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Leaky-mode waveguide in layered dielectric gratings

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Abstract. **The diffraction of light on the corrugated surface of a layered structure was investigated. It was shown that the excitation of waveguide modes in the layered structure alters significantly the diffraction efficiency of the corrugated structure. It was found that in the autocollimation regime the diffraction efficiency of the grating can reach 100% for moderate depths of the grating grooves. The suitability of a waveguide-grating mirror in dye lasers was demonstrated experimentally.**

1. Introduction

Metal diffraction gratings are used widely in spectroscopic instruments and laser devices. However, their low diffraction efficiency for TE-polarisation waves and low optical strengths have stimulated studies of the properties of metal – dielectric and purely dielectric gratings. Several interesting suggestions have been put forward recently on this subject. For example, a metal – dielectric grating operating efficiently for TE waves was proposed [1]. In another study a purely dielectric grating with a high optical strength was suggested. In the first case a corrugation was formed on a dielectric layer lying on a plane metal mirror, while in the second case a similar layer was deposited on a multilayer dielectric mirror. However, in both cases the corrugated dielectric layer acted as a leaky-mode waveguide. It has been shown [3] that a high diffraction efficiency of the grating is attained when this waveguide is excited by an externally incident light beam. The aim of the present study was to investigate the diffraction properties of a waveguide – grating structure with the minimum possible number of dielectric layers and to search for conditions under which 100% diffraction efficiency of the grating is attained with the minimum possible depth of grooves in this grating.

2. Analysis of the diffraction properties of a single-layer corrugated structure

Fig. 1 presents the layout of the simplest leaky-mode waveguide. In contrast to a conventional waveguide in which the guiding layer has a refractive index n_f greater than that of the substrate n_s, the waveguide under consideration has a dielectric layer with $n_f < n_s$. The modes of this waveguide undergo

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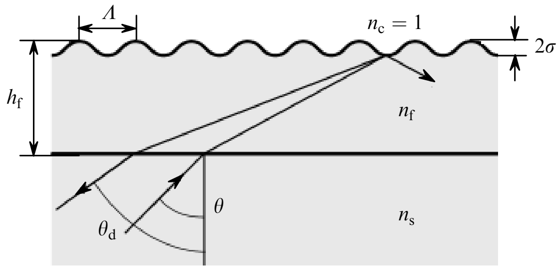

Figure 1. Schematic diagram of the simplest corrugated leaky-mode waveguide structure (θ_d is the diffraction angle).

total internal reflection at the interface between the layer and air and only partial reflection at the interface between the layer and the substrate. When the upper interface is corrugated, the expression for the diffraction efficiency of the grating in relation to a TE-polarisation light beam, incident from the substrate onto the waveguide at an angle θ greater than $\theta_{cr} = \arcsin(n_c/n_s)$ may be formulated as follows:

$$\eta_{-1} = \frac{(k\sigma)^2(n_f^2 - n^{*2})^{3/2}[n_f^2 - (n^* - N)^2]^{3/2}}{[n_f^2 - n^{*2} - (n_f^2 - n_s^2)\cos^2(\Delta_0/2)]} \times \frac{1}{[n_f^2 - (n^* - N)^2 - (n_f^2 - n_s^2)\cos^2(\Delta_0/2)]}, \quad (1)$$

where

$$\Delta_0 = 2kh_f(n_f^2 - n^{*2})^{1/2} - 2\arctan\frac{|N_c^0|}{N_f^0} - \pi\,;$$
$$\Delta = 2kh_f[n_f^2 - (n^* - N)^2]^{1/2} - 2\arctan\frac{|N_c^{-1}|}{N_f^{-1}} - \pi\,; \quad (2)$$

$N = \lambda/\Lambda$; $N_i^r = [n_i^2 - (n^* + rN)^2]^{1/2}$; r is the diffraction order; $i =$ c, f, s; $k = 2\pi/\lambda$; h_f is the thickness of the dielectric layer; σ is the amplitude of the sinusoidal corrugation; $n^* = n_s \sin\theta$; n_c is the refractive index of the surrounding medium; Λ is the corrugation period; λ is the wavelength of light. Formula (1) was obtained in terms of the Rayleigh approximation for small depths of the grating grooves by using a geometrical-optical approach to consider the propagation of light in a dielectric layer [4].

In the autocollimation regime, when $N = 2n^*$, formula (1) simplifies significantly and assumes the form

$$\eta_{-1}^{\text{auto}} = \frac{(k\sigma)^2(n_f^2 - n^{*2})^3}{[n_f^2 - n^{*2} - (n_f^2 - n_s^2)\cos^2(\Delta_0/2)]^2}\,. \quad (3)$$

It is evident from formula (3) that, subject to the condition

$$\Delta_0 = 2\pi m, \quad m = 1, 2, 3, \ldots \tag{4}$$

the efficiency η_{-1}^{auto} is maximal.

In relationship (4), the left-hand side represents the phase shift of the wave which has traversed the path from one interface to the other and back again. Equality (4) represents the condition for the existence of a leaky mode in the dielectric layer under consideration. Thus, the maximum diffraction efficiency of the grating on the layer is attained subject to the condition $\Delta_0 = 2\pi m$, i.e. in essence on excitation of a waveguide mode which interacts with the grating until it has completely leaked out from it. The depth of the grating grooves corresponding to 100% autocollimation light reflection from the grating was calculated by a computer program formulated on the basis of the 'sources' method [5]. This program makes it possible to calculate the parameters of various corrugated structures with large ($2\sigma \sim \Lambda$) grating groove depths. For example, in the case of a layer with $n_f = 1.383$ (MgF_2), lying on a substrate with $n_s = 1.458$ (SiO_2) with the corrugation period $\Lambda = 0.273$ μm, the optimal grating groove depth is $2\sigma = 360$ nm for a thickness of the layer $h_f = 0.43$ μm when a light beam with the wavelength $\lambda = 0.63$ μm is incident from the substrate at the angle $\theta = 52.6°$. Such a great depth combined with a small grating period makes the grating fabrication an extremely difficult process. We therefore examined corrugated waveguide structures with a longer region of interaction of the mode with the grating.

3. Analysis of the diffraction properties of a two-layer corrugated structure

Fig. 2 is a schematic diagram of the structure. One of the layers of this structure is a buffer layer with a refractive index $n_b < n_f$, whereas the other is a guiding layer with $n_f \leqslant n_s$. This structure can support leaky modes of two types. The leaky mode of the first type is characterised by a large effective refractive index n^*, i.e. $n_b < n^* < n_f$, whereas the mode of the second type has a small refractive index n^*, i.e. $1 < n^* < n_b$. Modes of both types undergo total internal reflection at the air – dielectric layer interface. At the dielectric layer – substrate interface the leaky mode of the first type experiences frustrated total reflection, whereas the mode of the second type undergoes only the usual Fresnel reflection. This is responsible for the considerable difference between the diffraction efficiencies of light at the corrugated interface of the dielectric layer.

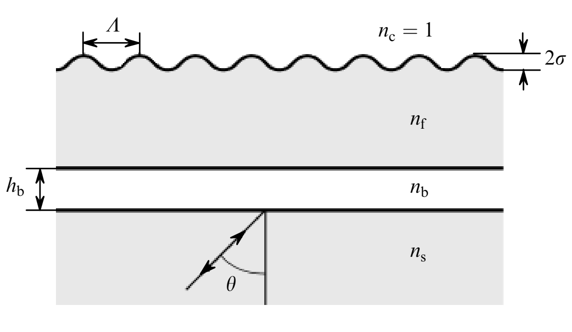

Figure 2. Schematic diagram of a corrugated waveguide structure with an additional buffer layer.

We shall consider initially the autocollimation reflection of light with participation of leaky modes of the first type ($n_b < n^* < n_f$). The reflection coefficients were calculated on the basis of the computer program already mentioned. As expected, these calculations confirmed that the coefficient of the autocollimation reflection of light incident from the substrate reaches a maximum only if the waveguide mode is excited in the corrugated waveguide. For a specified groove depth 2σ it is possible to attain 100% autocollimation light reflection by varying the buffer layer thickness.

Fig. 3 presents the dependences of the reflection coefficient R_{-1} on the thickness of the buffer layer h_b for three groove depths with $n_f = n_s = 1.458$ (SiO_2), $n_b = 1.383$ (MgF_2), $\Lambda = 0.2227$ μm, $\lambda = 0.633$ μm, $n^* = 1.42$, $h_f = 0.675$ μm, and $\theta = 77°$. In the calculations, the corrugation was assumed to be sinusoidal. It can be seen from Fig. 3 that the smaller the groove depth, the greater the thickness of the buffer layer for which $R_{-1} = 100\%$ is attained. This relationship between the groove depth 2σ and the buffer layer thickness h_b results from an increase in the distance traversed by the mode in the waveguide and hence from an increase in the length of the region of interaction between the mode and the grating with increase in h_b.

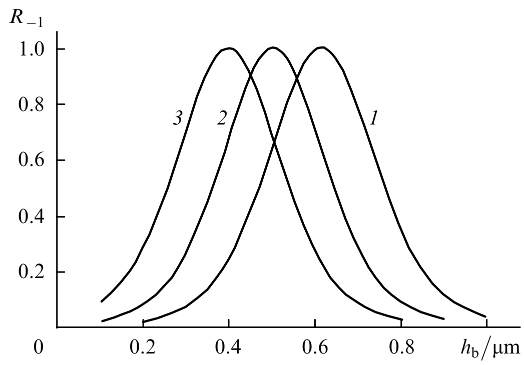

Figure 3. Dependences of the diffractive light reflection coefficient on the buffer layer thickness ($n_b < n^* < n_f$) for $2\sigma = 25$ nm (*1*), 50 nm (*2*), and 100 nm (*3*).

We shall now consider leaky modes of the second type ($1 < n^* < n_b$). As already mentioned, they are characterised by the absence of total internal reflection on the plane interface of the waveguide (Fig. 2). On increase in the buffer layer thickness, the Q-factor of these modes varies periodically, which gives rise to different dependences of R_{-1} on h_b in the excitation of these leaky modes than in the excitation of modes of the first type. Fig. 4 presents the dependences of R_{-1} on the buffer layer thickness for the structure with $n_s = n_f = 1.458$ (SiO_2), $n_b = 1.383$ (MgF_2), $\Lambda = 0.264$ μm, $h_f = 0.85$ μm, $n^* = 1.2$, and $\theta = 55.4°$ and two depths of the corrugation grooves. The maximum coefficient is $R_{-1} = 8.5\%$ for $2\sigma = 50$ nm and 80% for $2\sigma = 200$ nm. These coefficients are attained for the buffer layer thicknesses h_b close to $\lambda(2m+1)/4n_b\cos\theta_b$, where $m = 0, 1, 2, \ldots$. The separation between the R_{-1} maxima is exactly $h_b = \lambda/2n_b\cos\theta_b$. The diffraction efficiency of the grating in the case examined here is appreciably lower owing to the low Q-factor of these leaky modes ($1 < n^* < n_b$), i.e. owing to their short transit distance in the corrugated layer.

An increase in the transit distance of the second-type leaky modes can be attained in a structure with a larger

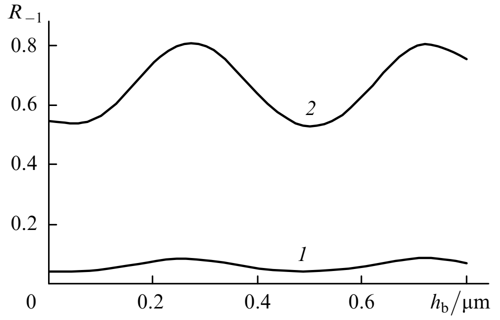

Figure 4. Dependences of the diffractive light reflection coefficient on the buffer layer thickness ($1 < n^* < n_b$) for $2\sigma = 50$ nm (*1*), and 200 nm (*2*).

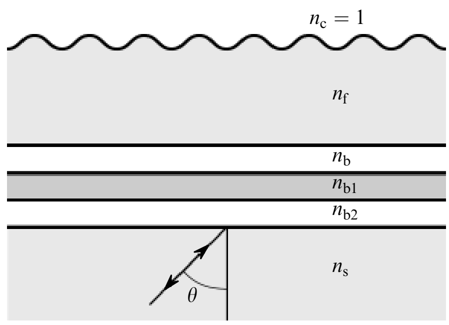

Figure 5. Schematic diagram of a corrugated waveguide structure with three buffer layers.

number of layers, illustrated in Fig. 5. The thicknesses of two additional buffer layers in this structure are selected on the basis of the condition

$$h_{b1,b2} = \frac{\lambda}{4n_{b1,b2}\cos\theta_{b1,b2}}, \tag{5}$$

i.e. the condition for constructive interference of the beams reflected from the layers and forming the waveguide mode. Such interference increases the light reflection coefficient and leads to an increase in the Q-factor of the mode. Calculations of the autocollimation reflection have shown that in this structure (Fig. 5) the reflection coefficient R_{-1} reaches 99.2% for $2\sigma = 50$ nm. However, if we confine ourselves to only one additional buffer layer with $n_{b1} = 2.1$, then $R_{-1} = 82\%$ for the same groove depth, i.e. it is ten times greater than for the structure without additional layers with $n_b = 1.383$. Thus, an increase in the Q-factor of the corrugated-structure mode makes it possible to increase the light diffraction efficiency in this structure.

4. Autocollimation reflection of light in the excitation of leaky modes of the second type

The autocollimation reflection of light in the excitation of leaky modes with a high effective refractive index $n^* > n_b$ occurs for a large angle of incidence of light on the grating ($\theta \sim 90°$) and a short grating period, which is not always acceptable in practice. Furthermore, the high Q-factor of these leaky modes narrows sharply the spectral range corresponding to a high diffraction efficiency of the grating.

We therefore made a detailed study of a corrugated layered structure with n^* within the range $1 < n^* < n_b$. This structure is shown schematically in Fig. 5. The spectral dependence of the diffractive reflection coefficient was calculated with the aid of the computer program mentioned above. The parameters of the structure were as follows: $n_f = 1.458$, $n_b = 1.383$, $n_{b1} = 2.05$, $n_s = 1.512$, $h_f = 0.37$ μm, $h_b = 0.164$ μm, $h_{b1} = 0.081$ μm, and $\Lambda = 0.273$ μm.

The results of the calculation for various angles of incidence of light on the grating are given in Fig. 6. Evidently, a high diffraction efficiency of the grating was attained for angles of incidence of light $\theta = 44.6°$ and also for angles close to the critical value ($R_{-1} \sim 1$, $\theta = 42°$, $\lambda = 0.64$ μm). This feature is determined by the selection of $n^* = 1.06$ and in particular by the selection of the waveguide layer thickness.

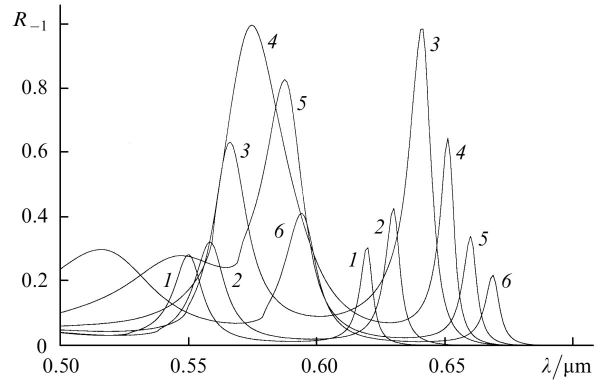

Figure 6. Spectral dependences of the diffractive light reflection coefficient for a corrugated layered structure with $1 < n^* < n_b$ ($h_f = 0.37$ μm) and $\theta = 38°$ (*1*), 40° (*2*), 42° (*3*), 44° (*4*), 46° (*5*), and 48° (*6*).

A change in the waveguide layer thickness for constant other parameters of the structure may alter significantly the spectral dependences of the coefficient of R_{-1}. These changes are especially clear if the angular dependence of the autocollimation reflection of light by the investigated corrugated structure is plotted on the basis of the spectral dependences. Fig. 7 gives this dependence for two structures with $h_f = 0.37$ and 0.325 μm in the short-wavelength range $0.55 < \lambda < 0.60$ μm.

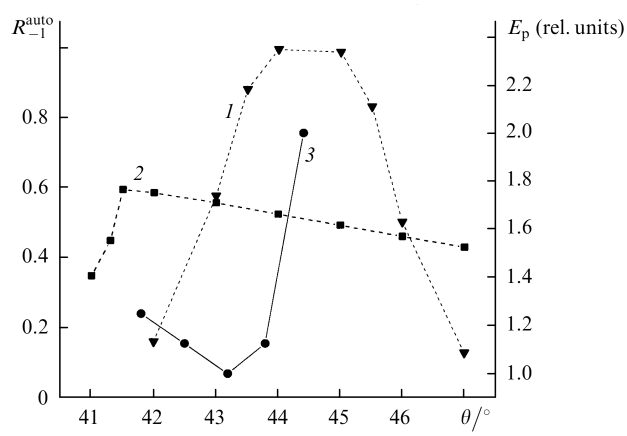

Figure 7. Angular dependences of the autocollimation light reflection coefficient R_{-1}^{auto} for a corrugated structure with $h_f = 0.37$ μm (*1*) and 0.325 μm (*2*), and the angular dependence of the threshold pump energy E_p of a dye laser (*3*).

It follows from our calculations that broadening of the angular dependence of the autocollimation reflection is the result of a decrease in the autocollimation reflection coefficient. The spectral (angular) range of sufficiently large autocollimation reflection coefficients is extremely important in the construction of tunable lasers, for example dye lasers, for which the width of the gain spectrum $\Delta\lambda$ does not exceed ~ 50 nm. The corrugated layered (dielectric) structure examined here is entirely usable in lasers of this kind.

A waveguide – grating structure with the indicated parameters was constructed to test experimentally this possibility. It was used as a resonantly reflecting mirror in a dye laser. The experimental setup is illustrated schematically in Fig. 8. Rhodamine 6G dissolved in ethanol was used as the dye and pumping was by radiation with $\lambda = 0.53$ μm. The angular dependence of the dye-lasing threshold was determined. The angular laser tuning range obtained was compared with the calculated range. The results of the comparison are given in Fig. 7. Lasing was achieved in the wavelength range 0.55 – 0.58 μm, where variation of the autocollimation reflection coefficient of the investigated structure was small so that the behaviour of curve *3* in Fig. 7 was determined by the spectral dependence of the dye gain in this range.

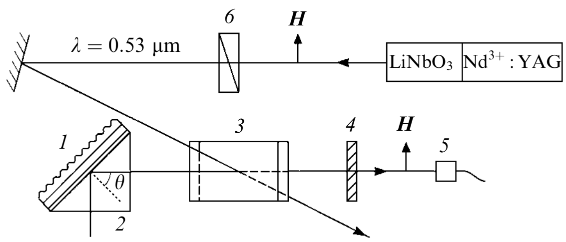

Figure 8. Schematic layout of a dye laser with a waveguide – grating mirror: (*1*) investigated structure; (*2*) prism; (*3*) dye cell; (*4*) output mirror of the dye laser; (*5*) photodetector; (*6*) polariser; ***H*** is the vector representing the magnetic field strength.

In conclusion, one should note that the condition for the autocollimation reflection in corrugated layered structures containing a leaky-mode waveguide is equivalent to the condition for the Bragg reflection of the guided modes in such a waveguide. Indeed, by substituting the relationship $n^* = n_s \sin\theta$ in the autocollimation condition $\Lambda = \lambda/2n_s \sin\theta$, we obtain $\lambda = 2n^*\Lambda$. This means that a distributed-feedback waveguide laser with coupling out of the generated radiation into the substrate can be constructed from this kind of a corrugated waveguide with amplification. In particular, the diode laser described in Ref. 6 can be of this kind.

5. Conclusions

An analysis of the diffraction of light in corrugated layered structures showed that the excitation of leaky modes in such structures can ensure a high diffraction efficiency of the grating in the autocollimation regime. Furthermore, a numerical analysis demonstrated and an experiment confirmed that the use of leaky modes with $n^* \sim 1$ makes it possible to obtain a fairly wide working spectral range for waveguide – grating structure of this kind.

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