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On the Feasibility of Using Inverse Scattering to Optimize the Design of EBG Devices

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Abstract

In this contribution the possibility to improve the performance of EBG devices through the exploitation of inverse design strategies is investigated. The Scattering Matrix Method is adopted as design tool and the usefulness of the proposed approach is assessed in case of a 2D EBG waveguide.

1 Introduction

The concept of electromagnetic waves interacting with periodic structures is widely explored amongst microwave engineers, especially since the large diffusion of metamaterials. In particular, the most adopted approach is the exploitation of the capability of photonic crystals (PC) [1] in guiding the flow of light due to the periodicity of their electromagnetic properties.
PC are indeed structures composed by dielectric-on-air or air-on-dielectric small inclusions whose periodic arrangement allows the electromagnetic field inside PC. Electromagnetic bandgap (EBG) structures [2] exploits instead forbidden bands of wavelength of PC to get different kind of devices. More in detail, by perturbing the lattice, e.g., by introducing defects, it is possible to generate localized or guided electromagnetic modes. For that reason, EBG structures are employed in designing waveguides, cavities, oscillators, filters, antennas, and so on, at the frequencies of actual interest [3]-[5].
As far as the design of EBG systems is concerned, it is basically rested on the electromagnetic theory for periodic structures. In this respect, many approaches have been developed to analyze these kind of geometries, that could be grouped into 'macroscopic' (related to homogenization theories) or 'microscopic' one. Amongst approaches in the latter class, in this contribution we rely herein on the Scattering Matrix Method (SMM) [6]-[8].
In particular, we use here the SMM together with inverse scattering tools to propose and test design tool rather than an analysis one. To this aim, we take advantage from the inverse scattering problems framework to determine the suitable electromagnetic parameters of the EBG structure's small inclusions in order to fulfill assigned specifications, depending on the device at hand [9,10].
We will show how the proposed approach allows to control the electromagnetic field inside the EBG-based device, thus improving its performance.
The remainder of the paper is organized as follows. In Section 2 some basics of the SMM are recalled to define the terminology used in Section 3, where a new method for designing an EBG-based waveguide is proposed and assessed. Conclusions follow.

2 Basics of the SMM

The SMM has been introduced by Maystre and co-workers in 1994 [6] as an effective and rigorous tool for the evaluation, in analytical form, of the scattered field[1] from a set of small inclusions with cylindrical section.
It is based on the cylindrical harmonics expansion of the fields and the use of the scattering matrix associated to each cylinder to get a linear system of equations for the evaluation of the scattered field.
The linear system involved in the SMM is reported in Eq.(1) in matrix form, wherein $\boldsymbol{T}_{\boldsymbol{\ell},i}$ is a square blocks matrix whose elements are related to mutual interactions amongst cylinders, $\mathbf{Q}_{\boldsymbol{\ell}}$ is the blocks column matrix depending on the kind of primary source, $\boldsymbol{S}_{\boldsymbol{\ell}}$ is the "scattering matrix" [11] of the ℓ-th inclusion depending on its geometrical and electrical characteristics, while $\mathbf{b}_{\boldsymbol{\ell}}$ is the blocks column matrix of the unknowns scattering coefficients and N is the total number of inclusions.

$$\mathbf{b}_{\boldsymbol{\ell}} - \sum_{i=1, i\neq \ell}^{N} \boldsymbol{S}_{\boldsymbol{\ell}} \boldsymbol{T}_{\boldsymbol{\ell},i}\, \mathbf{b}_{\boldsymbol{i}} = \boldsymbol{S}_{\boldsymbol{\ell}} \mathbf{Q}_{\boldsymbol{\ell}}\,, \quad \ell = 1,..,N \qquad (1)$$

Provided that the scattering matrices $\boldsymbol{S}_{\boldsymbol{\ell}}$ of all cylinders are known or have been preliminary evaluated, Eq.(1) can be easily solved and the scattered field in any point outside the cylinders can be finally calculated.

3 EBG waveguide design

When a line of inclusions is removed from the periodical lattice a new guiding effect can be obtained. As a matter of fact, the line defect turns into a waveguide for an electromagnetic wave with a frequency within the band gap of the (non-defective) crystal. An example of this mechanism, whose geometrical parameters can be detailed in [7], is shown in Fig. 1.
In particular, it is possible to see how an impinging field (f = 288.46 THz) is guided through the lattice because of the reduction of the prohibited band in the defective case, see the band map in Fig. 1(a).

[1] The theory holds in the region of space outside the minimum circle enclosing the particle, around each of them.

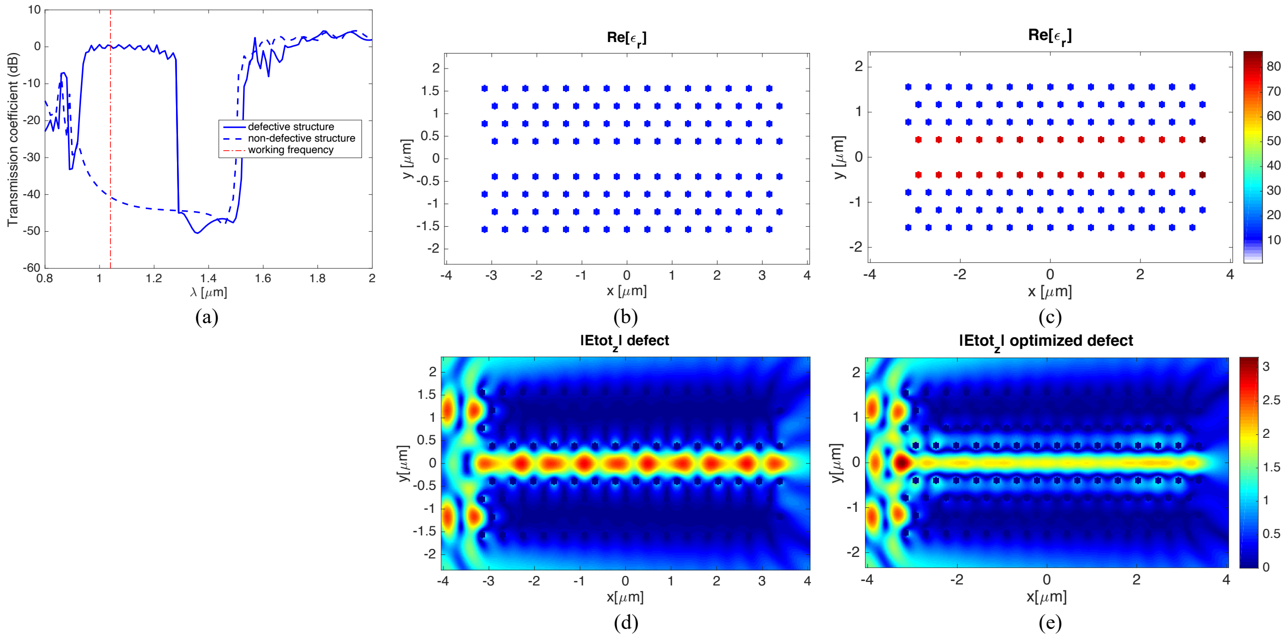

Figure 1. Design of an EBG straight waveguide. (a) Band map. Real part of the dielectric permittivity for the (b) initial and (c) optimized structure. Amplitude of the z-component of the electric field on domain for the (d) initial and (e) optimized waveguide.

Notably, such a structure is able to confine and somehow guide the field, but an unsatisfactory Voltage Standing Wave Ratio (VSWR) is obtained. In fact, wave reflections due to the discontinuity in the space produce oscillations of the field inside the guiding region, as demonstrated from the field plot in Fig. 1(d).

In this respect, we suggest that the exploitation of inverse scattering tools to optimize the permittivity value for (some of) the inclusions can allow to improve VSWR and get a better design. Amongst the different possibilities one can explore to that aim, in this paper we consider the SMM as model of the problem and adopt the following strategy:

Find the dielectric permittivity ε_r of defect edge inclusions such to minimize the ripple of the field amplitude inside the defect.

The proposed approach reveals effective, as it can be observed from the plot in Fig. 1(e) which is relative to the synthesized EBG device reported in Fig. 1(c). Quantitatively comparing the synthesized results with the initial one, we experienced a reduction of the ripple of about 75%.

It is worth to highlight that the design problem is still a non-linear problem, like the usual inverse scattering problem. For this reason, amongst several solutions one could achieve, a good starting point and a-priori information can be useful to reach the optimal one. For the example at hand, the only a-priori information is the symmetry of ε_r between the top and the bottom edge, so that the overall symmetry of the structure is kept. Also note (see [9]) that one can eventually act on the dimensions of these inclusions rather than on their permittivity values.

4 Conclusions

Electromagnetic band gap (EBG) devices deserves interest because of their very promising performance. In this paper, a possible approach to improve such performance has been proposed by exploiting an inverse design approach. It has been proved to be effective through an assessment in case of EBG waveguide for which the guiding properties have been improved by means of properly synthesized inclusions' permittivity. Encouraged by these preliminary results, work is in progress for the design of other kind of devices.

7 References

1. J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the Flow of Light*, 2nd ed. Princeton University Press, 2008.
2. F. Yang and Y. Rahmat-Samii, *Electromagnetic Band Gap Structures in Antenna Engineering*, ser. Cambridge books online. Cambridge University Press, 2008.
3. S. Ceccuzzi, C. Ponti, and G. Schettini, "Directive EBG antennas based on lattice modes," *IEEE Transactions on Antennas and Propagation,* vol. 65, no. 4, pp. 1691-1699, 2017.
4. G. S. Mauro, A. Locatelli, G. Torrisi, L. Celona, C. De Angelis, and G. Sorbello, "Woodpile EBG waveguide as a DC electrical break for microwave ion sources," *Microwave and Optical Technology Letters*, vol. *61*, no. 3, pp. 610-614, 2019.
5. G. Torrisi, G.S. Mauro, L. Celona, D. Mascali, S. Gammino, G. Sorbello, C. De Angelis, and A. Locatelli, "Numerical Study of Photonic-Crystal-Based Dielectric Accelerators ", Journal of Physics: Conference Series, vol. 1350, doi:10.1088/1742-6596/1350/1/012060, 2019.

6. D. Felbacq, G. Tayeb, and D. Maystre, "Scattering by a random set of parallel cylinders", *Journal of the Optical Society of America A*, vol. 11, no. 9, pp. 2526-2538, 1994
7. L. Crocco, F. Cuomo, and T. Isernia, "Improved scattering matrix method for the analysis of two-dimensional PBG devices", *Microwave and Optical Technology Letters*, vol. 48, no.12, pp. 2564-2570, 2006.
8. L. Crocco, F. Cuomo, and T. Isernia, "Generalized scattering-matrix method for the analysis of two-dimensional photonic bandgap devices", *Journal of the Optical Society of America A*, vol. 24, no. 10, pp. A12-A22, 2007
9. R. Palmeri, M.T. Bevacqua, A.F. Morabito, and T. Isernia, "Design of artificial-material-based antennas using inverse scattering techniques", *IEEE Transaction on Antennas and Propagation*, vol. 66, no. 12, pp. 7076-7090, 2018.
10. R. Palmeri and T. Isernia, "Volumetric Invisibility Cloaks Design Through Spectral Coverage Optimization", *IEEE Access*, vol. 7, pp. 30860-30867, 2019.
11. D.S. Jones, *Acoustic and Electromagnetic Waves*, Oxford Science Publications, 1986