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Dynamics of frequency-selective operation of a CO laser tunable in a wide spectral range

A.K. Kurnosov, A.P. Napartovich

Abstract. **This paper presents a computational/theoretical analysis of the generation of a single pulse by a frequency-selective electron-beam sustained discharge CO laser. The calculations have been performed using a theoretical model in which the entire set of VV exchange processes involving CO molecules at high vibrational levels is taken into full account. We present calculated pulse shapes for a wide range of transitions, including transitions between high vibrational levels, and examine the possibility of raising the laser output intensity by optimising the density and composition of the gain medium.**

Keywords: *frequency-selective CO laser, transitions between high vibrational levels, theoretical model, single- and multi-quantum VV exchange processes.*

1. Introduction

Electron-beam sustained discharge (EBSD) CO lasers operating at cryogenic temperatures of their gain medium offer one of the highest efficiencies (up to 60 %) among electric discharge gas lasers [1]. Without selection of individual transitions, the emission spectrum of such lasers has the form of a set (~10) of rovibrational transitions in vibrational bands from $v = 4 \rightarrow 3$ to $v = 12 \rightarrow 11$. Note that more than 90% of the emission energy is typically accounted for by transitions with a vibrational quantum number of the upper laser level $v < 10$.

Frequency selection enables lasing on individual rovibrational transitions in a considerably wider range of vibrational transitions, up to the $v = 39 \rightarrow 38$ band inclusive [2]. Moreover, in each vibrational band, lasing can be obtained on a relatively large number (~10) of rotational transitions. A wide spectral tuning range, with the long-wavelength limit corresponding to transitions in the $v = 38 \rightarrow 36$ band, including about 400 rovibrational transitions, is also characteristic of frequency-selective CO overtone lasing [3]. The corresponding tuning ranges are 5–8.7 μm for the fundamental frequency and 2.5–4.2 μm for overtone lasing. The emission spectrum for a number of rovibrational transitions of CO molecules in these ranges overlaps with absorption bands of various atmospheric impurities, including many organic and inorganic compounds, and falls in atmospheric transmission windows. For these reasons, the use of frequency-selective CO laser operation allows one to resolve many applied issues, which were discussed e.g. in Refs [3–6].

Since experimental investigation of characteristics of frequency-selective EBSD CO lasers in a wide range of transitions is expensive and difficult to perform, there is much need for computational/theoretical studies of such lasers. Moreover, theoretical studies allow one to gain insight into the typical behaviour of laser characteristics upon variations in gain medium and cavity parameters in significantly wider ranges than is possible with a particular experimental setup or even several setups. The current level of theoretical models for the gain medium of CO lasers allows one to adequately describe laser characteristics, not only qualitatively but also quantitatively, including lasing on transitions with vibrational quantum numbers of the upper laser level $v > 20$. In the case of CO molecules at these high vibrational levels, the rate constants of multi-quantum VV exchange processes are of the same order as those of single-quantum processes. Today, the most detailed and reasonable description of vibrational energy exchange processes in the gain medium of CO lasers in a wide range of vibrational levels is ensured by a theoretical model reported in Refs [7, 8].

It was used to study the energy performance of frequency-selective pulsed EBSD CO lasers operated on a single rovibrational transition or a few transitions in neighbouring vibrational bands [9]. Frequency-selective lasing was shown to be capable of substantially increasing the emission energy of CO lasers operated on a single rovibrational transition or a few neighbouring transitions relative to the energy emitted on the same transitions in the case of a CO laser having a nonselective cavity with the same threshold level. The largest increase in emission energy is ensured by selective lasing on transitions between comparatively high vibrational levels. A similar conclusion was drawn by Aleksandrov et al. [10]: in calculating characteristics of frequency-selective CO lasers, vibrational kinetics were described in a significantly simplified way; namely, only single-quantum VV exchange processes were taken into account. This approach is only justified in describing VV exchange processes between CO molecules at lower vibrational levels with $v < 10$, which limits the applicability of the results obtained in that study [10]. The above simplification was shown to significantly distort calculation results for transitions between high vibrational levels [9].

Previous theoretical predictions [9, 10] do not help assess the feasibility of practical application of frequency-selective pulsed EBSD CO lasers, because they contain only calculated

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energy characteristics of the lasers. In practice, researchers are often interested in the laser pulse shape because high light intensity is required in many applications. In this paper, we report a computational/theoretical study of the dynamics of frequency-selective pulsed EBSD CO laser operation on individual rovibrational transitions. We present the shape of light pulses in a wide range of transitions, including transitions between high vibrational levels, and examine the possibility of raising the laser output power by optimising the density and composition of the gain medium.

2. Calculation results and discussion

As in a previous study [9], our calculations rely on a model for the gain medium in which the entire set of single- and multi-quantum vibrational energy exchange processes in a $CO-N_2-He/Ar$ gas mixture is taken into full account. The model was described in detail elsewhere [7, 8] and is not presented here.

The dynamics of frequency-selective lasing were first calculated for the same conditions as in a previous study [9]: gas number density of 0.2 amg, mixture composition $CO:N_2 = 1:9$, initial temperature of 100 K, reduced electric field strength $E/N = 1\times10^{-16}$ V cm^2 and pump pulse duration of 30 μs. The pulse energy per unit gas density was 200 J L^{-1} amg^{-1}. The unit of number density used here, amagat, is the number of ideal gas molecules per unit volume under normal conditions. Current and voltage pulses were taken to be rectangular and the density of the medium was thought to be constant. Calculations were made for a threshold gain coefficient in the cavity $G_{th} = 5.27\times10^{-4}$ cm^{-1}. For a 100-cm-long gain medium, this G_{th} value corresponds to a round-trip cavity loss of 10%. Possible passive losses (due to absorption and scattering) in the cavity were left out of consideration. Frequency-selective laser pulses in various vibrational bands were calculated for a fixed rotational number, $J = 12$, of the lower laser level. Transitions with this rotational number were chosen because the associated gain approaches the maximum values at the above parameters of the gain medium. In calculating overtone lasing, we assumed that there was no lasing in the fundamental band.

Figure 1 shows laser pulse shapes calculated for single-frequency selective lasing on the $v = 10 \to 8$ P(12), $v = 14 \to 12$ P(12), $v = 24 \to 22$ P(12) and $v = 34 \to 32$ P(12) overtone transitions at the above gain medium, pump and cavity parameters.

It is easy to see that increasing the vibrational quantum number v of the upper laser level sharply increases the frequency-selective pulse duration and reduces the light intensity. The half-power pulse duration was 40.1, 91.8, 441.9 and 511.4 μs for pulses *1*, *2*, *3* and *4*, respectively (Fig. 1). The main cause of the significant differences in pulse shape between these transitions is that lasing on them occurs in different stages of the formation of the quasi-stationary distribution function (QDF) of CO molecules. Whereas lasing on lower transitions begins after the excitation wave passes through the upper laser level and stops mainly before a quasi-stationary QDF sets in throughout the plateau, the duration of lasing on a transition between high vibrational levels can be of the same order as the quasi-stationary QDF lifetime.

If it is necessary to raise the power of selective lasing on transitions between high vibrational levels, special measures should be taken to accelerate VV exchange processes, which ensure pumping of the upper laser level. In particular, this can be achieved by using a higher density gain medium, while maintaining the specific energy deposition per molecule constant or increasing it. In this context, it is worth noting work by Konev et al. [11], who examined ways of reducing the pulse duration for selective lasing on individual transitions of the P branch in the $v = 10 \to 9$ band by raising the density of the gain medium consisting of a gas mixture with $CO:Ar = 1:10$. According to calculation results in that study, the full pulse duration at half maximum drops by about one order of magnitude as the gas pressure is raised from 100 to 1000 Torr, without changes in specific energy deposition. The decrease in selective lasing pulse duration with an increase in the density of the gain medium, reported by Konev et al. [11], should show up as well in the case of selective lasing on transitions between higher vibrational levels, but to quantitatively describe it one should take into account VV exchange processes with different numbers of quanta being exchanged, which is brought about by a theoretical model presented in Refs [7, 8].

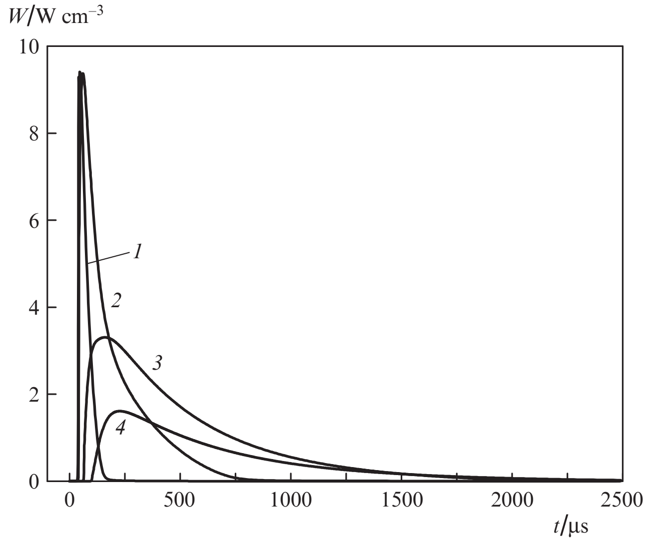

Figure 1. Shape of frequency-selective CO overtone lasing pulses for the (*1*) $v = 10 \to 8$ P(12), (*2*) $v = 14 \to 12$ P(12), (*3*) $v = 24 \to 22$ P(12) and (*4*) $v = 34 \to 32$ P(12) transitions. Gas number density is 0.2 amg.

The output power on an individual rovibrational transition can also be raised by cavity Q switching in the case of generation of both a single pulse and a series of pulses with a duration in the range 1–10 μs and a repetition rate of $\sim10^5$ Hz [12].

As mentioned above, in this study we numerically investigate the effect of an increase in the density of the gain medium on the dynamics of frequency-selective EBSD CO laser operation. We assume that, with increasing gain-medium density, specific energy deposition remains unchanged. This can be ensured in an EBSD by using a higher voltage across the discharge gap and a higher current density of high-energy electrons. In this context, note a study by Basov et al. [13], who examined operation of an EBSD CO laser at a density of the gain medium increased to 1 amg. In calculations for an increased gain-medium density, neither resonance amplification nor absorption of laser light on the P or R branch of neighbouring vibrational bands of $^{12}C^{16}O$ or $^{13}C^{16}O$ molecules was taken into account. In frequency-selective lasing experiments at an increased gas density, the effect of the indicated overlap of spectral lines can lead to both amplification and attenuation of the lasing intensity on the required rovi-

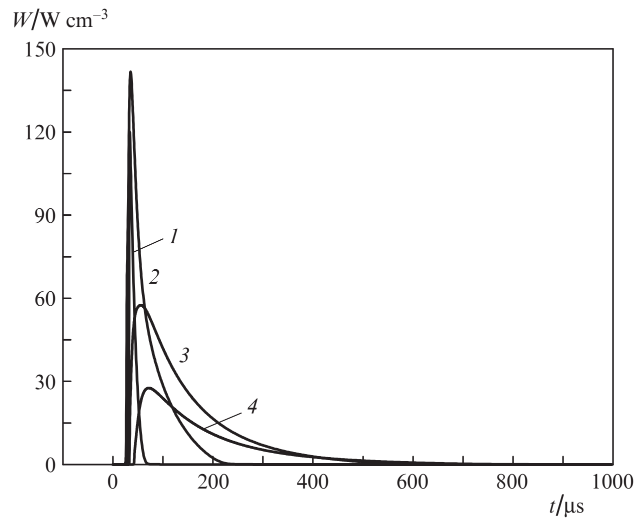

Figure 2. Shape of frequency-selective CO overtone lasing pulses for the (*1*) $v = 10 \rightarrow 8$ P(12), (*2*) $v = 14 \rightarrow 12$ P(12), (*3*) $v = 24 \rightarrow 22$ P(12) and (*4*) $v = 34 \rightarrow 32$ P(12) transitions. Gas number density is 0.8 amg.

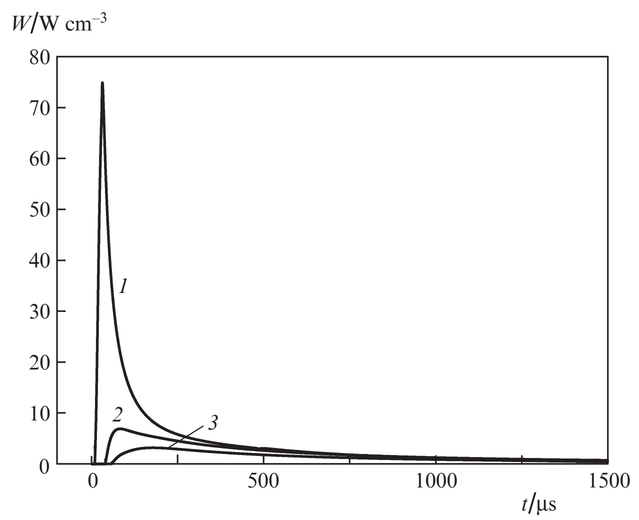

Figure 3. Shape of frequency-selective CO laser pulses for the (*1*) $v = 7 \rightarrow 6$ P(12), (*2*) $v = 20 \rightarrow 19$ P(12) and (*3*) $v = 27 \rightarrow 26$ P(12) transitions. Gas number density is 0.2 amg.

brational transition. If necessary, this effect can be taken into account in calculations [13].

Figure 2 shows laser pulses calculated for the same transitions as in Fig. 1 at a gas density increased by four times.

In those calculations, the other parameters of the gain medium, cavity and discharge were the same as above. It is easy to see that the fourfold increase in gas density is accompanied by a considerable rise in output power and a decrease in pulse duration. The characteristic pulse durations $\tau_{0.5}$ for the $v = 10 \rightarrow 8$ P(12) (*1*), $v = 14 \rightarrow 12$ P(12) (*2*), $v = 24 \rightarrow 22$ P(12) (*3*) and $v = 34 \rightarrow 32$ P(12) transitions decreased by a factor of 4.1, 3.4, 4.3 and 4.2, respectively, and the maximum output power per unit volume of the gain medium, W_{max}, for these transitions increased by a factor of 12.8, 15.1, 17.4 and 17.2, respectively. Note that, in a spatially uniform model, the specific output power is related to the output intensity I by $I = WL$, where L is the length of the gain medium. The above increase in specific power is mainly due to two factors: the increase in pump power per unit density and the acceleration of the VV exchange processes responsible for population inversion. Similar changes in lasing dynamics in response to an increase in the density of the gain medium at a constant energy deposition were obtained in calculations of characteristics of a frequency-selective CO laser at the fundamental frequency. Figure 3 shows laser pulses calculated for single-frequency selective lasing on the $v = 7 \rightarrow 6$ P(12), $v = 20 \rightarrow 19$ P(12) and $v = 27 \rightarrow 26$ P(12) transitions at a gas density of 0.2 amg and the same parameters of the gain medium, pumping and cavity as above.

The duration $\tau_{0.5}$ of the pulses was 36, 316 and 488 μs, respectively. Laser pulses calculated for the same transitions but at a gas density of 0.8 amg are shown in Fig. 4. Their duration $\tau_{0.5}$ is a factor of 1.4, 4 and 4.3 shorter than that of the pulses in Fig. 3. The maximum output power per unit volume for the transitions under consideration is about one order of magnitude higher than that of the pulses in Fig. 3.

The calculation results presented in Figs 1–4 were obtained for a relatively high-finesse cavity with a threshold gain coefficient $G_{th} = 5.27 \times 10^{-4}$ cm^{-1}. For an overtone laser, such low G_{th} values are necessary to reach acceptable electro-optical efficiency values. In EBSD CO lasers, the small-signal

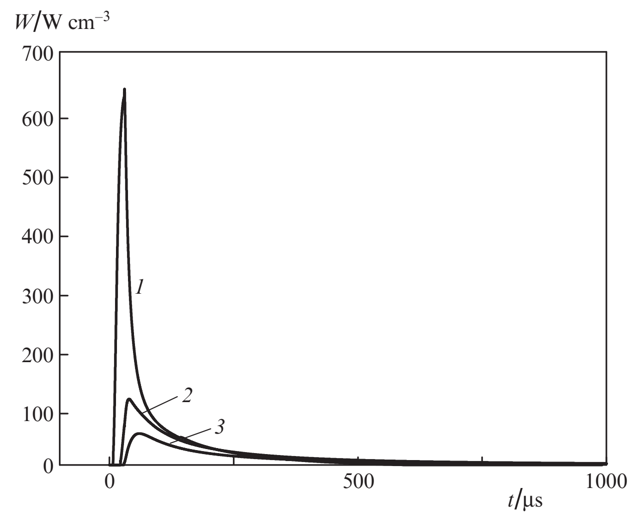

Figure 4. Shape of frequency-selective laser pulses for the (*1*) $v = 7 \rightarrow 6$ P(12), (*2*) $v = 20 \rightarrow 19$ P(12) and (*3*) $v = 27 \rightarrow 26$ P(12) transitions. Gas number density is 0.8 amg.

gain coefficient (SSGC) at the fundamental frequency can be an order of magnitude higher than that for overtone transitions [3] and, hence, G_{th} in the selective cavity of a CO laser at the fundamental frequency can be several times higher. Because of this, calculations for lasing dynamics at the fundamental frequency were also made for a high G_{th} value of 0.002 cm^{-1}, corresponding to a round-trip cavity loss of 33% in a 100-cm-long gain medium. In the calculations, the characteristic laser pulse durations varied only slightly compared to the calculation results at $G_{th} = 5.27 \times 10^{-4}$ cm^{-1} because the gain coefficients strongly exceeded the threshold values indicated. The composition of the gain medium can also have a significant effect on the laser pulse shape. Calculations of frequency selective lasing were made for not only a nitrogen-containing mixture with $CO:N_2 = 1:9$ but also helium-containing mixtures with CO:He = 1:9 and 1 : 2. In the calculations for these mixtures, the E/N parameter and the pump pulse shape and duration were the same as above. The density

Table 1. Characteristics of frequency-selective EBSD CO laser pulses at various parameters of the gain medium and cavity.

$v \to v'(J)$ transition	N/amg	G_{th} /10^{-3} cm^{-1}	$CO:N_2 = 1:9$		$CO:He = 1:9$		$CO:He = 1:2$	
			W_{max}/W cm^{-3}	$\tau_{0.5}$/μs	W_{max}/W cm^{-3}	$\tau_{0.5}$/μs	W_{max}/W cm^{-3}	$\tau_{0.5}$/μs
$10 \to 9(12)$	0.1	2	10.3	99.9	27.4	50.7	7.3	127
$10 \to 9(12)$	0.8	2	430	26.2	731	23	371	23
$35 \to 34(12)$	0.1	2	0.37	876.3	0.49	270	0.17	567
$35 \to 34(12)$	0.8	2	25.9	105	30.7	34.4	11.7	73.4
$14 \to 12(12)$	0.1	0.527	2.07	177	7.03	102	1.49	224
$14 \to 12(12)$	0.8	0.527	142	27.2	309	23.8	109	31.3
$32 \to 30(12)$	0.1	0.527	0.39	960	0.67	243	0.25	532
$32 \to 30(12)$	0.8	0.527	28.6	117	43.5	31.5	17.6	70.6

Table 2. Frequency-selective EBSD CO laser efficiency at various parameters of the gain medium and cavity.

$v \to v'(J)$ transition	N/amg	G_{th} /10^{-3} cm^{-1}	$CO:N_2 = 1:9$		$CO:He = 1:9$		$CO:He = 1:2$	
			efficiency (%)	efficiency* (%)	efficiency (%)	efficiency* (%)	efficiency (%)	efficiency* (%)
$10 \to 9(12)$	0.1	2	16.1	3.9	15.1	5.28	9.70	3.56
$10 \to 9(12)$	0.8	2	17.4	5.4	15.6	8.47	10.2	3.97
$35 \to 34(12)$	0.1	2	2.21	1.24	0.65	0.55.	0.52	0.39
$35 \to 34(12)$	0.8	2	2.44	1.31	0.66	0.54	0.56	0.43
$14 \to 12(12)$	0.1	0.527	2.95	1.43	5.56	2.76	2.32	1.32
$14 \to 12(12)$	0.8	0.527	3.93	1.82	6.2	3.45	3.14	1.64
$32 \to 30(12)$	0.1	0.527	2.41	1.47	0.82	0.70	0.71	0.54
$32 \to 30(12)$	0.8	0.527	2.78	1.62	0.85	0.70	0.82	0.63

of the gain medium was varied, whereas the specific energy deposition was also taken to be constant at 200 J L^{-1} amg^{-1}. The calculations were made for selective lasing pulses at the fundamental frequency and an overtone in the above mixtures at gas densities of 0.1 and 0.8 amg. The calculation results are illustrated by the data in Table 1, which presents the calculated parameter $\tau_{0.5}$ and output power per unit volume, W_{max}. These data illustrate major trends in the variation of the output pulse shape with the composition and density of the gain medium in relation to the vibrational quantum number of the upper laser level.

In addition to the shape and duration of CO laser pulses, it is important to know the energy characteristics of the laser: emission energy and efficiency. In the range of gain medium densities examined and at a constant specific energy deposition, the emission energy rises roughly in proportion to the gas density. Table 2 presents the calculated lasing efficiency at the same gain medium and cavity parameters as in Table 1.

Since in a number of cases the calculated output power slowly falls off over time, it is of interest to find efficiency values corresponding to the energy emitted in the time interval during which the output power is greater than or equal to $W_{max}/2$. Such efficiency values are also given in Table 2 (denoted as efficiency*).

The slight increase in efficiency with increasing gain-medium density is mainly due to the reduction in the role of VT relaxation processes and vibrational energy redistribution between CO and N_2 as a result of the decrease in pulse duration. The efficiencies presented in Table 2 were calculated for the case where the cavity loss is only due to output coupling. A real cavity has internal losses as well. To take these into account, the efficiency values in Table 2 should be multiplied by a correction factor: the ratio of the transmission loss to the total loss.

3. Conclusions

Calculations of the dynamics of frequency-selective EBSD CO laser operation at gain-medium densities of 0.1 and 0.2 amg indicate that, as the vibrational quantum number v of the upper laser level rises, the calculated frequency-selective pulse duration rises sharply and the output power drops. This behaviour is most pronounced in the case of transitions with $v > 20$, which may impede practical application of light from EBSD CO lasers at their fundamental frequency or an overtone in the wavelength ranges 6–8.7 and 3–4.2 μm. The present results demonstrate the possibility of considerably reducing the pulse duration and raising the maximum output power on such transitions (by about one to two orders of magnitude) by increasing the density of the gain medium to 0.8 amg without changing the specific energy deposition. The calculation results for gas mixtures with $CO:He = 1:9$ and $1:2$ are qualitatively similar to those obtained for a $CO:N_2$ mixture.

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References

1. Mann M.M. *AIAA J.*, **14**, 549 (1976).
2. Ionin A.A., Kinyaevskiy I.O., Klimachev Yu.M., Kotkov A.A., Kozlov A.Yu. *Opt. Lett.*, **42**, 498 (2017).
3. Ionin A.A., Kurnosov A.K., Napartovich A.P., Seleznev L.V. *Laser Phys.*, **20**, 144 (2010).
4. Eerkens J.W. *Appl. Phys.*, **10**, 15 (1976).
5. Urban W. *Infrared Phys. Technol.*, **36**, 465 (1995).
6. Ionin A.A., Klimachev Yu.M., Kozlov A.Yu., Kotkov A.A., Romanovskii O.A., Seleznev L.V., Sinitsyn D.V., Kharchenko O.V., Shelestovich A.V., Yakovlev S.V. *Izv. Vyssh. Uchebn. Zaved., Fiz.*, **11**, 76 (2008).

7. Billing G.D. Coletti C., Kurnosov A.K., Napartovich A.P. *J. Phys. B: At., Mol. Opt. Phys.*, **36**, 1175 (2003).
8. Cacciatore M., Kurnosov A., Napartovich A., Shnyrev S.L. *J. Phys. B: At., Mol. Opt. Phys.*, **37**, 3379 (2004).
9. Kurnosov A.K., Napartovich A.P., Shnyrev S.L. *Quantum Electron*., **34** (1), 1 (2004) [*Kvantovaya Elektron.*, **34** (1), 1 (2004)].
10. Aleksandrov B.S., Belavin V.A., Dymshitss B.M., Koretskii L.P. *Quantum Electron*., **27** (7), 584 (1997) [*Kvantovaya Elektron*., **24** (7), 601 (1997)].
11. Konev Yu.B., Kochetov I.V., Pevgov V.G. *Sov. J. Quantum Electron*., **9** (8), 947 (1979) [*Kvantovaya Elektron*., **6** (8), 1605 (1979)].
12. Ionin A.A., Klimachev Yu.M., Kobza G., Sinitsyn D.V. *Quantum Electron*., **27** (3), 189 (1997) [*Kvantovaya Elektron*., **24** (3), 195 (1997)].
13. Basov N.G., Dolinina V.I., Zimina O.V., Kazakevich V.S., Kovsh I.B., Suchkov A.F., Urin B.M. *Sov. J. Quantum Electron*., **12** (4), 476 (1982) [*Kvantovaya Elektron*., **9** (4), 772 (1982)].