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CONTROL OF LASER RADIATION PARAMETERS

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Dispersion cavities with volume holographic gratings

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***Abstract*. The analysis and experimental testing of dispersion cavities with volume holographic transmission gratings are performed. Depending on the angular selectivity and dispersion of the gratings, which determine the lasing linewidth, the required tuning range is accessible by rotating only one of the cavity mirrors or the grating – mirror unit about a given axis. The angular selectivity of the volume gratings is shown to play a decisive role in determining the lasing linewidth, making it possible to realise single-mode lasing in nanosecond lasers without using telescopic optics.**

***Keywords*:** *photopolymer holographic materials, volume phase holographic gratings, spectral-angular selectivity, dispersion cavities, single-mode lasing, polymer active media, laser frequency tuning.*

Volume holographic gratings (VHGs) belong to the class of elements whose diffraction follows the Bragg condition [1]. There are several kinds of phase holographic materials that can be used to record optical diffraction elements (dichromated gelatin, photopolymers, and photorefractive crystals). For the purposes of creating transmission diffraction gratings, self-developing photopolymers are clearly the most promising materials – both in the real-time recording technology and the actual characteristics [2, 3].

Within the framework of the two-wave theory [1], the angular selectivity of transmission VHGs with a harmonic modulation of the refractive index can be determined from the expression for the diffraction efficiency:

$$\eta = \frac{\sin^2(\xi^2 + \nu^2)^{1/2}}{1 + \xi^2/\nu^2}, \qquad (1)$$

where $\nu = \pi n_1 T/\lambda \cos\theta_0$ is the power of the transmission phase grating; n_1 is the modulation amplitude of the refractive index in the photopolymer of thickness T; θ_0 is the Bragg angle in the medium;

$$\xi = \frac{2\pi T}{\lambda}(\sin\theta_0)\Delta\theta$$

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is the detuning from the angle – wavelength resonance, with $\Delta\theta$ being the detuning from the Bragg angle in the medium. At $\nu = \pi/2$ and $\Delta\theta = 0$, the transmission grating has the maximum efficiency of 100 %.

A detuning reduces η_{max}; at $\eta/\eta_{max} = 0.5$ the angular and spectral FWHMs are given by

$$2\Delta\theta \approx \frac{\Lambda}{T}, \quad 2\Delta\lambda \approx \lambda_0 \frac{\Lambda}{T}\cot\theta_0, \qquad (2)$$

where Λ is the spatial period of the grating.

One can see that the thickness T of a VHG is the key parameter for controlling the spectral and angular selectivity of such gratings. Regarding the possibility of varying T, photopolymers are favourably distinguished among other recording materials [4]. Accordingly, transmission VHGs differ from relief gratings by their variable spectral-angular selectivity.

The condition for the diffraction of light from a grating, $\Lambda(\sin\theta \pm \sin\varphi) = m\lambda$ (with φ the angle of diffraction and $m = 1, 2, ...$), in general does not limit the angle of incidence, θ (with the exception of the Littrow autocollimation mounting and diffraction gratings). Therefore, such gratings do not produce any monochromatisation of light unless the incident light is collimated. This is the paramount condition for the practical utilisation of diffraction gratings in spectral devices.

The angular dispersion of a grating can be determined from the above diffraction equation for $\theta = \text{const}$, yielding $\mathrm{d}\varphi/\mathrm{d}\lambda = m/\Lambda\cos\varphi$. For a beam divergence of $2\delta\varphi$, the spectral width of the selected line is $\delta\lambda = 2\delta\varphi\Lambda\cos\varphi/m$ and the resolution is $\lambda/\delta\lambda = Nm$, with N being the spatial frequency of the grating rulings that are illuminated by this collimated beam. To minimise the lasing linewidth of a tunable laser, one therefore either employs dispersion cavities that contain telescopic beam-expansion systems [5] or increases N by employing grazing incidence of the beam on the grating [6].

The situation is different for Bragg gratings whose selectivity is based on the angular dispersion. Since in this case $\sin\theta = \sin\varphi$, the angular dispersion of the grating is

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} = \frac{1}{2\Lambda\cos\theta} = \frac{1}{\lambda}\tan\theta. \qquad (3)$$

However, in this case there is no need to illuminate the grating by a collimated beam because, due to its intrinsic angular selectivity, the grating itself collimates the analysed radiation. Assume only that the divergence of a beam that is formed by this grating is given by relations (2). Then, the spectral width of the selected line is

$$2\delta\lambda = \frac{2\Lambda^2 \cos\theta}{T}. \qquad (4)$$

The resolution of a spectral device containing such a grating is defined as

$$\frac{\lambda}{\delta\lambda} = \frac{T\lambda}{2\Lambda^2 \cos\theta} = \frac{T}{\Lambda}\tan\theta. \qquad (5)$$

It follows from Eqn (5) that the resolution of a VHG is the inverse angular selectivity multiplied by the tangent of the angle of incidence, which coincides with the Bragg angle. Like in the case of relief gratings, the resolution equals the effective number of phase planes of the grating that are involved in the diffraction. One can see that the resolution of a transmission Bragg grating is independent of the transverse dimensions of the beam. Therefore, the use of such gratings in spectral devices in general and in dispersion cavities in particular does not require recording large-area gratings and illuminating them completely with a collimated beam.

As yet, VHGs are not routinely used in optical devices because of the absence of data indicating their advantages over relief reflection gratings based on reflection-coated photoresists (Jobin-Yvon, France). The latter are widely used in spectral and laser devices instead of ruled gratings, allowing one to preserve the developed optical schemes while offering higher spatial frequencies and the absence of Rowland ghosts.

In this work, we employ volume phase gratings in the dispersion cavity of a tunable laser. The main goal of creating such cavities is to realise single-frequency lasing along with a simple mechanism for the frequency tuning within the gain profile of the laser medium. This goal was achieved by employing a reflection grating together with a Fabri – Perot etalon, or two gratings one of which operates in the grazing-incidence geometry [5, 6].

Cavities employing reflection gratings in the Littrow scheme [5] were historically the first and still are the most popular due to the technical simplicity of their tuning. The first volume transmission gratings based on dichromated gelatine also used the geometry of the Littrow scheme. To this end, transmission gratings with a diffraction efficiency of $\eta = 50\,\%$ were converted into autocollimation gratings with $\eta = 100\,\%$ by installing a reflection mirror or a total internal reflection prism at the back side of the grating [7, 8]. To minimise the lasing linewidth and realise single-mode lasing, the beam in a dispersion cavity with such a grating was expanded with the help of an optical telescope. Since the thickness of a dichromated gelatine layer is limited to ~ 20 μm by a number of technological reasons, this variant of utilising transmission phase gratings in dispersion resonators is justified.

In Ref. [4], we demonstrated a possibility of the holographic recording of transmission VHGs the recording layer with thicknesses up to 1 mm, while the angular selectivity was of the order of a few angular minutes and $\eta \approx 100\,\%$. Note that the thickness of a self-developing photopolymer layer was limited not by the photopolymerisation, but by the amplification of noise holograms, which intensified with increasing layer thickness. The accumulated efficiency of holographic light scattering by these noise holograms reduced the diffraction efficiency of the main hologram-grating.

In the case of the self-developing FPK-488 polymers, the thickness can vary from 10 to 1000 μm while preserving $\eta \approx 100\,\%$, thereby changing the angular and spectral FWHMs, $2\delta\theta$ and $2\delta\lambda$, by orders of magnitude. Changing T, one can realise both weakly and strongly selective gratings. For example, in the case of $\lambda = 600$ nm, $\Lambda = 1$ μm, $\theta = 25^\circ$, $2\delta\theta = 5.3^\circ$, and $T = 10$ and 200 μm, we have $2\delta\lambda = 60$ and 3 nm, respectively. For a grating with $T = 10$ μm whose Bragg angle is in resonance with the centre of the gain profile, the tuning range of $\Delta\lambda = \pm 300$ nm can be scanned by rotating the mirror by $\pm 4.5^\circ$.

For a grating with $T = 200$ μm, this tuning range requires the same mirror rotation. However, the angular interval of $\pm 4.5^\circ$ exceeds the angular selectivity of the grating, 0.26°, by one and a half orders of magnitude. This means that, with this grating, one cannot realise a tuning range of 60 nm by rotating only the mirror – the entire mirror – grating unit should be rotated instead. In the general case, these two tuning possibilities are described by the following two inequalities:

$$\frac{\Delta\lambda}{2\Lambda\cos\theta} < \frac{\Lambda}{T} \qquad (6)$$

for rotating a single mirror and

$$\frac{\Delta\lambda}{2\Lambda\cos\theta} > \frac{\Lambda}{T} \qquad (7)$$

for rotating the mirror – grating unit.

Fig. 1 shows the scheme of a laser with a dispersion cavity that is based on a volume transmission grating. In the case described by inequality (6), the lasing frequency is tuned by rotating one of mirrors, *1* or *2*, while keeping the grating fixed. The laser emission can be traditionally decoupled from the cavity through a semitransparent mirror. However, even best volume transmission gratings have $\eta \lesssim 100\,\%$. Choosing a grating with the optimal η is similar to choosing a mirror with the optimal transmission, which reduces to the problem of optimising the efficiency over the transmission of the cavity mirrors for a given pump power. Thus, the beam that remains fixed during the frequency tuning can be decoupled in the zeroth order of diffraction (output 1, Fig. 1), whereas the beam that scans the tuning angle can be decoupled in the first order of diffraction (output 2, Fig. 1).

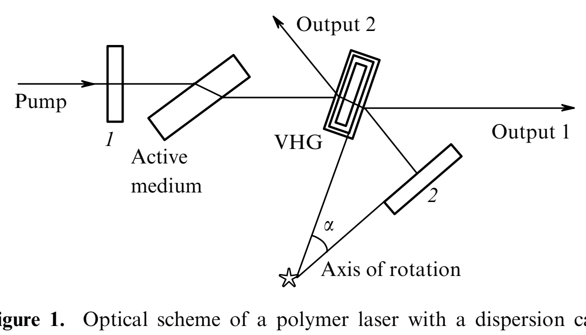

Figure 1. Optical scheme of a polymer laser with a dispersion cavity based on a volume holographic transmission grating.

If the angle of the Bragg diffraction is smaller than the Brewster angle, the laser can emit linearly polarised light, with the polarisation determined by the inclination of the active medium and the polarisation of the pump. In the case of a circularly polarised pump, the laser can emit unpolarised light.

The case described by inequality (7) is realised for larger grating thicknesses T, when the lasing linewidth should be ultimately reduced to the linewidth of the lasing on a single longitudinal mode. The lasing frequency can then be tuned over the gain profile of the laser medium by simultaneously rotating a mirror and the grating. The kinematics of this rotation is simple due to a linear relation between the Bragg angle and the angle of diffraction and the resulting equality of their increments, $\pm\delta\theta \equiv \pm\delta\varphi$. For the resonator to stay aligned, the angle of incidence of the diffracted beam on mirror *2* should remain equal to 90° during the frequency tuning.

This tuning kinematics is realised when the mirror and the grating are rigidly connected (α = const), and the mirror – grating unit is rotated about the axis that is indicated by a star in Fig. 1 and is perpendicular to the plane of the figure.

Fig. 2 shows typical tuning spectra of a laser on dyes in a polymer matrix. The laser was longitudinally pumped by the second harmonic of a Nd^{3+} : YAG laser and contained a 1200-mm^{-1} volume phase grating with $T = 10$ μm. The angular selectivity of the grating satisfied inequality (6); therefore, the frequency was tuned by rotating mirror *2* only, and the emission was decoupled in the zeroth order of diffraction.

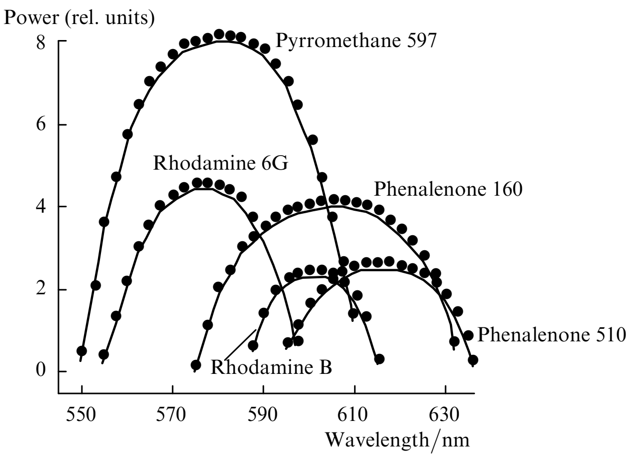

Figure 2. Tuning curves of the polymer laser.

Fig. 3 shows the angular selectivity of the volume phase gratings that were recorded in the FPK-488 polymer we developed. The measurements were performed for the s- and p-polarisations using the emission of a He – Ne laser (632.8 nm). The diffraction efficiency was defined as the ratio of the radiation power diffracted to the first order, to the power of the incident radiation, that is, without subtracting the reflection losses. For a power of the diffracted radiation equal to half the power of the incident radiation, the full angular width was 1.6° and 3.1° for $T = 25$ and 20 μm, $N = 2000$ and 1200 mm^{-1}, respectively. These results agree with the predictions of the two-wave theory [1]; however, the maximum efficiency remained the same for both polarisations.

This result, observed systematically for polymers of various compositions, contradicts the theory [1], which was

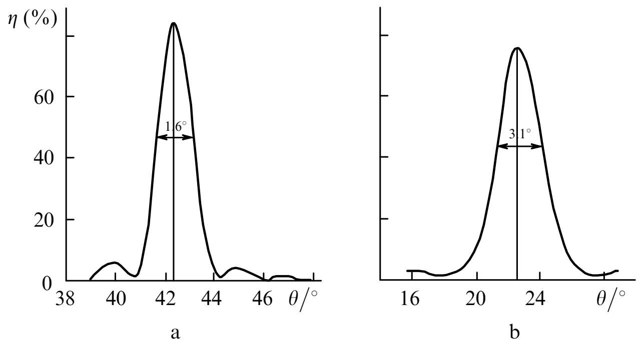

Figure 3. Angular selectivity of the transmission VHGs with $N = 2000$ (a) and 1200 mm^{-1} (b), $T = 25$ (a) and 20 μm (b).

developed for the case of the harmonic modulation of the refractive index of an isotropic material and which predicts different η for the s- and p-polarisations. We attribute this fact to the anisotropy induced during the recording, when the addition n_1 to the isotropic refractive index of the photopolymer layer that is due to the recording – polymerisation process in a gradient light field gives rise to the birefringence.

A dispersion cavity with a VHG already differs significantly from a similar cavity with a relief reflection grating. For example, comparing the angular divergence averaged over the ~ 20-ns pulse durations of the lasers with equally long 25-cm cavities, we have found that the laser employing a cavity with a volume holographic grating (1200 mm^{-1}, T 20 μm) has a systematically lower divergence than the laser employing a cavity with a relief diffraction grating (1200 mm^{-1}). For the laser with a relief reflection grating, the divergence of the output beam was 3.5 mrad at the threshold and 4.5 mrad in the case of the tenfold excess of the pump intensity over the threshold. For the laser with a VHG, the respective quantities were 2 and 2.5 mrad. None of the lasers contained telescopic systems. This result confirms the conjecture that the angular selectivity of the VHG acts as a telescopic system on the beam in the cavity, reducing its divergence.

The combined effect of the angular dispersion of the VHG and its angular selectivity significantly increases the

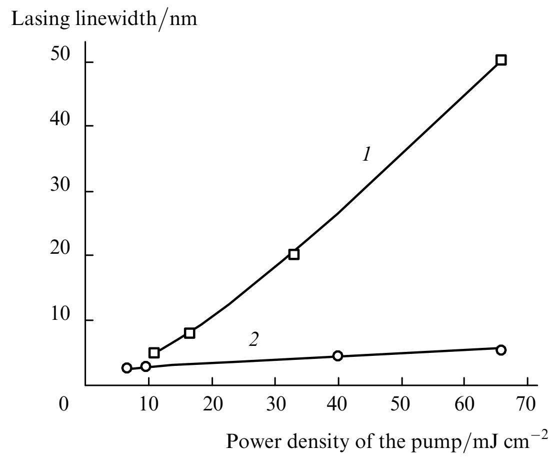

Figure 4. Dependence of the lasing linewidth on the power density of the pump in the case of a cavity with a ruled grating (*1*) and a VHG (*2*).

spectral selectivity of the cavity by weakening the dependence of the linewidth on the divergence. For equal dispersions of the 1200-mm^{-1} gratings, the linewidth of a pulsed dye laser was narrowed by approximately an order of magnitude. The relevant results are shown in Fig. 4.

As we changed over to a 2000-mm^{-1} VHG with an angular selectivity of 1.6°, the lasing linewidth reduced to below 1 pm, becoming comparable to the mode spacing. We will present a detailed analysis of single-mode lasing in VHG-based cavities in a separate communication.

Due to the high selectivity of the Bragg resonance in a VHG, one can even abandon dispersion cavities altogether, using instead an arrangement of two equivalent gratings with the dispersion subtraction. Earlier, we have described a similar scheme for an optical monochromator based on volume holographic gratings [9].

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