Roma-Tre University, Rome, Italy
in framework of SYMAT - COST ACTION “Future Communications with Higher-Symmetric Engineered Artificial Materials“

Electromagnetic Band-Gap Leaky-Wave Antennas Based on Dielectric Lattices

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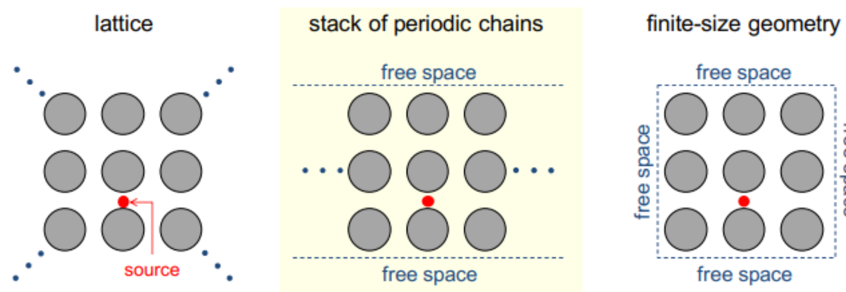
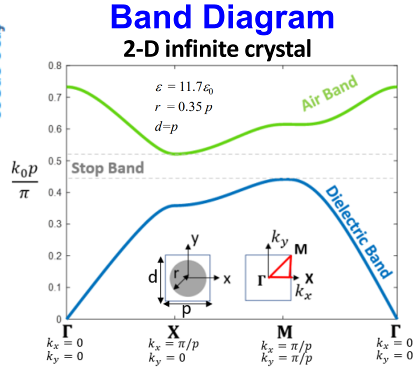
Photonic Band Gap (PBG) structures: 2-D infinite crystals, 1-D periodic open waveguides, and finite-size structures

2-D infinite crystal | **1-D periodic open waveguide** | **truncated structure**



2-D PBG structures: The radiation from 2-D lattices made with lossless dielectric cylinders, typically optimized by using the Bloch analysis of the corresponding 2-D photonic crystals, is originally investigated in terms of leaky waves.



P. Baccarelli, L. Tognolatti, V. Jandieri, S. Ceccuzzi, C. Ponti, and G. Schettini, “Leaky-wave radiation from 2-D dielectric lattices excited by an embedded electric line source”, *IEEE Trans. Antennas Propag.*, vol. 69, no. 11, 2021.

Full-wave modal solver for multilayered periodic chains

Space-harmonic complex wavenumber

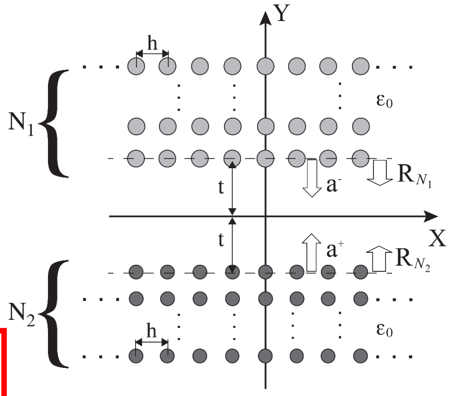
$$k_{xn} = \beta_n - j\alpha, \quad n = 0, \pm 1, \pm 2, ..$$

$$\beta_n = \beta_0 + \frac{2\pi n}{p}$$

Space-harmonic phase constant

Modal attenuation (leakage) constant

Derivation of the complex wavenumbers for bound modes in their stop-band regimes and leaky modes in their physical and non-physical regions.



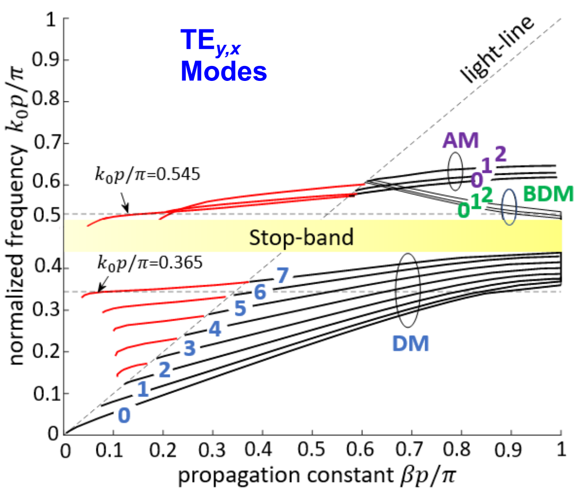
The ***proper*** or ***improper*** features can be easily determined by imposing the appropriate square root determination for the vertical wavenumber k_{yn}.

Dispersion equation for the eigenmodes

$$\det\left[\mathbf{I} - \mathbf{D}(k_{x0}) \cdot \mathbf{R}_{N_1}(k_{x0}) \cdot \mathbf{D}(k_{x0}) \cdot \mathbf{R}_{N_2}(k_{x0})\right] = 0$$

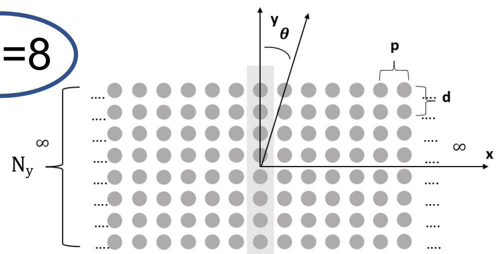
V. Jandieri, P. Baccarelli, G. Valerio, and G. Schettini, "1-D periodic lattice sums for complex and leaky waves in 2-D structures using higher order Ewald formulation," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2364–2378, Apr. 2019

Modal analysis of 1-D periodic PBG open waveguides



Brillouin diagram for the *n* = 0 and *n* = −1 space harmonics of the TE bound and leaky modes of the structure

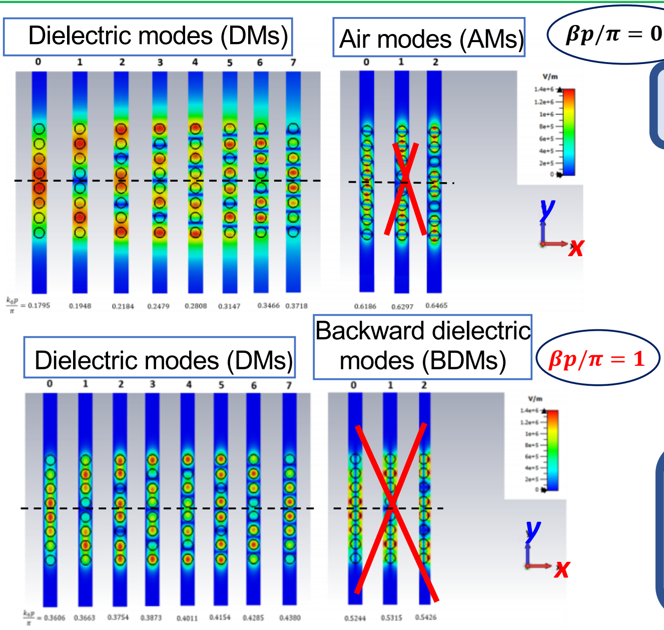
N_y=8



$\varepsilon = 11.7\varepsilon_0$
$r = 0.35\,p$
$d = p$

- At low frequencies, below the light line, **eight bound Dielectric Modes (DMs)** are observed.
- At higher frequencies, **Backward Dielectric Modes (BDMs) and Forward Air Modes (AMs)** propagate.
- Each forward and backward guided mode presents an improper or proper, respectively, leaky-wave branch in the fast-wave region on the left of the light line.
- **Highly multimodal scenario.**

PBG open waveguide: TE Modal fields and symmetries



Goal: selective excitation of only one leaky mode in absence of any other bound and/or leaky mode.

An alternation of modes with **Perfect Magnetic Conductor (PMC)** or **Perfect Electric Conductor (PEC) symmetry planes @ *y* = 0** is observed, with **AM_1** being of the former kind.

BDMs close to the highest edge of the stopband are **antisymmetric**, i.e., the electric field is maximum at the unit-cell borders and equal to zero **@ *x* = 0**.

The **existence of symmetry planes** of the lattice structures makes it possible to choose the position of the electric line source in order to excite the dominant leaky AM_1 in the absence of other guided modes.

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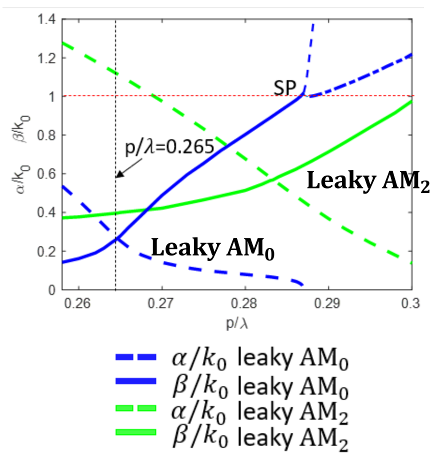
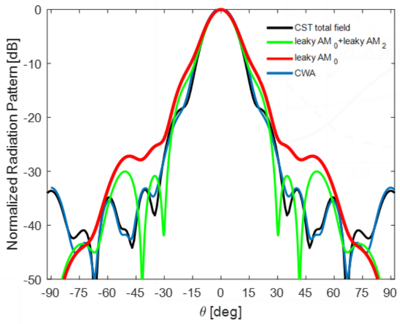
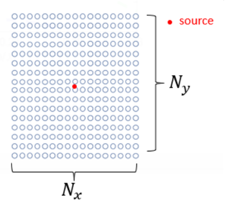
PBG open waveguide: Leaky-wave radiation

- The far-field radiated by an elementary line source embedded in the infinite PBG lattice waveguide is derived by using a suitable spectral-domain method, which also allows for **rigorously accounting for the residue contributions of the excited leaky modes** of the open waveguide.





N_y=16



$$N_x = -\ln(1-\eta_r)/2\pi\hat{p}\hat{\alpha}$$

$\hat{p}$=p/λ
$\hat{\alpha} = \alpha/k_0$

Radiation Efficiency:

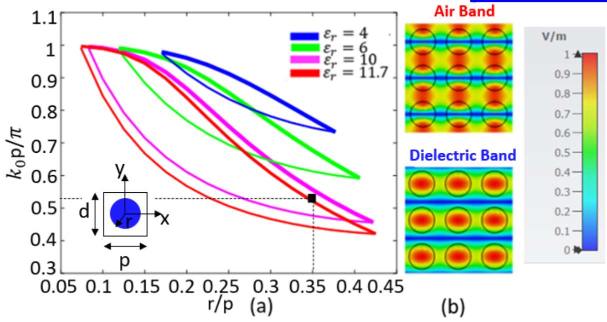
$$\eta_r = 95\%$$

N_x=17

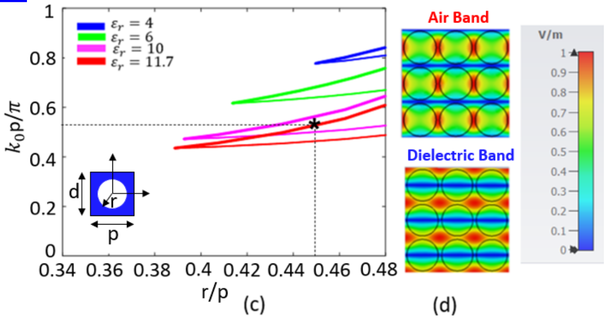
Band gaps in dielectric rod and holey PBG structures

Band-Gap Diagrams in 2-D infinite photonic crystals

Dielectric Rod Photonic Crystals (DRPCs)



Holey Photonic Crystals (HPCs)



Comparative study of the directive radiation obtained from two kinds of 2-D photonic crystal structures

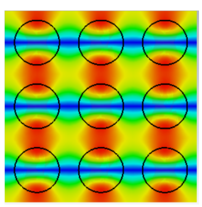
Definition of design rules to achieve highly directive leaky-wave radiation

L. Tognolatti, V. Jandieri, S. Ceccuzzi, C. Ponti, G. Schettini, and P. Baccarelli, "Highly directive leaky-wave radiation in 2-D dielectric photonic crystals," *IEEE Antennas Wireless Propag. Lett.*, Dec. 2022.

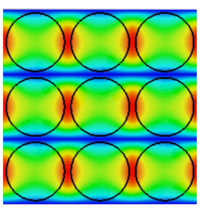
Modal fields and symmetries in dielectric rod and holey PBG structures

Air Band Modal Fields in 2-D PCs

Rods in free space

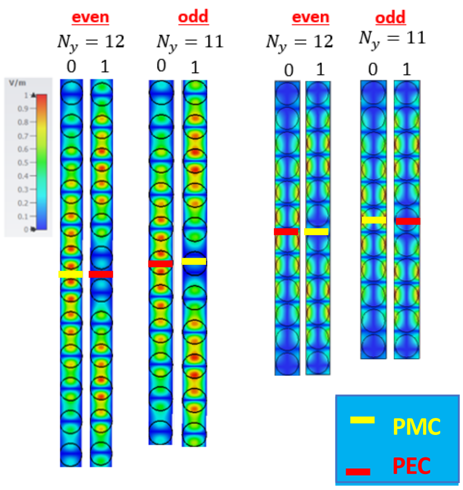


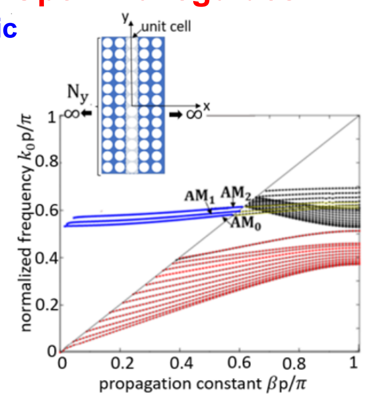
Voids in a dielectric medium



Air Modes in 1-D Periodic PBG Open Waveguides

Rods in free space — **Voids in a dielectric medium**

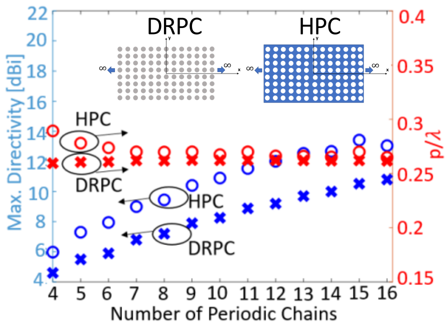




L. Tognolatti, V. Jandieri, S. Ceccuzzi, C. Ponti, G. Schettini, and P. Baccarelli, "Highly directive leaky-wave radiation in 2-D dielectric photonic crystals," *IEEE Antennas Wireless Propag. Lett.*, Dec. 2022.

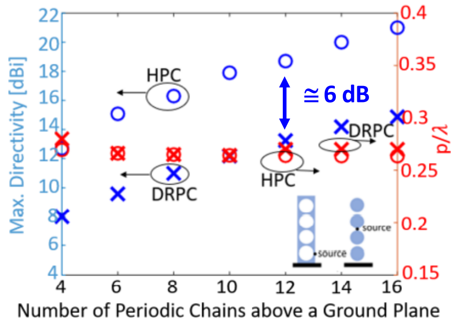
Directive leaky-wave radiation in symmetric and bisected dielectric rod and holey photonic crystal leaky-wave antennas (PCLWAs)

Simmetric Open Waveguide



DRPC r/p =0.35
HPC r/p =0.45
$\varepsilon_r = 11.7$

Metal Bisected Open Waveguide



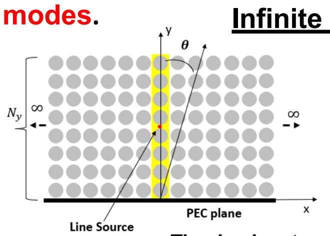
A quite stable operating normalized frequency, at which maximum directivity at broadside is observed, is obtained in both PCs independently of the number of periodic chains

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

2-D metal bisected dielectric rod PCLWA

The symmetry of the structure is exploited by bisecting it with a PEC plane and thus selecting only the **odd modes**.

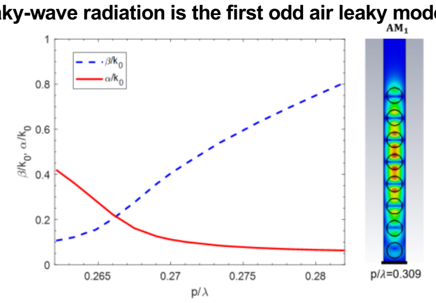
Infinite structure



The dominant mode responsible for the leaky-wave radiation is the first odd air leaky mode (AM_1).

N_y=8

$\varepsilon = 11.7\varepsilon_0$
$r = 0.35\,p$
$d=p$

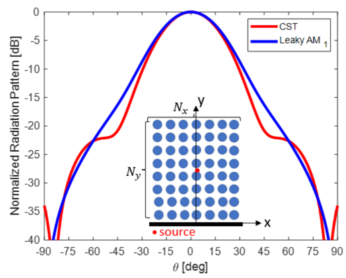


Truncated structure

Radiation Efficiency:
$\eta_r = 96\%$

$N_y = 8$
$N_x = 7$

$p/\lambda = 0.2648$



Comparison between the normalized radiation pattern obtained by CST Microwave Studio and the dominant leaky mode AM_1.

Directivity=11.0 dB

L. Tognolatti, P. Baccarelli, V. Jandieri, S. Ceccuzzi, C. Ponti, and G. Schettini, "Electromagnetic Band-Gap Leaky-Wave Antennas Based on Grounded Dielectric Lattices," *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*, 2021, pp. 1329-1330

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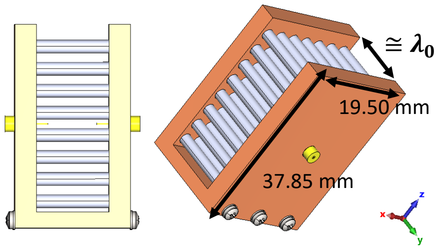
3-D LWA design

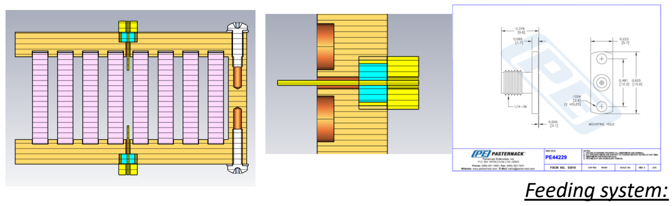
Based on the parametric studies carried out, it was also possible to design antennas with the same directivity and impedance matching at the same working frequency, but made with different dielectrics, different cylinder radius and period sizes.

The antenna is designed to operate at **f=24 GHz**.

Alumina cylinders

$\varepsilon_r = 9.8$



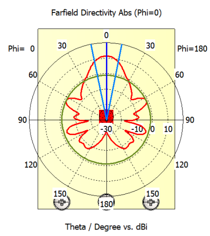


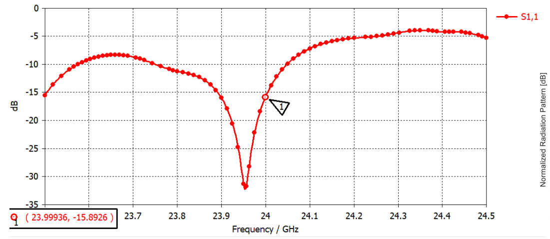
Feeding system: two monopoles with counterphase sources

Cylinder radius r=2.49/2 mm

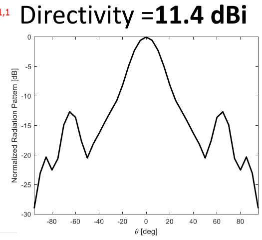
Period p=4.1 mm

Total cylinder length= 15 mm





Directivity =**11.4 dBi**



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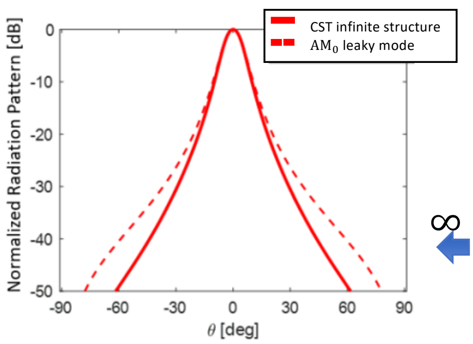
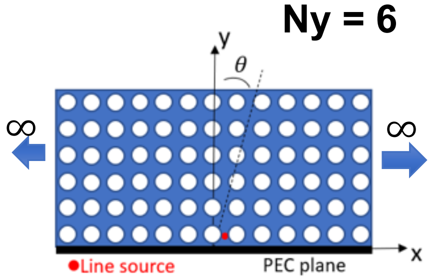
2-D Metal Bisected Holey PCLWA

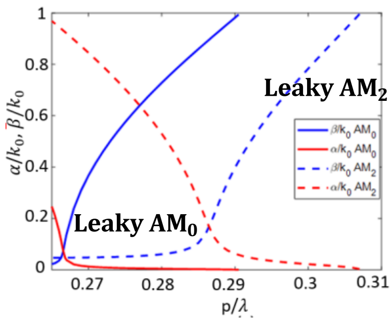
Highly directive bisected holey PCLWA



Infinite structure

Ny = 6





Directivity 15.1 dBi

$p/\lambda = 0.2663$

L. Tognolatti, V. Jandieri, S. Ceccuzzi, C. Ponti, G. Schettini, and P. Baccarelli, "Highly directive leaky-wave radiation in 2-D dielectric photonic crystals," *IEEE Antennas Wireless Propag. Lett.*, Dec. 2022.

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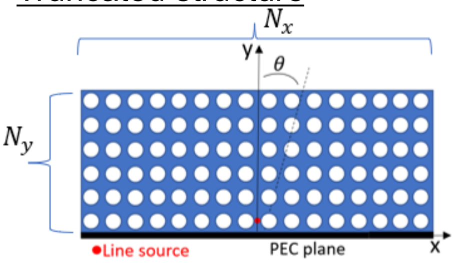
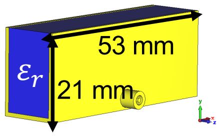
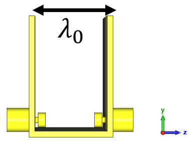
Directive Leaky-Wave Radiation in Holey Photonic Crystals

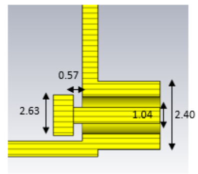
3-D Holey photonic crystal leaky-wave antenna

Truncated structure







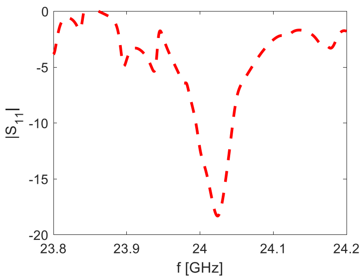


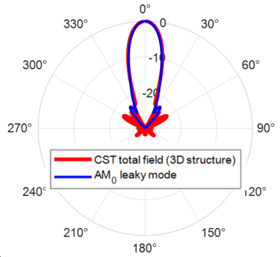
$N_x = 16$ $\eta_r = 96\%$

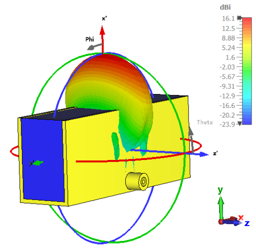
$N_y = 6$

f=24.04 GHz

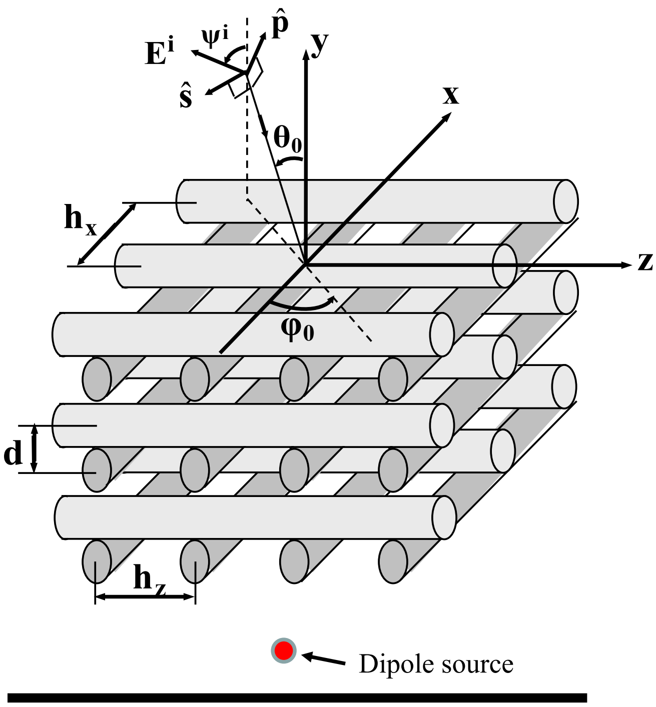
Directivity 16.1 dBi







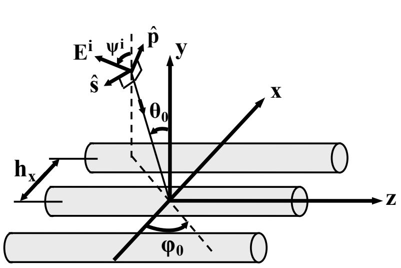
Woodpile LWAs: Extension of the modal and radiative analyses to 3-D EBG structures (1)



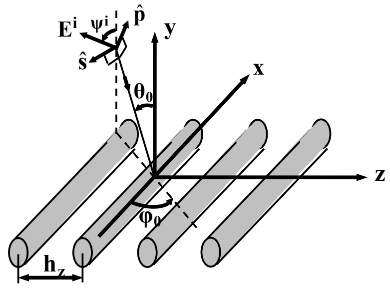
- ***A very general and rigorous approach*** to formulate the radiation from a dipole source coupled to 3-D woodpile EBGs is proposed.
- ***The dipole source is transformed into an infinite periodic array of linearly phased dipole sources in the spectral domain.*** Coupling between TM and TE scattered waves is taken into account in our formalism.
- Spectral response of woodpile EBGs to the dipole excitation is calculated using LST. The method allows us to calculate the near field of a non-periodic source excited in an infinite periodic structure.
- Complex propagation wavenumbers can be derived for both bound modes in their stop-band regimes and proper and improper leaky modes in their relevant physical and non-physical regions.

V. Jandieri, S. Ceccuzzi, P. Baccarelli, G. Schettini, D. Erni, W. Hong, D.H. Werner and K. Yasumoto, "Efficient Analysis of Radiation from a Dipole Source in Woodpile EBG Structures," *IEEE Transactions on Antennas and Propagation,* vol. 70, no. 1, pp. 389 - 400, 2022.

Woodpile LWAs: Extension of the modal and radiative analyses to 3-D EBG structures (2)



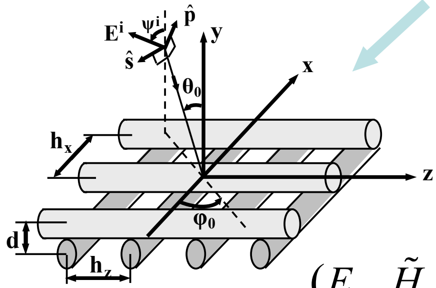
Z-array: $\mathbf{R}_{\|},\ \mathbf{F}_{\|}\ (E_z, \tilde{H}_z)$



X-array: $\mathbf{R}_{x},\ \mathbf{F}_{x}\ (E_x, \tilde{H}_x)$

Coordinate transformation

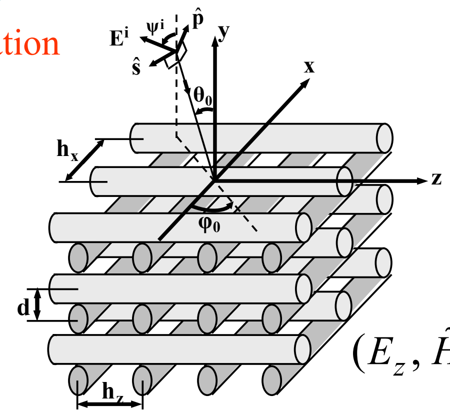
$\mathbf{R}_{\perp},\ \mathbf{F}_{\perp}$
$(E_z, \tilde{H}_z)$



$(E_z, \tilde{H}_z)$

Crossed-array: $\mathbf{R}_{\times}^{(+)}, \mathbf{F}_{\times}^{(-)}, \mathbf{R}_{\times}^{(-)}, \mathbf{F}_{\times}^{(+)}$

Stacked



$(E_z, \tilde{H}_z)$

Layered crossed-arrays

Z-array

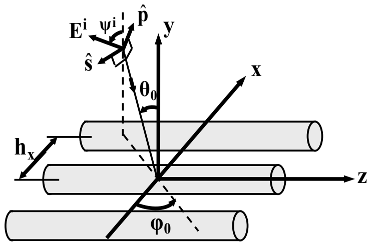
- Amplitude vectors of space harmonics

$$\mathbf{e}_z = [\mathbf{e}_z(-M)\cdots\mathbf{e}_z(0)\cdots\mathbf{e}_z(M)]^T,\ \mathbf{e}_z(m) = [e_{z,-L,m}\cdots e_{z,0,m}\cdots e_{z,L,m}]^T$$

$$\tilde{\mathbf{h}}_z = [\tilde{\mathbf{h}}_z(-M)\cdots\tilde{\mathbf{h}}_z(0)\cdots\tilde{\mathbf{h}}_z(M)]^T,\ \mathbf{h}_z(m) = [\tilde{h}_{z,-L,m}\cdots \tilde{h}_{z,0,m}\cdots \tilde{h}_{z,L,m}]^T$$

- Reflection matrix

$$\begin{bmatrix}\mathbf{e}_z^r \\ \tilde{\mathbf{h}}_z^r\end{bmatrix} = \left[\mathbf{R}_{\|}\right]\begin{bmatrix}\mathbf{e}_z^i \\ \tilde{\mathbf{h}}_z^i\end{bmatrix} = \begin{bmatrix}\mathbf{R}_{\|}^{ee} & \mathbf{R}_{\|}^{eh} \\ \mathbf{R}_{\|}^{he} & \mathbf{R}_{\|}^{hh}\end{bmatrix}\begin{bmatrix}\mathbf{e}_z^i \\ \tilde{\mathbf{h}}_z^i\end{bmatrix}$$



- Transmission matrix

$$\begin{bmatrix}\mathbf{e}_z^t \\ \tilde{\mathbf{h}}_z^t\end{bmatrix} = \left[\mathbf{F}_{\|}\right]\begin{bmatrix}\mathbf{e}_z^i \\ \tilde{\mathbf{h}}_z^i\end{bmatrix} = \begin{bmatrix}\mathbf{F}_{\|}^{ee} & \mathbf{F}_{\|}^{eh} \\ \mathbf{F}_{\|}^{he} & \mathbf{F}_{\|}^{hh}\end{bmatrix}\begin{bmatrix}\mathbf{e}_z^i \\ \tilde{\mathbf{h}}_z^i\end{bmatrix}$$

X-array

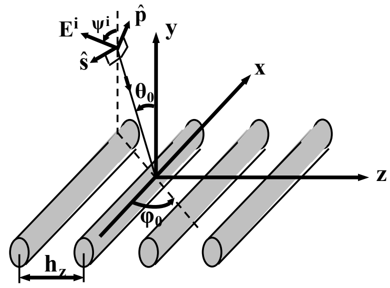
➡ Amplitude vectors of space harmonics

$$\underset{\to}{\mathbf{e}}_x = [\underset{\to}{\mathbf{e}}_x(-L)\cdots\underset{\to}{\mathbf{e}}_x(0)\cdots\underset{\to}{\mathbf{e}}_x(L)]^T,\ \underset{\to}{\mathbf{e}}_x(\ell) = [e_{x,-M,\ell}\cdots e_{x,0,\ell}\cdots e_{x,M,\ell}]^T$$

$$\underset{\to}{\tilde{\mathbf{h}}}_x = [\underset{\to}{\tilde{\mathbf{h}}}_x(-L)\cdots\underset{\to}{\tilde{\mathbf{h}}}_x(0)\cdots\underset{\to}{\tilde{\mathbf{h}}}_x(L)]^T,\ \underset{\to}{\tilde{\mathbf{h}}}_x(\ell) = [\tilde{h}_{x,-M,\ell}\cdots\tilde{h}_{x,0,\ell}\cdots\tilde{h}_{x,M,\ell}]^T$$

➡ Reflection matrix

$$\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^r\\ \underset{\to}{\tilde{\mathbf{h}}}_x^r\end{bmatrix} = [\mathbf{R}_x]\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^i\\ \underset{\to}{\tilde{\mathbf{h}}}_x^i\end{bmatrix} = \begin{bmatrix}\mathbf{R}_x^{ee} & \mathbf{R}_x^{eh}\\ \mathbf{R}_x^{he} & \mathbf{R}_x^{hh}\end{bmatrix}\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^i\\ \underset{\to}{\tilde{\mathbf{h}}}_x^i\end{bmatrix}$$

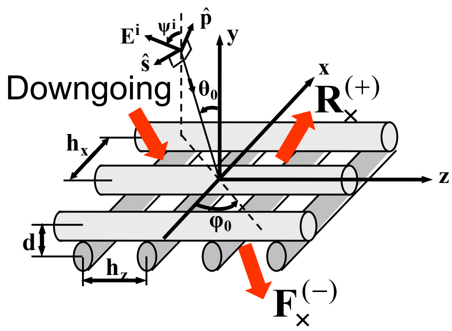


➡ Transmission matrix

$$\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^t\\ \underset{\to}{\tilde{\mathbf{h}}}_x^t\end{bmatrix} = [\mathbf{F}_x]\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^i\\ \underset{\to}{\tilde{\mathbf{h}}}_x^i\end{bmatrix} = \begin{bmatrix}\mathbf{F}_x^{ee} & \mathbf{F}_x^{eh}\\ \mathbf{F}_x^{he} & \mathbf{F}_x^{hh}\end{bmatrix}\begin{bmatrix}\underset{\to}{\mathbf{e}}_x^i\\ \underset{\to}{\tilde{\mathbf{h}}}_x^i\end{bmatrix}$$

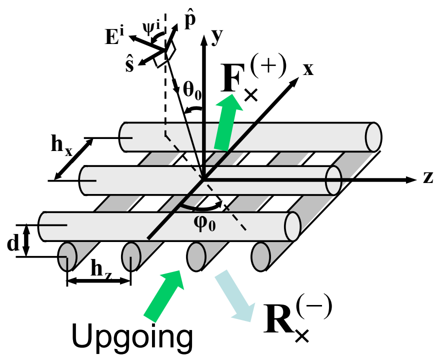
Crossed-arrays

$$\mathbf{R}_\times^{(+)} = \mathbf{R}_{\|} + \mathbf{F}_{\|}\mathbf{W}\mathbf{R}_\perp\mathbf{X}\mathbf{W}\mathbf{F}_{\|}$$
$$\mathbf{F}_\times^{(-)} = \mathbf{F}_\perp\mathbf{X}\mathbf{W}\mathbf{F}_{\|}$$



$$\mathbf{R}_\times^{(-)} = \mathbf{R}_\perp + \mathbf{F}_\perp\mathbf{W}\mathbf{R}_{\|}\mathbf{Y}\mathbf{W}\mathbf{F}_\perp$$
$$\mathbf{F}_\times^{(+)} = \mathbf{F}_{\|}\mathbf{Y}\mathbf{W}\mathbf{F}_\perp$$

$$\mathbf{X} = [\mathbf{I} - \mathbf{W}\mathbf{R}_{\|}\mathbf{W}\mathbf{R}_\perp]^{-1}$$
$$\mathbf{Y} = [\mathbf{I} - \mathbf{W}\mathbf{R}_\perp\mathbf{W}\mathbf{R}_{\|}]^{-1}.$$
$$\mathbf{W} = [\mathrm{e}^{i\gamma_\ell(m)d}\ \delta_{\ell\ell'}]$$



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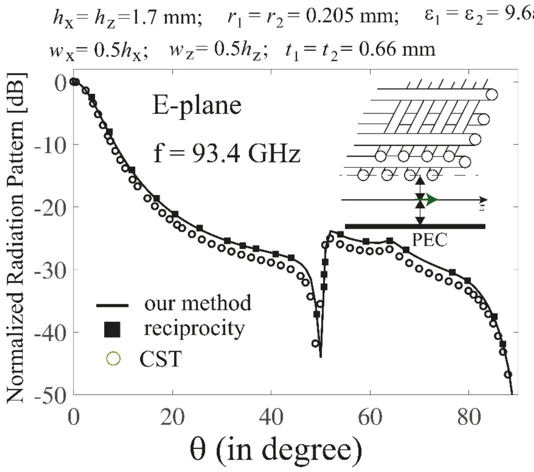

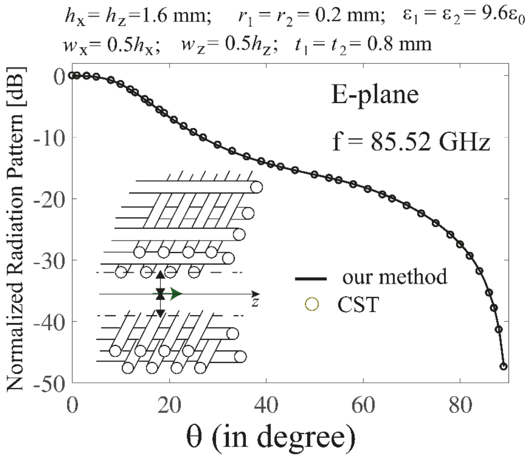

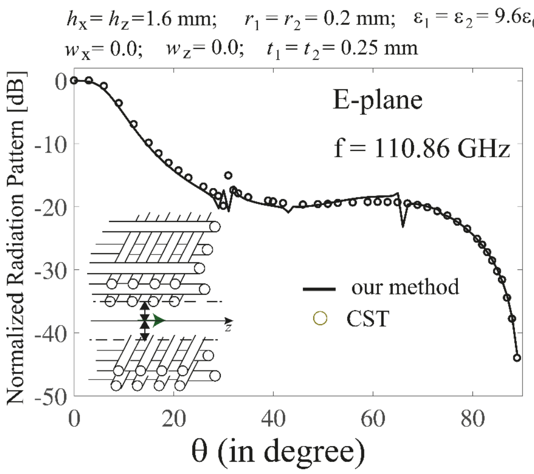

TABLE I

COMPARISON OF COMPUTATION TIME TO CALCULATE THE NORMALIZED RADIATION PATTERNS IN E-PLANE AND H-PLANE AT $\theta = 0^0$ AND $\theta = 89^0$ FOR THREE NUMERICAL EXAMPLES USING THE PROPOSED METHOD IN SECTION II AND CST.

		E-plane (Time [sec])		H-plane (Time [sec])	
	θ	Proposed Method	CST	Proposed Method	CST
Case 1	0^0	0.80	24	0.75	25
	89^0	0.95	22	0.85	21
Case 2	0^0	2.15	237	2.05	43
	89^0	2.50	204	2.10	34
Case 3	0^0	6.10	583	6.60	578
	89^0	6.90	538	7.20	546

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Conclusions

- A systematic investigation of the directive radiation by an electric line source in dielectric PBG structures, formed by stack of periodic chains of dielectric cylinders in free space or of circular voids in dielectric media, is presented.

- On the basis of an in-depth 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 bandgap 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 0-*th* order leaky air mode in the former (latter) configurations.

- All these insights easily lead to an effective design for such class of directive leaky-wave antennas.

Thank You!