Quantum Electronics **34** (7) 625 – 629 (2004)

PACS numbers: 42.55.Lt; 42.60.Lh
DOI: 10.1070/QE2004v034n07ABEH002814

Experimental investigation of the effect of HBr additions on the lasing characteristics of a CuBr laser

D.V. Shiyanov, V.B. Sukhanov, G.S. Evtushenko, O.S. Andrienko

***Abstract*. It was experimentally determined that introducing small additions of HBr into the active elements of a CuBr laser is similar to the addition of hydrogen and significantly improves the output laser parameters. The effect of additions to small-volume active elements is most pronounced (up to a five-fold increase in output power) and is less pronounced in large-volume active elements (up to a twofold increase). A special-purpose HBr generator was elaborated, making it possible to promptly provide the requisite concentration of the active addition in a sealed-off active element.**

Keywords: *copper bromide vapour laser, hydrogen bromide generator.*

1. Introduction

At present, primary emphasis in the investigation of metal vapour lasers (MVLs) is placed on lasers in which the active medium is modified with the use of different halogen-containing compounds of the working metal with subsequent addition of hydrogen or active impurities (HCl, HBr, etc.) to the active medium [1, 2]. The above modification allows an improvement both of the energy and repetition-rate characteristics and of the output beam quality for these lasers. Because of this, such lasers find application in the modern systems for high-speed optical data storage, material microprocessing, laser atmospheric probing, laser isotope separation, etc. [2 – 4]. Among MVLs, copper and copper compound vapour lasers are known to attract the greatest interest for practical applications.

The improvement of energy characteristics and the extension of the range of optimal pulse-repetition rates for a copper vapour laser by the addition of molecular hydrogen were first reported as far back as 1980 [5]. Quite recently it was reported that the Istok State Research and Production Association started developing the production of sealed-off 'Kristall' active elements with a hydrogen addition, which made it possible to increase the average output power by a factor of 1.5 [6]. As for the addition of hydrogen to the active medium of a copper bromide vapour laser, it resulted not only in a twofold increase of the output power, but a substantial rise in the lasing efficiency as well (up to 3 %) [7]. The idea of introducing hydrogen into the active media of metal salt vapour lasers was realised in hybrid lasers (HyBrID), where a hydrogen halide (HBr) was pumped through the working region together with a buffer gas (neon). The free bromine atoms, which were produced after the dissociation of HBr molecules, form CuBr molecules in the interaction with metal copper. Then, similarly to the copper bromide vapour laser [8, 9], the CuBr dissociation in a repetitively pulsed discharge produces the required working density of free copper atoms. It has been just this type of an MVL which has allowed achieving the maximum radiation output from a single active element equal to more than 200 W, the lasing efficiency of over 3 % [10], and the highest specific average output power equal to 2 W cm^{-3} [11].

Despite the fact that most outstanding lasing characteristics were obtained for hybrid lasers and the lasers with improved kinetics [12], these systems are gas-flow lasers and are therefore of limited utility. Employing the Ne – H$_2$ or Ne – HBr mixtures in sealed-off Cu or CuBr lasers implies the solution of the problem of long-term maintenance of the required amount of hydrogen in the active element of the laser. In the last few years, this became possible by using selective reversible hydrogen leak (SRHL) systems, produced by the Pulsed Technologies Ltd (Ryazan) [13], or a special-purpose HBr generator [14].

In this work, we studied experimentally the effect of HBr additions on the energy characteristics of a copper bromide laser in comparison with the effect of hydrogen additions for the purpose of developing a sealed-off active element.

2. Experimental

The energy characteristics of CuBr lasers with the additions of HBr (H$_2$) were investigated with gas-discharge tubes (GDTs) scalable in the length and diameter of the active region. The GDTs were made without diaphragms limiting the beam aperture. We used two GDT design versions (Fig. 1), which differed in the method of supplying the working substance vapour to the active region: with an independent heating of containers with CuBr [15] or with self-heating [16]. The parameters of these GDTs are collected in Table 1.

D.V. Shiyanov, V.B. Sukhanov, O.S. Andrienko Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Akademicheskii prosp., 1, 634055 Tomsk, Russia;
G.S. Evtushenko Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Akademicheskii prosp. 1, 634055 Tomsk, Russia; Tomsk Polytechnical University, prosp. Lenina 30, 634050 Tomsk, Russia

Received 24 February 2004
Kvantovaya Elektronika **34** (7) 625 – 629 (2004)
Translated by E.N. Ragozin

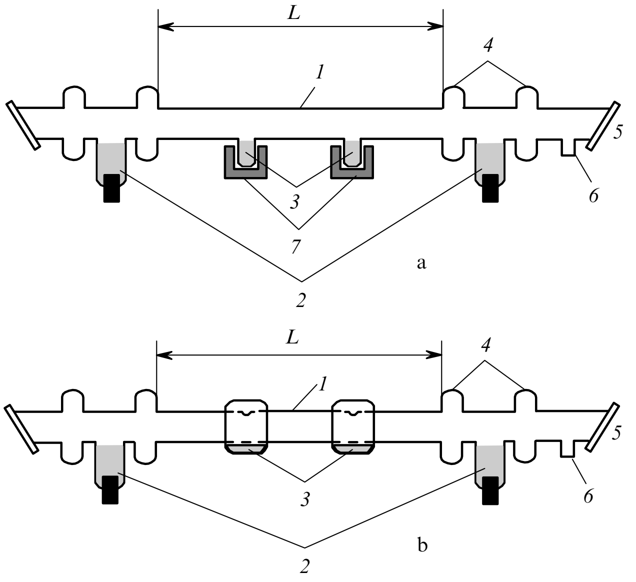

Figure 1. Scheme of GDTs with the independent heating of containers (GDTs No. 1 and 2) (a) and self-heating (GDTs No. 3, 4 and 5) (b): (*1*) working channel; (*2*) electrodes; (*3*) containers with CuBr; (*4*) traps; (*5*) output windows; (*6*) HBr (H_2) generator; (*7*) heaters; *L* is the length of the active region of the GDT.

The GDTs had a built-in reversible HBr generator, which fulfilled the function of not only supplying HBr to the active laser medium, but also of pumping out the hydrogen bromide back into the generator. The HBr concentration was controlled over a wide range by the temperature of the heater, and the addition was optimised for the maximum output power. For a constant heater temperature, the HBr concentration settled at a constant level. The GDTs with a built-in hydrogen generator (SRHL) were designed in a similar way.

The GDT was excited in the traditional dc discharge circuit, when a KVI-3 working capacitor was discharged through the GDT with the aid of a thyratron switch. When pumping the GDTs No. 1 – 3 with the commutation power below 2.5 kW, use was made of a water-cooled TGI1-1000/25 thyratron. To commute a power higher than 2.5 kW in the case of the GDTs No. 4 and 5, the pumping was effected by way of alternate triggering of two thyratrons. To increase the voltage across the tubes with a long interelectrode distance (the GDTs No. 4 and 5), a pulse cable transformer was inserted in the circuit, like in Ref. [17]. The transformer is wound round 10 ferrite rings measuring 100 × 60× 15 mm, the transformer winding is made of a cable with a PVTFE Teflon insulation, the number of turns is equal to three in the primary winding and to six in the secondary one.

The current, voltage, and laser pulses were recorded using a Rogowski loop, a low-inductance divider with TVO resisters, and an FK-22 coaxial photocell, respectively. The signals were recorded with a Tektronix TDS 3032 oscilloscope. The output power was monitored with an IMO-2 power meter and the GDT wall temperature with a chromel-alumel thermocouple.

The first measurements of the energy characteristics of the tubes under investigation were conducted as follows. A GDT was brought to the steady-state operating mode without additions of HBr (H_2) and its output power was measured (see Table 1). Then, the heater of the HBr generator was turned on to deliver hydrogen halide to the GDT. In the initial stage of the test, the optimal density of the halide was determined visually from the discharge column diameter. The optimal partial pressure of HBr was typically equal to 0.1 – 0.2 Torr. When the HBr density exceeded the requisite one, HBr was partly pumped out from the GDT to the generator without changing the pressure of the main buffer gas – neon. Unfortunately, this procedure is impossible when the optimal partial pressure of H_2 is exceeded, and even complete replacement of the working mixture does not ensure the absence of hydrogen in the discharge.

3. Results and discussion

Our experiments showed that the character of settling of the steady-state laser mode (from the instant of discharge initiation) in small-volume active elements (with a tube diameter below 2 cm) is distinctly different from that of large volume active elements (with a tube diameter above 2 cm). On reaching the maximum output power in the narrow tubes (GDTs No. 1 and 2), the gradual delivery of HBr to the discharge initially resulted in an improvement of the output parameters followed by their lowering owing to the excess of the vapour of the working substance. This could be visually judged from the transfer of the working substance to the near-electrode and end regions. Further delivery of HBr impeded the discharge and resulted in its termination. Only after lowering the CuBr-container temperature did the discharge become stable and the output power exceeded the initial addition-free mode value by a factor of 4 – 5 (Table 1). For instance, to attain the maximum output power (2.5 W) from the active medium of GDT No. 2 with an addition of HBr, in circumstances where a buffer gas (pure neon) was present we were forced to set (by lowering the furnace temperatures of the CuBr containers) the output power at 0.3 W, which

Table 1. Overall dimensions and energy parameters of GDTs studied in the paper.

GDT No.	Tube diameter/cm	Active region length/cm	Power consumption/kW	Output power without additions of H_2 and HBr/W	Output power with an addition of H_2/W	Output power with an addition of HBr/W
1	1.1	16	0.4 – 0.5	0.15	0.8	0.8
2	1.6	36	0.8	0.5	2.5	2.5
3	2.6	76	1.4 – 1.5	5	10	10.5
4	3.6	120	2.5 – 3.0	13	25 (36)	26 (38)
5	5.3	145	4.0 – 5.0	22	41 (55)	40 (55)

Notes. Given in parentheses is the output power for GDTs No. 4 and 5 obtained employing the pulse cable transformer circuit. The pressure of the Ne buffer gas was 15 – 30 Torr, the pulse repetition rate was 17 – 22 kHz. GDTs No. 1 and 2 were made with an independent container heating, GDTs No. 3 – 5 were designed with a self-heating.

is below the optimum, and then add HBr. It may be suggested that one of the two additional mechanisms of CuBr production is realised in the discharge, which is similar to the mechanism that takes place in a hybrid laser:

$$\begin{gathered}\text{Cu (solid phase)} + \text{Br (gas)} \rightarrow \text{CuBr (gas)}, \\ \text{Cu (solid phase)} + \text{HBr (gas)} \rightarrow \text{CuBr (gas)} + \text{H (gas)}.\end{gathered} \quad (1)$$

Testing self-heating GDTs No. 3–5 showed that the addition of HBr resulted in a gradual increase in the output power from 5, 13, and 22 W to 10.5, 26, and 40 W, respectively. In this case, it was not necessary to change the thermal insulation layer on the CuBr containers, which signified that the temperature and density of CuBr remained unchanged. Employing the pulse cable transformer provided a possibility to additionally increase the output power of GDTs No. 4 and 5 up to 38 and 55 W, respectively.

The above experimental results allow a conclusion that the additions of HBr to the active medium of a CuBr laser result in an efficient improvement of the output parameters up to the values comparable to the parameters of a CuBr laser with the additions of H_2. We had previously measured the output characteristics of these GDTs with the additions of H_2 in the sealed-off and unsealed versions. In the case of an unsealed GDT, hydrogen was puffed in it from a vessel via a pipe. GDT No. 4 operated in the sealed-off mode, with an SRHL-1 hydrogen generator soldered to it. A comparison of the output powers and efficiencies of the lasers with the additions of H_2 and HBr revealed that they were virtually similar. Figure 2 depicts the oscilloscope traces of current, voltage, and output laser pulses for GDT No. 3 with pure Ne as well as with the additions of H_2 and HBr under identical excitation conditions and the same temperature of the GDT wall. Under these conditions, the output laser power was equal to 5 W in the absence of hydrogen and to 10 and 10.5 W with the additions of hydrogen and hydrogen bromide, respectively.

The HBr generator elaborated is devoid of the drawback inherent in the SRHL type hydrogen generator when using it in the CuBr laser. This drawback is related to the absence of the process of H_2 withdrawal to the generator in the case that the H_2 density in the discharge is excessive.

Figure 3 shows the evolution of current and voltage pulses over a long period of time (on the order of several hours) in pumping HBr out from the discharge. One can see that the pulse shapes after de-energising the heater of the HBr generator regain their initial shape [curves (1′) and (1)] corresponding to the pulse shape in the GDT operation with pure Ne (without additions) as the buffer gas. The rate of withdrawal of HBr from the discharge to the generator depends on its density in the generator.

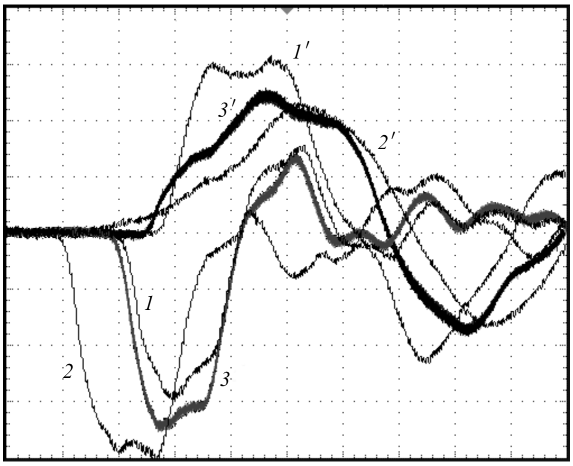

Figure 3. Evolution of current J ($1'-3'$) and voltage U (1–3) pulses in the course of HBr withdrawal from GDT No. 3 to the HBr generator in the laser operation by pure Ne without additions ($1'$, 1), with the addition of HBr for an above-optimal density ($2'$, 2), and 20 min after de-energising the heater of the HBr generator ($3'$, 3).

Note that the newly elaborated HBr generator can also be employed for degassing the GDT from atmospheric gases and operation by-products, which exert an adverse effect on the lasing capacity. In particular, it is well known that free bromine is accumulated in CuBr lasers during the GDT operation [2]. The results of the experiments of Refs [12, 18] as well as numerical calculations indicate [19] that bromine additions exert an adverse effect on the characteristics of copper and copper bromide vapour lasers. It is conceivable that optimising the operating conditions of the hydrogen bromide generator will allow a lowering of free bromine density in the discharge.

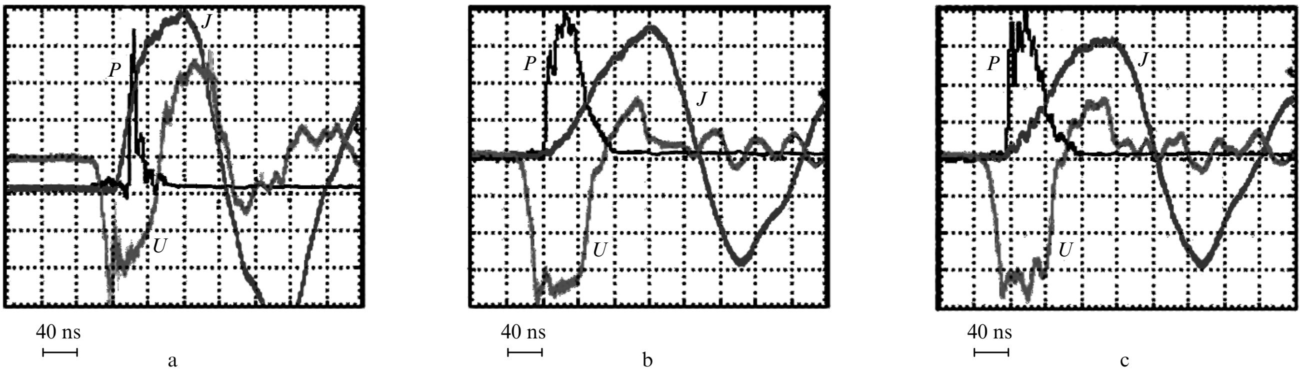

Figure 2. Oscilloscope traces of current J, voltage U, and output laser P pulses for GDT No. 3 with pure Ne (a) and with additions of H_2 (b) and HBr (c) for a capacitance of the working capacitor of 825 pF, a pump pulse-repetition rate of 17.2 kHz, and a pressure of the Ne buffer gas or an Ne–HBr (Ne–H_2) mixture of 20 Torr. The voltage and current of the power supply are 6.2 kV and 0.22 A (a) and 6.2 kV and 0.21 A (b, c).

Our attention is engaged by the behaviour of the average output power (summed over both lines) in relation to the pressure of the buffer gas. One can see from Fig. 4 that the maximum of the average power with HBr additions shifts towards lower pressures in comparison with the case of pure neon. A similar behaviour was also observed by Little [2]. With an increase in mixture pressure, probably the voltage across the GDT needs to be increased, which may be technically difficult to realise when employing the TGI1-1000/25 thyratrons. An indirect confirmation of this assumption is the fact that the output power is 30 % – 50 % higher when use is made of a pulse cable transformer.

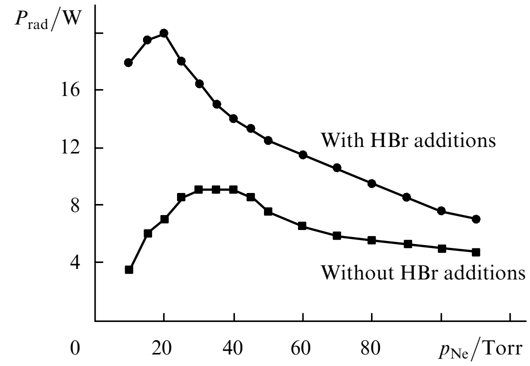

Figure 4. Output power of the CuBr laser P_{rad} (the GDT diameter is 3.6 cm and the length is 96 cm) versus buffer gas pressure p_{Ne}. The HBr pressure at each measurement point is optimised for maximum output power. The capacitance of the working capacitor is 1175 pF, the pump pulse-repetition rate is 17 kHz, and the power consumed from the rectifier is ~ 2 – 2.4 kW.

The first results of CuBr – Ne – HBr laser operation for several tens of hours without replacement of the working mixture suggest that the laser exhibits features characteristic of a hybrid laser. In particular, in hybrid lasers there emerges the problem of limitation of the active region aperture due to the production of dendrites in small-diameter GDT channels after several hours of service. To eliminate this effect, the authors of Ref. [8] proposed that the hydrogen density and the tube temperature should be controlled by way of careful selection of the thermal insulation in order to avoid thermal spikes. Observed in our case was a uniform deposition of copper vapour on the inner wall of the narrow tube, which with time resulted in the production of a circularly shaped copper foil of a sort. Subsequently, this 'foil' would exfoliate and span the discharge channel. We made preventive efforts to eliminate the above process. A discharge was ignited in the GDT with pure Ne (without heating the containers, i.e., virtually without CuBr vapour). The power introduced into the GDT was slightly higher than the power optimised for steady-state laser operation. After heating the GDT in this mode for some time (several tens of minutes) there occurred 'foil' removal with the deposition of its decay products in the cold regions (specially designed traps).

We attribute the occurrence of excessive atomic density of the working substance in the discharge region of GDTs No. 1 and 2 to precisely the progress of reactions (1): apart from the fact that the CuBr vapour is delivered to the discharge from the containers, Br atoms and HBr molecules additionally detach the copper atoms from the GDT wall, which found their way to the wall owing to the tube metallisation. It is noteworthy, however, that this process was not observed in GDTs No. 3 – 5. We believe that processes (1) turn out to be less efficient in large-diameter GDTs. In these tubes, in particular, the energy inputted in a unit volume is significantly lower and, as a consequence, the HBr molecule dissociation is lower. Accordingly, the density of active bromine is also lower, and therefore the additional production of copper bromide [Cu (solid phase)+ Br (gas) → CuBr (gas)] becomes negligible. Furthermore, in going over to larger-diameter GDTs there lengthens the HBr-molecule diffusion distance to the GDT wall, where reactions (1) proceed and a significant radial non-uniformity of the gas temperature is observed. Under these conditions, the main part in the improvement of lasing characteristics is supposedly played by the dissociative attachment of electrons to the HBr molecule [20].

4. Conclusions

We have studied the output parameters of a CuBr laser with the additions of HBr. Experiments with five GDTs of different overall dimensions showed that the addition of HBr to the active medium of the CuBr laser results in a increase of its output power and efficiency comparable to the increase obtained with these GDTs on addition of hydrogen. The analysis of the electrical characteristics (the amplitude and duration of the pump pulses, the power input) of the CuBr – Ne – HBr and CuBr – Ne – H_2 lasers also demonstrated their complete similarity.

Based on the data obtained with the use of small-diameter tubes (less than 2 cm), we suggested that the requisite CuBr vapour density in the active region of the CuBr – Ne – HBr laser was attained not only due to the delivery of the working substance from containers. The CuBr molecules can be produced in part by bromine (or hydrogen bromide) 'tearing away' the copper atoms from the GDT walls, which resembles the principle of operation of a hybrid laser.

Tests of the HBr generator showed that the density of the HBr addition in the laser can be varied over wide limits. This generator differs from the existing H_2 generators in that it possesses the property of reversibility when used in CuBr lasers. The excess of HBr density, which is responsible for a reduction of the output power, is easy to eliminate by de-energising the heater of the generator.

The results obtained are used as the basis for the currently conducted development of a sealed-off copper bromide vapour laser with controllable additions of HBr. It is pertinent to note that we had no way to substantially (up to 50 – 100 kHz) increase the pump pulse-repetition rate in the experiments outlined above. At the same time we believe that, similar to the copper bromide vapour laser with the additions of hydrogen, the additions of HBr will result in an increase of the optimal repetition rate and the output laser power [21].

Acknowledgements. The authors thank V.D. Bochkov, the General Director of the Pulsed Technologies Ltd, for the delivery of the SRHL generator and O.V. Zhdaneev for participating in the discussions of the results obtained.

References

1. Batenin V.M., Buchanov V.V., Kazaryan M.A., Klimovskii I.I., Molodykh E.E. *Lazery na samoogranichennykh perekhodakh atomov metallov* (Lasers Utilising Self-Terminating Transitions of Metal Atoms) (Moscow: Nauchnaya Kniga, 1998).
2. Little C.E. *Metal Vapor Lasers: Physics, Engineering & Applications* (Chichester, UK: John Wiley & Sons Ltd., 1998).
3. Soldatov A.N., Solomonov V.I. *Gazorazryadnye lazery na samoogranichennykh perekhodakh v parakh metallov* (Gas-Discharge Self-Terminating Metal Vapour Lasers) (Novosibirsk: Nauka, 1985).
4. Little C.E., Sabotinov N.V. (Eds) *Pulsed Metal Vapor Lasers* (New York: Kluwer Acad. Publ., 1996) Vol.5.
5. Bokhan P.A., Silant'ev V.I., Solomonov V.I. *Kvantovaya Elektron.*, **7**, 1264 (1980) [*Sov. J. Quantum Electron.*, **10**, 724 (1980)].
6. Kazaryan M.A., Kolokolov I.S., Lyabin N.A., Paramonov V.S., Prokhorov A.M., Ugolnikov S.A., Chursin A.D. *Laser Phys.*, **12**, 1281 (2002).
7. Astadjov D.N., Dimitrov K.D., Jones D.R., Kirkov V.K., Little C.E., Sabotinov N.V., Vuchkov N.K. *IEEE J. Quantum Electron.*, **33**, 705 (1997).
8. Jones D.R., Little C.E. *Proc. SPIE Int. Soc. Opt. Eng.*, **2619**, 52 (1995).
9. Isaev A.A., Jones D.R., Little C.E., et al. *IEEE J. Quantum Electron.*, **33**, 919 (1997).
10. Jones D.R., Maitland A., Little C.E. *IEEE J. Quantum Electron.*, **30**, 2385 (1994).
11. Sabotinov N.V., Akerboom F., Jones D.R., Maitland A., Little C.E. *IEEE J. Quantum Electron.*, **31**, 747 (1995).
12. Withford M.J., Brown D.J.W., Carman R.J., Piper J.A. *Opt. Commun.*, **135**, 164 (1997).
13. Bochkov V.D., Gosheva-Marazova M., Klimovskii I.I. *Opt. Atmosfery i Okeana*, **14**, 1027 (2001).
14. Shiyanov D.V., Sukhanov V.B., Bochkov V.D., et al. *Program VI Int. Conf. 'Atomic and Molecular Pulsed Lasers'* (Tomsk, 2003) p. 18.
15. Evtushenko G.S., Petrash G.G., Sukhanov V.B., Fedorov V.F. *Kvantovaya Elektron.*, **28**, 220 (1999) [*Quantum Electron.*, **29**, 775 (1999)].
16. Sukhanov V.B., Evtushenko G.S., Shiyanov D.V., Chernyshev A.I. *Opt. Atmosfery i Okeana*, **13**, 1053 (2000).
17. Elaev V.F., Lyakh G.D., Pelenkov V.P. *Opt. Atmosfery i Okeana*, **2**, 1228 (1989).
18. Astadzhov D.N., Vuchkov N.K., Petrash G.G., Sabotinov N.V. *Tr. Fiz. Inst. Akad. Nauk SSSR*, **181**, 122 (1987).
19. Boichenko A.M., Evtushenko G.S., Yakovlenko S.I., Zhdaneev O.V. *Laser Phys.*, **14** (6) (2004).
20. Zemskov K.I., Isaev A.A., Petrash G.G. *Kvantovaya Elektron.*, **24**, 596 (1997) [*Quantum Electron.*, **27**, 579 (1997)].
21. Shiyanov D.V., Evtushenko G.S., Sukhanov V.B., Fedorov V.F. *Kvantovaya Elektron.*, **32**, 680 (2002) [*Quantum Electron.*, **32**, 680 (2002)].