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GENERATION OF TWO IDENTICAL ns LASER PULSES AT SINGLE μs SPACING BY SWITCHING OUTPUT MIRROR TRANSMISSION

Marek Skórczakowski, Waldemar Żendzian, Zdzisław Jankiewicz

Military University of Technology, Institute of Optoelectronics, gen. S. Kaliskiego 2, 00-908 Warsaw, Poland
(✉ *marek.skorczakowski@wat.edu.pl*, +48 261 83 75 58, *waldemar.zendzian@wat.edu.pl*, *zdzislaw.jankiewicz@wat.edu.pl*)

Abstract

Generation of two identical ns laser pulses spaced by a single μs time interval by means of sequential switching of the output mirror transmittance in a diode-pumped Nd:YAG laser is reported, to our knowledge, for the first time. The theoretical study of the process of transmission losses switching is developed. This analysis confirms the possibility of generation of two identical Q-switched laser pulses with 100% efficiency with respect to the referenced single pulse energy. The detailed characterization of the laser in free-running, single and double Q-switching regimes is presented. The laser can be applied in different branches of metrology as PIV, LIBS or holographic interferometry.

Keywords: double pulse Q-switched laser, pulsed holographic interferometry, transmission losses switching, diode pumped Q-switched laser.

1. Introduction

Short, nanosecond pulses of high peak power can be generated primarily by switching resonator losses. In this method, the active medium should be characterized by a fairly long laser level lifetime (hundreds of microseconds or more), and thus the ability to accumulate energy supplied to it during the pumping process. This condition is met by many crystalline media doped with rare earth ions. The pumping of such media is performed by absorption of flash or laser diodes. These sources should emit radiation of appropriate spectral, time and spatial parameters. For reasons of pumping efficiency, this process should be as short as possible but technical constraints generally do not allow sufficient energy to be supplied to the medium in less than a few hundred microseconds. The entire generation and pre-pumping process therefore takes such a long time that it can be repeated only after a period of several hundred microseconds. In contrast, a single pumping operation usually results in the generation of a single short, strong pulse, and the generation of the next one requires the cycle to be repeated or the pumping time to be significantly extended [1].

However, there are some needs for at least two strong and short pulses whose time interval is much shorter and is only a few microseconds. This concerns *e.g.* holographic interferometry

[2–4], various types of anemometry, fast photography [5], PIV method [6–10], LIBS method [11–14]. Then it is impossible to complete the task with one Q-switched laser. The simplest solution is to use two synchronized Q-switched lasers but it is too expensive and complicated. Another option is to build a pulse-generating laser by switching losses gradually [15, 16]. Such a solution was used in holocameras a long time ago. It consisted in a two-stage switching of losses (transmittance) of the switch inside the resonator resulting, under strictly defined conditions, in the generation of two pulses of equal energies or peak powers. The disadvantage of such an approach was that it was impossible to generate two identical impulses (of the same energies and duration) and not to fully use the energy accumulated in the active medium as a result of pumping, because part of the energy of the first impulse was deposited on the intermediate losses of the switch.

The multitude of applications of the laser generating ns double pulses causes this problem to be still addressed by various researchers [17, 18]. In this paper we propose to modify the method of gradual loss switching by replacing switchable dissipation losses (resulting from the switch's finite transmittance) with switchable useful losses (variable step-by-step transmission of the output mirror). In such a case it is possible to fully utilize the energy accumulated in the active medium and divide it into two pulses in any proportion (especially 1:1), so that the sum of the energy of two pulses is exactly equal to the energy of a single pulse of an optimally coupled laser. Furthermore, under certain conditions it is possible to generate two pulses of equal energy and peak power.

2. Switching transmission losses

The process of generating laser pulses by switching losses for a laser of not very high gain is usually described by rate equations [19], which can be written as:

$$\frac{\mathrm{d}g}{\mathrm{d}t} = -\frac{gJ}{E_S}, \tag{1}$$

$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{1}{\tau_R}\left(g - \rho_{tot}\right) J \tag{2}$$

with initial conditions:

$g(0) = g_0$ – initial gain due to previous pumping,

$J(0) = J_0 = J_0(g_0)$ – the power density of the noise flux in the solid angle of the resonator mode, where:

$g = g(t) = kl = \sigma_{em}\Delta nl$ – gain per one pass of the active medium being the product of the stimulated emission cross section [cm^2], population inversion [cm^{-3}] and length of active medium [cm]; k – gain coefficient [cm^{-1}],

$J = J(t)$ – averaged over the length of the active medium, the power density of the sum of streams propagating in both directions in the resonator [W/cm^2],

E_S – saturation fluence [J/cm^2],

$\tau_R = \dfrac{L_{opt}}{c}$ – the propagation time of light between the mirrors of the resonator [s],

$\rho_{tot} = \rho_T + \rho_d$ – total losses being the sum of transmission and dissipation (passive) losses,

$\rho_T = \rho_T(t) = \dfrac{1}{2}\ln\dfrac{1}{R(t)}$ – transmission losses.

After simple mathematical operations on equations (1) and (2) we obtain the following useful formulas:

$$g_0 - g_f = \rho_{tot}\ln\frac{g_0}{g_f}, \tag{3}$$

– dependence of the gain remaining in the medium after the pulse is generated g_f on initial gain and total losses (transcendent equation),

$$E = E_S \frac{\rho_T (g_0 - g_f)}{\rho_{tot}}, \tag{4}$$

– pulse output energy density [J/cm^2],

$$g_f = \rho_d, \tag{5}$$

– the condition of laser energy optimization, *i.e.* the generation of the maximum energy pulse for the set g_0 and ρ_d,

$$\rho_{Topt} = \frac{g_0 - \rho_d}{\ln \dfrac{g_0}{\rho_d}} - \rho_d, \tag{6}$$

– optimal transmission losses for the set g_0 i ρ_d,

$$\tau_{1/2} = \frac{\tau_R}{g_0} \frac{x(x - x_f)}{(x - 1 - \ln x)}, \tag{7}$$

– pulse duration at half peak power level [s],
where

$$x = \frac{g_0}{\rho_{tot}}, \qquad x_f = \frac{g_f}{\rho_{tot}}. \tag{8}$$

Let us introduce the parameter:

$$q = \frac{g_0}{\rho_d}, \tag{9}$$

which can be called the *laser figure of merit* (FOM) because it expresses the ratio of what the laser offers for use (stored energy) to what must inevitably be lost. Then, the expression for the initial gain normalized optimal transmission losses takes the form of:

$$\frac{\rho_{Topt}}{g_0} = \frac{q - 1 - \ln q}{q \ln q}. \tag{10}$$

The relationship above is illustrated graphically in Fig. 1.

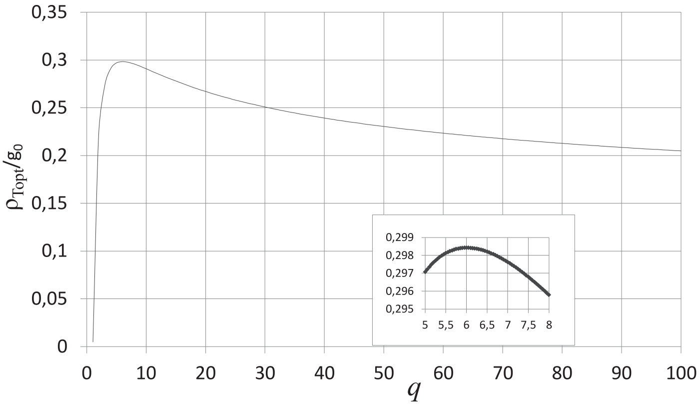

Fig. 1. Relative transmission losses of an optimally coupled Q-switched laser (in relation to the initial gain value) depend on parameter q, where the change of q is made by changing the dissipation losses.

In the case of impulse generation with fixed initial gain, the optimal transmission losses normalized to the initial gain reach their maximum close to 0.3 for $q = 6$. This means that both low and very high FOM lasers need to be more closely coupled (similarly to the stationary generation).

The relationship between gain and loss in practice is better expressed by threshold exceeding that is easily measurable. It can be shown that for an optimally coupled pulsed laser the threshold exceeding dependence on the laser FOM is expressed by the formula:

$$x = \frac{g_0}{\rho_d + \rho_{T\,opt}} = \frac{q \ln q}{q - 1} \cong \ln q \qquad \text{for } q \gg 1. \tag{11}$$

This logarithmic relationship is illustrated in Fig. 2. Exceeding the threshold of an optimally coupled pulse laser is poorly dependend on its FOM and in practice for reasonable and practically available FOM values, it is between about 2.5 and about 5. A Q-switched laser should not work too high above the threshold.

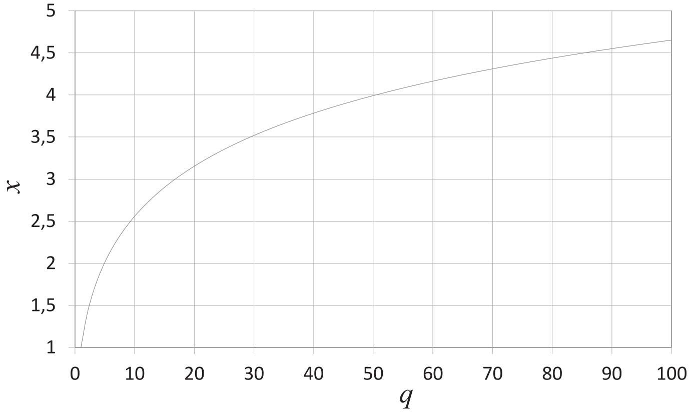

Fig. 2. The dependence of exceeding the threshold of an optimally coupled Q-switched laser on q parameter.

The primary purpose of switching losses immediately is to extract the energy stored in the active medium as quickly as possible, thus minimising the pulse duration. The product of the normalised pulse duration and the initial gain is expressed as:

$$\frac{\tau_{1/2}}{\tau_R} g_0 = \frac{x\left(x - x_f\right)}{(x - 1 - \ln x)} = \tau(x), \tag{12}$$

and depends solely on exceeding the threshold, since the normalised final gain x_f depends also solely on x. This dependence (11) is illustrated in Fig. 3. It is worth noting that the duration of the impulse at constant gain hardly depends on exceeding the threshold (or losses, mainly transmission losses) in the range of $x > 2$ and its minimum value is (for $x \sim 3$):

$$\tau_{1/2} \cong \frac{9.4\tau_R}{g_0}. \tag{13}$$

The impulse duration is inversely proportional to the initial gain over the whole range of the threshold exceeding which is characteristic of the Q-switching process (as shown in Fig. 2). It is worth noting that the recommended threshold exceeding range of the Q-switched laser is similar both in terms of optimization of the impulse energy and minimization of its duration and concerns a wide range of FOM. It is, therefore, a general indication.

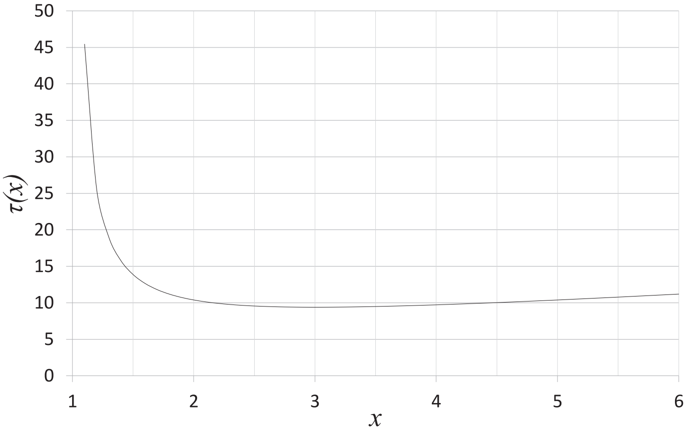

Fig. 3. Relationship between the relative duration of the impulse and exceeding the threshold at fixed gain.

3. Two-pulse generation

The analysis of the process of generating two pulses in a laser with set parameters g_0 and ρ_d with the method of switching transmission losses can be reduced to solving the system of 3 non-linear algebraic equations presenting subsequently: transcendent equation for the first impulse, transcendent equation for the second impulse and equal energy condition of the first and second impulse. These equations are as follows:

$$g_0 - g_{f1} = (\rho_{T1} + \rho_d) \ln \frac{g_0}{g_{f1}}, \tag{14}$$

$$g_{f1} - \rho_d = (\rho_{T2} + \rho_d) \ln \frac{g_{f1}}{\rho_d}, \tag{15}$$

$$\frac{\rho_{T1}}{\rho_{T1} + \rho_d} \left(g_0 - g_{f1}\right) = \frac{\rho_{T2}}{\rho_{T2} + \rho_d} \left(g_{f1} - \rho_d\right), \tag{16}$$

where the unknown of this system of equations mean:

ρ_{T1} – transmission losses after the first switching of the mirror transmission,

ρ_{T2} – transmission losses after the second switching of the mirror transmission,

g_{f1} – final gain after the first pulse is generated as the initial gain for the second pulse.

Knowledge of solutions of the above equation system including laser parameters g_0 and ρ_d allows the calculation of basic parameters (output energy, pulse duration, *etc.*) of a two-pulse laser as well as parameters of a single-pulse reference laser under the same conditions. It should be assumed that the single-pulse reference laser is optimally coupled (its final gain is equal to the dissipation losses) and the coupling (the losses ρ_{T2}) for the second impulse is also optimal, therefore $g_{f2} = \rho_d$.

The system of equations (13), (14), (15) was solved numerically and using appropriate formulae, pulse duration, pulse energies, output mirror transmittances and threshold exceedances have been calculated for initial gain $g_0 = 0.5$. The results are presented in Figs. 4–7 in the form of dependence of laser parameters and generated pulses on the parameter $\boldsymbol{q} > 2$.

In the full range of variability of parameter $\boldsymbol{q}$, *i.e.* for each laser, the pulse energy of the reference laser optimally coupled increases with its FOM to the limit which is the energy accumulated

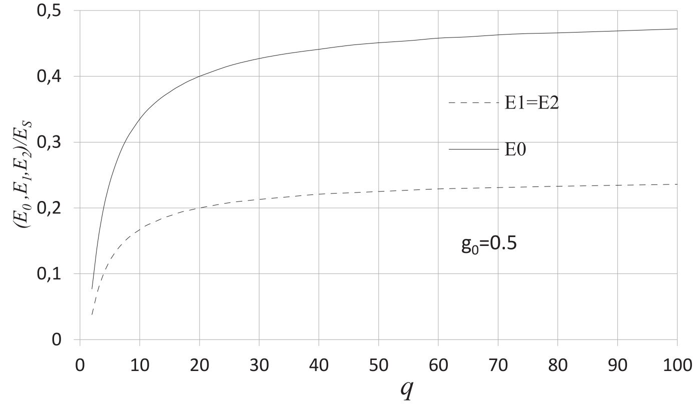

Fig. 4. Energy dependence of reference pulse E_0 and double pulse energy E_1 and E_2 from laser FOM when switching transmission losses for an initial gain of 0.5 (energy stored in the active medium is $0.5E_S$). In each case, the condition $E_0 = 2E_1 = 2E_2$ is met $i.e.$ the energy generated in one pulse can be divided exactly in half between two pulses. The nature of these graphs does not depend on the initial gain; only the values of these energies change in proportion to the values of g_0.

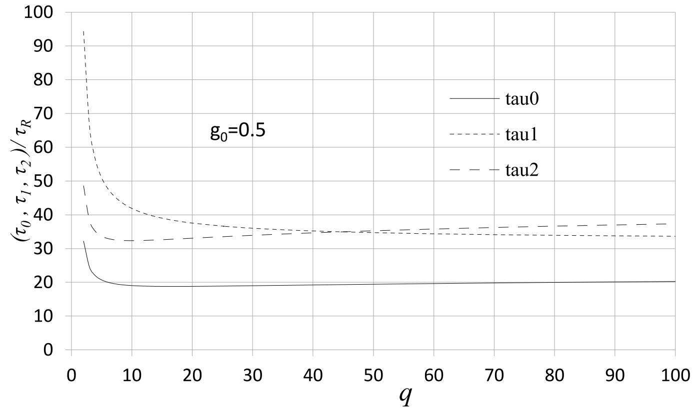

Fig. 5. Dependence of the duration of the reference pulse (τ_0) and duration of double pulse (τ_1 i τ_2) from the laser FOM in switching transmission losses for an initial gain of 0.5. The nature of these graphs does not depend on the initial gain; only the duration values change in inverse proportion to the values of g_0. In theory, two pulses of equal energy and duration (peak power) can only be generated for a laser FOM of approximately 45.

in the active medium. In this case, two pulses of exactly the same energy can always be generated by switching transmission losses, the sum of which is equal to the energy of a single (reference) optimal pulse. Furthermore, for q above 20 (dissipation losses account for 5% of the initial gain) the energy increase is very slow. For q of 100 the laser efficiency (the ratio of the energy of the reference pulse to the stored energy) is about 95%. It should be stressed that the nature of the graphs in Fig. 4 is the same for any initial gain, the energy values are proportional to the gain.

The durations of both single and double pulses decrease very quickly with an increase in laser FOM and above q equal to 10 stabilize at a value inversely proportional to the gain. The nature of the curves in Fig. 5 is the same for any gain. For example, for a reference pulse, the pulse duration stabilises at ca. 20 times the time of τ_R which for gain $g_0 = 0.5$ is consistent with relation (12).

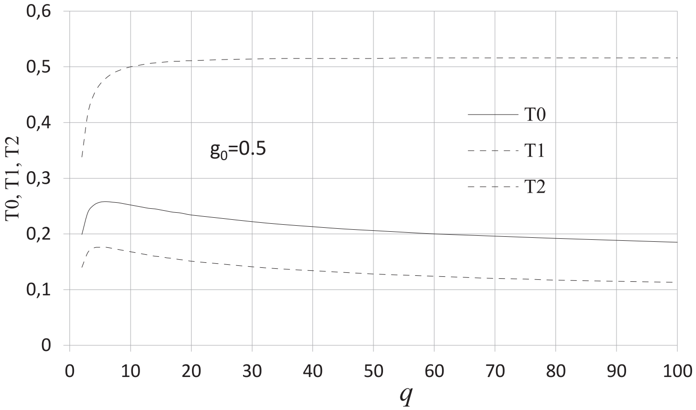

Fig. 6. Dependence of output mirror transmittance for reference pulse (T0) and for double pulses (T1 and T2) on laser FOM when switching transmission losses for initial gain equal 0.5. The nature of these graphs does not depend on the initial gain; only the transmittance values change depending on g_0. The reference pulse and the second pulse of the series are generated under optimal conditions, as shown by the nature of T0 and T2 waveforms in comparison with those in Fig. 1.

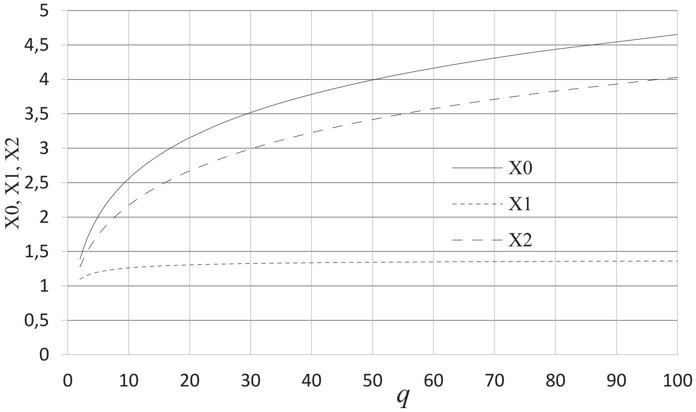

Fig. 7. Dependence of exceeding the threshold for a reference laser (X0) and a two-pulse laser (X1 and X2) on the laser FOM when switching transmission losses. The graphs are identical for any initial gain value. The reference pulse and the second pulse of the series are generated under optimal conditions which is also indicated by the nature of the X0 and X2 waveforms compared to the waveforms in Fig. 2.

The duration of the first of the double pulses is longer than the duration of the reference pulse because the threshold for it is less than 2 and is about 1.3 in the whole range of the laser FOM (see Fig. 7). The duration of the second pulse is longer than the duration of the reference pulse because for the second pulse the initial gain is lower than for the single pulse. The threshold exceeding for the first pulse, although it is approximately only about 30%, increases slowly with an increase in q (Fig. 7) and, therefore, the saturation of the gain by the first pulse also increases with an increase in q. For these reasons, the duration of the second impulse increases and the first impulse decreases with an increase of q.

For a value of q equal to approximately 45 (this is quite an extreme requirement for the quality of Q-switched laser resonator components) the duration of double pulses is exactly equal.

However, in the wider range of variability of the parameter q (approximately 30 to 80), the differences in double pulse durations are significantly lower than 10%. Due to fluctuations in the parameters of Q-switched lasers (especially pulse durations), these differences can only be of practical importance in well stabilized single frequency lasers. Therefore, on the basis of the results of calculations shown in Figs. 4 and 5, it can be concluded that in the case of switching transmission losses, it is possible to generate two pulses of equal energies and peak powers (durations) with efficiency of about 90%.

The nature of the dependence of the output mirror transmittance for the reference pulse and the double pulses at the gain value of 0.5 on laser FOM (Fig. 6) shows that the reference pulse and the second pulse of the series are expected to be generated under optimal conditions (compare Fig. 1). The losses (or transmittance of the output mirror which is equivalent in meaning) for the first pulse of the series are significantly higher and almost constant in the range of FOM corresponding to lasers with acceptable efficiency. This results in a very low threshold exceeding for the first pulse of the series in the corresponding range of FOM (see Fig. 7). This can be considered as a disadvantage of the double-pulse generation process because in practice the energy and time stability of the pulses is poor at low threshold exceedance.

The exceeding of the threshold as a function of laser FOM, which according to the dependence from Fig. 2 for the optimally coupled laser should depend only on parameter q, shows a quantitative differentiation for the reference and second pulse in the series with both curves having the same character. This is due to the lower gain for the second pulse, so that the value of parameter q is different from that of the reference pulse used for the calculation. Of course, both the reference and the second pulse are generated under optimal coupling conditions.

The threshold for the first pulse for $10 < q < 100$ varies between 26% and 36%. The consequence of this is a change in the duration of the series pulses as shown in Fig. 5.

The relationships shown in Fig. 7 are universal for the generation of double pulses by switching transmission losses in any laser.

Summing up the analysis of the mono-pulse generation, the following can be stated:

1. Any Q-switched laser should work at a not too high threshold exceeding, practically in range 2.5 to 4.5. This is due to both optimization of the pulse energy and minimization of its duration.
2. In this range of exceeding the threshold the pulse duration depends only on the gain (for the fixed length of the resonator).
3. By switching transmission losses gradually, two pulses with exactly the same energies (or with a fixed relationship between them) can be generated.
4. Within the acceptable range of laser FOM, the duration of both pulses is practically the same when switching transmission losses.
5. From the practical point of view, such pulses are identical, but in the strict sense they have only the same energies and durations.
6. The second of the series of pulses is generated under optimal coupling conditions, with the threshold exceeding being high enough.
7. The first pulse is always generated at a very low threshold which can adversely affect the stability of its parameters.

4. Experiment

The premises resulting from the theoretical analysis were verified in an experimental laser system whose diagram is shown in Fig. 8.

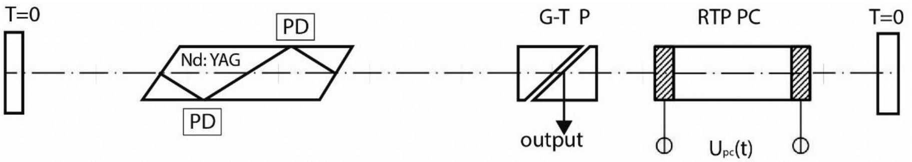

Fig. 8. Laser diagram with switching transmission losses; PD – pump diode, G–T P – Glan–Taylor polarizer, RTP PC–RTP crystal Pockels cell.

The active medium of the laser was an Nd:YAG crystal formed in the shape of a plate of parallelogram cross-section and the dimensions of 4 × 4 × 50 mm^3, with the input and output planes having a Brewster cut. Inside the plate, the laser beam was totally internally reflected from opposite surfaces. In these reflection areas, radiation from pumping diodes was introduced. These surfaces were covered with anti-reflection layers for the pump wavelength (808 nm). Such geometry forced vertical polarisation in the resonator.

Two Dilas GmbH pulse diode arrays with a total power of 4 kW were used as pumping sources. The diodes were powered by two power supplies providing trapezoidal current impulses (Fig. 13) with a duration of 200 µs.

The laser head containing the active crystal and the pumping diodes were cooled with water. The same head was used in the study [20].

The laser resonator was formed by two flat fully reflecting mirrors. The optical length of the resonator was 120 cm (4 ns) in order to provide a large TEM_{00} mode volume and, thus, the output energy. Inside the resonator a diaphragm was placed forcing the fundamental transversal mode.

A classic electro-optical switch consisting of a Pockels cell based on a quarter-wave RTP crystal with $U_{\lambda/4} = 800$ V was used as a variable transmission mirror along with Glan–Taylor's polarizer. The laser output beam left the resonator as shown in Fig. 8, bouncing off the slanted surface of the polarizer and had a horizontal polarization. The transmission of such an electrically controlled mirror for lossless elements is expressed by the formula:

$$T_{oc} = \sin^2 \frac{\pi}{2} \frac{U}{U_{\lambda/4}}, \tag{17}$$

where: U – the voltage applied to the electrodes of a Pockels cell.

In the absence of voltage on the Pockels cell, the resonator was completely closed (minimum loss) and in the case of a quarter-wave voltage, completely open (maximum loss). Intermediate voltages caused transmission losses increasing with increasing voltage. The dynamic change of transmittance of such an electrically controlled mirror consisted in a two-stage switching of voltage from the initial constant quarter-wave voltage It was realized by supplying to the electrodes of the Pockels cell two impulses of voltage of reverse polarity and values complementing the voltage corresponding to the desired transmittance to the quarter-wave voltage.

4.1. Laser characterization in a free-running generation

Having an electro-optical system that performs the function of a variable-transmission mirror opens up new possibilities of laser characterization. So far, the input-output characteristics have usually been measured for a set of mirrors with specific transmittances and from these measurements, *e.g.* losses (Findlay–Clay's method), optimal coupling *etc.* have been deducted. In the case of a mirror with variable transmittance, the optimal operating conditions can be determined directly, easily and quickly – also depending on the pump. Fig. 9 shows the results of measurements of the laser output energy in free-running mode depending on the constant voltage of the Pockels cell which is equivalent to dependence on transmission losses (higher voltage means higher losses). There is a commonly known property consisting in the increase of optimal losses with increase in gain (current of pumping diodes).

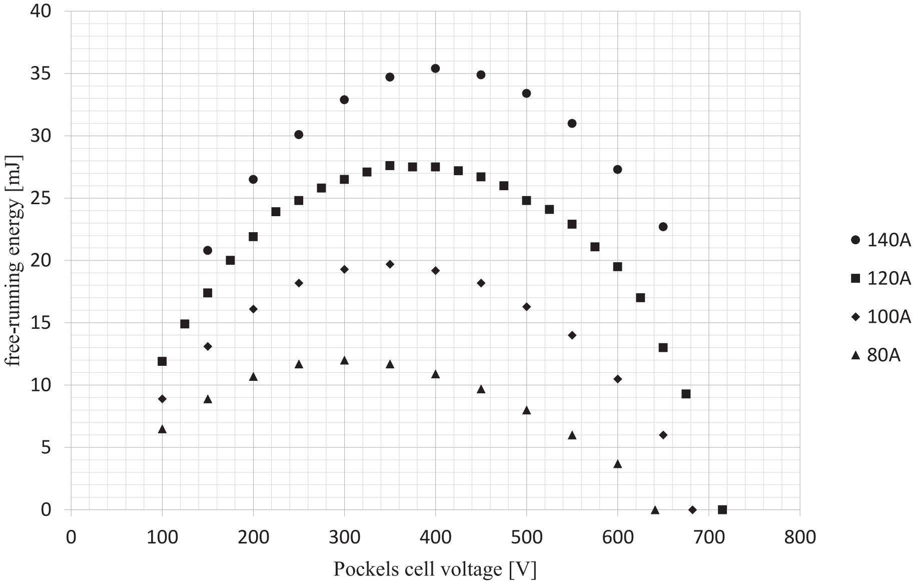

Fig. 9. Dependence of the output energy in the free-running mode on a constant voltage on a Pockels cell of an electro-optically controlled mirror for selected pumping diode currents. The threshold voltage values on the Pockels cell are: 641 V, 682 V and 715 V for the currents: 80, 100 and 120 A respectively.

In order to verify the correctness of defining the transmittance of the electro-optically controlled output mirror, comparative measurements of the output energy for the resonator were performed, in which one of the completely reflecting mirrors was replaced with a flat mirror of known transmittance and a resonator with an electro-optically controlled mirror. Mirrors with the following transmission factors were used: 25, 40, 60, 85 and 96%. In each case, very good agreement of input-output characteristics was obtained for the case of fixed mirror transmittance and some constant voltage on the Pockels cell, at which the compliance of the energy measurement results was the best in both cases. Sample measurement results are shown in Fig. 10.

A summary of generation comparison results for a mirror with a set transmittance and electro-optically controlled is given in Fig. 11. The measuring points have the following coordinates: ordinate – the value of the mirror's transmittance, abscissa – the voltage value on the Pockels cell corresponding to the given mirror at which the same output energy was obtained. The theoretical curve corresponds to the transmittance of an electro-optically controlled mirror and is a graphic illustration of the formula (16) for 800 V quarter-wave voltage.

The threshold voltage values on the Pockels cell for selected pumping diode supply currents: 80, 100, and 120 A were determined in a laser with an electro-optically controlled mirror. They were equal to 641, 682 and 715 V respectively. The corresponding transmission loss values are: 1.18, 1.47 and 1.79 respectively. Threshold values were determined based on visual observation of the laser generation threshold. The dissipative loss determined on the basis of these observations

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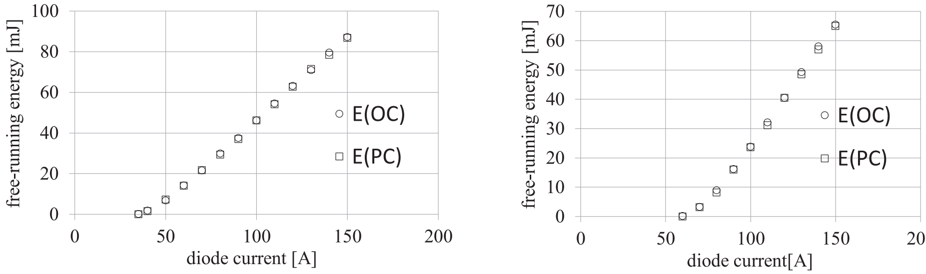

Fig. 10. Comparison of free-running generation energy for an output coupler with transmittance E(OC) and voltage on a Pockels cell E(PC), respectively: left – 40%, 350 V, right – 85%, 600 V.

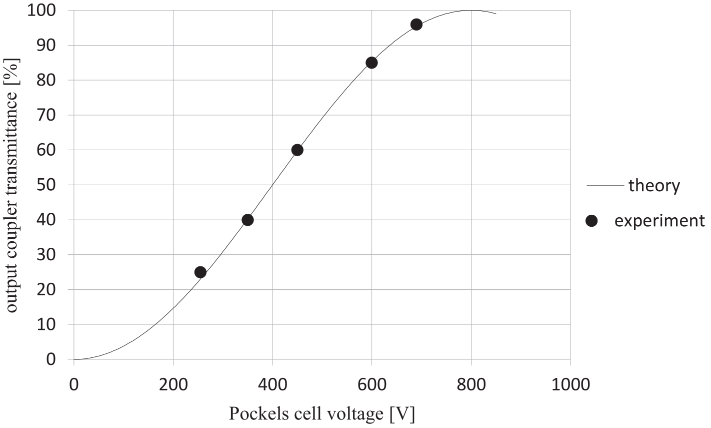

Fig. 11. Experimental confirmation of the validity of the dependence on the transmittance of an electro-optically controlled mirror.

using the Findlay–Clay's method was 0.045 which is illustrated in Fig. 12. This result seems reasonable, because the main source of internal resonator losses is the Glan–Taylor's polarizer whose losses are about 4%.

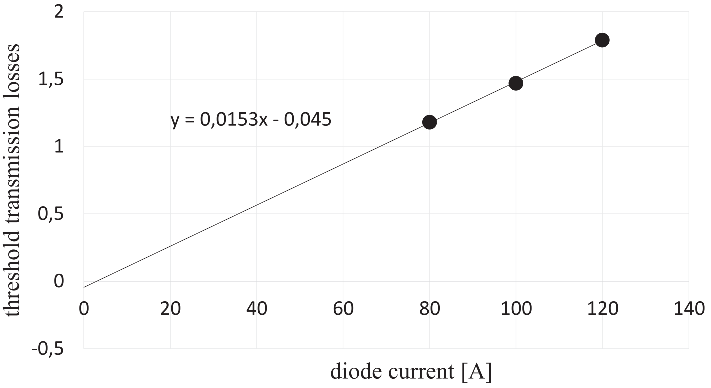

Fig. 12. Dependence of transmission threshold losses on the diode current (graph of the F–C method).

The dynamics of gain increase in the diode-pumped active laser medium was investigated by determining the delay of the moment of starting the free-running generation at known losses. Five of the same flat transmission mirrors with transmittances: 25, 40, 60, 85 and 96% and the dissipative loss value determined above were used. The idea of measurement is illustrated in Fig. 13, and the results are shown in Fig. 14.

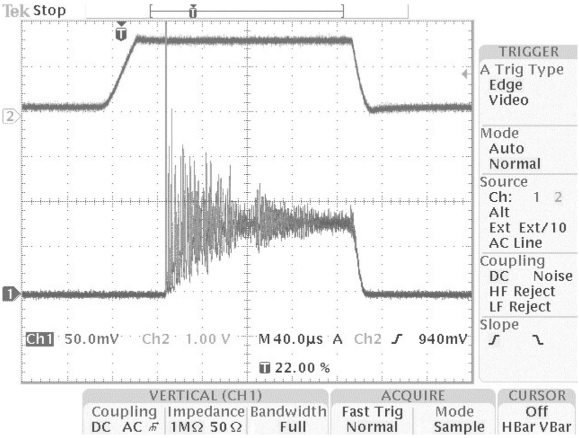

Fig. 13. Time course of the pumping diode current pulse (upper) and free generation (lower). Generation delay measured from the beginning of the current rise to the beginning of the generation pulse.

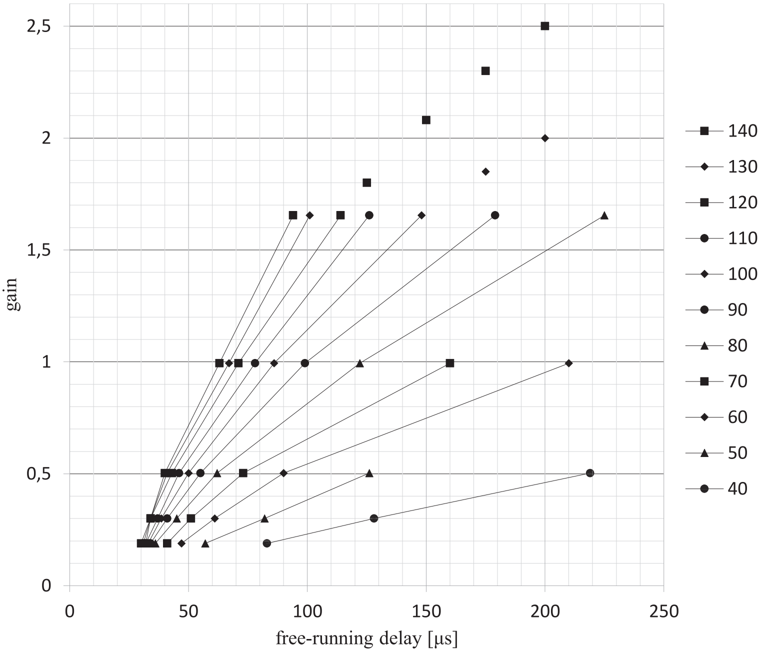

Fig. 14. Dynamics of gain increase when pumping with current pulse shaped as in Fig. 13 for pumping diode currents in range 40 A to 140 A. The measurement results are connected by broken lines, the isolated points are the result of extrapolation.

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4.2. *Mono impulse generation*

In accordance with the adopted methodology, the dependence of the output energy of mono-pulses and their duration was measured depending on the voltage surge with the opposite polarization supplied to the pre-polarized quarter-wave voltage of the Pockels cell. As a result, the voltage on the Pockels cell at the time of mono-impulse generation was equal to the difference in these voltages. These relationships are shown in Figs. 15 and 16. This approach resulted from two reasons. First, the reverse voltage value of the reverse polarity was set directly in the voltage generator. Second, with the increase in the value of this step voltage, the losses at the moment of generation decreased, *i.e.* the threshold exceeding increased. Therefore, the graphs presented (in particular in Fig. 16) correspond to the results of the calculations.

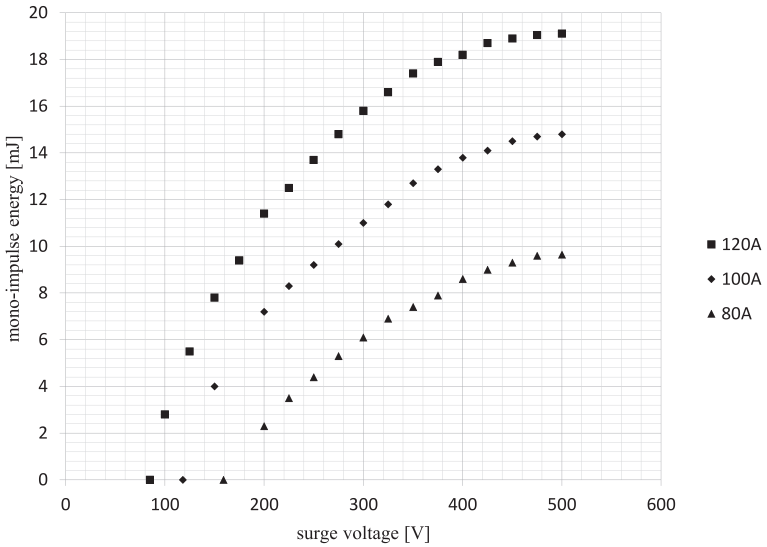

Fig. 15. The dependence of mono-impulse energy on the voltage surge (electro-optically controlled mirror transmittance which decreases with increasing voltage surge) applied to the quarter-wave voltage powered Pockels cell for several pumping diode currents. The threshold values are 159 V, 118 V and 85 V for the currents: 80, 100 and 120 A respectively.

Figure 15 shows the dependence of mono-impulse energy on this voltage surge, *i.e.* its effect on transmission losses while the losses decrease with the increase of the voltage surge. The threshold values correspond, as expected, to the complements (to a quarter-wave voltage of 800 V) of the threshold values of constant voltages on the Pockels cell shown in Fig. 9 and they are 159 V, 118 V and 85 V for pumping diode currents equal respectively 80, 100 and 120 A. The measurements were limited to a voltage surge of 500 V for fear of damage to the optical elements in the resonator, and, therefore, the optimal transmission values (Pockels cell voltage) for the mono-impulse generation were not precisely determined. We assume that they do not differ much in the diode current range tested.

Figure 16 shows the dependence of the mono-impulse duration on the same voltage surge for several pumping diode currents (initial gains of the laser medium). These graphs resemble the dependence of the pulse duration on exceeding the threshold at constant gain (see Fig. 3), however, the mapping of the abscissa in both cases is not linear but monotonic. A characteristic very wide plateau is visible which is confirmed by the statement about the dependence (with a fixed length of the resonator) of the mono-impulse duration only on the gain in a wide range of

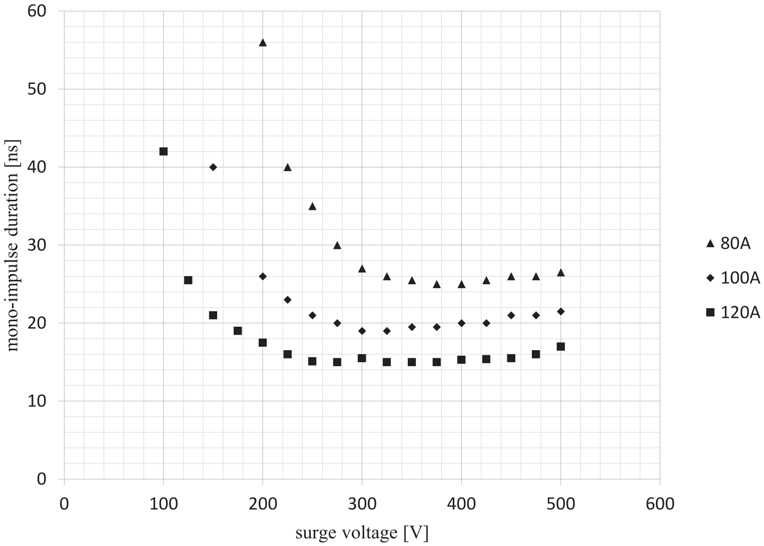

Fig. 16. The dependence of the mono-pulse duration on the surge in voltage applied to a quarter-wave Pockels cell powered for several pumping diode currents. In the plateau areas, the duration values are in range 14–16 ns, 18–20 ns and 24–26 ns for the pumping diode currents 120, 100 and 80 A respectively.

loss changes. It seems that this measurement of the pulse duration is the simplest and surest way to determine the gain value. Conversely, designing a laser with a set duration determines in the first place the value of the gain because the length of the resonator is related to the volume of the fundamental mode and is usually not arbitrary.

The gain value calculated on the basis of these measurements is 1.5 for 80 A, 1.98 for 100 A and 2.51 for 120 A respectively. These values are in very good agreement with the values obtained as a result of a rather tedious measurement of generation dynamics supplemented by the measurement of dissipative losses which can be found in Fig. 14. This compliance indicates the correctness of measurements and the advantage of measuring the duration of the pulse to determine gain.

The results of gain measurements and previously dissipative loss measurements lead to a positive conclusion. Namely, the estimated FOM of the tested laser is 33, 44 and 55 for diode currents 80, 100 and 120 A respectively. There are premises for practically acceptable generation of double pulses of equal energy and peak power (duration).

4.3. Double pulse generation

The generation of two mono-pulses with an interval of about 2 µs was demonstrated in a diode-pumped laser pulse with a duration of 200 µs. Pulse parameters were measured for diode currents 80, 100 and 120 A. Since the conditions for optimal coupling in the Q-switched mode for a single (reference) pulse depending on the energy (current) of the pump were not precisely defined, the conditions for generating the reference pulse were similar for all the pumping levels (voltage surge around 500 V). The energy of a single pulse was recorded, after which the voltage surge was reduced (transmission losses increased) so as to obtain a pulse with half the energy of the reference pulse. Then, a second voltage surge was introduced, which appeared after about

2 μs from the first one with the amplitude selected so that the measured energy of two pulses was equal to the energy of the reference pulse. The obtained pulse parameters and control voltage values are presented in the Table 1.

Table 1

Diode current [A]	**First pulse energy E1 [mJ]**	**Double pulses energy E1 + E2 [mJ]**	**Voltage surge1 [V]**	**Voltage surge2 [V]**	**Reference pulse duration τ_0 [ns]**	**First pulse duration τ_1 [ns]**	**Second pulse duration τ_2 [ns]**
80	4.8	9.7	240	540	24–26	30 ± 1	30 ± 1
100	7.5	15.2	200	480	18–20	22 ± 1	22 ± 1
120	9.4	18.2	140	350	14–16	19 ± 1	19 ± 1

It should be emphasized that if it were only possible to generate a voltage surge with the desired amplitude (the generator had some limitations), it was always possible to choose a set of two voltage surges to "divide" the reference pulse into two equal parts and the sum of energy of two pulses was equal to energy reference pulse with an accuracy of 0.1 mJ. As can be proved, this is only possible when switching transmission losses. The duration of double pulses was in each case the same, however, it was slightly shorter than expected based on the calculations. The explanation for this fact can be the quantitative inadequacy of the rate equation laser model used in the calculations, assuming a small net gain value which in the case of the examined laser did not take place. An example of the time course of the generation of two pulses including the voltage waveform on the Pockels cell is illustrated in Fig. 17, while the example of a reference pulse and one of the double pulses for 120 A current in Figs. 18 and 19.

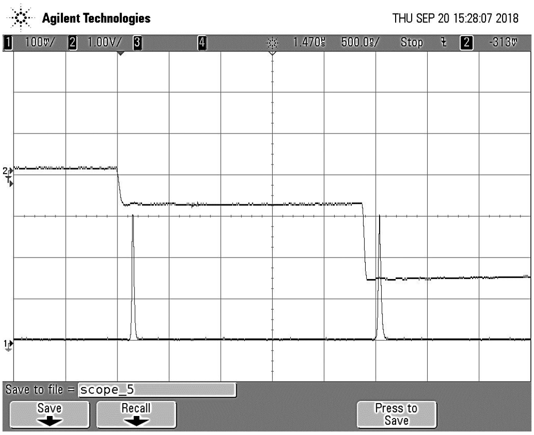

Fig. 17. Typical time course of double pulses generation. The same amplitudes are visible, which with the condition of equal energy means the generation of practically two identical pulses. Time base 0.5 μs/g, upper course – voltage on the Pockels cell.

Attention should be paid to the time structure of the pulses. Occurring irregular oscillations caused by the beating of longitudinal modes and the heterogeneity of gain and losses in the resonator significantly disturb the measurement of pulse parameters (especially duration) and are the reason for the increase in uncertainty of the measured quantities. In this situation, the exact

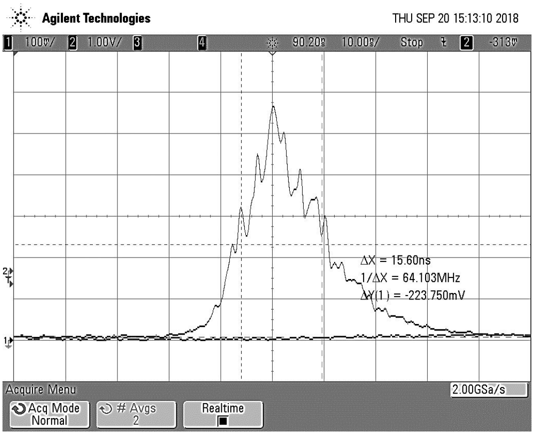

Fig. 18. Typical time course of reference pulse for 120 A diode current.
Time base 10 ns/g.

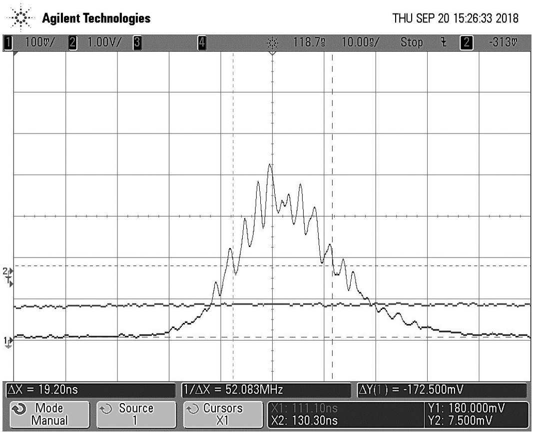

Fig. 19. Typical time course of one of the double pulses for 120 A diode current.
Time base 10 ns/g.

fulfilment of the condition $q = 45$ is not necessary and in the range of measurement error two identical pulses have always been obtained.

5. Summary

In conclusion, a method, in our opinion unique, of switching resonator losses has been demonstrated by changing the transmittance of the laser output mirror. This effect was achieved by using a properly controlled Pockels electro-optical switch in a system with the removal of quarter-wave voltage in the resonator with fully reflecting mirrors. Additionally, this realization took place in a diode pumped laser which, to our knowledge, is the first such demonstration.

The theoretical prediction of 100% efficiency of the generation of double pulses in relation to the reference pulse at the same energy accumulated in the active medium after the pumping is completed was confirmed.

Two identical pulses (of the same energies and duration) were obtained independently on the initial gain (energy accumulated).

A new approach to the analysis of the Q-switching process was demonstrated by examining the properties of this generation from the ratio of initial gain to internal losses of the resonator, which makes this analysis universal.

Work is currently underway to narrow down the generation spectrum to a single longitudinal mode which should significantly improve energy and time stability as well as improve the performance of the laser in application areas where high radiation coherence is important.

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