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Holographic reflective Bragg gratings of gain and their role in the operation of high-power pulsed lasers

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Abstract. **The influence of reflective Bragg gratings that are formed in an active medium due to the spatial periodic modulation of gain on the spectral properties of lasing are investigated by an example of a pulsed Nd:YAG laser. It is shown that, at a certain choice of the formation regime of reflective gratings of gain, the lasing bandwidth can be reduced by a factor of 3–5, with a corresponding increase in the pulse energy and significant improvement of spatial beam quality.**

Keywords: *Bragg gratings, high-power pulsed lasers.*

1. Introduction

Holographic gratings that are formed either due to the periodic modulation of the refractive index of material or as a result of periodic modulation of its absorption coefficient have been widely discussed in the modern literature. In the former case, it is accepted to speak about refractive-index gratings or phase gratings Δn. In the latter case, the concept of gratings of absorption coefficient of a material or amplitude gratings $\Delta\alpha$ is used [1]. Strictly speaking, changes in the refractive index of material are related to changes in its absorption coefficient via the Kramers–Kronig relation [2]. The mechanisms of formation of gratings of these types by a recording beam were described in detail in [3, 4].

In this paper, we report the results of studying the holographic Bragg gratings formed as a result of modulation of active-medium gain g. As shows our experience in the experimental research and development of high-power pulsed lasers, this situation is characteristic of cavities in which a generated light beam can intersect itself several times when passing through the active medium (Fig. 1). In this case, the occurrence of interference pattern with a spatial period Λ causes a corresponding periodic modulation of the refractive index and gain of the medium. Since the length T of the region occupied by the interference pattern may be as large as several tens of millimeters, the relative spectral selectivity of the arising reflective grating can be estimated as $\Delta\lambda/\lambda \approx \Lambda/T = 10^{-5}-10^{-6}$ [1, 5]. Such a high spectral selectivity of reflective grating affects the spectral characteristics of lasing.

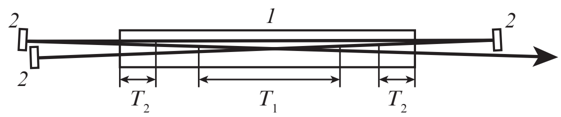

Figure 1. Example of occurrence of interference pattern regions of length T_1 and T_2 in the active medium of multipass laser: (*1*) active medium and (*2*) mirrors.

When studying the self-starting lasing in a laser with a loop cavity and without an output mirror, attention was paid (apparently, for the first time) to the influence of Bragg reflective gratings arising in the cavity [6]. Later on, a possibility of enhancing the feedback due to the increase in the number of beam path loops in the cavity was demonstrated in [7].

These cavities narrow significantly the lasing spectrum in comparison with the Fabry–Perot cavity [8]. This effect is related, first, to the increase in the efficiency of longitudinal-mode competition in the cavity due to the self-modulation of Q factor and, second, to the phenomenon of spectral and angular selectivity of the gain grating written in the active medium [6]. Selection of one mode manifests itself both in the case of free lasing [9, 10] and under conditions of passive Q switching [11–13].

Since the processes of mode formation in a loop cavity are random, the laser wavelength may change from pulse to pulse. The stabilisation of the wavelength and its controlled change are important for some applied problems of spectroscopy and generation of harmonics.

The purpose of this work was to investigate the influence of Bragg reflective gratings, both those arising in the active medium during lasing and those installed in the loop cavity of pulsed lasers with a YAG:Nd^{3+} crystal playing the role of active element (λ = 1064 nm), on the spectral properties of generated beam.

2. Stabilisation of radiation wavelength

A schematic of the pulsed phase-conjugate laser and system for measuring the radiation spectrum are presented in Fig. 2.

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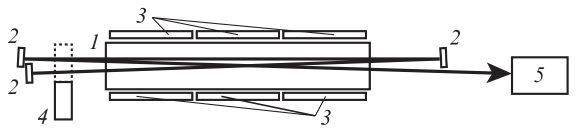

Figure 2. Schematic of a pulsed phase-conjugate laser: (*1*) active element YAG : Nd^{3+}; (*2*) mirrors; (*3*) pumping LED arrays SLM-02; (*4*) passive gate YAG : Cr^{4+}; (*5*) detection system, including Fabry–Perot etalon, OPHIR Spiricon camera, avalanche photodiode, and broadband oscilloscope.

Transverse pumping of an active element (*1*) (YAG : Nd^{3+} crystal 6.3 mm in diameter and 110 mm long, with a Nd^{3+} ion concentration of 0.6 at%) was performed by six SLM-02 LED arrays (*3*) with a total peak power of 13.9 kW. Being developed from spontaneous luminescence, radiation is successively reflected from cavity mirrors (*2*). The cavity feedback is provided by self-pumped phase-conjugate mirrors in the active medium. The convergence angle of beams does not exceed 1°, due to which their intersection is provided throughout the entire active element. The passive *Q*-switching regime was used; to this end, along with the self-modulation of the *Q*-factor due to rewriting gain gratings in the active medium, we applied a passive gate (*4*) in the form of a YAG : Cr^{4+} crystal with an initial transmittance of 10%. Special attention was paid to the detection system (*5*), which makes it possible to record simultaneously (in the linear regime) the spectral and temporal characteristics of generated pulses with a high accuracy. Figure 3 shows dependences demonstrating a sequence of pump and laser pulses for the operation modes under study. In all experiments the repetition rate of pump pulses was 10 Hz, and their duration ranged from 100 to 475 μs. The *Q*-switching regime provided generation of trains composed of several 'giant' pulses. With a change in the pump pulse duration from 100 to 475 μs, the number of pulses in the train varied from 1 to 10 (Fig. 3).

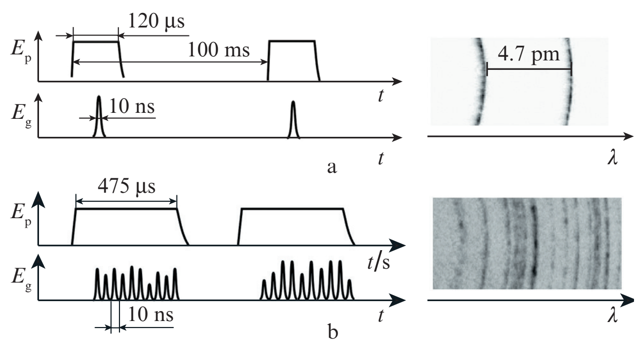

Figure 3. Pump pulses E_p and trains of generated pulses E_g and their spectra in the cases of generation of (a) 1 and (b) 10 pulses.

The single-pulse radiation is a single-mode one. Its spectral width is 0.2 to 0.3 pm, independent of the number of pulses in the train. The presence of one longitudinal mode is observed only in the case of an open cavity with dynamic feedback provided by gain gratings. In the presence of the output mirror or in the case of diffraction extraction of radiation from a closed cavity, several longitudinal modes are generated. The reason is as follows: in the case of lasing without an output mirror the feedback is determined by the diffraction efficiency of grating, whose contrast depends on the radiation intensity at a given wavelength. The higher the mode intensity, the more efficient the feedback. At the same time, the output mirror uniformly provides feedback for all longitudinal cavity modes.

In the case of generation of a sequence of pulse trains, the pulse radiation frequencies differ within a train [14]. A statistical study of the number of longitudinal modes in the spectrum of generation of one train consisting of *N* pulses makes it possible to verify the fundamental possibility of forming pulses with close lasing frequencies within one train. Since the gain line spectrum for a laser with a phase-conjugate cavity without an output mirror is continuous, the probability of generating uncoupled pulses at the same frequency tends to zero. During the experiment we recorded simultaneously oscillograms and interference patterns for trains with different numbers of pulses. The interval between trains amounted to ~0.1 s, i.e., was much longer than the train duration (which did not exceed 0.5×10^{-3} s). Therefore, it was assumed that the thermodynamic state of the active element is the same for different numbers of giant pulses in the train. Based on this assumption, the radiation spectra can be estimated in dependence of the number of pulses in the train (*N*). For each number *N*, estimation was performed over 16 experiments. Figure 4 shows a distribution of the number of longitudinal modes as a function of *N*.

We detected single-mode lasing for trains composed of 6 to 8 pulses. Therefore, rewriting of the gain grating does not necessarily lead to a change in the radiation frequency. The lasing bandwidth in the regime of trains composed of several pulses is 2.5 pm, which is smaller than the bandwidth of a laser with a Fabry–Perot cavity. Within the error it corresponds to the spectral selectivity of a gain grating at a specified length of the active element; this circumstance explains the narrowing of the total bandwidth in the regime of generation of pulse trains by the operation of a dynamic gain grating as a spectral filter.

3. Narrowing of the lasing spectrum of a phase-conjugate laser

The radiation frequency is stabilised in an adaptive optical system based on a self-pumped phase-conjugate laser with a passive gate (Fig. 5) under conditions of multiple four-wave mixing. The dynamic loop cavity is switched on during lasing development. A Bragg grating (*11*) was used as a spectral selector. The cavity was formed by a highly reflecting mirror (*2*) and seven rotational mirrors (*3*–*9*). The maximum pump energy amounted to 10.3 J. The free-dispersion range of the Fabry–Perot etalon turned out to be 28 pm.

Frequency was stabilised with the aid of a Bragg transmission grating written in photothermorefractive glass [9] using UV radiation of a He–Cd laser (λ = 325 nm), with allowance for the a wavelength of 1064 nm in a 1-mm-thick glass sample. The diffraction angle for the working wavelength was 27.1°, and the diffraction efficiency was about 90%. The spectral selectivity of the grating can be estimated as 0.5 nm (or 150 GHz), a value comparable with the Nd : glass gain bandwidth (120 GHz), and its angular selectivity can be estimated as 0.05°.

We investigated the lasing both in the case of spectral selection using a Bragg grating and without it. The grating

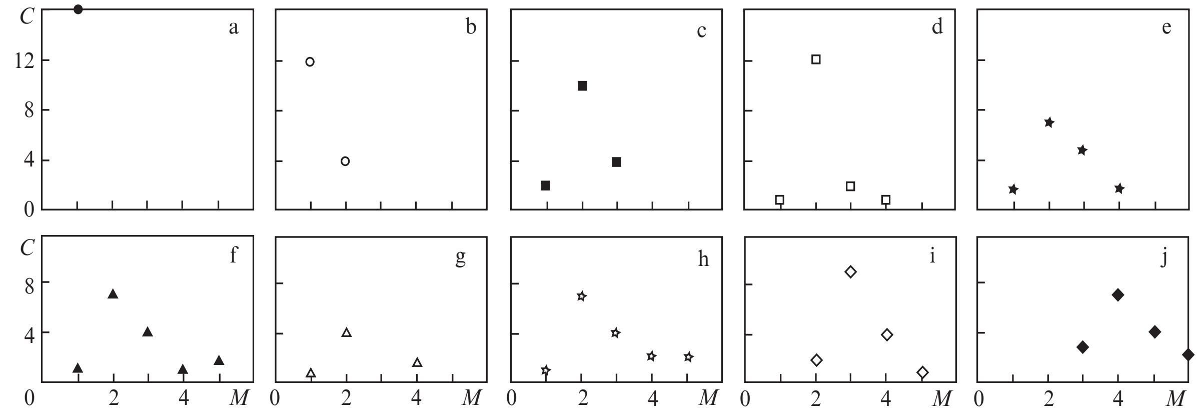

Figure 4. Number of longitudinal modes M in dependence of the number of pulses in a train from (a) 1 to (j) 10 (C is the number of trains).

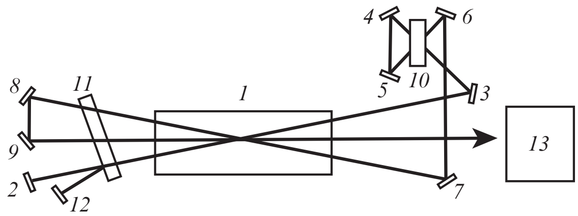

Figure 5. Schematic of a self-pumped phase-conjugate laser: (*1*) active element; (*2*, *12*) mirrors; (*3*–*9*) rotational mirrors; (*10*) passive gate LiF : F_2; (*11*) external Bragg grating; (*13*) system for recording the second harmonic.

was installed in the cavity before mirror *2* so as to make the radiation incident on it satisfy the Bragg condition. Due to the high angular selectivity of the grating in use, other intracavity beams did not interact with the grating. Since the grating diffraction efficiency exceeded 90%, mirror *2* was not involved in lasing when the grating was present in the scheme. The radiation fell in the first diffraction order and reflected off from mirror *12*.

Lasing begins with noise emission in the active element. While lasing develops, the crossed beams in the active element write transmission gratings of gain, which form an adaptive cavity. Redistribution of the radiation field and its phase conjugation occur on the newly formed dynamic gratings. The Bragg grating selects the central components of the gain profile, due to which the lasing frequency is stabilised. The dynamic gratings written in the active medium, in combination with the stationary Bragg grating, select spatial, spectral, and polarisation characteristics. A passive gate (*10*) implements the passive *Q*-switching regime and provides a train of nanosecond pulses. The train energy was up to 2.5 J, and the pulse energy in train amounted up to 200 mJ.

Figure 6 shows the interference patterns obtained in the regime of generation of an 11-pulse train, both in the absence and in the presence of a selective Bragg grating. In the former case, the interference pattern contains from 2 to 6 longitudinal modes within one interference order. The total spectral width in the absence of a grating was 18 pm; in the presence of a grating, it did not exceed 4 pm. The centre radiation frequency remained constant. It is noteworthy that laser generates pulses with a high energy and peak power and that the radiation is single-mode and single-frequency, due to which

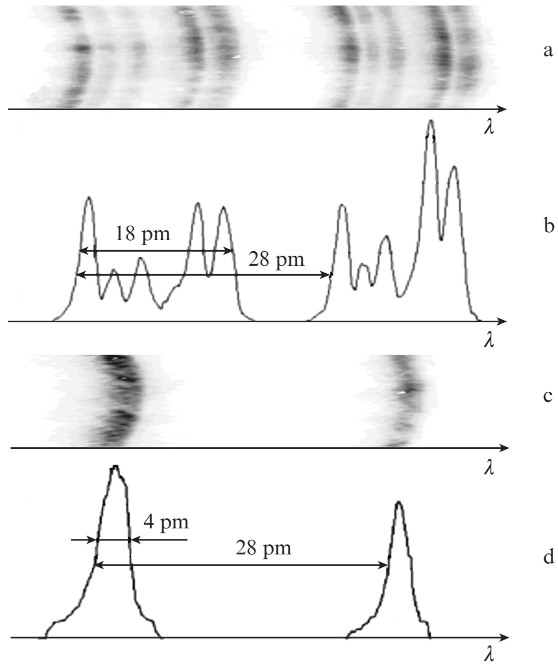

Figure 6. Emission spectra under conditions of generation of a pulse train: (a, c) interference patterns and (b, d) cross sections of interference patterns in the absence and in the presence of a stationary Bragg grating.

the laser can successfully be used in many practical problems of holography, spectroscopy, harmonic generation, precise treatment of materials, etc.

4. Narrowing of the lasing spectrum using a reflective Bragg grating

A schematic of a phase-conjugate laser with a reflective Bragg grating acting as a selecting element is shown in Fig. 7. A comparison of the radiation parameters for a laser with a multiloop self-pumped phase-conjugate cavity and a similar laser with an intracavity Bragg grating showed that the use of a reflective Bragg grating makes it possible to exclude losses (which are inevitable when a transmission grating is used) and stabilise at the same time the radiation frequency. The maximum pump pulse energy was 4 J.

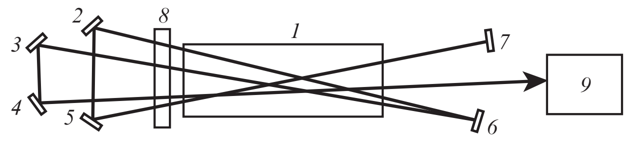

Figure 7. Schematic of a phase-conjugate laser: (*1*) active element; (*2–7*) mirrors; (*8*) passive gate; (*9*) system for recording the second harmonic.

In this experiment, a rotational mirror (*6*) was replaced with a reflective Bragg grating; its period and thickness were, respectively, 0.5 μm and 17.5 mm, which corresponds to a spectral selectivity of 0.05 nm. The diffraction efficiency exceeded 90%. The spectrum was studied using a Fabry–Perot etalon with a free-dispersion range of 27 pm. Figure 8 shows a laser beam interference pattern for the cases of absence and presence of a reflective Bragg grating in the cavity. The lasing spectral width was reduced approximately from 27.0 to 5.3 pm. Due to the diffraction from the intracavity Bragg grating, the radiation coherence increases with each pass through the cavity. As a result, the feedback coefficient becomes spectrally dependent. Correspondingly, the degree of radiation coherence and the feedback coefficient for each wavelength differ. The coefficient value is determined by the goodness of fit of the intracavity grating to the Bragg angle. Thus, the introduction of small additional spectrally dependent losses changes significantly the lasing spectrum.

The use of a reflective intracavity Bragg grating allows one to reduce optical losses as compared with the case of a transmission grating. The dependences of the lasing energy on the pump energy for a multiloop cavity with a Bragg grating and without it are shown in Fig. 8. It can be seen that the laser efficiency is 2.5% in the absence of a grating and decreases to 2.2% when a grating is used. Under conditions of maximum pumping in the passive *Q*-switching regime, the radiation energy in a 6-pulse train is about 86 mJ; it decreases to 78 mJ in the case of an intracavity grating. The energies per pulse are, respectively, 14 and 13 mJ.

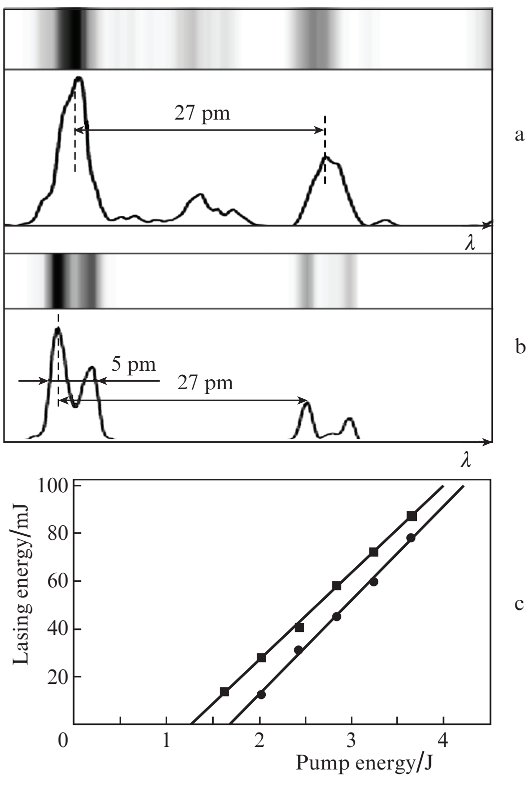

Figure 8. Interference patterns obtained for a phase-conjugate cavity (a) without a grating and (b) with a reflective Bragg grating and (c) the dependences of the lasing energy on the pump energy for a multiloop cavity with a Bragg grating (•) and without it (■).

5. Conclusions

The influence of the Bragg gratings formed in the active medium due to the spatial periodic modulation of gain on the spectral characteristics of lasing was experimentally substantiated. Wavelength stabilisation and lasing spectrum narrowing were demonstrated for different schemes of a phase-conjugate laser.

The radiation of lasers with multiloop self-pumped phase-conjugate cavities, despite the high frequency selection due to the presence of dynamic gain gratings, is not absolutely single-frequency because of the change in the radiation frequency within the gain line range. The results of studying the mode composition of pulse trains under modulation conditions showed that the grating rewriting by a subsequent train pulse is not a hindrance for emission at the same frequency. It was shown that narrowing of lasing spectrum is also observed even for a pulse in train, despite the fact that the spectral grating width exceeds significantly the spectral widths of the lasing pulse and gain line. Using a transmission or reflective Bragg grating in a cavity, one can narrow significantly the generated pulse spectrum (from 18 to 4 pm) at pulse and train energies to 200 mJ and 2.5 J, respectively.

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