Cavity Dumping by the Second Harmonic Generation in the Mode-Locked Nd:YAG Laser

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A method of cavity dumping by the second harmonic generation that allows one to obtain short and intensive pulses of laser radiation in the visible band is considered. It is based on intracavity second harmonic generation in lasers with highly-reflective mirrors for the fundamental frequency radiation. The second harmonic generation is obtained with the type II crystal and is controlled with the use of a polarizer and a voltage-activated electrooptic crystal inside the cavity. The method enables one to retain the laser beam quality and propagation direction after transformation into the second harmonic.

The method may be implemented in solid-state laser systems operating in different modes: mode-locking, Q-switching, and CW. Most effective second harmonic generation is realized in the mode-locked lasers with ps-duration output pulses and peak intensity up to GW/cm².

We propose a theoretical model and analysis of the cavity dumping by the second harmonic generation in the mode-locked solid-state lasers that is based on the Herman A. Haus approach. The dynamics of the pulse formation in the mode-locked regime is investigated; the parameters of the output second harmonic pulses and their dependence on the main system characteristics are determined. It is shown that the output pulse peak intensity, length, and energy per unit area depend on the pump power and loss coefficient in the cavity: to obtain pulses with higher intensity, energy and smaller length, the pump power should be increased and losses decreased to the minimal value possible. One can obtain the output pulses with the energies per unit area coming to several mJ/cm². The output pulse parameters may also depend on the dumping period. The cavity dumping repetition rate may be as high as MHz.

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1. Introduction

Generation of short and ultrashort laser pulses remains one of the relevant issues for the sphere of scientific research and engineering associated with optical data transmission and processing systems. Most commonly the pulses with ns-fs duration are obtained with the use of mode-locked lasers providing a series of sequential pulses, from which a single pulse is selected. Single pulses may be selected by the cavity dumping techniques, when the polarizing prism and an electrooptical voltage-driven shutter are used to change the direction of the beam propagation and dump the radiation out of the cavity [1]. One of the disadvantages of such realization consists in different directions of the initial and output laser beams. We propose a new method of the cavity dumping by the second harmonic generation that enables retention of the beam propagation direction as the polarizing prism is not used. The output pulses of the second harmonic radiation are obtained through the energy transformation in the anisotropic second harmonic crystal within the cavity. The method is especially effective in the mode-locked lasers with highly-reflective mirrors for the fundamental frequency, allowing one to obtain the most intense and short pulses. In this case the efficiency of the energy transformation into the second harmonic

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may be above 50%. Such output pulse parameters as peak intensity, duration, and energy are determined by the system parameters and may be controlled.

A setup for the cavity dumping by the second harmonic generation in the mode-locked solid state lasers is considered and a theoretical model of the process is proposed; the results of numerical simulations are analyzed. A theoretical analysis is based on the Haus theory of mode locking with a fast saturable absorber that enables one to investigate dynamics of the pulse formation in the cavity.

2. Setup description

The proposed method of cavity dumping is based on the intracavity energy transformation into the second harmonic and dumping through the transparent output mirror in the form of short pulses. The method may be used for lasers working in different modes. The basic setup enabling to form the pulses with duration shorter than the cavity round-trip time in CW- and Q-switched regimes was discussed in [2–5]. The setup used for the cavity dumping in the mode-locking regime has the same structure but contains an additional element required to obtain the mode-locked generation. A typical setup is shown in Fig. 1.

Most commonly solid-state lasers having high relaxation times as a Nd:YAG laser are passively mode-locked with the use of a fast saturable absorber (for example, semiconductor SESAM mirrors or quantum-dot passive shutters). Besides, passive methods of the mode-locking are most convenient for the cavity dumping realization by the second harmonic generation. In what follows we consider a fast saturable absorber as an element necessary for mode-locking.

The cavity includes two highly reflective mirrors and four main elements: laser crystal, electro-optical shutter, second harmonic crystal, and a fast saturable absorber.

1. Cavity mirrors
To obtain higher efficiency, both cavity mirrors should be highly reflective for the fundamental frequency radiation, the output mirror having almost zero reflectivity for the second harmonic radiation.

2. Electro-optical voltage-driven shutter and polarizer
An electro-optical shutter (Pockels cell) and a polarizer are the elements essential for switching between the second harmonic and fundamental frequency generation regimes. Zero voltage corresponds to a linear polarization and maximal quality of the system. In this case the phase matching conditions are not fulfilled and the second harmonic is not generated. When the quarter-wave voltage is applied, polarization of the fundamental frequency radiation changes to circular, leading to the energy transformation into the second harmonic. As the reflected fundamental frequency radiation has linear polarization orthogonal to the initial one, it is scattered by the polarizer after double pass of the EO shutter. The intensity of the fundamental frequency radiation decreases by several orders after a number of cavity round-trips, thus limiting maximal length of the output second harmonic pulses. The described technique of cavity dumping requires no use of polarizing prisms and hence the propagation direction and quality of laser beams is retained.

3. Second harmonic crystal
Second harmonic crystal used is a type II crystal corresponding to the oee nonlinear interaction. In our investigations the KTP nonlinear crystal 0.5 cm in length was used. The parameters and properties of the crystal are discussed in [6].

4. Passive shutter
Any fast saturable absorber with a relaxation time considerably shorter than the cavity round-trip time may be used to obtain mode-locking. Numerical simulations were carried out using the SAM-1064-2-1ps-x [7] SESAM fast saturable absorber model.

5. Laser element
In general, the laser element may be any crystal
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used in solid-state lasers. In the model proposed the Nd:YAG laser crystal (1% ion concentration) is considered. The associated energy levels and transitions are illustrated in Fig. 2.

The main parameters of a Nd:YAG laser element are listed in Table 1 [8].

Table 1: Laser parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump wavelength $\lambda_a$, nm</td>
<td>808</td>
</tr>
<tr>
<td>Generation wavelength $\lambda_e$, nm</td>
<td>1064</td>
</tr>
<tr>
<td>Absorption cross-section $\sigma_a$, $10^{-20}$ cm$^2$</td>
<td>7.7</td>
</tr>
<tr>
<td>Emission cross-section $\sigma_e$, $10^{-20}$ cm$^2$</td>
<td>28</td>
</tr>
<tr>
<td>Crystal length $L_{LC}$, cm</td>
<td>6</td>
</tr>
<tr>
<td>Crystal diameter $a$, cm</td>
<td>0.5</td>
</tr>
<tr>
<td>Crystal pump area $s_{LC}$, cm$^2$</td>
<td>9.425</td>
</tr>
<tr>
<td>Lifetime at $^4$F$_{3/2}$ level $\tau_2$, mcs</td>
<td>230</td>
</tr>
<tr>
<td>Lifetime at $^4$F$_{5/2}$ level $\tau_2$, ns</td>
<td>10</td>
</tr>
<tr>
<td>Lifetime at $^4$I$_{11/2}$ level $\tau_2$, ns</td>
<td>30</td>
</tr>
<tr>
<td>Total Nd$^{3+}$ ion density (conc. 1%) $N_e$, cm$^{-3}$</td>
<td>1.38·10$^{20}$</td>
</tr>
<tr>
<td>Refractive index, $n$</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Pumping is considered to be uniform in time and over the active element surface. The pump power is determined as

$$P = \eta E/\tau,$$  (1)

where $\tau = 300$ $\mu$s is a duration of the pump pulse, $E$ is a pump energy (J), $\eta = 3\%$ is a pump radiation absorption efficiency. It is assumed that the total absorbed radiation is characterized by the pump power $P$ and photon flux density $R_0$.

The pump energy range corresponds to that of the prototype laser system coming to 5-30 J; the pump power range is 0.5–3 kW.

The pump photon flux density is defined as

$$R_0 = \frac{P \lambda_a}{s_{LC} c},$$  (2)

where $s_{LC} = \pi a l_{LC}$ is an irradiated area of the active element surface; $l_{LC}$ is a length of the pumped area of the active element (that is equal to the total element length $L_{LC}$). The pump power $P = 1$ kW corresponds to the pump photon flux density $R_0 = 5.683\cdot10^{14}$ photon/cm$^2$/µs.

### 3. Theoretical model

The setup considered has two working regimes requiring different approaches to simulation. First regime corresponds to the generation of the fundamental frequency radiation during 1-100 $\mu$s, while the second regime is associated with the second harmonic pulses formation during the period of a few ns. According to such time scales, laser generation in dynamics is simulated only in the first regime.

The main goal of simulation in the second regime
is to calculate the form and parameters of the output second harmonic pulses. Typically, the dynamics of laser generation is calculated in the approximation of a point model of the active medium. The rate equations for the described laser model and the 4-level scheme are as follows:

\[
\begin{align*}
\frac{dS_1}{dt} &= \mu v \sigma e S_1 (n_2 - n_1) - S_1 r_{tc}, \\
\frac{dn_1}{dt} &= \sigma e S_1 (n_2 - n_1) - \frac{n_1}{\tau_1} + \frac{n_2}{\tau_2}, \\
\frac{dn_2}{dt} &= \sigma e S_1 (n_1 - n_2) - \frac{n_2}{\tau_2} + \frac{n_3}{\tau_3}, \\
\frac{dn_3}{dt} &= \sigma a R_0 (N_s - n_1 - n_2 - n_3) - \frac{n_3}{\tau_3}
\end{align*}
\]

where \( S_1 \) correspond to the fundamental frequency radiation photon flux density in the cavity, \( n_i \) describe the carrier densities at different energy levels.

\[
\mu = \frac{nL_{LC}}{L_{opt}},
\]

\[
r_{tc} = \frac{c (\gamma L_{LC} - \frac{1}{2} ln(\rho))}{L_{opt}} \to \frac{c\gamma L_{LC}}{L_{opt}}.
\]

The coefficients \( r_{tc} \) and \( \mu \) characterize an inverse photon lifetime and a degree of the cavity filling with the active medium; \( \gamma \) represents the coefficient of inactive losses in the cavity; the mirror reflectivity is \( \rho = 1 \). The cavity optical length used in the calculations is \( L_{opt} = 64.92 \) cm and corresponds to the geometrical length of 60 cm.

These equations are used for modeling of the CW and Q-switched laser generation when the spectral characteristics of radiation are disregarded. Such an approach is not valid for
the mode-locked lasers when the form of pulses depends on the generation spectrum and the properties of a fast saturable absorber. Therefore, to calculate the dynamics of pulse formation in the mode-locked regime, the standard rate equations should be modified adequately.

The dynamics of passive mode-locking with the use of a fast saturable absorber was described in detail in the works of Herman A. Haus [1, 9–12]. The Haus theory of mode locking allows one to obtain the general equation determining the pulse formation in dynamics. Our model uses the enhanced rate equations derived on the basis of the above-mentioned saturable absorber. Therefore, the use of a fast saturable absorber was described in detail in the works of Herman A. Haus [1, 9–12]. The Haus theory of mode locking allows one to obtain the general equation determining the pulse formation in dynamics. Our model uses the enhanced rate equations derived on the basis of the Haus approach in combination with a point model of the active laser medium.

There are some approximations and assumptions essential for the model:

1. The active medium is a slow saturable absorber. The average per cavity pass dimensionless gain coefficient at a maximum of the gain circuit \( g_0 \) is determined by the average per cavity pass pulse intensity or by its energy.

2. The output pulse spectral width is assumed much smaller than the full line width of the gain spectrum \( \omega_g \).

3. Phase characteristics are not taken into account in the model as they have little influence on the effect studied.

4. Maximal saturated gain of the active medium \( g_0 \ll 1 \) (also \( g(\omega) \ll 1 \)). This condition allows for the use of point model as it corresponds to a slow change of \( S_1 \) with time.

5. Losses in a system are defined by the inactive loss coefficient \( \gamma \) (because the mirror reflectivity is taken equal to 100%) and are considered constant.

6. The losses introduced by a fast saturable absorber depend on the instant intensity of the pulse within the cavity. In this case the losses are specified as

\[
q(t) = \frac{q_0}{1 + |A(t)|^2/I_{sat}},
\]

where \( I_{sat} = F_{sat}/\tau_A \) is an absorber saturation intensity. Parameters of the above-mentioned saturable absorber (\( F_{sat} = 60 \mu J/cm^2, \tau_A \approx 1 \) ps, non-saturable loss = 0.8% = 0.008) correspond to \( I_{sat} = 60 \) MW/cm\(^2\), \( q_0 = 0.004 \).

Taking into account all the above assumptions, the main equation determining the generation dynamics in a mode-locked laser is obtained as follows. A field in the cavity is described by the complex amplitude \( A(t) \) that defines the pulse intensity profile

\[
I(t) = |A(t)|^2,
\]

where \( t \) is a time characterizing the pulse profile. The spectral amplitude \( A(\omega) \) is related to \( A(t) \) through the Fourier transform [1]. The spectral amplitude \( A(\omega) \) is changed when the pulse propagates through the active medium with the gain spectrum \( g(\omega) \):

\[
A'(\omega) = A(\omega) \exp(-i\omega n L_{LC}/c) \exp(g(\omega)).
\]

It is considered that the Nd:YAG active-medium gain spectrum is described by the Lorentz profile (homogeneous broadening). Thus the amplitude gain coefficient is defined as

\[
g(\omega) = \frac{g_0/2}{1 + 2i(\omega - \omega_0)/\omega_g},
\]

where \( \omega_0 \) corresponds to the central frequency of the gain profile, \( \omega_g = 195 \) GHz for FWHM gain profile [13, 14], \( g_0 \) is a coefficient, describing relative power gain at \( \omega = \omega_0 \) averaged over the cavity single-trip time. Expanding the expression (9) into the Taylor series, we obtain

\[
g(\omega) = \frac{g_0}{2} (1 - 2i(\omega - \omega_0)/\omega_g)
\]

\[
+ \frac{g_0}{2} \left(-4(\omega - \omega_0)^2/\omega_g^2 + 8i(\omega - \omega_0)^3/\omega_g^3 \right)
\]

\[
+ \frac{g_0}{2} \left(16(\omega - \omega_0)^4/\omega_g^4 + \ldots \right).
\]
With regard to the assumption (2), the third-order and higher terms may be neglected. This assumption corresponds to the parabolic approximation of the Lorentz gain profile. Thus, we obtain

\[ A'(\omega) \approx A(\omega) \exp \left( \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2) \right) \times \exp \left( -i\omega nL_{LC}/c - ig_0(\omega - \omega_0)/\omega_g \right). \]  

(11)

Note: consideration of the high-order terms in (10) corresponds to the allowance for the high-order time derivatives in (16) according to the property of the Fourier transform (15). The term \( \exp \left( -i\omega nL_{LC}/c - ig_0(\omega - \omega_0)/\omega_g \right) \) describing the phase change is not considered in the model because the pulse delay is not an object of simulation here. The term \( \exp \left( \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2) \right) \) characterizes the gain profile with the corresponding bandwidth, limiting the minimal length of the generated pulses. The assumption (4) \( (g(\omega) \ll 1) \) enables simplification of the obtained expression:

\[ \exp \left( \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2) \right) \approx 1 + \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2), \]  

(12)

\[ A'(\omega) = A(\omega) \left( 1 + \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2) \right). \]  

(13)

Taking into account the constant losses l_0 and the losses added by a fast saturable absorber q(T), we obtain the following equation:

\[ A'(\omega) = A(\omega) \left( 1 + \frac{g_0}{2} (1 - 4(\omega - \omega_0)^2/\omega_g^2) \right) + A(\omega) \left( \frac{g_0}{1 + A(\omega)^2/I_{sat}} - \frac{l_0}{2} \right), \]  

(14)

where \( l_0 \) is a coefficient describing a relative power loss in the cavity. Equation (14) describes a change in the pulse complex amplitude after the cavity single-trip. To write (14) in the time domain, the Fourier transform properties are used

\[ (i(\omega - \omega_0))^n A(\omega) \to \frac{d^n A(t)}{dt^n}. \]  

(15)

Applying (15) to (14) yields

\[ T_R \frac{dA(t, T)}{dT} = \left( \frac{g_0(T)}{2} - \frac{2g_0(T) d^2}{\omega_g^2 dt^2} \right) A(t, T) \]

\[ + \left( \frac{g_0}{1 + A(t, T)^2/I_{sat}} - \frac{l_0}{2} \right) A(t, T), \]  

(16)

where \( T \) describes the pulse amplitude evolution during the generation time, \( T_R = \frac{L_{opt}}{c} \) is a cavity single-trip time. Eq. (16) is the main equation describing a dynamics of the pulse formation in the mode-locked regime. The coefficients \( g_0(T) \) and \( l_0 \) which characterize the gain and loss in the cavity are determined for the specific laser model. This equation may be solved for the steady-state generation when \( g_0 \) and \( l_0 \) are constant. In this case the pulse form is described by the sech^2(t/\tau) function [10, 12]. In order to simulate the generation in dynamics, the time dependence of \( g_0 \) should be taken into account. It is defined by the carrier density inversion and may be found from the rate equations (3–5) for the laser model described above:

\[ g_0(T) = \left( \frac{d < I >_{gain}}{dT} \right) \frac{T_R}{< I >} = \mu v_c \sigma_c (n_2(T) - n_1(T)) T_R. \]  

(17)

This may be done if the assumption (1) is valid. This makes it possible to apply a point model to the active medium; when the active medium is a slow saturable absorber, the gain coefficient depends on the average pulse intensity/energy and changes slowly with time. In this case its value may be averaged over \( \Delta T = T_R \). The average loss coefficient \( l_0 \) is also determined from the rate equations (3–5) as follows:

\[ g_0(T) = \left( \frac{d < I >_{loss}}{dT} \right) \frac{T_R}{< I >} = r_{lo} T_R. \]  

(18)

Thus, a complete system of equations includes the main equation for the pulse complex amplitude (16) combined with 3 rate equations for the carrier densities at different levels, which are needed to determine the gain coefficient time dependence:
The average photon flux density in the cavity is determined from the amplitude $A(t,T)$ as

$$S_1(T) = \int_{t=0}^{T_R} A(t,T)^2 dt \cdot \frac{1}{T_R h \nu_e}.$$  \hspace{1cm} (20)$$

The system (19–20) is used to simulate the dynamics of the mode-locked laser generation in the first regime corresponding to the fundamental frequency generation. It enables one to determine the pulse intensity profile at the specified instant of time and to calculate the time dependence of the average photon flux density and carrier densities in the cavity.

\subsection{Simulation notes}

There are some restrictions for the $t$ and $T$ variables due to their interrelations. A minimal step for $T$ should be equal to $T_R$ (or multiple of $T_R$) as in the model considered the amplitude $A(t,T)$ is varying over the cavity single-trip. This condition also corresponds to the restriction for the variable $t$ describing the form of the pulse propagating in the cavity – it should vary over the range of $T_R$. This system of equations was solved with the use of the Euler method with the step $dT = T_R$. The mesh for $t$ was chosen to be nonlinear with the minimal step $dt_{\min} = 2$ ps corresponding to the center of the pulse ($t = 0; t \in [-T_R/2, T_R/2]$). The maximal step $dt_{\max} = 50$ ps corresponds to the ends of the interval ($t = -T_R/2, T_R/2$). Taking into account that the pulse length in the mode-locked regime is about 50-200 ps and its intensity is close to zero for the remaining part of the time interval ($\Delta t = T_R = 2.17$ ns), such mesh is convenient. The boundary conditions for $A(t)$ were considered to be periodic: $A(-T_R/2) = A(T_R/2)$. The initial values of system’s variables were set to $(S_{10}, n_{10}, n_{20}, n_{30}) = (10^{-10} \text{photon} \cdot \text{cm}^{-2} \cdot \text{μs}^{-1}, 0, 0, 0)$. The initial $A(t,0)$ distribution was defined as a sum of the constant amplitude with a Gaussian profile, its maximal value corresponding to $t=0$:

$$A(T,0) = A_0 + A_0 C \exp\left(-\left(t/t_p\right)^2\right),$$  \hspace{1cm} (21)$$

where $C = 0.1$, $t_p = T_R/4$. The value of $A_0$ is chosen so that the initial photon flux density defined by (20) is equal to $S_{10}$. For these values of $C$ and $t_p$ we have $A_0^2 = 0.916 S_0 h \nu_e$.

\section{Fundamental frequency generation}

In this section the simulation results of laser generation in the first regime are discussed. At this step dynamics of the fundamental frequency pulse formation is investigated, whereas the second harmonic is not generated. To this end, equations (19–20) are solved numerically for the conditions and parameters discussed above. Fig. 3 shows the simulation results obtained: the average intensity time dependence and the intensity profile of the pulse generated within the cavity in the mode-locked regime.

The profile for pulses generated in the CW mode-locking regime is well fitted by the $\text{sech}^2(t/τ)$ function. The pulse form slightly varies with time until generation reaches the steady-state and depends on the main system variables determining the generation dynamics: pump power $P$ and coefficient of inactive losses $γ$. So, the pulse form remains very close to $\text{sech}^2(t/τ)$ in the steady-state regime for the parameters

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corresponding to a relatively great pulse duration. In the case when the parameters correspond to the smaller pulse duration, the pulse form approaches the Gaussian one: the higher the pulse intensity, the closer the agreement.

The peak pulse intensity and length vary with time, as demonstrated in Fig. 4. Also, it illustrates the normalized pulse intensity profiles at different moments of time: initial, corresponding to the steady-state generation, and to the maximal pulse intensity. The pulse formation takes about 2 \( \mu \text{s} \) and corresponds to changes of the pulse length from the initial value to a minimum, while the peak intensity is increased from zero to a maximum. It is seen that the pulse length decreases and peak intensity increases with an increase of the average intensity in the cavity. The minimal pulse width corresponds to the maximal intensity and is about 30 ps (FWHM).

Passive mode-locking with a fast saturable absorber may be realized in CW and Q-switched regimes [15, 16]. The final regime depends on the system and saturable absorber parameters. Figs. 3, 4 show CW mode-locking realized for

FIG. 3. Time dependence of the average intensity in the cavity (a) and the pulse intensity profile at time \( T = 40 \mu \text{s} \) (b) for CW mode-locking. Pump power \( P = 3 \text{ kW} \), coefficient of inactive losses \( \gamma = 0.003 \text{ cm}^{-1} \).

FIG. 4. Time dependence of the average intensity in the cavity, peak pulse intensity relative to the average intensity and pulse length (a); pulse normalized intensity profiles at different instants of time: initial (\( T = 0 \)), corresponding to the maximal pulse intensity (\( T = 4.48 \mu \text{s} \)), and the steady-state generation (\( T = 40 \mu \text{s} \)) (b). Pump power \( P = 3 \text{ kW}, \gamma = 0.003 \text{ cm}^{-1} \).
the saturable absorber saturation intensity $I_{\text{sat}} = 60 \text{ MW/cm}^2$ and maximal loss coefficient $q_0 = 0.004$. Q-switched mode-locking is realized for smaller saturation intensities of the absorber and higher maximal loss values $q_0$. Some sets of the absorber parameters correspond to only one possible regime of generation (CW or Q-switched) irrespective of the pump power and coefficient of inactive losses values.

Fig. 5 illustrates the time dependence of the average intensity at two different pump powers and the pulse intensity profile in the case of Q-switched mode-locking. In this case the absorber is characterized by $I_{\text{sat}}=10 \text{ MW/cm}^2$, $q_0=0.004$.

For some saturable absorber parameters both generation regimes are available, depending on the pump power $P$ and the loss coefficient $\gamma$. Q-switched mode-locking is realized for smaller pump powers and/or higher losses than in the case of CW mode-locking.

5. Second harmonic generation

When the fundamental frequency mode-locked generation is established, the quarter-wave voltage may be applied to the electrooptic shutter to obtain the output second harmonic pulses at the required times. After the light polarization is changed, some part of the energy transforms into the second harmonic, and the rest of the fundamental frequency radiation is scattered faster than the cavity round-trip time. In this case a single second harmonic pulse is obtained at the output.

The second harmonic pulse profile at any moment of time is determined by the intensity profile of the fundamental frequency pulse in the cavity (22-23). After the voltage is switched on, light polarization changes from linear to circular, and the intensities of the $o$ and $e$ components in the second harmonic crystal are equal. In this case the intensities of the second harmonic radiation and of the fundamental frequency for the $o$ and $e$ components are determined as [17]:

$$I_2(t,T) = I_1(t,T)th^2\left(\sqrt{\alpha I_1(t,T)}\right), \quad (22)$$

$$I_o(t,T) = I_e(t,T)$$

$$= \frac{1}{2}I_1(t,T)\text{sech}^2\left(\sqrt{\alpha I_1(t,T)}\right), \quad (23)$$

where $I_1 = I_o + I_e$ is a total fundamental frequency pulse intensity (intensity of the linearly polarized radiation). The coefficient $\alpha$ is determined by the second harmonic crystal.
parameters; for the KTP crystal 0.5 cm in length it is equal to 0.0161 cm$^2$/MW, corresponding to the efficiency of the energy transformation to the second-harmonic 1.6\% for $I_1 = 1$ MW/cm$^2$. When the condition $I_o = I_e$ is not fulfilled or the pulse length is small and coefficient $\alpha$ becomes frequency dependent, the general system of nonlinear equations should be solved to determine $I_2$, $I_o$ and $I_e$ at the output of the second harmonic crystal [17, 18].

Fig. 6 illustrates the average intensity at the fundamental frequency in the cavity as a function of time (a) and the pulse intensity profiles before (fundamental frequency pulse) and after (output second harmonic pulse) the cavity dumping (b). Cavity dumping is realized after the system reaches the steady-state and has the period 20 $\mu$s.

The total pulse energy per unit area is 3.23 mJ/cm$^2$ for the fundamental frequency pulse and 1.58 mJ/cm$^2$ for the second harmonic output pulse. The efficiency of the energy transformation into the second harmonic is 49%.

The main parameters of the output second harmonic pulses (peak intensity, length and energy) – per unit area of the beam cross-section – depend on the pump power and coefficient of losses in the cavity. The corresponding dependencies are presented in the Figs. 7–9.

The repetition rate of the output pulses (period of cavity dumping) may be changed coming to several MHz. If the repetition rate is high enough and a system fails to reach the steady state at the moment of cavity dumping, the output pulse parameters become dependent on the dumping repetition rate and may be unstable in time.

Cavity dumping by the second harmonic generation in mode-locked Nd:YAG lasers enables one to obtain the output pulses with the lengths 20–200 ps and peak intensities about 10–100 MW/cm$^2$. The pulse energy per unit area comes to a few mJ/cm$^2$ at efficiencies of the energy transformation to the second-harmonic 50% and higher. The generation of such pulses requires rather high pump powers (5 kW and higher) or low losses (0.001 cm$^{-1}$ and less).

6. Summary

We have presented the method of cavity dumping by the second harmonic generation and its implementation in a solid-state passively mode-locked laser. Dumping is realized through the energy transformation into the second harmonic in the intracavity second harmonic crystal. As the polarization prisms are not
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involved, the proposed method enables one to conserve the beam propagation direction. Highly reflective cavity mirrors are used to increase the efficiency of energy transformation into the second harmonic and to obtain higher output pulse energies.

The proposed theoretical model describing the process is based on the Haus theory of passive mode-locking and on rate equations for a point model of the active medium. It allows to simulate the mode-locked generation in dynamics and to investigate the process of the fundamental frequency pulse formation in a cavity. It is shown that the mode-locked generation may be realized

in two different regimes - CW and Q-switched - depending on the saturable absorber and system parameters. The generated pulse length is not time constant; the higher average intensity in the cavity, the smaller the pulse length and the higher its peak intensity.

The intensity profile for the output second-harmonic pulses and their parameters are determined by the fundamental frequency pulses formed in the cavity. The output pulse peak intensity, length and energy per unit area depend on the pump power and coefficient of losses in the cavity: to obtain shorter pulses with higher intensity and energy, the pump power should be

![FIG. 7. Dependence of the second harmonic pulse peak intensity on the pump power for $\gamma = 0.003 \text{ cm}^{-1}$ (a) and coefficient of inactive losses in the cavity for $P = 3 \text{ kW}$ (b).](image1)

![FIG. 8. Dependence of the second harmonic pulse length (FWHM) on the pump power for $\gamma = 0.003 \text{ cm}^{-1}$ (a) and coefficient of inactive losses in the cavity for $P = 3 \text{ kW}$ (b).](image2)
increased and the losses decreased to the possible minimum. Under the corresponding conditions, one can obtain the output pulses with energies per unit area up to several mJ/cm². The output pulse parameters may also depend on the dumping period. The cavity dumping repetition rate may be as high as MHz.

FIG. 9. Dependence of the second harmonic pulse energy per unit area on the pump power for $\gamma = 0.003$ cm$^{-1}$ (a) and coefficient of inactive losses in the cavity for $P = 3$ kW (b).

References