Directive EBG Antennas Based on Lattice Modes

Silvio Ceccuzzi, Cristina Ponti, Member, IEEE, and Giuseppe Schettini, Senior Member, IEEE

Abstract—The emission of radiators can be shaped by means of Electromagnetic Band-Gap (EBG) materials exploiting proper Bloch waves supported by the lattice rather than its band-gaps. So far such a method has only relied on the dispersion diagram of the periodic structure, i.e., on the eigenvalues of the lattice, neglecting the particular configuration of the associated eigenfunction. This paper explores the radiation mechanism under a novel viewpoint, which is mostly focused on the electric field pattern of lattice modes, allowing a deeper understanding of the underlying physics. Such an approach is profitably used here to improve the performance of antennas based on different Bloch waves by reducing spurious lattice modes. Geometrical configurations coupled to a line source are provided with little adjustments, getting EBGs to work at a frequency where they had no band-gap originally. As a proof-of-concept of proposed perspectives, a compact antenna using a cheap, low-permittivity dielectric is conceived, fabricated and successfully tested.

Index Terms—electromagnetic bandgap materials, directive antennas, periodic structures.

I. INTRODUCTION

Electromagnetic Band-Gap (EBG) materials were inspired by the ability of crystals in shaping the flow of light due to the periodicity of their electromagnetic properties [1], [2]. By means of scaled lattice parameters, EBGs achieve the typical behaviour of crystals at microwaves, where they have been successfully employed to enhance the performance of several devices such as waveguides, oscillators, shields, filters and antennas [3]–[5].

As far as radiation problems are concerned, periodic structures have been adopted to emulate high impedance surfaces [6], [7], to realize reflectors [8], to reduce the coupling between patch antennas [9], [10] and to enhance the directivity of primary radiators [11], [12]. They can prevent wave propagation within some frequency bands and this feature was mostly exploited so far. In particular the directivity enhancement achieved with resonator antennas has undergone significant development and advancement in terms of efficiency, reduction of dimensions, frequency tuning, bandwidth increase or multiple beams [13]–[18]. Such configurations, also known as Fabry-Pérot antennas, rely on metal grids and EBGs working in the band-gap, and acting as spatial filters.

A periodic structure can behave as spatial filter and shape the radiation pattern of antennas also working outside the band-gap. Enoch et al. [19], [20] proposed and experimentally demonstrated this alternative approach, explored to a modest extent in [21] and further developed only with reference to degenerate band edge crystals [22], [23]. Recently [24], the directivity enhancement by this mechanism has been compared to the one achieved by resonator antennas, showing that, for compact structures, the former delivers higher performance and efficiency.

The alternative approach to Fabry-Pérot antennas works with a lattice mode excited by a source embedded in the periodic medium, as shown in Fig. 1. The directivity enhancement was generally explained by similarity with the behaviour of Epsilon Near Zero (ENZ) materials, nevertheless a different physics rules the phenomenon, enabling the exploitation of peculiar properties that ENZ or other metamaterials do not share. More precisely, the excited mode is a solution of the lattice eigenvalue equation with its own dispersion relation and eigenfunction. By adopting this novel viewpoint, deeper understanding as well as improvements to this kind of lattice mode antennas are explored in the present paper by referring to EBGs realized as periodic arrangements of cylinders.

The analysis and design of EBG structures have been addressed with manifold methods such as plane-wave expansion [1], finite-difference [25], finite-element [26], [27], transfer matrix [28], coupled equations [29], equivalent circuits [30], [31], lattice sums [32], Fourier modal approach [33], cylindrical waves [34], [35], combined methods [36], [37]. Three formulations are adopted throughout the paper: the plane wave expansion (PWE), the time domain solver (FIT) of a commercial software [38] and the cylindrical wave approach (CWA). The first two are not explained here because they are widespread techniques, whereas the CWA is briefly addressed in appendix as regards the most suitable settings of this semi-analytical approach for the present geometries.

The paper is organized as follows: section II describes the behaviour of angular selective lattices following the original approach and introducing the new perspective. The importance of lattice eigenfunctions in designing directive antennas is elucidated under a two-dimensional scheme for EBGs made...
II. 2-D LATTICE MODE ANTENNAS

We refer to a square lattice of alumina rods with circular cross-section and infinite length in a vacuum on the $xz$ plane. The dispersion diagram for TM modes (electric field parallel to the cylinder axis), calculated along the border of the Irreducible Brillouin Zone (IBZ), is shown in Fig. 2.

Each Bloch wave is allowed to propagate along a given direction so that, if a localized omnidirectional source excites only a few lattice modes, the radiation is spatially filtered. For instance the eigenvalues in the shaded region of Fig. 2 are in correspondence of the X-point and, owing to the symmetry of the reciprocal lattice, an antenna based on the associated modes would have four main lobes along the in-plane coordinate axes. Fig. 3 clarifies this behaviour: a three-dimensional plot depicts the first two Brillouin bands and a constant plane at 14.8 GHz and eigenfunctions of the lattice modes at the same frequency.

Mode patterns offer a different perspective on how to realize directive antennas with a single lobe for $k_x \geq 0$ and $k_z > 0$. So far an approach based on shaping the bands of eigenvalues has been adopted to this aim, e.g., in [20], where the horizontal period of a triangular lattice is decreased to lift some parts of the air band above the working frequency and avoid unwanted intersections. For a square lattice, angular lobes other than the upper one may be also suppressed by placing an infinite ground plane along the centers of a row of cylinders. This change introduces a new boundary condition, whose effect can be intuitively explained in terms of lattice eigenfunctions. As shown in Fig. 4, the horizontal perfect electric conductor (PEC) matches the modal pattern responsible for the lobes along $z$, whereas it violates the one associated with horizontal propagation since it crosses the electric field anti-nodes.

In order to apply previous concepts to realistic antennas, lattices must be truncated and localized current sources must be embedded in the periodic medium to excite modes. Lattice behaviour and mode patterns are well reproduced in periodic structures with finite dimensions when the latter are large enough. As to current sources, similarly to the excitation of waveguide modes [39], a good choice for their location is where the eigenfunction of the working mode exhibits a maximum. When the size of the periodic medium is reduced to attain compact antennas, boundary effects become more pronounced. Spurious (unwanted) lattice-like modes are thus excited to a larger extent, impairing desired electric field pattern and antenna performance. The eigenfunctions of lattice modes can suggest some adjustments of the periodic medium to enhance mode purity. In the following they are investigated with the CWA using a current wire as a source. Both cylinders and source are aligned with the $y$-axis, along which translational invariance is assumed.

A. Working with Dielectric Modes

In Fig. 2 other modes exist in correspondence of the X-point at around 10 GHz. Those Bloch waves, belonging to the dielectric band, can spatially filter radiation too. Yet, they have never been used to realize directive antennas because a continuous angular spectrum is excited at the same frequency, leading to a strong competition of spurious modes. The pattern
of the electric field for the desired mode is shown in Fig. 5 together with a radiating structure conceived to work with it. The geometry has been derived truncating the lattice to a number of rows NR and a number of columns NC; ground plane and line source have been placed in correspondence of a nodal line and a field maximum of the eigenfunction, respectively. A structure of this kind, employing from 3 to 5 layers with 8 cylinders, can achieve a directivity of the order of 10 dB having optimized the lattice period. The optimization is required to compensate a little detuning due to finite dimensions. Although the positions of ground plane and line source contribute to enhancing the purity of the desired Bloch wave, some spurious modes are always excited. These modes produce grating lobes, which become dominant in configurations with many cylinders per layer.

Broadside ($\theta = 0$) directivity can be improved through the modified structure of Fig. 6, where we inserted layers of metallic posts with a diameter of 0.5 mm between the layers of dielectric rods. The former comply with the boundary conditions of the wanted mode, whereas they suppress spurious waves whose pattern does not vanish in their position. The lattice period $a$ of the structure in Fig. 6 with and without metallic posts has been optimized with respect to the broadband directivity, which is maximized for $a = 6.0$ and 5.7 mm, respectively. The corresponding H-plane radiation patterns are compared in Fig. 7. The case with metal posts is more directive, improving the gain from 8.5 dB to about 13 dB, with the Half Power Beam Width (HPBW) decreasing from 46 deg to 16 deg. This improvement is due to an enhanced purity of the desired lattice mode, leading to a more planar wavefront coming out from the uppermost layer of cylinders. The overlays of Fig. 8 reveal an electric field that spreads with substantial amplitude over a longer extent of the layers, when metal posts are used. This is mostly evident in the lowest row of dielectric cylinders, which is the furthest from antenna edges: being the structure finite, multiple partial reflections at its boundaries impair the ideal mode pattern.

A meaningful parameter to be considered is the aperture efficiency calculated here as

$$\eta_{AP} = \frac{D_{\text{real}}}{D_{\text{ideal}}} = \frac{\lambda^2 D_{\text{real}}}{4\pi A_{\text{ph}}}$$

where $\lambda$ is the vacuum wavelength, $D_{\text{real}}$ the maximum directivity and $A_{\text{ph}}$ the physical area of the aperture. The latter is taken as large as the geometry and with height along $y$ equal to a wavelength. In absence of metal cylinders, $\eta_{AP} = 25\%$, whereas in the other case it almost reaches 70\%. An explicative plot is presented in Fig. 9, showing the electric field magnitude (a) and phase (b) taken at a distance of one lattice period above the uppermost layer of the optimized geometries, i.e., along an imaginary line aligned with the $x$-axis of Fig. 6, which can be considered the radiating edge of the structure. In the case with dielectric cylinders only, the amplitude of the electric field decays more rapidly and its phase presents higher variation. In the same plot, ideal curves relevant to the pattern of Fig. 5a are also shown as a term of comparison; such a distribution of electric field would give an aperture efficiency of 98.3\%. It is useful stressing that these curves pertain to an infinite lattice with no ground plane, posts, or sources.

The purity enhancement of the wanted mode by metal posts is also proved by a negative consequence on the antenna efficiency. The purer the mode, the closer the field pattern to the one of Fig. 5, where the electric field is mainly localized inside dielectric cylinders. Assuming a loss tangent of $2 \times 10^{-4}$ for alumina, the radiation efficiency decreases from 99.2% to 97.9% in the optimized configuration with metal posts.
Fig. 9. Normalized magnitude (a) and phase (b) of the electric field along the upper radiating edge of the optimized structures with and without metal posts; the ideal pattern in a lattice is also plotted.

B. Working with Air Modes

When working at the lower edge of the air band, the proposed approach finds useful application to lattices with low dielectric contrast, where the band-gap is very short or even absent. An example is the polyether ether ketone (peek), a semicrystalline thermoplastic whose complex permittivity has been measured at 10 GHz with the rectangular dielectric waveguide technique, obtaining $\varepsilon_r = 3.1$ and $\tan \delta = 0.01$.

Fig. 10 depicts the dispersion diagram along the IBZ border of a square lattice of peek cylinders, showing that the operational region is no longer monomodal.

The electric field of the working mode presents an almost complementary pattern compared to that of Fig. 5. The normalized magnitude in a lattice section is depicted in Fig. 11, where the relevant finite-size antenna provided with ground plane, source and metal cylinders is shown too. We have located again these elements so as to match the desired pattern. A diameter of 0.5 mm has been used for the metal posts.

A set of structures with different number of layers and cylinders in each layer has been optimized with respect to the lattice period, aiming at the maximization of the gain. The outcome of this study is depicted in Fig. 12; it must be noted that the gain of the line source is 0 dB, hence the figures in the plot can be interpreted as the gain enhancement achieved by the periodic arrangement of cylinders. After a given aspect ratio (NC/NR > 3), the gain approaches an asymptotic value, which increases by stacking more and more layers. At the same time the optimal lattice period approaches 13 mm, which is the nominal value for the infinite crystal. The configurations with low number of layers are more exposed to adverse boundary effects occurring at the antenna edges, so the relative gain enhancement is higher between these curves and slowly reduces as NR increases. For the same reason, the optimal configurations for a given gain curve are those with aspect ratios in the range $1 \div 2$, i.e., for compact geometries.
that suffer less from boundary effects.

Among previous structures, we have selected the configuration with 6 layers of 6 dielectric cylinders as study case owing to its good balance between geometrical dimensions and performance. It achieves a gain of 12.6 dB with a lattice period of 13.9 mm; aperture and antenna efficiencies are respectively 52.1% and 88.3%. It is worth noticing that, despite the high loss tangent, the power lost due to dielectric losses is moderate. This happens because the nodal lines of the relevant eigenfunction pass through cylinder axes (see Fig. 11a), entailing a low absorption of the electric field.

III. PROOF OF CONCEPT

Previous concepts have been implemented in the design of a realistic three-dimensional antenna whose geometry is depicted in Fig. 13. It is a relatively compact structure made of $6 \times 6$ peek cylinders: the base is less than $2.7 \lambda \times 2.9 \lambda$ and the height is around half a wavelength. Dielectric cylinders have a diameter of 8.58 mm and a distance of 13.4 mm ($d = 0.64\lambda$), optimized to work at 10 GHz. They are located between top and bottom aluminium plates in shallow (depth $\approx 0.4$ mm) circular recesses of the plates. The latter force the electric field to be aligned with the $y$-axis as in parallel plate waveguides, thus mimicking the two-dimensional environment of Fig. 11b. The aluminium plates are fixed to a back-plane and provided with holes to insert pins made of stainless steel with a diameter of 0.8 mm. The structure is fed with a 50 $\Omega$ SMA coaxial connector whose inner conductor enters the structure for about 12 mm while the filling medium (PTFE) stops at around 5 mm. The parts of the antenna have been shaped with a Computer Numeric Control (CNC) machine. A photo of the realized prototype is given in Fig. 14. It is worth stressing that the feeder and pins allow the excitation of the proper lattice mode. They do not behave like the driven and parasitic elements of a mutually coupled array from the radiation viewpoint.

The antenna prototype is the result of a numerical optimization carried out with a commercial software (CST Microwave Studio), started from the 2-D preliminary design of section II-B and subjected to practical constraints from off-the-shelf components. Resulting radiation patterns on the principal planes are plotted in Fig. 15. The maximum gain of 11.7 dB is mostly constrained by the emission on the E-plane ($yz$) where diffraction effects from the short aperture dominate (HPBW = 77 deg). Contrariwise, the H-plane ($xz$) emission benefits from lattice-induced shaping, which is largely improved thanks to the use of pins, as demonstrated in the simulated patterns of Fig. 16. The latter plot also shows the radiation of a half-wavelength dipole with a reflector for comparison. Despite the low electrical conductivity of steel, pins weakly contribute to antenna losses: efficiencies simulated with and without them are 79.7% and 80.4%, respectively.

Besides the gain enhancement due to metal cylinders, an improvement as regards frequency behaviour is obtained too, as can be observed in Fig. 17. Pins help the wanted crystal mode to preserve its shape further from the operational frequency.
Fig. 16. Simulated normalized H-plane radiation patterns at 10 GHz for the geometry of Fig. 13 with and without pins and of a dipole with a groundplane. The latter is a quarter wavelength apart and as large as the antenna back-plane.

Fig. 17. Broadside ($\theta = 0$) gain vs. frequency.

with respect to fully dielectric lattices. Fig. 17 also shows that the antenna with mixed lattice can be further optimized for 10 GHz operations, but we preferred to relax the maximum gain to the benefit of the Side Lobe Level (SLL), which was evaluated in -15 dB.

The gain of previous plots does not include losses arising from impedance mismatches. The antenna impedance at 10 GHz is $5.5 - j33 \Omega$, leading to the high reflection coefficient of Fig. 18 and a realized gain of 6.8 dB. An external matching network can be readily used to overcome this drawback, e.g., a combination of shifter and stub has been tried experimentally as shown in Fig. 18, obtaining a 10 dB bandwidth of 333 MHz.

With no matching networks, a simple way to enhance the absolute gain of the present prototype is by changing the length of the inner coaxial conductor. A variation of the latter produces a rotation of the antenna impedance $Z_a$ in the Smith chart, allowing the attainment of the resonant condition $\text{Im}\{Z_a\} = 0$. Yet, the corresponding real part $R_a$ is quite small, leading to a minimum $S_{11}$ of -5.5 dB at 10 GHz and a maximum realized gain of 10.5 dB. The value of $R_a$ at the resonance can be slightly increased reducing the antenna height. This approach also entails a gain worsening that the improvement of internal matching can no longer balance for antenna heights shorter than 10 mm. This behaviour has been studied for antennas with no PTFE in their interior; predicted realized gains are plotted in Fig. 19.

Further enhancements of previous structure are possible, e.g., by acting on the back-plane, increasing the number of cylinders, optimizing the lattice periods separately along $x$ and $z$, or varying rod radius. The first option has been pursued in order to reuse the same antenna, after substituting the back-plane for another with enlarged dimensions by a wavelength along each direction. Such a change reduces back-radiation, resulting in an antenna gain at 10 GHz equal to 13 dB. The latter is slightly higher than the simulated one, most likely owing to an overestimated value of the peak loss tangent retrieved from measurements. Predicted antenna efficiencies of 79.5% (with pins) and 79.9% (without pins) would be thus
lower than the actual ones. The realized gain is 8.1 dB if none of previous matching strategy is adopted. Fig. 20 shows the radiation patterns in the principal planes: HPBW and SLL at 10 GHz in the H-plane are 25 deg, -17 dB. Gain vs. frequency curves are plotted in Fig. 21, confirming a larger region with constant gain for the geometry with pins.

A. Advantages vs. Resonator Antennas

The arrangement of cylinders in the proposed design is similar to resonator antennas [12], but different physical properties are exploited. The former relies on the modes supported by the lattice, whereas the latter works in the forbidden band, where no mode is allowed. The two approaches have been benchmarked against 2-D [24] and 3-D [40] structures for several lattice types, identifying strengths and weaknesses of each approach independently from the particular lattice.

Given a number of cylinders and a primary radiator, antennas based on Bloch waves achieve a higher gain enhancement than resonator antennas in the case of compact structures, i.e., when lattices have relatively low aspect ratio. Moreover they exhibit higher bandwidth because they do not exploit resonant effects and they also attain higher efficiency, when air modes are used.

IV. CONCLUSIONS

The design of antennas working with lattice modes can be carried out by considering the eigenfunctions of Bloch waves rather than their eigenvalues as usually done so far. This approach provides a deeper insight on such radiating structures, also allowing their enhancement and paving the way for future developments.

The key concepts of these antennas have been illustrated by referring to the square lattice of dielectric rods. Antennas working with modes in either dielectric or air band have been presented, demonstrating that low-index-contrast lattices can be profitably employed if the electric field pattern of particular modes is exploited in a proper fashion. A proof of concept has been conceived, built and tested using dielectrics with similar properties to plastic materials employed in 3-D printing. The emission of a primary radiator has been successfully shaped by the periodic structure where pins, introduced according to lattice eigenfunctions, further improved the antenna behaviour. Even better performances have been eventually demonstrated by replacing the back-plane with a larger one, while possible enhancements of the realized gain have been presented.

Possible developments of the present work are the study of TE modes, triangular lattices or 3-D periodic structures suitable for applications requiring dual polarization.

APPENDIX

The cylindrical wave approach is semi-analytical method that employs a multipole expansion based on cylindrical functions [21], [34], [35]. It is mostly fast and effective in addressing scattering problems from cylindrical objects with circular cross section, being able to deal at the same time with lossy dielectric and metal cylinders, multiple sources and infinite ground planes under a two-dimensional approximation.

Being a semi-analytical method, a critical parameter for its usage is the truncation index \( L \) of the harmonic expansions, which affects result accuracy and computational load. A criterion is proposed in [21] for its choice, but it resulted unsatisfactory for the geometries of this paper. Hence a new empirical convergence rule has been derived by studying the impact of \( L \) on the directivity of a broad set of structures made of either dielectric or metal cylinders. In the case of dielectric scatterers with the same normalized radius \( \alpha_d \), an accuracy of 0.01 on the linear directivity was fulfilled by the following scaling law

\[
L_d = \text{ceil} \left\{ 0.5 + 828 \alpha_d^{0.8} \rho_{\text{min}}^{-0.12} \right\}
\]

where \( \text{ceil}(x) \) gives the smallest integer \( \geq x \) and \( \rho_{\text{min}} \) is the minimum normalized distance between two elements in the...
geometry. The normalization of radii and distances is carried out by multiplication for the vacuum wavenumber $k_0 = 2\pi/\lambda$. As regards metal cylinders with radius $\alpha_m$, the same accuracy was achieved according to the law

$$L_m = \text{cell} \left\{ 547 \alpha_m^{0.72} \rho^{-0.11} \right\}$$

With reference to the structures presented in this paper, extensive parametric analyses provided sound confidence that the choice $L = \max\{L_d, L_m\}$ represents a satisfactory criterion.

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REFERENCES


Silvio Ceccuzzi was born in Rome, Italy, in 1983. He received the 1st and 2nd level Italian degrees (*cum laude*) in electronic engineering and the Ph.D. degree in applied electronics from “Roma Tre” University, Italy, in 2005, 2008 and 2015, respectively. After an internship in Telespazio and another one in Thales Alenia Space, in 2009, he started a 3-years scholarship for scientific training across European labs on high-power RF systems. In 2013 he joined ENEA for EUROfusion, Frascati, Italy as a researcher. His main interests are EBG, microwave components, nuclear fusion.

Dr. Ceccuzzi is the author/co-author of more than one hundred works on technical reports, journals, and conference proceedings. He received the 2015 IEEE MTT-S award of the Chapter central and southern Italy and the “Sannino” award of the Italian meeting RiNEm 2012.

Cristina Ponti (M’11) received the First Level Laurea (*cum laude*) and the Laurea Magistralis (*cum laude*) in electronic engineering from “Sapienza” University of Rome in 2004 and 2006, respectively. In 2006 she joined the Applied Electronics Department of “Roma Tre” University, Rome, Italy, where from November 2006 to October 2009 she attended the Doctoral School in Biomedical Engineering, Electromagnetism, and Telecommunications. She received the PhD in March 2010.

From February to December 2010 she was Assistant Researcher, and since December 2010 she is a Researcher in Electromagnetic Fields. Her main research interests are in electromagnetic analysis, scattering problems, buried-objects detection, numerical methods, and antennas.

Dr. Ponti is a member of the Institute of Electrical and Electronics Engineers (IEEE), IEEE Antennas and Propagation and Women in Engineering Societies, National Interuniversity Consortium for Telecommunications (CNIT), Italian Society of Electromagnetics (SIEm).

Giuseppe Schettini (SM’02) 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 components and antennas for the heating of thermonuclear plasmas. In 1992 he joined “La Sapienza” University as Researcher of electromagnetics. In 1998, he joined the Applied Electronics Department, now Department of Engineering, 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 and Antennas since 2005. 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 Electromagnetic Band Gap (EBG) media, anisotropic media.

Prof. Schettini is a member of the Italian Electromagnetic Society (SIEm), the European Microwave Association (EuMA), The Institute of Electronics, Information and Communication Engineers (IEICE), and the Optical Society of America (OSA).