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One dimensional disordered photonic structures characterized by uniform distributions of clusters

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ABSTRACT

We investigated one dimensional disordered photonic structures by grouping high refractive index layers in clusters, randomly distributed within layers of low refractive index. We control the maximum size of the high refractive layer clusters and the ratio of the high–low refractive index layers, which we call the dilution of the system. By studying the total transmission of the disordered structure within the photonic band gap of the ordered structure as a function of the maximum cluster size, we observe a dip of the total transmission for a specific maximum cluster size. This value increases with increasing dilution. Moreover, within one dilution we observe oscillations of the total transmission with increasing cluster size.

1. Introduction

In the last years a large effort has been devoted to study the optical properties of disordered photonic structures [1–4]. Such studies have been catalysed by intriguing applications of these materials, such as random lasers [5–7]. In a photonic crystal, where the alternation of high and low refractive index materials in one, two and three dimensions is periodic [8–11], a laser can be obtained by exploiting the edges of a particular spectral region (namely, the photonic band gap), in which light is not allowed to pass through [12–15]. Instead, in a random photonic structure, with high and low refractive index materials randomly distributed [16–18], laser emission is observed in correspondence of random transmission depths [19–20].

In one dimension, disordered photonic systems are realized with a simple, random alternation of high and low refractive index layers [21]. Nevertheless, the optical properties of these materials are very intriguing, testified by several recent works. For example in 2005, Bertolotti et al. experimentally observed optical necklaces [22], while in 2007 Ghulinyan observed periodic oscillations in the average transmission as a function of the sample length [23]. Lately, the Shannon index, a diversity index used in information theory and statistics [24], has been used to quantify the evenness in one dimensional photonic crystals [25,26].

In this paper, we investigate the optical properties of one dimensional disordered photonic structures by grouping high refractive index layers in clusters, randomly distributed. We control the maximum size of the cluster and the ratio between high and low refractive index layers (in the following referred to as dilution). By studying the total transmission as a function of the maximum cluster size, we observe a trend with a dip in the transmission followed by periodic oscillations.

2. Methods

We have considered within this study photonic crystals with unit cells of different dimensions. As shown in Fig. 1a, a unit cell is created by m layers containing one high refractive index layer; the unit cell then contains $m-1$ low refractive index layers. $1/m$ depicts the high refractive index layer dilution in the medium. For example, if $m = 10$, 1 layer each 10 layers in the medium will be a high refractive index layer, and we refer to this structure as a 1/10 diluted structure. In this work, we have used different dilutions: 1/2, 1/4, 1/6, 1/8, 1/10 and 1/12. For the different photonic crystal structures we always have 100 unit cells, i.e. 100 high refractive index layers, such that the total number of layers in the structure is, respectively, 200 for $m = 2$, 400 for $m = 4$, 600 for $m = 6$, 800 for $m = 8$, 1000 for $m = 10$, 1200 for $m = 12$.

To realize disorder in the structures, we grouped the high refractive index layers in clusters corresponding to each photonic crystal. The cluster size ranges from 1 to k_{max}, where k_{max} is the maximum cluster size. Thus, by increasing the parameter k_{max}, we increase the possible cluster size of high refractive layers in the structure. Once the cluster distribution is computed, we randomly distribute these clusters in the structures. The k_{max}

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parameter can be viewed as a way to control the homogeneity of the medium: the larger k_{max} is, the less homogeneous the medium.

Thus, all the crystals investigated in this study show the same number of refractive elements, but differ in the manner of aggregation of the high refractive layers, i.e. homogeneity. The photonic crystals present the high refractive layers with periodic arrangement, evenly distributed among the crystal, while the disordered structures show high refractive index clusters of sizes up to k_{max} and a stochastic distance among them.

To give an example, a structure with $m = 4$ and $k_{max} = 2$ has 100 high refractive index layers, 300 low refractive index layers, and the clusters made with high refractive index layers have a maximum size of 2 layers. Differently, a structure with $m = 4$ and $k_{max} = 5$ has 100 high refractive and 300 low refractive index layers, but the clusters made with high refractive index layers have a maximum size of 5 layers. In this manner, the $k_{max} = 2$ crystal is more uniform (more homogeneous) than the $k_{max} = 5$ medium. Examples of disordered structures for $m = 4$ and $k_{max} = 1$, 2 and 3 are shown in Fig. 1b, where only the first 24 layers are depicted.

Calculations of the light transmission through the media (in the spectral region corresponding to the photonic band gap of the periodic photonic crystal) are performed with the transfer matrix method [27]. We have considered isotropic, non-magnetic materials that shape the system, where glass is the sample substrate, the multilayer structure and air, and the light incidence normal to the stacked layer surface. n_0 and n_S are the refractive indexes of air and glass, respectively. E_m and H_m are the electric and magnetic fields in the glass substrate. To determine the electric and magnetic fields after passing through the multilayer structure, E_0 and H_0, we have solved the following system:

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = M_1 \cdot M_2 \cdots M_n \begin{bmatrix} E_m \\ H_m \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} E_m \\ H_m \end{bmatrix} \tag{1}$$

where

$$M_j = \begin{bmatrix} A_j & B_j \\ C_j & D_j \end{bmatrix},$$

with $j = (1,2,\ldots,m)$, is the characteristic matrix of each layer. The elements of the transmission matrix *ABCD* are

$$A_j = D_j = \cos(\phi_j), B_j = -\frac{i}{p_j} sin(\phi_j), C_j = -ip_j sin(\phi_j) \tag{2}$$

where n_j and d_j are contained in the angle ϕ_j, and represent the effective refractive index and the thickness of the layer j. In the case of normal incidence, the phase variation of the wave passing the j-fold layer is given as $\phi_j = (2\pi/\lambda)n_j d_j$, while the coefficient $p_j = \sqrt{\varepsilon_j/\mu_j}$ for the transverse electric wave and $q_j = 1/p_j$ for the transverse magnetic wave. Inserting Eq. (2) into Eq. (1) and using the definition of the transmission coefficient,

$$t = \frac{2p_s}{(m_{11} + m_{12}p_0)p_s + (m_{21} + m_{22}p_0)} \tag{3}$$

gives the light transmission as

$$T = \frac{p_0}{p_s}|t|^2 \tag{4}$$

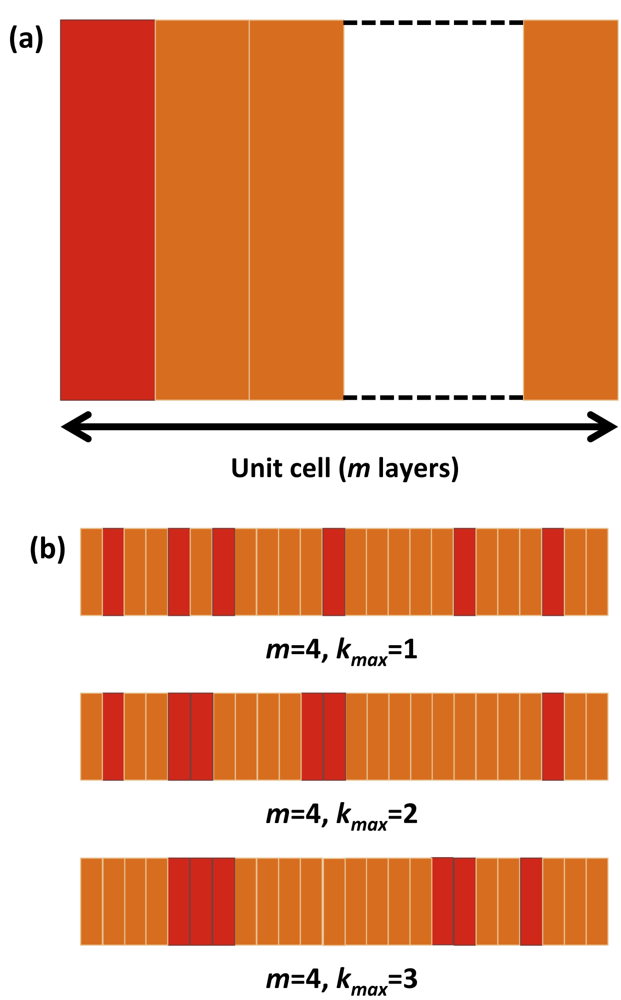

Fig. 1. (a) Scheme of the unit cell of a photonic structure with periodic arrangement. For each high refractive index layer (red layer), the unit cell contains $m-1$ low refractive index layers (orange layers). m is an index of the high refractive index layer dilution in the medium. For example, if $m = 10$, 1 layer each 10 layers in the medium will be a high refractive index layer, and we refer to this structure as a 1/10 diluted structure. (b) Examples of disordered structures for $m = 4$ and $k_{max} = 1$, 2 and 3 (we depict only the first 24 layers). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

In Fig. 2 we show the transmission spectra of a periodic photonic crystal and of a disordered photonic crystal with $m = 8$. In

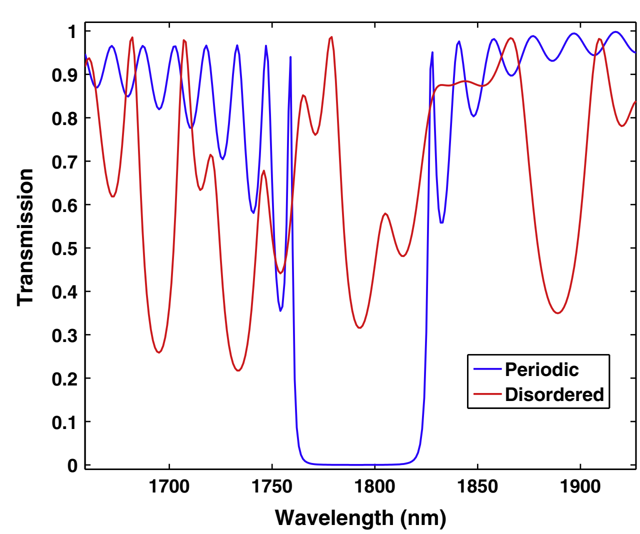

Fig. 2. (a) Transmission spectra of a periodic photonic crystal; the photonic crystal is made by 100 unit cells and each unit cell consists of 1 high refractive index layer and 7 low refractive index layers (we call it a crystal with 1/8 dilution). (b) Transmission spectra of a disordered photonic structure with 1/8 dilution and with maximum cluster size $k_{max} = 4$.