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X-ray filter using multilayers with modulated refractive index

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Abstract

We have numerically computed the reflectivity of X-rays incident normally onto metallic multilayers. The structure consists of two alternating types of constituent layers. One type has the same refractive index whereas the refractive index of the other type is modulated by a Gaussian function along the normal direction. We have found that the reflectivity of the structure becomes unity in a wide range of wavelengths. The bandwidth of the reflection can be finely tuned by varying the width of the Gaussian function. © 1998 Published by Elsevier Science B.V.

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1. Introduction

Recent developments in multilayer technology have made it possible to tailor specific properties of artificial materials to nearly arbitrary precision. Multilayer structures of different materials have been designed and fabricated to reflect X-rays, which are more difficult to reflect than visible light [1,2]. Recently, a novel and sophisticated design has been proposed for a broad bandwidth X-ray mirror using a multilayer of alternating high and low refractive indices lying in a vacuum, where the thickness of each layer is random [3]. Similarly, selective X-ray filters can be designed using quasiperiodic multilayers, where layers of high and low refractive indices alternate according to the Fibonacci sequence [4].

In a different context, Tung and Lee [5] have recently proposed a novel quantum mechanical energy band-pass filter using semiconductor superlattices with Gaussian potential profile, allowing the incident electrons to be nearly unscattered when the impinging electron energy lies in the passband. In this Letter we exploit the ideas of Tung and Lee [5]. We propose a novel broad bandwidth X-ray filter based on a multilayered system where the constituent layers are of two different types. One type has the same refractive index whereas the refractive index of the other type is modulated by a Gaussian function along the normal direction. We shall demonstrate that Gaussian multilayers (GMs) could be used as improved soft X-ray mirrors with tunable bandwidth where the reflection characteristic is completely flat. This may be compared with recent results reported on multilayers with randomly varying thicknesses, where reflectivity presents sharp dips in the reflecting band [3]. We will compare the refractive patterns obtained with both approaches later.

The system we study in this work is a GM placed in vacuum, consisting of two different kinds of layers, A and B, of thickness d_A and d_B, respectively. Ev-

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ery layer of type A has the same refractive index n_A. However, the refractive index of the k-layer of type B is set according to a Gaussian function expressed by $n_B \exp[-(k-k_0)^2/\sigma^2]$, where k_0 labels the innermost layer of type B. The width of the Gaussian function is controlled by varying the parameter σ. The reflectivity of X-rays incident normally onto the GM structure is then easily computed numerically using the Rouard method (see, e.g., Ref. [3]). We have considered that $d_A = d_B$ although we have checked that our general conclusions are independent of this constraint. To facilitate direct comparison with previous studies of Yoo and Cue in random multilayers [3], we have taken the same physical parameters, namely $n_A = 0.9200$ and $n_B = 0.9995$. In this way we can separate those features of the reflectivity spectrum stemming from the Gaussian modulation in a straightforward manner.

In periodic multilayers, where the refractive indices take on two values arranged according to a periodic sequence $n_A n_B n_A n_B \ldots$ with $d_A = d_B = 50$ Å, the reflectivity shows a pronounced peak centered at 192 Å, with a bandwidth of about 11 Å [3], as shown in Fig. 1a for 102 layers. The periodic multilayer can be viewed as a GM whose width is much larger than the length of the system along the normal direction. Figs. 1b and 1c show the behavior of the reflectivity pattern in GM on decreasing σ. The number of layers is $N = 102$ in each case. Increases in the bandwidth are clearly seen with decreasing σ. It is most remarkable that a completely flat stopband results and the boundaries between the stopbands and passbands are abrupt, especially in the high wavelength region.

Absorption in the materials leads to a lower reflectivity. Dashed lines in Fig. 1 show the effects of the absorption on the reflectivity pattern. The absorption comes from the imaginary part of the dielectric constant and can be analyzed by taking complex refractive indices $\tilde{n}_A = n_A + i\beta_A$ and $\tilde{n}_B = n_B + i\beta_B$. In our example we have taken $\beta_A = 0.005$ and $\beta_B = 0$. In addition, we have also assumed that the imaginary part of the refractive index is modulated by the same Gaussian function. It becomes clear from Fig. 1 that the stopband remains extremely flat even in the presence of absorption.

Now we compare our results to previous approaches based on random multilayers [3]. Fig. 2a displays the reflectivity pattern of a nonabsorbing GM with $N = 102$, $\sigma = 50$ and $d_A = d_B = 75$ Å. According

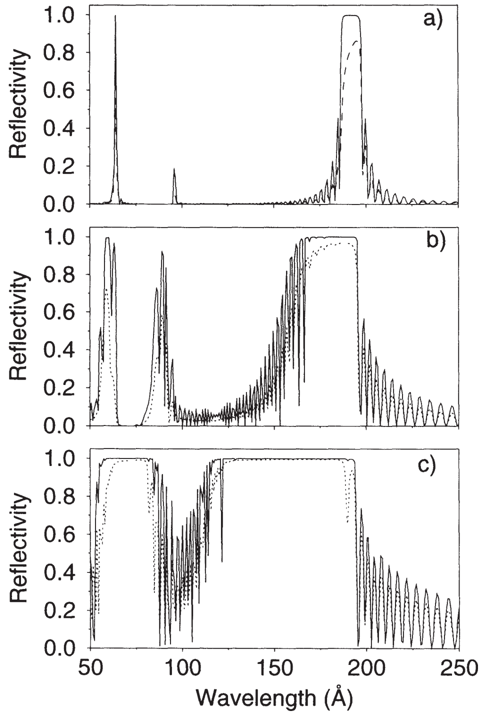

Fig. 1. X-ray reflectivity of nonabsorbing N-multilayer structures ($N = 102$) with two basic layers of refractive indices $n_A = 0.9200$ and $n_B = 0.9995$, each layer thickness being $d_A = d_B = 50$ Å. (a) A periodic arrangement of layers; (b) and (c) GMs with $\sigma = 100$ and $\sigma = 50$, respectively. Solid (dashed) lines correspond to nonabsorbing (absorbing) structures.

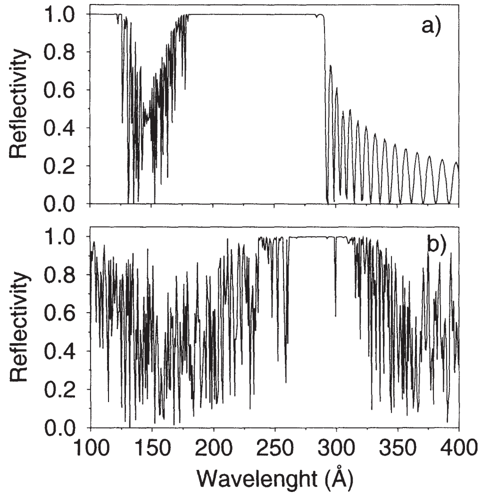

Fig. 2. Comparison of the reflectivity of the nonabsorbing (a) GM with $d_A = d_B = 75$ Å, $\sigma = 50$, and $N = 102$ with the (b) random multilayer with $d_{\text{mean}} = 75$ Å, $d_{\text{fluc}} = 25$ Å and $N = 1002$.

to Ref. [3], random multilayers are obtained by allowing the thickness of the k-layer to fluctuate randomly, $d_k = d_{\mathrm{mean}} + \xi_k d_{\mathrm{fluc}}$, where $-1 \leqslant \xi_k \leqslant 1$ is a random number with uniform probability distribution. Fig. 2b presents the reflectivity of a nonabsorbing random multilayer with $N = 1002$, $d_{\mathrm{mean}} = 75$ Å and $d_{\mathrm{fluc}} = 25$ Å. Sharp dips in the reflectivity can be seen in the case of random multilayers, whereas reflectivity is completely flat in the case of GMs. In addition, the boundaries between the stopbands and passbands are not well defined in random multilayers. It was shown previously by Yoo and Cue [3] that these dips can be significantly reduced by increasing the number of layers and would lead to better performance of the mirror. We notice that GMs present better reflection properties even when the number of layers is one order of magnitude smaller. This result is important for applications since absorption effects should be much lower in GMs than in random multilayers.

In summary, we have proposed a novel X-ray filter using multilayers with Gaussian-modulated refractive index. The additional parameter we introduce, namely the width of the Gaussian function, allows us to finely control the reflectivity pattern. In particular, we have found a completely flat broadband in the X-ray reflection. Most important, this characteristic is preserved even when absorption is considered. Our design improves previous ones based on random multilayers [3] because there are not dips in the stopband and also the number of layers can be dramatically reduced. Therefore, GMs open new possibilities in the *engineering* of soft X-ray devices.

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