Bragg Reflections From Periodic Multilayers as a Means for the Generation of X-ray Guided Modes

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Introduction

It is well known that critical-angle x-ray specular reflection from high-density reflecting layers can effectively be used in experiments for the excitation of x-ray guided modes [1,2]. Standard waveguide structures based on such a reflection consist of a low-density guiding film sandwiched in between the reflecting layers [1] or represent an air gap between two reflecting slabs [2]. A set of guided modes can be generated inside the waveguide by illuminating it with a parallel monochromatic x-ray beam. The x-ray beam produces the guided modes at specific discrete grazing angles lying below the critical angle for total external reflection for the reflecting layers [1,2]. The guided mode is a wave propagating in a guiding film (or an air gap) plane. At the same time, a standing wavefield appears along the direction normal to this plane and the amplitude of the mode exponentially decays deep into both the cladding layers. In fact, the critical-angle waveguides are x-ray counterparts of thin-film optical waveguides that employ total internal reflection of visible light.

In the mean time, in addition to the thin-film optical waveguides, Bragg reflections of artificial multilayers with a periodically modulated refraction index can be used for guiding visible light [3]. At present, one-dimensional periodic synthetic multilayers ’’tuned to’’ the x-ray wavelength are also easily available. In this conference paper we analyze the possibility of generating hard x-ray guided modes, which is connected with the use of Bragg reflections from multilayers. The x-ray refraction index is nearly equal to 1. Therefore, to demonstrate substantial Bragg reflection the x-ray multilayers are to be composed of, at least, a few tens of bilayers. The intensity of such a reflection is also reduced by interface roughnesses. In the paper, we show that although the x-ray multilayers have the above-mentioned peculiarities, nevertheless their Bragg reflections can be employed for the x-ray guided mode generation. Our analisys is based on the results of a comprehensive theoretical study which are presented in Refs [4,5].

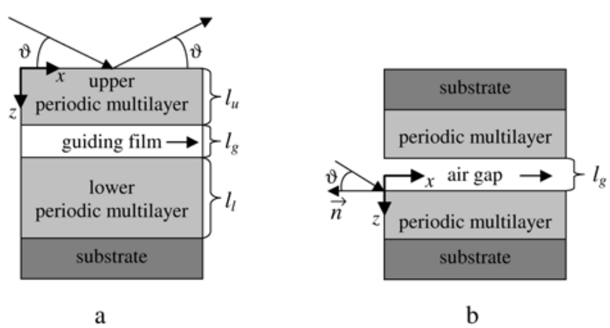

Fig. 1.

Schematic view of multilayer-based waveguides of two types. (a) A guiding film is sandwiched between two periodic multilayer structures; l_u, l_g and l_l are the thicknesses of the upper multilayer, the guiding film and the lower multilayer, respectively. ϑ is the grazing angle for a primary X-ray beam that is incident on the z = 0 surface of the upper multilayer. (b) A primary X-ray wave illuminates an air gap between two identical periodic multilayers and generates a guided mode within it; ϑ is the grazing angle; l_g is the width of the gap. From [5].

Methods and Materials

We consider multilayer-based waveguides of two types. One waveguide represents a guiding film that is placed between upper and lower periodic multilayers (Fig.1a). The thicknesses of these multilayers are different. A primary x-ray beam is incident on the z=0 surface of the upper multilayer. The appearance of the guided wave inside the guiding film is accompanied with a dip in an x-ray specular reflectivity curve from the waveguide.

The other waveguide consists of an air gap between two space-separated multilayers (Fig. 1b). An x-ray beam illuminates the gap entrance and gives rise to a guided wave which propagates in the x-axis direction. After this wave reaches the gap exit, it continues to spread outside the waveguide like a compressed x-ray beam.

In the paper a hypothetical Ni/C multilayer-based waveguide is investigated and numerical simulation of the guided modes is performed. Details of a numerical modelling approach can be found in Refs. [4,5]. The multilayer is located on an Si substrate. Each bilayer of the multilayer is composed of the particular layers with the thicknesses $l_{Ni}=l_C=5$ nm. The period of the multilayer is $T= l_{Ni}+l_C=10$ nm. In numerical modelling we used the following values of the densities of the materials: $\rho_{Ni}=8.87$ g/cm^3, $\rho_C=2$ g/cm^3, $\rho_{Si}=2.32$g/cm^3. The r.m.s. roughness σ was assumed to be 0.5 nm for all the interfaces.

Results

Here we consider numerical modeling examples of hard x-ray guided modes generated with s-polarized CuKα radiation. These modes are TE$_m$ guided modes, where m is the mode number, m=0,1,2,... . The electric field vector of the TE$_m$ mode is perpendicular to the xz plane (see Fig.1). In the case of the planar multilayer-based waveduide (see Fig.1a), the guided mode appears in a guiding film sandwiched in between two periodic multilayers. The guided waves can be excited within a high-intensity Bragg reflection domain. The primary x-ray beam tunnels into the guiding film and forms the guided mode by means of subsequent Bragg reflections from the lower periodic multilayer and the reverse side of the upper periodic multilayer. To effectively excite the guided wave inside the guiding film, the lower and upper parts of the waveguide should be characterized by strong Bragg reflections. However, the upper part should also have an optimal thickness which provides both

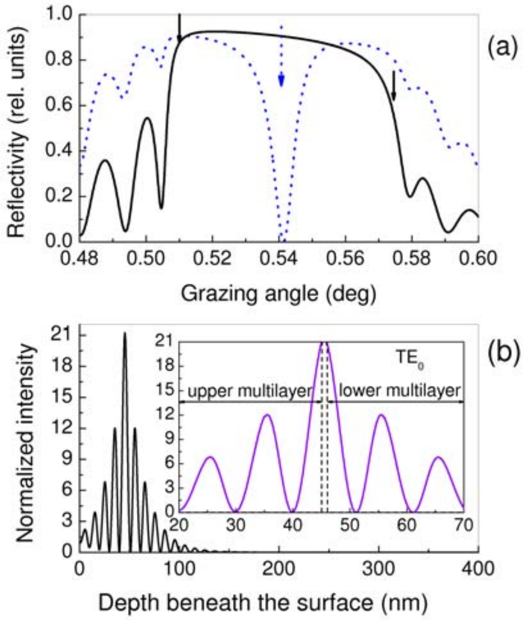

Fig. 2.

(a) A calculated X-ray specular reflectivity curve from a multilayer-based waveguide with a carbon guiding film (dotted line). The thickness of the film is l_g=1 nm. The dotted arrow shows a dip in the reflectivity curve caused by the excitation of the TE_0 guided mode inside the guiding film. The solid line represents a reflectivity curve from the lower multilayer (see Fig.1a). The solid arrows indicate the beginning (ϑ=0.510°) and the end (ϑ=0.574°) of the first-order high-intensity Bragg reflection domain where the guided modes can be effectively generated. The structural parameters of the waveguide are presented in the text. (b) The calculated distribution of the intensity of the TE_0 guided mode inside the multilayer-based waveguide with a carbon guiding film (see main text). The distribution corresponds to the grazing angle ϑ=0.542° that lies inside the dip shown in Fig2a. The inset indicates the neighborhood of the guiding layer on an enlarged scale. The guiding layer area is bounded by two vertical dashed lines. From [5].

strong Bragg reflection and effective penetration of the primary x-ray beam inside the guiding layer. If the upper multilayer is too thick, then the primary x-ray beam can not reach the guiding film because of extinction phenomenon caused by strong (dynamical) Bragg diffraction from the multilayer. By using a simple formula [5], one can calculate the thickness of the guiding film which is needed for exciting the TE_m mode, m=0,1,2,..., at a given grazing angle ϑ lying in the high-intensity Bragg reflection domain. As a numerical example, we show the TE_0 mode in a carbon guiding film with the thickness of 1 nm. (Fig.2). The lower periodic multilayer consists of twenty Ni/C bilayers, while the upper multilayer involves 4.5 bilayers: four Ni/C bilayers and one additional Ni layer (one-half the bilayer). The structural parameters of the bilayers are presented in the previous section "Methods and Materials". The Bragg angle for the first-order reflection is 0.548° and the first-order Bragg reflection domain is determined by 0.510°≤ϑ≤0.574°. For the modes with the numbers m=0,1 to be excited within this Bragg reflection domain, the guiding layer thicknesses should be in the regions l_g≤3.9 nm and l_g=5.8-13.3 nm, respectively. As is seen from Fig.2, the appearance of the TE_0 mode causes a dip in the reflectivity curve and is accompanied by a 21-fold x-ray intensity enhancement inside the guiding layer. The amplitude of the guided mode exponentially decays upon moving away from the guiding film deep into each of the multilayers (see Fig2.a).

In the case of the multilayer-based waveguide with the air gap (see Fig.1b), the propagation of a guided mode in the x-axis direction is governed by a propagation length l_p. The $exp(-x/l_p)$ law determines the decrease of the intensity of the guided mode when it runs from the gap entrance at x=0. This decrease is due to x-ray absorption and x-ray diffuse scattering in the cladding multilayers. A numerical approach developed in Ref.5 makes it possible to calculate the propagation length depending on the air gap width and mode number m. By way of a numerical example, let us investigate the air gap between two identical 20-period Ni/C multilayers. In particular, if the width of the gap is l_g =3 nm, then only the TE_0 mode can be generated in the waveguide. This mode has the propagation length l_p=0.09 mm. The wider the air gap is, the more guided modes can be excited in the waveguide. If the gap width l_g= 500 nm, then the gap supports eight modes with the numbers m=58-65. All these modes have different propagation lengths. For example, the propagation lengths for the m=59 and m=65 modes are l_p=0.8 mm and l_p=0.17 mm, respectively. The value of the propagation length increases as the width of the air gap increases.

Discussion

The numerical modeling results presented in this paper demonstrate that Bragg reflections of multilayers produce hard x-ray guided modes. A substantial x-ray intensity increase in the guiding film upon the guided mode excitation can be achieved if the multilayer-based waveguide has optimal parameters. In particular, the TE_0 guided mode generation is accompanied by a 21-fold x-ray intensity enhancement inside the guiding film with the thickness of the order of 1 nm (see Fig.2b). Such an enhancement may be used in an experimental study of structural properties of thin buried films inside periodic materials. It should be noted that the low-density carbon guiding film is considered in the example presented above. However, numerical simulations, not shown here, indicate that guided modes appear in a high-density nickel guiding layer as well. In this case the intensity gain is lower in comparison with the guiding film made of carbon. Also, the intensity increase is restricted by the interface roughness and other imperfections [4].

For the multilayer-based waveguide with the air gap (see Fig.1b), the propagation of the low-order guided modes inside the waveguide is characterized by greater intensity losses than that of the high-order guided modes. The high-order modes are confined within a wide air gap, so that the penetration depth of the mode inside each of the cladding multilayers is substantially smaller than the width of the gap. Therefore the losses of the intensity inside the multilayers have a weak influence on the guided mode propagation.

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