CHARACTERISTICS OF A Q-SWITCHED RUBY LASER

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A Q-switched laser using a rotating totally reflecting prism has been constructed. A power of 50 megawatts in a 40-50 nanosecond pulse width has been obtained. Theoretical expressions for obtaining maximal values of the peak power and radiated energy from the laser are presented. The negative absorption coefficient for ruby with antireflecting coatings at the ends (length 115 mm, diameter 12 mm) is determined. It is shown that in order to obtain maximal energies (in the laser pulse) mirrors with high transmittance should be used and that the mirror should operate as a mode selector. The radiation spectrum is investigated with a Fabry-Perot interferometer. Generation of a single spectral component was observed when a 3 mm thick mirror was employed.

WE have investigated the properties of a Q-switched ruby laser with an output power up to 50 megawatts.

A ruby rod 115 mm long, 12 mm in diameter and with anti-reflection coated ends was used as the active element in the laser. The ruby was water cooled. As a Q-switching device, a totally reflecting prism was used and was rotated at 425 rps. A plane parallel plate with multi-layer dielectric coating deposited chemically was used as the partially transparent mirror. The coefficient of reflection of this mirror was varied between 70 and 16% (the latter being the reflectivity of the plate without coatings). Two separate pulses were produced under strong excitation.

The operation of such a laser has already been considered theoretically by a number of authors[1-5]. The basic properties of a Q-switched laser can be obtained from theoretical calculations given in [1] for the case of instantaneous Q-switching. Although such a treatment is valid only under certain restrictions, it allows one to obtain analytical expressions which may easily be compared with experiment. The calculations made in [3-5] lead to the same expressions. One exception is the paper in which account is taken of the finite switching time [2] and in which it is shown that in this case it is possible to generate more than one pulse.

In what follows we will be interested only in conditions under which a single pulse is generated. Using the formulas given in [1] we can derive the conditions for obtaining the maximum energy and peak power for given internal losses. As usual we call the difference between the number of particles in the upper level and in the lower level the number of active particles.

Let $n(t)$ be the density of active particles, $n(0) = n_0$, $x = n(t)/n_0$; whence it is clear that $x(t) \leq 1$. The laser field density vanishes for two values of x, which may be found from the equation

$$1 - x + (\alpha_0/\alpha_b)\ln x = 0, \quad (1)$$

where α_b is the absolute magnitude of the negative absorption coefficient, and α_0 is the magnitude of the absorption coefficient describing all losses. One of the roots of this equation is $x' = 1$; the second root x'' depends on α_0/α_b.

Knowing x' and x'' one may find the total energy emitted per unit volume of the crystal during the duration of laser action, namely

$$W = {}^1/_2 n_0 h\nu(x' - x''). \quad (2)$$

Part of this energy goes into emission and the rest into the internal losses. Let the losses connected with the output radiation be described by an effective absorption coefficient α_0', and let the internal losses be described by a coefficient α_0''. We then have

$$\alpha_0 = \alpha_0' + \alpha_0''. \quad (3)$$

According to (1) and (3) the energy radiated will be

$$W' = \frac{\alpha_0'}{\alpha_0' + \alpha_0''}W = \frac{\alpha_0'}{2(\alpha_0' + \alpha_0'')}h\nu n_0(x' - x''). \quad (4)$$

Since α_0'' does not vary when α_0' does, we may find the maximum radiated energy by varying α_0', that is by varying the mirror transmission. From (4) and (1), the maximum radiated energy is obtained when $x'' = \alpha_0''/\alpha_b$. Putting this value of x'' in (1) we obtain an equation determining the optimum value of α_0' as a function of α_0''. The equation is

$$1 - \frac{\alpha_0''}{\alpha_b} + \frac{\alpha_0' + \alpha_0''}{\alpha_b} \ln \frac{\alpha_0''}{\alpha_b} = 0. \quad (5)$$

Knowing α_0' we may obtain the optimum reflectivity from the formula

$$k = \exp(-2\alpha_0' l). \quad (6)$$

Let $\alpha_0'' = 0.025\ \mathrm{cm}^{-1}$ and let $\alpha_b = 0.25\ \mathrm{cm}^{-1}$. Then according to equation (5) $\alpha_0' = 0.29\ \alpha_b$ and the optimum reflectivity for the mirror with $2l = 23$ cm. is $k = e^{-1.67}$, i.e. about 19%. It follows from this calculation that for α_b approximately 0.2 to 0.3 cm^{-1} one must choose mirrors with large transmissions, provided the internal losses are not extremely large.

We are also interested in the condition for obtaining maximum peak emitted power. The peak radiated power is determined by differentiating the maximum energy density ρ_{max} with respect to the quantity α_0'. According to [1] we have

$$\rho_{max} = \frac{h\nu n_0}{2}\left(1 - \frac{\alpha_0}{\alpha_b} + \frac{\alpha_0}{\alpha_b} \ln \frac{\alpha_0}{\alpha_b}\right). \quad (7)$$

The peak power is maximized when

$$\partial(\alpha_0' \rho_{max}) / \partial \alpha_0' = 0, \quad (8)$$

i.e.,

$$1 - \frac{\alpha_0' + \alpha_0''}{\alpha_b} + \frac{2\alpha_0' + \alpha_0''}{\alpha_b} \ln \frac{\alpha_0' + \alpha_0''}{\alpha_b} = 0. \quad (9)$$

If the internal losses may be neglected, then the optimum value of α_0' is $0.285\,\alpha_b$.

It is clear from (5) and (9) that the conditions for obtaining maximum energy and maximum peak power are different. For example, for $\alpha_b = 0.25\ \mathrm{cm}^{-1}$ and $\alpha_0'' = 0.025\ \mathrm{cm}^{-1}$, the optimum value of α_0' is $0.27\ \alpha_b$. The duration of the pulse (between half-power points) is, according to [1], given by

$$\tau = (2-4)\frac{n_0 h\nu (x_1 - x_2)}{\alpha_0 v \rho_{max}}, \quad (10)$$

where v is the velocity of light, and x_1 and x_2 are the roots of the equation

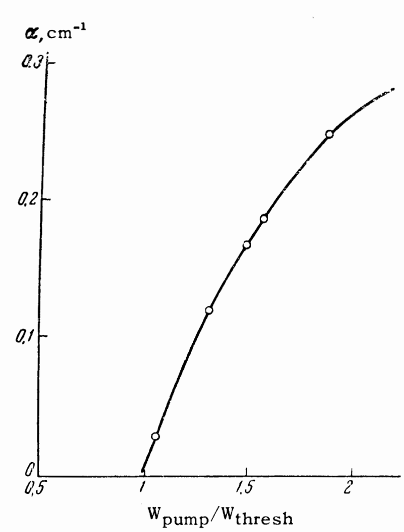
$$x - \frac{\alpha_0}{\alpha_b} \ln x = \frac{1}{2}\left(1 + \frac{\alpha_0}{\alpha_b} - \frac{\alpha_0}{\alpha_b} \ln \frac{\alpha_0}{\alpha_b}\right).$$

The pulse length is determined by all losses, and its minimum duration depends only on the ratio α_0/α_b.

It is clear from what has been said above that the optimal values of the energy, power and pulse length occur for different values of the mirror transmission and that the optimum transmission of the mirror depends on the inversion obtainable, i.e., on α_b and on the magnitude of the internal losses. Unfortunately detailed comparison of theory with experiment is made difficult by the fact that the ruby rod is excited nonuniformly. This fact has already been established [6].

In order to know the value of α_b obtainable in our case, measurements were made of the dependence of the magnitude of α_b on pump energy for a ruby in an elliptical cavity excited by a IFE-5000 flash lamp. The form of this dependence (cf. the Figure) agrees with similar data obtained in [7]. The magnitude of α_b was determined from the laser threshold for various reflectivities of the cavity mirrors when the laser was operated in the normal regime. It turned out that for antireflection coated ends of the ruby, a value of α_b greater than 0.25 cm^{-1} was attainable. This value of α_b refers only to the central part of the cross-section of the crystal. The value of α_b may be considerably smaller in the peripheral regions of the cross section. In the Q-switched regime we obtained the maximum energy per pulse when the reflector was made from K-8 glass without dielectric coatings. This corresponds to a reflectivity of 16% since laser action takes place at wavelengths for which the reflections from the near and far surfaces of the plate are in phase. This experiment supports the conclusions of the theory concerning the necessity of using a mirror with a large transmission if α_b is sufficiently large and the internal losses are small.

This is of course also interest in investigating the spectral properties of the output of such a laser. To do this we used a Fabry-Perot inter-



ferometer (R = 86%, plate separation 3 or 2 mm). The spectrum consisted of a set of relatively narrow lines, the number of which varied from 1 to 7 and was not always the same for similar operating conditions of the laser. The width of the individual components for small pump powers was determined by the instrumental width for t = 3 mm (0.08 cm^{-1}). With increasing pump powers, several of the components broadened considerably and became as wide as 0.15 cm^{-1}. The total width of the spectrum for small pump powers was 1.5 cm^{-1}. For larger pump powers the width of the spectrum decreased and was on the average about 0.6 cm^{-1}.

In working with the reflecting plate of K-8 glass of 12.5 mm thickness several spectral components were observed having a constant separation between them of 0.26 cm^{-1}. As already pointed out this effect can be explained by the fact that the reflecting plate in this case acts as a mode selector for the axial cavity modes. Only those cavity modes are excited for which the thickness of the reflector equals an integral number of half-wavelengths. In this case the separation between nearest laser modes must satisfy the requirement

$$\Delta\nu = {}^1/_2\, nl \ [cm^{-1}],$$

where n is the index of refraction of the plate material and l is its thickness. If one uses a plate with a thickness less than 3 mm, only a single spectral component is excited; its width is of the order of 0.1 cm^{-1} and exhibits a very high degree of parallelism. Probably this is one of the best methods for obtaining giant pulses of narrow spectral width at room temperature [1)].

When the beam of a giant pulse is focused by a lens in air one observes a phenomenon analogous to electrical breakdown. The threshold value of the pulse power at which the spark appears depends on the parameters of the focusing lens and in our experiments was about 5-10 megawatts [9]. This agrees with data given in [10]. The dimensions of the luminous volume increase with increasing pulse power; in certain cases, for very high pulse powers, we observed breakdown sparks in several luminous regions. In these cases we used a simple plate without coatings as a mirror; this is very convenient since, in contrast even to very good mirrors, the plate does not burn up.

[1)] An article has recently appeared describing an analogous mode selector for a ruby laser operating in the usual regime [8].

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