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Optical properties of periodic, quasi-periodic, and disordered one-dimensional photonic structures

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ABSTRACT

Photonic structures are building blocks for many optical applications in which light manipulation is required spanning optical filtering, lasing, light emitting diodes, sensing and photovoltaics. The fabrication of one-dimensional photonic structures is achievable with a variety of different techniques, such as spin coating, sputtering, evaporation, pulse laser deposition, or extrusion. Such different techniques enable facile integration of the photonic structure with many types of devices. Photonic crystals are characterized by a spatial modulation of the dielectric constant on the length scale of the wavelength of light giving rise to energy ranges where light cannot propagate through the crystal – the photonic band gap. While mostly photonic crystals are referred to as periodic arrangements, in this review we aim to highlight as well how aperiodicity and disorder affects light modulation. In this review article, we introduce the concepts of periodicity, quasi-periodicity, and disorder in photonic crystals, focussing on the one-dimensional case. We discuss in detail the physical peculiarities, the fabrication techniques, and the applications of periodic, quasi-periodic, and disorder photonic structures, highlighting how the degree of crystallinity matters in the manipulation of light. We report different types of disorder in 1D photonic structures and we discuss their properties in terms of light transmission. We discuss the relationship between the average total transmission, in a range of wavelengths around the photonic band gap of the corresponding photonic crystal, and the homogeneity of the photonic structures, quantified by the Shannon index. Then we discuss the light transmission in structures in which the high refractive index layers are aggregated in clusters following a power law distribution. Finally, in the case of structures in which the high refractive index layers are aggregated in clusters with a truncated uniform distribution, we discuss: i) how different refractive index contrast tailors the total light transmission; ii) how the total light transmission is affected by the introduction of defects made with a third material.

1. Introduction

In the last years many researchers have reported various works on the light propagation through photonic structures. Photonic structures can be grouped in three sets, depending on their crystallographic properties: i) a periodic spatial modulation of the dielectric constant gives rise to a photonic crystal [1–9]; a modulation of the dielectric constant that follows a deterministic generation rule results in a photonic quasicrystal [10–19]; a random modulation of the dielectric constant gives rise to a disordered photonic structure [20,21]. Myriads of possible applications arise for the three different structures, such, as photonic crystal lasers [22,23] and quasicrystal lasers [24,25], optical fibers [26,27], and sensors [28–30], when concerning photonic crystals and quasicrystals. Instead, focussing on disordered photonic structures, a variety of interesting features have been discovered in different fields, as random lasing [31–37], diffuse optical imaging [38], and light harvesting for solar devices [39–42]. Many physical effects have been observed in one-dimensional disordered

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photonic structures, as the Anderson localization of light [43,44], the optical Bloch oscillations and necklace states [45–48], and an interesting oscillation of the average light transmission as a function of the sample length [49]. In the next three subparagraphs we will briefly introduce the topological aspects of photonic crystals, photonic quasicrystals, and disordered photonic structures:

1.1. 1D, 2D, and 3D photonic crystals

The dielectric function (and, consequently, the refractive index) can be periodically modulated in one-, two-, and three dimensions (Fig. 1).

The 1D photonic crystal is an alternated sequence of two materials with different refractive indexes. Instead, 2D and 3D crystals can be designed taking into account different types of symmetries [50]. In Fig. 1, for example, we depict a 2D square lattice and a 3D simple cubic lattice.

1.2. 1D, 2D, and 3D photonic quasicrystals

A quasicrystal does not show a translational symmetry as periodic photonic crystals do, but is generated by a substitution rule that is based on two building blocks, resulting in a long-range order [17].

There are many different types of photonic quasicrystals [19]. For example, the 1D photonic quasicrystal in Fig. 2 is generated by following the Fibonacci sequence [51–53], while the 2D photonic quasicrystal in the centre of the Figure is a Penrose structure [24,54,55]. Finally, the 3D photonic quasicrystal depicted in Fig. 2 is an icosahedral quasicrystalline structure [56,57].

1.3. 1D, 2D, and 3D disordered photonic structures

The disordered (or random) photonic structures are the optical analogue of electronic amorphous materials [58]. Neither a short-range nor a long-range order is expected to be observed in disordered photonic structures.

In Fig. 3 we show a 1D photonic structure obtained by a random sequence of two materials (depicted in black and white in the figure), a 2D structure where squares of a high refractive index material (black in the figure) are randomly dispersed in the low refractive index matrix, and a 3D structure in which high refractive index spheres are randomly dispersed in a matrix. Of course, the 2D and 3D structures can be made with different shapes and sizes of objects dispersed in the matrix [20].

In this review article we focus on 1D periodic, quasiperiodic, and disordered photonic structures. We describe some theoretical methods to study the structures, also discussing the refractive indexes of the most used dielectric materials. We discuss the optical response, the fabrication methods, and the most significant applications of 1D periodic, quasiperiodic, and disordered photonic structures. Concerning 1D disordered photonic structures, we particularly focus on 1D photonic structures in which the disorder is obtained in different ways: i) with a random sequence of high and low refractive index layers [45]; ii) with a random arrangement of a fixed number of high refractive layers between a fixed number of low refractive index layers [59,60]; iii) with a random variation of the thickness of the layers in a periodic structure [61–63].

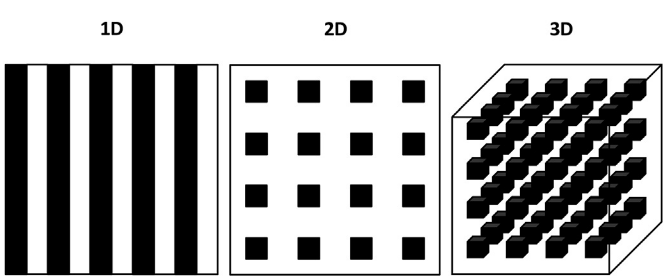

Fig. 1. 1D (left), 2D square (center), and 3D simple cubic (right) photonic crystals.

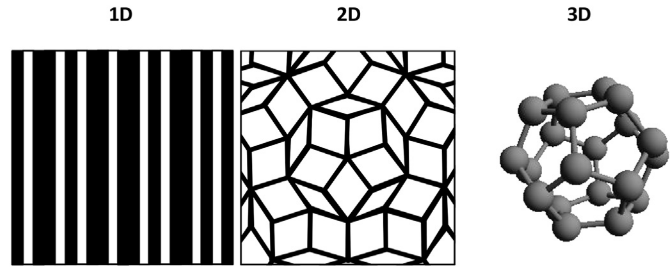

Fig. 2. (Left) 1D photonic quasicrystal following the Fibonacci sequence ABAABABAABAABABAABABA. (center) 2D Penrose photonic quasicrystal. (right) 3D icosahedral quasicrystal.

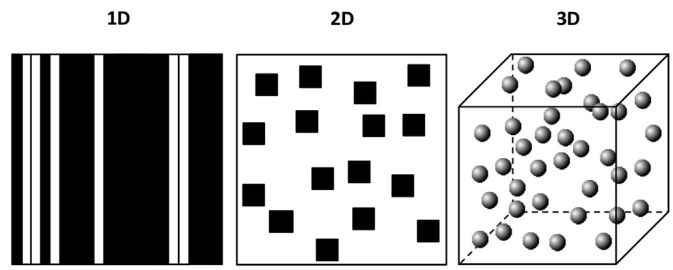

Fig. 3. 1D (left), 2D (center), and 3D (right) random photonic structures.

2. Theoretical methods

2.1. Brief summary of the theoretical methods to study photonic structures

A wide variety of well-established theoretical methods to design and simulate the optical properties of photonic crystals is reported in literature. Most of the methods are exhaustively listed and discussed in the work of Prather et al. [64], as for example plane-wave expansion method (PWEM) [65–69]; finite-difference time-domain (FDTD) method [70,71] and finite element method [72,73].

In the particular case of one dimensional photonic structures, the transmission spectra can be simulated with different numerical tools, as finite element method [74], finite difference time domain methods [75]. The matrix methods are particularly interesting as they can be solved analytically, and we devote the following paragraph to introducing the transfer matrix method as a compelling tool to simulate the transmission spectra of 1D photonic crystals.

2.2. Matrix methods for 1D photonic structures

The matrix methods are very simple and versatile to simulate the optical properties of 1D photonic structures. Studies employing the scattering matrix method [76–78], impedance matrix method [79], and transfer matrix method [80–83] are reported.

For all the simulations presented in this manuscript we have employed the transfer matrix method. We consider a system (e.g. glass/multilayer/air) that is impinged by the light with normal incidence. The parameters related to air and substrate are just their