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A narrow-band optical filter based on a corrugated one-dimensional photonic crystal

B.A. Usievich, V.A. Sychugov

***Abstract*. A narrow-band optical filter based on a multilayer dielectric mirror deposited onto a corrugated substrate is proposed and investigated. It is shown that, by optimising the thickness of the mirror layers and depth of corrugations, it is possible to obtain a filter with a pass band two orders of magnitude narrower than that of a standard flat filter with a half-wavelength layer surrounded by multilayer dielectric mirrors with the same number of layers as in the filter proposed. It is also shown that the range of angular tuning of the wavelength at which the maximum transmission is achieved is determined by the requirements to the value of losses in this filter. In particular, at permissible losses of 0.8 %, the wavelength tuning range reaches 20 nm for a filter transmission pass band of 0.08 nm.**

Keywords: *corrugated waveguide, one-dimensional photonic crystal, narrow-band optical filter.*

1. Introduction

Anomalous light reflection by the surface of a corrugated waveguide, which was discovered in 1985 [1], opens up new opportunities for creating efficient laser elements. The reflection observed has a resonant character and arises within a very narrow spectral range at a fixed angle of incidence or upon very small changes in the angle θ of incidence of light and a fixed wavelength λ. The type of the excited waveguide mode (TE or TM) does not affect the character of reflection but determines the angular (spectral) shift of the resonance position. Moreover, the reflection in the normal direction is also possible. The features mentioned above make it possible to create interesting laser elements, such as mirrors of a laser resonator.

The authors of paper [2] studied the operation of an alexandrite laser whose resonator contained a waveguide grating reflector used as one of the mirrors. Narrow-band lasing (in a two-mirror resonator) and laser wavelength tuning (in a three-mirror resonator), which was accomplished by turning the waveguide grating reflector, were achieved. In the course of experiments it was found that the waveguide-grating element can operate in a laser resonator with ordinary mirrors as a narrow-band filter, whose transmission wavelength is determined by the angle of the filter rotation with respect to the resonator axis.

This experimental fact was explained on the basis of an analysis of the angular (spectral) dependence of the coefficient of anomalous light reflection from the surface of the waveguide-grating element. It is known [1] that an anomalously high light reflectivity is accompanied by a minimum. This minimum is always present in film waveguides (structures) with distinct interfaces between media and is absent in diffused waveguides with smooth junctions between the waveguide layer and a substrate. As a rule, this minimum is small compared to the Fresnel reflection coefficient, but, in the case of alexandrite crystals, it is sufficient to narrow the lasing spectrum.

This raises the question whether the reflectivity of the structure can be significantly reduced in a sufficiently narrow spectral range to create a narrow-band filter based on a multilayer dielectric mirror with a layer thickness close to $\lambda/4$. A well-known version of such a filter is a multilayer structure with a half-wavelength layer at the centre. Here, we present a new version of the filter in which the waveguide properties of the multilayer structure are related to its reflection properties, and this relation is achieved by corrugating the substrate on which the multilayer structure is deposited.

2. Waveguide propeties of a multilayer structure

The aim of this work is to create a structure with a high nonresonant reflection and zero reflection at the resonance. We performed this earlier for TM-polarised optical waves [3]. Consider now the case of TE-polarised waves.

A multilayer dielectric structure based on a conventional mirror, which is composed of alternating quarter-wavelength layers with low and high refractive indices, was taken as the initial structure. An optical filter based on such a structure can be manufactured by successive deposition of dielectric layers on a corrugated substrate. The diffraction of light by a multilayer grating was calculated using the C method [4], which allows one to precisely calculate diffraction processes for a fairly deeply corrugated substrate. The selection of the number of pairs of the structure layers was based on the analysis of the waveguide properties of this structure. The following layer parameters were used: the refractive indices $n_{\rm low} = 1.46$ and $n_{\rm high} = 2.005$; the refractive indices of the substrate $n_{\rm s} = 1.51$ and

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upper environment (air) $n_c = 1$; the optical thicknesses of layers $d_i n_i = \lambda/4$.

Figure 1 shows the dependences of the effective refractive index n^* for TE modes on the number N of pairs of the structure layers. One can see that the number of modes of the structure increases with increasing optical thickness of the waveguide layer (i.e., the number of layers in the structure). The dispersion curves for TM modes are similar. However, n^* for TE modes exceeds that for TM modes for the same number N of pairs. This anisotropy of n^* is typical of layered waveguides.

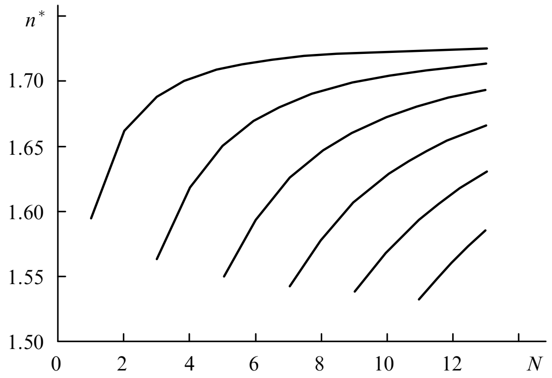

Figure 1. Dependences of the effective refractive index n^* of TE-polarised waveguide modes on the number N of pairs of layers of a multilayer mirror.

The period Λ of the substrate corrugation is determined by the expression

$$\Lambda = \frac{\lambda}{n^* - \sin\theta}, \tag{1}$$

if the angle θ of light incidence, the wavelength λ, and the refractive indices $n^*_{\mathrm{TE,TM}}$ for the TE and TM polarisations are specified. To avoid the excitation of two counter-propagating modes, the angle of incidence was taken equal to 3.5°, $\lambda = 750$ nm, and the polarisation of light corresponded to the excitation of TE modes of a multilayer waveguide. In subsequent calculations, the angle of incidence of light on the grating remained constant. This was achieved by a change in its period with changing n^*. The grating period Λ was close to 450 nm for $\theta = 3.5°$. This ensures the existence of only the zero-order diffraction in air and the substrate, thus allowing us to avoid undesirable light losses in other diffraction orders.

3. Reflection properties of the structure

In the further analysis of the optical properties of the multilayer structure, we restrict ourselves to seven pairs of layers. This is explained by the fact that we will neglect the effect of a decrease in the grating depth with increasing number of layers. However, this effect is observed in practice. In addition, the number of modes propagating in the structure increases with the number of layers, resulting in an increase in the number of resonances and complication of the reflection and transmission spectra.

Figure 2 presents a typical spectral dependence of the reflectivity R of a multilayer corrugated structure ($dn = \lambda/4$, the corrugation depth is $\sigma = 20$ nm). Sharp peaks and dips in the plot $R(\lambda)$ are related to excitation of waveguide modes in the structure. Let us select one of them and answer the question what parameters of the resonance, which cause the appearance of this mode, are interesting from the viewpoint of using this structure as a filter. This is primarily the reflectivity value R_0 at the resonance (Fig. 2). The value of the off-resonance reflectivity $R_0 + \Delta R$ and the width of the resonance $\Delta\lambda$ can be also important in some applications.

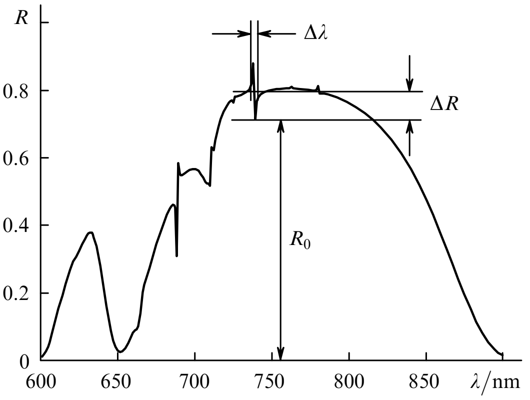

Figure 2. Spectral dependence of the reflectivity R of a multilayer corrugated dielectric mirror.

The calculations of the reflectivity of a structure with quarter-wavelength layer thicknesses (Fig. 2) shows that the transmission of the structure under study is far from being 100 %. Therefore, in order to obtain a high-quality filter, the parameters of the structure should be optimised. At the first stage, we varied the grating depth and, proportionally, the thicknesses of all layers using the modified Davidon–Fletcher–Powell method [5]. The empirical function

$$F = R_0 + C(1 - \Delta R)^2, \tag{2}$$

served as an optimisation criterion, where C is a constant.

Figure 3 shows the dependence of the reflectivity R on the wavelength λ for the optimised structure No. 1. One can see that the reflectivity at the resonance is almost zero. For comparison, a similar curve for a conventional flat dielectric filter with 29 layers (two multilayer mirrors with 14 layers each and the central half-wavelength layer) is also plotted.

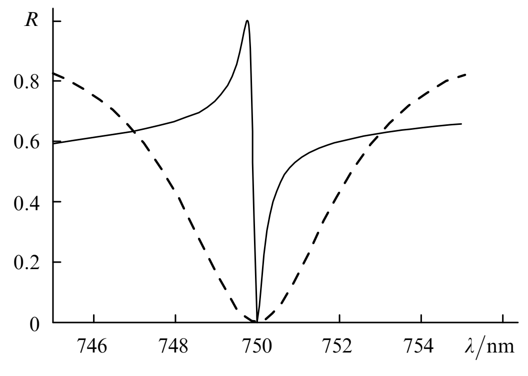

Figure 3. Spectral dependences of the reflectivity R of the partially optimised structure No. 1 (solid curve) and a conventional filter (dashed curve).

One can easily see from Fig. 3 that the corrugated structure makes it possible to obtain a narrower 100 %-transmission line. In a conventional filter, this can be achieved only by increasing the number of pairs in the structure layers. Note that, as a result of the optimisation, the optical thickness of the layers proved to be substantially different from the initially assumed thickness $\lambda/4$ (the optimised thickness was larger by 10 %), and the resonance was shifted closer to the edge of the mirror reflection band.

Upon further optimisation of the structure, its layer thicknesses were varied independently. As a result, a structure with the reflection spectrum shown in Fig. 4a was obtained. A significant improvement of the filter parameters is obvious, but the layers of the structure had now substantially different thicknesses (Fig. 5). As a consequence, its practical implementation becomes individual.

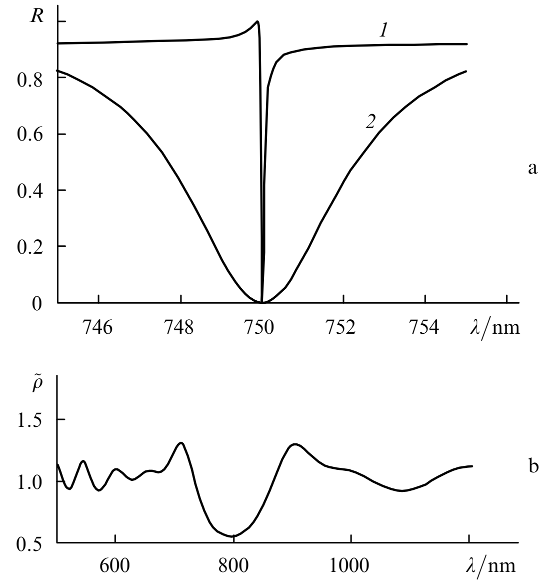

Figure 4. (a) Spectral dependences of the reflectivity R of the fully optimised structure No. 1 (*1*) and a conventional filter (*2*), and (b) the dimensionless optical mode density $\tilde{\rho}$ for structure No. 1.

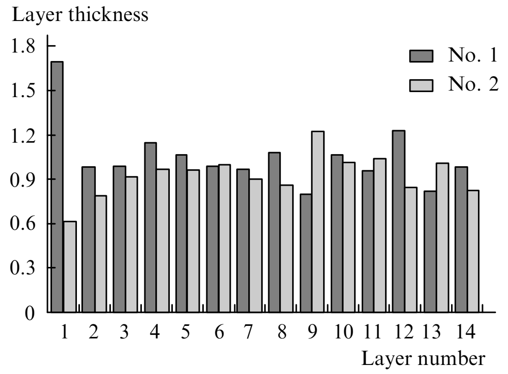

Figure 5. Layer thicknesses for the fully optimised structures Nos 1 and 2.

Bearing in mind that the optimising program searches for a local minimum, we changed the initial conditions and tried to find another version of the optimised filter structure. As before, the optimisation was performed in two stages. At the first stage of a proportional change of the layer thickness, the layer thicknesses were selected smaller than $\lambda/4$. As a result, structure No. 2 was obtained whose reflection spectrum is shown in Fig. 6a. Figure 5 presents the dependence of the layer thicknesses on the layer number. Comparison of the parameters of two filters shows that their filtering properties almost coincide, but, from the practical viewpoint, it is easier to manufacture a filter with $dn > \lambda/4$ than with $dn < \lambda/4$. Note also that the optimisation yielded a smaller depth of the grating for the second structure (σ = 17.9 nm) compared to 25.8 nm for structure No. 1. This suggests that the smoothing effect will be less pronounced for the first structure.

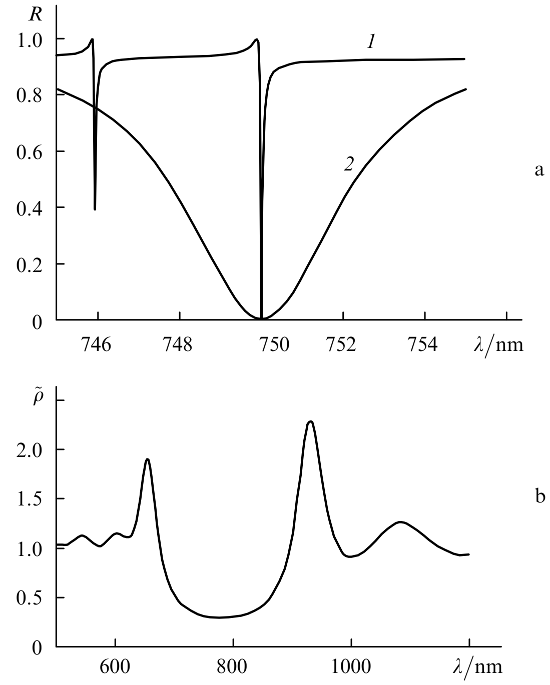

Figure 6. (a) Spectral dependences of the reflectivity R of the fully optimised structure No. 2 (*1*) and a conventional filter (*2*), and (b) the dimensionless optical mode density $\tilde{\rho}$ for structure No. 2.

4. Filter as a one-dimensional photonic crystal

A flat multilayer dielectric mirror, which can be treated as a one-dimensional photonic crystal, is characterised by the density of optical modes (DOM) [6]. It is known that the DOM exhibits sharp peaks near the edges of the reflection band of the mirror. Apart from the two peaks, a standard filter with a half-wavelength layer at the middle of the structure has a high peak in the spectral distribution of the DOM at the centre of the reflection band. The spectral positions of this peak and the narrow pass band of this filter coincide. In the case of the filter proposed, the relation between the DOM and transmission spectra is also of interest. To answer this question, we calculated the DOM spectra for the optimised multilayer corrugated structures. The DOM $\rho(\omega)$ is defined in terms of the real and imaginary parts of the amplitude transmission coefficient $t \equiv x + iy \equiv \sqrt{T}e^{i\varphi}$ of the structure:

$$\rho(\omega) = \frac{dk}{d\omega} = \frac{1}{D}\frac{y'x - x'y}{x^2 + y^2}, \qquad (3)$$

where D is the total physical thickness of the structure, and the prime implies the differentiation with respect to ω. It is more suitable to use a normalised density of states $\tilde{\rho} = v_b \rho$, where $v_b = cD/L_{opt}$ is the averaged velocity of light propagating across the structure, L_{opt} is the optical thickness of the structure, and c is the velocity of light in vacuum.

When calculating the DOM, we took into account the presence of a grating in the structure by averaging the permittivity in the region occupied by the grating. The results of calculations are shown in Figs 4b, 6b. One can see that the positions of the transmission peaks of the filters coincide with the minima in the spectral distribution of the DOM. In our opinion, this is associated with the necessity for the transmission peak to be accompanied by the 100 % light reflection outside of the resonance transmission, which is equivalent to the requirement of a minimal DOM level for the one-dimensional photonic crystal in this wavelength region. It is this result that we obtained after the optimisation of the structures. We obtained a similar result for the TM-polarised light [3].

5. Tuning the filter transmission wavelength

To study the possibility of tuning the laser wavelength by turning the filter, we calculated the wavelength dependence of the filter transmission for various angles of light incidence on the filter. Note that, during the optimisation, a significant decrease in the radiation loss factor α_{rad} of the excited waveguide mode is observed, which is accompanied by a narrowing of the resonant transmission peak. Too low values of α_{rad} lead to the necessity of using wide beams, because the efficient filter operation requires the fulfillment of the condition $\alpha_{rad}D \gg 1$.

According to our calculations, the off-resosnance reflection and the width of the resonance are independent of the filter rotation angle. The filter transmission coefficient at the resonance begins to decrease as the angle deviates from the optimal value (Fig. 7). The acceptable tuning range is determined by the permissible energy loss level in the resonator. If the loss level is 0.8 %, the given structure ensures the tuning within a range of 20 nm with a transmission bandwidth of 0.08 nm upon filter rotation by an angle of $\Delta\theta = 3°$ narrower than in the case of a conventional flat dielectric filter with the same (or larger) number of layers. The tuning range of the filter transmission wavelength is determined by the tolerable loss level and is several ten times wider than the filter transmission bandwidth.

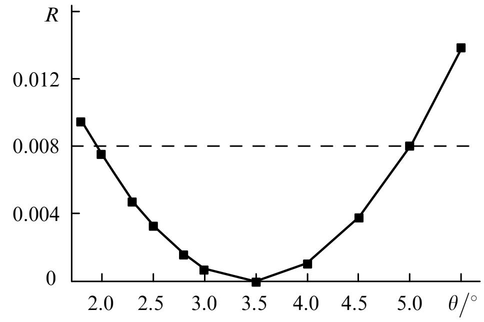

Figure 7. Dependences of the reflectivity at the resonance on the filter rotation angle.

6. Conclusions

It is shown that the optimisation of a multilayer corrugated structure makes it possible to obtain a filter with satisfactory characteristics, and the resonance can be much

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