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Line competition in gas lasers

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Abstract. Simultaneous lasing on two lines having a common upper level is analysed. Within the framework of the two-level model, a formula for the gain in each line is obtained. Two possible types of line competition are found: symbiosis and quenching. It is shown that competition in the quenching regime can be used to study the rates of population of the lower levels. The results are illustrated by competition diagrams for the 2.65-μm and 2.03-μm of the Xe atom in the Ar – Xe mixture and the 703.2-nm and 724.5-nm lines of the Ne atom in the Ne – Ar mixture.

1. Introduction

In a number of experimental studies of lasing in an active laser medium excited by a gas discharge, an electron beam, or products of nuclear reactions, simultaneous lasing on two lines having a common upper level has beens observed. In this case, two qualitatively different types of interaction between two competing lines is possible: (1) the output laser power at both lines monotonically increases with increasing pump power or (2) lasing on the line with a higher threshold quenches (sometimes totally) the first line characterised by the earlier start of lasing.

The first case is illustrated by the experiment [1], where the lasing was observed on two lines of the Ne atom at 724.5 and 703.2 nm in the Ne – Ar mixture ($p_{\mathrm{Ne}} = 1$ atm, $p_{\mathrm{Ar}} = 28$ Torr) excited by uranium fission fragments. For both lines, the laser power monotonically increased with increasing pump power (Fig. 1a). In the experiment [2], where the Ar – Xe mixture ($p_{\mathrm{Ar}} = 0.5$ atm, $p_{\mathrm{Xe}} = 3.8$ Torr) was excited by uranium fission fragments, lasing on two lines at 2.03 and 1.73 μm was obtained. Lasing on the 2.03-μm line, which has a lower threshold, completely ceased after the development of lasing on the 1.73-μm line.

A similar situation was observed for the lines of the Xe atom at 2.03 and 2.65 μm excited in the Ar – Xe mixture ($p_{\mathrm{Ar}} = 0.25$ atm, $p_{\mathrm{Xe}} = 1.9$ Torr), quenching being caused by the line at 2.65 μm [3] (Fig. 1b). Similar results were obtained for the Ar-Xe mixture pumped by an electron beam [4, 5].

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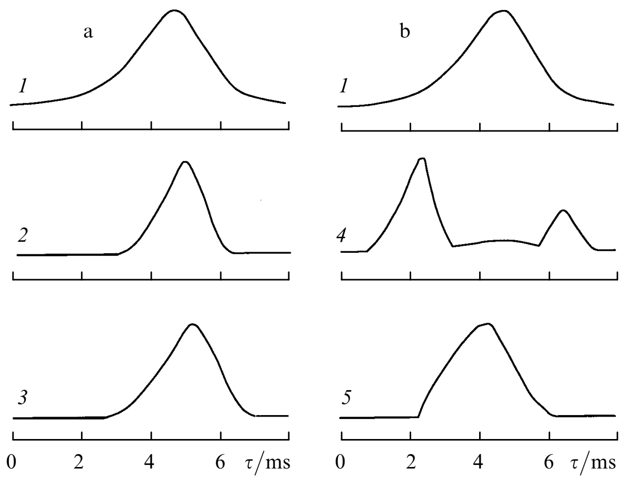

Figure 1. Oscillograms of pump pulses (*1*) and laser pulses at 724.5 (*2*) and 703.2 nm (*3*) for the Ne atom in the Ne – Ar mixture ($p_{\mathrm{Ne}} = 1$ atm, $p_{\mathrm{Ar}} = 28$ Torr) (a) and at 2.03 (*4*) and 2.65 μm (*5*) for the Xe atom in the Ar – Xe mixture ($p_{\mathrm{Ar}} = 0.25$ atm, $p_{\mathrm{Xe}} = 1.9$ Torr) (b).

The aim of this paper is to classify types of competition between two laser lines in the general form without solving the question of mechanisms responsible for the population of the upper and lower working levels. This classification naturally follows from the expression for the gain in the case of simultaneous lasing on two lines. The approach proposed here enables one to make qualitative conclusions and to obtain some quantitative estimates.

2. Kinetic equations

Consider N energy levels: 1 is a common upper working level; and 2, 3, ..., N are lower working levels. The energy level diagram is shown in Fig. 2. We use the following notations: $g_1, g_2, \ldots, g_N$ are the level degeneracy multiplicities; $\tau_1, \tau_2, \ldots, \tau_N$ are the level lifetimes; $A_{12}, A_{13}, \ldots, A_{1N}$ are the probabilities of the spontaneous $1 \to i$ transitions; and $R_1, R_2, \ldots, R_N$ are the rates of population of working levels. The model will take into account the following processes: the population of the upper and lower working levels from the continuum with the rates R_i; spontaneous $1 \to i$ transitions; induced $1 \leftrightarrow i$ transitions; and collisional level quenching. We assume that radiative coupling between the lower levels is absent. Because all the formulas are symmetric with respect to the subscripts $2 - N$, we can make the substitution $i \leftrightarrow j$ ($i \neq j = 2, 3, \ldots$

N). In further analysis, all processes in a plasma are assumed to be stationary. This assumption is rather well fulfilled for nuclear-pumped lasers [1 – 3] because characteristic times of chemical reactions in a plasma ($\tau_{pc} < 10$ ms) are much shorter than the pump pulse duration ($\tau_p \sim 1$ μs).

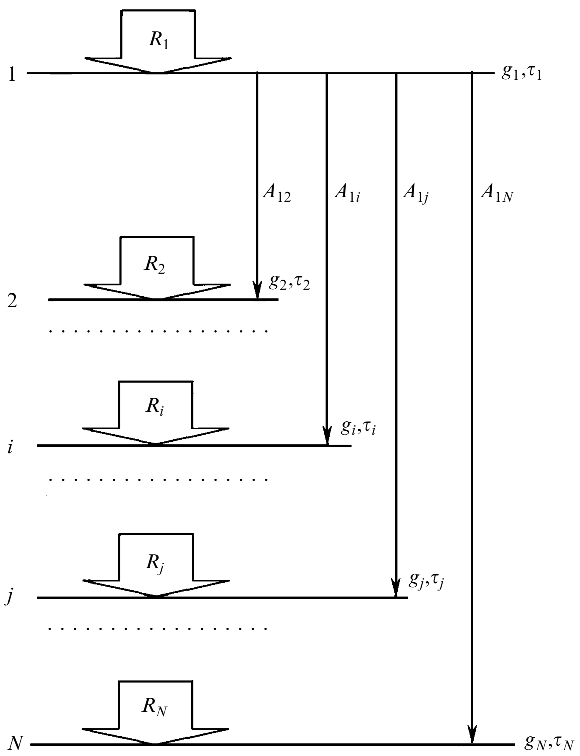

Figure 2. Energy level diagram.

The gain for the $1 \to i$ transition can be determined from the expression [6]

$$\alpha_{1i} = \sigma_{1i}\left(n_1 - \frac{g_1}{g_i}n_i\right), \quad \sigma_{1i} = \frac{c^2 A_{1i}}{4\pi^2 \nu_{1i}^2 \Delta\nu_{1i}}, \tag{1}$$

where σ_{1i} is the cross section for the stimulated $1 \to i$ transition; n_1 and n_i are the populations of the upper and lower working levels; c is the speed of light; and ν_{1i} and $\Delta\nu_{1i}$ are the frequency and Lorentzian width of the $1 \to i$ emission line. Kinetic equations for level populations have the form

$$R_1 - \frac{n_1}{\tau_1} - \sum_{i=2}^{N} \gamma_{1i} I_{1i}\left(n_1 - \frac{g_1}{g_i}n_i\right) = 0, \quad \gamma_{1i} = \frac{\sigma_{1i}}{h\nu_{1i}},$$
$$R_i - \frac{n_i}{\tau_i} + \gamma_{1i} I_{1i}\left(n_1 - \frac{g_1}{g_i}n_i\right) + A_{1i}n_1 = 0, \quad i = 2, 3, ..., N, \tag{2}$$

where I_{1i} is the radiation intensity and h is Planck's constant.

For the gain in the $1 \to i$ line corresponding, we obtain the expression

$$\alpha_{1i} = \frac{\alpha_{1i}^0 + \sum\limits_{j=2, j\neq i}^{N} \beta_{ij} I_{1j} + ... + \mu_i \prod\limits_{j=2, j\neq i}^{N} I_{1j}}{1 + \sum\limits_{j=2}^{N} (I_{1j}^{s})^{-1} I_{1j} + \sum\limits_{j=2}^{N}\sum\limits_{k>j}^{N} \delta_{jk} I_{1j} I_{1k} + ... + \varepsilon \prod\limits_{j=2}^{N} I_{1j}}, \tag{3}$$

where α_{1i}^0 is the initial gain and I_{1j}^{s} is the saturation parameter. These and other parameters $\beta_{ij}, \delta_{jk}, \mu_i, \ldots \varepsilon$ represent coefficients in the expansion of the corresponding minors of the expanded matrix of system (2) in a Maclaurin series in powers of I_{1j}. Note that the numerator of expression (3) is independent of the radiation intensity I_{1i} for the $1 \to i$ transition. The coefficients in the denominator are positive and symmetric with respect to the permutation of any two subscripts $i \leftrightarrow j\,(i \neq j = 2, 3, \ldots, N)$. This is not the case for the coefficients in the numerator.

3. The gain

Because expressions (3) are cumbersome, we will analyse simultaneous lasing on two lines $1 \to i$ and $1 \to j$ ($i \neq j$). In the presence of the competing $1 \to j$ line, the gain for the $1 \to i$ transition has the form

$$\alpha_{1i} = \frac{\alpha_{1i}^0 + \beta_{ij} I_{1j}}{1 + (I_{1i}^{s})^{-1} I_{1i} + (I_{1j}^{s})^{-1} I_{1j} + \delta_{ij} I_{1i} I_{1j}}, \tag{4}$$

where

$$\alpha_{1i}^0 = \sigma_{1i}\left[\tau_1 R_1\left(1 - \tau_i A_{1i}\frac{g_1}{g_i}\right) - \tau_i R_i \frac{g_1}{g_i}\right];$$

$$\beta_{ij} = \sigma_{1i}\gamma_{1j}\frac{g_1}{g_j}\left\{\tau_1\tau_j(R_1 + R_j)\left(1 - \tau_i A_{1i}\frac{g_1}{g_i}\right) - \tau_i R_i\left[\tau_j(1 - \tau_1 A_{1j})\frac{g_1}{g_i} + \tau_1\frac{g_j}{g_i}\right]\right\}; \tag{5}$$

$$\frac{1}{I_{1i}^{s}} = \gamma_{1i}\left[\tau_i(1 - \tau_1 A_{1i})\frac{g_1}{g_i} + \tau_1\right];$$

$$\delta_{ij} = \gamma_{1i}\gamma_{1j}\frac{g_1^2}{g_i g_j}\left[\tau_i\tau_j(1 - \tau_1 A_{1i} - \tau_1 A_{1j}) + \tau_1\tau_i\frac{g_j}{g_1} + \tau_1\tau_j\frac{g_i}{g_1}\right];$$

δ_{ij} is the mutual saturation coefficient and β_{ij} is the competition parameter taking into account the effect of radiation emitted on the $1 \to j$ transition. For $I_{1j} = 0$, from (4) follows the well-known formula for the gain in one line [6]. All the other coefficients are obtained from (5) using the substitution $i \leftrightarrow j$. Gain coefficients α_{1i} and α_{1j} have similar denominators, with $I_{1i}^{s} > 0$, $I_{1j}^{s} > 0$, and $\delta_{ij} = \delta_{ji} > 0$. The numerator of expression (4) is proportional to the rates of population of working levels, whereas the denominator is independent of these rates and takes into account the effect of saturation.

In the one-dimensional approximation, lasing on both lines is possible for $\alpha_{1i}^0 > k_{1i}$ and $\alpha_{1j}^0 > k_{1j}$, where

$$k_{1i} = \rho_{1i} - \frac{\ln\left(r_{1i}^{(1)} r_{1i}^{(2)}\right)}{2L} \tag{6}$$

is the total loss coefficient for the $1 \to i$ transition [6]; ρ_{1i} is the distributed-loss coefficient; $r_{1i}^{(1)}$ and $r_{1i}^{(2)}$ are the reflectivities of cavity mirrors (at the $1 \to i$ transition frequency); and L is the active length of an optical cavity; the form of expression (6) for the $1 \to j$ transition is similar. One should differentiate four cases depending on the sign of competition parameters: (1) $\beta_{ij} > 0$, $\beta_{ji} > 0$; (2) $\beta_{ij} < 0$, $\beta_{ji} > 0$; (3) $\beta_{ij} > 0$, $\beta_{ji} < 0$; and (4) $\beta_{ij} < 0$, $\beta_{ji} < 0$.

4. Variants of line competition

Let us analyse different variants of the competition between laser lines. To simplify the analysis, we neglect the non-uniformity of the spatial distribution of the total radiation intensity in the active medium; i.e., the local radiation intensity is assumed to be equal to the average intensity: $I_{1i} = \bar{I}_{1i}$. In the case of steady-state lasing, the average gain is equal to the total loss coefficient [6]: $\bar{\alpha}_{1i} = k_{1i}$. Under these assumptions, lasing on two lines can be described by the expression

$$\frac{\bar{\alpha}_{1i}}{\bar{\alpha}_{1j}} = \frac{\alpha^0_{1i} + \beta_{ij} I_{1j}}{\alpha^0_{1j} + \beta_{ji} I_{1i}} = \frac{k_{1i}}{k_{1j}}. \tag{7}$$

In what follows, we take for the rates R of population of the upper and lower working levels their values averaged over the length of an active medium and omit the averaging sign for simplicity. Moreover, we assume that the $1 \rightarrow i$ transition has a lower threshold than the $1 \rightarrow j$ transition, i.e., $k_{1j}\alpha^0_{1i} > k_{1i}\alpha^0_{1j}$. In this case, we obtain from (7)

$$\frac{\mathrm{d}I_{1i}}{\mathrm{d}I_{1j}} = \frac{k_{1j}\beta_{ij}}{k_{1i}\beta_{ji}}. \tag{8}$$

From this, it follows that the intensities of lasing on the $1 \rightarrow i$ and $1 \rightarrow j$ lines are mutually dependent. The character of line competition should be qualitatively determined by the relation between the signs of competition parameters β_{ij} and β_{ji}. Consider some different situations.

(1) $\beta_{ij} > 0, \beta_{ji} > 0$. This variant includes the partial case of $R_i = R_j = 0$ and corresponds to a peculiar kind of symbiosis of laser lines: For a sufficiently high pump power, lasing occurs simultaneously on both lines. Therefore, symbiosis represents the competition regime in which an increase in the intensity of one laser line is accompanied by an increase in the intensity of the second line; in this case, the intensity maxima of both laser lines are observed under the same conditions. The intensity of both laser lines increases with increasing pump power. For instance, simultaneous lasing on the lines of the Ne atom at 724.5 and 703.2 nm in the experiment [1] takes place in the symbiosis regime.

(2) $\beta_{ij} < 0$, $\beta_{ji} > 0$. In particular, this is valid for $\tau_i > 0$ and $\tau_j = 0$. In this case, the $1 \rightarrow j$ line quenches the $1 \rightarrow i$ line because lasing on the $1 \rightarrow i$ line completely ceases when the intensity of the $1 \rightarrow j$ emission transition reaches the critical value

$$I^{\mathrm{cr}}_{1j} = \frac{k_{1i}\alpha^0_{1j} - k_{1j}\alpha^0_{1i}}{\beta_{ij}k_{1j}} = \frac{\alpha^0_{1i} - k_{1i}}{k_{1i} - \beta_{ij}I^{\mathrm{s}}_{1j}} I^{\mathrm{s}}_{1j}. \tag{9}$$

The points where $I_{1i} = 0$ will be called critical points (Fig. 1b).

Thus, quenching represents the competition regime in which an increase in the intensity of one laser line causes a decrease in the intensity of the other line and vice versa. As the pump power increases, the $1 \rightarrow j$ laser line intensity monotonically increases, whereas the $1 \rightarrow i$ line intensity decreases. As the pump power is increased further, the intensity I_{1j} reaches a critical value, and lasing on the $1 \rightarrow i$ transition completely ceases at the critical point. From formula (8), it follows that the intensity maximum for one of the laser lines corresponds to the intensity minimum of the other line, the convexity of the curve describing the lasing intensity on one of the lines corresponds to the concavity of the curve for the other line, etc. For instance, lasing on the lines of the Xe atom at 2.03 and 1.73 μm (2.65 μm) takes place in the quenching regime, and the 1.73-μm line (2.65 μm) quenches the 2.03-μm line [2, 3].

(3) $\beta_{ij} > 0, \beta_{ji} < 0$. Quenching is caused by the $1 \rightarrow i$ line, which, in addition, has a lower threshold. Here, only one situation is possible: Lasing on the $1 \rightarrow i$ transition, which begins on reaching the threshold, makes lasing impossible on the second line.

(4) $\beta_{ij} < 0, \beta_{ji} < 0$. Both lines are of the quenching type, but the result does not differ from the one obtained in the previous case because lasing on the $1 \rightarrow i$ line makes lasing impossible on the second line. Note that this case, as follows from (5), is possible only for $g_i \neq g_j$ in a very narrow range of variation of the population rates R_1, R_i, and R_j.

All the aforesaid is conveniently illustrated in the diagram of competition of two laser lines (Fig. 3). On the axes, the relative population rates R_i/R_1 and R_j/R_1 are plotted. If the electron mixing of levels is insignificant and the gas temperature changes weakly, the dependence of the proportion $R_j : R_i : R_1$ on the pump power may be neglected. One may approximately assume that each combination of laser mixture, gas temperature, and pump regime is characterised by a point in the competition diagram. Simultaneous lasing on two lines is possible only inside the rectangle bounded by the straight lines $R_i/R_1 = 0$, $R_j/R_1 = 0$, $\alpha^0_{1i} = 0$, $\alpha^0_{1j} = 0$.

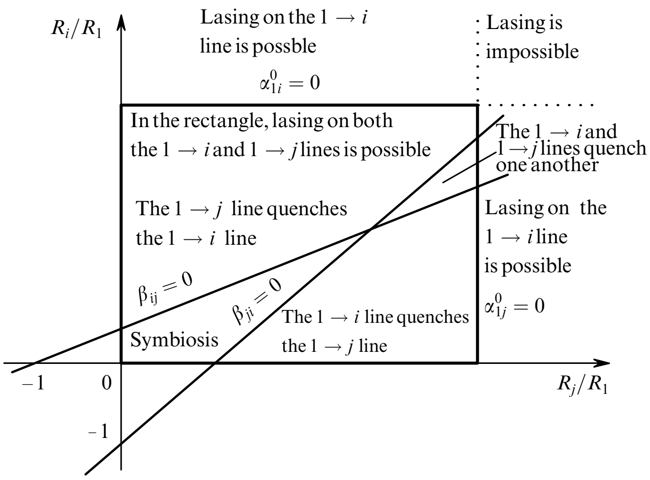

Figure 3. General view of the diagram for the competition of two laser lines.

The straight lines $\alpha^0_{1i} = 0$ and $\alpha^0_{1j} = 0$ divide the first quadrant into four domains, which qualitatively differ in the character of lasing. The spatial region inside the rectangle is divided, in turn, by the straight lines $\beta_{ij} = 0$ and $\beta_{ji} = 0$ into several domains. Note that the straight line $\beta_{ij} = 0$ necessarily passes through point $-1, 0$, and the straight line $\beta_{ji} = 0$ necessarily passes through point $0, -1$. Depending on the arrangement of these straight lines, the number of parts into which the rectangle is divided can change from one to four.

The only domain that should be necessarily present in each diagram is the symbiosis domain. Simultaneous lasing on two lines can take place only in two of four possible domains. For $\alpha^0_{1i}k_{1j} > \alpha^0_{1j}k_{1i}$ (the $1 \rightarrow i$ line has a lower threshold than the $1 \rightarrow j$ line), they represent the symbiosis domain and the domain where the $1 \to j$ line quenches the $1 \to i$ line. In two other domains, lasing can be observed only on the $1 \to i$ line. Thus, having constructed the competition diagram for the desired transition and knowing the competition type (for example, from the experiment), one can directly find the region of possible variations of the relative rates of transitions to the lower levels R_i/R_1 and R_j/R_1. Additional information (for example, the output laser power in each line) can be used to determine the population rates for the upper and lower working levels as functions of the pump power.

5. Mutual influence of competing lines

One can see from formula (4) that the intensity of radiation emitted on the $1 \to j$ transition affects the gain for the $1 \to i$ transition. Let us find the sign of the derivative of α_{ij} with respect to radiation intensity for the $1 \to i$ transition:

$$\operatorname{sign}\left(\frac{\mathrm{d}\alpha_{1j}}{\mathrm{d}I_{1i}}\right) = -\operatorname{sign}\alpha_{1i} = \operatorname{sign}\beta_{ij}\operatorname{sign}\left[I_{1j}^{\mathrm{cr}}(0) - I_{1j}\right], \tag{10}$$

$$I_{1j}^{\mathrm{cr}}(0) = I_{1j}^{\mathrm{cr}}(k_{1i} = 0) = -\alpha_{1i}^{0}(\beta_{ij})^{-1}.$$

Consider a change in the gain for the $1 \to j$ line caused by an increase in the radiation intensity I_{1i}. In the case of symbiosis, the competition parameter $\beta_{ij} > 0$, and an increase in I_{1i} results in a decrease in α_{1j}. A similar effect takes place when the $1 \to i$ line quenches the $1 \to j$ line. If, on the contrary, the $1 \to j$ line quenches the $1 \to i$ line, we have $\beta_{ij} < 0$, and an increase in I_{1i} may result both in an increase and a decrease in α_{1j}. In this case, the following variants of competition in the quenching regime can be realised depending on I_{1j} (for $\alpha_{1i}^0 > k_{1i}$, $\alpha_{1j}^0 > k_{1j}$, $\beta_{ij} < 0$, and $\beta_{ji} > 0$): (1) $0 < I_{1j} < I_{1j}^{\mathrm{cr}}$. Lasing can take place on both lines; (2) $I_{1j} = I_{1j}^{\mathrm{cr}}$. Lasing on the $1 \to i$ line vanishes; (3) $I_{1j}^{\mathrm{cr}} < I_{1j} < I_{1j}^{\mathrm{cr}}(0)$. Lasing on the $1 \to i$ line is impossible, but $\alpha_{1i} > 0$; (4) $I_{1j} = I_{1j}^{\mathrm{cr}}(0)$. The gain for the $1 \to i$ line vanishes, i.e., $\alpha_{1i} = 0$; (5) $I_{1j}^{\mathrm{cr}}(0) < I_{1j}$. The induced absorption for the $1 \to i$ line exceeds the induced gain, i.e., $\alpha_{1i} < 0$.

Thus, in the quenching regime with $I_{1j}^{\mathrm{cr}}(0) < I_{1j}$, the induced absorption at the $1 \to i$ transition exceeds the induced emission, which leads to an increase in the gain for the $1 \to j$ transition at the expense of radiation absorption at the $1 \to i$ line. One can use this effect in lasers and amplifiers to increase the lasing efficiency or increase the quenching line intensity.

Consider for illustration the line competition when the lifetime of the jth level is zero, i.e., $\tau_j = 0$. One can easily see from (5) that all coefficients are independent of the population rate R_j. As a result, we have

$$\beta_{ij} = -\sigma_{1i}\gamma_{1j}\tau_1\tau_i R_i g_1 g_i^{-1} < 0, \tag{11}$$

$$\beta_{ji} = \sigma_{1j}\gamma_{1i}\tau_1\tau_i(R_1 + R_i)g_1 g_j^{-1} > 0\,.$$

In this case, lasing takes place in the quenching regime: The $1 \to j$ line quenches the $1 \to i$ line. Given I_{1j}^{cr}, one can find the population rates R_1^{cr} and R_j^{cr} at the critical point. The corresponding formulas have the form

$$R_1^{\mathrm{cr}} = \frac{k_{1j}}{\sigma_{1j}\tau_1}\,\frac{1 + \tau_1\gamma_{1j}I_{1j}^{\mathrm{cr}}}{1 - \tau_i A_{1i} g_1 g_i^{-1}}, \tag{12}$$

$$R_i^{\mathrm{cr}} = \frac{1}{\tau_i}\frac{g_i}{g_1}\left(\frac{k_{1j}}{\sigma_{1j}} - \frac{k_{1i}}{\sigma_{1i}}\right).$$

It is interesting to note that the population rate R_i of lower working levels at the critical point is independent of the critical radiation intensity and depends only on the parameters of an optical cavity and the characteristics of laser transitions. This fact can be used to determine the dependence of R_i on the pump power by changing the cavity parameters, say, by using mirrors with other reflectivities. Indeed, a change in useful loss has no effect on chemical processes in a plasma but affects the position of the critical point, which will correspond to a different pump power.

6. Calculation results

Calculations were made for the competition of Ne atomic lines at 724.5 and 703.2 nm [1] and Xe atomic lines at 2.65 and 2.03 μm [3]. The $1 \to i$ transition corresponds to the lines at 724.5 nm or 2.65 μm, and the $1 \to j$ transition corresponds to the lines at 703.2 nm or 2.03 μm. Characteristics of the $3p[1/2]_1$, $3s[1/2]_1^{\mathrm{o}}$, and $3s[3/2]_2^{\mathrm{o}}$ levels and of the $3p[1/2]_1 \to 3s[3/2]_1^{\mathrm{o}}$ and $3p[1/2]_1 \to 3s[3/2]_2^{\mathrm{o}}$ transitions of the Ne atom are presented in Tables 1 and 2. The Ne–Ar mixture ($p_{\mathrm{Ne}} = 1$ atm, $p_{\mathrm{Ar}} = 28$ Torr) was used. The transmission of mirrors in the 700–725-nm range was 0.65 and 2.3 % [1]. Characteristics of the $5d[3/2]_1^{\mathrm{o}}$, $6p[1/2]_0$, and $6p[3/2]_1$ levels and of the $5d[3/2]_1^{\mathrm{o}} \to 6p[3/2]_1$ and $5d[3/2]_1^{\mathrm{o}} \to 6p[1/2]_0$ transitions of the Xe atom are presented in Tables 3 and 4. The Ar–Xe mixture ($p_{\mathrm{Ar}} =$ 0.25 atm,

Table 1. Characteristics of atomic transitions in Ne.

Transition notation	Transition	λ/nm	$A/10^6$ s^{-1}	$\Delta\nu/10^{10}$ s^{-1}	$\sigma/10^{-14}$ cm^2
$1 \to i$	$3p[1/2]_1 \to 3s[3/2]_1^{\mathrm{o}}$	724.5	9.4 [11]	4 [8]	3.13
$1 \to j$	$3p[1/2]_1 \to 3s[3/2]_2^{\mathrm{o}}$	703.2	25 [11]	4 [8]	7.83

Table 2. Characteristics of atomic levels of Ne.

Level notation	Level	Degeneracy multiplicity	τ_{rad}/s	$k_{\mathrm{Ne}}/10^{-14}$ cm^3 s^{-1}	$k_{\mathrm{P}}/10^{-11}$ cm^3 s^{-1}	$k_{2\mathrm{Ne}}/10^{-34}$ cm^6 s^{-1}	τ/ns
1	$3p[1/2]_1$	3	$26.7\cdot10^{-9}$ [11]	$1.7\cdot10^3$ [14]	6.3 [15]	0	1.53
i	$3s[3/2]_1^{\mathrm{o}}$	3	$51\cdot10^{-6}$ [12]	5.1 [12]	16 [16]	40 [12]	6.15
j	$3s[3/2]_2^{\mathrm{o}}$	5	22.4 [13]	0	9.7 [16]	4.8 [15]	10.37

Table 3. Characteristics of atomic transitions in Xe.

Transmition notation	Transmition	$\lambda/\mu m$	$A/10^6\ s^{-1}$	$\Delta\nu/10^{10}\ s^{-1}$	$\sigma/10^{-14}\ cm^2$
$1 \to i$	$5d[3/2]_1^o \to 6p[1/2]_0$	2.65	1.3 [7]	1.5 [8]	14.23
$1 \to j$	$5d[3/2]_1^o \to 6p[3/2]_1$	2.03	2.5 [7]	1.93 [8]	13.5

Table 4. Characteristics of atomic levels of Xe.

Level notation	Level	Degeneracy multiplicity	τ_{rad}/ns	$k_{Ar}/10^{-13}\ cm^3\ s^{-1}$	$k_{Xe}/10^{-12}\ cm^3\ s^{-1}$	τ/ns
1	$5d[3/2]_1^o$	3	200 [7]	1 [9]	200 [9]	52.3
i	$6p[1/2]_0$	1	22.4 [7]	140* [9] 200 [19]	5.8* [9] 5.9 [19]	1.02
j	$6p[3/2]_1$	3	30 [7]	20* [10] 17.6 [18]	115* [9] 113 [18]	18.3

* Values of constants used in the calculations.

$p_{Xe} = 1.9$ Torr) was used. The transmission of mirrors was 0.5 and 1 % for the 2.03-μm line and 50 % for the 2.65-μm line [3]. In both cases, an optical cavity had the active length $L = 2$ m. The lifetime of Xe atomic levels in the Ar–Xe mixture is determined by the formula

$$\tau^{-1} = \tau_{rad}^{-1} + k_{Ar}[Ar] + k_{Xe}[Xe], \tag{13}$$

where τ_{rad} is the radiative lifetime and k_{Ar}, k_{Xe} are constants of collisional quenching of the above levels by argon and xenon atoms. The total reciprocal lifetime of Ne atomic levels in the Ne-Ar mixture is given by

$$\tau^{-1} = \tau_{rad}^{-1} + k_P[Ar] + k_{Ne}[Ne] + k_{2Ne}[Ne]^2, \tag{14}$$

where k_P is the constant of Penning process and k_{2Ne} is the rate constant of the three-body process $Ne^* + 2Ne \to Ne_2^* + Ne$.

Fig. 4 presents competition diagrams for Xe lines at 2.65 and 2.03 μm and Ne lines at 724.5 and 703.2 nm. The domains with semibold italic lettering correspond to the results of experiments [1, 3]. Note that the symbiosis domain for Ne is the dominant one, and therefore lasing on the lines at 734.5 and 703.2 nm can take place only in this regime, which was observed in the experiments [1]. From Fig. 4b, it follows that lasing on two lines is much more difficult to obtain in neon than in xenon because the relative rates of population of the lower working levels should not exceed 0.2 and small variations in the concentration of Ar, which quenches the lower working levels, can cause changes in the laser emission spectrum. Indeed, in experiment [1], the authors observed lasing on the 724.5-nm line for the partial argon pressure $p_{Ar} = 19$ Torr and on the 703.2-nm line for $p_{Ar} = 61$ Torr, and lasing on two lines was observed only for $p_{Ar} = 28$ Torr.

Because of the relatively short lifetime of the lower working levels $6p[1/2]_0$ and $6p[3/2]_1$ of the Xe atom compared to the lifetime of the upper working level $5d[3/2]_1^o$, the Ar–Xe mixture has a considerably lower sensitivity to a change in the component concentration. The competition diagram (Fig.4a) shows that simultaneous lasing on two lines is possible even if the relative rates of population of the lower working levels exceed unity. Note that, the lifetime of the $6p[1/2]_0$ level is

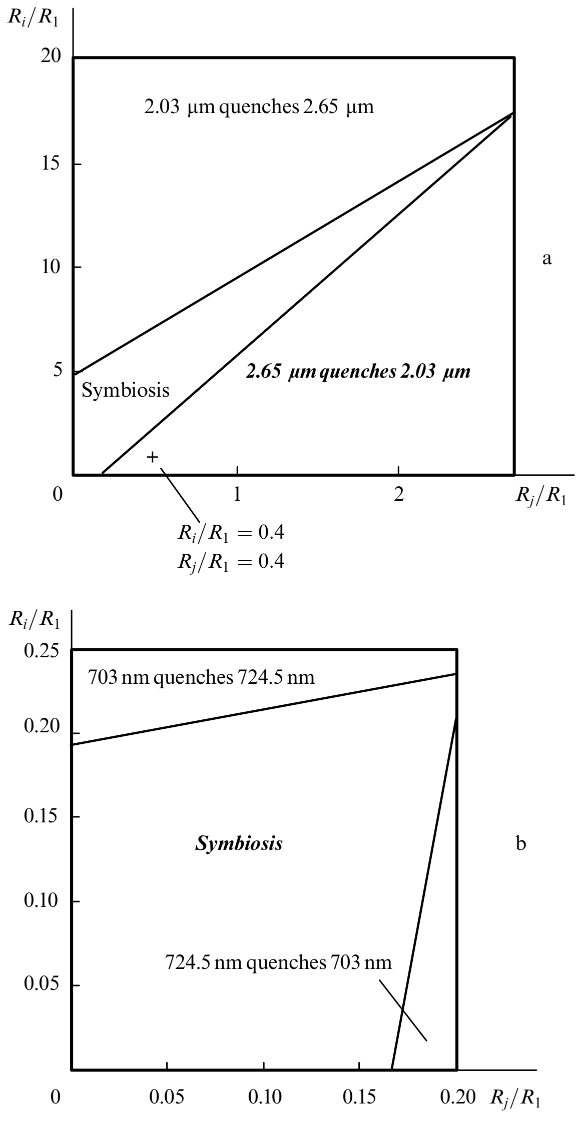

Figure 4. Diagrams for the competition of two laser lines of the Xe atom at 2.03 and 2.65μm in the Ar–Xe mixture ($p_{Ar} = 0.25$ atm, $p_{Xe} = 1.9$ Torr) (a) and two lines of the Ne atom at 724.5 and 703.2 nm in the Ne–Ar mixture ($p_{Ne} = 1$ atm, $p_{Ar} = 28$ Torr) (b).

of the xenon atom shorter than the lifetime of its $6p[3/2]_1$ level by a factor of about 20, whereas the population rates of these levels are approximately equal. As a result, the 2.65-μm line quenches the 2.03-μm line.

To estimate the population rate of the $6p[3/2]_1$ level at the critical point, we set $\tau_i = 0$. By assuming that the distributed-loss coefficients ρ_{1i} and ρ_{1j} are zero, we obtain from formula (12) that the population rate of the $6p[3/2]_1$ level at critical points is $R_j^{\mathrm{cr}} \approx 1.2 \times 10^{18}$ s^{-1} cm^{-3}. In this case, the neutron fluxes at critical points are approximately equal, and their values are about 10^{15} cm^{-2} s^{-1} [3] (Fig. 1b). By assuming that the $5d[3/2]_1^{\mathrm{o}}$ level of the Xe atom is selectively populated due to dissociative recombination of the Xe_2^+ molecular ions with electrons [17], the population rate of the $5d[3/2]_1^{\mathrm{o}}$ level at critical points can be estimated as $R_1^{\mathrm{cr}} \approx 3 \times 10^{18}$ s^{-1} cm^{-3}. If the relative population rates of the lower working levels are approximately equal, we have $R_i/R_1 \approx R_j/R_1 \approx 0.4$. The position of this point in Fig. 4a is indicated by the cross.

7. Conclusions

The analysis of the competition between two laser lines having a common upper level suggests the following conclusions:

(1) Two qualitatively different kinds of competition are possible, namely, symbiosis and quenching. The character of competition is determined by the signs of competition parameters.

(2) Symbiosis is possible for those transitions whose lower working levels differ in characteristics insignificantly and have close lifetimes, degeneracy multiplicities, and population rates. Symbiosis is characterised by parallel changes in laser line intensities: An increase in the intensity of one line is accompanied by an increase in the intensity of the other line, the intensity maxima and minima of the lines coincide with one another, etc.

(3) The quenching regime is typical of 'asymmetric' lines (strongly different in lifetime or the population rate of the lower working levels). Lasing in the quenching regime is characterised by antiparallel behaviour. An increase in the intensity of one line is accompanied by a decrease in the intensity of the other line, the intensity maximum of one line corresponds to the intensity minimum of the other one, etc.

(4) One can plot a competition diagram for each of the competing levels. Lasing can be qualitatively different depending on the population rates of the upper and lower working levels. To each competition type corresponds a certain domain of variation of the population rates of the upper and lower levels in the diagram.

(5) In the case of competition in the quenching regime, one can obtain at the critical point two relationships between the population rates of the upper and lower working levels. The simplest case is obtained for the zero lifetime of the lower level of the quenching line. In this case, one can theoretically determine the population rate of lower level of the quenched line at the critical point. This fact can be used to determine the population rate of the lower level of the quenched line by varying parameters of an optical cavity.

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