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Anomalous behaviour of light reflection in crystals with different homogeneity

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ABSTRACT

The light reflection as a function of the sample length has been studied for an ideal two-dimensional photonic crystal and for a two-dimensional photonic structure with smaller homogeneity with respect to the photonic crystal. We have found that, although the number of the scattering elements is constant for the two structures, the behaviour of the light reflection increases linearly with the sample length in the less homogeneous photonic structure, while it is strongly sub-linear in the photonic crystals.

1. Introduction

In the last two decades great attention has been devoted to the study of the light transmission in photonic structures. In such structures, for a certain range of energies and certain wave vectors, light is not allowed to propagate through the medium [1–3]. This behaviour is very similar to the one of electrons in a semiconductor, where energy gaps arise owing to the periodic crystal potential at the atomic scale. Photonic structures can possess a periodical modulation of the dielectric constant. These structures are called photonic crystals and they are present in nature or can be fabricated through a wide range of techniques, with the dielectric periodicity in one, two and three dimensions [4–7]. Several efficient mathematical methods can predict the light transmission in photonic crystals [8–11] and these instruments can be useful for different applications, such as the fabrication of distributed feedback lasers [12]. Instead, these calculations become very cumbersome for aperiodic and random structures. Recently, concepts and methods widely used in statistics have been successfully applied to explain light transport phenomena in materials where the local density of scattering elements is position-dependent [13–15]. To efficiently predict the optical properties of such complicated systems, also as a function of the sample length, the implementation of simple and not time consuming methods can be very useful.

In this work, we have studied the light reflection as a function of the sample length in a non-trivial engineered two-dimensional photonic structure. This structure is less homogeneous with respect to a perfectly ordered structure, i.e. a 2D photonic crystal [16]. We have observed that the less homogeneous structure shows a linear behaviour of the average reflection, over a wide range of wavelengths, as a function of the sample length, while an ordered photonic crystal, with the same number of scattering centres, shows a strong sub-linear behaviour.

2. Outline of the method

For this study, we first consider an ideal two-dimensional photonic crystal [3]. This photonic structure is a square lattice of dielectric circular pillars, where the pillars have a diameter d of 75 nm and are made of Titanium dioxide. The lattice constant a of the crystal is 300 nm and the matrix where the pillars are embedded is Silicon dioxide. The refractive indexes of TiO_2 and SiO_2 are $n_T = 2.45$ and $n_S = 1.46$, respectively. Note that, for such a geometrical setting $n_T d \sim n_S\ (a–d)$ is satisfied [3]. We consider 12×12 cell photonic crystal, to have a size of 3.6×3.6 μm (Fig. 1, crystal PC1). In order to analyse the light transmission as a function of the sample length, we have built the structures depicted in Fig. 1, where PC2 is PC1 repeated two times and PC3 is PC1 repeated three times. We have realised structures from PC1 up to PC7, where PC7 is PC1 repeated sevenfold.

The other photonic structure we have used for this study is already reported in Ref [16]. Briefly, to design this crystal, we have assigned pillars in cells by a fitness model [16,17]. We have used this model in order to realise a crystal space with skewed clusters size without benchmark distribution. Thus, we have obtained a random crystal in which the clusters size distribution (i.e. pillars for cells distribution) is skewed. The whole structure has the same size 3.6×3.6 μm of PC1 and is depicted in Fig. 2 (R1 diagram). Also for this structure, R2 is the structure R1 repeated two times, R3 is

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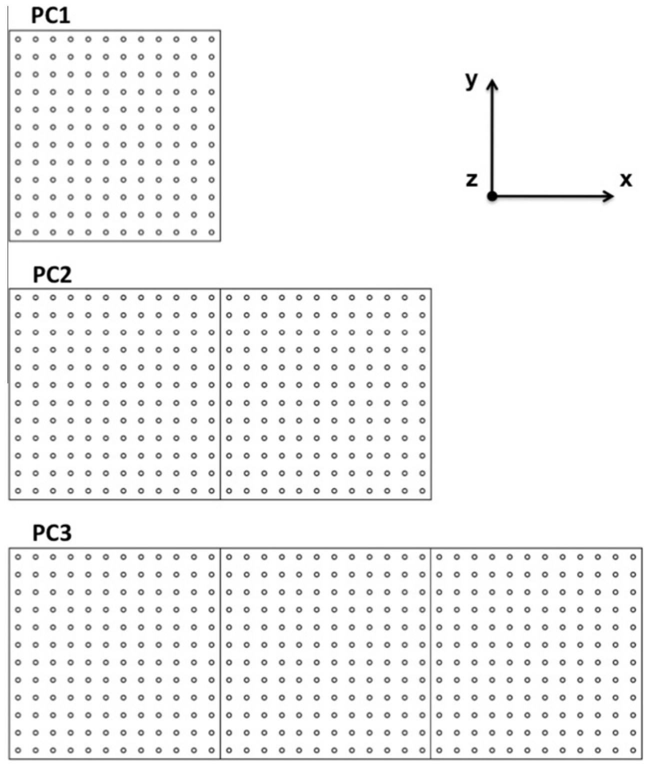

Fig. 1. Ideal two-dimensional photonic crystal (PC1). PC2 is PC1 repeated twice, PC3 is PC1 repeated threefold.

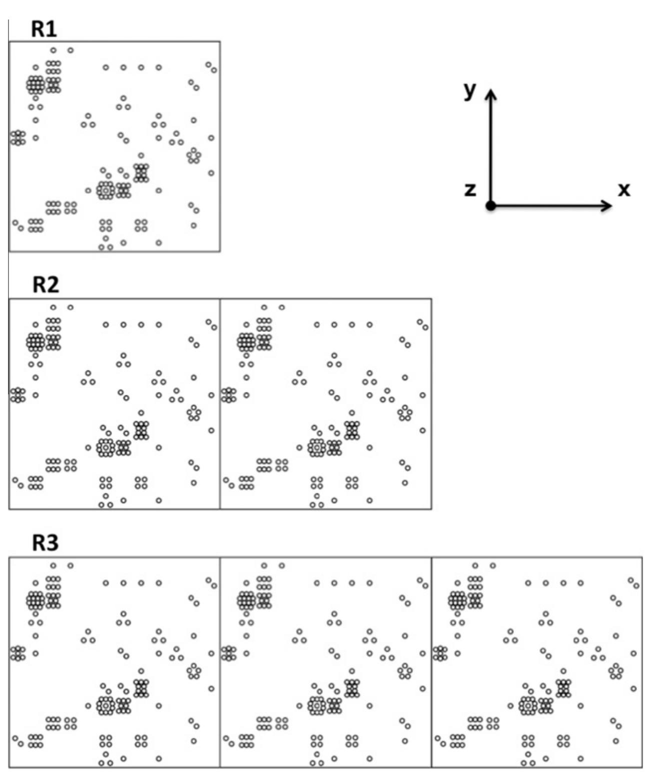

Fig. 2. Photonic structure made by a fitness model (R1). R2 is R1 repeated twice, R3 is R1 repeated threefold.

R1 repeated three times, up to structure R7, where R7 is R1 repeated sevenfold. To simplify, we call the two series of structures PCn and Rn, where $n = 1,\ldots,7$.

It is possible to correlate the distribution of the pillars in the structure to the Shannon–Wiener index [18,19]. The Shannon–Wiener H' index is a diversity index widely used in statistics and information theory, defined as

$$H' = -\sum_{j=1}^{s} p_j \log p_j \tag{1}$$

where p_j is the proportion of the j-fold species and s is the number of the species. For PC1, i.e. the ideal two-dimensional photonic crystal, the Shannon–Wiener index has a value of 1, corresponding to the maximum of the homogeneity. Instead, for the fitness model crystal R1 the value of the Shannon–Wiener index is 0.7, implying that R1 is less homogeneous than PC1.

For what concerns the calculation of the light transmission (and reflection) of the photonic structures through finite element method, we assumed a TM-polarized field and used the scalar equation for the transverse electric field component E_Z

$$(\partial_x^2 + \partial_y^2)E_Z + n^2 k_0^2 E_Z = 0 \tag{2}$$

where n is the refractive index distribution and k_0 is the free space wave number [3,20]. As input field, a plane wave with wave vector k directed along the x-axis has been assumed. Scattering boundary conditions in the y direction has been used.

3. Results and discussion

By using a finite element method, we have calculated the transmission spectra for the structures PCn and Rn [3,20]. Then, we have compared the light transmission as a function of the sample length for these two different systems. In Fig. 3 the transmission spectra, in the range 450–1400 nm, for PCn and Rn are displayed. As one

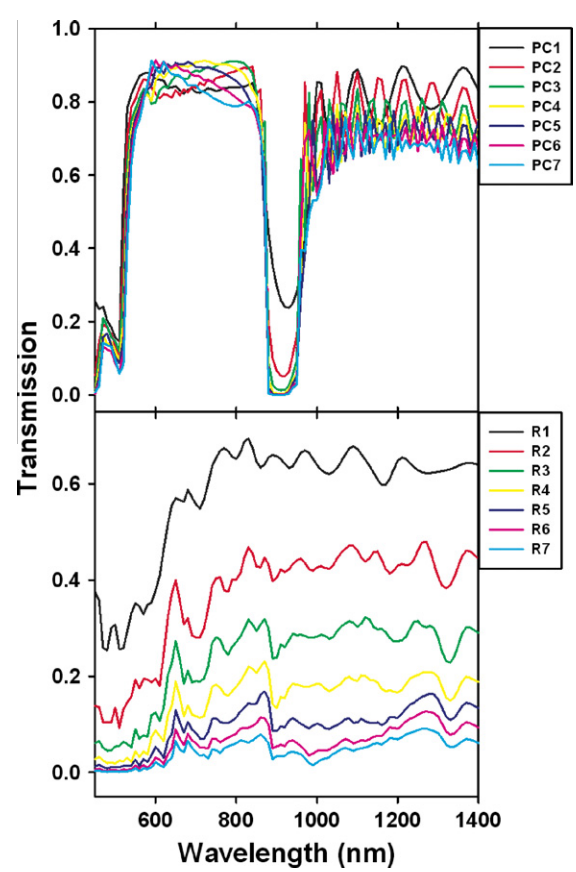

Fig. 3. Light transmission in the range 450–1400 nm for structures PCn and Rn.