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On pulse duration of self-terminating lasers

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***Abstract*. The problem of the maximum pulse duration τ_{max} of self-terminating lasers is considered. It is shown that the duration depends on the transition probability in the laser channel, on the decay rate of the resonant state in all other channels, and on the excitation rate of the metastable state. As a result, τ_{max} is found to be significantly shorter than previously estimated. The criteria for converting the 'self-terminating' lasing to quasi-cw lasing are determined. It is shown that in the case of nonselective depopulation of the metastable state, for example in capillary lasers or in a fast flow of the active medium gas, it is impossible to obtain continuous lasing. Some concrete examples are considered. It is established that in several studies of barium vapour lasers ($\lambda = 1.5$ μm) and nitrogen lasers ($\lambda = 337$ nm), collisional lasing is obtained by increasing the relaxation rate of the metastable state in collisions with working particles (barium atoms and nitrogen molecules).**

Keywords: *self-terminating laser, lasing duration, collisional lasing.*

1. Introduction

Despite a long history of development of self-terminating lasers (STLs), certain basic principles specifying their main characteristics still remain unclear. These include, in particular, the problem of the maximum pulse duration τ_{max}. Bennet [1] assumed it 'obvious' that $\tau_{max} \leqslant 0.5A_{rm}^{-1}$, where A_{rm} is the radiative transition probability. Later, Soldatov and Solomonov [2] showed that in the case of the linear-time growth of the pump pulse power

$$\tau_{max} = 2A_{rm}^{-1}, \tag{1}$$

and according to [3, 4], in the case of the rectangular pump pulse

$$\tau_{max} = 1.6A_{rm}^{-1}. \tag{2}$$

Relationships (1) and (2) were obtained for the case when the only channel of deexcitation of the upper (resonant) state (RS) is its radiative decay on the working transition, and the only channel for populating the lower (metastable) state (MS) is the optical transition from the RS. We can show that under these conditions, the lasing efficiency η is equal to the quantum efficiency η_q. In fact, for the STLs $\eta \ll \eta_q$ [4–6], and $\tau_{max} \ll A_{rm}^{-1} = \tau_{sp}$ [2, 4–7], where τ_{sp} is the spontaneous lifetime of the RS with respect to the laser transition. In this connection, criteria (1), (2) are inapplicable to real laser media.

The issue of the maximum duration of generation on a self-terminating transition becomes urgent when studying the possibilities of converting it into quasi-cw or cw collisional regime. Batenin at al. [3] believe that the collisional lasing is meaningful only when the pulse duration τ_g exceeds τ_{max}, determined by criterion (2):

$$\tau_g > \tau_{max} = 1.6A_{rm}^{-1}. \tag{3}$$

Criterion (3) was used by the authors of papers [3, 8] to analyse the generation regimes of lasers with specific working media – vapours of Ba, Eu, Eu^+, Pb, Sn, etc. Since criterion (3) is not fulfilled for these lasers in most experiments, the conclusion was drawn that collisional lasing was not achieved. Relation (2) is inapplicable in the case of real media; therefore, criterion (3) and the results of papers [3, 8] should be also reviewed. The aim of this paper is to clarify the reasons leading to the difference between the experimental data on τ_{max} for the STLs and the theoretical data, as well as to find the new criterion, which characterises the transition of the self-terminating lasing to quasi-cw lasing.

2. Duration and lasing efficiency of self-terminating lasers

Regardless of the method of pumping (gas discharge or electron beam) at least two processes should be included in consideration when long pump pulses are used: spontaneous decay of the RS to the ground state (GS) with a probability A_r and population of the MS in collisions between electrons and atoms in the GS. For a rectangular pump pulse and $n_0 \gg n_r \sim n_m$, the rate equations for the populations of the RS (n_r) and MS (n_m) can be written in the form:

$$\dot{n}_r = n_0F - n_rA_\Sigma, \quad \dot{n}_m = n_rA_{rm} + \theta n_0F, \tag{4}$$

where n_0 is the population of the ground state; F and θF are the rates of population of the RS and MS (in a self-terminating laser $\theta g_r/g_m = \theta_1 < 1$); g_r and g_m are the

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statistical weights of the RS and MS, respectively; $A_\Sigma = A_{\rm rm} + A_{\rm r}$.

Expressions

$$n_{\rm r} = \frac{n_0 F}{A_\Sigma}[1 - \exp(-A_\Sigma t)],$$
$$n_{\rm m} = n_0 F \frac{A_{\rm rm}}{A_\Sigma}\left[t - \frac{1}{A_\Sigma} + \frac{\exp(-A_\Sigma t)}{A_\Sigma}\right] + \theta n_0 F t \quad (5)$$

are the solutions of system (4) at $n_{\rm r}(t=0) = 0$, $n_{\rm m}(t=0) = 0$. In the saturated power approximation [9], the generation of the STL terminates when the pump rates of the upper and lower working levels are equalised:

$$\dot{n}_{\rm r}/g_{\rm r} = \dot{n}_{\rm m}/g_{\rm m}. \quad (6)$$

Based on this condition and relation (5), we find the expression for $\tau_{\max}$:

$$\tau_{\max} = -\frac{1}{A_\Sigma}\ln\left(\frac{A_{\rm rm}/A_\Sigma + \theta}{A_{\rm rm}/A_\Sigma + g_{\rm m}/g_{\rm r}}\right). \quad (7)$$

Similarly, we can find the expression for the lasing efficiency:

$$\eta_{\max} = f\,\frac{(E_{\rm r} - E_{\rm m})(n_{\rm r} - n_{\rm m} g_{\rm r}/g_{\rm m})}{(E_{\rm r} n_{\rm r} + E_{\rm m} n_{\rm m})(1 + g_{\rm r}/g_{\rm m})}, \quad (8)$$

where $E_{\rm r}$ and $E_{\rm m}$ are the RS and MS energies (with respect to the GS energy); $n_{\rm r}$ and $n_{\rm m}$ are calculated from relations (5) for the instant of time defined by (7); f is the fraction of the pump energy spent to excite the RS and MS. Under optical pumping in the absence of decay of the RS in the GS, the population $n_{\rm m} \approx 0$ and, according to (8), $\eta_{\max} \to \eta_{\rm q}$, where

$$\eta_{\rm q} = \frac{E_{\rm r} - E_{\rm m}}{E_{\rm r}}\left(1 + \frac{g_{\rm r}}{g_{\rm m}}\right)^{-1}$$

is the quantum efficiency of the STL.

An important parameter, on which $\tau_{\max}$ and $\eta_{\max}$ depend, is the probability $A_{\rm r}$ in the expression for the decay rate of the RS ($A_\Sigma = A_{\rm rm} + A_{\rm r}$). The value of $A_{\rm r}$ is determined by the probability of spontaneous decay A_0 of the resonance state to the ground state in a vacuum and by the imprisonment of resonance radiation [10]:

$$A_{\rm r} = g A_0, \quad (9)$$

where g is the escape factor of radiation from the active medium. In analysing the mechanism of the STL generation, it is generally assumed that the resonance radiation is 'completely trapped' [2, 4], so that $A_{\rm r} \ll A_{\rm rm}$. Under this assumption, expression (7) transforms into relation

$$\tau_{\max} = -\frac{1}{A_{\rm rm}}\ln\left(\frac{1+\theta}{1 + g_{\rm m}/g_{\rm r}}\right). \quad (10)$$

It follows from (10) that at $A_\Sigma = A_{\rm rm}$, $\theta = 0$, and $g_{\rm r} = g_{\rm m}$, the duration

$$\tau_{\max} = 0.693 A_{\rm rm}^{-1}, \quad (11)$$

which differs significantly from $\tau_{\max}$, determined by condition (2). This is explained by the fact that unlike the saturated power approximation used in this study, Batenin et al. [4] obtained expression (2) from the equalisation condition of the RS and MS populations by neglecting the stimulated emission, i.e., in the absence of the generation, which is incorrect. If the saturated power approximation is fulfilled, lasing stops when the rates of changes in the RS and MS populations become equal [condition (6)]. If this approximation is not satisfied, lasing terminates earlier. Therefore, in search experiments, even under optical pumping and complete trapping of resonance radiation, we should use criterion (11) rather than (2).

If the MS relaxes at a noticeable rate $A_{\rm m}$, equation (4) for $\dot{n}_{\rm m}$ should be supplemented with the term $-n_{\rm m} A_{\rm m}$. In this case, $\tau_{\max}$ will be found from the expression

$$\tau_{\max} = -\frac{1}{A_\Sigma - A_{\rm m}}\ln\left[\left(\theta + \frac{A_{\rm rm}}{A_\Sigma - A_{\rm m}}\right)\times\left(\frac{g_{\rm m}}{g_{\rm r}} + \frac{A_{\rm rm}}{A_\Sigma - A_{\rm m}}\right)^{-1}\right]. \quad (12)$$

In mixtures with electronegative gases it is possible to obtain the excitation pulse with a growth in the pump rate $F = F_0 t$ that is linear in time or close to it. In this case, $\tau_{\max}$ is found from the solution of the expression

$$\frac{g_{\rm m}}{g_{\rm r}}\frac{1}{A_\Sigma} - \left(\theta + \frac{A_{\rm rm}}{A_\Sigma}\right)\frac{1}{A_{\rm m}} - \left(\frac{g_{\rm m}}{g_{\rm r}} + \frac{A_{\rm rm}}{A_\Sigma - A_{\rm m}}\right)\frac{\exp(-A_\Sigma\tau)}{A_\Sigma} + \left(\theta + \frac{A_{\rm rm}}{A_\Sigma - A_{\rm m}}\right)\frac{\exp(-A_{\rm m}\tau)}{A_{\rm m}} = 0, \quad (13)$$

which at $A_{\rm m} \to 0$ transforms to the equation

$$\frac{g_{\rm m}}{g_{\rm r}}\frac{1}{A_\Sigma} - \left(\frac{g_{\rm m}}{g_{\rm r}} + \frac{A_{\rm rm}}{A_\Sigma}\right)\frac{\exp(-A_\Sigma\tau)}{A_\Sigma} - \left(\theta + \frac{A_{\rm rm}}{A_\Sigma}\right)\tau = 0. \quad (14)$$

In the experiments, the $\tau_{\max}$ at $A_{\rm m} \to 0$ (depending on the nature of the pump pulse) can be between the values determined by expression (7) and by solving (14).

As follows from (7), $\tau_{\max}$ is strongly influenced by the quantities θ and A_Σ. For example, in the most efficient STL – a copper vapour laser – $\theta_1 = 0.5$ under the optimal condition [11]; as a result, $\tau_{\max}$ decreases immediately down to $0.29 A_\Sigma^{-1}$. If $A_\Sigma \approx 5 A_{\rm rm}$, which is typical of ion lasers or of the STLs with a developed MS structure, for example, lead vapour lasers, $\tau_{\max}$ is much smaller and when $\theta_1 = 0.5$ it is equal to $\sim 0.1 A_{\rm rm}^{-1}$. In the case of high-power pumping, due to electron deexcitation of the RS A_Σ increases and the lasing duration also decreases [12]. It follows from (12), (13) that when assessing the possibility of converting lasing on a self-terminating transition to the quasi-cw collisional regime, it is necessary to take into account the inequality $A_{\rm m} > A_\Sigma$, instead of $A_{\rm m} > A_{\rm rm}$. Therefore, the issue about the real value of A_Σ requires a more focussed approach than has been done in [2, 4].

3. Lifetime of resonance states in self-terminating lasers

In the STLs, the pressure of the working gas is typically 10 – 100 Pa, and the pressure of the buffer gas lies in the range from several to 100 kPa. Under these conditions, Doppler and collisional widths of resonance lines are comparable [13]. However, in the case of the collisional broadening, the escape factor for the laser tube centre is $g_c \propto (k_0 r)^{-1/2}$, while in the case of the Doppler broadening, $g_D \propto (k_0 r)^{-1}[\lg(k_0 r)]^{-1/2}$, i.e., $g_c \gg g_D$ at a large value $k_0 r$ (here k_0 is the absorption coefficient at the centre of the resonance line, and r is the radius of the working tube). Then according to [10]

$$g = g_c = 1.115(\pi k_0 r)^{-1/2}, \tag{15}$$

where

$$k_0 = \frac{\lambda_0^2 n_0}{2\pi} \frac{g_r}{g_0} \frac{\Delta\nu_0}{\Delta\nu_c};$$

λ_0 is the wavelength; g_0 is the statistical weight of the GS; $\Delta\nu_0$, $\Delta\nu_c$ are the half-widths of the spectral lines determined by the natural and collisional broadenings, respectively.

For atoms with the angular momenta $J_0 = 0$ in the GS and $J_r = 1$ in the RS (Ba, Ca, He, Hg, etc.), the half-width of the line, determined by the collisional broadening in collisions with its own atoms, is $\Delta\omega_c = 2.33[\pi e^2/(m\omega_0)] \times f_{0r} n_0$ [13], where e and m are the electron charge and mass; ω_0 is the angular frequency; $f_{0r} = 1.5 A_0 \lambda_0^2 (g_r/g_0)$ is the oscillator strength for the resonance transition. Substituting (15) into (9) and taking into account that $\Delta\nu_0 = \Delta\omega_0/(2\pi) = A_0/(2\pi)$, we find

$$A_r = 0.192 A_0 \sqrt{\lambda_0/r}. \tag{16}$$

As a result of collisions with its own atoms, the impact broadening is complemented by the broadening due to the static wing. For atoms with $J_0 = 0$ and $J_r = 1$ the intensity distribution in the static wing has the same form as the impact broadening, but with a different coefficient [13]. This increases the probability of A_r due to the static wing up to

$$A_r = 0.238 A_0 \sqrt{\lambda_0/r}. \tag{17}$$

For atoms with $J_0 = 1/2$ and $J_r = 1/2$, 3/2 (Cu, Au, etc.), according to [13] we have

$$A_r' = 0.168 A_0 \sqrt{\lambda_0/r} \quad \text{for the } {}^2\mathrm{S}_{1/2} - {}^2\mathrm{P}^{\mathrm{o}}_{1/2} \text{ transition,}$$
$$A_r'' = 0.213 A_0 \sqrt{\lambda_0/r} \quad \text{for the } {}^2\mathrm{S}_{1/2} - {}^2\mathrm{P}^{\mathrm{o}}_{3/2} \text{ transition.} \tag{18}$$

As can be seen from (15) – (18), for STLs the escape factor g and the rate A_r of the resonance radiation yield from the emitting volume does not depend on the concentration of working particles. In particular, this feature of resonance radiation makes it convenient to use it for determining the relaxation rates of the MS by resonance fluorescence method [14].

For many atoms, which are the working medium of the STL, the cross sections for resonant collisions, leading to a line broadening, are measured and the effect of the hyperfine level structure on the resonance radiation yield is also studied. It is found that when at concentrations of atoms $10^{15} - 10^{16}$ cm^{-3} (typical of the STLs), the hyperfine structure does not affect the A_r even in atoms with a high atomic weight, such as a Pb atom [15], and the broadening parameters agree well with those calculated by the method of [13].

Resonance lines are also broadened in collisions with buffer gas atoms whose concentration is usually two orders of magnitude larger than the concentration of metal atoms. The cross sections of broadening by buffer gases is smaller than the cross sections of broadening by their own atoms, for example, for Sr and Pb they are smaller by ~ 50 times [16] and for Xe – by 25 times [17] (for an approximate estimate of [13], these cross sections differ by an order of magnitude). Consequently, in calculating A_r we should also take into account the broadening due to collisions with a buffer gas. Unlike the broadening with its own atoms, in the case of the broadening by the buffer gas, the A_r depends on the pressure p of the latter, i.e., on the experimental conditions. With the predominance of the broadening by the buffer gas atoms, $A_r \propto \sqrt{p}$ as, for example, for the atmospheric pressure Cu laser. Below, for clarity of analysis, we assume the broadening of both types of collisions to be the same in the case of the STLs. Therefore, all values calculated by formulas (16) – (18) should be increased by $\sqrt{2}$ times.

4. Maximum pulse duration of some self-terminating lasers and analysis of the possibility of their transition to the collisional regime

4.1 Copper atom

A copper vapour laser ($\lambda_1 = 511$ nm and $\lambda_2 = 578$ nm) is investigated so far in detail, both theoretically and experimentally. Wang and Yang [18] reported the laser pulse duration (largest known to the author of the present paper) to be 140 ns at $r = 2.1$ cm. We will use the data for the radiative transition probabilities from [19]: $A_0(1)\,({}^2\mathrm{P}^{\mathrm{o}}_{3/2} - {}^2\mathrm{S}_{1/2}) = 1.38 \times 10^8$ s^{-1}, $A_0(2)\,({}^2\mathrm{P}^{\mathrm{o}}_{1/2} - {}^2\mathrm{S}_{1/2}) = 1.36 \times 10^8$ s^{-1}, $A_{rm}(\lambda_1 = 511 \text{ nm}) = 1.95 \times 10^6$ s^{-1}, $A_{rm}(\lambda_2 = 578 \text{ nm}) = 1.9 \times 10^6$ s^{-1}. According to (18) for the resonance lines $A_r(1) = 0.16 \times 10^6$ s^{-1} and $A_r(2) = 0.13 \times 10^6$ s^{-1}. Given that $\theta_1 = 0.5$, $\theta(\lambda_1) = (g_m/g_r)\theta_1 = 0.75$, $\theta(\lambda_2) = 1$, we obtain $\tau_{max}(\lambda_1) = 175$ ns and $\tau_{max}(\lambda_2) = 206$ ns.

In most cases, generation in STLs starts at the leading edge of the current pulse against the background of the drop in voltage and electron temperature T_e. As a result, generation in the Cu laser starts at the maximal $\dot{n}_r$ and continues with a gradual decrease in $\dot{n}_r$ [20], which leads to an increase in the parameter θ and a decrease in the lasing duration (shortening of the tail). Also, with the development of the pulse, the rate of the RS depopulation by the electrons increases. With this in mind, the proximity of the experimental duration τ_{max} to the calculated one is quite satisfactory.

Several papers, starting with [21], considered the possibility of converting lasing on a self-terminating transition to quasi-cw regime by increasing the rate of the MS decay in diffusion processes (capillary lasers [3]) or in a fast flow of the active medium gas (see [22] and references therein). In this case, τ_{max} should be calculated by formula (12) when substituting in it $A_\Sigma = A_{rm} + A_r + A_v$, where A_v is the probability of removing atoms from the excitation zone, which is the same for the RS and MS, i.e., $A_m = A_v$. As a result, we obtain

$$\tau_{max} = -\frac{1}{A_{rm} + A_r} \times$$

$$\times \ln\left[\left(\theta + \frac{A_{\rm rm}}{A_{\rm rm} + A_{\rm r}}\right)\left(\frac{g_{\rm m}}{g_{\rm r}} + \frac{A_{\rm rm}}{A_{\rm rm} + A_{\rm r}}\right)^{-1}\right]. \quad (19)$$

It follows from (19) that using capillary lasers or a fast flow, it is impossible to obtain cw lasing in a STL. Thus, for the Cu laser ($\lambda = 511$ nm), according to (18), (19), the duration $\tau_{\max} = 144$ ns for a capillary 1 mm in diameter, and in case of a fast flow of atoms and $A_{\rm r} \ll A_{\rm rm}$ is 183 ns. Under optical pumping (when $\theta = 0$), $\tau_{\max} = 470$ ns, i.e., even in this variant cw lasing of the Cu laser is impossible. To implement this regime we must find a process that selectively increases the rate of the MS relaxation.

4.2 Barium atom

Analysis of the generation mechanism of a barium vapour laser (the $6{\rm p}\,^1{\rm P}_1^{\rm o} - 5{\rm d}\,^1{\rm D}_2$ transition with $\lambda = 1.5$ μm) has received increased attention [3, 8, 14, 23, 24] due to the fact that it is used as a test laser in finding the feasibility of the collisional lasing regime. The authors of papers [14, 23, 24] obtained output pulses of long duration, and we [14] explain it by the establishment of the collisional regime in the case of the electron-beam pumping. The authors of papers [3, 8] deny the feasibility of such a lasing regime, in particular, due to a failure of criterion (3).

In a barium atom for the resonance line with $\lambda_{\rm r} = 553.7$ nm, the probability $A_0 = 1.19 \times 10^8$ s^{-1} and $A_{\rm rm} \leqslant 2.5 \times 10^5$ s^{-1} [25]. For the conditions of [14] at $r = 0.3$ cm, we have $A_{\rm r} = 5.44 \times 10^5$ s^{-1} and $A_\Sigma = 7.94 \times 10^5$ s^{-1}. In this case, $\tau_{\max}$ at $\theta = 0$ (e.g., under optical pumping) is 2.32 μs. Even in this ideal case, the laser pulse duration is much shorter than that determined by criterion (2) ($\tau_{\max} \leqslant 1.6 A_{\rm rm}^{-1}$ μs) and obtained in [14] ($\tau_{\max} = 5.8$ μs). The value of $\eta_{\max}$ (8) is 8.6 %, which is also much less than $\eta_{\rm q} = 23$ %.

Under real condition, as noted above, we always have $\theta > 0$. Figure 1 shows the dependences of $\tau_{\max}$ and $\eta_{\max}$ on θ_1 for a barium vapour laser. If we assume that the lasing conditions for this laser are the same as for the most efficient Cu laser, we have $\theta_1 = 0.5$ and $\theta = (g_{\rm m}/g_{\rm r})\theta_1 = 0.833$. In this case, $\tau_{\max} = 0.69$ μs, and since the quantity $A_{\rm rm}$ for a barium vapour laser is not precisely defined, it is advisable to calculate $\tau_{\max}$ in the limiting case $A_{\rm rm} \ll A_{\rm r}$. In (7) it is equal to 1.28 μs, which is less than the duration $\tau_{\rm g} = 5.8$ μs obtained in [14] (due to the growth of the rate of the MS relaxation with increasing pressure $p_{\rm Ba}$). In the barium vapour laser the rate of the step depopulation of the RS by the electrons is greater than the rate of the MS depopulation [26], as in a copper vapour laser [19]. According to (12), (19) this makes it impossible to get long pulses by the step processes in accordance with the mechanism considered in [8, 23]. Consequently, the duration $\tau_{\max}$ achieved in [14] is caused by the transition of self-terminating lasing to the quasi-cw collisional regime.

In the case of the gas-discharge excitation, we should expect the maximum pulse duration, as for the collisional He – Eu$^+$ laser, under conditions of uncompleted discharge [27]. These experiments were carried out in [24], where lasing with a pulse duration of more than 10^{-4} s was obtained. However, the output power of the barium vapour laser was much lower than that of the He – Eu$^+$ laser [27]. The low laser power has its natural explanation: it is due to low rates of the MS relaxation in the barium atom in the diffusion and collision processes [3, 14] (they are three orders of magnitude smaller than for the Eu$^+$ ions).

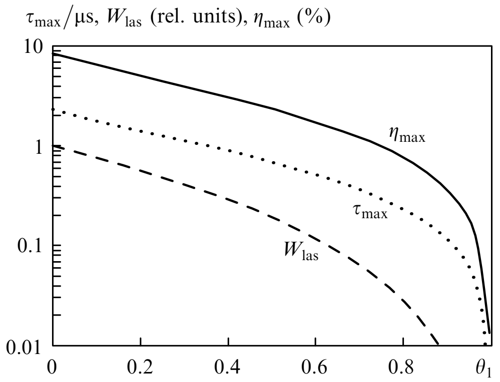

Figure 1. Dependences of $\tau_{\max}$, $\eta_{\max}$, and the lasing energy $W_{\rm las}$ on the ratio θ_1 of the MS and RS pump rates for a barium vapour laser.

4.3 Nitrogen molecule

The characteristics of the 337-nm nitrogen laser are studied in many papers devoted to the STLs. Attention to it in this paper is due to the fact that nitrogen is a medium with well-studied kinetics. In particular, this laser, in principle, can provide the collisional lasing, because the quenching rate constant of the lower working state $\rm B\,^3\Pi_g$ by its own molecules [$k_{\rm N_2}({\rm B}) = 5 \times 10^{-11}$ cm^3 s^{-1}] is much larger than the quenching rate constant of the upper state $\rm C\,^3\Pi_u$ [$k_{\rm N_2}({\rm C}) = 10^{-11}$ cm^3 s^{-1}] [28]. At a nitrogen pressure $p_{\rm N_2} = 15$ Torr (quite achievable in a $\rm N_2$ laser) and at room temperature, the relaxation rate of the $\rm B\,^3\Pi_g$ state becomes equal to the probability $A_{\rm rm} = 2.44 \times 10^7$ s^{-1} of the $\rm C\,^3\Pi_u - B\,^3\Pi_g$ transition [29].

Figure 2 shows the dependences of $\tau_{\max}$ on the relaxation rate $A_{\rm m}$ of the $\rm B\,^3\Pi_g$ state of the nitrogen molecule in different excitation regimes of the nitrogen laser. Because the $\rm N_2$ laser is less effective than the Cu laser, we used for it $\theta = 0.5$ as the upper bound. In the absence of relaxation of the $\rm B\,^3\Pi_g$ state, i.e., at low nitrogen pressures, $\tau_{\max} = 12$ ns for $F = $ const and 25 ns for $F = F_0 t$. In experiments with small and average pump powers, the pulse duration is typically implemented in this time range.

In high-power lasers at elevated pressures of nitrogen, the temperature $T_{\rm e}$ decreases and the mixing rate of working

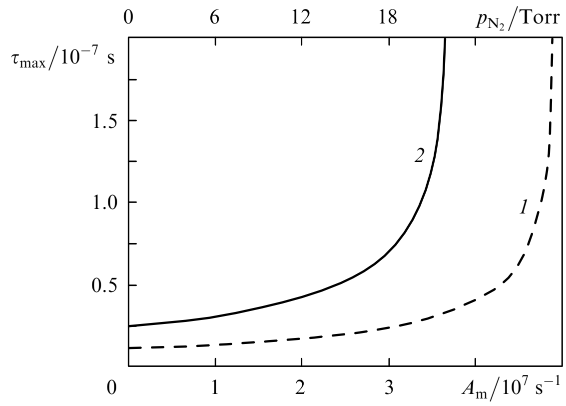

Figure 2. Dependences of $\tau_{\max}$ on the relaxation rate $A_{\rm m}$ of the $\rm N_2$ ($\rm B\,^3\Pi_g$) state and on the nitrogen pressure in the case of excitation of the $\rm N_2$ laser by rectangular pulses (*1*) and by pulses with the power increasing linearly in time (*2*).

states increases with the development of the excitation pulse. It does not allow one to obtain long pulses. However, the introduction of electronegative impurities significantly alters the current – voltage characteristics of the discharge, which makes it possible to obtain long pump and laser pulses. In [30], for a $N_2 - SF_6$ mixture at pressures $p_{N_2} = 50$ Torr and $p_{SF_6} = 60$ Torr, the pulse duration reached 150 ns at a pump rate approximately constant over time. This is more than an order of magnitude greater than $\tau_{max} = 12$ ns [curve (*1*) in Fig. 2] for a self-terminating lasing regime. In [31], the laser pulse duration of ~ 100 ns were obtained for the $N_2 - CF_4$ mixture at pressures $p_{N_2} = 20$ Torr and $p_{CF_4} = 90$ Torr also in the case of the quasi-steady-state pump excitation. Because in this case the duration $\tau_{max} \approx 30$ ns [curve (*1*) in Fig. 2] for pure nitrogen at $p_{N_2} = 20$ Torr, it is obvious that the molecule CF_4 take a significant part in the deexcitation of the lower state. Laser pulses up to 100 ns are also obtained in the case of a high-power pulsed pumping in wide-aperture N_2 lasers [32] at $p_{N_2} = 55$ Torr with small additions of NF_3 and SF_6 ($p_{NF_3} = 1.5$ Torr, $p_{SF_6} = 3$ Torr). Thus, we can assert that in [30 – 32] the collisional quasi-cw lasing regime was implemented in the N_2 laser.

5. Conclusions

Studies carried out in the present research have shown that the previously used estimate of the maximum pulse duration of the STLs, as well as criteria for their transition to quasi-cw regime do not apply in the case of real working media even when they are optically pumped. Because of the large collisional broadening of resonance lines in the working STL media the decay time of the RS is small enough and does not depend on the concentration of working particles, causing a decrease in τ_{max} and η_{max}. In the case of the gas-discharge or electron-beam excitation the electron population of the MS further (and significantly) reduces τ_{max}. The same result is obtained by increasing depopulation rate of the RS by electrons as the pump pulse develops. With decreasing radius (the characteristic size) of the active region the lasing duration decreases: $\tau_{max} \propto \sqrt{r}$.

Revision of τ_{max} values for the STL necessitates the reconsideration of the criteria for their transition to a quasi-cw lasing regime by increasing relaxation rate of the MS in collisions with particles of the working medium and other processes. We have shown that quasi-cw lasing can be obtained only when the decay rate of the MS exceeds the deexcitation rate of the RS across all the channels. This makes it futile to apply the proposed method of conversion of the STL generation to the quasi-cw regime with the help of nonselective processes of the MS depopulation, for example by providing a rapid flow of atoms or by using narrow channels.

The first evidence of transition to the collisional regime may be even a small increase in the pulse duration compared to the 'standard' pulse duration of the STL, determined by the structure of the working levels, cross sections of their excitation, and the pump regime. Using the proposed approaches in the analysis of published studies showed that the collisional lasing regime is implemented in the barium vapour lasers ($\lambda = 1.5$ μm) and nitrogen lasers ($\lambda = 337.1$ nm).

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References

1. Bennet W.R. *Appl. Opt.*, Suppl 61, 3 (1965).
2. Soldatov A.N., Solomonov V.N. *Gazorazryadnye lazery na samoogranichennykh perekhodakh v parakh metallov* (Gas-Discharge Lasers on Self-Terminating Transitions in Metal Vapours) (Novosibirsk: Nauka, 1985).
3. Batenin V.M., Kalinin S.V., Klimovskii I.I. *Kvantovaya Elektron.*, **18**, 189 (1991) [*Sov. J. Quantum Electron.*, **21**, 167 (1991)].
4. Batenin V.M., Buchanov V.V., Kazaryan M.A., et al. *Lazery na samoogranichennykh perekhodakh atomov metallov* (Lasers on Self-Terminating Transitions of Metal Atoms) (Moscow: Nauchnaya kniga, 1998).
5. Little C.E. *Metal Vapour Lasers* (Chichester – New-York – Weinheim – Singapore – Toronto: Wiley & Sons, 1999).
6. Tarasenko V.N. *Entsiklopedia nizkotemperaturnoi plazmy* (Encyclopaedia of Low-Temperature Plasma) (Moscow: Fizmatlit, 2005) Vol. XI-4, p. 721.
7. Petrash G.G. *Usp. Fiz. Nauk*, **105**, 645 (1971).
8. Petrash G.G. *Kvantovaya Elektron.*, **39**, 111 (2009) [*Quantum Electron.*, **39**, 111 (2009)].
9. Gerry E.T. *Appl. Phys. Lett.*, **7**, 6 (1965).
10. Holstein T. *Phys. Rev.*, **83**, 1159 (1951).
11. Carman R.J. *J. Appl. Phys.*, **82**, 71 (1997).
12. Eletskii A.V., Zemtsov Yu.K., Rodin A.V., et al. *Dokl. Akad. Nauk SSSR*, **220**, 318 (1975).
13. Vainshtein L.A., Sobelman N.N., Yukov E.A. *Excitation of Atoms and Broadening of Spectral Lines* (Berlin: Springer-Verlag, 1981; Moscow: Nauka, 1979).
14. Bokhan P.A. *Kvantovaya Elektron.*, **13**, 1837 (1986) [*Sov. J. Quantum Electron.*, **16**, 1207 (1986)].
15. Muradov V.G., Kudryavtsev Yu.N. *Opt. Spektrosk.*, **63**, 9 (1987).
16. Asadulina R.I., Bezgulov N.N., Borisov E.N., et al. *Opt. Spektrosk.*, **62**, 279 (1987).
17. Hadelaar G.J.M., Klein M.H., Snijkers R.J.M., et al. *J. Appl. Phys.*, **88**, 5538 (2000).
18. Wang T.L., Yang C.Y. *J. Appl. Phys.*, **66**, 4653 (1989).
19. Carman R.J., Brown D.J.W., Piper J.A. *IEEE J. Quantum Electron.*, **30**, 1866 (1994).
20. Borovich B.L., Yurchenko N.I. *Kvantovaya Elektron.*, **11**, 2081 (1984) [*Sov. J. Quantum Electron.*, **14**, 1391 (1984)].
21. Asmus J.F., Moncur N.K. *Appl. Phys. Lett.*, **13**, 384 (1968).
22. Buchanov V.V., Kazaryan M.A., Molodykh E.I., et al. *Kvantovaya Elektron.*, **21**, 1031 (1994) [*Quantum Electron.* **24**, 959 (1994)].
23. Batenin V.M., Kalinin S.V., Klimovskii I.I. *Kvantovaya Elektron.*, **13**, 2228 (1986) [*Sov. J. Quantum Electron.*, **16**, 1470 (1986)].
24. Bokhan P.A. *Kvantovaya Elektron.* **13**, 1595 (1986) [*Sov. J. Quantum Electron.*, **16**, 1041 (1986)].
25. Dzuba V.A., Ginges Y.S.M. *Phys. Rev. A*, **73**, 032503 (2006).
26. Trajmar S., Nickel J.C., Antoni T. *Phys. Rev. A*, **34**, 5154 (1986).
27. Bokhan P.A. *Pis'ma Zh. Tekh. Fiz.*, **10**, 210 (1984).
28. Kossyi I.A., Kostinsky A.Yu., Matveyev A.A., et al. *Plasma Sources Sci. Techn.*, **1**, 207 (1992).
29. Kuznetsova L.A., Kuz'menko N.E., Kuzyakov Yu.Ya., Plastinin Yu.A. *Veroyatnosti opticheskikh perekhodov dvukhatomnykh molekul* (Probabilities of Optical Transitions in Diatomic Molecules) (Moscow: Nauka, 1980).
30. Suchard S.N., Galvan L., Sutton D.G. *Appl. Phys. Lett.*, **26**, 521 (1975).
31. Coller F., Thiell G., Cottin P. *Appl. Phys. Lett.*, **32**, 739 (1978).
32. Konovalov N.N., Panchenko A.N., Tarasenko V.F., et al. *Kvantovaya Elektron.*, **37**, 623 (2007) [*Quantum Elektron.*, **37**, 623 (2007)].