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Narrowband optical filter based on a Fabry – Perot interferometer with two waveguide – grating mirrors

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Abstract. **The operation of a narrowband filter based on a Fabry – Perot interferometer formed by two waveguide – grating mirrors is studied upon normal incidence of light. In this case, two counterpropagating travelling waves and coupled modes are excited in a corrugated waveguide, while only one mode is excited in the case of oblique incidence of light on the filter. It is found that in the case of a small gap between the mirrors, the reflection spectrum of the interferometer depends on the phase shift $\Delta\varphi$ of one corrugation relative to the other. If light is incident normally on the interferometer, two or three lines appear in the transmission spectrum if $\Delta\varphi \neq 0$ or $\Delta\varphi \neq \pi$. The appearance of the additional resonances is attributed to symmetry breaking in the system. At large distances between the mirrors, the spectra at $\theta = 0$ do not exhibit any peculiarities.**

Keywords: *narrowband optical filter, anomalous reflection, waveguide – grating reflectors.*

1. Introduction

Narrowband optical filters continue to be the objects of intense research and development activity [1, 2]. Recently, we proposed a scheme and studied in detail a narrowband optical filter based on a Fabry – Perot interferometer containing one multilayer dielectric mirror and one waveguide – grating mirror.

It was found that a considerable change in the phase of a wave reflected from the waveguide – grating mirror leads to a considerable narrowing of the spectral transmission line of the filter (by about two orders of magnitude) even for a short distance ($h \approx 1$ μm) between the interferometer mirrors [3, 4]. Looking for new applications of waveguide – grating mirrors, we considered in this work the properties of a Fabry – Perot interferometer formed by two waveguide – grating mirrors, which is used as a narrowband optical filter.

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2. Analysis of the operation of a filter based on a Fabry – Perot interferometer

A conventional filter is usually formed by a dielectric layer (buffer layer) enclosed from both sides between multilayer dielectric mirrors. Note first that the buffer layer in a conventional filter is a waveguide with leaky modes. The dispersion relation describing the constants of light propagation in such a waveguide has the form

$$2kh\sqrt{n_b^2 - n^{*2}} = 2\pi m + \varphi_1 + \varphi_2, \tag{1}$$

where $k = 2\pi/\lambda$; φ_1 and φ_2 are the phase shifts of the wave upon reflection of light from the boundaries of the buffer layer ($m = 0,\ 1,\ 2,\ $); $n^* = n_b \times \sin\theta$ is the effective refractive index of this waveguide mode; n_b is the refractive index of the buffer layer; and θ is the angle at which light in the buffer layer falls at its boundary. For $\theta = 0$ and $\varphi_1 = \varphi_2 = \pi$, the thickness h of the buffer layer for the fundamental mode ($m = 0$) is equal to $\lambda/2n_b$ according to Eqn (1), while the thickness in the general case is described by the expression

$$h = \frac{\lambda}{2n_b}\left(m + \frac{\varphi}{\pi}\right). \tag{2}$$

The maximum intensity of light transmitted through the interferometer is determined by the relation

$$I_{max} = \left[1 - \left(\frac{r_1 - r_2}{1 - r_1 r_2}\right)^2\right] I_{in}, \tag{3}$$

where r_1 and r_2 are the amplitude coefficients of reflection of light by plane mirrors and I_{in} is the light intensity at the input. For $r_1 = r_2 = \sqrt{R}$, the transmittance of the filter reaches 100 %, and in the case of normal incidence, the spectral width of the transmission band is

$$|\Delta\lambda| = \frac{\lambda^2}{F(\lambda^2|d\varphi/d\lambda| + 2\pi n_b h)}, \tag{4}$$

where $F = \sqrt{R}/(1 - R)$ is the interferometer fineness. The quantity $\lambda^2|d\varphi/d\lambda|$ is often neglected compared to the second term, but this cannot be done in the case of waveguide mirrors [3].

In the new filter, we propose to replace the plane multilayer mirrors with corrugated waveguides, which are known [5] to be mirrors resonantly reflecting light in narrow spectral and angular ranges. The filter (Fig. 1) is a multilayer structure deposited on a quartz substrate. Corrugated waveguides of the same thickness h_f are deposited on both sides of the substrate, their refractive index n_f being larger than that for the buffer layer (n_b for SiO_2 is equal to 1.46). The waveguide surfaces bordering with air are corrugated with equal periods and represent diffraction gratings. The waveguides are formed by a Ta_2O_5 layer ($h_f = 210$ nm, $n_f = 2.02$, the corrugation amplitude and period are $2\sigma =$ 80 nm, and $\Lambda = 457$ nm, respectively) and are single-mode. The light losses in the waveguide are taken into account through absorption in the material of waveguide layers under the assumption that $\mathrm{Im}\,\varepsilon = 5 \times 10^{-4}$. Light falls on the filter normally to the waveguides ($\theta = 0$) and the transmission spectrum of the filter is related to the reflection of undesirable part of the incident light. It is important that in all diffraction orders, except the zeroth order, radiation propagates only inside the system and does not emerge outside. Note that for normal operation of the filter, the spectrum of radiation being analysed should be preliminary narrowed to the reflection band of one waveguide – grating mirror.

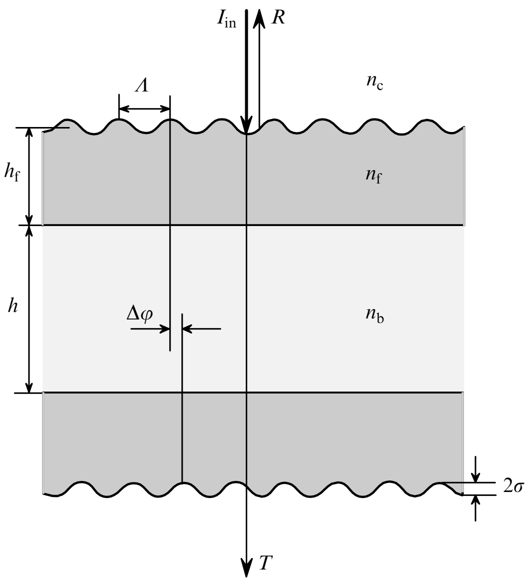

Figure 1. Scheme of an optical filter based on a Fabry – Perot interferometer with two waveguide – grating mirrors separated by a SiO_2 buffer layer.

3. Fabry – Perot interferometer for normal incidence of light on waveguide – grating mirrors

Normal incidence of light is a certain peculiarity of the process of reflection of light from the surface of a corrugated waveguide. The matter is that two modes counterpropagating are simultaneously excited in the waveguide for $\theta = 0$ [6]. Our investigations showed [6] that two reflection peaks are observed for $\theta \approx 0$. One of these peaks is narrow, while the other is twice as wide as the ordinary resonance. If the corrugated waveguide has dissipative losses, the reflection amplitude in the narrow peak becomes much smaller than the amplitude of the broad reflection peak. Moreover, irrespective of this, the narrowband peak vanishes altogether for $\theta = 0$.

Figure 2 shows the spectral reflection curves for a single corrugated waveguide in the case of incidence of light from a quartz substrate in a direction close to normal ($\theta = 0.05°$). Reflection was calculated by the Chandezon technique [7]. This method differs considerably from the Rayleigh method, which is frequently employed for calculating diffraction from a sinusoidal corrugation of small depth. In this technique, we use coordinate transformation that converts a corrugated surface into a coordinate plane in a curvilinear coordinate system, which makes it possible to calculate diffraction at a grating of arbitrary profile and depth. This is the main merit of the Chandezon technique. We used this technique because a sinusoidal and quite deep corrugation of waveguides was considered in our investigations. One can see from Fig. 2 that, if losses in a single-mode corrugated waveguide are equal to zero, the slope of the relatively broad reflection peak exhibits an additional resonance in which the reflection coefficient is close to unity. If, however, there are losses in the waveguide, the amplitude of the peak decreases noticeably.

Figure 3 shows the spectral dependence of the phase of a reflected wave in the case of incidence of light from the substrate on the waveguide (we also used the Chandezon

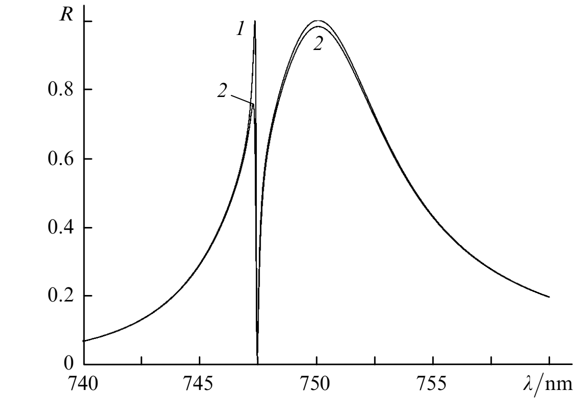

Figure 2. Dependence of the reflection coefficient of TM polarised light from the surface of a corrugated waveguide ($h_f = 210$ nm, $n_f = 2.02$, $2\sigma = 80$ nm, $\Lambda = 470$ nm) for $\theta = 0.05°$ without losses ($\mathrm{Im}\varepsilon_f = 0$) [curve (*1*)] and with losses ($\mathrm{Im}\varepsilon_f = 5 \times 10^{-4}$) [curve (*2*)].

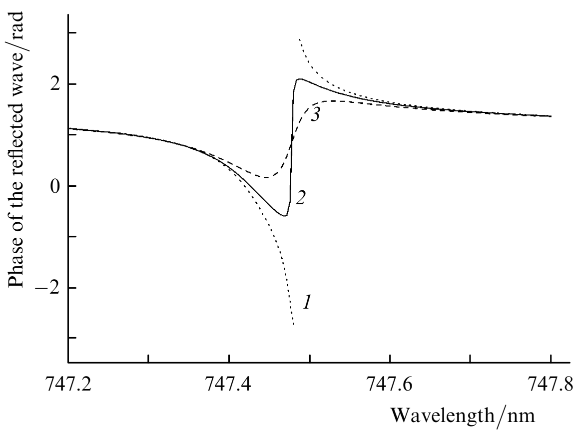

Figure 3. Spectral dependences of the phase of light reflected from the surface of a corrugated waveguide for $\theta = 0.05°$ in the region of the additional narrow resonance for waveguide losses $\mathrm{Im}\varepsilon_f = 0$ [curve (*1*)], 2×10^{-4} [curve (*2*)] and 5×10^{-4} [curve (*3*)].

technique). The results presented in Figs 2 and 3 can be used, in principle, to determine the optimal thickness of the filter, i.e., of a filter with the maximum transmission at the required wavelength.

However, it should be noted that the peculiarities of the spectral parameters of a filter formed by two waveguide – grating mirrors are not determined by a simple superposition of Fabry – Perot resonances on the spectral parameters of individual waveguide – grating mirrors. Apart from a relatively broad reflection dip caused by the transmission resonance of the Fabry – Perot interferometer, additional (one or two) considerably narrower transmission resonances are formed inside the reflection band of the waveguide – grating mirror. The position and relative width of these resonances, whose transmission coefficients are close to unity in the absence of losses, are determined by the grating phase shift $\Delta\varphi$.

For $\theta = 0$ and a phase shift $\Delta\varphi = \pi/2$, only one additional dip is observed in the reflection spectrum. For phase shifts $\Delta\varphi = 0$ and $\Delta\varphi = \pi$, there are two additional dips, but their width is vanishingly small, hence the angle of incidence of light on the filter is changed in Fig. 4 to determine the position of these dips. It is found that for an angle of incidence $\theta = 0.05°$ and a phase shift $\Delta\varphi$ from 0 to π, the range $\Delta\lambda$ of variation of the spectral position of high-transmission narrow resonances of the filter is 0.6 nm. Moreover, it is found that for an arbitrary value of the phase shift $\Delta\varphi$, there are two such dips moving towards each other on the wavelength scale. The presence of these dips is determined by a more complex form of the reflection band for normal incidence of light at the surface of a corrugated waveguide [6]. Additional dips fall in the region of narrow resonance for an individual waveguide.

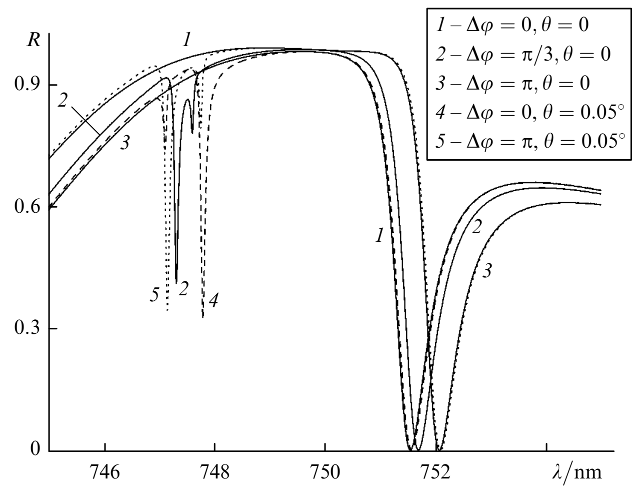

Figure 4. Spectral dependences of the reflection coefficient of light from an interferometer with two corrugated mirrors obtained for a buffer layer thickness $h = 1030$ nm and for different values of θ and $\Delta\varphi$.

It is important to note that the narrow dips observed in the reflection spectrum belong to the same interference order m of the Fabry – Perot filter. The pattern of dips in the reflection spectrum (or peaks in the transmission spectrum) is manifested only for a small distance h between the mirrors. This pattern disappears completely for $h > 2 - 3$ μm, thus confirming that it is related to tunnel coupling between corrugated waveguides.

Earlier, we considered in [6] the reflection of light from a two-side-corrugated waveguide for normal incidence of light on an asymmetric waveguide. The corrugations of this waveguide had different depths but the same period, and were arranged on different sides of the waveguide layer. The most important result of our calculations is the fact that for any phase relation between the corrugations, the reflection spectrum contains two reflection peaks of finite spectral width even for a strictly normal incidence of light ($\theta = 0$).

In the case considered above, i.e., for $h \approx 1$ μm, two waveguides are tunnel-coupled and represent virtually one combined waveguide corrugated from both sides with the same depth of corrugations. Therefore, for $\theta = 0$ and $\Delta\varphi \neq 0$ or $\Delta\varphi \neq \pi$, we observe in Fig. 4 dips in the reflection curve and hence peaks in the transmission curve of the filter based on Fabry – Perot interferometer with two waveguide – grating mirrors. Note that spectral positions of the narrow reflection lines [curve (*2*) in Fig. 4] and the broader line [curves (*1*) and (*3*) in Fig. 4] change upon an increase in $\Delta\varphi$.

Figure 5 shows the spectral dependence of the transmission coefficient of a filter nearly close to practical realisation and consisting of two corrugated waveguides separated by a buffer layer of thickness ~ 50 μm. Note first of all that the transmission peak is narrow and its spectral position changes with changing h. The decrease in the spectral peak width upon its displacement to the maximum of the reflection line of the waveguide – grating mirrors is caused by a high finesse F of the filter. However, this process is accompanied by a decrease in the peak amplitude due to waveguide losses.

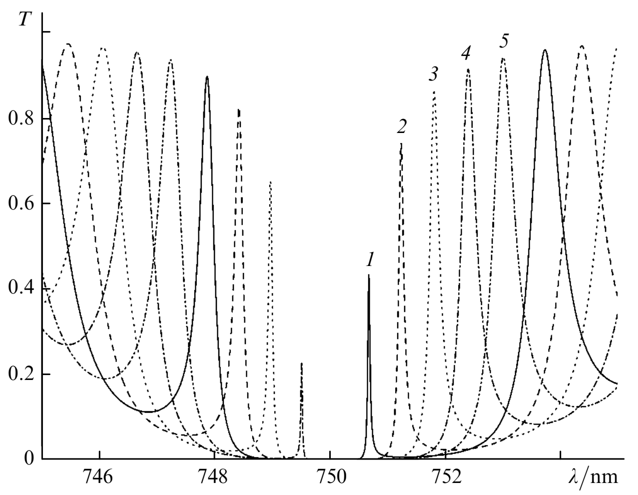

Figure 5. Spectral dependences of the transmission coefficient of light for an interferometer with two corrugated mirrors obtained for a buffer layer thickness of the order of 50 μm and for $\theta = 0$, $h = 49.85$ (*1*), 49.90 (*2*), 49.95 (*3*), 50.00 (*4*) and 50.05 μm (5).

4. Conclusions

Our study of the Fabry – Perot interferometer formed by two waveguide – grating mirrors has shown that for normal incidence of light on the waveguide surface, transmission spectrum of the interferometer does not differ significantly from the case of oblique incidence if the phase shift $\Delta\varphi$ between the gratings is equal to zero or π. However, for all other values of $\Delta\varphi$, the reflection spectrum of the filter displays two additional dips (or one dip) for small thicknesses h of the buffer layers even for $\theta = 0$. In our opinion, the disappearance of the additional resonances in the case of normal incidence and for a phase shift between the gratings equal to zero or π is due to the fact that the field distribution excited in these resonances is antisymmetric relative to the horizontal axis, while the grating profile and the incident field are symmetric. These resonances can be excited only by the symmetry breaking (phase shift between grating or inclination of the incident beam).

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