thus confirming the dominant leaky-wave nature of the radiation. Finally, a holey 3-D PCLWA is designed by truncating the structure longitudinally (a number of unit cells in the longitudinal direction equal to $N_x = 16$ is chosen, allowing for a theoretical leaky-wave radiation efficiency of 95% [21]) and sandwiching the HPC slab between two metal plates distant each other $\lambda/2$, as shown in Fig. 5(b). A standard coaxial cable [24], with a probe protruding within the holey PCLWA and a metal disk placed on the top of the probe, both optimized for having a good matching at the operating frequency and excitation of the leaky AM_0, is used as a feeder [see Fig. 5(b)]. A return loss of 18.8 dB and a directivity of 14 dBi at the operating frequency of 24 GHz (corresponding to $p/\lambda = 0.2663$) are obtained. A back radiation level of -17 dB, slightly lower than that reported in similar 3-D lattice antennas [8], is observed. In conclusion, a very good agreement between the CST and leaky AM_0 radiation pattern, where in the latter the truncation is modeled with a physical-optics approach [25], is shown in Fig. 5(c) for the main radiated lobe.

V. Conclusion

A systematic investigation of the directive radiation by an electric line source in dielectric photonic crystals, formed by a stack of periodic chains of dielectric cylinders in free space or of circular voids in dielectric media, is performed. On the basis of a thorough physical understanding of the Bloch modal field configurations in such multimodal structures, practical design rules for obtaining highly directive leaky-wave radiation are provided. First, the normalized frequency at which directive radiation at broadside is obtained is determined by the band-gap behaviors and, in particular, by the bottom edge of the air band; hence, by the geometrical and physical parameters of the 2-D photonic crystals. Second, the directivity increases with the number of periodic chains, and, hence, with the transverse dimension of the open waveguides, in all kinds of photonic crystal structures, by leaving almost unchanged the operating frequency. Third, highly directive radiation in antennas formed by an integer number of cylinders over a metal plate can be more preferably obtained by using holey lattices than by dielectric rods, due to the persistence (elimination) of the slowly attenuating fundamental zeroth-order leaky air mode in the former (latter) configurations. All these insights and considerations easily lead to an effective design for such class of directive leaky-wave radiators. A 3-D realistic antenna, fed by a standard coaxial cable, is simulated and validates the results predicted by the adopted leaky-wave model.

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