This article has been accepted for publication in IEEE Open Journal of Antennas and Propagation. This is the author's version which has not been fully edited and Journal of content may change prior to final publication. Citation information: DOI 10.1109/OJAP.2025.3564352

IEEE Open Journal of content m Antennas and Propagation

Received XX Month, XXXX; revised XX Month, XXXX; accepted XX Month, XXXX; Date of publication XX Month, XXXX; date of current version XX Month, XXXX.

Digital Object Identifier 10.1109/OJAP.2020.1234567

Dielectric EBG Leaky-Wave Antenna: Design and Experimental Validation

LUDOVICA TOGNOLATTI¹ (Member, IEEE), PAOLO BACCARELLI¹ (Member, IEEE), CRISTINA PONTI¹ (Member, IEEE), SILVIO CECCUZZI², VAKHTANG JANDIERI³ (Senior member, IEEE), and GIUSEPPE SCHETTINI¹ (Senior member IEEE)

 ¹Department of Industrial, Electronic and Mechanical Engineering, Roma Tre University, 00146, Rome, Italy
²Fusion and Nuclear Safety Department, ENEA, 00044 Frascati, Italy
³Department of General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, and CENIDE-Center for Nanointegration Duisburg-Essen, D-47048, Duisburg, Germany

CORRESPONDING AUTHOR: Ludovica Tognolatti (e-mail: ludovica.tognolatti@uniroma3.it). This work was partly supported by the Italian Ministry for Education, University, and Research through the Project PRIN 2017 (WPT4WID: Wireless Power Transfer for Wearable and Implantable Devices) under Grant 2017YJE9XK005

ABSTRACT This paper proposes a novel Electromagnetic Band-Gap (EBG) leaky-wave antenna (LWA) operating in the K-band with enhanced directivity at broadside. A rigorous method that combines the analysis of the band diagrams of Bloch waves propagating within two-dimensional (2-D) EBG structures and the properties of bound and leaky modes in transversely open lattice waveguides is used to design the antenna. For the first time, a three-dimensional (3-D) realistic configuration of the EBG structure is designed, manufactured, and measured in the K-band. An effective leaky-wave approach is applied in conjunction with the use of "ad-hoc" and commercial EM full-wave software for the accurate design of the structure to be realized. The prototype consists of 7×8 alumina cylinders positioned above a ground plane and supported by two vertical metal plates. The antenna is fed by two counterphase monopoles. A rat-race hybrid junction, located just below the antenna, feeds the two monopoles. The measurements show a very good agreement with the adopted leaky-wave model. Experimental results show a broadside directivity of 12.8 dBi and a return loss of 24 dB at the frequency of f = 24.6 GHz. The design reported operates in the K-band in reason of its application for the project PRIN 2017 WPT4WID under grant 2017YJE92K005.

INDEX TERMS electromagnetic band-gap, periodic structures, photonic crystals, leaky modes, leaky-wave antenna (LWA), K-band

I. INTRODUCTION

T HE investigation of focused electromagnetic emissions from a source within two-dimensional (2-D) photonic crystals (PCs) [1], also known as electromagnetic band-gap (EBG) structures, has been conducted in lattices composed of dielectric and metallic cylinders [1]–[13]. EBGs present frequency intervals (band-gaps) where electromagnetic propagation is not allowed, in between frequency ranges where the wave equation has solutions, corresponding to the Bloch modes of the 2-D lattice. Both features have been profitably exploited to improve antenna performance, but compared to the vast literature existing on cavity antennas operating within the band-gaps of the EBG superstrates [9], [11], [13]– [18], the use of EBG modes was instead explored to a minor extent. A recent example of application of the first approach is the realization of all-dielectric artificial materials employed as superstrates of Resonant Cavity Antennas (RCAs) [19]-[21]. Cavity antennas using alumina superstrates are presented in [15], [17]. Some pioneering works on the second approach can be found in papers by Enoch et al. [4], [6], [7], where the directivity of a primary radiator was enhanced by embedding it in a square lattice of dielectric cylinders working at the lowest edge of the air band. This physical mechanism, explained in terms of dispersion diagram (i.e., eigenvalues) of the lattice, paved the way to next studies, as for example an investigation of degenerate band edges [22] and assessment of alternative lattice configurations [23]. In particular, in [9], the two methods are evaluated in terms of directivity, with reference to several optimized 2-D layered configurations, based on either square or triangular arrays of dielectric rods. Various configurations with different number of layers and rods per layer, i.e., different vertical and

VOLUME .

horizontal dimensions, respectively, have been compared, clearly demonstrating that the first mechanism (cavity) is the most effective for low-profile structures, as it delivers the highest performance with a less number of layers, despite requiring extended antenna apertures. In contrast, the second approach (embedded source) proves to be more advantageous for compact structures, i.e., taller but less extended ones, as it outperforms resonator antennas when considering reduced apertures. Regarding bandwidth and antenna efficiency, line sources embedded within the EBG demonstrate superior properties compared to the cavity method.

The group of "Roma Tre" University improved the theoretical approach and realized experimental results proposed in [8]–[10], highlighting the peculiar strengths inside X band and opportunities offered by this approach compared to metamaterials and cavity antennas. In detail, the performance of Enoch's approach was compared to the one based on bandgaps in [8]; a more comprehensive design approach based on lattice eigenmodes rather than eigenvalues was introduced in [9], and its application to realize a dual-fed antenna was presented in [10]. The position of the primary source and the use of metallic vias play a crucial role in the design of this kind of antennas, which rely on generally multi-modal periodic structures, allowing to properly excite the desired mode and suppress the unwanted ones [24].

In [25], an in-depth investigation of the radiation mechanisms of 1-D open waveguides composed by 2-D dielectric lattices has been provided in terms of leaky modes. A method based both on the analysis of the band diagrams of the Bloch modes propagating in the 2-D EBGs and the properties of bound and leaky modes in transversely open lattice waveguides have been shown to provide an interesting perspective for effective antenna analysis. Furthermore, this viewpoint proves to be greatly beneficial for both antenna design and physical comprehension, leveraging the robust tools offered by the established theory of 1-D bidirectional leaky-wave antennas (LWAs) [30]. This theory is rooted in the knowledge of the complex wavenumbers associated with leaky modes [26], [27]. A list of practical design rules for the design of metal bisected EBG LWAs showing highly directive broadside beams are provided by the authors in [28].

Bidirectional LWAs have been successfully proposed, e.g., in the form of Fabry-Perot cavity antennas, to easily provide high-gain pencil beams at broadside [30]. Recent studies in the literature have focused instead on 1-D bidirectional LWAs, which show enhanced gain in the form of a fan beam at broadside, by leveraging on the compact size and planar configuration of the microstrip technology in the microwave range [31], [32]. An array antenna exhibiting comparable gain in the broadside configuration, but operating at lower frequencies, is presented in [33], whereas an array of stacked groove gap waveguide LWAs designed to operate in Ka band is presented in [34].



FIGURE 1. Band diagram along the edge of the irreducible Brillouin zone for a square lattice of cylinders with r = 1.245 mm and dielectric constant $\varepsilon_r = 9.8$. The period is p = 4.1 mm.

In this paper, for the first time, a 3-D realistic configuration of the EBG LWA, modeled by means of the 2-D leaky-wave approach in [25], is designed, manufactured, and measured in the K-band. First, a metal bisected 2-D lattice is studied, which allows, when excited by a bidirectional source, for a directive single beam radiation at broadside by means of the first higher order leaky air mode of the original lattice. The novelty of the present contribution lies in the subsequent implementation of this concept into a 3-D open waveguide structure, where dielectric cylinders are sandwiched between two metal plates and excited by a properly phased monopole feeder, ensuring consistency with the 2-D modal analysis. The structure is designed and simulated by using both suitable "ad hoc" codes [29], [35] and general purpose full-wave EM software, e.g., CST Microwave Studio [36], showing a very good agreement with the adopted leaky-wave model. An extensive parametric analysis has been performed, by considering manufacture tolerances which can affect the permittivity and the dimension of the circular dielectric rods. Experimental results, which validate our approach, are also presented and discussed on the basis of the available parametric studies and measured performance of all the adopted devices. The ultimate design showcased operates within the K-band frequency range, chosen specifically due to its suitability for integration into a wireless power transfer system tailored for biomedical applications [37], or other industrial applications [38], but the radiation concept is promising also at higher frequencies for 5G [39] and references therein, or future applications.

The methodology presented in this work offers a novel and versatile approach that can be applied to a wide range of structures, enabling the design of antennas and sensors with enhanced radiation efficiency and directivity. The proposed procedure also provides a certain easiness of fabrication, design process and low overall complexity. Specifically,



FIGURE 2. (a) 2-D EBG structure consisting of a finite number N_y of periodic chains of circular dielectric rods spaced by a distance d along the y-direction. The rods have radius r and they are spaced p along the direction of periodicity. d = p and r/p = 0.303. The unit cell is indicated with dashed lines. (b) Brillouin diagram for the m = 0 and m = -1 space harmonics of the TE bound and leaky modes of the structure in (a). The forward (bound) dielectric modes at lower frequencies are indicated with blue lines, with the corresponding backward modes at higher frequencies as black lines. The first three forward air modes are indicated with yellow (bound modes) and the improper leaky mode with red.

by envisioning design developments based on dual "holey" structures [28], such as antennas formed by lattices of vacuum cylinders embedded in a dielectric hosting medium, we can expect to obtain significant manufacturing advantages, especially how these structures can be efficiently produced using additive manufacturing techniques.

The paper is organized as follows: in Section II the theoretical approach is described, in Section III the antenna design is presented, in Section IV the experimental results of the prototype are presented.

II. THEORETICAL 2-D MODEL

We consider an open waveguide composed by a stack (along a transverse direction) of infinite periodic chains of dielectric cylinders placed above a ground plane, as shown in Fig. 2 (a). The fundamental advantage of the model presented in [25] lies in its capacity to provide a rigorous account of radiation losses in the free space above the stack of periodic chains. This is achieved by the appropriate consideration of the leaky and bound modes propagating along the x-axis



FIGURE 3. Dispersion diagram for the leaky $\mbox{AM}_1,$ with parameters as in Fig. 1.

of the waveguide. In particular, the radiative features of the lattice structure can be rigorously described in terms of a properly excited fundamental leaky mode, whereas all the other bound and leaky modes of the open waveguide are not excited.

A typical LWA can be obtained by exploiting the modal symmetries shown in [25] and bisecting the structure with a perfect electric conductor (PEC) plane. Here, we consider a 2-D PC structure which consists of a finite number N_y of periodic chains of circular dielectric rod spaced d along the y-direction and positioned above a ground plane. The cylinders have radius r and they are spaced by a distance p along the x-direction (in this work d = p). The dielectric constant of the cylinders is assumed to be $\varepsilon_r = 9.8$ and the ratio of their radius to the period of the structure is equal to r/p = 0.303.

Brillouin diagram for the m = 0 and m = -1 space harmonics of the TE bound and leaky modes of the structure is shown in Fig. 2 (b). The forward (bound) dielectric modes at lower frequencies are indicated with blue lines, with the corresponding backward modes at higher frequencies as black lines. The first three forward air modes are indicated with yellow (bound modes) and the improper leaky mode with red. The band diagram along the edge of the irreducible Brillouin zone for the square lattice corresponding to the structure of Fig. 2 (a) is illustrated in Fig. 1. The complete bandgap region extends from $k_0 p/\pi = 0.5$ to $k_0 p/\pi = 0.65$, which is in very good agreement with the stopband of the relevant 1-D periodic open waveguide in Fig. 2(b), since a bound mode of the open waveguide cannot propagate if all the plane waves of the 2-D lattice lie within the complete bandgap region.

Figure 3 shows the normalized phase and attenuation constants of the dominant leaky air mode AM_1 , obtained with the rigorous full-wave modal solver developed in [29],

VOLUME,



FIGURE 4. Comparison between CST total field (2-D and 3-D model) and the theoretical leaky-wave pattern of the leaky AM₁ ($p/\lambda = 0.328$). $N_x = 7$ and $N_y = 8$ in the 2-D model. In the 3-D model the dimensions are $21.50 \times 39.8 \times 28.7$ mm.

[40]. The complex multimodal behavior exhibited by this type of lattice waveguide may pose challenges in optimizing focused leaky-wave radiation. Specifically, an important characteristic of LWAs is the ability to excite a single dominant leaky mode at a given operating frequency, without interference from other bound or leaky modes supported by the structure. The existence of multiple leaky modes would lead to the formation of undesired beams pointing in different directions. Additionally, simultaneously exciting bound modes alongside the leaky modes would significantly reduce the efficiency of the LWA or cause unwanted spurious radiation at the truncation in real-world applications. However, unwanted effects can be reduced by choosing the source location appropriately as shown by the detailed modal analysis in [25].

The condition for maximum radiation power density at broadside, i.e., $\beta = \alpha$, which corresponds to the main beam on the verge of splitting into two separate beams (beam-splitting condition) [41], occurs at $p/\lambda = 0.328$. The normalized complex leaky-mode wavenumber at the normalized broadside frequency is $k_x/k_0 = 0.124 - j0.131$. The source is located in the middle of the unit cell (see Fig. 2 (a)).

Generally, the design of a LWA is based on the radiative behavior of a dominant leaky mode, which once excited by a suitable source, should radiate at least 90% of the injected power before reaching the antenna truncation. Indeed, on the basis of knowledge of the attenuation constant of the leaky AM₁ it is possible to truncate longitudinally the structure to have a desired radiation efficiency through the well-known formula $N_x = -ln(1 - \eta_r)/2\pi\hat{p}\hat{a}$ [30], where $\hat{p} = p/\lambda$ and the attenuation constant $\hat{a} = a/k_0$. In this case, to obtain a radiation efficiency of $\eta_r = 96$ % we take $N_x = 7$. The comparison between the theoretical leaky-wave pattern, obtained through a standard analytical formulation for a



FIGURE 5. Proposed 3-D EBG LWA. The structure consists of 56 alumina rods ($\varepsilon_r = 9.8$) supported by two metal walls. The dimensions are $21.50 \times 39.8 \times 28.7$ mm. The cylinders have radius r = 1.245 mm and the period is p = 4.1 mm. (b) Details of the feeding system. The structure is fed by two monopoles in counterphase.

truncated bidirectional LWA [30], and the total field for the 2-D model, obtained with the commercial electromagnetic simulator software CST Studio Suite, is shown in Fig. 4 with solid green and dashed red curves, respectively, demonstrating a very good agreement.

III. 3-D EBG LWA DESIGN AND FABRICATION

In this Section the design of a realistic 3-D implementation of the 2-D LWA modeled in Sec. II is performed carefully considering the manufacturing details for both the dielectric EBG antenna and the chosen feeder configuration.

The proposed 3-D structure, designed to operate in the K-band and sketched in Fig. 5, consists of 7×8 alumina rods with nominal dielectric permittivity of $\varepsilon_r = 9.8$. The cylindrical rods, of radius r = 1.245 mm, are placed above a ground plane and are embedded in two metal walls which are intended to mimic the 2-D environment. The cylinder spacing is equal to p = 4.1 mm. The size of the structure, dimensioned to operate at f = 24 GHz, is $21.5 \times 39.8 \times 28.7$ mm. A distance between the two metal walls is 13.5 mm, which roughly corresponds to the wavelength λ . The antenna is fed by two counterphase monopoles to maintain the symmetry of the radiation pattern and avoid the excitation of higher-order modes not included in the 2-D modeling presented in Section II. In fact, if we had chosen a distance between the metal plates slightly less than $\lambda/2$ and fed the structure with a single probe, a very narrow band structure with a non-symmetric beam would have been obtained in our





FIGURE 6. (a) Side view and (b) bottom view of the antenna prototype.



FIGURE 7. Comparison between measured and simulated broadside directivity and gain as a function of frequency in the range $f=23.5-25\,$ GHz.

implementation. A couple of 2.92 mm coaxial connectors used to feed two metallic pins, acting as monopoles, are constructed as shown in Fig. 5. The length and diameter of the monopoles have been appropriately chosen to achieve impedance matching in the low mm-Wave range. In particular, the radius of the monopole is 0.21 mm, while the height, relative to the side wall, is 2.23 mm. A rat-race 3-dB hybrid junction, positioned below the structure, as shown in Fig. 5, feeds the two monopoles to obtain adequate excitation of the designed antenna. In the manufacturing process, the cylinders were put by drilling holes in one of the two metal walls and inserting a conductive resin (shown in grey in Fig.

VOLUME,



FIGURE 8. Parametric studies on manufacturing tolerances. Comparison of broadside directivity as a function of frequency for different values of the relative dielectric constant of the cylinders (nominal radius is r = 1.245 mm).

5). Figure 6 shows the side and bottom views of the realized prototype.

The 3-D structure was simulated by using CST Studio Suite. The comparison between the theoretical 2-D leakywave model presented in Section II and the total field radiated by the simulated 3-D antenna, using the same geometrical and electrical parameters of the model, is illustrated in Fig. 4 as a dashed blue curve, obtaining a very good agreement.

The radiation pattern (H-plane) of the simulated 3-D structure shows a half power beam width (HPBW) of 28° and a sidelobes level SLL = -16.5 dB.

IV. SIMULATED AND MEASURED RESULTS

The antenna was built by Systems Developments and Support S.r.l (SDS) and measured by Microwave Vision Group (MVG) Italy with the multi-probe system StarLab.

Figure 7 shows the measured broadside directivity and gain as a function of frequency in the range 23.5 < f < 25 GHz. From the measurements, it can be observed that the peak values of broadside directivity and gain do not occur at the design frequency of f = 24 GHz, but rather at a slightly higher frequency, specifically at f = 24.6 GHz. In addition to the frequency shift, a difference of about 3 dB between the broadside gain versus directivity can be observed. Indeed, at f = 24.6 GHz the measured directivity and gain are 12.7 and 9.7 dBi, respectively.

Afterwards, a tolerance analysis of the structure was conducted to investigate the underlying cause of the frequency shift of the directivity peak. Several parametric studies were conducting using CST Microwave Studio.

At first, a study was conducted on the tolerances related to the dielectric constant of the cylinders. Figure 8 shows the variation of broadside directivity as a function of frequency for different values of the dielectric constant. Considering



FIGURE 9. Parametric studies on manufacturing tolerances. Comparison of broadside directivity as a function of frequency for different values of cylinder radius ($\varepsilon_r = 9.2$).



FIGURE 10. Measurement of \mathbf{S}_{ij} between the input and each of the outputs of the rat-race.



FIGURE 11. Amplitude in dB of the measured reflection coefficient.

a variation from $\varepsilon_r = 9$ to $\varepsilon_r = 9.8$, a frequency negative shift of approximately 0.8 GHz in the peak directivity is observed. The dielectric constant value corresponding to the case where the broadside directivity peak occurs at f = 24.6GHz is $\varepsilon_r = 9.2$, which is within the 6% tolerance for the dielectric permittivity of the manufactured circular rods.

Regarding the tolerance on the cylinder radii, specific measurements were performed on the samples, and 56 cylinders with radii closest to the nominal radius, denoted as r = 1.245 mm, were selected for the prototype. However, we also tested the effects of varying the radius dimension from the nominal one. Hence, a parametric study was performed on the tolerance for the radii at the dielectric constant value ($\varepsilon_r = 9.2$) for which the broadside directivity profile most closely matches the measured one (Fig. 8). Figure 9 shows the variation of broadside directivity as a function of frequency for different values of the cylinder radii. Specifically, the nominal radius, denoted as r = 1.245mm, and a tolerance of $\pm 1\%$, were considered. A down and up shift in frequency of the curves of the broadside directivity has been observed for radii larger and smaller than the nominal one, respectively. A variation of the radius values by $\pm 1\%$ corresponds to a frequency shift of ∓ 0.2 GHz.

Figure 10 shows the measurements of the transmission coefficient S_{ij} between the input port and each of the two coupled output ports of the rat-race positioned below the antenna. It is possible to observe that the magnitudes are very close to 5 dB, instead of being close to the nominal 3 dB value. This corresponds to a loss of about 2 dB that is internally dissipated in the rat-race and affects the gain result, as shown in Fig. 7. The measured reflection coefficient in the frequency band between 23.5 and 25 GHz is shown in Fig. 11. At f = 24.6 GHz it assumes a value of $|S_{11}| = -24$ dB. The impedance matching bandwidth at -15 dB is 190 MHz.

Following the analysis of the several parametric numerical studies conducted on the tolerances, we decided to compare the measurement results with the case where the dielectric constant of the cylinders is $\varepsilon_r = 9.2$ and their radius is equal to the nominal value r = 1.245 mm.

The comparison between the measured and simulated, at $\varepsilon_r = 9.2$ and r = 1.245 mm, radiation patterns (E-plane and H-plane) is shown in Fig. 12. Specifically, Fig. 12 (a) shows the normalized radiation pattern of the directivity at f = 24.6 GHz in the H-plane. The measured H-plane sidelobes level is SLL = -11 dB, which is higher than the simulated one. The cross-polarization level, at broadside, is -24 dB. The half power beam width (HPBW) is 27°, in perfect agreement with the simulated one. The measured co-polar and the cross-polar components on the H-plane are indicated in red and green, respectively. Figure 12 (b) shows the normalized radiation pattern of the directivity in the E-plane. Figures 12 (c) and (d) show the normalized radiation pattern of the gain in the H- and E-plane, respectively. An overall good agreement

VOLUME .



FIGURE 12. Simulated and measured normalized radiation pattern at f = 24.6 GHz: directivity in the (a) H-plane and (b) E-plane; gain in the (c) H-plane and (d) E-plane. The measured broadside directivity is 12.7 dBi, 1.5 dBi below the simulated one.

between measured and simulated results is observed for the realized 3-D EBG LWA, where misalignment with respect to the ideal model is within the manufacturing tolerances.

V. CONCLUSION

In this paper an Electromagnetic Band-Gap leaky-wave antenna optimized for K-band has been presented. A rigorous design approach integrating analysis of Bloch-wave band diagrams within 2-D photonic crystals and properties of bound and leaky modes in transversely open lattice waveguides has been adopted. The structure consists of 7×8 alumina cylinders positioned above a ground plane and supported by two metal walls, mimicking the 2-D environment. A feeding system consisting of two counterphase monopoles has been designed. The structure has been fabricated and measured, showing a very good agreement with the adopted leaky-wave model. Experimental results, which validate our approach, have also been presented. In future works, the possibility of exploiting holey lattices will be considered. They are more effective for achieving highly directive radiation, primarily due to the excitation of a weakly attenuated fundamental leaky mode. Additionally, the study will explore the potential

to reduce the relative permittivity of the dielectric medium while maintaining the same key leaky-wave radiative properties. These holey structures can offer significant advantages in terms of 3-D printing manufacturing process and lower complexity.

ACKNOWLEDGMENT

The authors would like to thank Systems Developments and Support S.r.I (SDS) for the realization of the antenna and Microwave Vision Group (MVG) Italy for the antenna measurements. This work was supported in part by the Italian Ministry for Education, University, and Research through the project PRIN2017 (WPT4WID: Wireless Power Transfer for Wearable and Implantable Devices) under Grant 2017YJE9XK005.

REFERENCES

- J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the Flow of Light, 2nd ed., Princeton*, NJ, USA: Princeton Univ. Press, 2008.
- [2] Y. Rahmat-Samii and H. Mosallaei, "Electromagnetic band-gap structures: Classification, characterization and applications," in *Proc. Inst. Elect. Eng.-ICAP Symp.*, 2001, pp. 560–564.

- [3] D. Sievenpiper, M. Sickmiller, and E. Yablonovitch, "3D wire mesh photonic crystals," *Phys. Rev. Lett.*, vol. 76, no. 14, p. 2480, 1996.
- [4] S. Enoch, G. Tayeb, P. Sabouroux, N. Guerin, and P. Vincent, "A metamaterial for directive emission," *Phys. Rev. Lett.*, vol. 89, no. 21, 2002, Art. no. 213902.
- [5] P. A. Belov et al., "Strong spatial dispersion in wire media in the very large wavelength limit," *Phys. Rev. B, Condens. Matter*, vol. 67, no. 11, Mar. 2003, Art. no. 113103.
- [6] S. Enoch, G. Tayeb, and D. Maystre, "Dispersion diagrams of Bloch modes applied to the design of directive sources," *Prog. Electromagn. Res.*, vol. 41, pp. 61–81, 2003.
- [7] S. Enoch, G. Tayeb, and B. Gralak, "The richness of the dispersion relation of electromagnetic bandgap materials," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2659–2666, Oct. 2003.
- [8] S. Ceccuzzi, C. Ponti, and G. Schettini, "Directive EBG antennas based on lattice modes," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1691–1699, Apr. 2017.
- [9] S. Ceccuzzi, L. Pajewski, C. Ponti, and G. Schettini, "Directive EBG antennas: A comparison between two different radiating mechanisms," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5420-5424, Oct. 2014.
- [10] S. Ceccuzzi, P. Baccarelli, C. Ponti, and G. Schettini, "Effect of source position on directive radiation in EBG structures with epsilon-near zero behavior," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 6, pp. 1253-1257, June 2019.
- [11] Y. Ju Lee, J. Yeo, R. Mittra, and W. S. Park, "Application of electromagnetic bandgap (EBG) superstrates with controllable defects for a class of patch antennas as spatial angular filters," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 224–235, Jan. 2005.
- [12] F. Frezza, L. Pajewski, E. Piuzzi, C. Ponti, and G. Schettini, "Radiation enhancement properties of an X-band woodpile EBG and its application to a planar antenna," *Int. J. Antennas Propag.*, vol. 2014, pp. 1–15, Jan. 2014.
- [13] C. Ponti, P. Baccarelli, S. Ceccuzzi, and G. Schettini, "Tapered all dielectric EBGs with 3-D additive manufacturing for high-gain resonant cavity antennas," *IEEE Trans. Antennas Propag.*, vol. 69, no. 5, pp. 2473–2480, May 2021.
- [14] C. Ponti, S. Ceccuzzi, P. Baccarelli and G. Schettini, "A resonantcavity antenna with high-gain and wide bandwidth with an alldielectric 3D-printed superstrate," *IEEE Access*, vol. 12, pp. 111982-111991, 2024.
- [15] A. R. Weily, L. Horvath, K. P. Esselle, B. C. Sanders, and T. S. Bird, "A planar resonator antenna based on a woodpile EBG material," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 216–223, Jan. 2005.
- [16] F. Frezza, L. Pajewski, E. Piuzzi, C. Ponti, and G. Schettini, "Analysis and experimental characterization of an alumina woodpile-covered planar antenna," in *Proc. 40th Eur. Microw. Conf.*, Sep. 2010, pp. 200–203.
- [17] Y. Lee, X. Lu, Y. Hao, S. Yang, J. R. G. Evans, and C. G. Parini, "Low-profile directive millimeter-wave antennas using free-formed threedimensional (3-D) electromagnetic bandgap structures," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 2893–2903, Oct. 2009.
- [18] Y. Ge, K. P. Esselle, and T. S. Bird, "The use of simple thin partially reflective surfaces with positive reflection phase gradients to design wideband, low-profile EBG resonator antennas," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 743–750, Feb. 2012.
- [19] T. Hayat, M. U. Afzal, F. Ahmed, S. Zhang, K. P. Esselle, and Y. Vardaxoglou, "Low-cost ultrawideband high-gain compact resonant cavity antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, pp. 1271–1275, 2020.
- [20] T. Hayat, M. U. Afzal, A. Lalbakhsh, and K. P. Esselle, "3-D-printed phase-rectifying transparent superstrate for resonant-cavity antenna," *IEEE Antennas Wireless Propag. Lett* vol. 18, pp. 1400–1404, 2019.
- [21] A. A. Baba, R. M. Hashmi, M. Attygalle, K. P. Esselle, and D. Borg, "Ultrawideband beam steering at mm-wave frequency with planar dielectric phase transformers," *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 1719–1728, Mar. 2022.
- [22] S. Yarga, K. Sertel and J. L. Volakis, "A Directive Resonator Antenna Using Degenerate Band Edge Crystals," *IEEE Trans. Antennas Propag.*, vol. 57, no. 3, pp. 799-803, March 2009.
- [23] L. Pajewski, L. Rinaldi, and G. Schettini, "Enhancement of directivity using 2-D electromagnetic crystals near the band-gap edge: a full-wave approach," *Progr. Electromagn. Res.*, vol. 80, pp. 179-196, 2008.

- [24] S. Ceccuzzi, P. Baccarelli, C. Ponti, L. Tognolatti, and G. Schettini, "On the input impedance of probe-fed electromagnetic bandgap antennas based on lattice modes," *IET Microw. Antennas Propag.*, vol. 16, no. 14, pp. 847-859, Sept. 2022.
- [25] 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, pp. 7404–7418, Nov. 2021.
- [26] T. Tamir and A. A. Oliner, "Guided complex waves. Part 1: Fields at an interface," *Proc. Inst. Electr. Eng.*, vol. 110, no. 2, pp. 310–324, 1963.
- [27] T. Tamir and A. A. Oliner, "Guided complex waves. Part 2: Relation to radiation patterns," *Proc. Inst. Electr. Eng.*, vol. 110, no. 2, pp. 325–334, 1963.
- [28] 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 Wirel. Propag. Lett.*, vol. 22, no. 4, pp. 819-823, Apr. 2023.
- [29] 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, n. 4, pp. 2364-2378, 2019.
- [30] D. R. Jackson and A. A. Oliner, "Leaky-wave antennas", in *Modern Antenna Handbook*, C. A Balanis, ed. New York, NY, USA: Wiley, 2008, ch. 7.
- [31] H. D. Li and L. Zhu, "A standing-wave microstrip leaky-wave antenna on EH₁/EH₃ modes with enhanced broadside gain," *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 11313-11323, 2022.
- [32] H. D. Li and L. Zhu, "Compact EH₀-mode microstrip leaky-wave antenna with enhanced gain in broadside," *IEEE Trans. Antennas and Propag*, vol.70, no. 3, 2022.
- [33] K.E. Kedze et al., "Application of metamaterial wall for mutual coupling mitigation of a dual differential fed 2x 2 patch array antenna," *IEEE Access*, vol. 12, pp. 151251-151260, Oct. 2024.
- [34] N. Castro and E. R. Iglesias, "Array of stacked groove gap waveguide leaky wave antennas for the synthesis of a broad-beam radiation pattern," *IEEE Trans. Antennas Propag.*, vol. 73, no. 3, pp. 1515-1522, March 2025.
- [35] V. Jandieri, K. Yasumoto, and H. Toyama, "Radiation from a line source placed in two-dimensional photonic crystals", J. Infrared Millim. Terahertz Waves, vol. 28, pp. 1161-1173, 2007.
- [36] (2024). CST, Computer Simulation Technology GmbH. [Online]. Available: https://www.cst.com
- [37] A. Costanzo et al., "Wireless Power Transfer for Wearable and Implantable Devices: a Review Focusing on the WPT4WID Research Project of National Relevance," 2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS), Rome, Italy, 2021, pp. 1-4.
- [38] Y. He, K. Ma, N. Yan, Y. Wang, and H. Zhang, "A cavity-backed endfire dipole antenna array using substrate-integrated suspended line technology for 24 GHz band applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4678-4686, Sept. 2018.
- [39] S. Kumar, A. S. Dixit, R. R. Malekar, H. D. Raut and L. K. Shevada, "Fifth Generation Antennas: A Comprehensive Review of Design and Performance Enhancement Techniques," *IEEE Access*, vol. 8, pp. 163568-163593, 2020.
- [40] V. Jandieri, P. Baccarelli, G. Valerio, K. Yasumoto, and G. Schettini, "Modal propagation in periodic chains of circular rods: Real and complex solutions," *IEEE Photon. Technol. Lett.*, vol. 32, no. 17, pp. 1053–1056, Sep. 1, 2020.
- [41] G. Lovat, P. Burghignoli, and D. R. Jackson, "Fundamental properties and optimization of broadside radiation from uniform leaky-wave antennas," *IEEE Trans. Antennas Propag.*, vol. 54, no. 5, pp. 1442–1452, May 2006.





LUDOVICA TOGNOLATTI (Member, IEEE) was born in Rome, Italy, in April 1994. She received the B.S. degree and M.S. degree (summa cum laude) in electronic engineering froma Roma Tre University, in 2017 and 2019, respectively. She received the PhD (with Doctor Europaeus label) in Applied Electronics at Roma Tre University in May 2023. Since April to July 2022, she was a visiting PhD student at KTH Royal Institute of Technology, Stockholm, Sweden. Her current research interest include periodic structures, nu-

merical methods, leaky-wave antennas, EBG antennas and electromagnetic scattering. She is currently an assistant professor (not-tenure track position) at Roma Tre University. She was a recipient of the Young Scientist Award (YSA) at the 4th URSI Atlantic Radio Science Meeting, Gran Canaria, Spain. She is a member of the Italian National Electromagnetic Society (SIEm)



PAOLO BACCARELLI(Member,IEEE) received the Laurea degree in electronic engineering and the Ph.D. degree in applied electromagnetics from the "La Sapienza" University of Rome, Rome, Italy, in 1996 and 2000, respectively. From April 1999 to October 1999, he was a Visiting Researcher with the University of Houston, Houston, TX, USA. In 2000, he joined the Department of Electronic Engineering at "La Sapienza" University of Rome, where he was an Assistant Professor from November 2010 to June 2017. In 2017, he joined

the Department of Engineering, University of "Roma Tre", Rome, Italy, where he was an Associate Professor, from July 2017 to October 2023. In November 2023, he achieved the role of a Full Professor in the sector of electromagnetic fields with the Department of Industrial, Electronic, and Mechanical Engineering, University of "Roma Tre". He has co-authored more than 300 papers in international journals, conference proceedings, and book chapters. His research interests include the analysis and design of leaky-wave antennas and arrays, numerical methods for integral equations and periodic structures, propagation and radiation in anisotropic media, metamaterials, graphene, and electromagnetic bandgap structures. He has been a member of the TPCs of several international conferences. He was the Secretary of the EuMW 2009 and a member of the Local Organizing

Committee of the XXXIV URSI GASS 2021.



CRISTINA PONTI (Member, IEEE) received the Laurea (cum laude) and Laurea Magistralis (cum laude) degrees in electronic engineering from the Sapienza University of Rome, Rome, Italy, in 2004 and 2006, respectively, and the received the Ph.D. degree in biomedical engineering, electromagnetism, and telecommunications from Rome Tre University, Rome, Italy, in March 2010. In 2006, she joined the Applied Electronics Department, Rome Tre University, where she is an Associate Professor in in electromagnetic fields. In 2023, she

received the National Scientific Qualification for the role of Full Professor of electromagnetic fields in Italian universities. Her main research interests are in electromagnetic analysis, scattering problems, buried-objects detection, ground penetrating radar, through-the-wall radar, numerical methods, electromagnetic-bandgap materials, antennas, and microwave components for high-power applications. She has coauthored more than 100 articles, in international journals, conference proceedings and book chapters. She is an Associate Editor of IET Microwaves, Antennas and Propagation. She has been a Co-Convener of several conference sessions on the theme of scattering and antennas, and served in the technical program committees of international conferences. She is a member of the IEEE Transactions on Antennas and Propagation, Microwave Theory and Technique, and Women in Engineering Societies, National Interuniversity Consortium for Telecommunications (CNIT), Italian Society of Electromagnetics (SIEm).



SILVIO CECCUZZI was born in Rome, Italy, in 1983. He received the Laurea di Primo Livello and Laurea Specialistica (cum laude) degree in electronic engineering and the Ph.D. degree in applied electronics from Rome Tre University, Rome, Italy, in 2005, 2008, and 2015, respectively.

He did an Internship with Telespazio, Rome, and Thales Alenia Space, Rome, in 2009. He started a three-year scholarship on high-power RF systems across European Labs. In 2013, he joined as a Researcher with the Italian Energy and Environ-

ment Agency, Frascati, Italy, where in 2021, he became responsible for the ion-cyclotron heating system of the Divertor Tokamak Test facility. Since 2016, he has been a Visiting Researcher with Rome Tre University. He has authored or coauthored more than 150 works on technical reports, journals, and conference proceedings. His current research interests include EBG, microwave components, and nuclear fusion.

Dr. Ceccuzzi received the 2015 IEEE MTT-S Award of the Chapter Central and Southern Italy and the Sannino Award of the Italian meeting RiNEm 2012.



VAKHTANG JANDIERI(Senior Member, IEEE) (M'08 SM'14) received the "Doctor of Engineering" degree specializing in Computer Science and Communication Engineering at Kyushu University, Fukuoka, Japan, in 2006. In 2007 - 2010 he was with Kumamoto University, Kumamoto, Japan as Post-doctoral JSPS (Japanese Society for Promotion of Science) Fellow. He was visiting Professor at School of Electronics Engineering and Computer Science, Kyungpook National University, Republic of Korea in 2010 - 2013, at

Nanotechnology Centre, Technical University of Ostrava, Czech Republic in 2015, at Department of Engineering, Roma Tre University, Italy in 2015. Dr. Jandieri is a recipient of paper prize from IEEJ (Institute of Electrical Engineers of Japan) in 2004 and URSI Young Scientist Award in 2010. He is recipient of two Fulbright Awards at University of Illinois at Urbana-Champaign, USA, in 2015 - 2016 and the Pennsylvania State University, USA, in 2021. Dr. Jandieri is also recipient of Alexander von Humboldt Award at the University of Duisburg-Essen, Germany, in 2016 - 2018. Now, he is with General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, and CENIDE - Center for Nanointegration Duisburg-Essen, Duisburg, Germany. Dr. Jandieri's research interests are in electromagnetic wave theory, analytical and numerical techniques on microwave and optical photonic crystal devices. Dr. Jandieri is a Senior member of IEEE and OSA.



GIUSEPPE SCHETTINI(Senior Member, IEEE) received the Laurea degree (cum laude) in electronic engineering, the Ph. D. degree in applied electromagnetics, and the Laurea degree (cum laude) in physics from "La Sapienza" University of Rome, Rome, Italy, in 1986, in 1991, and 1995, respectively. Upon his graduation in electronic engineering he joined the Italian Energy and Environment Agency (ENEA), where he was initially involved with free electron generators of millimeter waves and then on microwave compo-

nents and antennas for heating of thermonuclear plasmas. In 1992 he joined "La Sapienza" University as Researcher of electromagnetics. In 1998, he joined the Department of Applied Electronics, of "Roma Tre" University of Rome, Rome, Italy where he has been an Associate Professor from 1998 to 2005, and a Full Professor of Electromagnetic Fields since 2005, from 2021 he joined the Department of Industrial, Electronic and Mechanical Engineering, where he is Director of the Laboratory of Electromagnetic Fields EMLAB3. From 2013 to 2017 he has been Deputy Director for Research of the Department, and, from 2017 to 2022, Roma Tre University Rector's delegate for North America technology transfer. His scientific research is focused on structures for guiding and radiation of electromagnetic fields for microwave and millimeter waves applications, scattering, diffractive optics, plasma heating and current drive, artificial and Electromagnetic Band Gap (EBG) media, anisotropic media. Prof. Schettini is member of several scientific and technical societies in the frame of Information Technology, in particular in the field of electromagnetic systems. He is also member of the editorial boards and technical program committees of several international journals and conferences in the field of microwaves and antennas. He is an Associate Editor of the IEEE OPEN JOURNAL OF ANTENNAS AND PROPAGATION.