Waveguide RF excited $^{13}C^{16}O_2$ - laser tunable from 11.04 to 11.31 µm for LIDAR applications

A.A. Boyko[*a], A.I. Karapuzikov[b], S.B. Chernikov[b], V.V. Spitcin[b], Yu.N. Ponomarev[c], M.K. Starikova[a], M.Yu. Shtyrov[a], I.B. Kuznetcova[a], I.I. Tikhonyuk[a], I.B. Miroshnichenko[a], M.B. Miroshnichenko[a], A.A. Karapuzikov[a]

[a]Special Technologies, Ltd, 1/3 Zeljonaja Gorka st., Novosibirsk, Russia; [b]Institute of Laser Physics SB RAS, 13/3 Ac. Lavrentyev's prosp., Novosibirsk, Russia; [c]Institute of Atmospheric Optics SB RAS, 1 Academician Zuev square, Tomsk, Russia

ABSTRACT

We report automated waveguide RF excited $^{13}C^{16}O_2$ - laser based on Z-shaped resonant cavity. The laser possesses possibility of wavelength tuning from 9.5 to 11.5 µm by means of the cavity's diffraction grating position management. The diffraction grating position is driven by precision motorized linear actuator. The lasing lines of P-branch from 11.04 to 11.31 µm were studied in details. Operating mode selection is performed with specially designed PC software "Tunable CO_2 – Laser". P-branch 11P(10) – 11P(32) lines' tuning time does not exceed 3 sec.

Keywords: waveguide $^{13}C^{16}O_2$ - laser, Z – shaped resonator, LIDAR, RF excitation.

1. INTRODUCTION

In spite the fact that first LIDARs based on lasers appeared in the beginning of 1960th, interest to such system is still high nowadays. Recent years the list of LIDAR applications, including environmental monitoring, became wider. Intensive researches in remote sensing of the atmosphere shown that differential absorption LIDAR is the most perspective instrument for studying atmospheric parameters and pollutions [1 - 3]. LIDAR systems in mid-IR range from 8 to 12 µm have a certain superposition here as far as they correspond to the atmospheric transparency window. This spectrum range contains intensive and well isolated absorption lines of a number of atmospheric gases and pollutants [4].

The majority of LIDAR systems consist of three main parts: the transmitter, the receiver, and the data processing unit. The transmitter usually contains laser source and output laser beam forming optical system. Increasing of the operating lasing lines of the laser source is one of the perspective approaches for improvement of atmospheric remote sensing systems' possibilities. There are absorption lines of more than 90 chemicals like Freon's, NH_3, C_2H_2, H_2O, O_3, CO_2, N_2O, NO_2, HNO_3, SF_6 in the tuning range of CO_2 – lasers, including $^{13}C^{16}O_2$ isotope modification.

In our work we report results of studying waveguide pulse-periodic tunable CO_2 – laser developed for use in differential absorption LIDAR system. Such laser has lower power consumption, higher pulse power in comparison with CW lasers. Also in some cases it can work without liquid cooling system that is important for outdoor LIDAR systems. Relatively larger lasing line width and possibility of changing the lasing line to the neighboring one could be mentioned as disadvantages of such approach. However the negative effect from these disadvantages can minimized by use of suitable system design, correct tuning of the resonator and optimal operating parameters.

2. PROBLEM STATEMENT

Operation range, operation response time and reliability of the obtained information depend on the laser source lasing at the required wavelength. Therefore it becomes the most important part of the LIDAR system. Our approach is featured by the possibility of fitting the developed tunable laser to the requirements by the LIDAR system developer. In this particular case intensive collaboration with the differential absorption LIDAR system developer (Institute of

[*] sales@lc-solutions.com; phone +7 383 334 80 81; fax +7 383 334 80 81; http://www.detectors.lc-solutions.com/

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Atmospheric Optics of the Siberian Branch of Russian Academy of Sciences) allow us adjusting different parts of the laser while development as well as after tests of the tunable CO_2 – laser.

The main technical requirements to the tunable laser source:

— Wavelength range	11.04 ÷ 11.31 μm
— Beam diameter at e^{-2}	≤ 2 mm
— Beam divergence	≤ 12 mrad
— Beam quality M^2	≤ 1.3
— Peak power at 100 Hz	20 W
— Scan time through the wavelength range	3 sec

Also the LIDAR developers issued an additional requirement caused by the specific of LIDAR applications – the time stability of the directional pattern while operating at one line as well as while all lasing lines scanning.

Beside the above mentioned, outstanding reliability and simplicity of operation of the laser were required. The waveguide RF excited CO_2 – laser with Z-shaped resonator mainly matches the stated requirements. Due to the large length of the cavity high amplification factor is reached in such laser. That allows compensation of the resonator losses caused by adding wavelength selection units for lasing line tuning mode. Waveguide CO_2 – lasers of that type are featured by high reliability, compact size and relatively small weight also. Experience of our team in development of similar RF-excited lasers together with LIDAR application of the laser determined our choice of combining laser head, RF-exciter and the electronic control system in a single unit. Such decision provided minimal electro-magnetic noise level while operation as well as simple managing of the laser. Also we add output beam power meter to the system for normalization of the LIDAR signals by power.

3. GENERAL ARRANGEMENT

3.1 Outer view

The developed waveguide RF excited $^{13}C^{16}O_2$ – laser tunable from 11.04 to 11.31 μm is shown on the Figure 1.

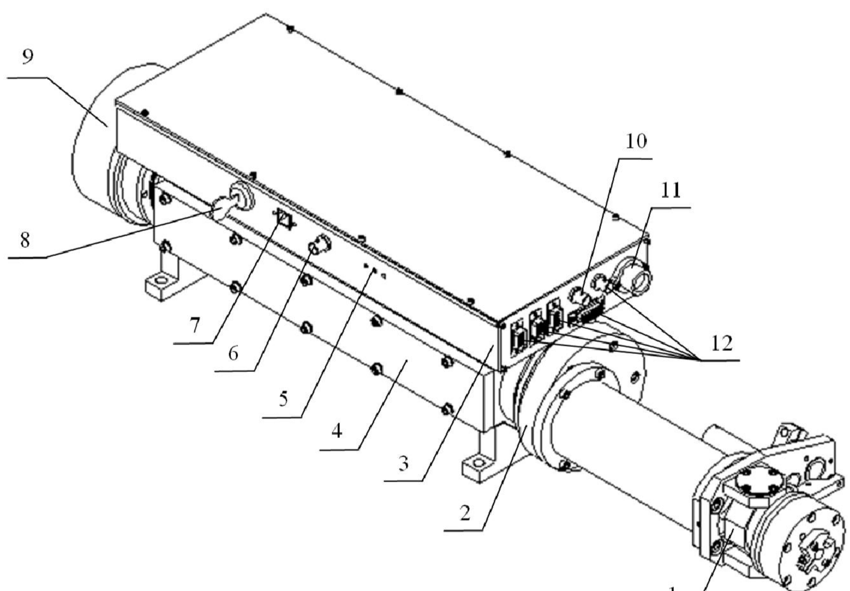

Figure 1 — Outer view, where: 1 — lasing line tuning unit; 2 — laser head body; 3 — electronic control unit combined with RF exciter (ECU); 4 — air/liquid heat exchanger; 5 — operation mode LED indication; 6 — synchronization signal OUT socket; 7 —USB B socket for PC control; 8 — safety key; 9 — power meter unit; 10 — power meter signal OUT socket; 11 — power cable socket; 12 — service sockets.

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The laser body is a hermetic stainless steel tube with the electrode unit and Z-shaped metal-ceramic waveguide installed inside on an original mount. Sides of the tube are closed with two flanges integrated with adjustment optical mounts for optical elements marked as M1 – M4 on the Figure 2. Heat removal from the discharge zone is provided by a massive Aluminum electrode having good heat and electrical contact with the internal surface of the tube. Combined air/liquid heat exchanger is mounted on the outer surface of the tube. The heat exchanger is also the basement of the laser for further installation into the LIDAR. Also it is used for mounting ECU.

Combining of the ECU and the laser head made possible to place RF exciter in a shielded compartment inside of the ECU right above the RF input of the laser. This allowed refusing of use additional RF cables and connectors and consequently decreases the level of the electro-magnetic noise produced by the RF exciter and improves electromagnetic compatibility of ECU in general.

ECU provides laser management according to commands from PC, as well as it makes self checking of the laser while working.

Three heat exchangers are installed in order to provide optimal temperature conditions. Two of them are installed alongside the laser body tube and another one is installed on ECU case right under the RF compartment of ECU for heat sink from RF exciter.

The design of the heat exchangers expects both air and liquid cooling. In the power mode below 2 W of average power the air cooling can be used. Over 2 W liquid cooling must be applied.

Photodetector MG-30 is used measuring output beam power by splitting a part of the beam with additional optical elements. MG-30 signals are processed in ECU.

3.2 Structural scheme

For obtaining lasing in the range from 11.04 to 11.31 μm the body of the laser is filled with working gas mixture with $^{13}C^{16}O_2$ isotope modification enriched up to 80 percent. The same laser can operate at other lasing line of the $^{13}C^{16}O_2$ isotope modification as well as with of the usual $^{12}C^{16}O_2$. That is why some parameters were measured over the mentioned range.

The laser works with outer DC power supply of 24 V and 300 W.

The structural scheme of the laser is shown on the Figure 2.

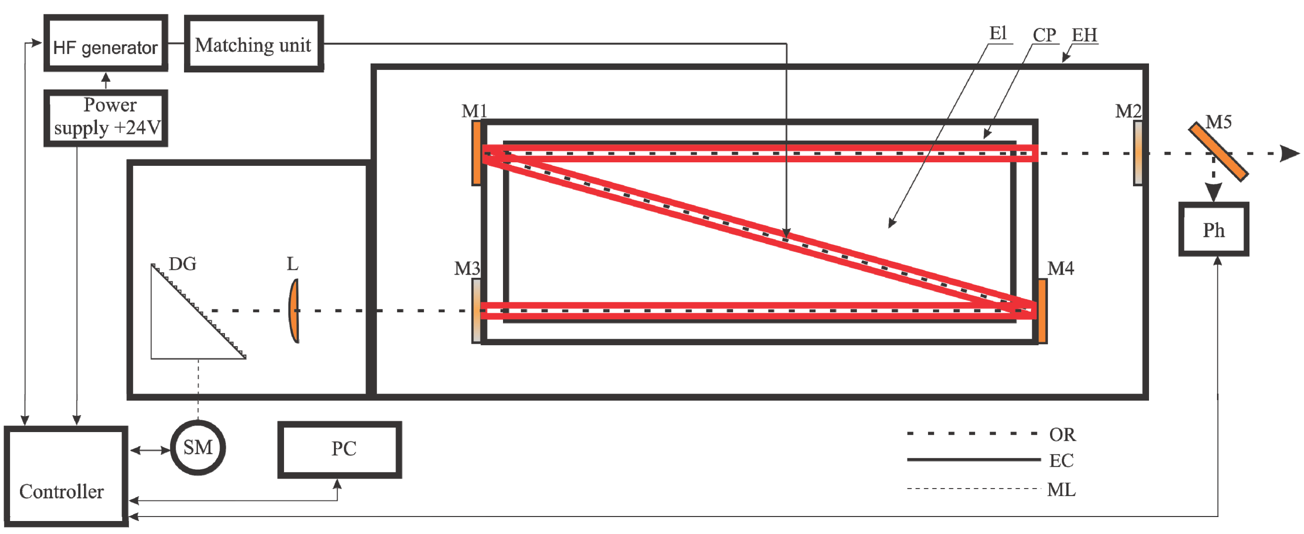

Figure 2. Structural scheme of the tunable laser, where: M1 and M4 Au/Si swivel mirror on adjustment mount, M2 - ZnSe output mirror with transmission 7%; M3 – AR coated ZnSe window; El -"hot" electrode; CP - ceramic plate with waveguide channels; EH - evacuated housing; M5 – beam splitter; L - lens (F = 254 mm); DG - 150/mm diffraction grating; Ph - photodetector MG-30; SM - stepper motor with encoder; PC - personal computer; OR - optical radiation; EC - electrical connection; ML - mechanical linkage.

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Z-shaped resonator is formed by the diffraction grating DG with 150 lines/mm, lens L, output coupler M2, mirrors M1, M4, window M3. The main advantage of Z-shaped resonator in comparison with traditional waveguide laser is higher amplification factor due to the large optical pass.

RF excitation is performed with RF pulse at 144 MHz to the "hot" electrode through the RF input placed at the center of the laser body. The internal resonant circuit is aligned to fit 144 MHz in "cold" condition for avoiding the reactive part of the discharge impedance while lasing.

The matching unit made of reactive components is used for fine tuning of the laser impedance with RF exciter output impedance.

Wavelength tuning is performed by changing the angular position of DG in relation to the optical axis of the resonator with precision linear actuator driven by a stepper motor with encoder and mechanical adaptor.

3.3 Management of the laser

ECU consisting of microcontroller, RF exciter, photodetector and temperature measurement units provides management of laser operation modes, forming necessary signals for other units and collecting operational data.

The microcontroller provide setting necessary lasing line, pulse width and pulse repetition rate, as well as self checking based on the data from photodetector and temperature measurement units. Also it provide implementation of following modes of operation:

- Scanning,
- Stabilization.

In the scanning mode rotation of DG is performed with constant velocity and all lasing lines appeared in series without stops a line. The minimal time of scanning through all the range is 3 sec. This time is provided by the stepper motor velocity of 780 steps per sec. The maximal time of scanning is 290 sec at 8 steps per sec.

In the stabilization mode the microcontroller places DG in the position corresponding to a certain lasing line. After that RF exciter gets trigger signal with user defined pulse width and pulse repetition rate. Pulse repetition rate can vary from 10 Hz to 2 kHz whereas pulse width can vary from 20 to 150 µs. For better temperature conditions the duty cycle must be less 10%.

Photodetector unit provides forming electrical signal corresponding to the output power of the laser. The signal from the photodetector is used as feedback for placing FG into the optimal position for a certain lasing line.

Monitoring of the thermal conditions of the laser and RF exciter are provided by the microcontroller according to the data from temperature measurement units installed in bodies of the RF exciter heat exchanger and the laser head heat exchangers.

Special PC software "Tunable CO_2-laser" was developed for management of the laser. Screenshot of the software main window is shown on the Figure 3.

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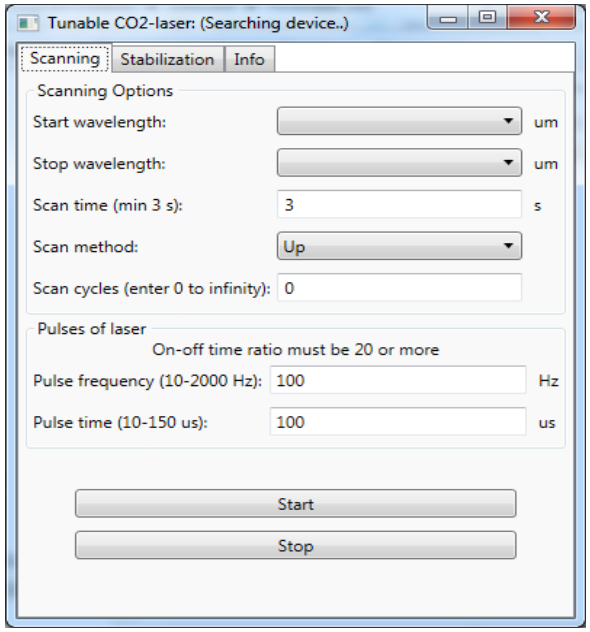

Figure 3. "Tunable CO_2-laser" software main window screenshot.

3.4 Main results

Here we report results obtained while measuring main parameters of the CO_2-laser in the working wavelength range. The scheme of the measurements is shown on the Figure 4. In order to get rid of the influence of beam splitters on measurement values (beam profile and intensity amplitude), we use scheme which expects direct installation of the measuring devices on the optical axis of the laser without additional optical elements. Also installing a photodetector directly on the axis allows avoiding mutual interference between the output coupler and beam splitters. So, we performed consequent measurements of the laser parameters according to the mentioned scheme and methodic. For providing high accuracy the fast detector and wavelength meter were installed on precision stages. Whereas the laser beam analyzer was installed unmovable. Such approach provided us with laser performance data with minimal distortion caused only by time delay between measurement sessions, but we could avoid sufficient distortion due to additional optical elements when measuring all parameters simultaneously.

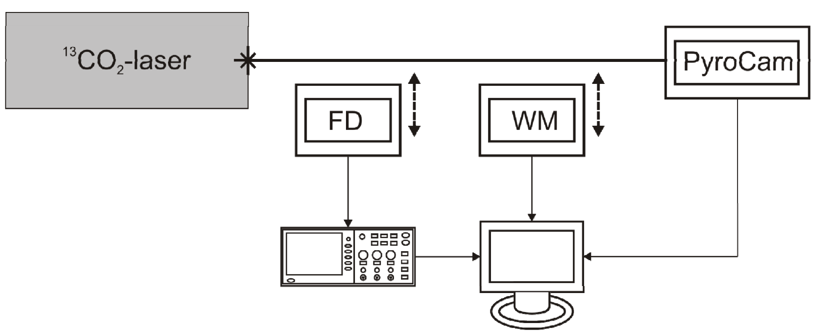

Figure 4. Scheme for measuring the main parameters of the tunable CO_2-laser in working wavelength range, where: FD – fast detector (Vigo system PVM-10.6); WM – Wave length Meter (Angstrom WS6-200 IR-III); PyroCam - laser beam analyzer (Ophir Spiricon Pyrocam III)

All measurements were performed with following parameters of the laser:

— Pulse repetition rate 100 Hz;

— Pulse width 100 μs;

— Duty cycle 1%;

— RF pulse power 1 kW.

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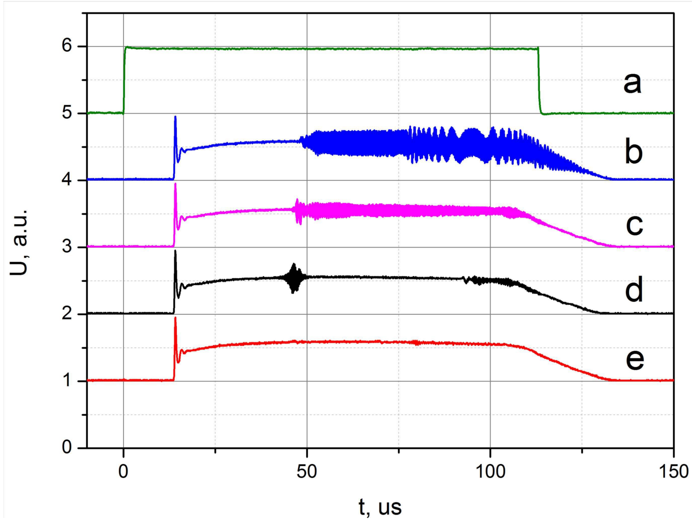

Figure 5. RF exciter trigger pulse (a) and output laser pulses measured with fast detector (b, c, d, e).

The oscillograms of RF exciter trigger pulse and lasing pulses with different position of DG within one lasing line are shown on the Figure 5. The oscillogram (b) corresponds to the optimal resonator alignment. This conclusion was made due to the minimal pulse width and symmetrical beam profile information provided by wavelength meter and PyroCam respectively. As it follows from this oscillogram the lasing pulse has beats provided by existence of parasitic transverse modes [5]. The beat frequency change relates to lasing frequency sweeping due to thermal effects and other processes. As far as the frequency pass zero point on the oscillogram we can estimate its sweeping rate as about 50 kHz per μs.

In general case existence of these mode beats is an undesirable effect, but when using heat detectors they are integrated and do not effect the result. Nevertheless we tried to get rid of them. The oscillograms (c, d, e) show that they can decrease or even disappear when aligning the DG position. But in the case presented by the oscillogram (e) the wavelength meter shown two neighboring lasing lines existing simultaneously. This is an unstable lasing mode that is also an undesirable effect.

Decreasing RF pumping power that is equal putting to additional losses into the resonator happened to be more simple way to avoid these effects. In this case the beats disappear right after placing DG into the optimal position. In general it shows not enough level of reduction of parasitic modes in the resonator. It is known that the most effective way to reduce undesirable mode beats is optimization of parameters of the matching lens in resonator [6] installed before DG for increasing of selectiveness. We think better effect will provided adding into the resonator a telescope expanding the beam several times for better selectiveness of DG at large inclination from the blazing angle.

Average power data measured with IMO-2N at different lasing lines from 11.04 to 11.31 μm are shown in the Table 1.

Table 1. Average power at different lasing lines.

Lasing line	λ, μm	P_{LASER}, mW
P10	11.04474	460
P12	11.06540	510
P14	11.08564	520
P16	11.10664	500
P18	11.12784	560
P20	11.14944	550
P22	11.17134	430
Lasing line	λ, μm	P_{LASER}, mW
P24	11.19354	475
P26	11.21614	490
P28	11.23940	435
P30	11.26234	410
P32	11.28594	375
P34	11.30994	370

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2-D and 3-D beam profiles of the laser obtained with intensity profile analyzer PIROCAM III by Ophir are shown on the Figure 6.

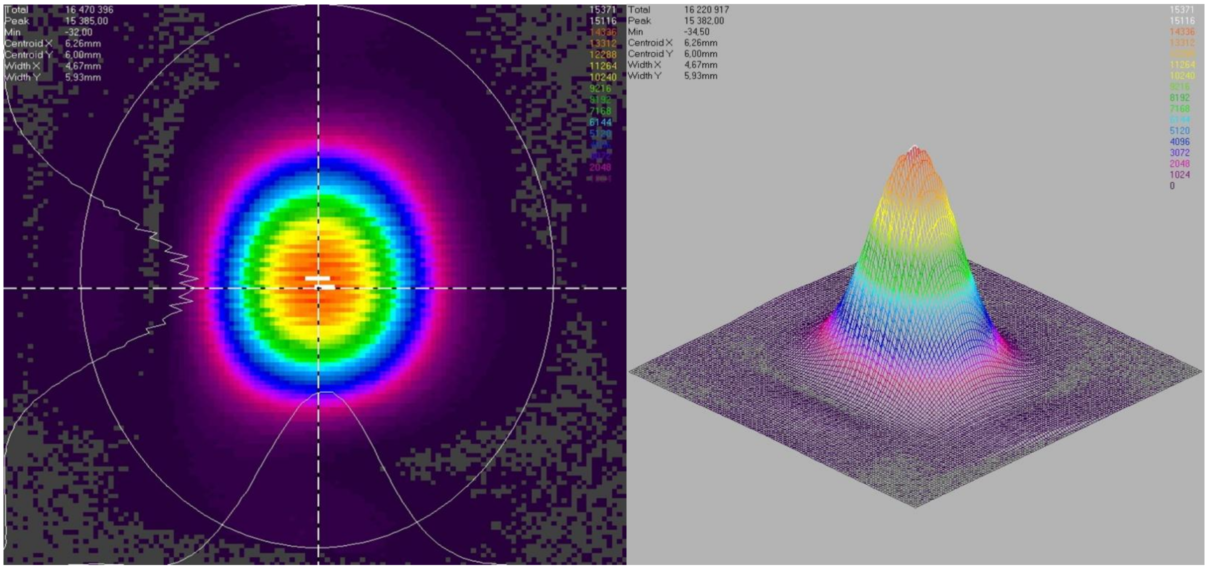

Figure 6. 2-D and 3-D beam profiles at 11P(20) line.

The beam profiles were captured at 11.14944 μm. Use of such equipment allows fine tuning of the resonator and lasing parameters in real time.

The maximum beam diameter at e^{-2} level is 5.93 mm as measured by the analyzer. The divergence angle does not exceed 9 mrad.

Beam quality criteria M^2 was calculated with use of formulas (1), (2) from [7]:

$$M_{x,y}^2 = \frac{\pi \cdot d_0 \cdot \theta_{x,y}}{4 \cdot \lambda}, \tag{1}$$

$$M^2 = M_x^2 \cdot M_y^2, \tag{2}$$

where: d_o – beam diameter at constriction (waveguide end in our case), θ – beam divergence, λ – wavelength.

Assuming according to [8], that $d_0 = 0.7032*d$, where d – rectangular waveguide cross section size (2.5 mm in our case) we get $M^2 \approx 1{,}23$, that is typical value for single mode waveguide CO_2-lasers and fits the issued requirements.

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For evaluation of directional pattern stability in time we observed the beam profile with Pyrocam during 2.5 hours. Beam diameter changed within 2% for that time that shows rather high stability of the spatial structure of the beam. While this experiment the laser was cooled only by natural convection of the ambient air. Obtained divergence data corresponds to such for different gas mixtures based on $^{12}C^{16}O_2$ and $^{13}C^{16}O_2$.

The developed design of the system provides additional piezo actuator for resonator length fine tuning for better frequency and power stabilization at a particular lasing line. This work is continued.

4. CONCLUSION

The pulsed periodic $^{13}C^{16}O_2$-laser with Z-shaped metal-ceramic waveguide resonator is developed. Wavelength tuning is characterized from 11.03 to 11.31 µm. The laser was specially designed for installation into LIDAR system by Institute of Atmospheric Optics, Tomsk, Russia. Due to its features and possibility to work with different isotope modifications of carbon dioxide the laser is a universal laser source for different applications like:

- LIDARs;
- Molecule Spectroscopy;
- Optical Pumping Source, e.g. for chemical lasers or frequency conversion;
- Reference for calibration wavelength meter systems.

Several types of carbon dioxide lasers can be made on the developed unified platform. For example:

- $^{12}C^{16}O_2$ ($^{13}C^{16}O_2$) – fixed wavelength laser source;
- $^{12}C^{16}O_2$ ($^{13}C^{16}O_2$) – tunable wavelength laser source;
- $^{12}C^{16}O_2$ ($^{13}C^{16}O_2$) – Q-switched laser source.

The unified platform is formed by single unit solution of combined laser head and ECU with integrated RF exciter. By changing contents of different isotope modifications of carbon dioxide in the working mixture lasing at the wide range from 9.2 to 11.8 µm can be easily obtained.

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