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A method to obtain the pulse operation of a power CO_2 laser working in continuous regime

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There are presented pulse excitation methods of CO_2 lasers, which permit the growth of the number of their applications in material processing. It is also presented a pulse excitation system of CO_2 lasers, with continuous flow of the gas, with electrical discharge in glass pipes, which allows the pulse operation of the laser and automatic control of its parameters during the material processing. By Spice simulation was tested in time and frequency domains the Half-Bridge converter, and its stability was analyzed.

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1. Introduction

Thermal processing with laser beam have a large industrial application field for thermal treatments operations, surface mixing of metal pieces, holing, cutting, trimming of electronic components, engraving, static and dynamic equilibration, welding etc., by changing the thermal state of the processed material.

The processing by laser beam is conditioned by the interaction between laser beam and substance, at least the partial absorption of the incident beam energy during the processing of the material and results from mobile or standing irradiation in continuous wave regime or impulses. The local development of certain power densities is capable to produce various physical effects: chemical, hydrodynamic, physical damaging etc..

The laser processing of a material consists in bringing this material to vaporization and melting by interaction with the focused laser beam. The large electromagnetic energy of the laser beam is transferred into the crystalline network of the material thus creating a great amount of heat in small volumes and in short periods of time. The destruction of the crystalline network of the material and its bringing in the vaporization state, along a pre-established curve, is done by the energy of photons created inside the material, and also by the jet of the active gas (O_2). This active gas contributes to the intensification of the material destruction due to the passible exothermal reactions.

The performances of the technological action are mainly given by the structure and the long time functionality of laser system and also by the working object defined features. In this complex situation, the choice of the best laser source for a given technological application has a primordial importance, and it is a common problem of lasers users.

To obtain the pulsed operation of CO_2 laser, it is very important for the enlargement of its applications in the materials processing. One of the material processing requires an intermittent application of the laser beam (cutting by the controlled fracturing process, engraving etc.).

For the particular periods of the laser pulses there is possible to generate super-pulses laser, the emitted power during this process being 5…10 greater than in a continuous wave regime. The super-pulse conditions it is used for the processing of the hardly fusible materials, allowing to obtain upper levels of the processing quality.

For these raisons, most of CO_2 lasers, commercially available, have the possibility to operate in pulsed conditions. For example, Coherent General with the lasers: EVERLASE E7000 and E3500, which have performances almost similar to CO_2 lasers, have been realized in the Institute of Atomic Physics, Bucharest, Romania.

2. Pulsed excitation methods of CO_2 lasers

A procedure used to obtain the CO_2 pulsed operation is their pulsated excitation. The period of these pulses so obtained is generally greater than 50 μs, and the repetition frequency is maximum 2 kHz, while the typically values are 200 μs and respectively 1 kHz. The pulse operation may be obtained both in a direct current excitation conditions as in radio frequency excitation (RF).

The radio frequency excitation conditions are easy to realize, the obtained pulses having a period of 1…100 μs and a repetition frequency of until 2.5 kHz. The most frequently used frequencies for CO_2 lasers excitation are 13.6 MHz and respectively, 27.3 MHz [1].

In radio frequency excitation case, the energy coupling to the laser plasma can be realized capacitively by using a dielectric material. The absence of the contact between laser plasma and the metallic surfaces reduces appreciably the chemical degradation of the gases. The discharge stabilization is made because of a voltage drop on the dielectric layer and by modifying its thickness, it results the wished homogeneity of the discharge. This homogeneity can be maintained until the value of power density in discharge becomes 5 times higher than in a continuous current, and this advantage is maintained in pulse operation. The increased homogeneity of the active medium leads to a laser beam with an ameliorated quality regarding the mode structure and the divergence.

The solution of the radio frequency discharge requires however high power radio frequency generators, which are, generally, expensive and they are not fabricated in Romania. Moreover the coupling of the radio frequency energy to the geometrically structure of the discharge tube is difficult and requires high voltages of the order of 5…8 kV. For this reason this solution is spread to the lasers with fast axial or transversal flow of gas.

The electrical discharge for CO_2 lasers excitation is a self-maintaining discharge having a characteristic current-voltage with a negative resistance. The discharge current in the supply circuit is stabilized with a limitation resistance (ballasting resistance) whose value is higher than the negative resistance of the discharge. Modifying the limitation resistance, it is possible to obtain the modulation of the discharge current.

Because the voltage drop on the ballasting resistance is approximately 2…7kV [2], the task of the ballasting resistance can be accomplished by an electronic tube of high voltage. His internal resistance has the same function as the ballast resistance of the discharge; modifying the control gate potential can modulate the supply current. On this principle, Coherent General Inc. realized a CO_2 pulsated laser used for the cutting by fracture of the ceramics slices with a thickness of 0.3…0.5 mm.

Another solution for discharge current modulation is the utilization of a high voltage switch mode power supply for the laser, the discharge current being stabilized and modulated in the primary circuit of the high voltage transformer.

In case of an electrical discharge of continuous current, energy is coupled to de laser plasma by some metallic electrodes, resulting in time a chemical degradation of the gases. The continuous current discharge tends to be contracted especially in the edge and corner zones of the electrodes and when the density of the power exceeds a certain value, generally situated between 10…20 W/cm^3, these constrictions degenerate in an electric arc. The stabilization of the discharge can be realized by segmenting the electrodes, by introducing some turbulences etc.

In the last years, a new technique of excitation has appeared: silent discharge, at the frequency of about 100 kHz. The cost of power generators in this field is reduced but there is a disadvantage which consists in the necessity to utilize a dielectric with a very high dielectrical rigidity.

3. Pulse excitation system of CO_2 power laser

The adopted solution, for the pulse operation of the CO_2 power lasers, with continuous flow of the gas is the excitation in continuous current discharge. In this case the discharge voltage is obtained by increasing the voltage of a converter, which can oscillate between 20…100 kHz. The secondary armature high voltage of the transformer is rectified and applied to the laser tube. The known load characteristic of a laser tube, for 30…100 mA interval, is presented in Table 1 [1].

Table 1 The load characteristic of a laser tube.

I_n (mA)	30	40	50	60	70	80	90	100
U_n (kV)	8.90	8.30	7.80	7.30	7.00	6.80	6.60	6.50
R (kΩ)	–60	–60	–50	–50	–30	–30	–20	–20

The designed electric power source is designated to supply the 400 W CO_2 lasers, with a continuous flow of gas. The purpose was to obtain a pulse operation of CO_2 power lasers, for the enlargement of the spectrum of their applications in the processing materials field and realize compact electronic equipment with reduced volume and high efficiency, which allows the automatic control of the laser beam power.

For 400 W CO_2 lasers, with a continuous flow of gas, the electric discharge is achieved in four laser tubes and it appears between a central anode and two cathodes situated at the extremities of the tube. From electrical point of view, the four laser tubes are connected in derivation and from optical point of view they are serially connected, the length of the active medium being of approximately 8 m. The laser beam is passed from a tube to another with the support of two mirrors for each tube situated at 45 degrees against the axis of the tube. The designed equipment contains four modules connected in derivation [2].

For the electric power source design, which satisfies the imposed requirements, we have (it was considered the minimum efficiency for the electric energy conversion in laser energy of 12,5 %) [2]:

- Output nominal voltage: U_o = 8…10 kV;
- Output nominal power: P_o = 800 W;
- Load nominal current: I_o = 80 mA;
- Peak power: P_{omax} = 4 kW;
- Peak current: I_{omax} = 400 mA;
- Pulse repetition frequency: f_r = 0…1 kHz;
- Pulse duration: t_i =0.2 ms;
- Minimum efficiency: η = 0.78%;
- Discharge firing voltage: U_a = 20 kV;
- Pulse shape: rectified half-wave trains, at the converter without waveform special conditions;
- Ballasting resistance elimination from the laser supply circuit;
- Laser power automatic control between certain allowed limits by the variation of the discharge current in the laser tube.

The elimination of the ballasting resistance may be realized with a current power source of the laser tube discharge. One of the solutions can be the transformation of a voltage supply in a current one by introducing a reaction loop for the stabilization of the load current. Because the characteristic development time of the plasma instabilities is of 1…5 ms, there is possible to use a converter with the oscillation frequency of about 100 kHz, which to be contained in the reaction loop. Thus, the response time will be of approximately 10 μs.

Having in view the necessary nominal output power (P_0 = 800 W) and the operation specific conditions, which impose the peak power of 4…4.5 kW, it was established for the power module a Half-Bridge converter configuration.

The output current control is realized with a reaction circuit, which use the current information from the primary winding of the high voltage transformer to determine the control signals duty cycle for the switching transistors.

Depending of the output and input imposed conditions there were established the functional units, which composed the supply equipment (Fig. 1).

These are the follows: protective unit against radio-electronic interferences in / from network; rectification and filtering unit for supply voltage; trigger circuit, which makes the discharge firing voltage; power modules; command circuit of power module and operation mode achievement.

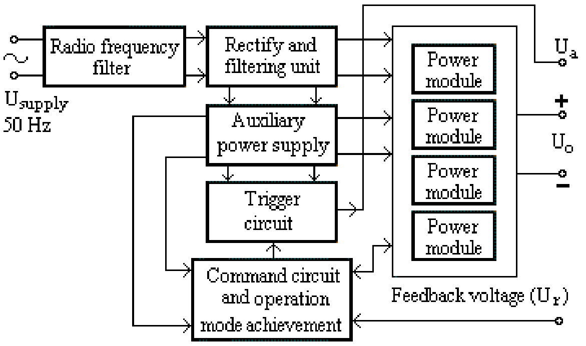

Fig.1. Block diagram of the laser supply equipment.

The block diagram of power module is presented in Fig. 2.

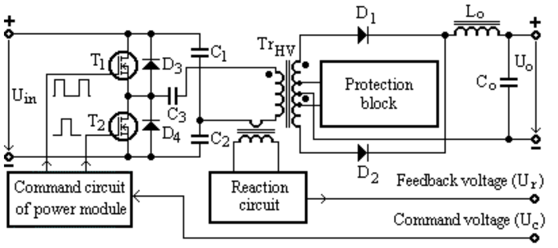

Fig.2. Block diagram of power module.

The power block is composed of four power modules connected in derivation, each of them having an output power of 800 W. A power module contains a Half-Bridge converter, the command circuit of power module and protection auxiliary circuits. The continuous voltage obtained at rectifies and filtering unit output (U_{in}) is applied to the Half-Bridge converter. By the switching elements from the converter there are obtained rectangular impulses of the voltage, with a firm (fixed) frequency and with an imposed duty cycle by the command circuit. The chosen commutation frequency is approximately 100 kHz. From that results a diminution of volume for the ferromagnetic core of the high-voltage transformer.

The command circuit realizes charge and discharge of the gate-drain capacitance of Power MOS transistors, determining the saturation or blocking them. High-voltage transformer delivers the necessary voltage to supply the laser equipment. The load matching is created as well. The transfer of energy is made in sin-phase.

The command and operation mode achievement circuit generates impulses for the switching elements in the converters and allows the automatic control of the laser power during the operation. Thus, it is compared the information referring to the output-controlled parameter (laser power that can diminish due to the voltage decrease from the supply network or to the chemical degradation of the gases, which form the active medium) obtained from the reaction circuit (U_r), with a prescription value, which determines the modification of the load nominal current between some allowed limits.

The control of the output current is achieved by a reaction circuit, which uses the current information from the primary circuit of the high voltage transformer to determine the command pulses duty cycle of the power transistors.

4. The space analysis of the designed power module

By Spice simulation [6] was tested in time and frequency domains the power supply of laser equipment. In order to simplify the analysis and to reduce simulation time, from the designed power supply was considered only the power module.

The power supply is in essence a closed loop control system [3] (see Fig. 3), and it must be analyzed for its stability.

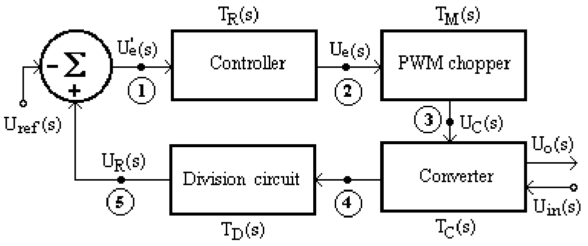

Fig.3. Power supply as a closed loop control system.

The reference signal, $U_{ref}(s)$, is compared with the feedback signal, $U_R(s)$, and it results the error signal, $U_e(s)$, which is amplified by the error amplifier. The converter control-output transfer function is determined with the averaging method applied in the state variables field [4].

It results:

$$T_C(s)=\frac{U_o(s)}{U_C(s)}=K\frac{1+\frac{s}{s_1}}{\frac{s^2}{\omega_o^2}+\frac{s}{\omega_o\cdot Q}+1} \qquad (1)$$

where: $K=\frac{n\cdot\delta}{2}U_{in}$, $\omega_o=\frac{1}{\sqrt{L_o\cdot C_o}}$, $s_1=\frac{1}{r_C\cdot C_o}$, Q – the filtering circuit (L_o, C_o) quality factor, r_c – the equivalent serial resistance of the filtering capacitor, C_o.

Equation (2) allows to calculate the closed loop system transfer function [5]:

$$F(s)=\frac{U_o(s)}{U_{ref}(s)}=\frac{T_R(s)\cdot T_M(s)\cdot T_C(s)}{1+T_D(s)\cdot T_R(s)\cdot T_M(s)\cdot T_C(s)}=\frac{S(s)}{1+T_D(s)\cdot S(s)} \qquad (2)$$

$$S(s)=T_R(s)\cdot T_M(s)\cdot T_C(s) \qquad (3)$$

where: $T_m(s)$ is the PWM chopper transfer function, $T_r(s)$ – the controller transfer function, $T_d(s)$ – the transfer function of the division circuit, s(s) – the open loop gain, and $T_D(s)\cdot S(s)$ – the open loop transfer function.

To determine the poles of the closed loop system the transfer function is got by solving the equation:

$$1+T_D(s)\cdot S(s)=0 \qquad (4)$$

The frequency attenuation characteristic and envelope-delay characteristic (phase response), for controller, converter, and whole system, are presented in Fig. 4…6.

The converter transfer function has a zero introduced by the filtering capacitor serial resistance, r_c, at a frequency upper than 500 MHz, and a double pole at frequency of 3.825 kHz. The controller transfer function has a pole in fixed point and a zero at frequency of 2.894 kHz.

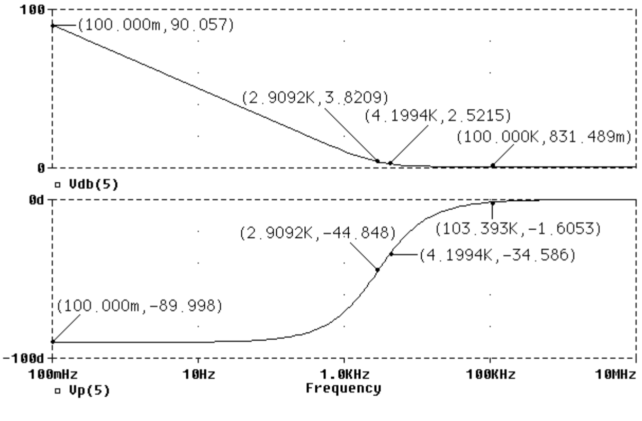

Fig.4. Controller waveforms in frequency domain.

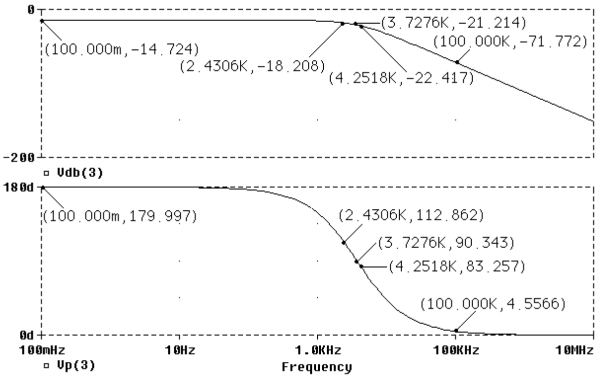

Fig.5. Converter waveforms in frequency domain.

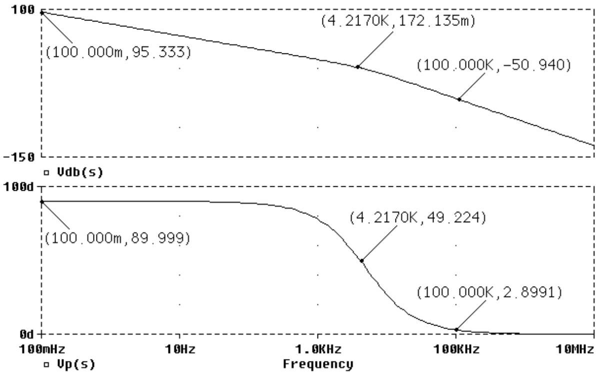

Fig.6. System waveforms in frequency domain.

The open loop transfer function of the system has a pole in fixed point, which is introduced by the controller, a double pole introduced by the converter, and two zero, one introduced by the controller and the other one introduced by the converter. The presence of pole in fixed point ensures a high gain at low frequencies. The zero introduced by the controller is placed near the double pole introduced by the converter, so that the passing through f_{cross} is realized with value: 20db/dec.

It results f_{cross} = 4.2 kHz. The phase edge is positive and has the value equal to $49{,}3^o$.

The waveforms for: drain currents, primary winding current of high-voltage transformer, filtering inductance (L_o) current, and laser supply voltage are presented in Fig. 7 and 8.

The load current variation is presented in Fig. 9.

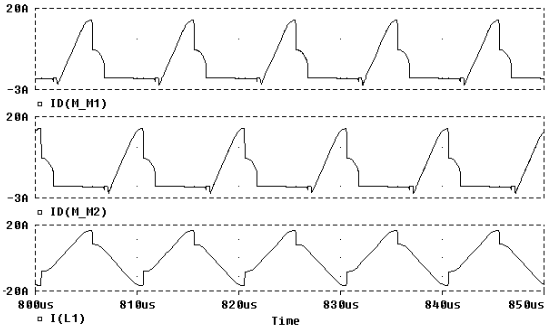

Fig.7. Waveforms for drain currents and primary winding current of high-voltage transformer.

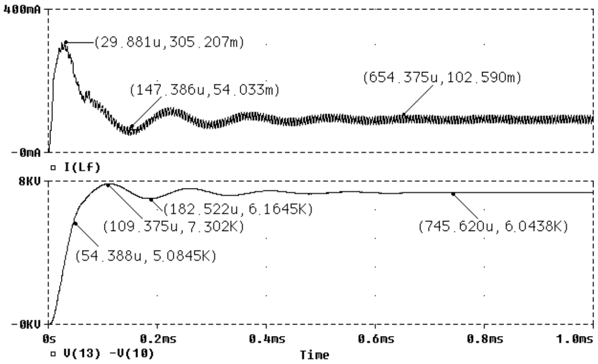

Fig.8. Waveforms for filtering inductance (L_o) current and laser supply voltage.

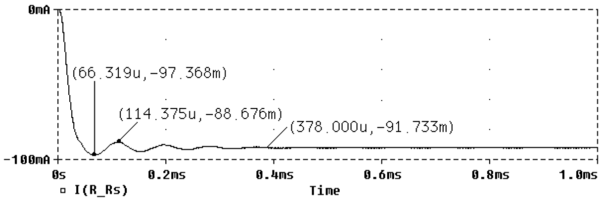

Fig.9. Waveform for load current variation.

It results (see Fig. 9) that load current intensity, which is generated by converter, is around 91.733 mA, and its maximal variation is around 9 mA.

5. Conclusions

The presented pulse excitation methods of CO_2 lasers permit the growth of the number of laser applications in material processing.

The adopted solution, for the pulse operation of the CO_2 power lasers, with continuous flow of the gas is the excitation in continuous current discharge.

The pulse excitation system of CO_2 power lasers, which was presented, allows the pulse operation of the laser and automatic control of its parameters during the material processing. For the control or monitoring of laser material processing, the in-process signals for the laser beam variables are the following: power, diameter, mode structure and location. In order to have a self-regulating system for a laser it must exhibit either an open or closed loop controller.

By Spice simulation was tested in time and frequency domains the power supply of laser equipment.

Considering the results of performed analyis it is allowed to affirm that the open loop transfer function of the system ensures its stability.

From the performed Spice analysis, it results that the evolution in time of the electrical quantities and the obtained signal levels are in good agreement with the calculated values.

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