SELECTIVE LASER CAVITY WITH COMPOUND DIFFRACTION GRATINGS

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In this paper we discuss a new design of a laser cavity with compound diffraction gratings. It is shown that for broad beams such a cavity allows efficient narrowing of the lasing line, keeping the possibility to vary widely the lasing wavelength.

1. Single-mode lasing in lasers with small-aperture cavities and wide-band gain (dye lasers, color center lasers, and others with laser pumping) can be easily obtained in most cases by using diffraction gratings with angles of light incidence about 89–89.5° (Ref. 1). However, for lasers with wide-aperture cavities (solid-state and lamp pumping dye lasers) this way of obtaining the single-mode lasing is inapplicable, because the size of the diffraction grating for such angles must 60–115 times exceed the beam diameter. An absence of the papers, in which the single-mode lasing is reported to be obtained in the lasers with wide-aperture cavities by using the diffraction gratings, is also indicative of the problem complexity.

This paper describes a new design of a dispersion element of high selective capabilities[2] as applied to broad beams.

2. The lasing linewidth of a laser with a diffraction grating in the cavity is determined by the grating resolution

$$R = Lmk , \quad (1)$$

where L is the grating length; m is the number of grooves per 1 mm; k is the diffraction order.

To form the diffraction pattern, the condition $mk \le 2/\lambda$ (λ is the radiation wavelength) must be met, and correspondingly

$$R_{max} = 2L/\lambda . \quad (2)$$

It follows herefrom that large gratings should be applied to obtain the narrow-band lasing. However, because the laser size is restricted by some reasonable value, direct enhancement of the grating length or use of compound gratings (we have managed to arrange cophasely five gratings) give no desirable effect.

It is shown in Ref. 3, that when analyzing spectral composition of radiation, two identical gratings can be used to increase the resolution. The gratings should be arranged in such a way as to be an in-phase prolongation of each other (Fig. 1). Angular energy distribution given by such a system can be presented as[3,6]:

$$I = A^2 \frac{\sin^2 u}{u^2} \left(\frac{\sin M\nu}{\sin \nu}\right)^2 4 \cos^2 N\nu , \quad (3)$$

where the factor A^2 is proportional to the energy per one grating groove; the second multiplier describes the angular distribution of energy at diffraction on one groove; the third multiplier describes a standard diffraction pattern from one grating with M grooves; and the last multiplier describes the result of interference of two diffracted beams;

$$u = \frac{\pi}{\lambda} \cos\phi \sin(\varphi - \phi)\, d \ ; \ \ \nu = \frac{\pi}{\lambda} (\sin\varphi - \sin\phi)\, d \ , \quad (4)$$

where ϕ and φ are the angles of the radiation incidence and diffraction on the grating; $d = 1/m$ is the grating constant; the distance between the grating centers $W = Nd$ is expressed in units of the grating constant; N is the integer number.

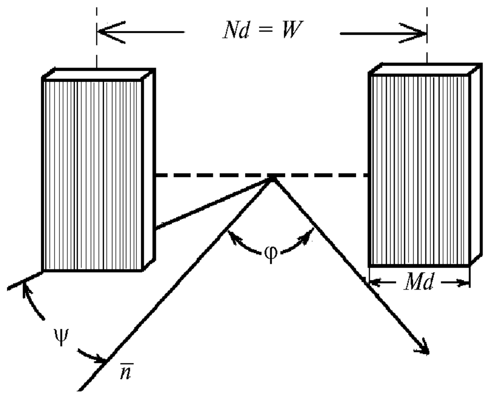

FIG. 1. Diagram of compound grating.

The widths of the diffraction peak of the system under consideration $\delta\varphi_1$, single grating $\delta\varphi_2$, and a combined large grating of the size equal to the distance Nd between the individual gratings, $\delta\varphi_3$, as well as the corresponding resolutions are calculated by the traditional method[6] as follows:

$$\delta\varphi_1 = \frac{\lambda}{2Nd \cos\varphi} , \quad R_1 \frac{\lambda}{\delta\lambda} = 2Nd; \quad (5)$$

$$\delta\varphi_2 = \frac{\lambda}{Md \cos\varphi} , \quad R_2 = Md; \quad (6)$$

$$\delta\varphi_3 = \frac{\lambda}{Nd \cos\varphi} , \quad R_3 = Nd. \quad (7)$$

As seen, the resolution of the system under consideration not only exceeds the resolution of a single

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grating, what is natural, but it is twice the resolution of the combined grating. We explain the latter circumstance by interference of beams from both gratings, while the reason for the increased resolution of the system is the interference of diffracted beams from the gratings' edges. Thus, "removal" of the grating's central part does not worsen its resolution. Nevertheless, direct application of such devices in lasers would result in significant worsening of power characteristics of the laser radiation due to catastrophically increasing loss, although the radiation spectrum can be narrowed therewith to the single-mode one.

To conserve the radiation energy, both "rest" parts of the grating should be shifted normally to the laser cavity axis so that their projections onto the plane normal to the laser beam do not intersect each other and have no gap. The distance between the grating parts along the beam path is denoted as M

Figure 2 shows schematically the versions of the cavity design proposed by us.

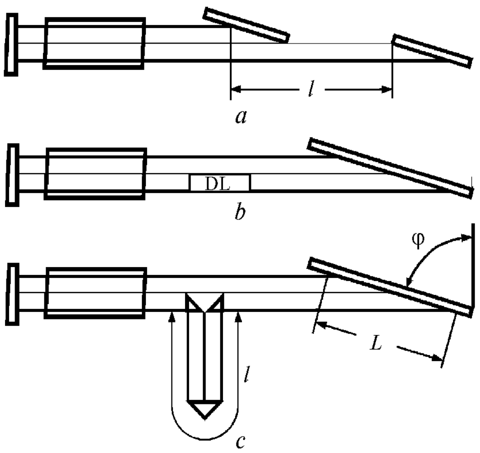

FIG. 2. Versions of the cavity design.

The diffraction gratings arranged as shown in Fig. 2*a* can be used as a reflector for non-tunable cavity at autocollimation installation. However, to change the lasing wavelength, one should rotate the gratings, and then a "gap" arises between them or one grating begins to shade another. This drawback can be eliminated by placing the gratings tightly to each other and inserting an optical delay line (DL) of length M in the path of a beam incident on the "far" grating. In this case, a single grating can be used in spite of two ones (Fig. 2*b*). A possible realization of the delay line in the laser is shown in Fig. 2*c*.

The ratio ξ between the resolutions of the system under discussion and the single grating of length L is equal to

$$\xi = \frac{2M}{L \sin \varphi} + 1 \, . \tag{8}$$

If the grating is completely overlapped by radiation beam of diameter D, then

$$\xi = \frac{2M}{D \tan \varphi} + 1 \tag{9}$$

and the resolution is

$$R_1 = \frac{2L}{\lambda} \left(\frac{2M}{D \tan \varphi} + 1 \right) . \tag{10}$$

These expressions allow the needed value of the delay to be estimated.

3. Consider the function I given by Eq. (3) in greater detail. The calculated results for a set of parameters (N, M, d, λ, $\varphi = -\phi$) corresponding to the experimental measurements are shown in Fig. 3 (the abscissa is the same in Figs. 3 and 4; it is plotted in relative units). As seen, narrowing of the central diffraction peak and, finally, the lasing line is payed by arising additional peaks of noticeable intensity. In fact, this means that some dips arise on the diffraction peak attributed to a single grating. And the larger is the delay, the greater is the number of dips. Correspondingly, the larger is the delay and the wider are the additional maximums, the slower is their decay.

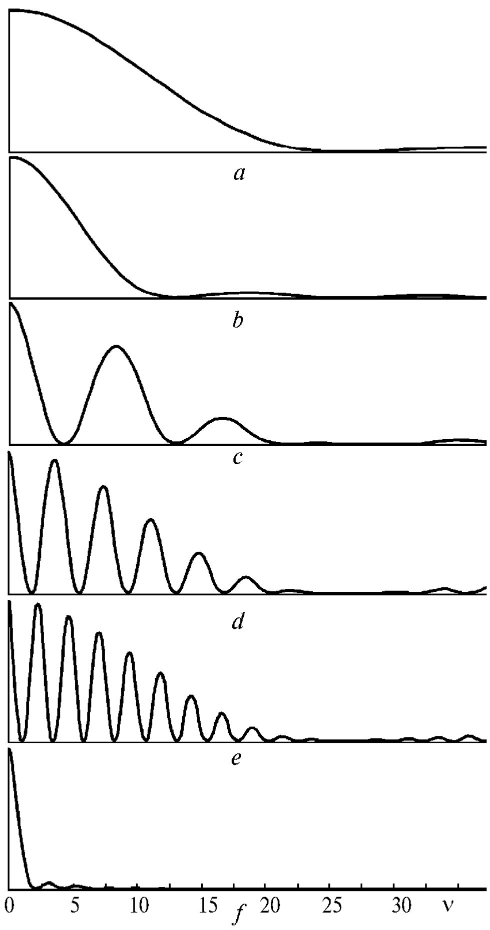

FIG. 3. The calculated dependence of the instrumental function of the "split" diffraction grating on the distance N between the grating parts: M = 150 *(a–e) and* 1800 *(f); N =* 0 *(a, f);* 150 *(b),* 450 *(c),* 1050 *(d), and* 1650 *(e).*

The experimental records of the diffraction pattern for the gratings with different distances between them are shown in Fig. 4. In the experiment, two gratings were modeled by placing a mask with slots in front of the grating. The size and arrangement of slots are shown in the right-hand part of the figure. The diffraction was observed in the He–Ne-laser radiation field. Good qualitative and quantitative agreement with the calculated results is clearly seen.

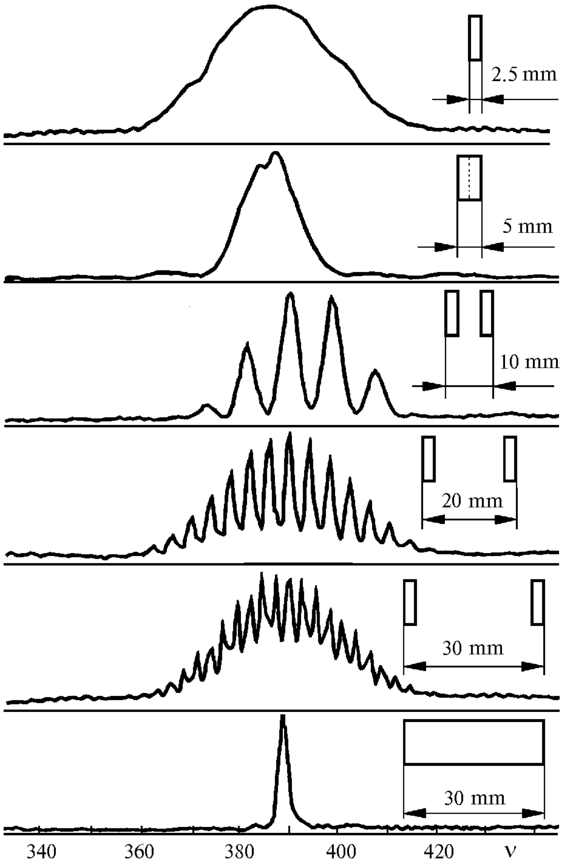

FIG. 4. The experimentaM dependence of the instrumentaMfunction of the “spM” diffraction grating on the distance between its parts.

4. The possibility to tune the laser frequency using the “split” grating has been analyzed computationally. As the laser media, we have considered the ruby ($\lambda' = 693$ nm) and the 4-methylumbelliferon dye ($\lambda' = 460$ nm). The former medium is characterized by very narrow gain line (the halfwidth of the order of 0.5 nm), while the latter is characterized by the wider line and different shapes of line wings: the shortwave wing is well approximated by Gauss profile, while the longwave one is approximated by Lorentz profile.[5] The line halfwidth in both cases is 27–28 nm. It was assumed that the grating has 1200 groove/mm and works in the second and the third orders of diffraction, respectively.

The lasing threshold wavelength λ_{las} is determined by the standard condition of equality between the loss and the gain:

$$K_g^{\lambda'}(\lambda_{las}) = K_{los}^{\lambda_0}(\lambda_{las}) \ . \qquad (11)$$

The superscript λ' indicates that the gain is maximum at the wavelength λ', while the loss is minimum at the wavelength λ_0. The ruby laser is considered at non-selective loss $\rho = 0.05–0.15$ cm^{-1}, and the dye laser is considered at $\rho = 0.1–0.4$ cm^{-1}. The maximum gain, determining the possible tuning range is respectively 0.4 and 5 cm^{-1}, and the active medium lengths are 12 and 2 cm (transverse-excited laser).

We assume that the diameter of the ruby-laser beam incident on the grating is 6 mm, while for the dye laser it is 1.25 mm. Taking into account the laser wavelengths and the working orders of diffraction, we obtain that M in Eqs. (3), (5)–(7) must be equal to 6500 for the ruby laser and 4000 for the dye laser.

The calculated results are shown in Figs. 5 and 6. The difference $\Delta = \lambda_0 - \lambda'$ between the dispersion cavity tuning wavelength and the wavelength of the gain line center is plotted as an abscissa, and the difference $\delta = \lambda_0 - \lambda_{las}$ between the tuning wavelength of the dispersion cavity and the lasing threshold wavelength is plotted as an ordinate.

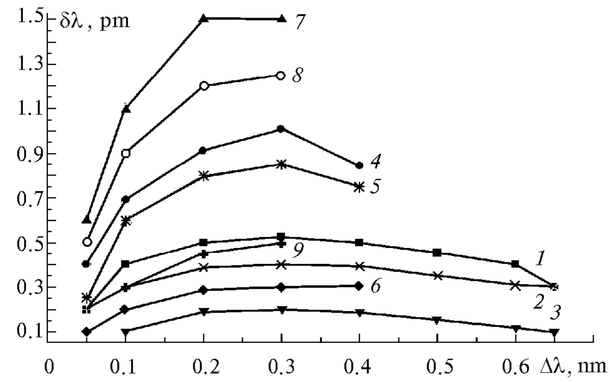

FIG. 5. The function $\delta\lambda(\Delta\lambda)$ for the ruby Mser (M = 6500); ρ = 0.05 (1–3), 0.1 (4–6), and 0.15 cm^{-1} (7–9); N = 6500 (1, 4, 7), 13000 (2, 5, 8), and 26000 (3, 6, 9).

Note two features of the obtained dependence. First, our attention is engaged by different behaviors of the curves – monotonic for Gauss profile of the gain line and nonmonotonic for Lorentz one. This difference can be explained by slight slope (increasingly slight with increasing $\Delta\lambda$) of Lorentz wing of the gain line. Second, the tuning accuracy becomes more dependent on the “distance” between the gratings (N) than on the grating width (M). It underlines the high efficiency of application of the cavity design under discussion.

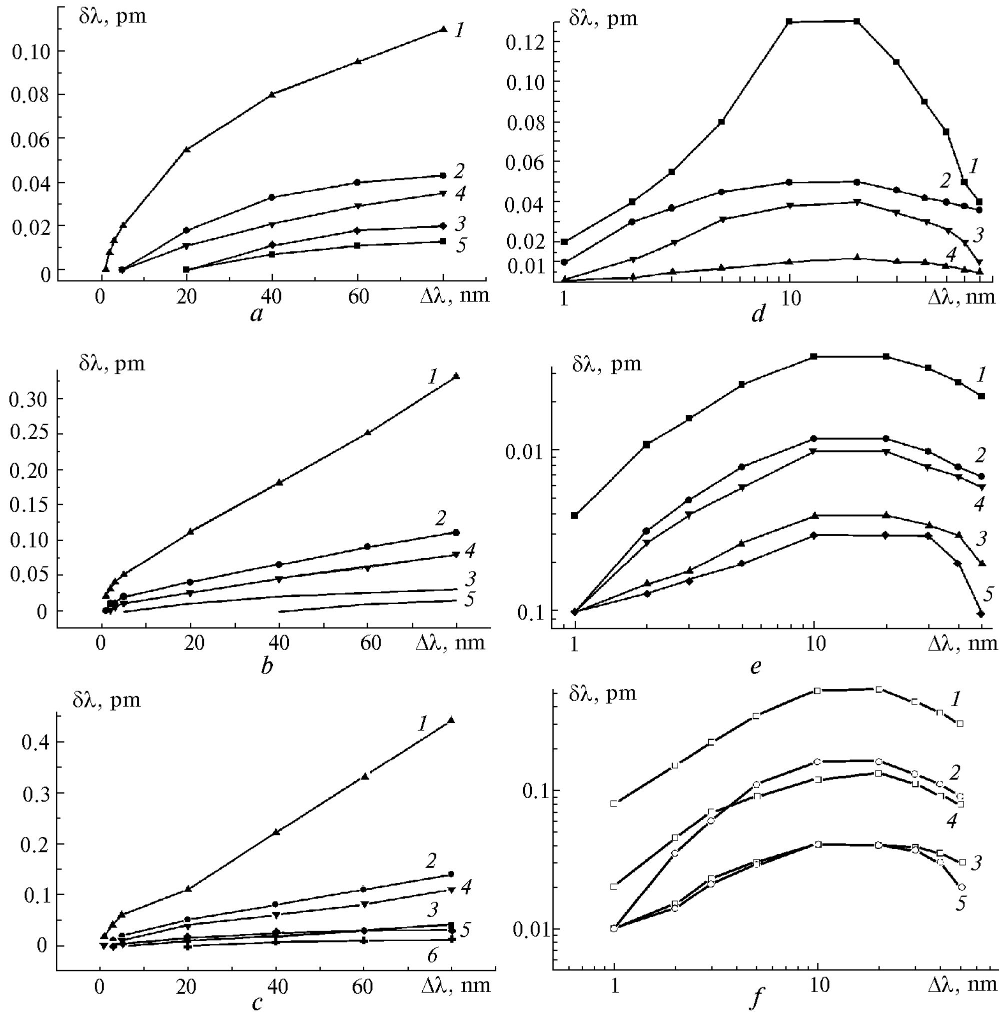

FIG. 6. The function $\delta\lambda(\Delta\lambda)$ *for the dye Mser; the Gauss-shape wing (a–c); the Lorentz-shape wing (d–f):* $M = 4000$; $N = 4000$ *(1),* 8000 *(2), and* 16000 *(3);* $M = 8000$; $N = 8000$ *(4) and* 16000 *(5);* $M = 8000$, $N = 32000$ *(6);* $\rho = 0.1$ *(a, d),* $\rho = 0.3$ *(b, e),* $\rho = 0.4\ \text{cm}^{-1}$ *(c, f).*

For initiation of lasing in the dye laser at the additional (next to the main one) diffraction peak, the gain must exceed the lasing threshold in the region of the main peak by 0.763, 0.203, 0.051, and 0.013 cm^{-1} at $N/M = 1$, 2, 4, and 8, respectively, for all the studied ranges of loss, cavity settings, gain curve shapes, and values of M.

5. It follows from the data presented that the use of compound diffraction gratings in the proposed designs of the laser cavity opens up the possibility for efficient control over laser wavelength, because the "stored" gain is sufficient for lasing within one diffraction peak. Obviously, the lasing line obtained at the proposed arrangement of the diffraction gratings becomes narrower as compared to the case of standard application of a grating.

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