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Control of the average light transmission in one-dimensional photonic structures by tuning the random layer thickness distribution

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ABSTRACT

In this work we have studied the optical properties of disordered photonic structures, in which we have controlled the distribution of the random layer thickness. Such structures are characterized by the usual alternation of high and low refractive index layers, but the layer thickness follows the aforementioned distribution. We have used two types of distributions: a distribution in which each thickness has the same probability to occur and one in which the thickness follows a Gaussian function. We have simulated the average transmission all over the spectrum for photonic structure characterized by a different width of the distribution. We have found that the choice of the distribution of the layer thickness is a control of the average transmission of a random photonic structure. Photonic structures, fabricated following these distributions, can be interesting for the fabrication of bandpass optical filters.

1. Introduction

Periodicity in one dimensional multilayer photonic structures is interrupted by introducing different materials, by randomizing the sequence of the layers, and by randomizing the thickness of the layers [1–3]. Another type of non-periodic photonic structures are quasicrystals [4–6] and, the breaking of the periodicity in photonic structures is widely studied also in two and three dimensions [7–9]. While periodic photonic crystals show a characteristic photonic band gap [10,11], with a spectral position that follows the Bragg–Snell law [12,13], the disordered structures show randomly arranged transmission depths in the transmission spectrum [1,14–16]. The disordered photonic structures can be employed for the realization of random lasers [2,17–19] and for light trapping in photovoltaic cells [20].

It has been theoretically proposed [21] and experimentally demonstrated [22] that the average transmission of a photonic structure characterized by a random layer thickness is lower with respect to the one of a periodic photonic crystal. But in these two studies an analysis of the influence of the distribution of the random layer thicknesses on the optical properties of the disordered structures is missing.

In this work we have studied, by using the transfer matrix method, the transmission spectrum of the disordered structures in which the layer thickness follows two types of distributions. The first distribution results in a range of thicknesses with the same probability to occur, while the second distribution follows a Gaussian function. The simulations take into account the Sellmeier equation of Silicon dioxide and Zirconium dioxide. We show that the choice of the distribution strongly affects the optical properties of the structures.

2. Methods

All the one-dimensional photonic structures studied in this work are composed by 28 alternating layers of Silicon dioxide and Zirconium dioxide, respectively. The dispersion formula (Sellmeier equation) of the refractive index of Silicon dioxide is

$$n_{SiO_2}^2(\lambda) - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}$$

as reported in [23], while the formula for Zirconium dioxide is

$$n_{ZrO_2}^2(\lambda) - 1 = \frac{1.347091\lambda^2}{\lambda^2 - 0.062543^2} + \frac{2.117788\lambda^2}{\lambda^2 - 0.166739^2} + \frac{9.452943\lambda^2}{\lambda^2 - 24.320570^2}$$

as reported in [24].

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The thicknesses of the layers are random, following two types of distributions. In the first case, the thickness of the ith layer is $d_i = d \pm s$, where d = 100 nm and s is an integer that spans from 0 to $\eta/2$ (η is an even number). For example, if $\eta = 20$, the random integer spans from 0 to 10. Since in this distribution all the layer thicknesses in the range η have the same probability to occur, we will call it flat distribution. In the second case, the probability of a random integer to occur follows a Gaussian function, centered at 100 nm and with a standard deviation σ. We simulate transmission spectra for different η and for different σ.

As shown in Fig. 1, a Gaussian function, with $\sigma = 30$, results in a probability for a 100 nm layer thickness of about 1.33%, while the probability to have a 90 nm thick layer is about 1.26%, for 70 nm the 0.55% etc. The Gaussian function is truncated to the range [1–200].

To simulate the transmission spectra of the photonic structures, we have employed the transfer matrix method [25–27]. We have integrated the transmission all over a range between 300 and 1200 nm (step of 1 nm), normalizing to the transmission of a perfectly transparent material (i.e. 100% transmission at any wavelength). For each η or σ, we have simulated 1000 different thickness random sequences.

3. Results and discussion

First, we have calculated the transmission spectra of random photonic structures with layer thicknesses following the flat distribution. For the readers information, the transmission spectrum of the periodic photonic crystal with the same parameters shows a photonic band gap centered at about 730 nm with a full width at half maximum (FWHM) of 190 nm. Instead, the disordered structure corresponding to $\eta = 120$ shows very intense transmission depths all over the studied spectral region (Fig. 2a). In Fig. 2b we show the histograms of the normalized average transmission for different values of η.

We observed that the normalized average transmission decreases by increasing η. Concomitant with the normalized average transmission lowering, a increase of the deviation from the mean value occurs (the histograms become broader by decreasing η). These findings are very clear looking at the trend of the normalized average transmission as a function of η.

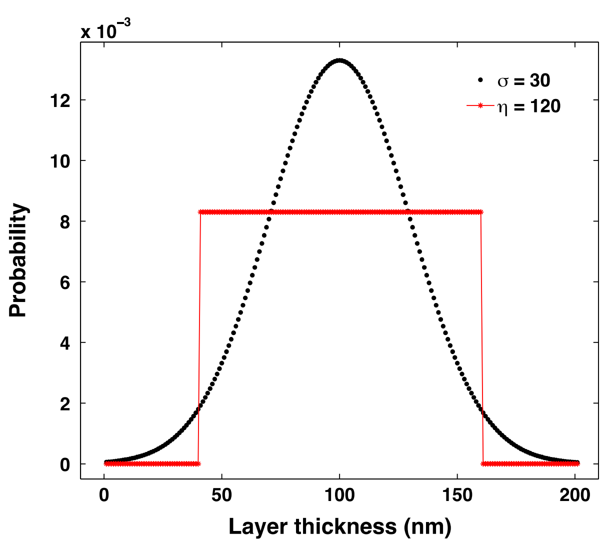

Fig. 1. Flat distribution with $\eta = 120$ (red stars with red line) and Gaussian function, with unitary area, centered at 100 nm and with $\sigma = 30$ (black circles). The Gaussian function is truncated to the range [1–200]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

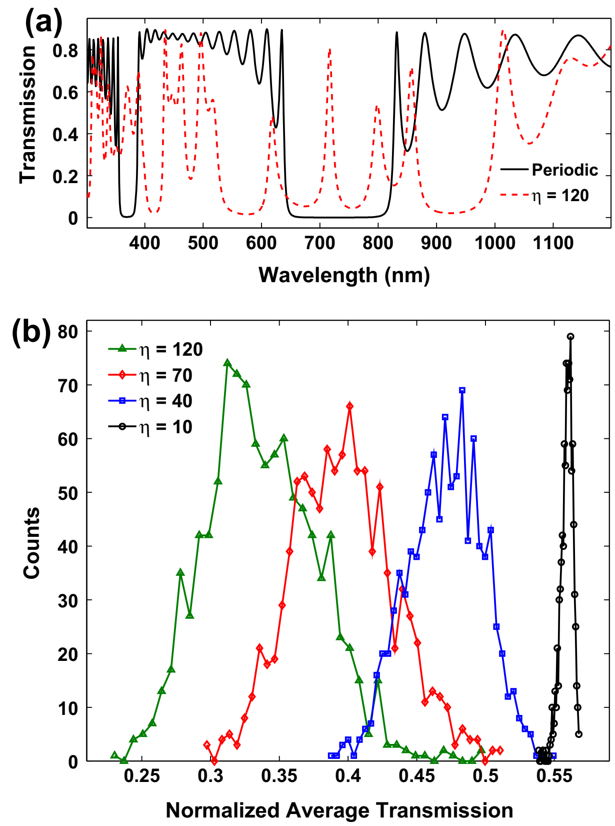

Fig. 2. (a) Transmission spectra of a periodic photonic crystal (black curve) and of a disordered photonic structure corresponding to $\eta = 120$ (red dashed line). (b) Histograms of the normalized average transmission, in the range 300–1200 nm, for different values of η of the distribution of the layer thickness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The values, together with the standard deviation of the normalized average transmission, are reported in Table 1. With $\eta = 0$ we have referred to the perfect periodic structure, in which all the layers are 100 nm thick.

The decrease of the normalized average transmission is quite remarkable for large values of η. For example, the normalized average transmission for $\eta = 100$ is already the 61% of the one of the periodic structure, testifying the significant role played by the non uniformity of the layer thickness. The increase of such non

Table 1
Normalized average transmission, with the corresponding standard deviation, as a function of the value of η.

η	Normalized average transmission	Standard deviation
0 (Periodic)	0.5691	–
10	0.5590	0.0044
20	0.5348	0.0123
30	0.5027	0.0207
40	0.4707	0.0275
50	0.4419	0.0323
60	0.4166	0.0358
70	0.3964	0.0370
80	0.3808	0.0386
90	0.3608	0.0402
100	0.3505	0.0386
110	0.3440	0.0396
120	0.3372	0.0405
150	0.3424	0.0435
200	0.3840	0.0535