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Bragg reflection from periodic helicoidal media with laterally graded refractive index

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ABSTRACT

Light interaction with a columnar structure of $In_xAl_{1-x}N$ where each column is a layered periodic helical medium with laterally graded refractive index is considered. It is demonstrated that such a columnar structure can be presented as a stack of layers with a gradient of the refractive index. To calculate reflectance in the proposed model, the 2×2 characteristic matrix method adopted for a gradient index medium was applied. The influence of the refractive indices (including absorption), parameters of the twisting, and thickness of the periodic structure on reflectance is studied. Cases of normal and oblique incident light are considered. The presented medium is a one-dimensional photonic crystal that can be utilized in many devices for light manipulation.

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1. Introduction

After interaction with a medium, an electromagnetic wave may change its direction of propagation, amplitude and polarization. Development of media for manipulation of electromagnetic waves is of particular interest in fundamental science as well as for practical applications. During the last decades, special attention has been paid to development of novel structured electromagnetic materials with a periodic texture on the scale of the wavelength of the interacting light. When the periodicity of the texture is roughly half the wavelength, these materials scatter photons in a manner similar to scattering of electrons by a crystalline array of atoms in a solid. Such materials possess a photonic bandgap, the optical analogue of the electronic bandgap in semiconductors and are known as photonic crystals [1,2]. These structures provide opportunities to shape and control the flow of light for optoelectronic and photonic applications [1–3]. Simple examples of one-dimensional (1D) photonic crystals are multilayered periodic structures that have found use in many applications in modern optics for example as filters and reflectors [4,5].

Chiral periodic structures are common in nature [6] and some of them exhibit unique optical properties [7]. For instance, there are no higher diffraction orders at normal incidence, the reflected light is elliptically polarized with the same handedness as the chirality of the structure, the ellipticity depends on the angle of incidence, and the elliptically polarized reflected light does not change its handedness as when it is reflected from achiral media [8]. Also, chiral structures are often employed in various optical systems, e.g. in cholesteric liquid-crystal-based devices [8–10], filters and fiber communication [11]. A feature shared between the natural and artificial chiral periodic structures reported earlier [7–11] is the birefringence of the twisted material, in which the optical axis is rotated in the plane of the structure. However, a twisted periodic medium can be locally isotropic with a helically modulated inhomogeneity. An example of such a medium based on a grading of refractive index is a columnar structure of $In_xAl_{1-x}N$ grown on a flat substrate as shown in the scanning electron microscopy image (Fig. 1a) [12]. Each column is a twisted hexagonal structure that can be presented as cylinder with a stack of thin layers, in which the refractive index monotonically changes along a fixed in-plane direction within a layer (Fig. 1b). The grading of the refractive index is depicted by shades of gray in Fig. 1b. Black and white correspond to the maximum (n_{max}) and minimum (n_{min}) values of the refractive index, respectively. The direction of the refractive index variation is uniformly twisted step-wise from one layer to the other.

The $In_xAl_{1-x}N$ lattice parameter increases internally from the Al-

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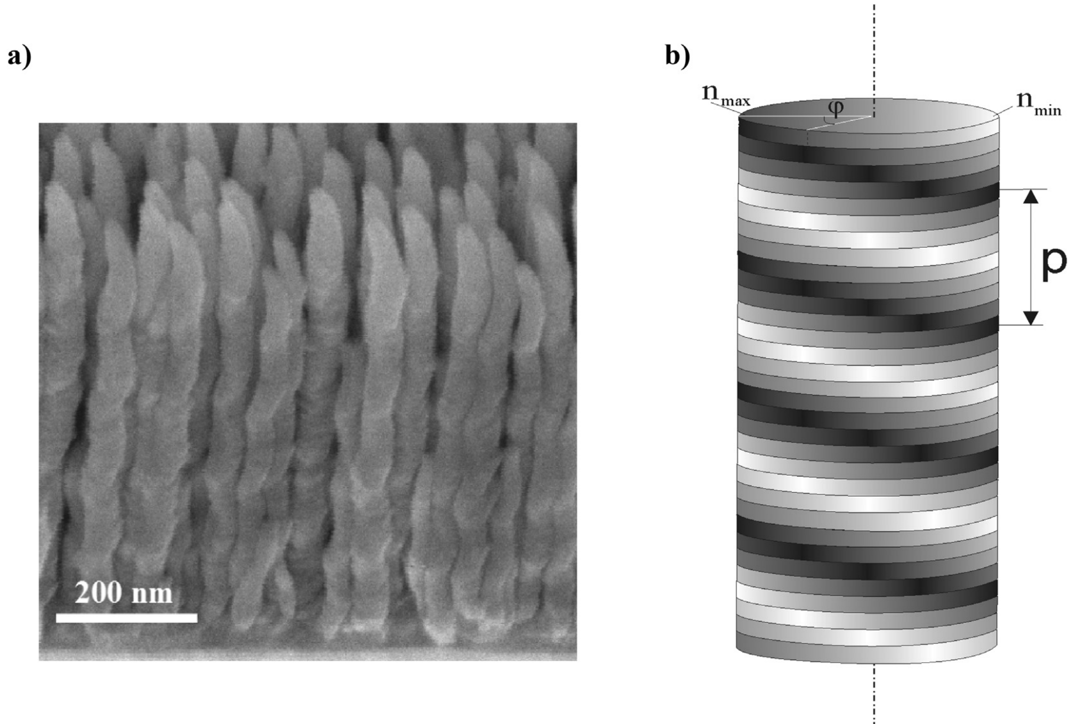

Fig. 1. A chiral periodical medium with laterally graded refractive index. a) A SEM image showing the columnar structure of an $In_xAl_{1-x}N$ alloy, b) Model presentation of the $In_xAl_{1-x}N$ alloy in the form of a layered twisted medium with laterally graded refractive index.

rich side of the column towards the In-rich side, producing a gradient lattice. This lateral gradient in composition and crystalline structure leads to a lateral variation of the physical properties such as band gap, electron mobility and optical constants. Another advantage of the twisted structure of $In_xAl_{1-x}N$ is that the columns are not bent which is the case non-twisted structures of the same material [13]. A regular arrangement of the layers in the column leads to high reflectance in a certain spectral range. The reflectance depends on the structure parameters such as the layer thicknesses, the twist angle between the layers and the period of the structure, and the gradient of the optical constants within the layers. In order to tailor optical properties, it is essential to have an insight into the influence of the structure parameters.

The goal of the present work is to study the reflectance of a periodic helical medium with a laterally graded refractive index as show in Fig. 1b and to explore how the structural parameters affect the optical characteristics. Specifically, the investigation will be carried out for a medium having the optical constants corresponding to $In_xAl_{1-x}N$ alloys. By doing so, the reflection characteristics of a twisted structure of laterally graded $In_xAl_{1-x}N$ can be predicted and utilized for development of physical devices.

2. Definition of the problem

The optical parameters of the columns, in particular the refractive index n, and its distribution, depend on the concentration x in the $In_xAl_{1-x}N$ alloy and the sample preparation conditions. This makes it possible to control n and, as a result, the optical properties of the whole structure in a desired way. The refractive index of the $In_xAl_{1-x}N$ alloys has been found [14–16] to have values between 2.1 ($x = 0.1$) and 2.8 ($x = 0.9$) in the visible spectral range. The absorption coefficient α can take values between 0 and $2.5 \cdot 10^5$ cm^{-1} depending on sample preparation conditions. The pitch of the structure and the number of layers per period are defined in the fabrication process.

Although it is evident that the layered periodic structure will cause Bragg reflection, many questions related to details of this reflection arise. For example, it is unclear what the maximum reflectance for unpolarized light will be. Is it 0.5 as for twisted birefringent structures [8] or 1 as for layered achiral media [4]? Intuitively, it is understandable that a higher gradient of the refractive index leads to higher reflection. This is true for small widths of the columns when the reflection does not reach its saturation. However, without a detailed investigation, it is difficult to draw conclusions about how values of the structural parameters determine the saturation of the reflection.

The question regarding reflectance of the columnar periodic structure shown in Fig. 1a can be examined by computer simulations. In order to do this, it is necessary to propose a model that will be used for describing the optical properties of the studied structure. In the next section, we will demonstrate that a layered medium gradient index medium in a form of a cylinder (Fig. 1b) can be applied for these purposes. We will, however, allow the cylinder diameter to be much larger that the wavelength of the light making the specular reflection dominate over scattering.

The next step of the study of this model must include a calculation procedure for light interaction. Although this model looks much simpler than the real structure, finding its reflectance is still not a simple optical problem. Analytical and numerical methods for calculation of light propagation in layered isotropic and anisotropic media have been presented in many reports [4,5,8]. However, the cylinder shown in Fig. 1b cannot be considered as a medium in which optical properties change only in one direction that is typical for an ordinary layered medium [4]. Because of this, the standard techniques developed for layered one-dimensional (1D) media cannot be applied in the usual way. On the other hand, implementation of the techniques for direct solving Maxwell's equations in three dimensions (3D) is associated with huge computational

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