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Giant pulse generation for high exceeding of resonator losses

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In the paper the results of numerical analysis of giant pulse generation process in solid state laser systems with switched-off resonator losses are presented taking into account the influence of both the system amplification and the loss switch-off time. Also the conditions have been specified under which the averaged equations for energy transport may be considered sufficiently accurate for the description of the time-energy characteristics of the output pulses as well as the conditions under which the partial differential equations for the energy transport should be used to describe this type of generation.

1. Introduction

In the contemporary laser systems used to giant pulse generation the aim is to achieve the high surpass of the generation threshold. This allows to reach the extreme parameters of the laser pulse, i.e., the maximal power and energy of the pulse for its minimal duration. A number of works [1]–[5] indicate that in the solid-state lasers of high threshold exceeding (more than twice) the application of the classical Lengyel and Wagner [6] equations for the description of generation may lead to the results highly inconsistent with reality. This concerns especially the shape of the generated pulses and partially their energy parameters. For high threshold exceeding and rapidly switched-off resonator losses the existence, inside the resonator, of two mutually coupled streams of the photons propagating in opposite directions must be taken into account when the generation is described. The energy transport equations take the form of partial differential equations (1), [7]. Then we say that the stream model (SM) is applied to the generation description in place of the so-called averaged model (AM) following from the Lengyel and Wagner equations.

In this paper the numerical solution of the stream model equations for lasers with switched-off resonator losses (Q-switch) has been presented, the following factors being considered: amplification of the system and the Q-switching-off duration. The results obtained have been experimentally verified. Also the conditions under which the averaged model may be considered sufficiently accurate to describe the time-energy characteristics of the giant pulse and those under which in place of the averaged model the stream model should be employed, are specified.

2. Models of generation

2.1. Stream model (SM)

The scheme of a typical laser system to generate giant pulses is shown in Fig. 1.

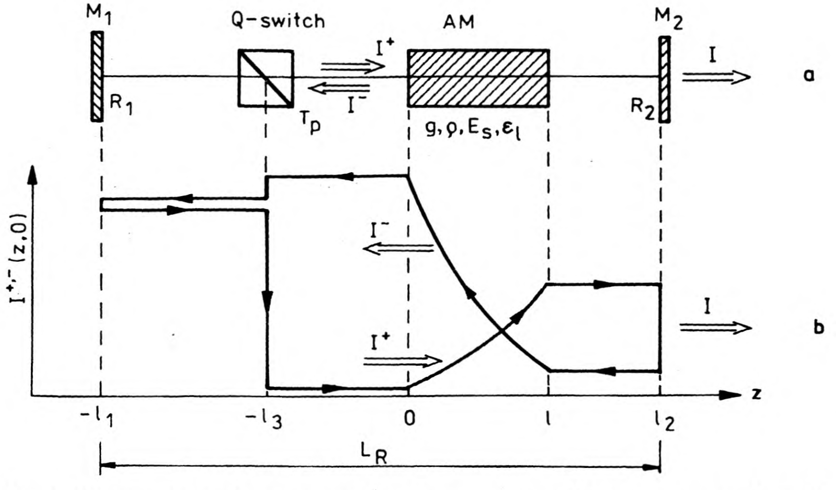

Fig. 1. Scheme of the laser system: M_1, M_2 – mirrors, AM – active medium (**a**), and initial photon flux distribution I^+, I^- inside the resonator (**b**)

The propagation of the photon flux I^+, I^- inside the resonator may be described by general equations of energy transport [7]

$$\pm\frac{\partial I^{+,-}(z,t)}{\partial z}+\frac{\partial I^{+,-}(z,t)}{v\cdot\partial t}=[k(z,t)-\varrho]\,I^{+,-}(z,t)+\varepsilon_l(z,t), \tag{1}$$

while the evolution of the energy accumulated in the active medium – by the equation [7]

$$\frac{\partial k(z,t)}{\partial t}=-\frac{k(z,t)}{E_s}[I^+(z,t)+I^-(z,t)] \tag{2}$$

where: $I^{+,-}$ – radiation intensity (photon flux), (in W/cm^2) in the positive "+" and negative "–" directions on the resonator axis,

ε_l – source factor (in W/cm^3), luminescence emitted from the unit volume element in the active medium,

v – light velocity (cm/s),

ϱ – linear losses coefficient (cm^{-1}),

k – amplification coefficient (cm^{-1}),
E_s – saturation energy density (J/cm^2).

In SM the photon flux emitted outside the resonator is described by the relation

$$I(t) = (1 - R_2)\, I^+(l_2, t) \tag{3}$$

where R_2 is the reflection coefficient for the outcoupling mirror.

The solution of Eqs. (1) and (2) is possible to be arrived at only by using numerical method, and requires determination of the respective limiting (boundary and initial) conditions [4]. The initial distribution of photon flux $I^+(z, 0)$, $I^-(z, 0)$ for the system shown in Fig. 1**a** is presented graphically in Fig. 1**b**.

2.2. Averaged model (AM)

Usually, the classical set of equations in the forms [6], [7]:

$$\frac{du(t)}{dt} = \frac{2l}{T_R}[g(t) - \varrho_s(t)]\, u(t), \tag{4}$$

$$\frac{dg(t)}{dt} = -\frac{vg(t)\, u(t)}{E_s} \tag{5}$$

where: $g(t) = \frac{1}{l}\int_0^l g(z, t)\, dz$,

$u(t) = \frac{1}{vl}\int_0^l [I^+(z, t) + I^-(z, t)]\, dz$ – average energy density (in J/cm^3) of radiation inside the resonator,

$T_R = \frac{2L_{opt}}{c}$ – time of the round trip of the photon flux in the resonator (s),

l – length of active medium (cm),
L_{opt} – optical length of resonator (cm),
$\varrho_s = \varrho + \frac{1}{2l}\ln\frac{1}{R_2 T_p}$ – coefficient of total losses in the resonator (cm^{-1}), taking into account the losses due to output mirror transmission and that of the Q-switch,
R_2 – reflection coefficient of the outcoupling mirror,
T_p – transmission of the Q-switch,

is employed for the description of giant pulse generation. In contrast to this the output pulse for the AM is determined by the relation

$$I(t) = \frac{v}{2}\ln R_2 \cdot u(t). \tag{6}$$

The ordinary differential equation (4) may be derived immediately from the set of partial differential equations (1), if in the active medium the uniformity of distributions of the following magnitudes:

– gain coefficient $g(z, t) \approx g(t)$, (7)

– radiation energy density $u(z, t) \approx u(t)$ (8)

is assumed.

Usually, these assumptions are not fulfilled in the laser systems generating the giant pulses, especially for intensive pumping (high exceeding of the generation threshold). It turns out that the gain of the system and the Q-switching-off have the essential influence on the difference between the results obtained by application of the SM and AM for generation description [5].

In the further part of this work, the influence of these parameters on the energy parameters of the output pulses and also the range of particular model application have been presented.

3. Numerical analysis of the generation process and the results of experimental examination

Based on the AM and SM models presented above the numerical analysis of laser generation with electrooptic Q-switch (Pockels cell-polarizer) has been carried out. The transmission of the switch is described by the relation

$$T_p(t) = T_0+(T_k-T_0)\cos^2\left[\frac{\pi}{2}\frac{U(t)}{U_{\lambda/4}}\right],$$
$$\frac{U(t)}{U_{\lambda/4}} = \begin{cases}1 & \text{for } t<0\\ \exp(-t/\tau_0) & \text{for } t\geqslant 0\end{cases} \tag{9}$$

where: T_0 – minimal transmission, T_k – maximal transmission, U – voltage at the Pockels cell electrodes, τ_0 – characteristic time of voltage drop, treated as a measure of the switch-off time.

The following values of parameters corresponding to typical laser generator with active $YAG{:}Nd^{+3}$ medium have been assumed in calculations:

- active medium: $l = 6$ cm, $g_0 = 0.2$–0.4 cm^{-1}, $\varrho = 0.01$ cm^{-1}, $v = 2\times10^{10}$ cm/s, $E_s = 0.2$ J/cm^2,
- mirrors: $R_1 = 1$, $R_1 = 0.1$,
- loss Q-switch: $T_0 = 0.005$, $T_k = 0.5$, $\tau_0 = 0$–25 ns,
- system geometry: $L_R = 80$ cm, $l_1 = 62$ cm, $l_2 = 18$ cm, $l_3 = 37$ cm.

The analysis of generation, taking into account the nonimmediate Q-switching-off, has been carried out both for SA and AM systems.

In both models the change of Q-switching-off duration was realized by changing the characteristic time of voltage decay on PC (τ_0).

The results obtained from the AM model confirmed that independently of the amplification values, even for the very short times of Q-switching-off ($\tau_0 < T_R$), the laser pulses were of classical shape close to Gaussian curve. On the other hand, the energy parameters of the output pulses, the immediancy criterion [8] being satisfied, do not practically depend on the Q-switching-off time but they depend mainly on the system amplification, i.e., the higher amplification of the system the

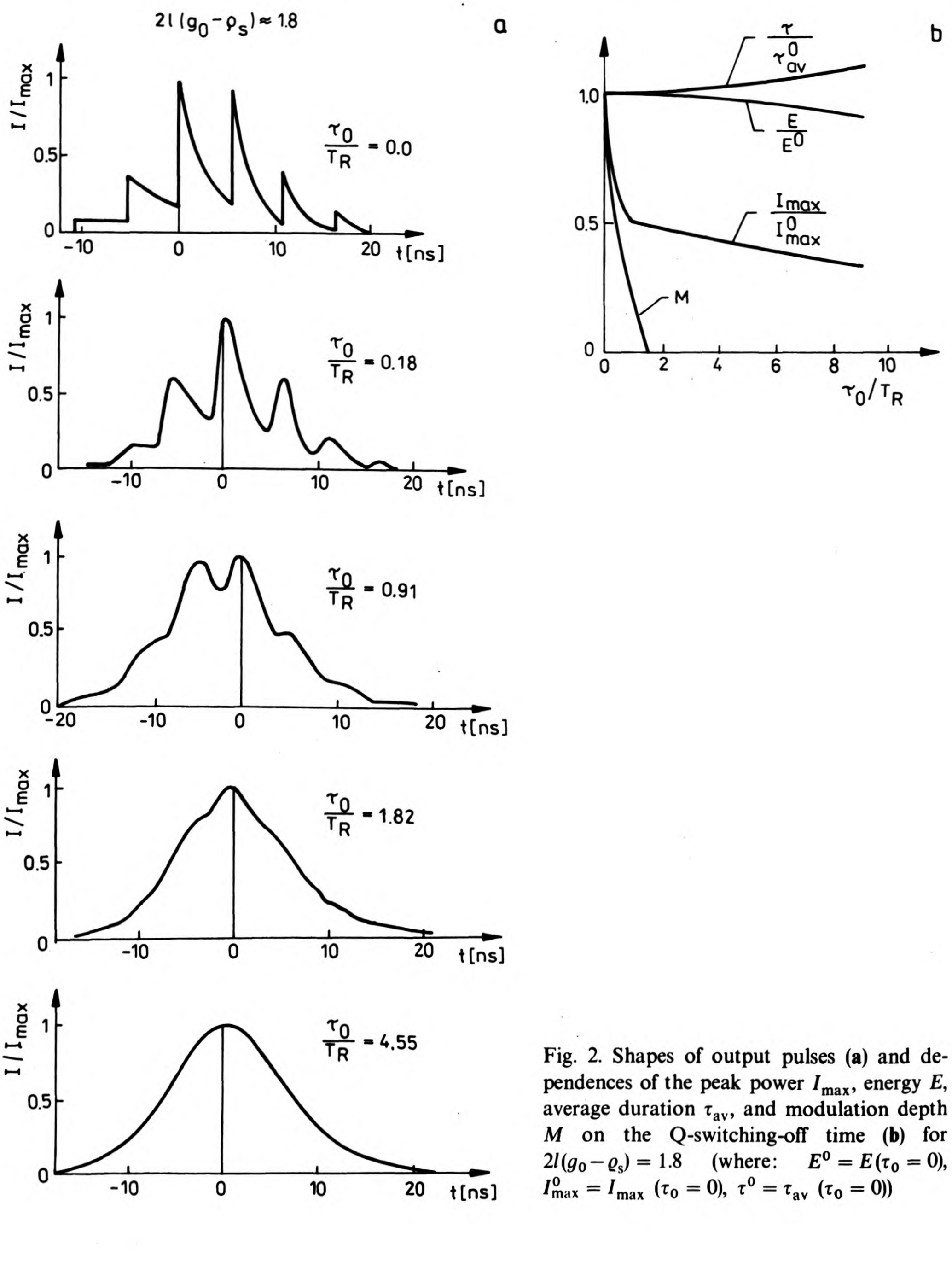

Fig. 2. Shapes of output pulses (**a**) and dependences of the peak power I_{max}, energy E, average duration τ_{av}, and modulation depth M on the Q-switching-off time (**b**) for $2l(g_0 - \varrho_s) = 1.8$ (where: $E^0 = E(\tau_0 = 0)$, $I^0_{max} = I_{max}(\tau_0 = 0)$, $\tau^0 = \tau_{av}(\tau_0 = 0)$)

higher both energy and the peak power, and simultaneously, the shorter pulse duration.

This is contradictory to the results obtained from the numerical analysis of the generation process based on SM model (Fig. 2), and this concerns the influence of the Q-switching-off time. It turns out that for short Q-switching-off times $0 \leqslant \tau_0 < 2T_R$ frequency overmodulation $(T_R)^{-1}$ appears in the shape of the laser pulse determined on the basis of the SM, while the higher the system gain the deeper the overmodulation (Fig. 3**a**) [2]. This is confirmed by the pulse oscillograms shown in Fig. 3**b** obtained in the YAG:Nd^{3+} laser test system. With the increase of the Q-switching-off time the time of oscillation growth increases while their amplitude and the top power decrease rapidly.

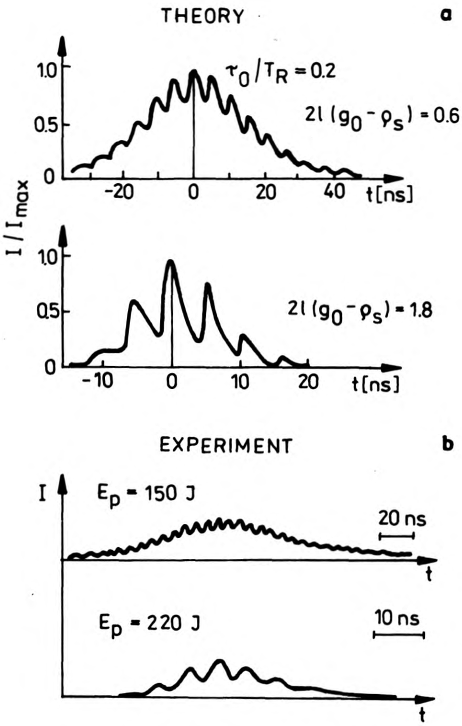

Fig. 3. Shapes of output pulses for different amplifications $2l(g_0 - \varrho_s)$ – **a**, and exciting energies E_p – **b**. The shown oscillograms have been obtained on a classical YAG:Nd^{3+} laser system containing electro-optic Q-switch composed of Pockels cell and polarizer

The changes in Q-switching-off time in this region have practically no influence on the energy and the average duration of pulse generation. For further elongation of the Q-switching-off time $\tau_0 > 2R_2$ a classical monoimpulse chaeracterized by a lack of overmodulation is generated in SM systems. Besides, an increase of switching-off time in this region (analogical to the AM case) leads to a slight drop of both the energy and the top power as well as to elongation of the pulse duration while its shape is preserved.

From the comparison of the energetic output pulse parameters determined on the basis of AM and SM, respectively, it follows that for the short times of Q-switching-off ($\tau_0 < 2T_R$) the pulse may differ significantly in both the shape and the top power, depending on the amplification of the system (Fig. 4). For the suitably long times of Q-switching-off ($\tau_0 > 2T_R$) these models even for high initial amplifications ($2l(g_0 - \varrho_s) > 1$) may be considered to be consistent as far as the description of the time-energy output pulse is concerned.

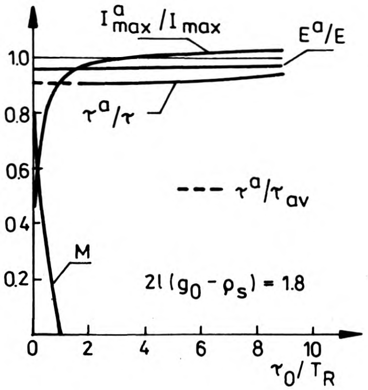

Fig. 4. Influence of Q-switching-off time on the differences of output pulse parameters determined on the basis of SM and AM for $2l(g_0 - \varrho_s) = 1.8$ (where parameter with index "a" denotes the value determined on the basis of the AM model)

4. Summary

The consistency of SM and AM approaches in the description of the giant pulse generation process in real laser systems with losses of lumped character being switched off, is decided about initial value of the amplification ($2l(g_0 - \varrho_s)$) and the Q-switching-off time τ_0, above all.

In Figure 5 the consistence region for SM and AM models is shown under assumption that these models are consistent as far as the description of the generation process is concerned if the differences concerning time behaviour of the power and such parameters of the output pulse as: energy and the duration do not exceed the conventional limit of 10% [5]. From the limits of applicability of SM and AM shown in Fig. 5 it follows that in the cases of generation at high

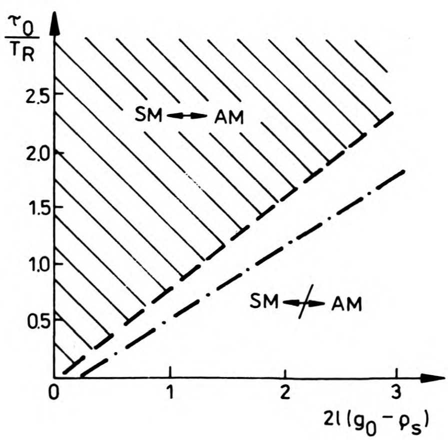

Fig. 5. Applicability limits for AM, for admissible value of error 10% (— — —), and 20% (—.—.—.)

threshold surpass $2l(g_0 - \varrho_s) > 1$, usually met in practice, a relatively slow Q-switching-off times ($\tau_0 \geqslant 2T_R$) is recommended. Then, the pulses generated are characterized by a monotonic front and back wavefronts while the energy parameters of these pulses may be estimated from the widely known analytic expressions [7]. In contrast to that, in the case of rapid Q-switching-off times ($\tau_0 < T_R$) the generated pulses are characterized by deep oscillations while the energy parameters of output pulses should be determined basing on SM.

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Моделирование процесса генерации в лазерах с исключением потерь резонатора

На основе представленных в работе струйной и усредненной моделей генерации проведен численный анализ процесса генерации гигантского лазерного импульса. Полученные результаты и принятый в работе критерий согласия позволили определить условия, исполнение которых разрешает считать широко применяемую усредненную модель достаточно точной для описания временно-энергетических характеристик гигантского импульса. Эти результаты дают тоже информацию об условиях применяемости струйной модели. Проведенный анализ показывает, что на применяемость усредненной модели основное влияние имеют прежде всего: время исключения потерь и увовень усиления излучения во время полного обхода резонатора.