A FREQUENCY RUBY LASER USING ULTRAHIGH-PRESSURE MERCURY CAPILLARY LAMPS

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A number of authors have indicated the possibility of using mercury pumping lamps for the construction of ruby lasers with a high repetition frequency [1, 2]. A new and efficient method of working with ultra-high-pressure mercury pumping lamps was studied in [3]; this became known as the mixed method, in which a voltage pulse was applied to a continuously emitting lamp. This arrangement is analogous to that in which the duty (pilot) arcs of xenon lamps operate [4, 5]. The use of the mixed procedure in the operation of mercury capillary lamps should clearly enable us to penetrate into the realm of higher laser repetition frequencies. In addition to this the thermal shock experienced by the lamp bulb is much less severe under these circumstances, and the bulb may fairly be expected to last longer. The application of the mixed method requires the solution of a number of practical problems. This paper is devoted to finding such a solution.

Three main features characterize the mixed pumping procedure. First, the threshold level and output power of the generator are determined not only by the capacitor discharge energy but also by the power of the 50-Hz supply source. Second, the operation of the generator takes place under conditions in which a strong thermal lens exists in the resonator. Third, in view of the small transverse dimensions of the discharge pinch of the lamp, the distribution of the pumping action in the active element is characterized by a high degree of nonuniformity. These characteristics change the energy relationships in the generator, determine the phase of the reference voltage corresponding to the instant of applying the pulse, and make special demands on the choice of the Q-modulation system; they also affect the output parameters of the laser radiation. Let us consider the first two of these relationships in more detail.

Direct measurements show that the intensity of the light emitted by the lamp for a 50-Hz supply source varies almost in proportion to the instantaneous electrical power. Since the longitudinal relaxation time $T_1 \approx 3.4$ msec of the working levels of the ruby is comparable with the rise and fall time of the exciting light ($T_{\text{exc}} = 5$ msec), the relationship between the populations of the levels $n_1$, $n_2$ and the electric power is not quasistationary. The maximum difference in the populations $\Delta n_1 = n_2(n_1)$ is reached at instant $t^*$ differing from the instant of the pumping maximum. A knowledge of $t^*$ is important, since it is at the instant $t^*$ that the voltage of the discharge capacitor should be applied to the lamp.

Let $y(t)$ be the relative difference in the populations of the metastable and ground levels. We assume that the intensity of the exciting light equals

$$I(t) = \alpha (1 - \cos \Omega t),$$

where $\alpha$ is the average (over the period) of $\alpha(t)$; $\Omega = 2\pi \cdot 100$ is the angular frequency. We shall neglect the splitting of the metastable level and the induced transitions (the latter is permissible for small transverse dimensions of the active element, which is an essential condition in the present case from the cooling point of view). By solving the balance equation [6] in the steady-state condition we then have

$$y(t) = 1 - 2 \left( \frac{\alpha}{\Omega} \right)^{\alpha} \left[ \frac{I_h(a/p)}{1 + a/p} + \sum_{k=1}^{\infty} I_h(a/p) \frac{2 \cos k\Omega t - \cos k\Omega t}{(1 + a/p)^2 + \frac{k \Omega^2}{p^2}} \right],$$


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Fig. 1. Threshold generation energy as a function of the base of the resonator. Length of the ruby element 32 mm, diameter 2.8 mm.

Fig. 2. Threshold generation energy as a function of the (angular) distuning of one of the resonator mirrors. Resonator base $L_b = 17.5$ cm.

where $p = 1/T_1$ and $I_k(z)$ are Bessel functions of a purely imaginary argument

$$\psi_n = \arctg \frac{k\Omega}{p + \alpha}.$$  

(3)

Usually in the mixed arrangement $\alpha/p \approx 0.2-0.4$. For such values of $\alpha/p$ it is sufficient to confine attention to the first two terms in the Fourier expansion of $n_2$, and to expand $I_0$ and $I_1$ as Taylor series in $\alpha/p$. For the amplitudes $A_k$ we then have

$$A_0 = \frac{\alpha/p}{1 + \alpha/p} \left[ 1 - \frac{0.5 \alpha/p}{(1 + \alpha/p)^2 + (\Omega/p)^2} \right],$$

$$A_1 = \frac{\alpha/p}{1 + \alpha/p} \frac{1}{\sqrt{(1 + \alpha/p)^2 + (\Omega/p)^2}}.$$  

(4)

The sum $A_0 + A_1$ gives the maximum value of $n_2/n_1$ while $\psi_1$ is the phase shift between the maximum values of the pumping and luminescence. For $\alpha/p \approx 0.4$ the shift is 3.2 msec.

The preceding relationships determine the instant of introducing the pumping pulse voltage $t^*$ and the initial difference in the populations $y_0$ at this instant. In describing the pulsed pumping action, relaxation from the metastable level may be neglected, since the pulse length is shorter than 200-300 $\mu$sec. Let $W$ be the pumping energy, $y$ the value corresponding to $W$, and $\alpha/p$ the relative population difference, while $W_{\text{thr}}$ is the threshold energy for the specified $\alpha/p$. We may then readily show that

$$y = 1 - \frac{(1 - y_{\text{thr}})^n}{(1 - y_{\text{thr}})^n - 1},$$

(5)

where $n = W/W_{\text{thr}}$. The quantity $n$ does not determine the true excess over the threshold, since allowance must still be made for pumping by the reference (steady) voltage. The true excess over the threshold $N$ is related to $n$, $y_0$, and $y_{\text{thr}}$ by the equation

$$N = 1 + (n - 1) \frac{\ln(1 - y_0)/(1 - y_{\text{thr}})}{\ln 2/(1 - y_{\text{thr}})}.$$  

(6)

We may also formulate one further equation establishing a link between the action of the pulsed and continuous generation. If $P_{\text{thr}}$ is the threshold power of continuous generation, then

$$P_{\text{thr}} = P + \frac{W_{\text{thr}}}{1.15 \xi T_1},$$  

(7)
Fig. 3. Block diagram of a single-pulse ruby laser.

Fig. 4. Typical radiation pulse sequence obtained under single-pulse conditions. Pulse repetition frequency $F = 6.25$ Hz.

Fig. 5. Scan of a single radiation pulse.

where $\xi$ is a coefficient indicating the difference between the efficiency of the pulsed and continuous pumping. The quantity $\xi > 1$. The reduction in the efficiency for the pulsed mode is associated with the appearance of a strong continuous background, with the less favorable matching between the emission spectrum of the mercury capillary lamp and the absorption spectrum of the ruby (the continuous background increases together with the electron concentration in the plasma; in the pulsed mode the electron concentration is $10^2 \sim 10^3$ times higher than in the continuous), with the expansion of the discharge channel (and hence the fall in the degree of focusing of the radiation in the ruby and the reduction in pumping efficiency), and also with the greater energy losses which occur in the capacitor discharge circuit. In our own experiments $\xi \approx 2$.

Equations (4)-(7) determine the contribution of the pulsed and continuous components of the mercury capillary lamp supply to the total pumping of the active element. Estimates based on (6) and (7) show that in all practical cases it is essential to allow for the contribution made by the continuous pumping component.

Measurement of the thermal lens arising as a result of the radiation of the duty arc showed that for a pumping power of 1-1.3 kW its focal length in a ruby 2.5 mm in diameter and $l = 32$ mm long was about 1 m. These measurements revealed a considerable nonuniformity in the distribution of the pumping energy over the cross section of the active element. The latter was also estimated by computation, and it was shown that a considerable fall in the amplification factor occurred for displacements of even $(0.1-0.15)r_0$ from the axis of the ruby. The existence of the lens and the considerable nonuniformity of the pumping action over the cross section of the ruby led to a number of practical effects. First, the generation threshold depended very considerably on the resonator base (Fig. 1). We associate this effect mainly with the pumping nonuniformity, since on using a large-diameter lamp (an IFP-800) for pumping it vanishes. As the resonator base increases, the fundamental mode spot diameter does likewise, and under conditions of nonuniform pumping the effective amplification factor declines. This leads to a rise in the threshold. Second, the appearance of the lens leads to a fall in the Q-switching rate on using a rotating prism as Q-modulator. Figure 2 shows the rise in the generation threshold as a function of the rotation angle of one of the resonator mirrors. A considerable increase in threshold occurs for distortions (angular rotations) of $5-6^\circ$, which for a reflector rotation rate of $3 \cdot 10^4$ rpm gives a considerable Q-switching time (around 0.5 $\mu$sec). The Q-switching time may be estimated more accurately by the method set out in [7]. For a 1.3-times excess over the threshold the angular distortion which leads to a break in generation is then about $5^\circ$; this leads to the same Q-switching time. A reduction may be achieved by increasing the rotation rate of the reflector and the laser resonator base.

The general block diagram of the generator is shown in Fig. 3. The ultrahigh-pressure mercury capillary lamp is fed from a source 1, giving a 50-Hz voltage within the range 0-3 kV, and from a source 2 giving voltage pulses 200-300 $\mu$sec long with an amplitude up to 2.5 kV. The instant of supplying the pulse is synchronized with the voltage phase by using a pulse-shaper 3, phase-shifter 4, divider 5 with division coefficients of 2, 4, 8, 16, and 32, and a blocking generator 6 operating in the waiting mode. The pulse from the latter is applied to the grid of the thyratron in the pulse supply source.

Q-modulation was effected by means of a prism rotating under the influence of a synchronous motor 10 operating at 30,000 rpm. The chain comprising the phase shifter 7, generator 8, and power amplifier 9 ensured exact matching between the position of the rotor of the electric motor and the phase of the pulsed and continuous ultrahigh-pressure mercury capillary lamp supply. The position of the prism was monitored
by means of a magnetic head 11, amplifier 12, and coincidence circuit 14. A pulse from the phase shifter
4 was applied to the second input through a delay circuit 13.

Figure 4 shows a typical sequence of pulses obtained in the modulated-Q mode, and Fig. 5 shows the
sweep of a single pulse. The generator operated at repetition frequencies up to 25 Hz (in the present cir-
cuit $F_{\text{max}} = 50$ Hz, the lower values of the working frequency $F$ being due to the inadequate power of the
pulse source). The pulse length (30-60 nsec) and amplitude did not remain constant, but varied by a factor
of 1.5-2 from one pulse to another. The pulse shape changed from Gaussian to a double-humped curve.
On increasing the resonator base to 50 cm the pulse shape and length became far stabler.

In our experiments the energy of a single pulse was 4-5 mJ ($P_{\text{max}} = 150$ kW) for a continuous supply
of 1 kW and a pumping pulse energy of 25 J. The threshold pumping energy was 16 J, but in the absence
of Q modulation 13 J. This quantity was about 20% higher than the threshold value on using a dense mirror
instead of a prism.

The comparatively low efficiency of the generator was due to the very small excess of the pumping
level over its threshold value. Estimates based on Eq. (6) show that the threshold was exceeded by no more
than a factor of 1.4 times. The fairly high threshold in turn was due to the low quality of the elements
employed: the rubies, illuminating systems, total internal-reflection prisms, and lamp bulb material.
Hence any conclusions as to the efficiency of the mode of operation under consideration are clearly pre-
mature.

Thus, the foregoing results illustrate the fundamental possibility of using the mixed operating con-
dition of an ultrahigh-pressure mercury capillary lamp for constructing a frequency ruby laser. The
results also establish relationships between the pumping action of the duty arc and the main pulse, and
reveal the principal characteristics of such lasers.

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