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Pulsed RF excitation inductive discharge CO_2 laser with the radiation energy of 1 J and high efficiency

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An efficient pulsed gas-discharge inductive CO_2-laser with a radiation energy of 1.05 J has been developed for the first time. In this case, the pulse duration of the laser radiation was about 10 msec. The maximum efficiency of 21.1% was obtained at a radiation energy of 340 mJ. HF current pulses propagated along the inductor conductor and, thus, an inductive discharge was formed to create a population inversion at the infrared (IR) transitions of CO_2^* molecules. The temporal and energy characteristics of the radiation of the inductive CO_2-laser depending on the duration of the pump pulse are investigated. The spatial characteristics and spectrum of the radiation of the developed laser are estimated. The divergence of the laser radiation was 0.52 mrad. The cross-sectional dimension of the laser output beam was about 35 mm in diameter.

Keywords: inductive discharge in a mixture of gases, high-frequency modulation of the pump voltage, population inversion, output characteristics of laser radiation.

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Introduction

As applied to the method for excitation of gas active media by electrodeless high-frequency (HF) discharge by magnetic field induction, several first papers should be noted. Thus, in 1965 an electrodeless „toroidal" discharge in gas media was mentioned in modulation of pumping pulses by HF electric signal [1]. Therefore, a method was proposed to obtain population inversion on electronic transitions of inert gas ions in electric discharge plasma, and lasing was reported in the visible range of optical spectrum. The author used a ferrite core and a solenoid, a conductor of which spread pulses of modulated pumping current. To continue study of this method capabilities, in 1966 the team of authors in paper [2] reported already the extended list of active laser media and proposed to modify the means for development of population inversion with pumping by continuous electrodeless HF discharge. In this paper authors used a solenoid located directly on a discharge tube capillary. In 1973 the authors of paper [3] came back to the subject of studies by the authors of paper [2], having extended both the list of gas active media and the range of lasing wavelengths using pulse mode of HF pumping. The mentioned papers (apart from the excitation method) combined the conditions for development of inductively coupled plasma at low pressures (to Torr units).

As applied to the method for excitation of gas active media of low and medium pressures by pulse electrodeless inductive discharge, let us mention several papers published in the period from 2005 to 2014 [4–12]. The table specifies the main experimental data for all (from 2005 to 2021) pulse inductive lasers designed at the time of publication creation (apart from active medium of inductive CO_2-laser, design of which will be described below). The paper [4] for the first time proposed and implemented in an experiment a pulsed inductive discharge generated by pulse electric high voltage excitation circuits to develop population inversion on transitions of atoms and molecules. To test the proposed method, the first active medium used was a gas mixture $He:F_2$, where the inductive discharge was formed in the range of pressures from units to hundreds Torr. As a result of completed research [4] the first pulsed inductive laser of visible range on electron transitions of fluorine atoms was designed.

To test inductive discharge (as a method of pumping of gas active medium on electron-vibrational self-limited transitions), experiments have been carried out, the results of which are published in paper [5].

To extend the possibility of lasing at other types of transitions using the new pumping method, studies have been carried out to find a way to create population inversion in gas active media at vibration-rotation transitions. The first result of this work — making of an inductive CO_2-laser, was reported in 2006, and then published paper in 2007 [6]. In papers [7–10] the subject of inductive CO_2-laser was continued.

It should be mentioned that basically the first publications of the results of CO_2-laser making as a new optical quantum generator are dated back to 1964 [13], and results of research related inter alia to explanation of nitrogen role in active medium of CO_2-laser (still recognized as valid), belong to the authors of paper in 1966 [14].

Pulse induction lasers

Laser	Composition of gas active medium	Pressure of gas mix p, Torr	Lasing wavelengths λ, μm	Energy of laser radiation E, mJ	Laser duration t(FWHM), ns	Pulse power of laser radiation P, kW	Divergence of laser radiation θ, mrad	Shape of output beam	Reference
N_2	N_2	7	0.3371 0.3577	11	10	1000	0.3	Ring ~ Ø 40 mm	[5,15]
HF	$He:H_2:NF_3=$ 45:1:4 $H_2:NF_3=1:4$	40	2.732 2.763 2.798 2.835 2.873 2.893 2.913	19	420	45	Was not measured	Ring ~ Ø 20 mm	[16] [17]
H_2	H_2	0.5–3	0.835 0.887 0.89 1.116 1.122	0.12	18	7	1.2	Ring ~ Ø 33 mm	[18] [12]
F I	$He:F_2=80:1$	40–50	0.624 0.635 0.641 0.704 0.713 0.731 0.740 0.756	2.6	80	32	0.4	Ring ~ Ø 42 mm	[4,7]
Ar I	He:Ar=3:1 He:Ar=7:1	1.5 2.5	1.213 1.240 1.270 1.694 1.791	0.1	5	20	Was not measured	Circle ~ Ø 7 mm	[19]
Xe I	Ar:Xe=1:1 He:Xe=1:1	1	0.8409 0.9045 0.9799 1.733 2.026	0.1	8	12.5	1	Ring ~ Ø 20 mm	[20]
Ne I	$Ne:NF_3=$ 500:1 $Ne:NF_3=$ 150:1 $Ne:NF_3=$ 250:1 $Ne:SF_6=$ 800:1	0.5 15	0.540 0.594 0.614	0.05	15 5	3.3 10	Was not measured	Ring ~ Ø 42 mm	[21]
Ne	$Ne:H_2=1:1$	19	0.5853	0.02	180	0.1	2	Ring ~ Ø 42 mm	[22]

Analysis of results published in papers [6–10] makes it evident that output energy of inductive CO_2-laser is proportional to diameter of discharge tube (DT), i. e. output energy and efficiency of laser increase with diameter increasing (from 20 to 42 mm). As a result of the above research, the need was identified to improve the efficiency of the designed inductive CO_2-laser, as well as the need to continue optimization of excitation parameters and composition of active medium. This was exactly the main objective of this research cycle [6–10].

Therefore, the possibility was identified to use pulse mode of ignition and maintenance of inductive discharge by voltage modulated by high frequency — HF pumping. Paper [10] provides the results showing that using pulse high-voltage excitation circuits leads to a preferential excitation of electronic states N_2 (most energy of the inductive discharge is spent on these processes). Whereas HF excitation systems make it possible to generate mostly low-energy electrons. This circumstance, in turn, prevents loss of pump energy to excite the electronic levels N_2, but excite its vibrational levels and effectively (resonantly) transmit excitation to molecules CO_2. In an attempt to optimize parameters of active medium excitation in inductive CO_2-laser, the experiment produced results published in [11,12]. As a result, despite the limitations in ignition of the inductive discharge in a DT with an internal diameter larger than 20 mm, it was demonstrated that the inductive CO_2-laser could operate with relatively high efficiency (about 17 %) and for the first time with a circular energy distribution rather than a ring shape of the output beam. Since the input energy was limited to 100 mJ, the output energy was not more than 20 mJ.

In connection with the above, the purpose of this paper is to develop an electrical excitation circuit based on a commercial HF power supply source with a matching device that provides optimal excitation parameters of active medium at vibrational-rotational transitions, and to design an effective pulsed inductive CO_2-laser.

Experimental setup and equipment to record/measure characteristics

An experimental setup is developed (fig. 1) with HF power supply source by „AdvancedEnergy" mod. „CESAR®RF" ($f_{\text{mod}} = 27.12$ MHz, 1000 W) („RF") and matching device „VarioMatch" („MN").

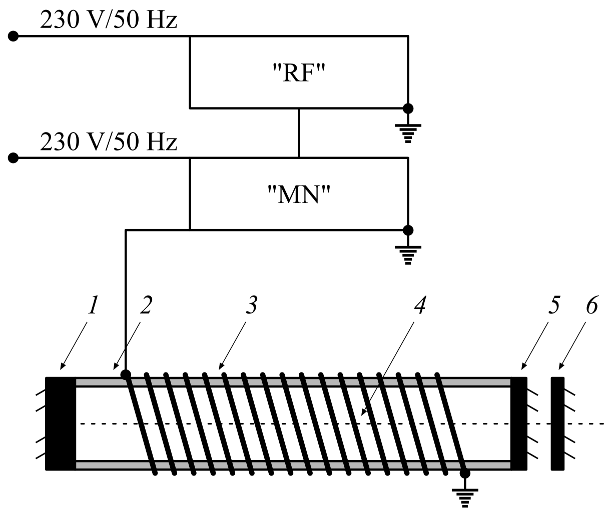

Figure 1. Electrical flowchart of excitation system and discharge tube of inductive CO_2-laser. *1* — „dense" silicon mirror; *2* — discharge tube; *3* — conventional image of laser inductor (solenoid); *4* — active volume; *5* — mirror (ZnSe), $R \sim 30\%$; *6* — output mirror (ZnSe), $R \sim 48\%$.

A gas filled DT used was a ceramic tube with length of 1600 mm and inner diameter of around 42 mm. DT material was chosen because of the need to provide for proper cooling of working gas mixture at the account of heat diffusion to DT wall. The inductor was a solenoid consisting of separate, double-wound sections oriented to DT and connected in parallel. A set of insulated strands of multicore wire (256 copper cores) of a certain length was used as inductor sections, which were optimized in the course of the operation. The inductor sections were placed in a series of coils on the outer surface of the DT. To ensure operation of the inductive CO_2-laser in the mode with a pulse repetition rate of more than 5 Hz, the working gas mixture was flowed along its optical axis. The flow rate of the working gas mixture in this case did not exceed ~ 9 l/h.

Flat mirrors for sealing and feedback were installed at the DT ends, perpendicular to the optical axis in the alignment nodes. The plane-parallel resonator formed by a rear flat mirror of silicon with reflection ratio of 99% (by „OphirOpticsGroup") and two front „semi-transparent" mirrors of ZnSe („OphirOpticsGroup") with reflection ratios (R) 30 and 48% at the working wavelength 10.6 μm.

To conduct research of energy characteristics of inductive CO_2-laser, a power/energy meter of radiation was used „OphirStarBright" with measuring head PE50 B-DIF-C by „OphirPhotonics".

To determine duration of lasing and shape of oscillograms, a photoresist (gold-doped germanium) cooled with liquid nitrogen and a Tektronix digital storage oscilloscope (TDS 2014B) were used together with it. To verify these results, a non-cooled IR pulse optical detector „VIGO" (HgCdTe) with a time constant up to 5 ns and spectral sensitivity ranging from 2 to 14 μm was used.

To evaluate duration and shape of oscillograms of pump pulses generated by HF power supply, a high-voltage probe „Tektronix" model P6015A, and the above mentioned digital oscilloscope were used.

Laser radiation spectrum was determined with a monochromator MDR-23 (with diffraction grating 75 l/mm) and measuring head PE50 B-DIF-C „OphirPhotonics" (as a photoelectric detector).

Spatial characteristics of inductive CO_2-laser radiation were estimated using thermal paper and thermal imaging device „HTI" model HT-301, IR matrix of which had resolution 384×288 pix. Spectral range of thermal imaging device operation $8-14$ μm.

The gas system made it possible to prepare multicomponent gas mixtures, to provide vacuumization of the DT and the gas pathway, to provide a regulated flow of the working gas mixture to maintain the working pressure with continued longitudinal pumping of the working mixture along the DT optical axis.

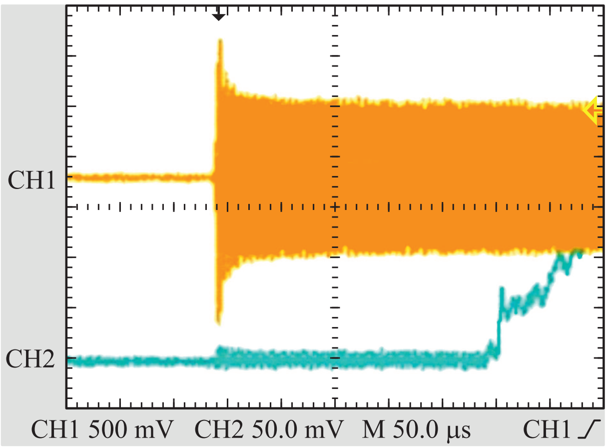

Figure 2. Initial regions of voltage pulse oscillograms in high-frequency power supply source (high frequency modulated electrical signal at input of the first oscilloscope channel — „CH1") and optical pulse of infrared laser radiation (electrical signal at input of the second oscilloscope channel — „CH2"). Time sweep of the oscilloscope corresponds to 50 μsec/cell.

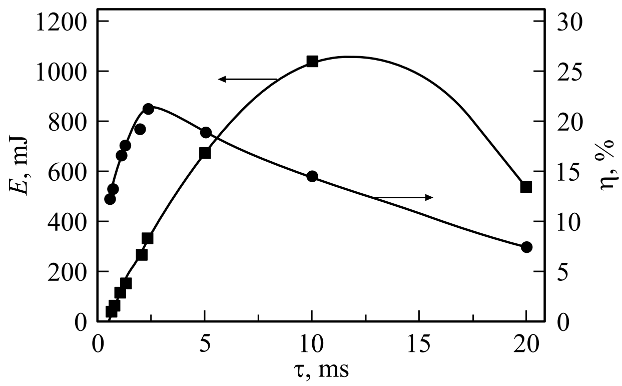

Figure 3. Dependence of energy (E) in radiation pulse of inductive CO_2-laser and its efficiency (η) on duration of pump pulse (τ).

Results and discussion

Based on the above (in the introduction), it follows that increasing active length and inner diameter of the DT enables high values of inductive CO_2-laser output energy. Therefore, to achieve the goal of the work, it was necessary to perform scientific-research work for optimization of laser inductor (solenoid) design on the DT with inner diameter of 42 mm and length 1600 mm while working mixtures $He:N_2:CO_2$ were pumped with HF current pulses of the power supply source „CESAR®RF".

As a result of the optimization performed, the inductor became a set of sections of 14 turns each, providing ignition of inductive discharge with an active length of 1150 mm at working mixture pressures up to 50 mbar.

As a result of optimization of the working gas mixture composition (by parameter of maximum energy in a pulse

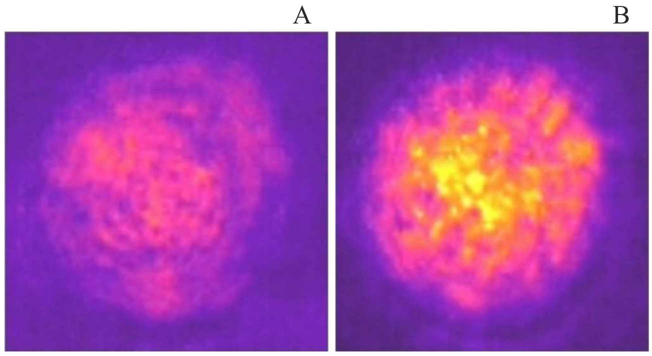

Figure 4. Thermal image of laser beam at $\tau = 10$ ms, obtained on the surface of polymethylmethacrylate target, after absorption of one pulse of laser radiation (A) and after a series of pulses ($f = 1$ Hz) of laser radiation (B).

of laser radiation of inductive CO_2-laser working in pulse mode with excitation pulse repetition rate up to 10 Hz), gas mixture $He:N_2:CO_2 = 8 : 2 : 1$ was selected at pressure of ~ 10 mbar.

When studying time characteristics of the developed laser, signals (fig. 2) were sent to the oscilloscope inputs: a pump voltage pulse (after attenuation by a high voltage probe 1000 times) and a voltage pulse (when the laser is operated with non-zero energy of radiation) formed on a photoresist cooled by liquid nitrogen (channel 2). The HF pump voltage pulse is sinusoid ($f_{mod} = 27.12$ MHz) of certain duration (τ) with vibration period of modulating signal ~ 38 ns. Value τ is set manually by hardware and can take specific values determined by a combination of two parameters: voltage pulse repetition rate (f, in Hz) and their duty cycle (S, in %). HF pump voltage amplitude (amplitude of sinusoidal vibrations) depends on whether the inductive discharge has developed or not. When the induction discharge develops, there is a „transient process" observed, which lasts $\sim 20\,\mu$s from the beginning of the HF pumping voltage pulse. HF pump voltage amplitude at the same time reduces from ~ 2.6 kV to „stationary" value ~ 1.5 kV.

Fig. 3 presents obtained dependencies of output energy of radiation (E) and efficiency (η, by stored energy) of designed CO_2-laser on duration of pump voltage pulse (τ) at maximum output power of HF source (in experiment ~ 720 W with power reflected from inductor of around 10 W). From the point of view of further practical use of the designed laser an important experimental result is overcoming the conditional value of output energy 1 J and realization of laser efficiency c η above 20%.

Therefore, in pulse mode of operation at $\tau = 10$ ms the energy reached 1.05 J, which corresponds to value $\eta \sim 14.5\%$. Besides, estimate of specific energy value makes ~ 0.85 J/l. In its turn in the mode of operation with $\tau = 2.25$ ms, value $\eta \sim 21.1\%$ is achieved with pulse energy ~ 340 mJ.

The important conclusion is that hardware reduction of output capacity in HF power supply source from values 720 W ($E \sim 1050$ mJ) and below (at constant $\tau = 10$ ms) radiation energy of inductive CO_2-laser also reduced almost linearly to $E \sim 250$ mJ (this value E is provided by output power of HF power supply source at the level of 300 W). A further decrease in pump power was accompanied by a sharper decrease in E up to the stall of generation at HF power supply source output power below 250 W ($E \sim 150$ mJ). Reduction of the pump power was accompanied by optimization (reduction) of the working mixture pressure in the DT.

Using a thermal imager „HTI" and generating a thermal image, energy distribution of the laser output beam in the perpendicular direction was evaluated when the IR radiation was absorbed by the target material. The target was placed at a distance of 3.5 m from the CO_2-laser output mirror. Three target materials were used: polyethylene terephthalate (0.1 mm thick film), polymethylmethacrylate (2 mm thick plate), and wood-fiber board. The most informative (from the point of view of no „image" highlight) of the three images are the images observed on targets made of polyethylene terephthalate and polymethylmethacrylate. The thermal imager was placed at an angle of about 30° towards direction of laser radiation propagation, on the left at a distance of 600 mm from the surface of the target. Fig. 4 shows images registered by the thermal imager on the target made of polymethylmethacrylate.

The images obtained show temperature of the irradiated target areas as a function of color. Thus, one can observe a trend of gradual increase of the target surface temperature from the periphery of the beam to the center.

Consequently, when dimensions are estimated, the main energy of laser radiation is concentrated in the output beam with diameter ~ 35 mm. This study was preceded by an analysis of the impact of laser radiation on the heat-sensitive surface of thermal paper in order to estimate the divergence angle of the laser beam in the investigated laser. Diameter of the thermal imprint boundaries at distances of 0.5 and 3.5 m from the output mirror of the laser resonator was evaluated. HF pumping parameters (HF pumping pulse duration τ) were chosen so that the thermal paper would display the boundary of the laser beam exposure after absorption of about thirty pulses of laser radiation. Therefore, the main energy of the laser pulses following each other with $f = 1$ Hz was limited to a circle with diameter depending on registration distance and was 37.6 mm (at 0.5 m distance) and 40.8 mm (at 3.5 m distance).

In order to evaluate the time characteristics of induction CO_2-laser emission at different values of τ, an experimental study was carried out. Fig. 5 shows typical oscillograms of the pump pulse voltage and optical pulse radiation of the designed laser.

Consequently, time behavior of investigated laser optical radiation pulse (when using HF pumping of the active medium) corresponds to the pump pulse and is characterized by a relatively rapid drop in the intensity of the laser radiation at the end of the pump pulse. The delay between the moment when the HF voltage is applied to the inductor and the moment when the generation of optical radiation pulse of the inductive CO_2-laser begins is $\sim 380\,\mu$s.

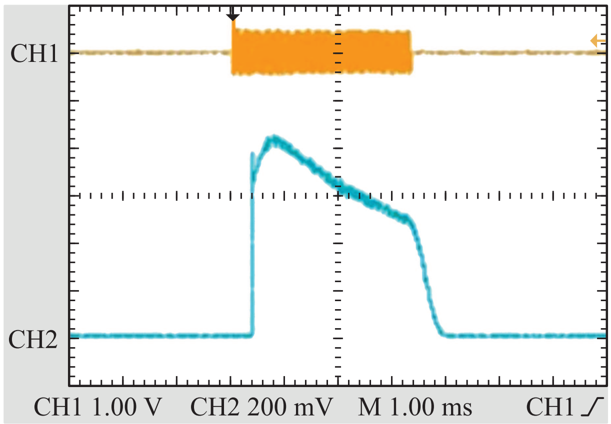

Figure 5. Oscillograms of pump pulse voltage (high frequency modulated electric signal at input of first channel of oscilloscope — „CH1" with duration 3.36 ms) and radiation pulse (electric signal at input of second oscilloscope channel — „CH2") CO_2-laser (duration of optical pulse $t_{puls} \sim 3.0$ ms („Full Width at Half Maximum" — „FWHM") when working mixture with composition $He:N_2:CO_2 = 8:2:1$ is excited (working mixture pressure of $p \sim 10$ mbar). Time sweep of the oscilloscope corresponds to 1.0 msec/cell.

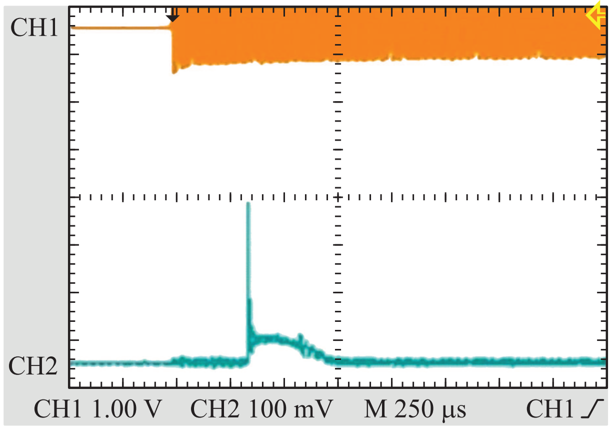

Figure 6. Oscillograms of pump pulse voltage (high frequency modulated electric signal at input of first oscilloscope channel — „CH1" with duration $\tau = 2.5$ ms. Figure presents only start of pump pulse) and radiation pulse (electric signal at input of second oscilloscope channel — „CH2") CO_2-laser (duration of optical pulse $t_{puls} \sim 0.28$ ms („Full Width at Half Maximum" — „FWHM") in medium of pure CO_2. Time sweep of the oscilloscope corresponds to 250 μsec/cell.

Analyzing voltage oscillogram of radiation pulse from induction CO_2-laser (fig. 5), it is necessary to note presence of a „peak" of minor amplitude, which, in our opinion, confirms presence of electron-excited CO_2^*-molecule radiation in the front of rising intensity of optical radiation pulse of CO_2-laser.

To confirm this conclusion, the voltage oscillogram of radiation pulse from inductive CO_2-laser in working mixture as pure CO_2 (fig. 6) was studied. With the same delay between the moment of HF voltage application to inductor and the moment of start of lasing, amplitude „of peak" with pure CO_2 is much higher compared to amplitude of the main optical pulse. Besides, there is a significant difference by parameter of inductive CO_2-laser optical pulse duration ($t_{\text{puls}} \sim 0.28$ ms (FWHM)), which was considerably below τ. Radiation energy in this case was 15 mJ.

To evaluate spectrum of spontaneous emission of inductive CO_2-laser in spectral range from 200 nm to 1 μm, optical elements of the resonator were replaced for plane-parallel plates from CaF_2, and a rear „dense" wide band flat aluminium mirror was installed. Replacement of ZnSe for CaF_2 was made to obtain information about UV spontaneous emission N_2 presence (present in the composition of active medium of CO_2-laser) when excited by plasma electrons. Paper [8] mentioned that excitation of three-component active medium of CO_2-laser with cylindrical induction discharge (with use of pulse high voltage excitation circuit), in spontaneous spectrum there is radiation of molecular nitrogen in the range from 300 to 400 nm.

The significant difference of this paper results is absence of radiation in the mentioned range, which indicates absence of unwanted losses of inductive discharge energy losses for excitation of electron-vibration transitions N_2.

Conclusion

As a result of conducted research, the first pulse inductive CO_2-laser was designed with radiation energy above 1 J. The result is achieved by repetitively-pulsed pumping of gas mixture with composition $He : N_2 : CO_2 = 8 : 2 : 1$ ($p \sim 10$ mbar) to DT ($Ø \sim 42$ mm) using HF source of power supply ($f_{\text{mod}} = 27.12$ MHz) with output power of up to 1000 W. Active length of discharge was 1150 mm.

Repetitively-pulsed mode of operation of the HF source of power supply makes it possible to adjust duration of optical pulse (from fractions to dozens ms), which, apart from the possibility to smoothly adjust output energy of radiation (from 50 to 1050 mJ) makes it possible to implement various operation modes of inductive CO_2-laser, expanding the possibilities and fields of using CO_2 laser unit.

This paper was first to demonstrate the possibility of operating inductive CO_2-laser with efficiency value above 21%.

Designed laser operates in free running mode, the radiation spectrum of which is investigated in spectral range from 6 to 16 μm, and according to the result of spectral composition evaluation is concentrated in the range from 9.8 to 10.6 μm.

Laser radiation energy distribution was evaluated in a tested laser output beam cross section, demonstrating a gradual increase in energy from the periphery to the laser axis. The total divergence angle of the laser beam was 0.52 mrad.

Using magnetic induction, the power supplied to the laser inductor by the HF power supply source was transferred to the gas mixture to ignite and maintain the inductive discharge. As a result of charge motion in the alternating magnetic field, circular electric currents were induced, which contributed to inversion of the vibration-rotation populations of CO_2^* molecule levels.

Therefore, the problem of creating inductively coupled plasma with electron parameters effectively providing a mechanism for inversion in the active medium of induction CO_2-laser has been solved.

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Conflict of interest

The authors declare that they have no conflict of interest.

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