*Quantum Electronics* **32** (3) 202–204 (2002)

PACS numbers: 42.55.Rz; 42.60.Gd; 42.60.Lh
DOI: 10.1070/QE2002v032n03ABEH002160

# Efficiency of a passively *Q*-switched erbium glass laser

V.N.Bykov, A.G.Sadovoi

***Abstract*. The methods for optimising the efficiency of low-threshold flashlamp-pumped passively *Q*-switched erbium glass lasers are studied. The optimisation is performed by varying the degree of filling an active element by the field of a lowest transverse mode.**

***Keywords***: *erbium glass laser, passive Q-switching, lowest transverse cavity mode.*

The passive *Q*-switching of erbium glass lasers attracts great recent interest. This is mainly explained by the possibility of wide applications of such lasers in eye-safe laser ranging, where the requirement of the exact timing of a laser pulse is not important, while the absence of the external control of a *Q* switch substantially simplifies the device design.

In most papers devoted to passive *Q* switches for erbium glass lasers, the physical parameters of various materials used in *Q* switches were studied, as well as the obtaining of *Q*-switching with the help of these materials. At the same time, the optimisation of the energy parameters of passively *Q*-switched lasers was not investigated [1–4].

In this paper, we study the efficiency of a passive *Q* switch in a low-threshold flashlamp-pumped erbium glass laser.

To analyse the factors determining the energy of a single pulse, we consider a simplified mathematical model of a laser containing a three-level active medium and a two-level intracavity passive *Q* switch. We assume that a change in the pump intensity and the spontaneous decay of populations in the active medium and the *Q*-switch medium during generation of a single pulse can be neglected. Then, by solving a system of kinetic equations for this model, we can represent the single-pulse energy in the form

$$E = h\nu \ln(R^{-1}) \frac{A_{\mathrm{g}}}{4\sigma_{\mathrm{g}}} \varphi(x, \beta), \tag{1}$$

where $h\nu$ is the energy of a laser photon; $R$ is the reflectivity of the output cavity of the laser cavity; $A_{\mathrm{g}}$ is the area of the cross section of the radiation field in the active medium; $\sigma_{\mathrm{g}}$ is the emission cross section for the active medium; $x$ is the ratio of the threshold inversion in the active medium at the instant of the generation onset to the threshold inversion during a complete bleaching of the *Q* switch;

$$\beta = \frac{\sigma_{\mathrm{a}}}{\sigma_{\mathrm{g}}} \frac{A_{\mathrm{g}}}{A_{\mathrm{a}}}; \tag{2}$$

$\varphi(x, \beta)$ is the function, which is determined from the equation

$$x = \frac{\beta\varphi + \exp(-\beta\varphi) - 1}{\beta[1 - \exp(-\varphi)] + \exp(-\beta\varphi) - 1} \quad (\varphi \geqslant 0, \ \beta > 1); \tag{3}$$

$\sigma_{\mathrm{a}}$ is the absorption cross section of the *Q* switch; and $A_{\mathrm{a}}$ is the area of the cross section of the field in the *Q* switch.

Fig. 1 shows the graphical solution of equation (3). The dashed curve corresponds to an ideal instantaneously switching *Q* switch ($\beta \to \infty$). The minimal value of $x$ ($x_{\min}$), for which $\varphi = 0$ and, therefore, a single pulse cannot be generated, can be obtained analytically by calculating the limit of expression (3) for $\varphi \to 0$:

$$x_{\min} = \frac{1}{1 - 1/\beta}. \tag{4}$$

One can see from Fig. 1 that the value of $\varphi$ increases with increasing both $x$ and $\beta$. Note that the required pump energy increases with increasing $x$ because of a low initial transmission of the *Q* switch. The value of $\beta$ can be

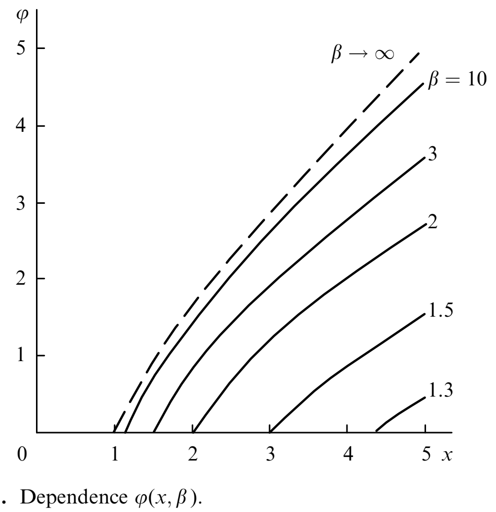

**Figure 1.** Dependence $\varphi(x, \beta)$.

**V.N.Bykov, A.G.Sadovoi** M.F.Stel'makh Polyus Research & Development Institute, ul. Vvedenskogo 3, 117342 Moscow, Russia

Received 30 January 2002
*Kvantovaya Elektronika* **32** (3) 202–204 (2002)
Translated by M.N.Sapozhnikov

increased [see (2)] by choosing an appropriate material for the $Q$ switch for a particular active medium ($\sigma_a/\sigma_g$) and (or) by employing a cavity with the required ratio $A_g/A_a$.

The single-pulse energy also depends on the reflectivity $R$ of the output cavity mirror. The value of $\ln(1/R)$ increases with increasing the mirror transmission, but $x$ and, hence, $\varphi$ simultaneously decrease.

It follows from expression (1) that the single-pulse energy $E$ is proportional to the cross-section area $A_g$ of the radiation field in the active medium. It seems, therefore, at first glance that the energy efficiency of the laser should be maximum in the case of multimode generation, when the active element is filled with the radiation field most completely. However, in practice the following picture is observed.

When the lasing threshold is achieved, a single pulse appears whose energy remains almost constant despite a further increase in the pump intensity. The delay time of the single pulse relative to the pump pulse decreases with the pump intensity. In this case, the transverse size of the radiation field in the active medium corresponds to the size of the lowest transverse mode of the cavity rather than to active-element aperture. A further increase in the pump intensity results in the generation of secondary single pulses, which appear either due to the repeated bleachings of the $Q$ switch at the same generation channel (in this case, the energies of single pulses are comparable) or due to the bleaching of the $Q$ switch at a large aperture (in this case, depending on the filling of the active element by the field of highest transverse modes involved in lasing, the energies of secondary single pulses can be substantially greater than the energy of the first pulse).

Leaving aside the question about the possibility of synchronisation of pulses from different modes in order to obtain a powerful single pulse, we increased the single-pulse energy by efficiently filling the active medium with the radiation field of the lowest transverse mode.

We studied experimentally the energy characteristics of a laser shown schematically in Fig. 2. The active medium was an LGS-KhM chromium–ytterbium–erbium phosphate glass [5] from which three active elements were manufactured of length 35 mm and diameters 1.7, 2.0, and 2.5 mm with the ends having antireflection coatings. The active elements were pumped by an INP-2/35 flashlamp placed inside a hollow cylindrical reflector with the elliptical cross section and silver mirror coating. The discharge circuit of a power supply provided a bell-shaped pump pulse with a FWHM duration of 0.9 ms.

The laser radiation was modulated with a passive $Q$ switch made of a $Co^{2+}:LaMgAl_{11}O_{19}$ crystal with ends having antireflection coatings (Polyus Research & Development Institute). When the electric-field strength vector of the light-wave field was parallel to the $c$ axis of the crystal [2], the initial transmission of the $Q$ switch at the lasing wavelength was of about 88 %. Such polarisation was obtained with the help of a plane–parallel silica plate, which was oriented at the Brewster angle to the laser-beam axis (Brewster plate).

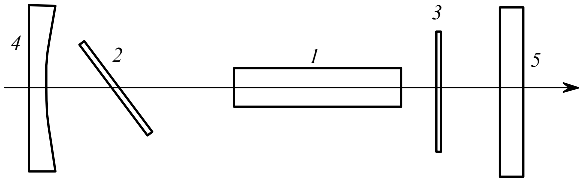

**Figure 2.** Optical scheme of the model laser: (*1*) active element; (*2*) Brewster plate; (*3*) passive $Q$ switch; (*4*) highly reflecting mirror; (*5*) output mirror.

The cavity of length 54 cm was formed by a plane output mirror with the transmission $\tau \approx 14\,\%$ and a concave spherical highly reflecting mirror whose radius of curvature $r$ was varied in experiments and was 0.6, 07, 1.0, 1.5, 2.0, 2.9, and 6.3 m, providing the variation in the transverse size of the field in a broad range within the stability region. The active element and $Q$ switch were placed near the plane mirror of the cavity. This eliminated the dependence of $\beta$ on the ratio $A_g/A_a$, which was retained close to unity despite the change in the curvature of the highly reflecting mirror. Because the ratio $\sigma_a/\sigma_g$ was $\simeq 20$ in our experiments, i.e., $\beta$ was sufficiently large, no additional focusing of the filed in the $Q$ switch was required.

Each of the three active elements was tested in several stable resonators with different calculated size of the mode in the element. The single-pulse energy and the pump energy were measured. The temporal profile of the single pulse was observed with a fast LFD-2 photodiode and a digital oscilloscope.

Fig. 3 shows the dependences of the single-pulse energy $E$ on the minimal pump energy $E_p$ at which the pulse appears.

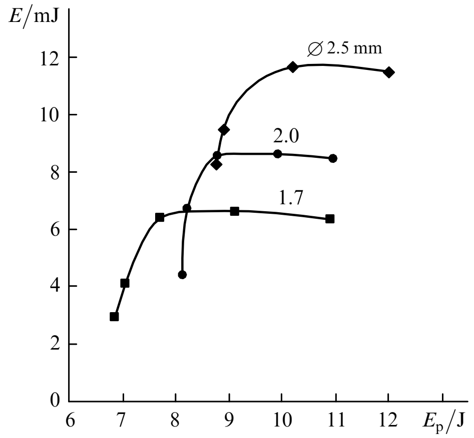

**Figure 3.** Dependences of the single-pulse energy on the minimal pump energy for active elements of different diameters.

Note that these dependences are not usual energy dependences because each point in the plot corresponds to a resonator of a certain configuration. An increase in the field size in the active element results in the increase in the single-pulse energy, which is accompanied by the increase in the pump intensity. One can see from Fig. 3 that the type of the dependence of $E$ on $E_p$ is the same for any diameter of the active element. Upon filling of the active-element aperture by the single-pulse radiation field, the increase in the output energy slows down and the dependence $E(E_p)$ 'saturates', which is mainly explained by a finite size of the active-element aperture. To obtain the greater output energy, the active element of a large diameter is required. One can see from Fig. 3 that the efficiency $\eta = E/E_p$ for the active element of any diameter depends on the filling of its aperture by the field.

Fig. 4 shows the dependences of the efficiency on the factor of filling $\kappa$ of the active-element aperture by the field of the lowest transverse mode. Here, $\kappa$ is the ratio of the calculated area of the cross section of the mode at the 1/e intensity level in the active element to the cross-section area of the latter.

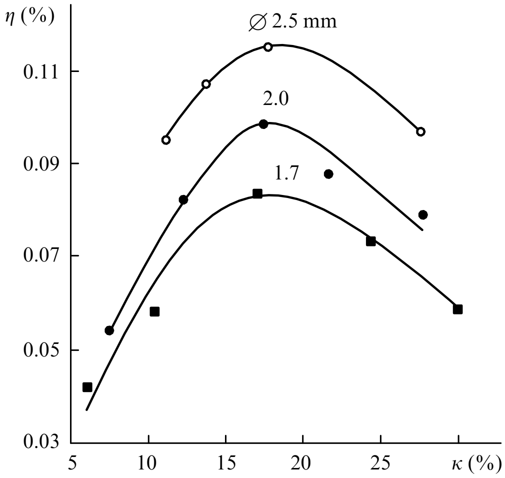

**Figure 4.** Dependences of the lasing efficiency on the factor of filling of the active-element aperture by the field of the lowest transverse mode for active elements of different diameters.

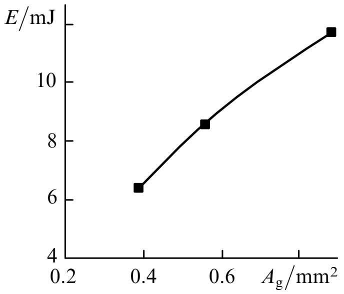

**Figure 5.** Dependence of the single-pulse energy on the cross section of the radiation field in the active element for the maximum lasing efficiency.

One can see from the curves in Fig. 4 that the maximum efficiency is achieved for $\kappa \approx 18\,\%$ and increases with the active-element diameter. The dependence of the single-pulse energy on the cross section $A_g$ of the radiation field in the active medium for the maximal efficiency is shown in Fig. 5.

One can see that the experimental dependence $E(A_g)$ is close to a linear one and well agrees with expression (1), from which it follows that the single-pulse energy is directly proportional to the cross section of the radiation field in the active medium (for $A_g/A_a = \mathrm{const}$).

When a more transparent output mirror was used in the resonator ($\tau \approx 21\,\%$), the lasing efficiency decreased. Thus, for example, the lasing efficiency in the active element of diameter 2.5 mm decreased from 0.115 % (Fig. 4) to 0.09 % in this case. Note also that the maximum energy of a single pulse increased from 11.7 mJ (Fig. 3) to 12.9 mJ when the output mirror with $\tau \approx 21\,\%$ was used, which was accompanied, however, by a further decrease in the lasing efficiency down to 0.084 %.

The use of output mirrors with the higher reflectivity ($\tau \leqslant 11\,\%$) can lead to the radiation damage of the optical elements of the laser.

Our study has shown that the effect of various factors on the single-pulse energy has a complicated mutually contradictory character. The optimisation of all the parameters should be performed in each particular case. Nevertheless, we can recommend the greater filling of the active element by the radiation field of the lowest transverse mode (up to the beginning of a strong increase in the radiation losses on the active-element aperture) as one of the possible ways for increasing the single-pulse energy and efficiency of low-threshold lasers studied in this paper.

The energy parameters obtained in this paper are of practical interest, in our opinion, for example, for applications in eye-safe laser ranging.

***Acknowledgements.*** The authors thank A.M.Onishchenko for useful discussions of the problem during the study, V.A.Pashkov for useful discussion of the results, A.V.Shestakov for placing the *Q* switches at our disposal, and P.I.Sadovskii for placing the active elements at our disposal.

## References

1. Galagan B.I., Godovikov E.A., Denker B.I., Meil'man M.L., Osiko V.V., Sverchko S.E. *Kvantovaya Elektron.*, **26**, 189 (1999) [*Quantum Electron.*, **29**, 189 (1999)].
2. Yumashev K.V., Denisov I.A., Posnov N.N., Mikhailov V.P., Moncorge R., Vivien D., Ferrand B., Guyot Y. *J. Opt. Soc. Am.*, **16**, 2189 (1999).
3. Wu R., Rhonehouse D., Myers M., Hamlin S., Myers J., Jiang Y. *OSA Proc. on Advanced Solid State Lasers* (Washington: Optical Society of America, 1995) Vol. 24, p. 440.
4. Yumashev K.V. *Kvantovaya Elektron.*, **30**, 37 (2000) [*Quantum Electron.*, **30**, 37 (2000)].
5. Izyneev A.A., Sadovskii P.I. *Kvantovaya Elektron.*, **24**, 791 (1997) [*Quantum Electron.*, **27**, 771 (1997)].