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Autocollimation diffraction gratings based on waveguides with leakage modes

V A Sychugov, B A Usievich, K E Zinov'ev, O Parriaux

Abstract. **It is shown that the leakage modes of multilayer corrugated dielectric and metal-dielectric structures are extremely important for the achievement of high efficiency of these structures as diffraction gratings. Three types of grating structures are considered: a corrugated waveguide layer on a flat multilayer dielectric mirror (type 1); a multilayer dielectric mirror on a corrugated substrate (i.e., a totally corrugated structure) (type 2); and a structure of the intermediate type (type 3). The performance characteristics of these structures used in the Littrow mounting are compared. A diffraction grating based on a double-layer waveguide is fabricated.**

1. Introduction

In paper [1], a metal-dielectric grating was proposed, which has the high diffraction efficiency in the Littrow mounting. The grating represents a corrugated dielectric layer on a flat metal substrate. As shown in [2], the high efficiency of this structure results from the waveguide properties of the dielectric layer and the existence of leakage modes, whose effective refractive index $n^* < 1$ and is determined by the relation

$$2kh\left(n_{\mathrm{f}}^2 - n^{*2}\right)^{1/2} = (2m+1)\pi, \qquad (1)$$

where h and n_{f} are the thickness and the refractive index of the dielectric layer, respectively; $k = 2\pi/\lambda$; λ is the radiation wavelength.

Fig. 1 shows the dispersion curves for the leakage modes of the dielectric layer with $n_{\mathrm{f}} = 1.458$, deposited on the surface of an ideal metal. The region $n^* > 1$ corresponds to the conventional modes that undergo the total internal reflection from both boundaries of the waveguide, while the region $n^* < 1$ corresponds to the leakage modes, which suffer only partial internal reflection. It is these modes that provide the high efficiency of the grating.

The leakage modes can be easily observed in a flat layer of an absorbing dielectric in the measurements of the reflectivity of light from the structure. Fig. 2 shows the dependence of the reflectivity R on the layer thickness for the light incident on the structure at $\theta_{\mathrm{in}} = 60^\circ$ (the angle is measured from the normal to the layer). The minima of the reflectivity correspond to excitation of the leakage modes and the resonance absorption of light in the structure. Analogous absorption peaks are observed for a transparent dielectric and a real metal.

The resonance absorption is a substantial disadvantage of the metal-dielectric grating. For this reason, we considered

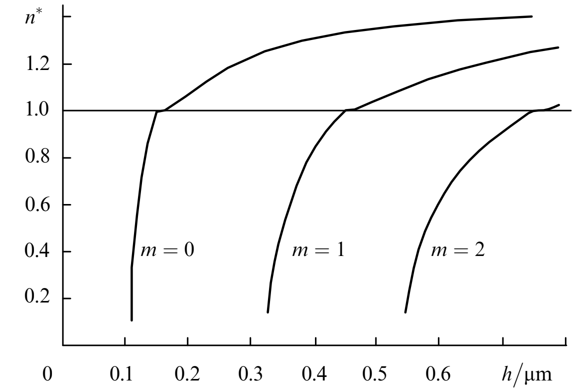

Figure 1. Dependences of the effective refractive index of the leakage modes on the thickness of a dielectric layer with $n_{\mathrm{f}} = 1.458$, deposited on an ideal metal, for TE-polarised light at $\lambda = 0.63$ µm.

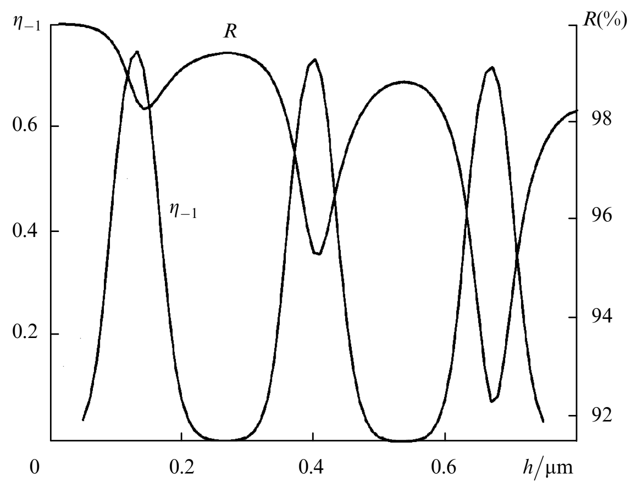

Figure 2. Reflection of light R from a flat waveguide metal-dielectric structure with leakage modes ($n_{\mathrm{f}} = 1.458 + \mathrm{i}\,0.001$), and the autocollimation reflectivity η_{-1} for the corrugated metal-dielectric waveguide with leakage modes ($n_{\mathrm{f}} = 1.458$, the corrugation depth is $2\sigma = 100$ nm) as functions of a dielectric film thickness ($\lambda = 0.63$ µm)

V A Sychugov, B A Usievich, K E Zinov'ev General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 117769 Moscow, Russia
O Parriaux Universite Jean Monnet, 23, rue du dr. Paul Michelon, 42023 St. Etienne, Cedex 2, France

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here multilayer dielectric gratings with the high radiation resistance and high diffraction efficiency. Unlike the metal-dielectric grating, the multilayer dielectric grating can be fabricated by several methods. A choice of the most proper method is a complicated problem. It is shown in this paper that the waveguide approach to the analysis of the performance of the multilayer grating allows one to successfully optimise its parameters.

2. Grating with a flat mirror

It was established in [2] that the autocollimation reflectivity from the corrugated nonabsorbing dielectric film on a metal with the corrugation period $\Lambda = \lambda/2\sin\theta$ for the TE-polarised light is equal to the diffraction efficiency in the -1st order:

$$\eta_{\text{avt}} = \frac{(k\sigma)^2\left(n_{\text{f}}^2 - 1\right)\left(1 - n^{*2}\right)\cos^4(\Delta/2)}{\left[n_{\text{f}}^2 - n^{*2} - \left(n_{\text{f}}^2 - 1\right)\cos^2(\Delta/2)\right]^2}, \tag{2}$$

where $\Delta = 2kh\left(n_{\text{f}}^2 - n^{*2}\right)^{1/2} - \pi$; and 2σ is the depth of a sinusoidal grating. The dependence of η_{-1} on the film thickness is shown in Fig. 2. The maxima of the grating efficiency are achieved for $\Delta = 2m\pi$, which corresponds to Eqn (1) and means that the maximum of the autocollimation reflectivity is achieved upon excitation of the leakage modes in the dielectric layer of the corrugated structure. Excitation of these modes by an incident beam of light provides the interaction of a waveguide mode with the grating over its entire propagation length along the grating and increases the efficiency of the diffraction process. The path length of the waveguide mode or, in other words, the mode quality factor is determined by the reflectivity of light from the interface between the dielectric layer and air.

An increase in the Fresnel reflectivity improves the mode quality factor, which results in the increase in the diffraction efficiency of the grating at a fixed corrugation depth. For instance, an increase in the angle of incidence θ_{in} up to 89° allows one to obtain the 100 % autocollimation reflection at the grating depth $2\sigma = 6$ nm, which is 63 times smaller than the grating depth required for obtaining such reflection in the SiO_2 layer at $\theta_{\text{in}} = 60°$ (Fig. 3). Analogous result can be achieved by increasing the refractive index of the dielectric layer at the fixed angle of incidence $\theta_{\text{in}} = 60°$. Obviously, in this case, the mode quality factor is also improved due to an increase in the light reflectivity from the interface between the layer and air.

So far we considered the substrate made of an ideal metal, which introduces no dissipative loss. In practice, however, any real metal substrate decreases the quality factor of the waveguide mode and reduces the diffraction efficiency of the structure at a given corrugation depth. A decrease in η_{avt} becomes especially notable at grazing incidence on the grating. Fig. 3 shows the spectral dependences of the autocollimation reflectivity for the corrugated structures with substrates, made of ideal or real (silver) metals at $\theta_{\text{in}} = 89°$. A substantial (by two times) decrease in the diffraction efficiency of the structure with a silver substrate is caused by the light absorption in silver. The absorption, in fact, has a resonance character because of the concentration of light inside the waveguide upon its excitation by the incident light beam.

The use of a multilayer dielectric mirror instead of a metal mirror is a natural way to improve the radiation resistance of

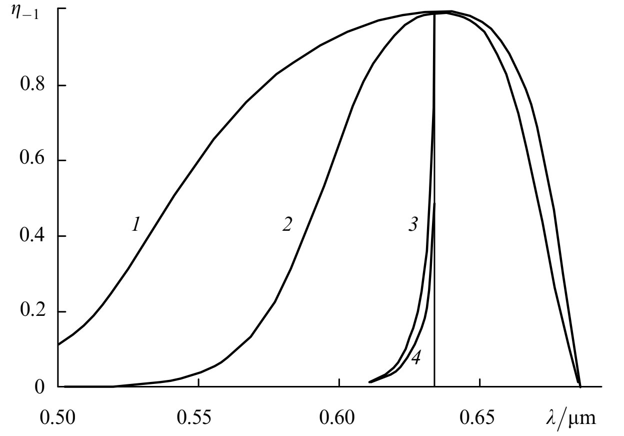

Figure 3. Spectral dependences of the diffraction reflection of light at $\lambda_{\text{avt}} = 0.63$ μm from the surface of corrugated waveguides made of the SiO_2 layer on a metal, $\theta_{\text{in}} = 60°, \Lambda = 365$ nm, $2\sigma = 380$ nm (*1*); the Ta_2O_5 layer on a metal, $\theta_{\text{in}} = 60°, 2\sigma = 60$ nm (*2*); the SiO_2 layer on an ideal metal, $\theta_{\text{in}} = 89°, \Lambda = 315$ nm, $2\sigma = 6$ nm (*3*); the SiO_2 layer on silver ($n = 0.072 + i\,3.465$), $\theta_{\text{in}} = 89°, 2\sigma = 6$ nm (*4*). The thickness of the waveguide was determined for the $m = 1$ mode.

the corrugated structure. Fig. 4 shows the spectral dependence of the autocollimation reflectivity for structures with metal and dielectric mirrors, as well as the spectral dependence of the reflectivity of the dielectric mirror itself. The dependence $\eta_{-1}(\lambda)$ was obtained for the corrugated structure with the optimal corrugation depth (the SiO_2 layer on a mirror), i.e., with the grating depth, at which the auto-collimation reflectivity reaches unity.

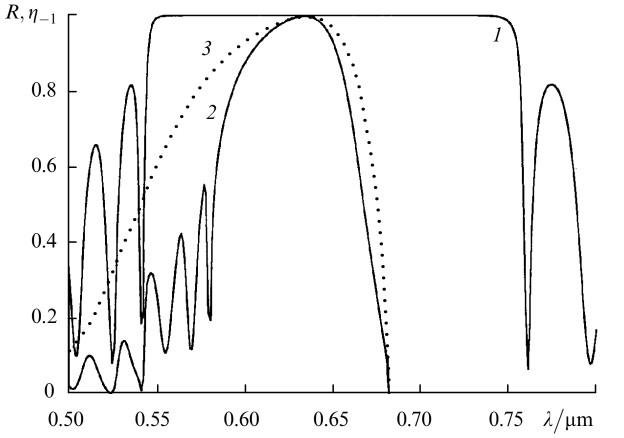

Figure 4. Spectral dependences of the Fresnel and diffraction reflection of light at $\lambda_{\text{avt}} = 0.63$ μm from the surface of different structures consisting of a flat dielectric mirror (15 pairs of the Ta_2O_5 and SiO_2 layers on a glass substrate), $\theta_{\text{in}} = 60°$ (*1*); the corrugated SiO_2 layer ($h = 0.33$ μm) on a flat multilayer mirror (14 pairs of the Ta_2O_5 and SiO_2 layers plus one quarter-wave Ta_2O_5 layer), $\theta_{\text{in}} = 60°$, $\Lambda = 365$ nm, $2\sigma = 380$ nm (*2*); and the SiO_2 layer ($h = 0.33$ μm) on a metal, $\theta_{\text{in}} = 60°, \Lambda = 365$ nm, $2\sigma = 380$ nm (*3*).

Note that the optimal corrugation depth of the dielectric structure does not differ from that of the metal-dielectric structure, unlike the spectral width of the reflection band. This is related to a distributed character of the light reflection by the dielectric mirror, i.e., in fact, to the field distribution of the leakage mode in the multilayer waveguide structure, which strongly differs from the mode-field distribution in the metal-dielectric structure.

Below, for simplicity, we will consider again an ideal mirror. As already noted, the improvement of the mode quality factor in the air-dielectric layer-metal substrate structure allows one to decrease the optimal corrugation depth. If the refractive index of the corrugated dielectric layer is not large (for instance, the SiO_2 layer with $n_f = 1.46$), then the light reflectivity from the interface between the dielectric layer and air can be increased by deposition on it a quarter-wave dielectric layer with $n_b > n_f$, for instance, the Ta_2O_5 layer ($n_b = 2.1$) of thickness

$$h_b = \frac{\lambda}{4n_b \sin\theta_b}, \tag{3}$$

where θ_b is the angle between the light propagation direction in this layer and the normal. The thickness of the SiO_2 waveguide layer is chosen according to the condition

$$2kh\left(n_f^2 - n^{*2}\right)^{1/2} = 2m\pi, \tag{4}$$

which represents the dispersion relation for the leakage modes of the dielectric layer on a metal covered by the medium with $n_b > n_f$.

Calculations show that the optimal grating depth in this case is $2\sigma_{opt} = 70$ nm, which is 5.5 times smaller than in the case of the structure without the additional layer. An analogous effect can be also obtained for the dielectric structure consisting of the SiO_2 layer on a multilayer dielectric mirror, if a quarter-wave layer of Ta_2O_5 is deposited over the corrugated layer. The calculated spectral dependences of η_{-1} for these cases are shown in Fig. 5. (Note that the results presented in Figs 3, 4, 5 and 8 are obtained using a computer code based on the method of sources [3]). The efficiency of the grating structure is mainly determined by the leakage modes excited in it. Is this situation conserved in a double-layer waveguide structure?

In the case of the TE waves, the dispersion equation for a waveguide consisting of two dielectric layers on a metal substrate has the form

$$\tan\left[kh_1\left(n_1^2 - n^{*2}\right)^{1/2}\right]\tan\left[kh_2\left(n_2^2 - n^{*2}\right)^{1/2}\right] = \left(\frac{n_1^2 - n^{*2}}{n_2^2 - n^{*2}}\right)^{1/2}, \tag{5}$$

where h_1 is the thickness of the first layer (n_1), which lies on a metal, h_2 is the thickness of the second layer (n_2), which covers the first layer and is adjacent to the air.

Fig. 6 shows the curves relating the values of h_1 and h_2 which satisfy the dispersion equation (5) for a given value of n^* for the leakage modes with $m = 0$ and 1. In the vicinity of the point A, the dispersion equation (5) can be written as

$$h_1 = \frac{\lambda}{4}\frac{\left(n_1^2 - n^{*2}\right)^{1/2} + 2\left(n_2^2 - n^{*2}\right)^{1/2}}{\left(n_1^2 - n^{*2}\right)^{1/2}\left(n_2^2 - n^{*2}\right)^{1/2}} - h_2. \tag{6}$$

Note that, if the position of the layers is changed, the grating structure retains the ultimately high diffraction efficiency, and $\eta_{avt} = 100$ % at a sufficiently small grating depth.

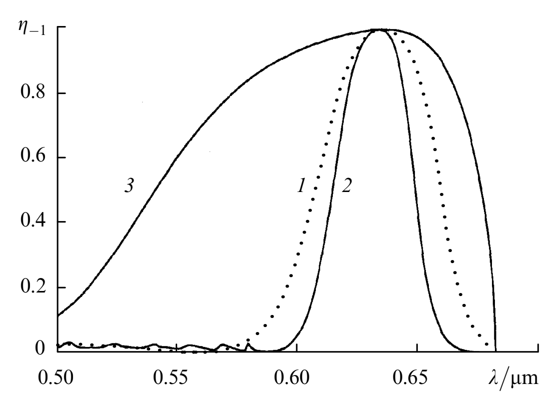

Figure 5. Spectral dependences of the diffraction reflection of light at $\lambda_{avt} = 0.63$ μm from the surface of different corrugated structures containing the additional quarter-wave Ta_2O_5 layer: the SiO_2 layer ($h = 0.265$ μm) on a metal, $\theta_{in} = 60°$, $\Lambda = 365$ nm, $2\sigma = 70$ nm (*1*); the SiO_2 layer ($h = 0.265$ μm) on a dielectric mirror (14 pairs of the Ta_2O_5 and SiO_2 layers plus one quarter-wave Ta_2O_5 layer), $\theta_{in} = 60°$, $\Lambda = 365$ nm, $2\sigma = 70$ nm (*2*); and the SiO_2 layer ($h = 0.33$ μm) on a metal without an additional layer, $2\sigma = 380$ nm (*3*).

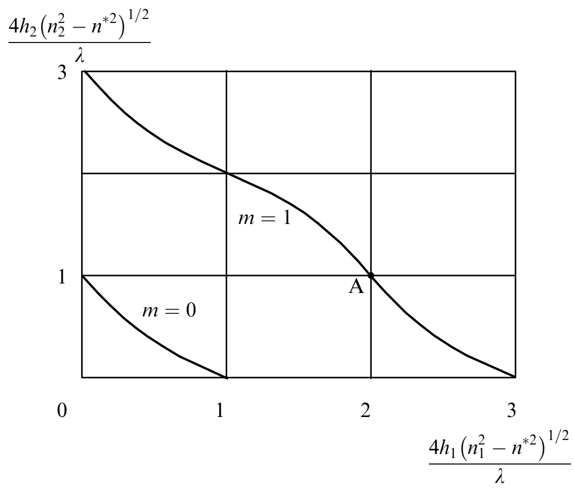

Figure 6. Ranges of the parameter values for a two-layer waveguide with leakage modes, formed by the SiO_2 and Ta_2O_5 layers on a metal substrate.

The optimal grating depth $2\sigma_{opt}$ can be further decreased by depositing pairs of quarter-wave layers with alternating values of the refractive index on the surface of the waveguide structure. These additional layers decrease the transmission of light through the waveguide-air interface resulting in the increase in the mode quality factor and in the conservation of the effective refractive index of the waveguide leakage mode.

3. Totally corrugated structure

Upon a further increase in the number of pairs of additional quarter-wave layers with alternating values of the refractive index, a new grating structure arises on the surface of the waveguide structure. This structure represents a dielectric multilayer mirror, whose layers have the same period, depth and phase of the corrugation. Such a structure can be obtained by the deposition of a multilayer dielectric mirror on a corrugated substrate. In the case of a flat multilayer mirror, the effect of the substrate on the mirror reflectivity decreases substantially with an increase in the number N of pairs of quarter-wave layers ($SiO_2 - Ta_2O_5$), and virtually disappears at $N \approx 15$. It is quite understandable, since the field of the incident and reflected wave decays exponentially deep in the mirror.

From the waveguide point of view, the multilayer structure under study is, in fact, a waveguide with a leakage mode, whose effective refractive index is detemined by the angle of reflection of light: $n^* = \sin\theta_{in}$. This is clearly illustrated in Fig. 1 in paper [4], which shows the dependence of the reflectivity of light, which is incident on the surface of the structure at an angle of θ_{in}, on the normalised layer thickness. This figure is analogous to Fig. 2 in this paper.

The corrugation of the considered structure with the period $\Lambda = \lambda/2n^*$ allows one to obtain a grating structure, which is resistant to radiation damage and has the high diffraction efficiency in the Littrow mounting at a sufficient small corrugation depth [4]. In this case, the effect of the substrate material on the autocollimation reflectivity at $N \approx 15$ is negligible. Moreover, the presence or the absence of a waveguide layer on the substrate does not affect the diffraction characteristics of the structure. Fig. 7 shows the spectral dependencies of η_{-1} for the optimal corrugation depth (the TE polarisation of light) for structures with $N = 15$ on a glass substrate, and on a glass substrate covered using a waveguide layer. These results were obtained using the computer code based on the Chandezon method [5].

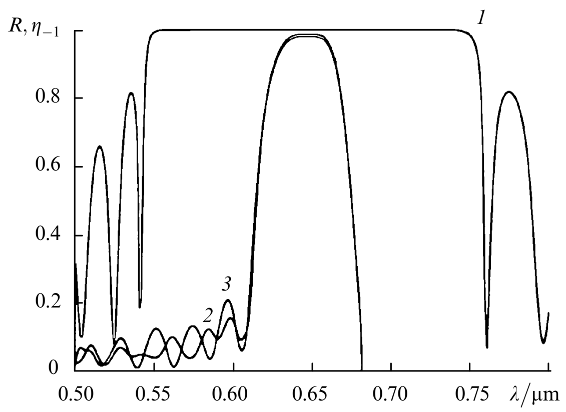

Figure 7. Spectral dependences of the Fresnel and diffraction reflection of light at $\lambda_{avt} = 0.63$ μm from a dielectric mirror (15 pairs of the Ta_2O_5 and SiO_2 layers) on a flat glass substrate, $\theta_{in} = 60°$ (*1*); a dielectric mirror (15 pairs of the Ta_2O_5 and SiO_2 layers) on a corrugated glass substrate, $\theta_{in} = 60°, \Lambda = 365$ nm, $2\sigma = 190$ nm (*2*); and a dielectric mirror on a corrugated substrate with a waveguide layer on a corrugated glass substrate $\theta_{in} = 60°$, $\Lambda = 365$ nm, $2\sigma = 190$ nm, the waveguide is formed by a lower Ta_2O_5 layer, $h = 165$ nm (*3*).

A comparison of the spectral linewidth of the autocollimation reflection of light from corrugated multilayer structures of three types, consisting of one corrugated layer on a multilayer mirror (type 1), two corrugated layers on a multilayer mirror (type 2), and a multilayer dielectric mirror on a corrugated substrate (type 3), shows that for the optimal corrugation depths, the minimal linewidth of reflection and the minimal optimal corrugation depth are achieved in the structure of type 2. The physical reason of these diffraction properties of the structure is related to the waveguide character of the structure distributed over its thickness and diffraction of light in it.

4. Experiment. The grating with an additional reflecting layer

In the fabrication of a dielectric grating on a corrugated substrate, the corrugation is smoothed as the number of dielectric layers is increased. Therefore, the fabrication of a grating on the surface of an upper waveguide layer is more preferable, in our opinion, especially because some correction of the structure parameters is possible in this case. The parameters of the two-layer diffraction structure with large η_{avt} can be corrected during the structure fabrication to satisfy Eqn (5). For example, if the thickness of the fabricated SiO_2 waveguide layer differs from the required thick-ness, by depositing the second Ta_2O_5 layer, whose thickness can be determined from the condition (5), the waveguide propertis of the structure at a given wavelenght for a given n^* can be retained.

We fabricated the dielectric grating from a multilayer structure consisting of four pairs of quarter-wave HfO_2-SiO_2 layers, one quarter-wave HfO_2 layer, and one SiO_2 layer of thickness 406 nm, which were deposited on a quartz substrate. A nine-layer mirror was calculated to obtain a maximum reflection ($R = 95$ %) of light with the TE polarisation at $\lambda = 1.18$ μm at the angle $\theta_{in} = 63°$. The grating can be fabricated by two methods. In the first method, the SiO_2 layer is corrugated and then is covered with the Ta_2O_5 layer, which will be also corrugated. In the second method, the Ta_2O_5 layer is first deposited and then corrugated.

Because, according to our calculations, the second method provides a larger diffraction efficiency in the autocollimation regime at a smaller corrugation depth of the wave-guide layer, we have chosen it for fabrication of the waveguide grating structure. The multilayer dielectric structure was produced by the method of magnetron sputtering. The surface of the Ta_2O_5 layer was corrugated ($\Lambda = 0.684$ μm) by standard methods: a photoresistive mask was fabricated by the holographic method, and ion etching was used to transfer the grating on the Ta_2O_5 layer.

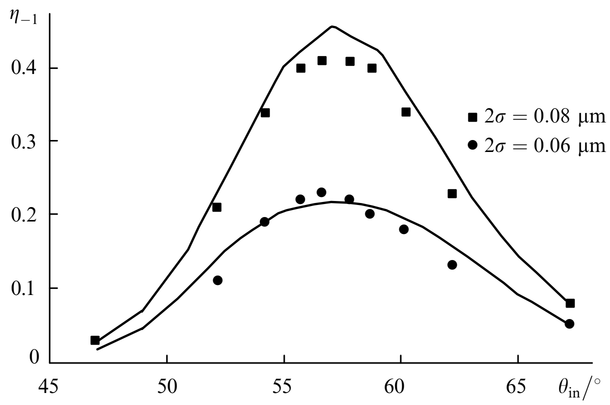

Figure 8. Experimental angular dependences of the efficiency of the diffraction reflection of light from the surface of a two-layer corrugated waveguide for $2\sigma = 0.08$ and 0.06 μm. The solid curves show the calculated dependences for the thickness of the Ta_2O_5 layer equal to 0.24 μm.

We used a 1.15-μm laser to measure the angular dependence of the diffraction efficiency of the fabricated gratings. Fig. 8 shows the results of measurements for two gratings of different depths. One can see that the calculated and experimental dependences agree satisfactorily. The thickness of the Ta_2O_5 layer, which was used in calculations, is close to the experimental one. The maximum autocollimation reflectivity for the grating with a larger corrugation depth ($2\sigma =$ 0.08 μm) is achieved at the wavelength $\lambda = 1.162$ μm and amounts to 56 %.

This grating was used as an output mirror in a F^{2-} colour centre LiF_2 laser. The laser was pumped by a *Q*-switched Nd^{3+} : YAG laser. The high resistance of the dielectric grating to the high power radiation damage provides stable operation of the colour centre laser at high pump levels without using any beam expanders. Note that the high diffraction efficiency (100 %) of the dielectric grating at grazing angles of incidence $\theta_{in} \approx 89°$ on the grating allows us to obtain a very narrow emission spectrum in the autocollimation scheme of the cavity both in cw and pulse regimes of lasing. The details of the spectral study of emission of a laser with grazing-incidence grating will be presented in our next publication.

Thus, the analyses of the autocollimation reflection of light from the multilayer corrugated structures showed that the high reflectivity is obtained only upon excitation of the leakage modes in these structures, and a small corrugation depth is achieved in the structures with the high quality factor of these modes.

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