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Small autonomous passively Q-switched Nd^{3+} : YAG laser with a Cr^{4+} : YAG Q switch emitting pulse trains

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***Abstract*. The energy and time characteristics of a passively Q-switched Nd^{3+} : YAG laser with a Cr^{4+} : YAG Q switch emitting pulse trains are studied and analysed theoretically. The description and technical parameters of a small autonomous laser with intracavity second-harmonic generation (ICSHG) in the pulse-train regime are presented. The laser provides a high total pulse-train energy for a relatively low peak power of a single pulse, stable operation in a wide temperature range, and has a small weight and size, which is convenient in operation. The enhanced reliability and stability of the laser operation are provided by its original technical design: the ICSHG scheme for type II phase matching without polarisers, the use of temperature-noncritical phase matching in KTP crystals, dust- and moisture-proof casing, and battery-operated pulsed power supply for the pump flashlamp.**

Keywords: *intracavity second-harmonic generation, passive Q switch, pulse train, rate equations.*

1. Introduction

The development of solid-state lasers with intracavity second-harmonic generation (ICSHG), which can efficiently convert the fundamental laser radiation frequency to the blue – green spectral region, is an important current problem of quantum electronics. The ICSHG regime has been used conventionally and successfully in cw lasers and in pulsed lasers for relatively low gains in the active medium (see, for example, [1 – 5]). In the case of pulsed pumping and Q-switching by an electrooptical Q switch (generation of pulses with a repetition rate up to 500 Hz), the optimal radiation losses during SHG are 5 % – 15 %, while, as a rule, the second harmonic pulse energy does not exceed 50 mJ for a pulse duration of 10 – 30 ns. The fundamental radiation in lasers with ICSHG is generated in cavities with highly reflecting mirrors, and the possibility of increasing the second harmonic pulse energy is restricted by the optical stability of intracavity elements.

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The generation of a pulse train during a single pump pulse, which is typical for Q-switching with the help of a passive (phototropic) Q switch opens up new possibilities for increasing the second-harmonic pulse energy [6 – 13]. In this regime, a high total energy of the pulse train can be obtained both at low and high single-pulse energies. As the pump energy is increased, the energy of each pulse remains almost constant, but the number of pulses in the train increases. In this case, the total energy of second-harmonic pulses below the optical stability threshold of the cavity elements may be as high as 200 mJ.

Unlike, for example, a copper vapour laser providing a pulse repetition rate of 10 – 20 kHz, the pulse repetition rate in a Nd^{3+} : YAG laser pulse train can exceed 300 kHz. Such lasers are of practical importance in applications requiring a high total output energy during a time period comparable with the pump-pulse duration (i.e., during a period of ~ 100 μs) for a comparatively low energy of a pulse in the train (10 – 30 mJ for a pulse duration of 10 – 30 ns). Passive Cr^{4+} : YAG (black garnet) Q switches are widely used in Nd^{3+} : YAG and Nd^{3+} : YVO_4 lasers. These Q switches have much better overall parameters than other Q switches, for example, F_2^- : LiF_2 Q switches, and are most convenient for use in portable lasers.

In this paper, we studied theoretically and described the technical parameters of a Q-switched Nd^{3+} : YAG laser with ICSHG and a Cr^{4+} : YAG passive Q switch emitting pulse trains.

2. Theory

We shall use a system of rate (balance) equations to estimate theoretically the radiation parameters of a passively Q-switched laser. The second harmonic generation is treated as nonlinear losses for the fundamental radiation. In approximations of plane waves, slowly varying amplitudes, and fixed fundamental radiation field, the expression for the second harmonic power can be written in the form [3 – 5]

$$P_{2\omega} = K_{\rm nl} \frac{l_{\rm cr}^2}{S_{\rm cr}} P_\omega^2 . \qquad (1)$$

Here

$$K_{\rm nl} = \frac{\omega^2 d_{\rm eff}^2}{c^3 \varepsilon_0 n_{\rm s}^{\omega} n_{\rm f}^{\omega} n_{\rm f}^{2\omega}};$$

$l_{\rm cr}$ is the nonlinear-crystal length; ω is the fundamental radiation frequency; d_{eff} is the effective nonlinearity coefficient; c is the speed of light in vacuum; ε_0 is the permittivity of vacuum; n_s^{ω}, n_f^{ω} and $n_f^{2\omega}$ are the refractive indices of the slow and fast fundamental waves and the second harmonic wave; and S_{cr} is the cross section of the fundamental radiation beam in the nonlinear crystal.

By expressing the photon density in the cavity in terms of the fundamental radiation power, we can write the expression for nonlinear losses related to the fundamental radiation conversion to the second harmonic [5]:

$$\delta_{nl} = \frac{P_{2\omega} t_c}{\hbar\omega \Phi S_{cr} L_c} = \frac{K_{nl}}{4\pi} \hbar\omega c l_{cr}^2 \Phi, \tag{2}$$

where Φ is the photon density in the cavity; $t_c = 2L_c/c$ is the round-trip transit time in a cavity of length L_c; and $\hbar$ is Planck's constant.

The system of rate equations for a passively Q-switched laser can be written in the form [4, 5]

$$\begin{aligned} \frac{d\Phi}{dt} &= \frac{\Phi}{t_c}\left(2\sigma_a n_a l_a - 2\sigma_{gs} n_{gs} l_s - 2\sigma_{es} n_{es} l_s - \ln\frac{1}{R} - \delta_{nl} - L\right), \\ \frac{dn_a}{dt} &= R_p - c\sigma_a n_a \Phi, \\ \frac{dn_{gs}}{dt} &= -c\sigma_{gs} n_{gs} \Phi + \frac{n_{es}}{\tau_s}, \\ n_{gs} + n_{es} &= n_0, \end{aligned} \tag{3}$$

where n_a is the inverse population in the active medium; σ_a is the effective cross section for stimulated radiation; l_a is the active-medium length; n_{gs} and n_{es} are the populations of centres in a saturable filter in the ground and excited states, respectively; n_0 is the initial density of the absorption centres; σ_{gs} and σ_{es} are the ground- and excited-state absorption cross sections of the passive Q switch, respectively; l_s is the passive Q switch length; τ_s is the photon excited-state lifetime in the passive Q switch; R is the reflectivity of the output mirror; L are the unsaturable (passive) cavity losses in all elements of the laser; and R_p is the pump rate.

The time and energy parameters of laser radiation depend to a considerable extent on the pump-pulse shape. We will solve system of equations (3) by representing the pump pulse in the form

$$g(t) = 2.7bt\exp(-bt), \tag{4}$$

where b is a coefficient determining the pump pulse duration (in s^{-1}).

Figure 1 shows the pump-pulse shape described by expression (4). Taking (4) into account, we can represent the pump rate in system of equations (3) in the from

$$R_p(t) = \frac{P_p^{max} \gamma_p g(t)}{V_a \hbar\omega_p}, \tag{5}$$

where P_p^{max} is the maximum peak pump power; γ_p is the pump efficiency; V_a is the active-medium volume; and $\hbar\omega_p$ is the photon energy at the pump radiation frequency.

The pulse energy and duration in a passively Q-switched laser depend on the initial transmission of the passive Q switch. This leads to a peculiar type of dependence of the output energy of such lasers on the optical pumping of the active element. Upon pumping by long enough pulses, a laser can generate two, three, and more pulses after emission of the first pulse. The pump energy required for generating the second and subsequent pulses depends on the pump rate, the initial density of the passive Q switch, and the rate of its darkening after pulse generation. If rapidly relaxing passive Q switches are used, periodic pulsations can develop in the laser [7]. In this case, the initial absorption of the passive Q switch is restored completely by the instant of generation of each pulse, and a train of pulses is generated within a single pump pulse.

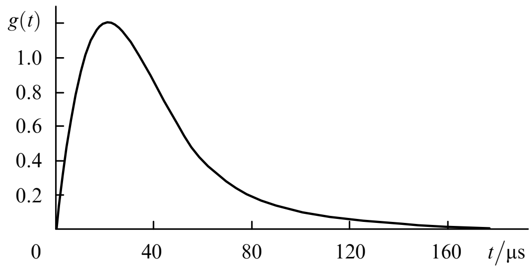


Figure 1. Pump-pulse shape described by expression (4) for $b = 5 \times 10^4\ s^{-1}$.

The discrete nature of radiation, which is related to the number of generated pulses, leads to a step dependence of the total radiation energy on the pump energy of the active element. After fulfilment of the condition for single pulse generation (upon an increase in the pump energy), the energy of a single pulse in the single-mode regime does not change, while its variation in the multimode regime is insignificant due to the development of generation in the cavity cross section [14]. This is due to the fact that the passive Q switch is locked after emission of the pulse, and the residual pump energy is insufficient for creating inverse population in the active element required for repeated bleaching of the Q switch. As the pump energy is further increased there comes a time when the passive Q switch can open twice during a pump pulse and thus the laser generates two pulses. If the pump energy and, hence, the pump rate are further increased, the laser will generate three, four or more pulses. Figure 2 shows the typical dependence of the output energy on the pump energy for a Q-switched laser with SHG. Calculations were made for the following values of the parameters: $\sigma_a = 8.8 \times 10^{-19}\ cm^2$, $l_a = 6.5$ cm, $L_c = 20$ cm, $R = 0.9$, $L = 0.1$, $\sigma_{gs} = 4.3 \times 10^{-18}\ cm^2$, $\sigma_{es} = 8.2\times$

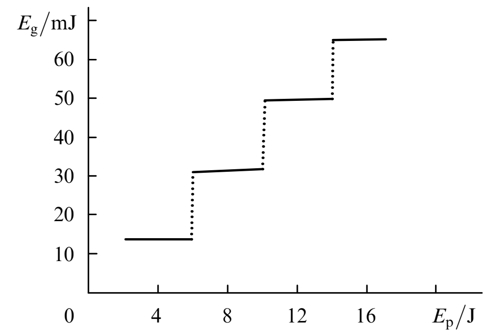


Figure 2. Typical dependence of the second harmonic generation energy on the pump energy for a passively Q-switched laser with SHG.

10^{-19} cm^2, $n_0 = 5.5\times10^{17}$ cm^{-3}, $l_s = 0.25$ cm, $\tau_s = 3.2\times10^{-6}$ s, $n_s^{\omega} = 1.830$, $n_f^{\omega} = 1.746$, $n_f^{2\omega} = 1.789$, $l_{cr} = 10$ cm, and $d_{eff} = 7.2\times10^{-12}$ m V^{-1}.

A decrease in the initial transmission of a saturable filter leads to an increase in the range of variation of losses and the inverse population. This results in a decrease in the pulse duration and an increase in the amplitude of pulses and the separation between them; also, the emission time of the first pulse increases (Fig. 3). As the pump energy is increased, the emission time of the first pulse in the train decreases. Figure 4 shows the dependence of the emission time of the first pulse on the pump energy.

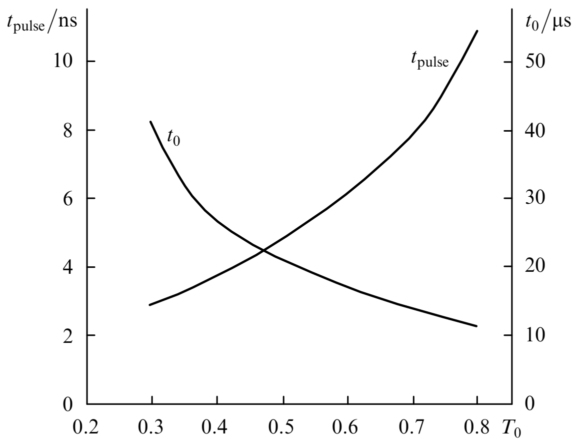


Figure 3. Dependences of the pulse duration t_{pulse} and the emission time t_0 of the first pulse in the train on the initial transmission coefficient T_0 of the passive Q switch [$T_0 = \exp(-\sigma_{gs} n_0 l_s)$].

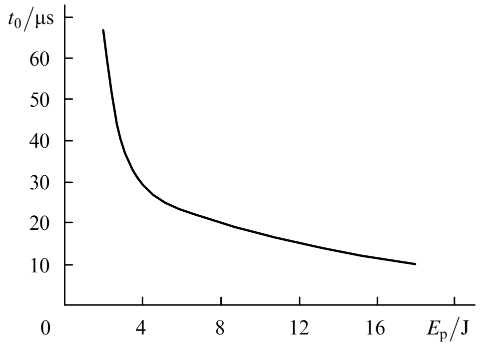


Figure 4. Dependence of the emission time t_0 of the first pulse from the train on the pump energy E_p.

Figures 5 and 6 show the results of calculation of lasing by using system of equations (3). These calculations provide qualitative estimates of the dependence of energy and time characteristics of the output laser radiation on the pump-pulse shape and energy, as well as on the parameters of the passive Q switch and active and nonlinear elements of the laser.

3. Description of the laser and experimental results

The design of the laser with ICSHG emitting pulse trains is based on some innovative solutions improving the stability and reliability of the laser. These include the ICSHG

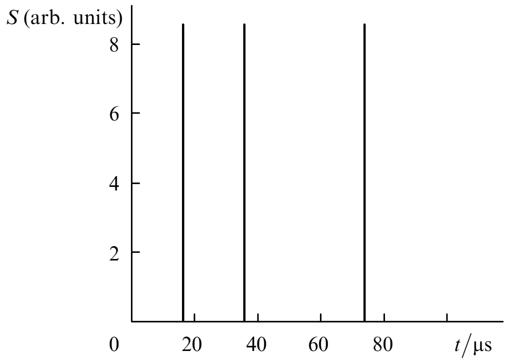


Figure 5. Pulse train of a passively Q-switched laser.

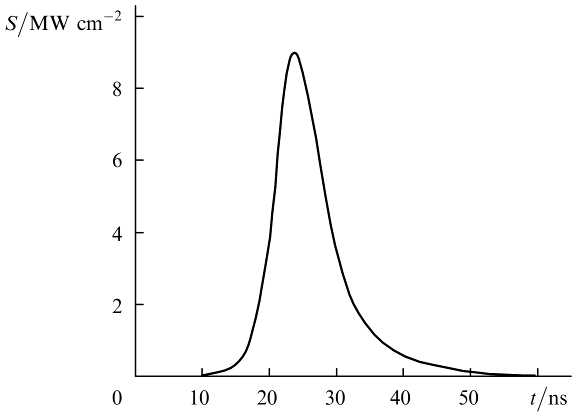


Figure 6. Typical shape of a pulse in a pulse train.

scheme for type II phase matching in the absence of polarisers, the use of temperature-noncritical phase matching in KTP crystals [15], a dust- and moisture-proof casing of the laser, and a pulsed power supply for the pump flashlamp running on AA accumulators. The scheme of the laser is shown in Fig. 7. The total length of the cavity is 200 mm. The active element and the pump flashlamp are encased in an elliptic reflector with convective cooling.

The Nd^{3+}:YAG active element was cut along the crystallographic axis [001] and oriented in the reflector in such a way that the [010] axis formed an angle of 45° with the plane containing the active element and the pump flashlamp. For such an orientation, depolarisation losses

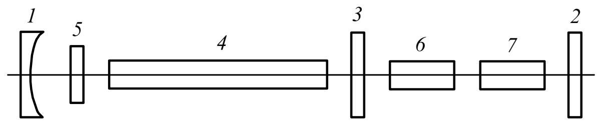


Figure 7. Scheme of the laser: (*1*) mirror with a radius of curvature 3 m and a reflectivity of no less than 99.5 % at the fundamental frequency and the second harmonic frequency; (*2*) mirror with a reflectivity of no less than 99.5 % at the fundamental frequency and no more than 8 % at the second harmonic frequency; (*3*) retroreflecting mirror with a reflectivity of no more than 0.5 % at the fundamental frequency and no less than 99 % at the second harmonic frequency; (*4*) Nd^{3+}:YAG active element (∅ 5 × 65 mm); (*5*) passive Cr^{4+}:YAG Q switch (∅ 5 × 2 mm) with a transmission of 50 % in the unbleached state; (*6, 7*) nonlinear KTP crystals of length 10 mm each.

for the fundamental mode polarised in the plane of the pump flashlamp and active element, or the plane orthogonal to it are minimal [16]. In the absence of intracavity polarisers, lasing in this case will occur with linear (or nearly linear) polarisation oriented in the direction of the minimum of the 'rosette' of the residual luminous flux (RLF). However, in view of the presence of two mutually orthogonal RLF minima, the polarisation direction is not stable and may abruptly change its orientation by 90°. One or another direction of polarisation can be obtained by adjusting the cavity, thereby introducing different modes to lasing.

The passive $Nd^{3+}:YAG$ Q switch was mounted in the cavity taking into account the anisotropy of saturable absorption [6, 13]. In the absence of nonlinear crystals, the polarisation of laser radiation corresponded to the spatial orientation of one of the two orthogonal groups of Cr^{4+} centres (the third group of Cr^{4+} centres is directed along the optical axis of the cavity). The passive Q switch was mounted in the cavity in such a way that the spatial orientation of one of the two orthogonal groups of Cr^{4+} centres coincided with one of the directions of the minimum of the RLF 'rosette'.

Two KTP crystals, cut at the angle of type II temperature-noncritical phase matching, were used as frequency converters. To realise type II phase matching, two fundamental waves with mutually orthogonal polarisations and different phase velocities should propagate in a nonlinear crystal. As a result, plane-polarised radiation may become elliptically polarised after passing through the nonlinear crystal.

In devices with acousto-optical and electro-optical Q-switching, as well as in the case when an additional polariser is used in the cavity, depolarisation of radiation in a nonlinear crystal can reduce the fundamental radiation power, i.e., introduce depolarisation losses in the laser cavity. In this case, phase shift in the nonlinear crystal is normally compensated by using a quarter-wave plate or by adjusting the nonlinear crystal to such a position that no phase shift occurs between the orthogonal components of the fundamental radiation during two successive passes, and the phase matching condition is fulfilled. However, such schemes are sensitive to temperature fluctuations of the environment which lead to fluctuations in the energy parameters of the laser.

A quite different picture is observed in a passively Q-switched laser in the absence of additional polarisers. Lasing occurs in modes with minimal depolarisation losses, i.e., modes whose polarisation is parallel to that of the fast or slow wave propagating in the nonlinear crystal. Recalling that two mutually orthogonal components (fast and slow waves) of the fundamental radiation are required for SHG of type II, it becomes obvious that efficient frequency conversion in such a scheme is impossible. Moreover, because resonator mirrors have a high reflectivity for fundamental radiation in the case of ICSHG, radiation will not emerge from the cavity and this may lead to 'burnings' of the optical elements of the laser.

To eliminate such an effect, we used two nonlinear KTP crystals in the laser, which were turned at an angle of 45° to each other around the optical axis of the cavity. In this case, two mutually orthogonal components of fundamental radiation will always propagate in at least one of the nonlinear crystals and hence the second harmonic will be generated.

Thus, 'burning' of the optical elements of the cavity was avoided by using pairs of KTP crystals turned at an angle of 45° to each other around the optical axis of the cavity, and no additional intracavity polarisers were required. Moreover, temperature-noncritical phase matching in nonlinear crystals provided stable lasing in the temperature range of laser operation (from -10 to $+50$ °C) without employing any thermal stabilisation devices.

We used a unidirectional second-harmonic radiation extraction scheme in the laser, and the converted radiation generated during the return passage through nonlinear crystals after the reflection of the fundamental radiation at the output mirror was extracted by means of a retroreflecting mirror. Such a mirror has a high transmission coefficient at the fundamental frequency and a high reflection coefficient at the second harmonic frequency. The second harmonic radiation power at the output of a laser with a retroreflecting mirror was 1.5 times higher than in a laser without the mirror. The relatively small increase in the output power is due to additional losses introduced by this mirror in the cavity.

Figure 8 shows the oscillogram of a pulse train of laser radiation. Each pulse in the train has a duration of 30 – 40 ns, and the duration of the train is about 100 μs. Some pulses in the oscillogram are broadened due to the inertia of the photodiode used for measurements. The duration of a single pulse was measured with the help of an avalanche photodiode.

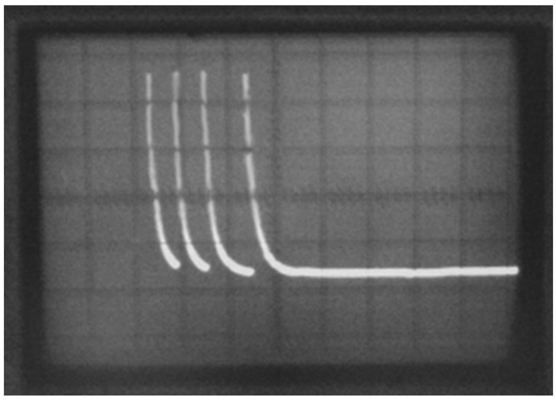
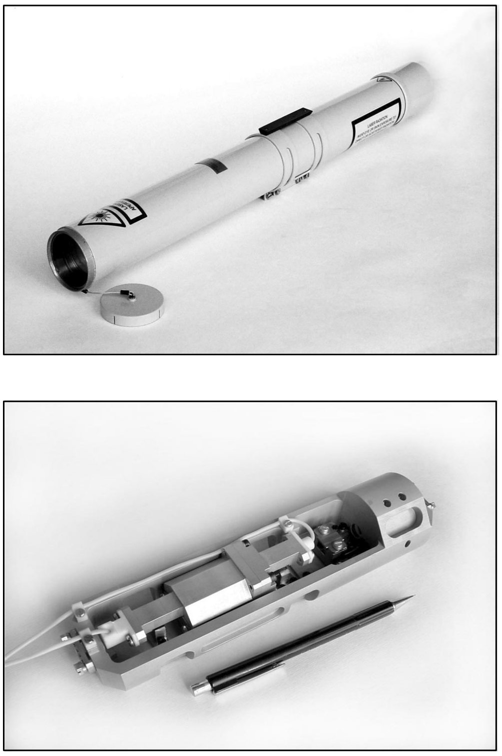


Figure 8. Oscillogram of a laser radiation pulse train.

The general view of the laser and the emitter without dust- and moisture-proof casing are shown in Fig. 9. The technical parameters of the laser are as follows:

Laser radiation wavelength/nm	532
Operation mode	pulse train
Pulse energy in the train/mJ	no less than 100
Pulse train repetition rate/Hz	no less than 0.2
Beam divergence (at 0.5 level)/mrad	no more than 1
Power supply	12V dc (8 series-connected AA 1.5-V accumulators)
Number of pulse trains (without battery replacement)	~ 200
Size:	
diameter/mm	64
length/mm	610



a

b

Figure 9. General view of (a) the laser and (b) emitter.

4. Conclusions

We have theoretically studied and analysed the energy and time parameters of a passively Q-switched $Nd^{3+}:YAG$ laser with a $Cr^{4+}:YAG$ Q switch emitting a pulse train.

The design and technical characteristics of a small autonomous laser with ICSHG emitting pulse trains are described. The reliability and stability of the laser operation were improved due to an original technical design (the ICSHG scheme for type II phase matching without polarisers), the use of temperature-noncritical phase matching in KTP crystals, dust- and moisture-proof casing, and AA-type accumulators for pulsed power supply for the pump flashlamp.

The laser provides a high total energy of the pulse train for a relatively low peak power of an individual pulse and stable operation over a wide range of temperatures. It has a small size and a small weight, which is convenient for exploitation.

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