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Influence of the switch parameters on the performance characteristics of a copper vapour laser

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***Abstract*.** **Analysis of the circuits for exciting the active medium of a copper vapour laser (CVL) has shown that the main factors limiting the mean output power of the CVL are the cathode emissive power of an electron tube and the permissible current rise rate in a thyratron switch. The laser operation reliability and the thyratron service life are determined by the reverse voltage across the thyratron anode. The service life of a TGI1-1000/25 thyratron in a CVL corresponds to its certified value, if the reverse voltage at the thyratron anode is within 3 kV.**

Keywords: *copper vapour laser, switch.*

1. Introduction

A repetitively pulsed copper vapour laser (CVL) belongs to the class of self-contained lasers and is one of the most efficient sources of stimulated radiation among gas lasers emitting in the visible region. To pump the active medium of these lasers efficiently, an excitation pulse should have a steep front and a duration comparable to the inversion lifetime [1]. Such an excitation pulse is usually shaped by a partial or complete discharge of a storage capacitor through the laser active medium using an electron tube or a thyratron [2]. The rise time of the voltage pulse across the active component R of the gas-discharge tube (GDT) impedance for circuits with a partial discharge of the storage capacitor is

$$\tau_{\rm c} \sim \frac{3L}{R}. \tag{1}$$

For circuits with a complete discharge [3], this time is determined by the natural oscillation frequency

$$\omega_{\rm fr} = \left(\frac{1}{LC} - \alpha^2\right)^{1/2}, \tag{2}$$

where L is the GDT inductance; C is the capacitance of the storage capacitor; and $\alpha = R/2L$ is the oscillation damping factor in the discharge circuit. Taking into account the switching time $\tau_{\rm com}$ of an actual switch, the build-up time of the voltage across R is determined by the expression

$$\tau = \left(\tau_{\rm cw}^2 + \tau_{\rm c}^2\right)^{1/2}. \tag{3}$$

According to (1)–(3), the energy characteristics (the mean output power and efficiency) of a CVL should increase with increasing voltage across the storage capacitor and natural oscillation frequency in the discharge circuit. The use of a switch may be one of the principal factors that limit these parameters. Not only the energy characteristics but also the service life and reliability of operation, which significantly depend on the properties of the switch, are important performance characteristics of a CVL [2, 4, 5]. The main parameters of thyratrons that determine their switching characteristics are as follows: the acceptable anode voltage $U_{\rm a}$, the permissible current rise rate $\mathrm{d}I/\mathrm{d}t$, the thyratron switching-on time $\tau_{\rm cw}$, and the acceptable reverse voltage $U_{\rm rev}$ across its anode. These parameters for an electron tube are as follows: the acceptable anode voltage $U_{\rm a}$, the anode-dissipated power $P_{\rm a}$, and the pulse current amplitude I_0, which is determined by the emissive power of the tube cathode. All the parameters of switches mentioned above limit the performance characteristics of CVLs [2, 4, 5]. However, the question which of these parameters (or their combination) is decisive still remains open. This does not allow one, on the one hand, to determine the switch parameters optimal for CVL pumping and, on the other hand, to perform engineering calculations of the laser performance characteristics. The aim of this work is to find the parameters of switches that determine the CVL performance characteristics. This study was accomplished by analysing the operation of various circuits for exciting the active medium.

2. Analysis of the operation of CVL excitation circuits

We compared the operation of various circuits for excitation of an GL-201 GDT (the inner diameter of the discharge channel was 2 cm and the length was 80 cm) placed inside an unstable resonator. Based on the excitation conditions and the laser radiation parameters achieved, we determined the factors that restrict these parameters and evaluated the advantages and drawbacks of the excitation circuits.

2.1 A direct excitation circuit is most widespread. In this case, the discharge circuit is a simple oscillatory circuit containing a thyratron, a GDT, and a storage capacitor.

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The latter is charged from a high-voltage rectifier through a charging choke, a diode, and a shunting inductor connected in parallel to the GDT. This excitation circuit was used with a TGI1-1000/25 thyratron, and a mean output power of 7 W at a laser pulse repetition rate of 11 kHz was obtained. The FWHM pulse duration was 20 ns, and the power consumed from the rectifier was 2.6 kW at a rectifier voltage of 5.4 kV and a capacitance of the storage capacitor of 2400 pF. The reverse voltage across the thyratron was up to ~ 3 kV in a steady-state lasing regime.

During the GDT active-volume heating, a decrease in U_{rev} and in the power consumed from the rectifier was observed, until the appearance of lasing. Then, as the laser was heated, both U_{rev} and the consumed power increased. Such a dependence of U_{rev} on the GDT temperature is explained as follows. During the initial period of the GDT heating, the discharge occurs in the buffer gas (neon) with a high degree of contraction. The discharge pinching increases the GDT inductance and is characterised by a high electron density in the discharge. This determines a low oscillation damping factor α in the discharge circuit and a high reverse voltage across the thyratron. As the GDT is heated, a discharge decontraction is observed [6, 7], which leads to an increase in the factor α and a decrease in U_{rev}. As the GDT temperature further increases (after the discharge decontraction), the factor α decreases and U_{rev} increases. An increase in the energy deposited into the GDT leads to a further increase in U_{rev}, and when the latter reaches the maximum acceptable value for the thyratron, an unstable lasing is initiated. The thyratron lifetime significantly shortens when operating with a high reverse voltage U_{rev}. The operating life tests of a TGI1-1000/25 thyratron performed with the above-mentioned pump parameters of the CVL, when $U_{\text{rev}} \sim 3$ kV is substantially lower than the maximum acceptable value (5 kV), have shown that the thyratron service life corresponds to that guaranteed by the manufacturer. By now, the thyratron has operated for >800 h.

2.2 Another circuit used for exciting the CVL is a direct excitation circuit with a partial discharge of the storage capacitor. Electron tubes (e.g., a GMI-29 pulsed modulator tetrode) are used as switches in this circuit. A mean output power of 15 W at a pulse repetition rate of 11 kHz was obtained using such a circuit with a GMI-29A tube. The FWHM durations of the pump and radiation pulses were 60 and 12 ns, respectively. The power consumed from the rectifier was 3.1 kW for a rectifier voltage of 25.8 kV and a storage capacitance of 20 nF. Lasing was observed at the trailing edge of the exciting pulse with a delay of 40 ns relative to its onset. As the voltage across the storage capacitor increases, the laser pulse energy is expected to increase. However, this was not observed, because, although an increase in the voltage should result in an increase in the current in the circuit whose amplitude is limited by the emissive power of the GMI-29 tube. The current pulse amplitude in the laser circuit reached 300 A for the pump parameters presented above.

The CVL energy characteristics at a limited emissive power of the GMI-29 tube can be improved by increasing the length of the GDT discharge gap, because the ratio L/R must remain constant (L and R increase proportionally to the length of the GDT discharge gap). The substitution of a 'Kristall LT-40Cu' (the inner diameter of the discharge channel is 2 cm and its length is 1.2 m) for a GL-201 GDT made it possible to increase the mean output power almost twice at a pump pulse repetition rate of 11 kHz, a rectifier voltage of 28 kV, a consumed power of 4.2 kW, and a current amplitude of ~ 300 A.

2.3 The condition $R > (L/C)^{1/2}$ is not satisfied in the direct excitation circuit (see Section 2.1), and the discharge process in the circuit has an oscillatory character [3]. In this case, according to (2) and (3), an increase in the laser energy characteristics requires a decrease in the storage capacitance and a corresponding increase in the capacitor voltage. A computer simulation of this process has shown that, in order to reach the excitation parameters in this circuit comparable to the parameters of the circuit considered in Section 2.2, the rectifier voltage should be increased up to 7.5–8.5 kV and the storage capacitance decreased to ~ 1 nF. At such parameters, the voltage across the storage capacitor will be 24–26 kV, the reverse voltage will be 6–8 kV, and the current rise rate in the circuit will reach 6–8 kA s^{-1}. The main factors that limit the energy of a CVL output pulse are the maximum allowable values of the thyratron current rise rate and the reverse voltage across it. The reverse voltage across the thyratron involves the maximum difficulties in reaching the required discharge parameters.

In order to attain the required excitation parameters and reduce the reverse voltage across the thyratron to the certified value, a voltage multiplication circuit (Marx circuit) was used. This circuit containing two TGI1-1000/25 thyratrons connected in series (Fig. 1) operates as follows. Storage capacitors C_1 and C_2 are charged in parallel from the high-voltage rectifier through a charging choke L_1, diodes (*1*) and (*2*), and inductors L_3 and L_2. The next step is the simultaneous triggering of thyratrons (*3*) and (*4*). As a result, the storage capacitors turn out to be connected in series in the laser discharge circuit. After the discharge, the reverse voltage for each thyratron is determined by the voltage at each capacitor of the corresponding thyratron but not by the total voltage of the capacitors connected in series.

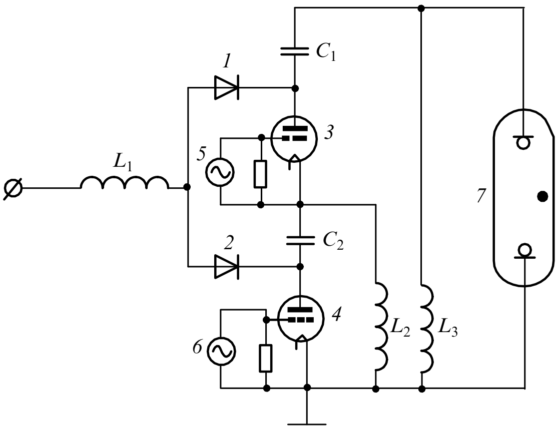

Figure 1. Electric circuit for exciting the CVL active medium with two thyratrons connected in series: (*1*, *2*) diodes; (*3*, *4*) TGI1-1000/25 thyratrons; (*5*, *6*) pulse generators for triggering the thyratrons; (*7*) GDT; (C_1, C_2) storage capacitors; (L_2) inductor; and (L_3) shunting inductor.

The mean output power obtained with this excitation network was 14 W at a laser pulse repetition rate of 11 kHz. The FWHM durations of the pump and output pulses were 90 and 20 ns, respectively. The power consumed from the rectifier was 3.5 kW at a rectifier voltage of 4.8 kV, a reverse voltage at the thyratron anode of ~ 2.5 kV, and storage capacitances $C_1 = C_2 = 2.2$ nF. Lasing was observed with a 40-ns delay after the onset of the pump pulse. The mean output power observed for a rectifier voltage of 5.4 kV and a pulse repetition rate of 8 kHz was 18 W.

According to (1)–(3), as the pump pulse repetition rate increases, the voltage build-up rate across the active component of the GDT impedance decreases due to an increase in the prepulse electron concentration. This can be prevented by increasing the voltage across the storage capacitor and reducing its capacitance. However, the possibilities of such measures are limited, on the one hand, by the switch and thermal conditions in the laser and, on the other hand, by the capacitance of the storage capacitor. As the latter decreases, the pump pulse duration shortens, but it cannot be shorter than the inversion lifetime [1]. Otherwise, a decrease in the output pulse duration is observed [3]. Therefore, higher CVL energy characteristics can be expected due to an increase in the working volume of the GDT, and their maximum increase should be observed due to an increase in the GDT active region length. This is confirmed by the energy characteristics of GL-201, 'Kristall LT-30Cu', 'Kristall LT-40Cu', and 'Kristall LT-50Cu' active elements [8]. Our estimates have shown that, using a GDT with a discharge-channel diameter of 3.2–4 cm and a length of 200 cm, a mean output power of ~ 200 W and an actual efficiency of $\sim 2\,\%-3\,\%$ can be achieved at a storage capacitor voltage of >40 kV, a reverse voltage across the thyratron of 10–12 kV, and a current rise rate of >10 kA s^{-1} in the circuit. Since no limitations are imposed on the number of thyratrons connected in series in the multiplication circuit (Fig. 1), the main factor that may restricts these energy parameters is the permissible current rise rate in the thyratron.

2.4 The current rise rate in the switch can be reduced to the certified values by using circuits with a pulse transformer and a subsequent pulse compression using nonlinear chokes [9, 10]. At present, both thyratrons and IGBT transistors are used as switches in such circuits, and the number of compression sections is up to three with a pulse duration of $\sim 10-30$ μs at the secondary winding of the transformer. A nonlinear choke of the first section is usually manufactured with a core of amorphous iron (the pulse compression factor is $\sim 20-30$). The chokes of the subsequent sections are made on ferrite rings (the compression factor is $\sim 2-3$) and provide the formation of 50–60-ns pump pulses in the GDT.

A computer simulation of this process has shown that the last compression section is the most important element in the formation of a pump pulse of the required duration in the GDT. This conclusion follows from the analysis of the pump-pulse compression process. Let us assume that it is necessary to shape a ~ 60-ns pulse in the GDT with an inductance of ~ 1 μH using a nonlinear choke (the compression factor is ~ 3). Therefore, a ~ 180-ns pulse should arrive at the input of the compression section (Fig. 2a). Fig. 2b shows a result of the computer simulation of the GDT current and voltage pulses for an input ~ 180-ns rectangular pulse with a 20-kV amplitude. One can see that a 60-ns pump pulse with a steep front and a preceding 120-ns part with a slowly rising current and voltage forms in the GDT. The parameters of this part are determined by the initial and final inductances of the nonlinear choke and by the current at which the choke saturation begins. In this case, the slowly rising current and voltage preceding the onset of the pump pulse may lead to an additional population of lower laser levels and thus degrade the laser energy characteristics.

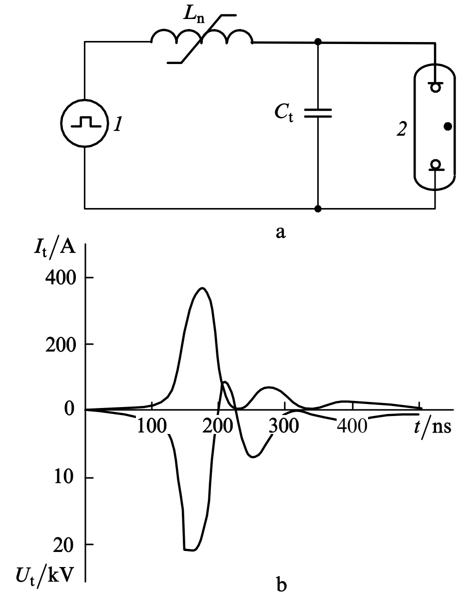

Figure 2. (a) Circuit of the section for compressing excitation pulses and (b) oscillograms of the GDT current I_t and voltage U_t pulses: (*1*) generator of rectangular excitation pulses at the input of the compression section; (*2*) GDT; (L_n) nonlinear choke; ($C_t = 165$ pF) peaking capacitor.

To verify experimentally this assumption, we stimulated such excitation conditions for the circuit presented in Fig. 3. The studies were performed with an UL-102 GDT (the inner diameter of the discharge channel was 2 cm, and its length was 40 cm). A pump pulse was formed by a TGI2-500/20 thyratron (*4*), and an additional pulse, which was generated 120 ns ahead of the excitation pulse, was formed by a TGI1-270/12 thyratron (*5*). The experiments were carried out with the following parameters: storage capacitors $C_1 = C_2 =$ 2200 pF, the pump-pulse repetition rate was 10 kHz, the

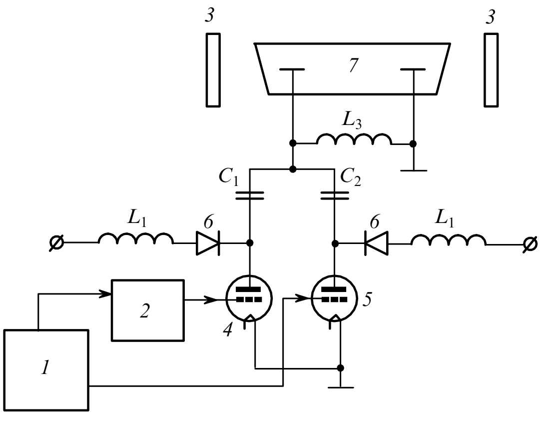

Figure 3. Schematic of the experimental setup: (*1*) master oscillator; (*2*) delay line; (*3*) cavity mirrors; (*4*, *5*) TGI2-500/20 and TGI1-270/12 thyratrons, respectively; (*6*) diodes; (*7*) GDT; (C_1, C_2) storage capacitors; (L_1) charging choke; and (L_3) shunting inductor.

rectifier voltage was 4.9 kV, the mean current consumed from the excitation source was 340 mA, and the output voltage of the additional-source rectifier was 0 – 1 kV. For these parameters, the reverse voltages across the thyratrons did not exceed the certified values. The maximum mean output power in a plane-parallel resonator under steady-state thermal conditions was ~ 5 W. The mean output power as a function of the rectifier voltage of the additional power supply is shown in Fig. 4. A change in the mean output power is accompanied by a simultaneous change in the time delay of the onset of the laser pulse with respect to the pump pulse.

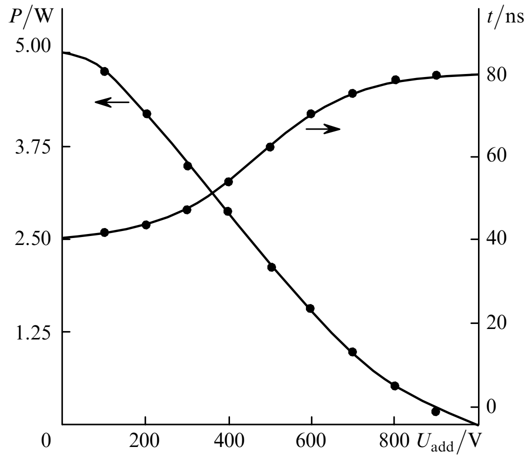

Figure 4. Mean output power P and time delay t of the onset of the laser pulse versus voltage U_{add} across the rectifier of the additional power supply.

A sharper decrease in the mean output power is observed at the radiation wavelength $\lambda = 510.5$ nm, and a change in the radial distribution of the laser power density takes place. As the voltage from the rectifier of the additional power supply increases, at first, a change to a circular structure of laser radiation at $\lambda = 510.5$ nm is observed, then the lasing disappears, and, subsequently, a similar effect is observed at $\lambda = 578.2$ nm. A further increase in the voltage up to 2 – 2.5 kV results in the initiation of lasing under the action of an additional pulse.

The investigations performed clearly demonstrate the possible influence of a pulse compression section on the laser energy characteristics.

3. Conclusions

The analysis of the operation of various excitation circuits has shown that the basic factors that limit the mean output power of a CVL are the emissive power of the cathodes of electron tubes and the maximum acceptable current rise rate in thyratrons. The ultimate reverse voltage across the thyratron anode determines the laser operation reliability and the service lifetime of the switch. The adequate choice of the GDT excitation conditions and their technical implementation makes it possible to set a minimum reverse voltage at which the service life and operation reliability correspond to the certified thyratron characteristics.

Therefore, we conclude that the formation of an excitation pulse with a steep front [1] requires the knowledge of the current rise rate in the laser circuit and the reverse voltage across the thyratron anode, and the excitation conditions can be optimised only within the limits of permissible values of the switch current rise rate and amplitude. When performing engineering calculations of the pump parameters and selecting an optimal excitation circuit, this allows one to use the existing computer programs for calculating and analysing the electric circuits or to make appropriate estimates on the basis of the current rise rate, its amplitude, and the reverse voltage across the thyratron anode in the operating laser. In this case, an actual switch can be replaced by an ideal one with an internal resistance R_{in}, which determines the energy loss in the switch, and, according to [4, 5], the active component of the GDT impedance can be replaced by the average resistance R_{av} over the pump pulse.

Tables 1 and 2 present the results of such calculations based on the experimental data of Sections 2.1 and 2.3 for CVL excitation conditions. The calculation data corresponding to the experimental conditions are given in bold type. The calculations that yielded the results listed in Table 1 were performed with the following parameters of the excitation circuit: the inductance of the charging choke was $L_1 = 0.3$ μH, the shunting inductance was $L_3 = 100$ μH, the rectifier voltage was $U_{\mathrm{add}} = 5.4$ kV, the inductance of the discharge circuit was $L_{\mathrm{c}} = 1$ μH, the storage capacitance was $C = 2400$ pF, and the thyratron switching-on time was $\tau_{\mathrm{cw}} = 50$ ns. These circuit parameters ensure a good agreement between the theoretical and experimental values of the reverse voltage U_{rev} across the thyratron, the current amplitude I_0 in the discharge circuit, and the voltage U_C across the storage capacitor for $R_{\mathrm{av}} = 12\ \Omega$ and $R_{\mathrm{in}} = 6\ \Omega$ (in Tables 1 and 2, U_{R0} is the voltage amplitude and $\mathrm{d}U_R/\mathrm{d}t$ is the voltage build-up rate across R_{av}). The calculation results agree with the measurements of R_{av} in a CVL [11] and the power dissipated in a thyratron [4].

The data of Table 2 were obtained for $L_1 = 0.3$ H, $L_3 = 100$ H, $U_{\mathrm{add}} = 4.8$ kV, $L_{\mathrm{c}} = 1.6$ μH, $C_1 = C_2 = 2200$ pF, and $\tau_{\mathrm{cw}} = 30$ ns. A decrease in the switching time of the switches in this case is determined by the thyratron switching-on regime in the circuit shown in Fig. 1. The thyratron (*4*) was actually triggered (Fig. 1), and the thyratron (*3*), determining the GDT voltage build-up time, operated as a three-electrode spark gap. The pump parameters obtained experimentally in this circuit are realised at $R_{\mathrm{av}} = 17\ \Omega$ and $R_{\mathrm{in}} = 8.5\ \Omega$ for each thyratron. An increase in R_{av} is caused by the pump pulse shortening and, thus, by a decreased role of step ionisation processes after the laser pulse [11].

An increase in R_{in} is caused by an increase in the initial losses in the thyratron due to a higher current rise rate in the discharge circuit [4]. The results of calculations listed in Tables 1 and 2 allow us to conclude that the laser pulse

Table 1.

R_{av} /Ω	τ_{c} /ns	τ /ns	I_0 /A	U_{R0} /kV	$\mathrm{d}I/\mathrm{d}t$ /kA μs^{-1}	$\mathrm{d}U_R/\mathrm{d}t$ /V ns^{-1}	U_{rev} /kV	U_C /kW
6	67	84	574	3.5	6.8	42.0	6.7	17.4
8	65	82	495	3.96	6.0	48.3	5.1	15.9
10	60	78	435	4.35	5.6	55.8	3.9	14.7
12	**60**	**78**	**390**	**4.68**	**5.0**	**60.0**	**3.0**	**13.8**
14	60	78	352	4.94	4.5	63.3	2.4	13.1
16	60	78	323	5.1	4.1	65.4	1.8	12.6
18	56	75	299	5.4	4.0	72.0	1.4	12.2
20	56	75	278	5.6	3.7	74.6	1.0	11.8

Table 2.

R_{av} /Ω	τ_c /ns	τ /ns	I_0 /A	U_{R0} /kV	dI/dt /kA μs^{-1}	dU_R/dt /V ns^{-1}	U_{rev} /kV	U_C /kW
11	54	61.7	432	4.75	7.0	77.0	3.8	13.4
13	53	60.9	404	5.25	6.6	86.2	3.3	12.9
15	52	60.0	381	5.7	6.35	95.0	2.9	12.4
17	**51**	**59.2**	**359**	**6.1**	**6.1**	**103.0**	**2.5**	**12.1**
19	51	59.2	341	6.5	5.7	109.0	2.2	11.7
21	50	58.3	324	6.8	5.55	116.0	1.8	11.4
23	49	57.4	309	7.1	5.38	123.0	1.6	11.2

energy will increase with decreasing the pump-pulse repetition rate. This is determined by the permissible current rise rate in the TGI1-1000/25 thyratron and was confirmed experimentally (Section 2.3). The voltage build-up rate and the voltage amplitude across the active component of the GDT impedance (and, correspondingly, the average laser output power) can be increased by reducing the time constant of the discharge circuit (the storage capacitance) and raising the rectifier output voltage. However, the implementation of this possibility is restricted by the ultimate current rise rate in the thyratron (~ 4 kA μs^{-1} for TGI1-1000/25). An average CVL output power of > 100 W can be achieved using TGI1-1000/25 thyratrons with an ultimate current rise rate of > 10 kA μs^{-1}.

References

1. Petrash G.G. *Usp. Fiz. Nauk*, **105**, 645 (1971).
2. Batenin V.M., Buchanov V.V., Kazaryan M.A., Klimovskii I.I., Molodykh E.I. *Lazery na samoogranichennykh perekhodakh atomov metallov* (Lasers on Self-Contained Transitions of Metal Atoms) (Moscow: Nauchnaya Kniga, 1998).
3. Yudin N.A. *Kvantovaya Elektron.*, **30**, 583 (2000) [*Quantum Electron.*, **30**, 583 (2000)].
4. Kel'man V.A., Klimovskii I.I., Fuchko B.Yu., Zapesochnyi I.P. *Preprint of Kiev Institute of Nuclear Research* (16) (Kiev, 1985).
5. Yudin N.A. *Kvantovaya Elektron.*, **25**, 795 (1998) [*Quantum Electron.*, **28**, 774 (1998)].
6. Bokhan P.A., Zakrevskii D.E. *Pis'ma Zh. Eksp. Teor. Fiz.*, **62**, 36 (1995).
7. Klimkin V.M. *Preprint of Institute of Optics of Atmosphere, Siberian Branch, RAS* (1) (Tomsk, 1999).
8. Lyabin N.A., Chursin A.D., Domanov M.S. *Izv. Vyssh. Uchebn. Zaved. Fiz.*, **42** (8), 68 (1999).
9. Zubov V.V., Lyabin N.A., Mishin V.I., et al. *Kvantovaya Elektron.*, **10**, 1908 (1983) [*Sov. J. Quantum Electron.*, **13**, 1266 (1983)].
10. Chatroux D., Maury J. *Proc. SPIE Int. Soc. Opt. Eng.*, **1859**, 145 (1993).
11. Yudin N.A., Klimkin V.M., Prokop'ev V.E. *Kvantovaya Elektron.*, **28**, 273 (1999) [*Quantum Electron.*, **29**, 828 (1999)].