Quantum Electronics **30** (7) 583 – 586 (2000)

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Lt; 42.60.Lh
DOI: 10.1070/QE2000v030n07ABEH001770

Influence of discharge circuit parameters on the repetition rate-energy output characteristics of a laser on self-terminating transitions of atomic copper

N A Yudin

Abstract. The excitation circuits of a copper vapour laser (CVL) with a partial or total discharge of the storage capacitor were analysed. Based on this analysis, the effect of prepulse electron density on the repetition rate-energy characteristics of a CVL was shown to be minimal when the following conditions are fulfilled: $R > 2(L/C)^{1/2}$ and $L/R < \tau_c$ (for partial-discharge pump schemes; C is the storage capacitor capacity, L is the discharge circuit inductance, R is the prepulse resistance of the active medium, and τ_c is the switch turn-on time) and for a high frequency of free oscillations in the discharge circuit of a CVL. The conclusion was drawn that traditional pump schemes limit the energy capabilities of a CVL. The repetition rate-energy characteristics of a CVL can be improved by resorting to schemes with a shock or complex excitation circuit or their combination.

1. Introduction

A copper vapour laser (CVL) belongs to the class of self-terminating lasers. To efficiently pump the active medium of lasers of this class, it is necessary to form excitation pulses with a rise time that is short in comparison with the inversion lifetime. Under these excitation conditions, the efficiency of a CVL may be as high as 10% [1]. Attempts to form the above excitation conditions in real lasers have not been successful, and, therefore, the laser energy characteristics and efficiencies have been appreciably lower than the predicted ones. Bokhan et al. [2] showed that the repetition rate-energy characteristics of lasing of a CVL are restricted due to a low rate of energy input into plasma because of the existence of inductance in the discharge circuit. The effect is that the heating rate of the electrons that persist since the previous pulse is not high enough for a gas-discharge excitation mode.

The latter, in turn, brings about an increase in the parasitic population of metastable levels and lowers the rate of excitation of the resonance states of atomic copper. Increasing the switching rate of the commutator upon formation of the excitation pulse does not imply a corresponding increase in the build-up rate of the voltage across the ohmic component of the impedance of the laser discharge circuit due to the presence of inductance and does not eliminate the above effect. Hence, to optimise the pump parameters of the active medium of a CVL, one needs to know how the pulse front of the voltage across the ohmic component of the impedance of the discharge circuit (across the plasma) varies with changes in the circuit parameters and the turn-on commutator time.

It is known that a discharge is aperiodic for

$$R_1 > 2\left(\frac{L}{C_1}\right)^{1/2}, \qquad (1)$$

where R_1,L, and C_1 are the resistance, the inductance, and the capacity of the discharge circuit, respectively. When $R_1 < 2(L/C_1)^{1/2}$, the oscillatory mode is observed and the energy in the circuit dissipates during many oscillation periods. Demkin et al. [3] showed that, in excitation schemes with a partial discharge of the storage capacitor, the storage capacitor can be selected at any electron density so that condition (1) is fulfilled at least up to the termination of the laser pulse.

Therefore, it is necessary to analyse the operation of two excitation schemes: the scheme with a partial discharge of the storage capacitor, when the discharge in the circuit is aperiodic, i.e., condition (1) is fulfilled, and the scheme with a complete discharge of the storage capacitor, when the discharge in the circuit is oscillatory. In CVL excitation schemes, a series discharge circuit is used, as a rule, which contains a storage capacitor, a switch, and a gas-discharge tube (GDT) paralleled by an inductor (Fig. 1).

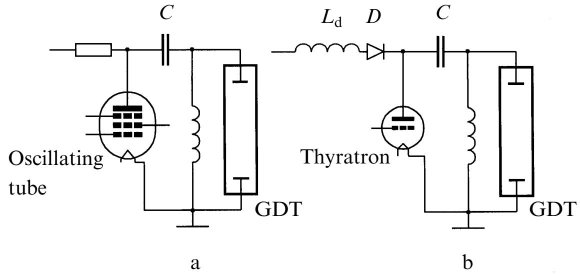

Figure 1. CVL excitation schemes with a partial (a) and complete (b) discharge of the storage capacitor C.

N A Yudin Institute of Semiconductor Physics, Siberian Division, Russian Academy of Sciences, pr.Akad.Lavrent'eva 13, 630090 Novosibirsk, Russia

Received 27 August 1999; revision received 1 February 2000
Kvantovaya Elektronika **30** (7) 583 – 586 (2000)
Translated by E N Ragozin; edited by M N Sapozhnikov

2. Excitation scheme with a partial discharge of the storage capacitor

This scheme (see Fig. 1a) employs, as a rule, oscillating tubes as a switch. The free-running process is aperiodic when the roots of the characteristic equation

$$p_{1,2} = -\frac{R_1}{2L} \pm \left(\frac{R_1^2}{4L^2} - \frac{1}{LC}\right)^{1/2} \tag{2}$$

are real, i.e., when condition (1) is fulfilled. Consider the limiting case of an infinitely large capacity of the storage capacitor C. In this case, $p_1 = 0$ and $p_2 = -R_1/L$, and the voltage across the capacitor, the current in the circuit, and the voltage across the inductor are determined by the expressions:

$$U_C(t) = U_0, \tag{3}$$

$$I(t) = \left(\frac{U_0}{R_1}\right)[1 - \exp(p_2 t)], \tag{4}$$

$$U_L(t) = -U_0 \exp(p_2 t). \tag{5}$$

The storage capacitor in real excitation schemes is selected so that the voltage across the capacitor is virtually constant during the discharge, i.e.,

$$E \ll \frac{CU_0^2}{2}, \tag{6}$$

where E is the energy of the excitation pulse. In this case, the amplitude of the voltage across the plasma may reach U_0 (for an ideal switch) and the voltage build-up rate is determined by the exponent $\exp(p_2 t)$, according to expressions (4) and (5).

To ensure a unique correlation between the commutator switching and the build-up time of the voltage across the plasma, the constant $\tau = 1/p_2 = L/R_1$ must be smaller than the turn-on time of the switch. The turn-on time of the oscillating tubes is $\sim$ 10 ns and the inductance of the discharge circuit does not exceed 1 μH for GDTs with an internal diameter of the discharge channel no below 20 mm. In this case, the prepulse plasma resistance should be no less than 100 Ohm, which is, as a rule, realised in schemes of this kind for an excitation pulse repetition rate (PRR) up to 10 kHz.

It follows from the above discussion that the conditions

$$R > 2\left(\frac{L}{C}\right)^{1/2}, \tag{7}$$

$$\frac{L}{R} < \tau_c, \tag{8}$$

should be fulfilled for efficient pumping of the active medium of a CVL. Here, R is the prepulse plasma resistance and τ_c is the turn-on time of the switch. We emphasise that the maximum practical efficiency of a CVL of $\sim$ 3% was obtained, as revealed by an analysis, under precisely these pumping conditions [4]. It is known that the plasma resistance is $R \sim p_{Ne}\sigma\langle V\rangle l/n_e T_g r^2$ and the inductance of a coaxial GDT is $L \sim \ln(r/r_2)l$. Here, p_{Ne} is the pressure of the buffer gas (neon), σ is the cross section for electron collisions with the atoms of the buffer gas, $\langle V\rangle$ is the average electron velocity, n_e is the electron density, T_g is the gas temperature, l and r are the length and the radius of the GDT channel, and r_2 is the radius of the reverse current guide of the GDT.

This means that matching the pump parameters to conditions (7) and (8) for given l and r is possible only by increasing the voltage across the GDT and the pressure of the buffer gas and also by reducing r_2. The best matching will be achieved, other conditions being equal, in active media with a lower working temperature, for instance, in lasers on vapours of chemical metal compounds. Soldatov et al. [5] experimentally confirmed the analysis conducted above, attaining a physical efficiency of a copper vapour laser of $\sim$ 9% under conditions (7) and (8) and a current disruption following the laser pulse. Condition (8) is the most critical because, in a real laser, we cannot significantly lower the inductance of the discharge circuit and the prepulse plasma resistance decreases with increasing PRR.

3. Excitation scheme with a complete discharge of the storage capacitor

This scheme of excitation of the active medium of pulsed lasers (see Fig. 1b) has gained the widest acceptance. It employs gas-discharge thyratrons as a switch. To analyse the operation of this scheme, the switch will be assumed to be an ideal switch capable of turning on instantly. To standardise the initial conditions, the time characteristics of the circuit are conventionally described by its response to a 'unit pulse'; the turning on of an ideal switch may be treated as the one.

Since the length of a unit pulse is infinitely small, the pulse response may be treated as a free oscillation in the circuit beginning from the time $t = 0$. The character of free oscillations is entirely determined by the differential equation of the circuit. Therefore, even with an ideal switch, the build-up time of the current and of the voltage across the plasma is determined by the frequency of free oscillations in the circuit:

$$\omega_{\text{free}} = \left(\frac{1}{LC} - \frac{R_1^2}{4L^2}\right)^{1/2}. \tag{9}$$

As the PRR increases, the rate of build-up of the voltage across the plasma lowers due to an increase in the prepulse electron density, i.e., due to a reduction of the plasma resistance. This is the major factor that initiates the mechanism described in Ref. [2]. The only way to retain or to increase the build-up rate of the voltage across the plasma upon increasing the PRR is, according to formula (9), to increase the frequency of free oscillations in the circuit. For a given inductance of the discharge circuit, this is accomplished by reducing the capacity of the storage capacitor, which permitted Soldatov and Fedorov [6] to obtain a CVL lasing PRR of $\sim$ 235 kHz.

The optimal storage capacitor may be thought of as having a capacity (by analogy with the aperiodic process considered above), whereby the energy stored in it is completely released in the ohmic load during the pulse. Modelling this process revealed that the optimal capacity of the storage capacitor lies in the $100 - 300$ pF range for typical parameters of the active medium and the CVL discharge circuit. However, these conditions are hard to fulfil in the scheme with a thyratron switch under consideration, because they lie outside the range of stable thyratron operation [7] and were realised only in the scheme with a tasitron [6].

4. Schemes with shock and complex excitation circuits

The above analysis of the operation of traditional schemes for pumping the active medium of a CVL revealed that the schemes under consideration limit the energy potentialities of a CVL. To improve its energy characteristics, one should use new schemes capable of operating at a high frequency of free oscillation in the discharge circuit. In this case, it is expedient to place the switch outside the discharge circuit in order to reduce its inductance. Schemes with a shock excitation circuit [8], which are widely used in induction heaters and other devices, comply with these requirements.

These schemes were used in self-terminating lasers only recently [9, 10]. The use of the shock excitation circuit to pump the active medium of self-terminating lasers improved their energy characteristics. However, an increase in the frequency of free oscillations results in a shortening of the length of the excitation pulse. This may also restrict the repetition rate-energy characteristics of a CVL when the length of the excitation pulse is shorter than the inversion lifetime in the active medium. These limitations manifest themselves most amply in a CVL with a shock circuit (Fig. 2), which is used to pump CuBr and hybrid lasers [10, 11].

Investigations were carried out employing a GL-201-type GDT (Istok Co.) and an unstable cavity in the range of excitation PRRs between 12 and 18 kHz. The gas-discharge channel of the GDT was made of an Al_2O_3 ceramics 20 mm in diameter and 800 mm in length. A TGI2-500/20 thyratron was employed as the switch. The maximum average output laser power of 11 W was obtained for an excitation PRR of 12 kHz and a voltage across the rectifier of 7.9 kV, with a storage capacitor in the shock circuit shown in Fig. 2. The average output power was observed to decrease virtually linearly to 3 W as the PRR was increased from 12 to 18 kHz. The resultant dependence of the average output laser power on the excitation PRR contradicts the above reasoning. However, this behaviour of the average output laser power becomes explicable if we consider the operation of the CVL discharge circuit given in Fig. 2.

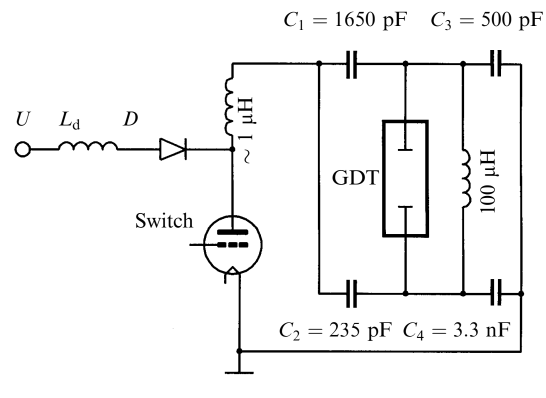

Figure 2. Scheme with a shock CVL excitation circuit.

A high-voltage rectifier charges the storage capacitors $C_1 - C_4$ through a choke-diode circuit $L_d - D$. After their charging and upon operation of the switch, the capacitors $C_1 - C_3$ and $C_2 - C_4$ recharge. The C_2 and C_3 capacitors are charged to a high voltage in the course of the recharge, and their potential difference is induced across the GDT electrodes. After the recharge of capacitors, two shock circuits are formed, which consist of the C_1,C_2 and C_3,C_4 capacitors and work for the GDT. It is precisely this kind of operation that should ideally permit forming excitation pulses with a high frequency of free oscillations.

However, during recharge of the storage capacitors, the current also flows through the $C_1 -$ GDT $- C_4$ circuit owing to a high prepulse electron density in the active medium. This results in a reduction of both the build-up rate of the voltage across the active medium and the amplitude of the voltage across the GDT.

As the excitation PRR increases, the prepulse electron density builds up, which enhances the process described above and is responsible for the observed dependence of the average output laser power on the PRR. In this case, the half-amplitude length of the laser pulse is significantly shorter ($\sim$ 10 ns for an output PRR of 12 kHz) than that typically realised in the traditional excitation scheme ($\sim$ 20 ns). It may be assumed that the reduction of the laser pulse length is associated with the fact that the excitation pulse length is shorter than the inversion lifetime in the active medium. The following series of experiments involving a CVL with a complex discharge circuit is evidence in favour of this assumption.

The investigations were carried out using a CVL with an unstable cavity and an LT-10Cu-type GDT of the Istok Co. The gas-discharge channel of this tube was made of an Al_2O_3 ceramics 14 mm in diameter and 400 mm in length. A TGI2-500/20 thyratron was used as the switch. The excitation scheme was a typical series circuit incorporating the thyratron, the GDT, and the storage capacitor (see Fig. 1b). A $\sim$ 100 μH inductor was placed in parallel with the GDT. A high-voltage rectifier charged the storage capacitor via a choke-diode circuit. The power supply was matched to the load by selecting the storage capacitor in such a way as to minimise the reverse voltage impressed on the thyratron anode [7].

For a rectifier voltage of 5.7 kV, an excitation PRR of 18 kHz, and a storage capacitor of 1240 pF, the reverse voltage at the thyratron anode did not exceed 500 V. The length of the current pulse at a level of 0.1 was 120 ns. The lasing commenced 40 ns after the onset of the excitation pulse. The half-amplitude length of the output laser pulse at a wavelength of 510.6 nm was $\sim$ 6 ns. The complex discharge circuit in the laser was formed by replacing the storage capacitor with a distributed four-chain capacity (Fig. 3) equal to 1240 pF, which is equivalent to replacing a simple oscillatory circuit by a complex circuit made up of four simple ones.

The parameters of every chain were selected from the condition that the wave impedance of each subsequent chain should be lower than the preceding one, because the plasma resistance diminishes during the excitation pulse. All other factors being equal, the current pulse length at a level of 0.1 was observed to shorten to 90 ns, the pulse acquiring a more square shape. In this case, the half-amplitude width of the laser pulse at a wavelength of 510.6 nm rose to 12 ns with a corresponding increase in the output laser power.

It is pertinent to note that similar relationships are also observed for a CuBr laser, with a nearly threefold gain in output laser power obtained in this case. Clearly the operation of a CVL with a complex excitation circuit calls for a more thorough investigation than the foregoing one.

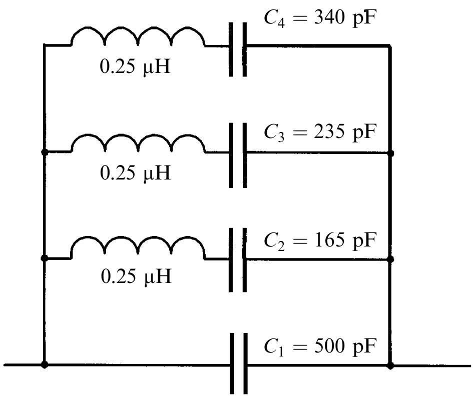

Figure 3. Distributed storage capacitor.

5. Conclusions

The above consideration of the schemes of excitation of the active medium and the experimental results obtained allow the following conclusions:

(1) In the case of schemes for active-medium excitation with a partial discharge of the storage capacitor, the effect of prepulse electron density is minimal when conditions (7) and (8) are fulfilled.

(2) For excitation schemes with a complete discharge of the storage capacitor, the effect of prepulse electron density diminishes as the frequency of free oscillations in the discharge circuit increases.

(3) The excitation conditions satisfying the criterion for efficient pumping of the active medium are impossible to form in a discharge circuit that represents a simple oscillatory circuit.

(4) The conditions for efficient pumping of the active medium may be amply realised in a laser having a discharge circuit in the form of a shock or complex oscillatory circuits or their combination.

Acknowledgements. The author thanks P A Bokhan for support of this work and helpful discussions.

References

1. Petrash G G *Usp. Fiz. Nauk* **105** 645 (1971)
2. Bokhan P A, Gerasimov V A, Solomonov V I, Shcheglov V B *Kvantovaya Elektron. (Moscow)* **5** 2162 (1978) [*Sov. J. Quantum Electron.* **8** 1220 (1978)]
3. Demkin V P, Soldatov A N, Yudin N A *Opt. Atmos. Okeana* **16** 659 (1993) [*Atmos. Oceanic Opt*. **6** 388 (1993)]
4. Bokhan P A, Gerasimov V A *Kvantovaya Elektron. (Moscow)* **6** 451 (1979) [*Sov. J. Quantum Electron.* **9** 273 (1979)]
5. Soldatov A N, Fedorov V F, Yudin N A *Kvantovaya Elektron. (Moscow)* **21** 733 (1994) [*Quantum Electron*. **24** 677 (1994)]
6. Soldatov A N, Fedorov V F *Izv. Vyssh. Uchebn. Zaved., Fiz.* **26** (9) 80 (1983)
7. Yudin N A *Kvantovaya Elektron. (Moscow)* **25** 795 (1998) [*Quantum Electron*. **28** 774 (1998)]
8. Artym A D, Donskoi A V *Elektrichestvo* (1) **51** (1960)
9. Lyabin N A, Chursin A D, Domanov M S *Izv. Vyssh. Uchebn. Zaved., Fiz*. **42** (8) 67 (1999)
10. Vuchkov N K, Astadjov D N, Sabotinov N V *Opt. Quantum Electron.* **23** 549 (1991)
11. Jones D R, Maitland A, Little C E *IEEE J. Quantum Electron.* **30** 2385 (1994)