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РАЗГРУЗКА РЕЗОНАТОРА ПОСРЕДСТВОМ ГЕНЕРАЦИИ ВТОРОЙ ГАРМОНИКИ В Nd : YAG-ЛАЗЕРЕ С МОДУЛЯЦИЕЙ ДОБРОТНОСТИ

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Рассматривается метод разгрузки резонатора через генерацию второй гармоники в неодимовом лазере, функционирующем в режиме модуляции добротности. Проводится теоретическое моделирование работы лазера при активной модуляции добротности, рассчитаны основные характеристики выходных импульсов и их зависимость от коэффициента потерь в системе и мощности накачки. Указанный метод может быть реализован в лазере с кристаллом второй гармоники внутри резонатора и электрооптическим затвором, на который подается импульс напряжения. Продолжительность этого импульса определяется временем, необходимым для формирования гигантского импульса в резонаторе, и составляет ~0,1–1,0 мкс в зависимости от мощности накачки. Длительность управляющего импульса напряжения должна быть постоянной с точностью до нескольких наносекунд. При этом на выходе лазера формируются наносекундные импульсы второй гармоники с пиковой интенсивностью порядка 10–100 МВт/см^2. Продолжительность выходных импульсов определяется только длиной резонатора в случае, когда время переключения электрооптического затвора меньше, чем время обхода резонатора светом. Для достижения максимальной пиковой интенсивности импульсов необходимо уменьшить потери в системе до минимально возможного уровня и увеличить мощность накачки.

Ключевые слова: Nd : YAG-лазер; разгрузка резонатора; балансные уравнения; модуляция добротности; электрооптический кристалл; кристалл второй гармоники.

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CAVITY DUMPING BY THE SECOND HARMONIC GENERATION IN THE Q-SWITCHED Nd : YAG LASER

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This paper presents the cavity dumping method by the second harmonic generation in a neodymium laser operating in the Q-switched mode. Theoretical modeling of the laser generation in dynamics is performed. The main characteristics of the output pulses and their dependence on the pump power and coefficient of losses are calculated. The proposed method can be implemented in the laser with a second harmonic crystal inside the cavity and an electro-optical crystal, which is operated by a step voltage pulse. The switching pulse length is defined by the time needed to achieve the maximum giant pulse intensity in the cavity, and is in the order of 0.1–1.0 μs depending on the pump power. Moreover, the voltage pulse jitter should not exceed several nanoseconds. In such case the second harmonic pulses with nanosecond duration and peak intensity of 10–100 MW/cm^2 are generated at the laser output. The output pulses duration is defined only by the cavity length under the conditions of a small response time of the electro-optical crystal compared to the cavity round-trip time. To achieve the maximal peak intensity, one should decrease the coefficient of inactive losses to the possible minimum and increase the pump power.

Keywords: Nd : YAG laser; cavity dumping; rate equations; Q-switching; electro-optical crystal; second harmonic crystal.

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The use of pulsed lasers in such areas as range finding, remote sensing, medicine, and the like requires stable energy characteristics and high-quality beam. Conventional Q-switched lasers have fundamental limitations on the stability of the pulse energy and the pulse length when operating in the nanosecond range. Lasers operating in the cavity dumping mode allow one to obtain highly stable pulses, the length of which is determined only by the gate switch time and the cavity length [1–3]. In such lasers thin-film or prism polarizers are usually used as an output mirror, and cavity dumping is achieved by rotation of the output-radiation polarization plane by an angle of 90° with the help of an electrooptical shutter.

An alternative method is cavity dumping by means of the second harmonic generation [4–6]. This method allows to output the energy stored in the cavity using the intracavity conversion into the second harmonic. The method can be implemented in various laser operation modes: free generation [4], Q-switching [5], and mode-locking [6]. The output pulses with the highest power and energy are formed when the cavity dumping by the second harmonic generation is realized in the Q-switched mode. In this paper, we present theoretical analysis and implementation of the cavity dumping method in the actively Q-switched neodymium laser.

The proposed setup is shown in fig. 1.

The cavity mirrors are chosen in such a way that their reflection coefficients are almost equal to 1 for the fundamental frequency radiation and 0 for the second harmonic radiation (for the output mirror). To convert radiation to the second harmonic, an anisotropic second harmonic crystal of type II is used (*oee* interaction, in our case this is a KTP crystal).

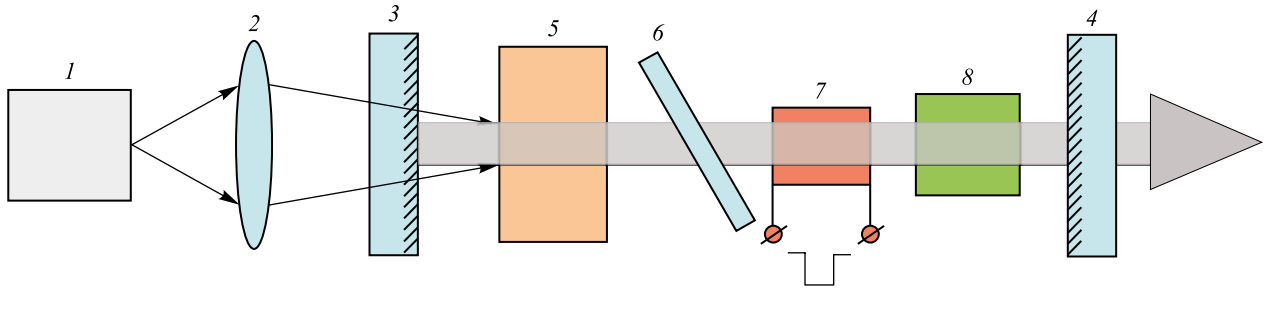

Fig. 1. Setup for the cavity dumping by the second harmonic generation in the actively Q-switched laser:
1 – diode laser; *2* – lens; *3*, *4* – resonator mirrors; *5* – laser crystal; *6* – polarizer;
7 – electro-optical crystal; *8* – second harmonic crystal

The generation of the output pulses with the scheme under consideration is realized in three stages, which are switched by changing the voltage on the electro-optical crystal (EOC). The first two stages correspond to the giant pulse generation under constant pumping. At the first stage, a quarter-wave voltage is applied to the EOC. The cavity Q-factor is low, the population of the upper laser level increases to the maximum value, but the generation does not start. At the second stage, the voltage on the EOC rapidly drops to zero, which leads to the formation of a giant pulse inside the cavity. At zero voltage, the generation of the second harmonic does not occur because the polarization of the radiation remains linear and the phase-matching conditions in the second harmonic crystal (SHC) are not fulfilled. At the third stage, the cavity is dumped. When the intensity inside the cavity reaches a maximum, the quarter-wave voltage is applied to the EOC again and an output second harmonic pulse is formed. The quarter-wave voltage on the EOC changes the polarization of radiation from linear to circular, which leads to the phase matching in the SHC and generation of the second harmonic pulse. The part of the fundamental frequency radiation that is not converted into the second harmonic is dispersed by the polarizer, and its intensity is reduced almost to zero over the cavity round-trip time.

A crystal of yttrium-aluminum garnet with neodymium (Nd^{3+} : YAG) operating according to the four-level scheme was considered as an active element of the laser.

To simulate the generation in dynamics at the first and second stages (generation of a giant pulse), we used the rate equations [6] written in the approximation of the point model of the active medium:

$$\begin{aligned}
\frac{dS_1}{dt} &= \frac{l}{L_{\text{opt}}} c\sigma_e S_1\left(N_2 - N_1\right) + K_s l \frac{N_2}{\tau_2} - S_1 r_{\text{tc}}, \\
\frac{dN_1}{dt} &= \sigma_e S_1\left(N_2 - N_1\right) + \frac{N_2}{\tau_2} - \frac{N_1}{\tau_1}, \\
\frac{dN_2}{dt} &= -\sigma_e S_1\left(N_2 - N_1\right) + \frac{N_3}{\tau_3} - \frac{N_2}{\tau_2}, \\
\frac{dN_3}{dt} &= \sigma_a R_{\text{pump}}\left(N_s - N_1 - N_2 - N_3\right) - \frac{N_3}{\tau_3}.
\end{aligned} \tag{1}$$

Here $l = 0.3$ cm is the active element length; $L_{\text{opt}} = 20.25$ cm is the cavity optical length; $\sigma_e = 28 \cdot 10^{-20}$ cm^2 is the stimulated emission cross-section; $\sigma_a = 7.7 \cdot 10^{-20}$ cm^2 is the absorption cross-section; S_1 is the fundamental frequency photon flux density in the cavity; N_i and τ_i, where $i = 1, 2, 3$, are the population densities and lifetimes at the lower laser level ($^4I_{11/2}$), the upper laser level ($^4F_{3/2}$) and the level $^4F_{5/2}$ respectively, where $\tau_1 = 10$ ns, $\tau_2 = 230$ μs, $\tau_3 = 30$ ns; $N_s = 1.38 \cdot 10^{20}$ cm^{-3} is the bulk density of neodymium ions in the crystal at a concentration of 1 %; $K_s = 10^{-10}$ is the fraction of spontaneous radiation in the generation channel; R_{pump} is the pump photon flux density determined by the pump power.

The relationship between the pump photon flux density and the incident pump power is determined as follows:

$$R_{\text{pump}} = \frac{P_{\text{pump}}}{h\nu_a s_{\text{cr}}},$$

where P_{pump} is the pump power incident on the surface of the crystal (end pumping); $h\nu_a$ is the pump photon energy; $a = 0.05$ cm is the pump radius and $s_{\text{cr}} = \pi a^2$ – the pump area of the crystal.

The value of r_{tc} is inverse to the photon lifetime in the cavity:

$$r_{\text{tc}}(t) = c\frac{\gamma + r_{\text{EOC}}(t)}{L_{\text{opt}}},$$

where γ is the coefficient of inactive losses in the cavity; $r_{\text{EOC}}(t)$ defines additional losses introduced by the EOC; c is the speed of light. In the considered setup, the output mirror reflectivity was taken equal to 1.

In the active Q-switching mode, the loss coefficient in the system depends on time. In the approximation of instant switching of the EOC, the additional loss coefficient introduced by it can be written as

$$r_{\text{EOC}}(t) = \begin{cases} r_0, \ t < T_{\text{EOC}}, \\ 0, \ t \geq T_{\text{EOC}}, \end{cases}$$

where r_0 is a sufficiently large loss coefficient (~100 %); $T_{\text{EOC}} = 300$ μs is the EOC switching time.

By solving the system of equations (1), it is possible to calculate the dependence of the intensity in the cavity on time for the fundamental frequency radiation.

Since the dumping time is approximately two orders of magnitude shorter than the duration of a giant pulse in the cavity, we assume that the intensity of the fundamental frequency does not change during this time. To determine the intensity profile of the second harmonic pulse generated at the third stage (cavity dumping), the following expression is used:

$$I_2 = I_1 th^2 \sqrt{\frac{\alpha I_1}{2}},$$

where I_1 is the intensity of the fundamental frequency radiation in the cavity, the coefficient α is determined by the parameters of the second harmonic crystal and is equal to 0.016 1 cm^2/MW for a 0.5 cm long crystal [7].

Due to the presence of a polarizer in the system, the second harmonic pulse length is determined by the cavity length and is less than the cavity round-trip time (1.35 ns for the system under consideration). However, if the EOC switching time is equal or higher than the cavity round-trip time, the output pulse length can increase and its intensity decrease compared to the ideal case when the switching time is small and can be neglected [4].

Figure 2 shows the time dependence of the intensity of the fundamental frequency radiation inside the cavity at the second stage (zero moment of time corresponds to the EOC switch). It is seen that a giant pulse is formed with a delay relative to the EOC switching time. This delay significantly depends on the pump power, as shown in fig. 3.

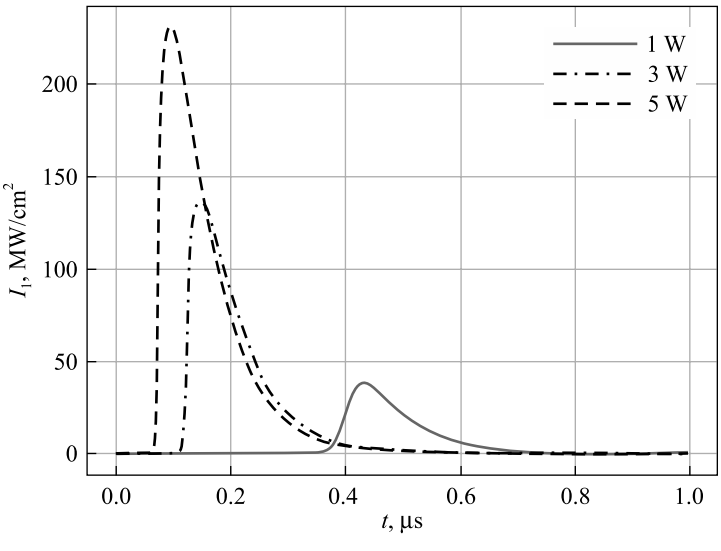

Fig. 2. Time dependence of the intensity of a giant pulse in the cavity within the active Q-switching mode for different pump powers. The coefficient of inactive losses in the cavity is 1 %

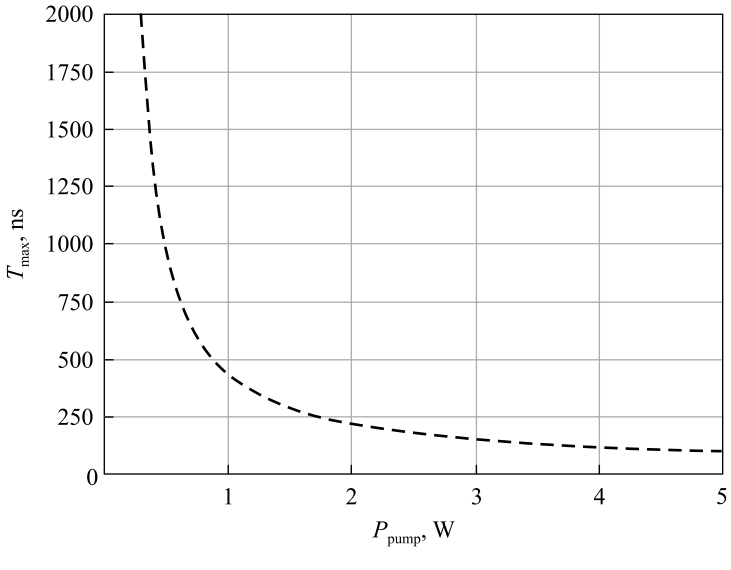

Fig. 3. The time needed to achieve a maximal intensity in the cavity as a function of the pump power. The inactive loss in the cavity is 1 %

The time needed to achieve the pulse maximum defines the duration of a voltage pulse applied to the EOC and ranges from 100 ns to more than 2 μs. It should also be noted that despite the closed cavity (the reflection coefficients of both mirrors are close to 1), the intensity of the giant pulse decreases rather quickly due to the inactive losses. This fact imposes a limitation on the jitter value of the shutter switching pulse, which should not exceed 10 ns.

Figure 4 shows the dependence of the peak intensity of the second harmonic output pulse and the fundamental frequency in the cavity on the pump power. It is seen that the peak intensity of the fundamental frequency increases almost linearly with increasing pump power. For the second harmonic radiation, the dependence is close to quadratic at low pump powers and becomes almost linear with increasing pump power.

Figure 5 shows the dependence of the peak intensity of the second harmonic output pulse and the fundamental frequency in the cavity on the coefficient of inactive losses in the cavity. It can be seen that this parameter has the strongest effect on the output pulse power. To obtain the maximum peak intensity of the output pulses, one should minimize the inactive losses as much as possible. In real laser systems, it is difficult to obtain inactive losses lower than 1 %.

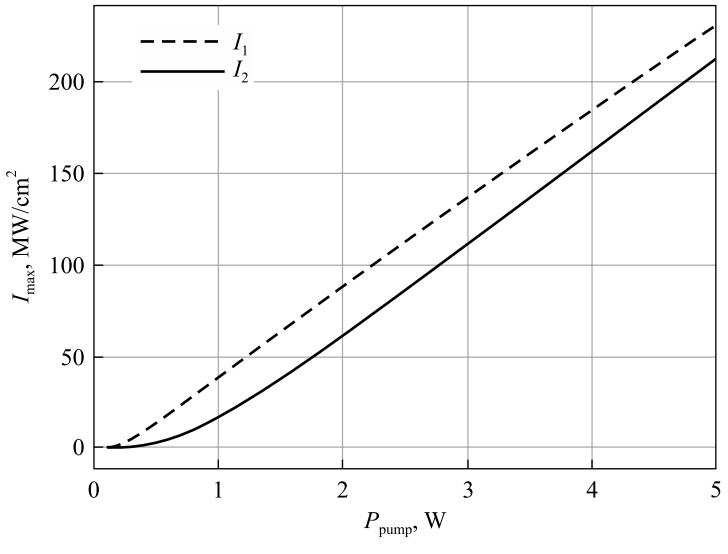

Fig. 4. Peak intensity of the giant pulse in the cavity and of the second-harmonic output pulse as a function of the pump power. The inactive loss in the cavity is 1 %

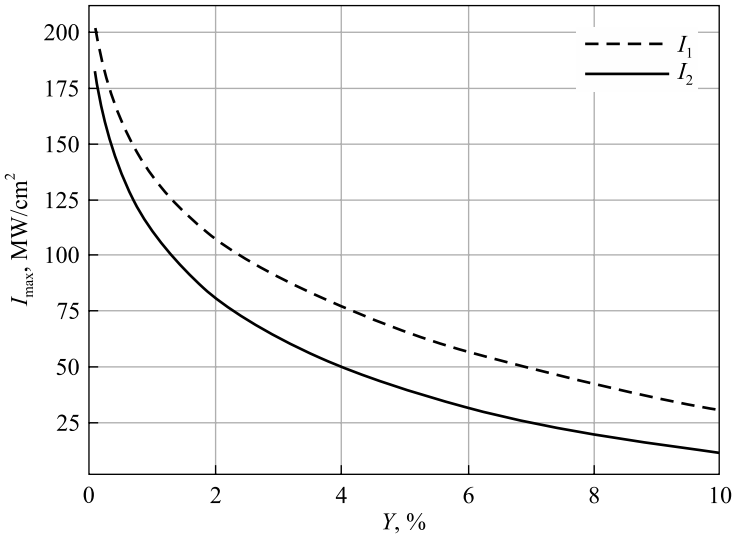

Fig. 5. Peak intensity of the giant pulse in the cavity and of the second-harmonic output pulse as a function of the inactive loss. The pump power is 3 W

The considered method of cavity dumping by the second harmonic generation in the actively Q-switched laser enables one to generate nanosecond pulses of the second harmonic radiation with the peak intensity of about 100 MW/cm^2. The peak intensity of the output pulses increases almost linearly with increasing pump power and decreases sharply with increasing inactive loss coefficient. The maximal intensity of the output pulses is limited by the minimal possible losses and damage threshold of the setup elements.

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