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Generation of Stark spectral components in Nd : YAP and Nd : YAG lasers by using volume Bragg gratings

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***Abstract*. Generation of Stark spectral components in free-running *Q*-switched Nd : YAP (1064 nm and 1073 nm) and Nd : YAG (1062 nm) lasers is obtained. For this purpose reflecting volume Bragg gratings placed into the laser resonator and permitting to tune the laser emission spectrum were used. Stable generation of Stark components in both lasers is obtained. The possibility of obtaining two-frequency generation in an Nd-glass laser with the help of these gratings is shown.**

Keywords: *neodymium laser, volume holographic gratings, stark components.*

1. Introduction

Production of volume Bragg gratings (VBGs) written in photothermorefractive glass is promising for their extensive application [1] as a diffractive optical element of a new type. Unusual properties of the photothermorefractive glass make it possible to write in it gratings with remarkable characteristics, which include first of all high radiation resistance, temperature and optical stability, high diffractive efficiency in a broad spectral range from visible to near-IR and unlimited lifetime. The use of VBGs as an optical element residing inside and outside the cavity makes it possible to improve considerably spectral and spatial laser characteristics and to monitor its output parameters [2, 3].

Unique spectral properties of volume Bragg gratings make them exceedingly useful for frequency selection of output laser radiation. The maximum diffraction efficiency of VBGs in the photothermorefractive glass exceeds 99 % both for reflection and transmission gratings. In this case, their spectral selectivity can be $\sim$30 pm and the angle selectivity – lower than 1 mrad. Efficient selection of longitudinal and transverse modes with the help of intracavity VBGs was demonstrated in various lasers [1, 4, 5]. The use of a reflecting Bragg grating as an output mirror in cw and pulsed solid-state lasers made it possible to narrow and stabilise their emission spectra without a drop in the output power [2, 6 – 8]. In this connection, it seems interesting to apply VBGs for spectral tuning of radiation from laser generating a set of frequencies which correspond to different intraatomic transitions.

In this paper, we present the results of experiments on the use of reflecting VBGs placed into the laser resonator, which serves as the optical switch of generated Stark spectral components in output radiation of Nd : YAP ($Nd^{3+}:YAlO_3$) and Nd : YAG ($Nd^{3+}:Y_3Al_5O_{12}$) lasers.

It is known that the $Nd^{3+}:YAlO_3$ crystal can emit several laser lines (Stark components) in the spectral range from 1058 to 1099 nm due to $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions [9]. The principal lines of these transitions correspond to the wavelengths of 1064.5 and 1079.5 nm. For a Nd : YAP laser rod cut out along the *b* axis, the absorption cross sections depend on polarisation so that 1079.5-nm radiation polarised along the *c* axis has the highest gain, while radiation polarised along the *a* axis has the highest gain at 1064.5 nm. Because the maximum gain for $\lambda = 1079.5$ nm is higher than that for $\lambda = 1064.5$ nm, the laser will generate radiation polarised along c axis in absence of another intracavity polariser. If the same linear polariser is placed into the laser resonator, its rotation will increase losses for the prevailing polarisation at 1079.5 nm, and the laser will generate light linearly polarised along the *c* axis at 1064.5 nm [10, 11]. To generate others Stark components, in particular at the intermediate wavelength of 1072.6 nm, it is necessary to modify the optical scheme of the laser by introducing additional dispersion elements for polarisation and spectral selection in the resonator [12].

Under normal operation conditions and at room temperature, the Nd : YAG laser emits at 1064.1 nm at the strongest $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. Lasing can be obtained at other frequencies by using, for example, etalons or the dispersion prisms placed into the laser resonator. These elements suppress undesirable frequency oscillations by preserving in this case the optimal conditions for generation of selected wavelengths. The use of these elements in the Nd : YAG laser made it possible to obtain lasing at various Stark transitions [13 – 15]. Lines at 1064.1 and 1061.5 nm have the lowest lasing threshold in the Nd : YAG laser. The 1064.1-nm transition dominates at room temperature, while the 1061.5-nm line has a smaller lasing threshold at lower temperatures.

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2. Experimental

The scheme of the experimental setup is shown in Fig. 1. Laser active element (*1*) representing a YAP or YAG crystal doped with neodymium ions was placed into the flashlamp-pumped cavity. The laser resonator was formed by two plane – parallel mirrors (*2*) and (*3*) with reflection coefficients of 100 % and 80 %, respectively, at 1064 – 1080 nm. Iris diaphragm (*4*) was used to select the fundamental transverse mode. Reflecting VBG (*5*) placed into the resonator served as a selector for the Stark spectral components. The grating could be rotated in a horizontal plane and reflect at various angles radiation of various wavelengths propagating in the resonator. Saturated absorber (*6*) ($YAG:Cr^{4+}$) with the initial transmission of 50 % provided the *Q*-switched regime. Glan prism (*7*) was used to obtain the necessary linear polarisation of the laser output. The laser could operate at various pulse repetition rates (0.1 – 50 Hz) depending on type of the active element. Energy, spectral and temporal parameters were measured with the corresponding equipment.

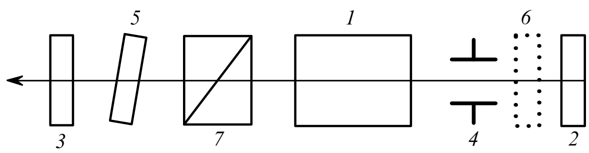

Figure 1. Scheme of the experimental setup: (*1*) laser active element; (*2*, *3*) plane – parallel mirrors; (*4*) iris diaphragm; (*5*) VBG; (*6*) saturating absorber; (*7*) Glan prism.

In the first part of the experiment, the Nd : YAP crystal cut along the *b* axis was used as an active element. The laser operated in the free-running regime. The Glan prism provided polarisation corresponding to the laser fundamental wavelength of ~1080 nm. The reflecting VBG had the maximum reflection of ~97 % with the half-width of 0.2 nm at the resonance wavelength of 1090.7 nm. Because the fundamental wavelength of the Nd : YAP laser is 1080 nm, the grating should be turned in the diffraction plane to fulfill the Bragg reflection condition. At this wavelength, the Bragg angle of incidence for the given grating is ~12%. If the grating was detuned from the Bragg angle, the laser oscillated at the fundamental wavelength (1080 nm). However, the rotation of the VBG in the direction of the Bragg angle changed the radiation frequency: the fundamental wavelength was coupled out from the resonator due to reflection from the grating and the laser started generating at the nearest neighboring Stark line (1073 nm). When the angle of the maximum diffraction efficiency is achieved for the fundamental laser frequency, the VBG operates as a narrow-band mirror, which cuts off radiation at 1080 nm and is transparent at 1073 nm. In this case, the threshold pump energy increased by ~15 % compared to lasing at 1080 nm. Insignificant detuning of the VBG from the Bragg angle allowed one to achieve a two-frequency lasing regime at the corresponding wavelengths.

In the *Q*-switched regime, frequencies were selected similarly. When the VBG was tuned to the maximum of the diffraction efficiency for the fundamental frequency, the laser emitted at 1073 nm. When the grating was detuned from the Bragg angle, the laser emitted at 1080 nm. In the lasing regime of the fundamental transverse TEM_{00} mode, the laser emitted at the threshold a single (40 – 50 ns) pulse with the output energy of ~17 mJ at 1073 nm or ~2 mJ at 1080 nm. In the case of two-frequency lasing, both pulses were emitted nonsimultaneously and the time interval between them varied from shot to shot in the range from 50 ns to 1 μs. The output radiation at 1073 nm as well as the fundamental one at 1080 nm was linearly polarised along the *c* axis.

The Nd : YAP laser action at 1064 nm was performed by rotating the Glan prism by 90° and by replacing the previously used VBG by another one. The latter had the diffraction efficiency of ~99 % at the central wavelength of 1065.1 nm and the reflection profile half-width of ~ 0.47 nm. When the grating was detuned from the Bragg angle for $\lambda = 1065.1$ nm, the laser generated radiation at this wavelength. By turning the VBG and tuning the angle of radiation incidence to the Bragg one, it was possible to obtain various combinations of generated wavelengths: one- (1064 or 1073 nm), two- (1064 and 1073 or 1073 and 1080 nm) and three-wave (1064, 1073 and 1080 nm) lasing (Fig. 2) both in the free-running and *Q*-switched regimes. The measured spectral width of Stark components was limited by the resolution of the spectrometer, which was equal to ~0.15 nm in this spectral range. Radiation of all the three wavelengths was linearly polarised along the *a* axis, which is caused by the orientation of the intracavity polariser.

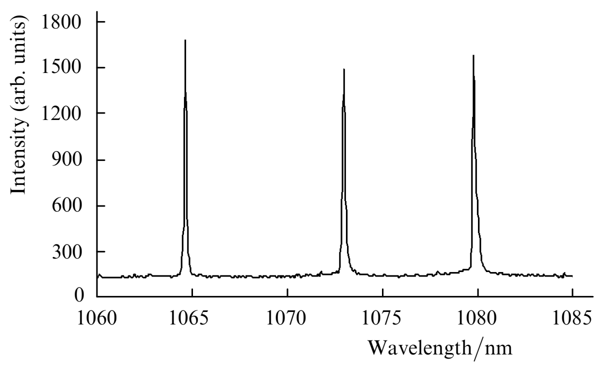

Figure 2. Emission spectrum of the *Q*-switched Nd : YAP laser.

In experiments with the Nd : YAG laser, the use of the above reflecting VBG with the centre of the diffraction efficiency at 1065.1 nm made it possible to obtain generation of the Stark spectral component with $\lambda \sim 1062$ nm at room temperature. By turning the grating in the diffraction plane it was possible to switch the laser to another fundamental wavelength – 1064 nm. Stable generation of the fundamental transverse TEM_{00} mode at both wavelengths was obtained both in the free-running and *Q*-switched regimes. At certain angles of radiation incidence on the VBG the laser could operate in the two-frequency regime.

The use of this VBG as the frequency filter in the neodymium laser resonator allowed one to obtain a steady regime of simultaneous generation of two spectral components, which are a part of the emission spectrum of neodymium glass. The scheme of the experiment was similar to that shown in Fig. 1 except for the saturable absorber. In this case, we used the $LiF:F_2^-$ crystal with the initial transmission of 70 %. The reflecting VBG had the reflection maximum of the order of 98.2 % with the half-width of 0.11

nm at 1064.4 nm. When the grating was not in the Bragg resonance and the pump energy was close to the threshold one, the laser emitted in the Q-switched regime a single ($\sim$400 ns) pulse with the energy of $\sim$3 mJ and a smooth spectrum centered at $\sim$1062 nm and the FWHM of $\sim$5 nm. By turning the grating in the direction of the Bragg angle, the emission spectrum was changed and at the corresponding position of the VBG the spectrum exhibited two lines with the FWHM of $\sim$0.13 nm (taking into account the spectral resolution of the spectrometer). The lines were separated from each other by $\sim$1.4 nm and were generated simultaneously (Fig. 3a). In this case, the pulse duration remained invariable and the total energy decreased down to 1 mJ.

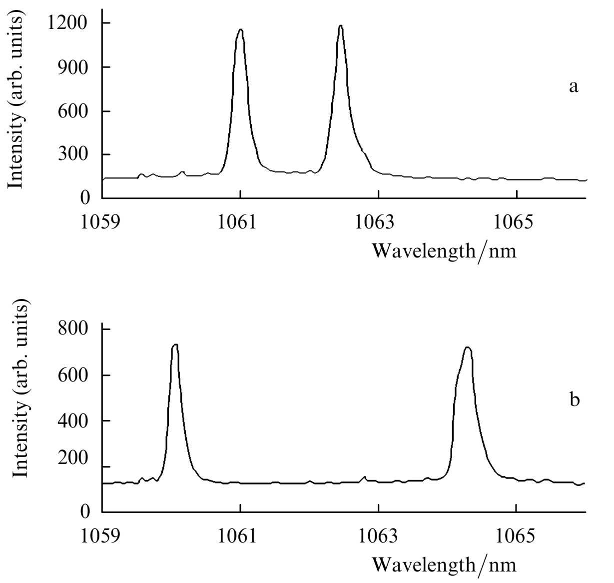

Figure 3. Emission spectrum of neodymium glass laser with an intracavity VBG having the reflection profile half-width of 0.11 (a) and 0.47 nm (b).

Simultaneous generation of two spectral components in the neodymium glass laser was also achieved by using several reflecting VBGs having different reflection profile half-widths. For five gratings the following spectral intervals between generated components were obtained: 1, 1.4, 1.8, 2.3 and 4.2 nm. As an example, Fig. 3b shows the emission spectrum of the laser with an intracavity VBG having the reflection profile half-width of $\sim$ 0.47 nm.

3. Conclusions

The possibility of using volume Bragg gratings written in photothermorefractive glass for generation of Stark components in solid-state lasers has been demonstrated. The experimental results on the use of reflecting VBGs placed in the laser resonator as the optical switch of generated Stark spectral components in the free-running, Q-switched Nd : YAP and Nd : YAG lasers have been presented. The use of the VBG as a frequency filter in the resonator of the neodymium glass laser has made it possible to obtain a stable simultaneous generation for two spectral components.

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