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INFLUENCE OF DISORDER ON A CHIRPED MIRROR BASED ON POROUS SILICON

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Abstract—We report on the modeling of light reflection in disordered chirped mirrors with a photonic band gap in the visible. The stop band limits have a threshold-like behavior as a function of disorder and sustain a certain amount of disorder before changing. We determine the disorder value that leads to a substantial broadening of the total reflection range.

1. INTRODUCTION

Photonic crystals (PC) [1] are versatile composite structures with an optical index that is periodic on the scale of the wavelength, which offer possibilities for controlling the light propagation. Striking progress has been achieved in three dimensional photonic crystal structures to obtain a complete photonic band gap [2]. However, serious technological problems and high cost of materials inhibit the applications of three-dimensional (3D) materials, especially in the visible. On the other hand, one-dimensional (1D) layered materials can be easily fabricated by various techniques. One of these technologies is based on the fabrication of porous silicon [3–6], and many devices have been suggested such as dielectric mirrors [7], time delay devices [8], and high quality filters [9].

Dielectric mirrors are the simplest one-dimensional case of photonic crystals. The dielectric mirror is made of low index materials and is designed to reflect a single wavelength of light. The dielectric constant is periodic along one axis, and the crystal is made by the repetition of an unit cell. In Fig. 1, we illustrate the dielectric mirror. In panel (a) we show the unit cell composed by two different

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materials, n_a and n_b. The thicknesses are d_a and d_b, respectively. The constitutive parameters of the unit cell are determined by the quarter wave condition $\lambda_0/4 = n_a d_a = n_b d_b$ in order to reflect the wavelength λ_0 that lies within the photonic band gap. The dielectric mirrors are illustrated in panel (b). These structures are widely used as effective mirrors in laser cavities [10].

A chirped mirror is made to reflect a wide range of frequencies. In panel (c) we illustrate the chirped mirror composed by the union of three sub-mirrors to reflect different wavelengths, λ_1, λ_2 and λ_3. The result is a mirror that reflects a range of frequency as large as desired.

Wide band gap is a milestone in the study of photonic crystals. Large refractive index and specific geometries are required to obtain the widest photonic band gap for two and three-dimensional structures [2, 11]. Nevertheless, the simplicity of fabrication and design of chirped mirrors make them an important option for technological applications where an efficient and compact mirror is desired [12, 13].

Now we turn to the question of disorder in chirped mirrors. According to theoretical [14] and experimental studies [15], disorder in photonic crystals leads a band gap extension due to the increment of coherent backscattering. On the other hand, the allowed modes in the pass-band region disappear due to the extinction of constructive interference. These disorder related effects have not been studied in chirped mirrors.

The aim of this paper is to investigate the disorder in chirped mirrors designed to reflect light in the visible region. We study the light reflection of disordered chirped mirrors under random variations of the layer thickness.

2. DISORDER ON CHIRPED MIRRORS

For the theoretical calculation we use the well-known Transfer Matrix Method [10]. We start our analysis by considering an experimental chirped mirror recently reported in [5], which is composed of alternating high and low refractive index layers ($n_a = 1.4$ and $n_b = 1.95$) and designed to reflect visible light. The thickness of adjacent mirrors increases following the empirical relation $\lambda_{i+1} = \lambda_i + 3nm$, where nm is the abbreviation of nanometer ($nm = 1 \times 10^{-9} m$) [6].

The presence of disorder on the thickness layers is illustrated in Fig. 2. We show in panel (a) the thickness $d^0_{a(b)}$ as the nominal value without disorder. The value of the thickness in presence of disorder, $d_{a(b)} = d^0_{a(b)} + \delta\sigma_{a(b)}$, is illustrated in panel (b). Here $\sigma_{a(b)}$ is the maximum variation of the thickness, and δ has a random value on the interval $\delta[0:1]$.

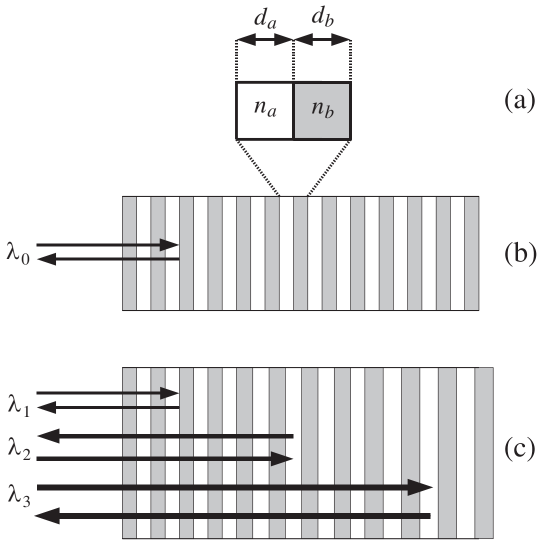

Figure 1. Schematic drawing of a dielectric mirror: (a) The unit cell, (b) the dielectric mirror and (c) the chirped mirror.

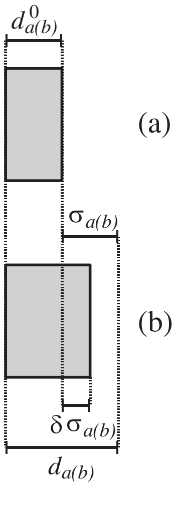

Figure 2. Disorder in the thickness. Panel (a) shows the layer of thickness $d^0_{a(b)}$ without disorder. Panel (b) illustrates the presence of disorder.

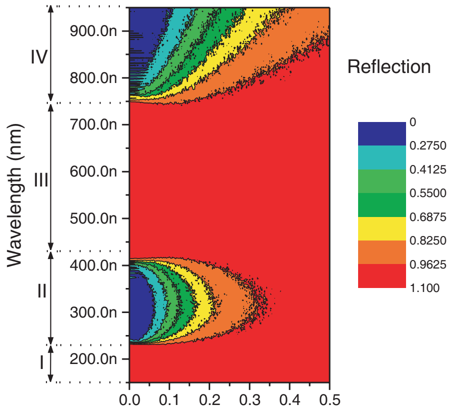

Figure 3. Variation of the light reflection as a function of the amount of disorder, δ. For $\delta = 0$ we identify four zones. Zone I and III have total reflection. Zone II and IV allow the light transmission through the chirped mirror.

We choose for our calculation the case of random variation of the individual layers, $\sigma_{a,b} = d^0_{a,b}$. In Fig. 3, we present the light reflection as a function of the disorder parameter δ. In the case of $\delta = 0$ we found a broad mirror in the visible in good agreement to the experimental result reported in Fig. 7 of [5]. For each non-zero value of disorder we have performed an average over 100 different disorder configurations to properly sketch the role of disorder [16].

For the case of $\delta = 0$ we identify four different regions for the light reflection. First, we identify a zone of total reflection from 100 nm to 236 nm which is related to the existence of a PBG. Second, we have a region from 236 nm to 433 nm with non-zero reflection. This zone is related to the existence of a band. The third region defines the existence of a mirror for the visible in the range from 433 to 750 nm. Finally, we show a fourth region from 750 to 900 nm where exists another band. We have observed that these four regions change as the value of the disorder increases. In the cases of the first and third regions, the total reflection enlarges as the disorder increases. Conversely, the regions II and IV diminish with the increment of the disorder. Moreover, region II disappears for a disorder value bigger than 0.35. The enlargement of region III is in good agreement with previous studies of disorder in 1D-PC where a broadening of the total reflection as disorder increases has been reported [14, 16]. Now, we can point out two important observations. First, we can only assure the sign of the photonic band (or the existence of high light transmission) in region II for $\delta < 0.05$. Further from this threshold value of disorder the light reflection changes drastically. The second conclusion is that the region II — the band — disappears for disorder values of $\delta > 0.35$.

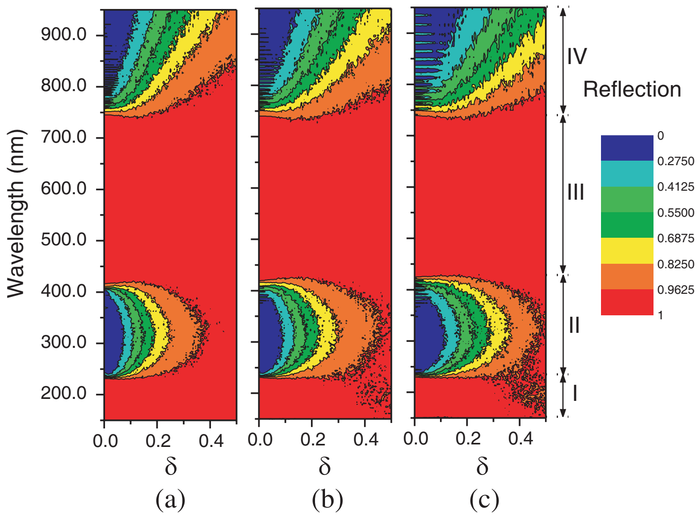

Figure 4. Variation of the light reflection as a function of the amount of disorder, δ. In panels (a), (b), and (c), we show the reflection for the case of three, two and one unit cell by submirror.

Now we turn our attention to the optimization of the chirped mirror. In [5] the chirped mirror is composed by the union of 77 submirrors; each one is composed of 4 unit cells, thus, with a total of 308 ($77 * 4$) unit cells. We investigate the influence of the disorder on the light reflection for the case of three, two and one unit cells in the submirrors. Fig. 4 shows the variation of the reflection as a function of the disorder for these three cases in panels (a), (b) and (c), respectively. We observe that in a similar way to the chirped mirror of 4 layers by submirror of the precedent case (Fig. 3), we define regions I, II, III and IV. We observe that region III always enlarges as the amount of disorder increases. On the other hand, region II becomes more resistant to the presence of disorder as the number of unit cells in the individuals sub-mirrors decreases.

3. CONCLUSION

In summary, we have studied the light reflection in disordered chirped mirrors under random variations of the layer thickness. Our results indicate that the stop band allows a certain threshold value of disorder before changing. After a certain value of disorder, the stop band region enlarges dramatically. Conversely, the pass band region gradually turns in a stop band because the constructive interference of the propagating modes disappears as the disorder increases. We conclude that even if the manufacturing process brings with it the practical reality of random errors introduced during the fabrication, a certain amount of these random errors will not affect the desirable stop bands of chirped mirrors.

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