Two-channel CO_2 laser system for heterodyne lidar

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The tunable waveguide RF-excited CO_2 laser is developed. Hooting modes are suppressed by optimization of the optical scheme of a waveguide cavity. The laser radiated at more than 70 lines with output of 0.3–3 W in single-mode and single-frequency regime. On the basis of two such lasers, the two-channel CO_2 laser system controlled by computer is developed, that is intended to operate in mobile heterodyne differential absorption lidar (DIAL). The laser frequencies can be stabilized at the centers of lines or synchronized with required frequency interval. The laser system was tested under field conditions in mobile heterodyne differential absorption lidar and has shown satisfactory results. The developed laser system can be used as a stabilized double-frequency source of radiation in trace gas analyzer with direct detection.

Introduction

In the context of growing rates of industrial environmental pollution, remote atmospheric sensing, including remote gas analysis, with the use of different lidar systems is now the issue of the day.[1–5] Among others, differential absorption (DIAL) lidar systems have the best concentration sensitivity.[1] In the UV and visible spectral regions, the DIAL technique permits one to detect only few important air pollutants: NO, O_3, SO_2, NO, NO_2 etc.[3–5] Most resolved absorption lines of different matters, including hydrocarbons, fall into the mid-IR spectral region (4–12 μm), that permits the remote gas analysis of the atmosphere with a high selectivity.

The ultimate sensitivity and operation range of DIAL systems of direct detection are limited into the mid-IR by dark currents of detectors (HgCdTe, InSb) with $D^* = 10^{10} \dots 10^{11}$ cm · Hz$^{1/2}$/W.[6] The quantum detection limit of the IR-lidars can be theoretically reached at heterodyne reception of lidar signals, when the range of sensing of heterodyne lidar systems increases significantly.[7] Therefore, the differential absorption heterodyne IR-lidars are of great interest despite their complexity and dearness as compared with lidars of the direct detection.

The heterodyne IR-lidar based on CO_2 lasers designed to measure the atmospheric aerosol and cloud scattering is described in Ref. 8. In the atmospheric sensing, we used a single-frequency pulse of the TEA CO_2 laser, formed under injection into the laser cavity of radiation of the cw CO_2 laser–injector with opto-galvanic frequency stabilization. To provide the heterodyne reception of lidar signals, the second cw CO_2 laser–heterodyne was used, whose frequency was locked with the laser–injector frequency with 30 MHz detuning. Both lasers emitted at the same wavelength and had no possibility of fast tuning to other lasing lines.

The development of modern systems of local and remote gas analysis of the atmosphere calls for lasers and laser systems capable to operate in the automatic mode for a long time. Such a mode of operation provides for automatic adjustment of lasing wavelengths to specified lasing lines according to the algorithm of the lidar system operation, change and stabilization of required lasing parameters under the mechanical–climatic impacts. Special demands are imposed on lasers for heterodyne lidar systems, because in this case single-frequency single-mode radiation with a definite frequency stability is required.

In this paper, a two-channel CO_2 laser system is represented, designed to operate as a part of differential absorption mobile heterodyne IR differential absorption lidar.[8] Basic elements of the system are two waveguide RF-excited CO_2 lasers with computer tuning and frequency stabilization to the center of the chosen lasing line.

1. Tunable waveguide laser

The waveguide CO_2 laser differs from CO_2 lasers of other types by small dimensions, as well as high laser gain, that is necessary for lasing at weak lines and extension of the tuning spectral range. The use of high-frequency excitation of CO_2 lasers allowed us to eliminate problems caused by high-voltage power supplies and to decrease the noise level.[9] Besides, the sealed-off RF-excited CO_2 lasers have the operating lifetime longer than DC-excited lasers.[10]

In this work, a waveguide RF-excited CO_2 laser with a cermet waveguide of a square cross section is used. The laser case is produced of a stainless steel pipe of 88 mm in diameter and 650 mm in length. The pipe serves as a vacuum envelope and an optical cavity base. Flanges are welded to both ends of the pipe, on which optical laser elements with vacuum seals are mounted. As experiments have shown, such lasers have a high constructive rigidity and a low sensitivity to external mechanical impacts.

The cermet waveguide of 2.2×2.2×450 mm in size is formed by two flat electrodes made of blown

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aluminum and two flat plates made of polished leucosapphire. The lower electrode is joined with the case, has a zero potential, and is cooled with running water. The upper electrode is insulated from the case and is cooled due to a high heat conduction of the leucosapphire plates. When RF-voltage is applied to the upper electrode, the capacitive discharge is ignited in the waveguide, which is used to excite the gaseous medium. Few inductors connected at definite points in parallel with the electrodes are used to equalize the RF-field strength along the electrodes. The LC-circuit is used to match the impedance and load of the RF-generator.

The presence of the waveguide in the laser increases the utilization coefficient of the active volume, but in some cases decreases the mode selectivity, that demands choosing a corresponding scheme of the optical cavity. Usually, flat mirrors placed right up to waveguide ends are used in the waveguide lasers. Such type of optical cavity is identified as type I according to the accepted classification.[11,12] In this case, intracavity losses are minimal and lasing power of the waveguide laser is maximal, but the mode and spectral selectivity of the cavity is low. To increase the selectivity, an optical cavity of type III is chosen,[11,12] where concave spherical mirrors with the radius of curvature R are placed at the distance

$$z = b = \pi w_0^2/\lambda = R/2, \qquad (1)$$

from the ends of the waveguide. Here, b is the confocal parameter of the "approximately Gaussian" beam; λ is the wavelength in free space; $\omega_0 = 0.7032a$ is the radius of the Gaussian beam waist, where coincidence of integral gauss with the mode distribution EH_{11} is the best into the square waveguide of the width $2a$.[11] According to Ref. 13, losses of the mode EH_{11} make up 14%, while losses of the mode EH_{12} make up 78% in such type of resonator. Thus, the optical cavity of type III provides for a high level of the transverse mode discrimination in the waveguide laser.

The schematic diagram of the tunable waveguide laser is shown in Fig. 1. Radiation outgoes through the plane half-mirror with a transmittance of 4%.

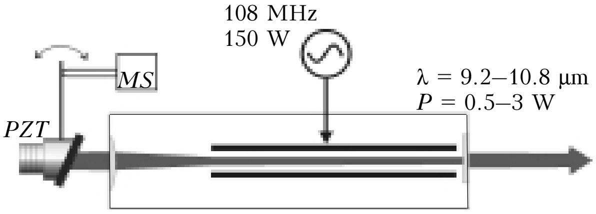

Fig. 1. The schematic diagram of tunable waveguide RF-excited CO_2 laser.

The coated plane-convex lens made of ZnSe in combination with the plane reflecting grating, operating in the Littrow mode, is used as the back totally reflecting spherical mirror, located according to the circuit of the optical cavity of type III. The effective focal length f of the "lens–grating–lens" system is determined by the focal length f_1 and the distance between the lens and the grating z_1. Moreover, according to Eq. (1), $z = R/2 = f$ and depends on λ. The results of calculations of $z = \pi\omega/\lambda$ and the corresponding radius of curvature R of the equivalent spherical mirror in dependence of wavelength are given in Table 1.

Table 1

Parameter	Wavelength, μm			
	9.2	9.6	10.2	10.8
$b = \pi w_0^2/\lambda$, mm	204	196	184	174
R, mm	408	392	368	348

The value of z changes from 204 to 174 mm within the tuning spectral range of CO_2 laser (9.2–10.8 μm) for the considered cavity with the waveguide cross section of 2.2×2.2 mm. Therefore, the best average value $z = 180$ mm was chosen corresponding to $\lambda \approx 10$ μm. Taking into account the distance between the lens and the grating $z_1 = 35$ mm, the focal length f_1 must be equal to 320 mm. Such a lens was used at the first stage of researching the laser. Under these conditions, experiments have shown minimal losses and the maximal output power.

The gold-coated reflecting grating with a period of 150 mm^{-1} is used in the laser. The efficiency of grating reflection with respect to the incident power is 0.93–0.95 for the first diffraction order for s-polarization. The direction of grating lines is selected normal to the plane of metal electrodes since radiation of waveguide lasers with cermet waveguides has a linear polarization and its vector is parallel to metal electrodes.

Note that spectral resolution of the reflecting grating increases, when it is located behind the lens, because the beam cross section is $\sqrt{2}$ times larger at a distance $z = b$ from the waveguide's end as compared to the waveguide's outlet.[14] Moreover, in this case the radiation power density at the grating decreases and makes about 1500–2000 W/cm^2 at location of the grating in the waveguide's cavity.

The grating is placed at a lever-type precision rotary unit with a lever of 80 mm in length. The grating is rotated with a commercial motorized screw (8MS00-25 model, EKSMA Co.) powered by a stepping motor drive (200 steps per rev., full strength of 25 mm, step of micrometer screw of 0.25 mm). Mechanical pickups of start and end positions are built in the motorized screw, but switching repeatability of the pickups is around ± 5 steps. To increase the accuracy of determination of the grating initial position, a radial optical sensor with one-step positioning accuracy is mounted at the stepping motor shaft. Such accuracy corresponds to the grating angular displacement $\Delta\varphi \approx 16$ μrad. The rotary unit makes it possible to adjust the required angular position of the diffraction grating with a high accuracy and repeatability, when tuning the laser to generation lines.

To operate with different isotopes of the CO_2 molecule, the middle and extreme positions of the diffraction grating were determined, which are presented in Table 2.

Table 2

Isotopes CO_2	$001 \rightarrow 02^00$ $R(40)$		$001 \rightarrow 100$ $P(40)$		Range, deg.	Middle position, deg.
	λ, μm	Angle, deg	λ, μm	Angle, deg		
$^{12}C^{16}O_2$	9.17	43.48	10.81	54.18	10.70	48.83
$^{13}C^{16}O_2$	9.58	45.95	11.38	58.63	12.68	54.48
$^{12}C^{18}O_2$	9.03	42.60	10.71	53.42	10.82	48.01
$^{13}C^{18}O_2$	9.52	45.54	11.16	56.79	11.25	51.17
$^{14}C^{16}O_2$	9.92	48.06	12.02	64.38	16.32	56.22
$^{14}C^{18}O_2$	9.94	48.20	11.66	60.96	12.76	54.58

Calculation for each isotope is bounded within the spectral range from the line $P(40)$ of the transition $001 \rightarrow 100$ to the line $R(40)$ of the transition $001 \rightarrow 02^00$, which is practically limiting for the laser of interest. Wave numbers are taken from Ref. 15. Thus, in particular, when using the molecule $^{12}C^{16}O_2$, the angular displacement of the grating ranges from 43.48 to 54.18° at a middle position of 48.83°.

The laser cavity length L = 66 cm is in agreement with the intermode interval $c/2L$ = 227 MHz. Fine tuning of laser frequency within the gain profile ($FWHM \sim 300$ MHz) is carried out using a pack of piezoelectric transducers of PP-12 type, which changes the cavity length. Under applying the voltage ± 250 V to the transducers, the laser cavity length changes by ± 4 μm, that allows a fixation of the laser frequency at any point of the gain profile including the lasing line center.

Analysis of spectral composition of radiation of the produced waveguide lasers has shown an occurrence of spurious mode beats at frequencies from units to 20–40 MHz at strong lasing lines especially in the 10 μm range. This effect, called "hooting modes," (Ref. 16) was described in a few papers. Its appearance is attributed to a slight difference of the waveguide's cross section from square one,[16] that is practically always true for actual waveguide lasers. The oscillogram of the line profile of a waveguide laser with the intracavity lens with f_1 = 320 mm, calculated above, is shown in Fig. 2*a*. As can be seen, with such a lens, the area of the pronounced mode beats is present at the slope of the lasing line profile. When RF pump power decreased, we managed to suppress the beats, but in this case the laser operated unstably near the lasing threshold.

To lower the unwanted mode beats, selective losses in the waveguide laser were increased. The experiments with a number of lenses with different focal lengths have shown that when increasing focal length of the intracavity lens, the region of mode beats decreases, and at $f_1 > 410$ mm, the mode beats are not observed at any lasing line. The oscillogram of the lasing line profile of the laser with the intracavity lens of f_1 = 450 mm is shown in Fig. 2*b*, where the mode beats are absent. Therewith, the laser radiation power decreased insignificantly (by 10–15%), but the single-frequency generation mode was achieved.

Investigation of a beam far zone has shown that the radiation intensity distribution in the beam cross section corresponds to the Gaussian profile, i.e., the laser emits at the lowest waveguide mode EH_{11}. The transverse radiation intensity distribution is presented in Fig. 3. The beam diameter $2r$ measured by the level e^{-2} at the distance 185 cm from the exit mirror amounts to 16.4 mm at λ = 9.2 μm and 17.3 mm at λ = 10.6 μm. The complete beam divergence (2θ) makes 8.8 and 9.4 mrad at wavelengths 9.2 and 10.6 μm, correspondingly. Radiation spectrum of the waveguide $^{12}C^{16}O_2$ isotope laser is shown in Fig. 4. The laser emits at more than 70 lines at a lasing power up to 2.5–3 W at strong lines and up to 0.3–0.5 W at weak lines. The radiation wavelength tuning is carried out automatically in accordance with the calibration table individual for each laser.

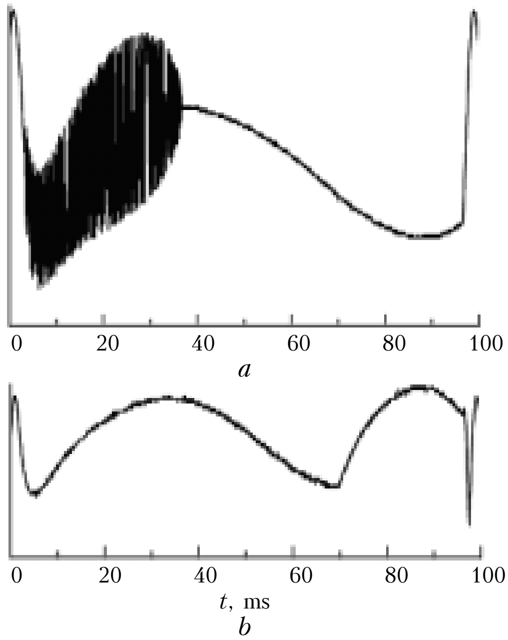

Fig. 2. The oscillograms of lasing line profile of a waveguide laser with the intracavity lens with focal lengths of 320 mm (*a*) and 450 mm (*b*).

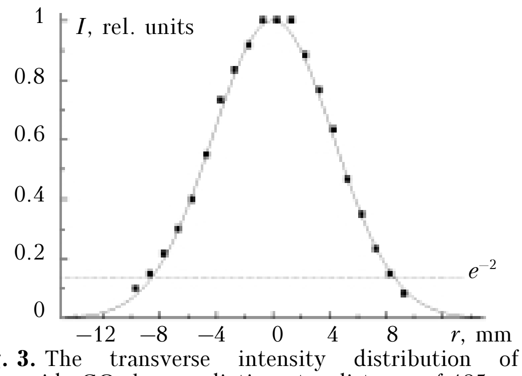

Fig. 3. The transverse intensity distribution of the waveguide CO_2 laser radiation at a distance of 185 cm from the laser (λ = 10.6 μm).

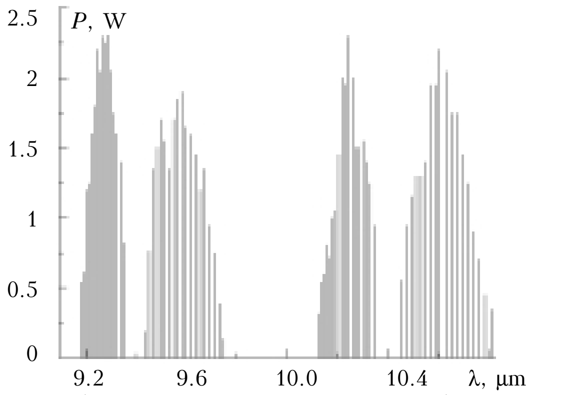

Fig. 4. Radiation spectrum of the waveguide CO_2 laser ($^{12}C^{16}O_2$ isotope).

The main characteristics of the developed tunable waveguide CO_2 laser are presented in Table 3, the laser appearance is shown in Fig. 5.

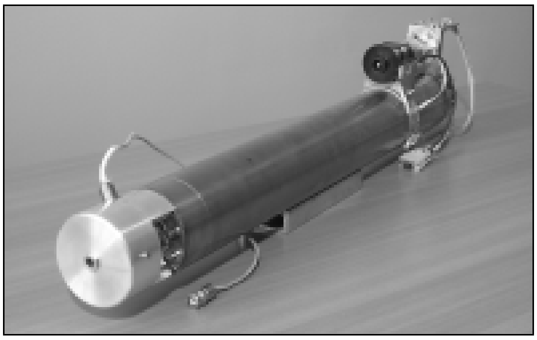
Fig. 5. Exterior view of the tunable waveguide RF excited CO_2 laser.

2. Two-channel CO_2 laser system

Two-channel CO_2 laser system is developed on the base of two tunable single-frequency waveguide CO_2 lasers described above for using as a part of a DIAL heterodyne lidar similar to that in Ref. 8. The laser system is designed to control for a sensing pulse spectrum of the TEA CO_2 laser by injection into its cavity a laser–injector stabilized to the center of its lasing line, as well as to provide the heterodyne reception of lidar echo signals within 9.2–10.8 μm spectral range.

The optical block-diagram of the two-channel CO_2 laser system is shown in Fig. 6. It includes two tunable waveguide CO_2 lasers with RF pumping oscillators, optomechanical circuit (beam-splitting and deflecting mirrors, detector, etc.), and a controller. Lasers *1* and *2* emit at wavelengths λ_1 and λ_2 according to their calibration tables. The lasers are excited by individual RF oscillators. Emission wavelength tuning is performed via angular displacement of reflecting gratings with the motorized screws *MS*. The piezoelectric transducers *PZT* are used for fine tuning of the laser frequency.

The main part of radiation of lasers *1* and *2* was used for destination. A small portion of the radiation (~5%) was splitted off from the main beam by the splitters *M1* and *M2*, then the beam wave fronts were matched at the splitter *M4*, and the lens *L* focused the beams at the detector *D*. As a detector, the PDI-10.6 "VIGO System" uncooled HgCdZnTe photovoltaic receiver with the time constant $\tau \le 1$ ns was used. The detector allowed us to control for the cw laser power, observe lasing line profile, size and frequency of RF-beats.

Table 3

Parameter	Value
Operation mode	CW, pulse-periodic
Radiation spectral range, μm	
for $^{12}C^{16}O_2$ isotope	9.2–10.8
for $^{13}C^{16}O_2$ isotope	9.6–11.4
Output power, W	
at strong lines	2.5–3
at weak lines	more than 0.5
Number of lasing lines (for $^{12}C^{16}O_2$)	more than 60
Mode structure of radiation	Single-mode, single-frequency
Polarization	Linear
Output beam diameter, mm	2
Total divergence (e^{-2}), mrad	8.8–9.4
Excitation of active media, MHz	RF discharge, 108
Power of RF pump oscillator, W	150
Cooling (laser + RF pump oscillator)	Water, 2 l/min
Supply voltage / Consumption	+24 V / 400 VA
Overall dimensions, mm	
laser	840×90×150
RF pump oscillator	433×100×42
Weight, kg	
laser	10
RF pump oscillator	3

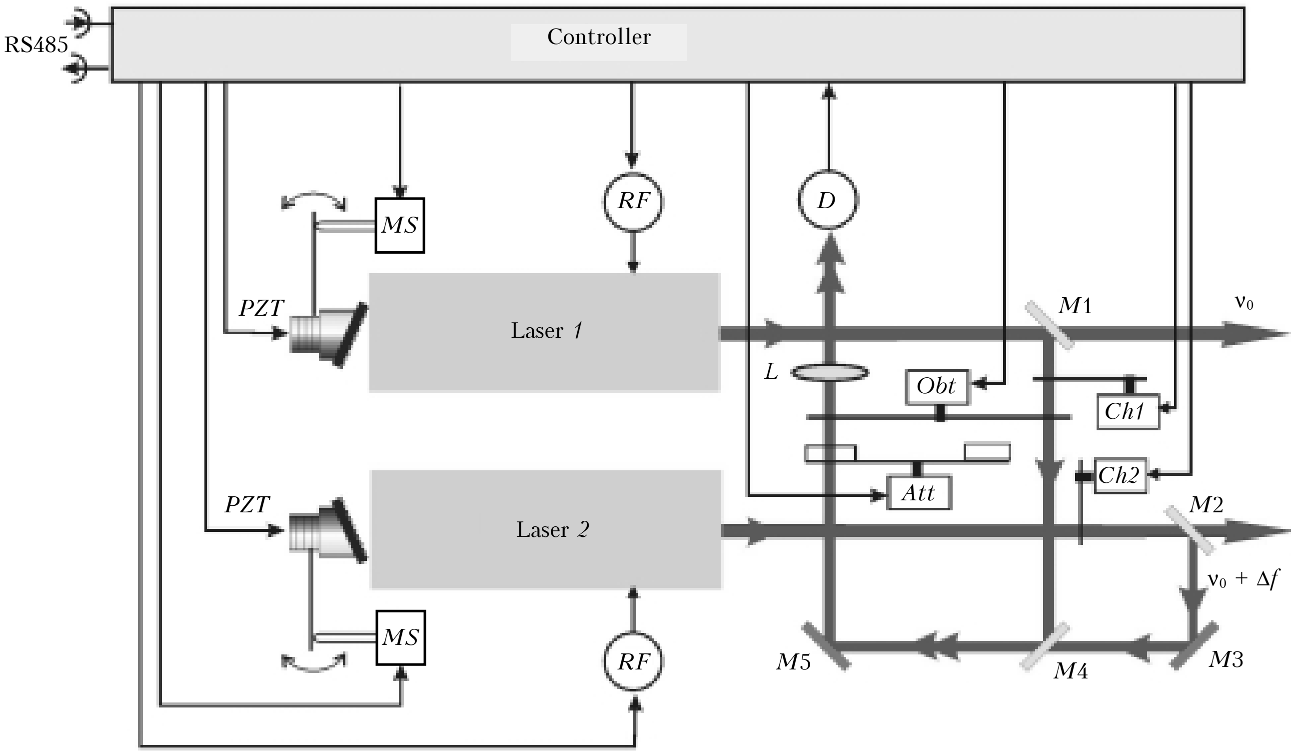

Fig. 6. The optical block-diagram of the two-channel CO_2 laser system.

Electromechanical choppers *Ch1* and *Ch2* were used for chopping separate laser beams incident upon the detector. The attenuator *Att* with different transmissions was mounted at a gun ring powered by stepping motor drive and was used for step-by-step power attenuation of the radiation incident upon the detector. Besides, the optical scheme provides for the use of an obturator *Obt* powered by the stepping motor drive, which chops the radiation incident upon the detector with 10-Hz frequency and simultaneously interrupts the optical communications between lasers *1* and *2*. The obturator was designed for overload protection of the detector when one of the lasers operated as an injector together with the TEA CO_2 laser and the other as the heterodyne. Switching on the TEA laser is possible only when the obturator hides the detector. The controller controls the RF pumping oscillator power, wavelengths λ_1 and λ_2, self-tuning of laser frequency, synchronization of operation of the attenuator *Att*, the choppers *Ch1* and *Ch2*, and the obturator *Obt*, as well as forms the laser system-ready signal via the interface RS485.

The main task of the controller of the two-channel CO_2 laser system was to choose an operating point at the gain profile and to attain the single-frequency generation mode. For preliminary analysis of the gain profile, independent scanning of continuous radiation power, as well as the power of RF (mode) beats for each laser was used. In that case, the choppers *Ch1* and *Ch2* shut one of the beams. The operating point of the lasers was defined as the maximum of the gain profile on condition that the mode beats were absent.

Into the heterodyne scheme, lasers must operate at one wavelength with a definite detuning from each other. In this case, the preliminary scanning of the gain profile and fixation of the operating point are carried out, and then the automatic frequency control algorithm (FCA) of detuning of one of the lasers starts. FCA starts when the obturator is open. At a preset detuning of the lasers (20 MHz), the scheme is switched to the holding mode, and the ready-signal is formed.

As was mentioned above, lasers of tubular design have a high rigidity and a low sensitivity to external mechanical impacts. These properties were evinced clearly when the lasers operated together with systems of frequency locking and synchronization under field conditions. The optical circuit of the laser facility permits one to observe the beat signals (0.1–30 MHz) between frequencies of both lasers on the oscillograph screen, when the lasers emit at the same wavelength. After warming-up during 15–20 min, lasers attain the operating mode, temperature drift of the cavities stops, and beat frequency fluctuates to ± 1–3 MHz over a period of 1–3 min. A small deviation of beat frequency was observed at tapping on the body of one of the lasers; after termination of the disturbance, the picture remained stable during several minutes. High passive stabilization of lasers' cavities and their weak sensitivity to external disturbances significantly simplifies the requirements to systems of frequency locking and synchronization.

The external view of the two-channel CO_2 laser system, designed as a laser monoblock, is shown in Fig. 7.

Fig. 7. External view of the two-channel CO_2 laser system.

The monoblock has the overall dimensions 1000×230×230 mm, the weight of 50 kg, the voltage of + 24 V from an external power supply (of the PSP-1000-27 "Meanwell" model), the power consumption up to 800 VA, and the water cooling (~ 2 l/min). Laser beams leave the monoblock through two outlets in the front panel. Beam height above the base is 75 ± 1 mm, the interbeam distance is 100 ± 1 mm, the non-parallelism of the beams does not exceed 1 mrad. Polarization is linear and vertical. Other laser radiation characteristics correspond to Table 3.

The designed two-channel CO_2 laser system is used as a part of a mobile heterodyne DIAL lidar, similar to Ref. 8, which was produced at "Laser Systems, Ltd." (St. Petersburg).[17–19] The system was tested under field conditions and showed satisfactory results. By now, at the "Laser Systems, Ltd.", several mobile lidar complexes including the above-described two-channel CO_2 laser system have been assembled and delivered to customers.

Another interesting variant of application of the two-channel CO_2-laser system is its incorporation into the DIAL gas analyzer of direct detection with the atmospheric sensing range about 1 km when working at diffusive topotargets. In this case, the lasers must operate at different wavelengths λ_1 and λ_2 according to the DIAL-method, and the frequency of each laser is tuned at the line center of the chosen transition.

Conclusion

Tunable waveguide CO_2 laser with RF pumping is designed by us for operation in heterodyne systems. It emits at more than 70 lines at a lasing power up to 2.5–3 W at strong lines and up to 0.3–0.5 W at weak lines. Tubular design of the laser provides for a high passive stabilization of its cavity and weak sensitivity to external disturbances. Through optimization of optical circuit of the waveguide cavity, we have succeeded to suppress parasitic mode beats and to attain single-mode single-frequency laser radiation suitable for heterodyne systems.

The two-channel laser system was designed on the base of two tunable waveguide CO_2 lasers for operation as a part of the mobile heterodyne DIAL lidar. The electronic unit of the laser system permitted us to fix laser frequencies at centers of chosen lines or to synchronize them when lasers emit at the same wavelength. Control for the radiation power, wavelength, and frequency self-tuning, as well as synchronization of operation of optomechanical elements was carried out via the interface RS485.

Few specimens of the two-channel CO_2 laser system were successfully tested under field conditions as a part of the mobile heterodyne DIAL lidar, designed at "Laser Systems, Ltd." (St. Petersburg), and showed satisfactory results. The designed two-channel CO_2 laser system can be used as a two-frequency source of stabilized radiation for the DIAL gas analyzer of direct detection.

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