Quantum Electronics **35** (5) 393 – 406 (2005)

INVITED PAPER

PACS numbers: 42.55.Ks; 42.60.By
DOI: 10.1070/QE2005v035n05ABEH002828

High-power mobile chemical lasers

A.S. Boreysho

***Abstract*. The prospects of equipping mobile carriers with continuous wave chemical lasers (cw CLs), which continue to be the most powerful sources of laser radiation providing the highest energy efficiency and a high optical quality of the beam, are considered. The technological problems involved in such a procedure, whose solution leads to the determination of real technical parameters of autonomous mobile laser systems, are discussed. It is shown that the technical parameters of real lasers must reflect the features of their installation and exploitation under conditions differing radically from the conditions in laboratories where their investigations are being continued.**

Keywords: *continuous wave chemical lasers, mobile laser systems, propagation of laser radiation.*

1. Introduction

Over the last decades, continuous-wave chemical lasers (cw CLs) have been the objects of most lively interest among civilian and military users, as well the developers of new technologies as the most promising sources of high-power laser radiation.

1970 – 80s. During the 1970s – 1980s, megawatt gas-dynamic CO_2 lasers (GDLs), developed in the USSR [1] and USA, allowed the first practical verification and estimate of the scale and complexity of the technological problems involved in the development of laser weapons. However, a large radiation wavelength (10.6 μm), and hence a high divergence of the laser beam, as well as a low energy efficiency of laser sources turned out to be serious technical obstacles preventing the mobile systems based on CO_2 gas-dynamic lasers from competing with the traditional weapons.

Nevertheless, these investigations strongly stimulated the development of control systems and information technologies, and laid the foundation for their unprecedented progress in the following decades.

From the 1980s to the present day. Continuous wave chemical HF(DF) lasers (cw CLs) paved the way for advancement almost in all technological fields and provided a considerable increase in the laser efficiency and a decrease in the wavelength. The HF cw CL radiation (in the wavelength range 2.7 – 3.1 μm) is absorbed strongly by the atmosphere, while the DF cw CL radiation (3.6 – 4.1 μm) lies entirely in the spectral window region. Therefore, HF lasers can have only extra-terrestrial applications, while the DF cw CL can be used under terrestrial conditions.

The experimental samples of megawatt HF(DF) lasers developed in the USA and equipped with a large-size optical system (about 1.5 m in diameter) were subjected to effective trials which confirmed the maturity of laser, optical, electronic and information technologies that could be used to solve many practical problems to the fullest extent.

The specific aim of investigations was to create a global laser weapon system for deployment in space and operating in conjunction with the satellite-based high-power Alpha chemical HF lasers for the purpose of destroying ballistic missiles in the active region of their trajectory.

The joint American – Israeli project Nautilus has been the subject of active discussions since mid-1990s. This project is based on a system including a DF cw CL of about 400 kW power, and is intended for striking unguided missiles like Katyusha.

At present, the number of projects based on the use of DF cw CLs for terrestrial applications being discussed and realised in actual practice has grown significantly and their geography has expanded considerably.

Another type of cw CLs, chemical oxygen – iodine lasers (COILs) has been developed from the beginning of 1990s. The wavelength of a COIL (1.315 μm) falls in the spectral window of the atmosphere, and also corresponds to the working range of fibre optics. This means that in principle there are no constraints on the use of such lasers under different atmospheric and exoatmospheric conditions. The short emission wavelength of such lasers provides a decrease in the diffraction limit, while the low density of the active medium in the cavity guarantees a laser beam of high optical quality. Therefore, the aperture of COIL mirrors providing the same radiation density on the target may be much smaller than for the HF(DF) lasers.

The Airborne Laser (ABL) project involves the deployment of a COIL onboard a wide-body aircraft (Boeing 747-400F) for striking ballistic missiles in the active region of their trajectory. Another military application of this complex is the destruction of satellites in the near-earth orbit.

A.S. Boreysho D.F. Ustinov Voenmekh Baltic State Technical University, Laser Systems Ltd., 1-ya Krasnoarmeiskaya ul. 1, 190005 St. Petersburg, Russia;
e-mail: office@lsystems.ru; website: www.lsystems.ru

Received 20 July 2004; revision received 13 January 2005
Kvantovaya Elektronika **35** (5) 393 – 406 (2005)
Translated by Ram Wadhwa

A new concept of a 'advanced tactical laser' (ATL) based on a 50–70-kW COIL has been discussed in recent years. It is assumed that such systems can detect and strike most airborne and terrestrial objects like cruise missiles, unguided missiles and unmanned aircrafts, as well as automobiles, missile launchers and observing systems, at distances from 8 to 25 km. The ATL will be based on the same technologies that are used in the ABL laser systems, but will have a much lower output power.

A new tendency of a shift of interests towards tactical laser systems can be easily perceived. The experience gathered from trials of experimental lasers leads to a better understanding of their scope, an expansion of the list of potential targets, an extension of the range and an even higher selectivity and precision of strike. All this stimulates a transition from giant first-generation laser systems (which are dictated rather by organisational factors than technical ones) to more efficient and compact mobile systems intended for a wider range of applications.

2. Operating principle of HF(DF) cw CLs

The operating principle of these lasers is based on direct transformation of chemical energy into laser radiation energy upon a rapid mixing of chemically active ultrasonic flows of an oxidant (containing atomic fluorine diluted mainly by a neutral gas, predominantly helium) and fuel (deuterium) (Fig. 1). The mixing of the flows is accompanied by the exothermic reaction

$$F + (H_2)D_2 \rightarrow HF(DF)(\upsilon) + H(D), \qquad (1)$$

which is accompanied by the formation of vibrationally excited DF molecules, the released energy being sufficient for populating vibrational levels right up to fourth ($\upsilon = 1-4$). As a result of these processes, an essentially nonequilibrium distribution (with respect to the translational temperature) of HF(DF) molecule over vibrational levels is formed in the active medium of the laser. This creates favourable conditions for the production of partial population inversion simultaneously for three lower vibrational bands ($1 \rightarrow 0$, $2 \rightarrow 1$ and $3 \rightarrow 2$). The chemical reaction of pumping is an irreversible process, i.e., the waste reaction products must be removed continuously from the gas-dynamic channel. This virtually rules out the possibility of realisation of a closed cycle operation of HF(DF) cw CLs.

Although the rate of pump reaction (1) is quite high, the level of working pressures in the active medium of HF(DF) cw CLs is quite low (as a rule, it does not exceed 5–10 Torr) due to a low rate of mixing of supersonic flows and especially because of a high rate of vibration–translation relaxation of excited molecules. With increasing pressure, the width of the laser zone decreases, which also restricts the working pressure of the active medium.

The low pressure rules out the removal of reaction products into atmosphere under terrestrial conditions due to intrinsic flow energy since the pressure of the gas is still much lower than the atmospheric pressure even after deceleration in the diffuser.

In DF lasers intended for working under atmospheric conditions, the pressure recovery system (PRS) consists of a supersonic diffuser (in which the supersonic flow is decelerated and passes to subsonic flow), a refrigerator (heat exchanger) and a gas ejector in which the pressure increases to values ensuring a stable operation in the open cycle mode.

In the HF laser mounted on aircraft or sky-labs, the complex and bulky PRS can be replaced by a device for discharging the waste mixture, which should ensure the minimum effect of gases on the structural components of the laser and the carrier and on their orientation in space by balancing the tractive force of the effluents.

The source of energy in a COIL is oxygen in singlet electron-excited state $O_2(^1\Delta)$. The energy parameters of the laser are determined mainly by the concentration of singlet oxygen (SO) in the active medium. The SO itself can be obtained by various methods. The most widely used technique is the chemical method based on the reaction of chlorination of an alkaline solution of hydrogen peroxide, which takes place in the generators of singlet oxygen (SOG) (Fig. 2).

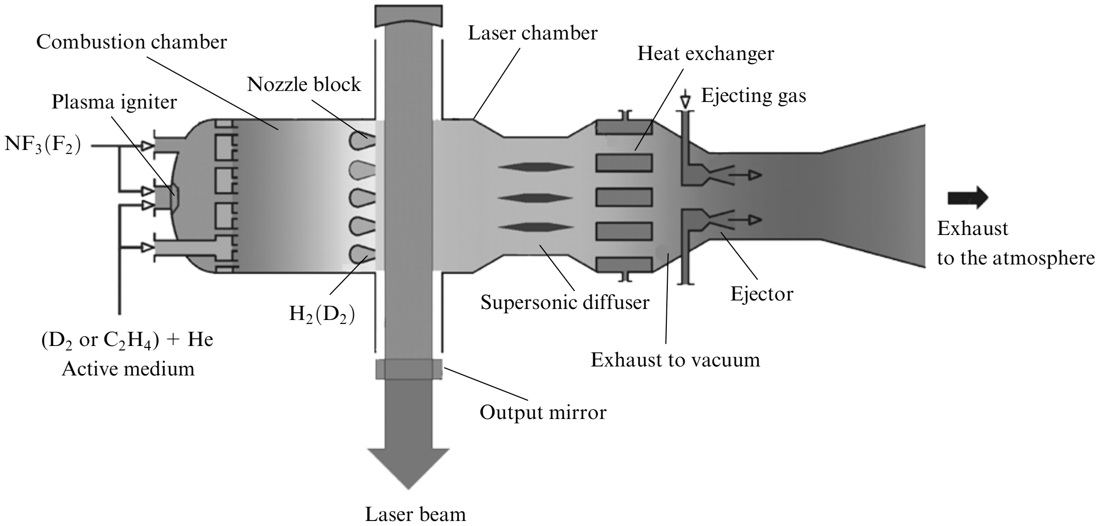


Figure 1. Functional diagram of a HF(DF) cw CL.

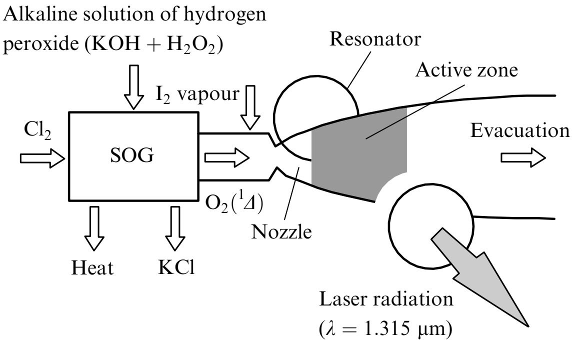


Figure 2. Functional diagram of a COIL with an SO jet generator.

Alkaline solution of hydrogen peroxide is prepared from aqueous solutions of hydrogen peroxide and alkali (usually potassium hydroxide, since for this compound the homogeneity of the liquid state is preserved over a wide temperature range). Mixing of the alkali and hydrogen peroxide leads to a number of electrolytic reactions accompanied by the heat release:

$$\begin{gathered} MOH + H_2O_2 \rightarrow M^+ + H_2O + HO_2^-, \\ Cl_2 + 2HO_2^- \rightarrow O_2(^1\Delta)\uparrow + H_2O_2 + 2Cl^-. \end{gathered} \tag{2}$$

The excited state $O_2(^1\Delta)$ is metastable. The radiative lifetime of SO in the gaseous phase exceeds 2000 s in the absence of quenching impurities [2]. Apparently, a high power requires a large expenditure of SO which is easier to realise for a supersonic circulation.

Gas-dynamic cooling of the active medium in a supersonic nozzle creates favourable conditions for laser energy extraction. The high circulation rate of the medium also ensures an extension of the active zone along the flow, thus leading to a uniform filling of the cavity aperture by radiation.

Iodine vapour mixed with the buffer gas is injected into the oxygen flow just in front of the cavity. In the presence of SO, molecular iodine dissociates into atoms. This is followed by a quasi-resonant energy transfer from electron levels of SO molecules to iodine atoms,

$$I + O_2(^1\Delta) \leftrightarrow I^* + O_2(^3\Sigma), \tag{3}$$

which pass to the upper excited states $I(^2P_{1/2})$.

The emission power of a COIL is defined by the relation

$$W_{\max} = \varepsilon \dot{M}_o (Y - Y_{th}), \quad Y_{th} = \frac{1}{2K_e + 1}. \tag{4}$$

Here, $W_{\max}$ is the potentially extractable power in watts; $\varepsilon = 90.6 \times 10^3$ J mole^{-1} is the energy per mole of $I(^2P_{1/2})$ atoms; $\dot{M}_o$ is the molar flow rate of oxygen at the SOG outlet (mole s^{-1}); Y is the SO yield; Y_{th} is the threshold fraction of SO (fraction of SO, starting from which the small-signal gain becomes positive); $K_e = 0.75 \exp(402/T)$ is the equilibrium constant of the reaction of energy exchange between electron levels of SO molecules and iodine atoms; and T is the temperature of the active medium in kelvins. As in a HF(DF) cw CL, the resonator is placed across the flow.

The waste gas mixture consists of oxygen, water vapour, iodine vapour, buffer gas (helium, argon, nitrogen) and a small amount of unutilised chlorine. Low-volatility iodine vapour and the residual chlorine are recovered in a cryogenic trap. Consequently, the waste gas mixture consists virtually of the buffer gas with a slight admixture of oxygen. Hence, in contrast to the HF(DF) cw CL, the efflux of this mixture into atmosphere does not pose an environmental hazard.

The following main parts of a COIL determine the design features and influence the laser operation [3, 4]: systems for preparation and storage of components (in which the alkaline solution of hydrogen peroxide, chlorine and molecular iodine are prepared), the SO generator, the supersonic mixing nozzle bank (ensuring a mixing of singlet oxygen with molecular iodine and the formation of supersonic flow of the active medium), the cavity, the optical resonator, and the PRS (ensuring laser operation in the atmosphere).

For moderate flow rates of the active medium, there is a real possibility of using a COIL under terrestrial conditions in closed-cycle mode with the help of cryosorption technology. In this technology, gaseous products are adsorbed by a cooled sorbent with a developed surface, e.g., zeolite. Recovery of the sorbent through heating, evacuation and subsequent cooling leads to the liberation of adsorbed gases and returns the system to its initial state.

3. Preparation of the active medium

A large number of initial components are required for a proper functioning of HF(DF) cw CL. These include nitrogen trifluoride (NF_3), ethylene (C_2H_4), helium (He), deuterium (D_2), cooling water for the active medium generator (AMG), oxygen (O_2), ethyl alcohol (C_2H_5OH) and water (H_2O) for the ejecting gas generator (EGG). An additional component (He) is used to protect the optical resonator mirrors. Gaseous components are stored in high-pressure cylinders.

The AMG system is shown in Fig. 1. The oxidant (F_2 or NF_2) and the primary fuel (H_2 or C_2H_4) are injected simultaneously into the combustion chamber under a pressure of 1 atm or higher. The use of nitrogen trifluoride (NF_3) as the oxidant is dictated by the fact that it has certain advantages over fluorine during the practical operation of the cw CL. This gas is much less aggressive and toxic than molecular fluorine. In addition, before entering the combustion chamber, the mixture of the primary fuel and the diluent participates in regenerative circulatory cooling of its casing (through cooling channels) and the fuel injector head (through channels in the massive bottom). The electroplasma ignition device is intended for igniting the fuel and oxidant mixture at the exit from the fuel nozzle head since NF_3 molecules are chemically inert and (unlike F_2) do not form combustible mixtures with H_2 or C_2H_4 at temperatures of functioning of the module.

The body of the combustion chamber being cooled, in which the reaction of combustion of C_2H_4 with NF_3 occurs, is hermetically sealed with the fuel nozzle head. The temperature attained in the combustion chamber (1700–1800 K) ensures a high degree of dissociation of excess NF_3 leading to the formation of atomic fluorine.

A laser chamber with windows in its lateral walls for the extraction of laser radiation is butt-jointed tightly with the nozzle bank downstream. Flanges at the entrance to the laser chamber and at the exit from it are used to seal it with the nozzle bank at one end and the supersonic diffuser of the exhaust system at the other end.

The most important structural element of the AMG is the nozzle bank in the form of a rectangular box with collectors for supplying secondary fuel (D_2) and coolant (H_2O), and with the nozzle array fixed in it. The nozzle array consists of cooling channels and alternating supersonic wedge-shaped fine slotted nozzles for the oxidant and the secondary fuel.

The alkaline hydrogen peroxide solution in a COIL is prepared in a special tank equipped with a coil and a cooling jacket. The cooling of the tank is necessary for compensating the heat released in the reaction between hydrogen peroxide and alkali during solution preparation, and also for maintaining its temperature constant in the course of the laser operation.

We used in our experiments hydrogen peroxide with a mass concentration of about 35 % and KOH solution prepared from the dry alkali. The heat released during the chemical reaction was compensated by a single-loop Freon refrigerator.

Liquified chlorine is stored in a cylinder at normal temperatures under a pressure of 6 – 7 atm. However, for the safety of the laser operation, chlorine is supplied to the SOG through an intermediate container in the form of an elastic bag in which chlorine is stored at a pressure slightly lower than atmospheric and occupies a volume sufficient for three or four runs.

The system for preparing iodine vapour is based on evaporation of crystalline iodine upon heating until the saturation vapour pressure is reached over the surface. During experiments, nitrogen (second buffer gas) is circulated over iodine crystals. It is nitrogen that transports iodine in the nozzle bank to the point of mixing with SO.

The entire iodine evaporation system must be thermally insulated reliably. Hot air is used for heating the vaporisers, nitrogen heaters as well as the system elements behind the vaporisers from outside.

The main source of the working mixture in a COIL is a SOG in which the physical and chemical processes occur at low temperatures and pressures, thus ensuring their irrefutable advantage from the safety point of view.

Fluid oscillators are used in modern high-efficiency COILs. The 15-kW generator of the experimental setup [3] developed at 'Laser Systems' (Fig. 3) has two symmetric reaction chambers [5]. Chlorine gas is supplied from the collector system through injector holes, while alkaline solution of hydrogen peroxide is also supplied into the reaction chamber from above through special orifices in the injector plates. The solution is supplied in the form of jets of diameter about 1 mm. The oxygen generated in the SOG escapes through two slits on top of the reaction chambers where it is mixed with nitrogen, the primary buffer gas. A record-high chemical efficiency (32 %) was attained [6] in this kind of a setup:

$$\eta_{\text{chem}} = \frac{W}{\varepsilon \dot{M}_{\text{c}}}. \qquad (5)$$

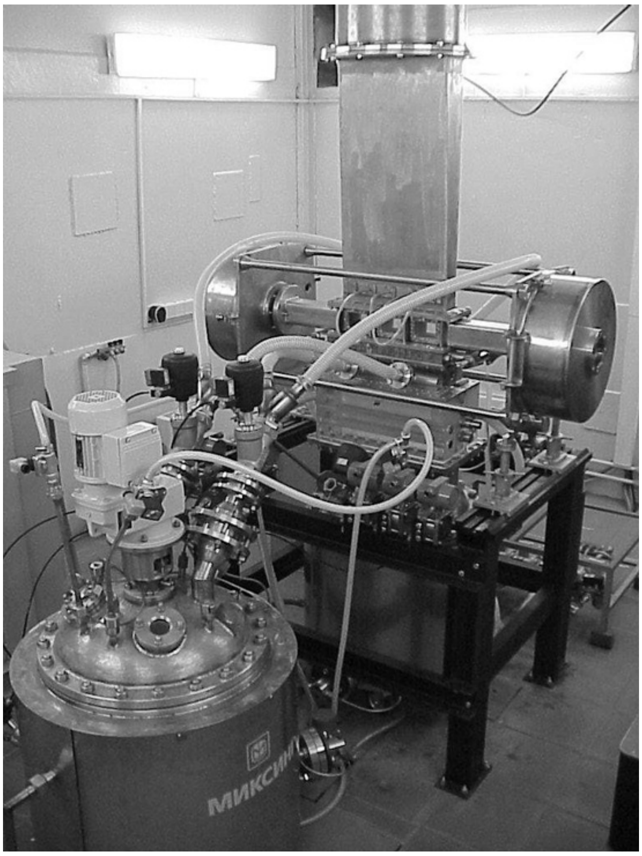


Figure 3. A 15-kW cw COIL ('Laser Systems', St. Petersburg).

In this expression, ε is the energy of one mole of iodine atoms; W is the laser power (in watts); and $\dot{M}_{\text{c}}$ is the molar flow rate of chlorine (mole s^{-1}). The spent solution can be circulated many times through the SOG, thus ensuring an almost continuous operation of the laser.

The nozzle bank is a set of slotted nozzles. The primary flow (SO diluted with the primary buffer gas) moves upwards from the SOG and is accelerated in the nozzles. Each nozzle has in its critical section a secondary flow (secondary buffer gas and iodine) injector. The injector is constructed in such a way that it has two rows of holes. Two rows of holes are also drilled in the nozzle blade forming one of the nozzle walls.

Special lateral blades for supplying pure nitrogen without iodine vapour are mounted at the end-faces of the nozzle bank. This is necessary for preventing iodine vapour from entering the resonator. The active medium flow emerging from the nozzle bank enters the laser chamber which has an expanding cross-section profile to compensate the heat liberation in the active medium flow during chemical reaction and relaxation processes. After passing through the laser chamber, the active medium flows into the supersonic diffuser where it is decelerated and the total pressure is recovered.

The properties of the initial components of HF(DF) lasers and the COIL, as well as of the processes of obtaining the active medium and its transformation in the gas-dynamic channels, determine the composition and parameters of the spent gases (Table 1).

Table 1.

Parameter	Combustion chamber of a HF(DF) laser	COIL SOG	Nozzle bank		Laser chamber	
			HF(DF) laser	COIL	HF(DF) laser	COIL
Pressure/Torr	1000 – 100000	20 – 40	5 – 10	2 – 3	10 – 20	4 – 8
Temperature/K	1600 – 1800	240 – 250	100 – 300	100 – 300	600	200 – 300

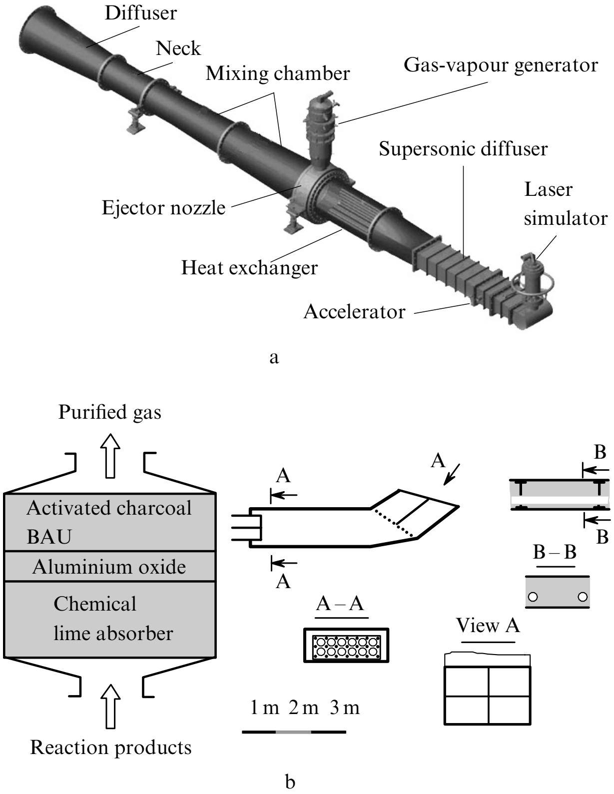


Figure 4. (a) Pressure recovery system for a high-power HF(DF) laser, and (b) noise suppression and exhaust-gas purification system.

4. Utilisation of the spent gas mixture

The potentialities of a mobile chemical laser are determined by the continuous heat removal from the working mixture under a pressure of a few Torr to tens of Torr. Obviously, the gas-dynamic problem of exhaust of the spent gas into atmosphere becomes redundant for lasers intended for use in space. The only problems that need to be solved in this case are to ensure that the spent gas stream should have the least influence on the structural elements and to compensate for the reactive force of the effluent jet stream.

Most serious difficulties arise in the case of land-based systems. In DF cw CL, this problem is solved with the help of PRS. Unfortunately, the intrinsic kinetic energy of the active medium flow is not sufficient for ejecting the spent gas mixture in the case of a cw chemical laser. An additional amount of energy must be supplied with the help of vacuum pumps or ejectors. The latter technique is used for high-power lasers.

One of the deciding criteria in the efficiency of PRS is the ejection coefficient, i.e., ratio of the flow rates of the spent gases in the laser operation and of the ejecting gas. Even for the most 'successful' DF laser systems, this ratio does not exceed 10 %, and its value may be even lower by an order of magnitude in the case of a low-pressure COIL. Hence it is the margin of the PRS components that determines the size and mass of the mobile terrestrial cw CL, which means that optimisation of PRS plays a vital role in the designing of such equipment.

It is also necessary to take into account the practical and operational constraints, the technical safety conditions, cost indices, etc. It is expedient to use the easily available cheap nontoxic gases or gas-vapour mixtures for the ejecting working body. The interaction of such a working body with the medium being ejected must not lead to a phase transformation (e.g., precipitation of solid particles, condensation of vapour, etc.) or an additional heat release that would lower the efficiency of the ejector.

In order to overcome these difficulties, a heat exchanger is installed between the diffuser and the ejector of the PRS for cooling the combustion products of the cw CL. The use of a compact cooling heat exchanger with a low flow friction of the setting as a part of the energy installation (Fig. 4a) also ensures an increase in the ejection coefficient since it is inversely proportional (other conditions remaining the same) to the square root of the temperature factor:

$$n \sim \sqrt{\frac{\mu}{\theta}}, \qquad (6)$$

where $\mu = \mu_2/\mu_1$; $\theta = T_{02}/T_{01}$; μ_1, μ_2, T_{01}, and T_{02} are the molecular weights and temperatures of the ejecting and the ejected gases, respectively.

PRS employing gaseous ejectors with gas-vapour generators based on the fuel components that are conventional in rocket and aerospace technology are of utmost interest for the cw CL intended for mobile installations. These include the exhaust products from the turbojet aviation engines, products of decomposition of highly concentrated hydrogen peroxide (H_2O_2), water-ballasted generator gas-vapour formed as a result of combustion of kerosene with liquid or gaseous oxygen, as well as water-ballasted generator gas-vapour formed as a result of combustion of ethyl alcohol (C_2H_5OH) with gaseous oxygen.

Since the exhaust products from aviation engines have low pressures, the ejection coefficients at the input to the ejector are also quite low. This circumstance leads to a considerable increase in the mass and size of PRS. However, such PRS do not require a special ejecting gas generator, nor is it necessary to store the oxidant (e.g., oxygen) supply. Hence the possibility of using the exhaust products of aviation engines as the ejecting gas must be considered in each specific situation [7, 8].

It is convenient to compare various fuel combinations on the basis of the values attained for the ejection coefficient (6) since it depends on the molecular weight and temperature of the reaction products. The ejection coefficient of the combustion products of hydrazine is 1.3 – 1.5 times higher than the ejection coefficient for the generator gases listed above. However, the hydrazine combustion products pose an environmental hazard.

Stationary PRS use the gas-vapour generators working on the combustion of ethyl alcohol in air. This is a reasonable fuel for laboratory setups since a high safety level is ensured at all stages of the operation. A drawback of such PRS is the large volume of high-pressure (up to 400 atm) cylinders filled with air, which is used as the oxidant.

A comparison of the energy efficiency of ejectors using various ejecting gas sources shows that irrespective of the choice of the source, the required flow rates differ by no more than 20 %. Hence great care must be exercised in giving preference to any of these sources, and their operational parameters and cost factors must be taken into account [9, 10].

According to the latter criteria, it is most expedient to obtain the ejecting gas by burning kerosene and ethyl alcohol in air or gaseous oxygen (followed by water-ballasting), as well as by decomposing concentrated hydrogen peroxide. The techniques for employing oxygen gas and hydrogen peroxide are quite familiar since such systems have been used for over half a century in gas generators of test equipment and in actual devices.

The main achievements of 'Laser Systems' in the field of PRS for chemical lasers are associated with unique compact high-efficiency one-stage ejectors capable of working under conditions of record-high pressure drops [10] that are sufficient for triggering oxygen – iodine lasers at a pressure even lower than in DF lasers.

Environmental safety is a serious problem associated with the use of DF lasers in terrestrial or atmospheric conditions. On the one hand, this is due to the use of toxic compounds like F_2 and NF_3 as the initial working fuel components. On the other hand, the presence of toxic materials (F_2, HF, DF) among reaction products requires their elimination before emission into the atmosphere. Hence, the gas-dynamic channel of the laboratory laser devices is equipped with a special neutralisation system employing either the 'dry' technique (with the help of degassing apparatus with dry filling) or chemical pumps.

The devices employing the 'dry' technique for degassing consist of units with three-level infilling (Fig. 4b). The first layer in the direction of escape of the reaction products is a layer of natural limestone or a chemical lime absorber (CLA). The purification level attained in the first layer is 99 %. About 2.5 kg CLA is required for binding 1 kg of HF. The second layer consists of alumogel (Al_2O_3) which absorbs the moisture separated in the course of the reaction in order to prevent caking of the charge and the formation of hydrofluoric acid. In the third layer (activated charcoal BAU), the gases are purified further to attain an impurity concentration of 3 – 5 times the maximum permissible concentration. The consumption of BAU for binding 1 kg of HF is 5 kg. The tower cross section is calculated on the basis of the required rate of flow of the reaction products being neutralised in it and amounts to about 0.02 – 0.05 m s^{-1}. Hence there is no justification in realising the entire gas purification complex for mobile autonomous systems.

Another common problem encountered during the use of ejector PRS is the noise that can assume quite high values (more than 120 dB). The solution of this problem requires special mufflers [11] that can be installed even on mobile systems.

Apart from the ejector PRS, radically new pumping systems like cryoadsorption of gases in gaseous condensates [12] can be used in a COIL. The molecules of the gas being removed collide with the adsorbent surface cooled to quite low temperatures, lose a part of their kinetic energy and are bound to this surface depending on the operating conditions.

The most widely used adsorbents are zeolites, i.e., alumosilicates of alkaline or alkali-earth metals, existing in nature or synthesised artificially [12, 13].

The sealed exhaust system is based on the use of a cryoadsorbtion pump, consisting of a tank filled with zeolite cooled to cryogenic temperatures. Such a cryopump can be used repeatedly by heating zeolite and cooling it again.

The possibility of using this technology in a mobile COIL was verified experimentally at 'Laser systems'. The parameters measured at the diffuser edge were found to be quite promising: a pressure of 10 Torr and a temperature of 450 K were attained for a gas flow rate of 350 g s^{-1}.

Figure 5 shows the operational diagram of a cryoadsorber of a 50-kW COIL, which ensured under terrestrial conditions a series of 10 runs of duration 5 s at an interval of 5 s, as well as the assembly of the entire cryoadsorption system, that can be mounted on a mobile carrier. The mass of zeolite contained in two tanks of size 3.5 m × 1.25 m ×1.25 m is equal to 1300 kg for the cryopump of a COIL.

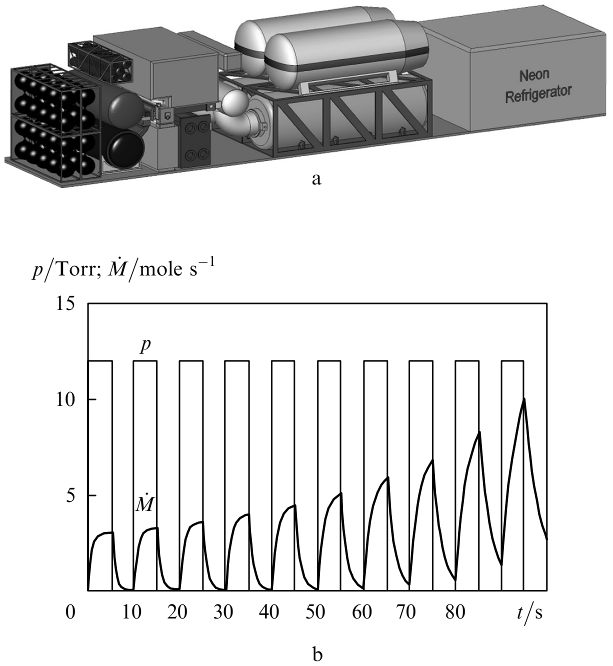


Figure 5. (a) Assembly of the cryoadsorption system for recovery of exhaust gases from a COIL on a mobile platform and (b) operational diagram of a cryoadsorber.

During its motion, the mobile system may experience considerable impact loads. Hence the cryopump must have a strong casing and zeolite itself should be placed in a frame 'suspended' from thermal bridges.

The frame consists of a cylindrical cage assembled from fibre-glass plastic rods inserted in a perforated partition upholstered from inside and outside by metal cloth. A heat-exchanger COIL with the coolant flowing through it is installed in the frame.

Unlike conventional applications involving low pressures (below 10^{-2} Torr) and low consumption of the adsorbed gas, the adsorption rate in the laser systems being considered by us has a finite value. A decisive role is played not only by the microgeometrical parameters of the adsorbent like the total area of the adsorbing surface and the microscale, but also the geometrical structure of the adsorbent at all intermediate scales. The method of supplying adsorbed gas with minimum loss of pressure and the method of removal of heat of adsorption are of prime importance. Hence it is expedient to use the empirical coefficient α of dynamic adsorbability as the main characteristic of the adsorbent. The dynamic adsorption of the spent active medium of the COIL is described by the differential equation

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{RT}{V}\dot{M} - p\,\frac{\alpha m}{V}, \qquad (7)$$

where p is the pressure in the pump cavity; T is the temperature of zeolite; V is the pump volume; $\dot{M}$ is the molar flow rate of the gas; $\alpha = C(1-f)(2\pi\mu_{\mathrm{g}}kT)^{-1/2}$ is the dynamic adsorption coefficient [12] in $\mathrm{m^3\ kg^{-1}\ s^{-1}}$; C is an empirical factor depending on the microgeometrical parameters of the adsorbent; f is the adsorbent surface saturation coefficient; μ_{g} is the molecular mass of the gas being adsorbed; m is the zeolite mass; and k is the Boltzmann constant. The first term in the right-hand side of the equation describes isothermal compression while the second term describes dynamic adsorption. Approximation of the experimental results by the solution of Eqn (7) gives the value 9.8×10^{-3} for the constant C.

5. Laser beam control and power extraction

This process is described by a number of independent and interdependent subsystems of the laser, e.g., the cavity, aerodynamic window, telescope, and the laser radiation control system.

Resonator. The optical resonator of a cw CL is intended for transforming the energy of the active medium into laser radiation, and for stable generation of a good quality laser radiation beam.

For a high energy efficiency, the amplification factors of the active media of a cw CL are comparatively small. While this does not impose any technical constraints on the choice of optimal optical diagrams and designs of the cavities for ultra-high-power systems with long active media, it is expedient to use multipass resonator designs for less powerful lasers with a limited length of the active medium.

The uncooled high-loaded mirrors with minimum scattering were made of silicon prepared by a special technology of 'deep polishing' with multilayer insulator coatings on its optical surface. However, the use of such mirrors in the two-pass systems may lead to technical problems and finally to a decrease in the output radiation power.

The optical quality of the output radiation is determined to a large extent by the level of optical inhomogeneities in the active medium of the cw CL. A relatively low working pressure in DF lasers provides a quite high optical quality of the active medium even when nozzle arrays with turbulising nozzles are used. The level of optical inhomogeneities in such lasers (at the working wavelength) does not exceed $\lambda/50$ for a 20-cm long active medium [9].

Special gas screens are used to protect the mirrors from the action of aggressive components of the active medium (F, F_2, HF, DF).

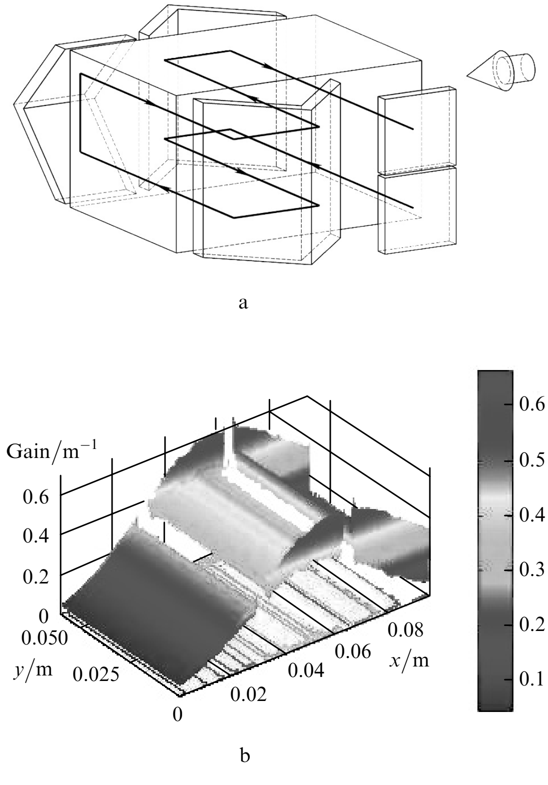
The energy extraction in a COIL is higher for the DF laser, while typical gains for the active medium are lower. Moreover, on account of a shorter wavelength, a COIL requires a much lower power than a DF laser to attain the same brightness of radiation at the target.

On the one hand, the formation of a low-divergence laser beam requires a large output aperture of the resonator. Consequently, the active medium may turn out to be too short for a high energy extraction which is a parameter of vital significance in the choice of the resonator optical diagram. In practice this indicates that a multipass scheme should be used in most of the prospective designs.

On the other hand, such designs are much more complex for adjustment and more sensitive to vibrations and other power loads. These difficulties are overcome by introducing dihedral reflectors in the diagram, which facilitates the solution of yet another problem that is typical of all cw CLs – a nonuniform distribution of the amplifying properties of the active medium over the aperture.

Most of the characteristic features of a cw CL are taken into account in the optical diagram of an unstable resonator [14] specially developed at 'Laser Systems' for a mobile COIL (Fig. 6a):

(i) the intensity at the output aperture of the resonator is levelled out by using dihedral mirrors 'reversing' the electromagnetic field distribution; the number and position of such mirrors is matched with the gain distribution in the resonator plane;



a

b

Figure 6. (a) Optical diagram of the multipass resonator of a high-power COIL, (b) distribution of the small-signal gain over aperture for a three-pass resonator scheme.

(ii) the resonator has a high energy efficiency since its mode is optimally matched with the distribution of gain in the active medium: as a result of reversals at dihedral mirrors, the radiation successively passes through zones with high and low gains, thus ensuring a uniform distribution of intensity over the aperture;

(iii) the presence of dihedral mirrors lowers the sensitivity of the resonator to maladjustments and vibrations;

(iv) all passes through the active medium in a given resonator are parallel, thus making it possible to use polarisation elements in it, including Brewster windows for separation of the active medium.

Figure 6b shows the distribution of the gain in a COIL resonator, obtained by using the approach described above.

A small part (4 %) of the laser radiation is diverted from the main radiation to control its power. The total energy accumulated during the generation of radiation and the time distribution of radiation power are measured.

Aerodynamic window (ADW). The main purpose of the window is the extraction of laser radiation from the lasing zone. Strictly speaking, two problems have to be tackled, namely, to ensure the hermeticity of the cavity and to minimise the wavefront distortion of laser radiation at the output aperture. For COILs, this problem is solved quite easily with the help of high-quality transparent quartz glasses even for megawatt lasers. At the same time, optically transparent materials used in longwave DF lasers have an inhomogeneous crystal structure and a higher adsorption coefficient. Hence the radiation density in DF lasers may exceed the optical stability threshold of the materials being used even for a laser radiation power exceeding 100 kW.

In principle, the ADO can replace transparent materials and ensure a reliable radiation extraction practically for all values of radiation density at the output aperture. However, it was assumed earlier that two-stage windows with vacuum pumping from the second stage are needed for a compression ratio exceeding 40.

New-generation one-stage ADWs, developed at 'Laser Systems' on the basis of the concept of differential ejectors are operating reliably for a compression ratio as high as 100 (Fig. 7).

Focusing telescope. Radiation is condensed with the help of a focusing telescope consisting of a reflecting objective with a movable secondary mirror (Fig. 8). The main mirror

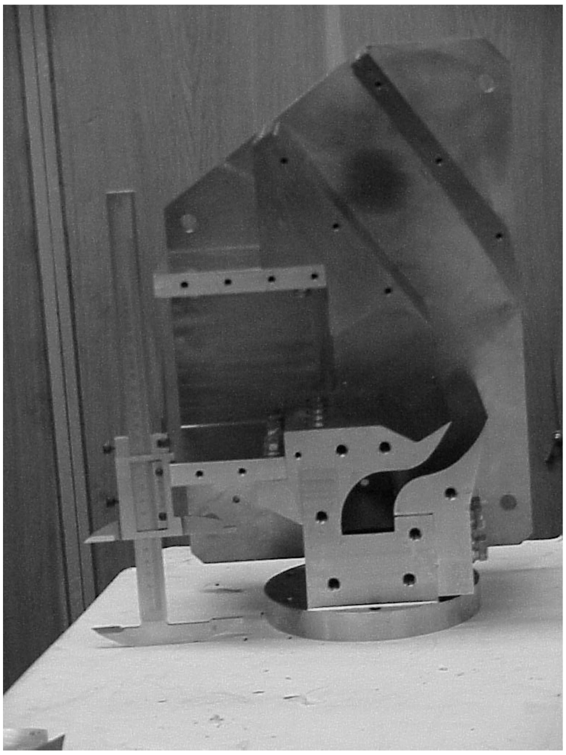


Figure 7. New one-stage aerodynamic window with a compression ratio of 100 for high-power chemical lasers.

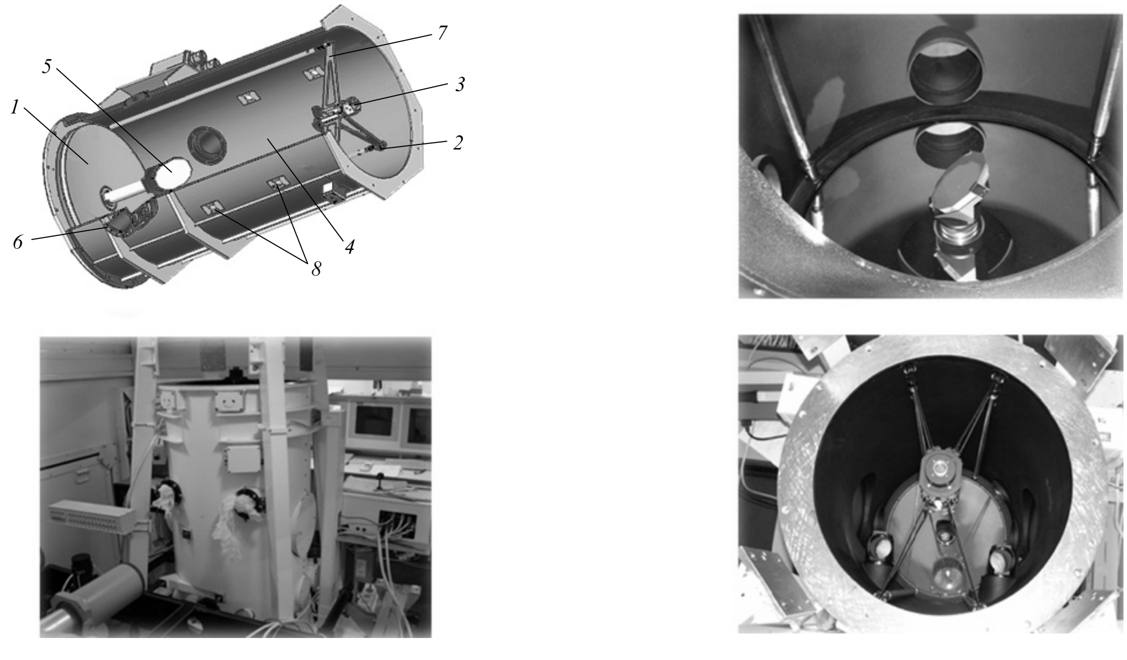


Figure 8. Focusing telescope for the beam control system: (*1*) main mirror; (*2*) secondary mirror; (*3*) refocusing mechanism; (*4*) telescope casing; (*5*) tip-tilt mirror; (*6*) radiation introduction channel; (*7*) spiders; (*8*) windows for installation of adjusting elements.

of the telescope in the form of a meniscus of diameter 502 mm, fastened to the frame and serving simultaneously as the base of the entire telescope, is mounted on an optical table. The reflecting objective is afocal and constructed according to the Mersenne scheme. The secondary lens module is fastened to the casing with the help of a suspension which ensures a displacement of this module along the optical axis relative to the casing under the action of temperature fields differing from the assembling temperatures.

Tuning of the focal length is carried out by moving the secondary mirror. The stability of positions of mirrors in the stationary state is ensured by thermal stabilisers made of Invar rods. The refocusing region extends from 500 m to infinity upon a displacement of the mirrors in the range 0 – 5 mm to within ±0.05 mm.

Target tracking systems include a television system with a wide field of view, a thermal imager and a pointing TV camera. The TV system with a wide field of view is intended for tracking the target and passing the information to the positioning system. The image is recorded by an array with 1024×1024 pixels. The camera has an angle of the field of view equal to 7°, and hence its position depends almost entirely on design considerations. The TV system with a wide field of view is usually fixed to the casing of the scanner or the telescope. The axis of the system is made coincident with the telescope axis to within 1 mrad by using an aligning-carrier unit.

The TV system makes it possible to visualise the tracking region under poor illumination. The pointing TV camera is mounted on the optical axis of the telescope in a zone free from the main radiation. The focusing telescope itself may serve as the objective of the TV camera. This solves the problem of aligning the axes of the camera and the telescope, and reduces the wind effect. However, problems associated with the rotation of images may arise when an external scanner is used.

A 512×512 array is used for registering the laser radiation spot on the target surface. The field of view of the pointing system is 7 mrad, which is at least double the angular size required in the region of application.

The beam direction can be controlled in two ways (Fig. 9) [15, 16], namely, by turning the mirrors mounted behind the stationary telescope (coelostat or heliostat), and by rotating the telescope fixed to a special suspension.

Each technique has its own advantages and drawbacks, the size of the laser aperture and the diameter of the main telescopic mirror being the critical parameters (Table 2).

The ultimate choice is made on the basis of the entire body of requirements imposed on the mobile complex, but the basic tendencies generalised in Table 2 can be used to obtain preliminary estimates.

Since the development of high-power lasers began with the longwave systems necessitating the use of large-diameter telescopes, it seemed reasonable to use rotating telescopes in control systems. However, the diffraction limit of the COIL is much lower than for DF lasers, and hence it is sufficient to use the beam extraction elements of diameter half a metre or less. In such situations, a stationary telescope with a scanner seem to be quite promising.

The airborne optical elements experience considerable stresses during flight, impacts and vibrations during the operation with such systems. For example, the acceleration for terrestrial systems may attain values up to $6g$, while its value for airborne and space lasers may be even higher. In this case, it is especially important to maintain the precision in the actuated parts of the telescope or the scanner, which are the bulkiest elements of the structure.

The pointing systems are used to control the laser beam parameters for ensuring the desired precision in the orientation of laser radiation and its intensity at the target. The elements of the system are shown in the optical diagram of the system of formation and control of laser radiation (Fig. 10). The basic elements of the system are the tip-tilt mirror and an adaptive mirror for wavefront adjustment (correction of aberrations).

The tip-tilt mirror is intended for pointing the laser beam at the target. In the general case, the laser with the resonator and the focusing telescope can be mounted on separate platforms. A dynamic tilting of the platforms and the ensuing unacceptable declension of the axis of the pointing beam, which is a part of the system, are possible in this case. The tip-tilt mirror ensures dynamic stability of the laser beam direction, compensating possible departures upon its extraction from the resonator and coinciding the laser beam with the line of sight of the telescope.

The tip-tilt mirror is controlled with the help of piezoceramic holder attachment unit from the signals of the control system analysing the data from the TV camera for pointing the line of sight of the telescope. The use of the tip-tilt mirror stabilises the beam direction to within a few microradians.

Adaptive mirror for wavefront correction. An adaptive mirror is used for correction of aberrations. The actual pattern of aberrations is registered by two wavefront sensors one of which is intended for analysing the laser radiation wavefront (Hartman sensor) and the other for the wavefront reflected from the operational zone. All information about aberrations of the wavefront is jointly processed by the control system. The wavefront is corrected at the adaptive mirror through microdisplacements of its surface, which compensate for the overall aberrations measured by both sensors [17, 18].

6. Propagation of laser radiation over operative distances

The efficiency of laser energy transfer is determined by the following factors:

(a) absorption and scattering;

(b) molecular composition of atmosphere;

(c) parameters and concentration of the atmospheric aerosol;

(d) the effect of turbulence;

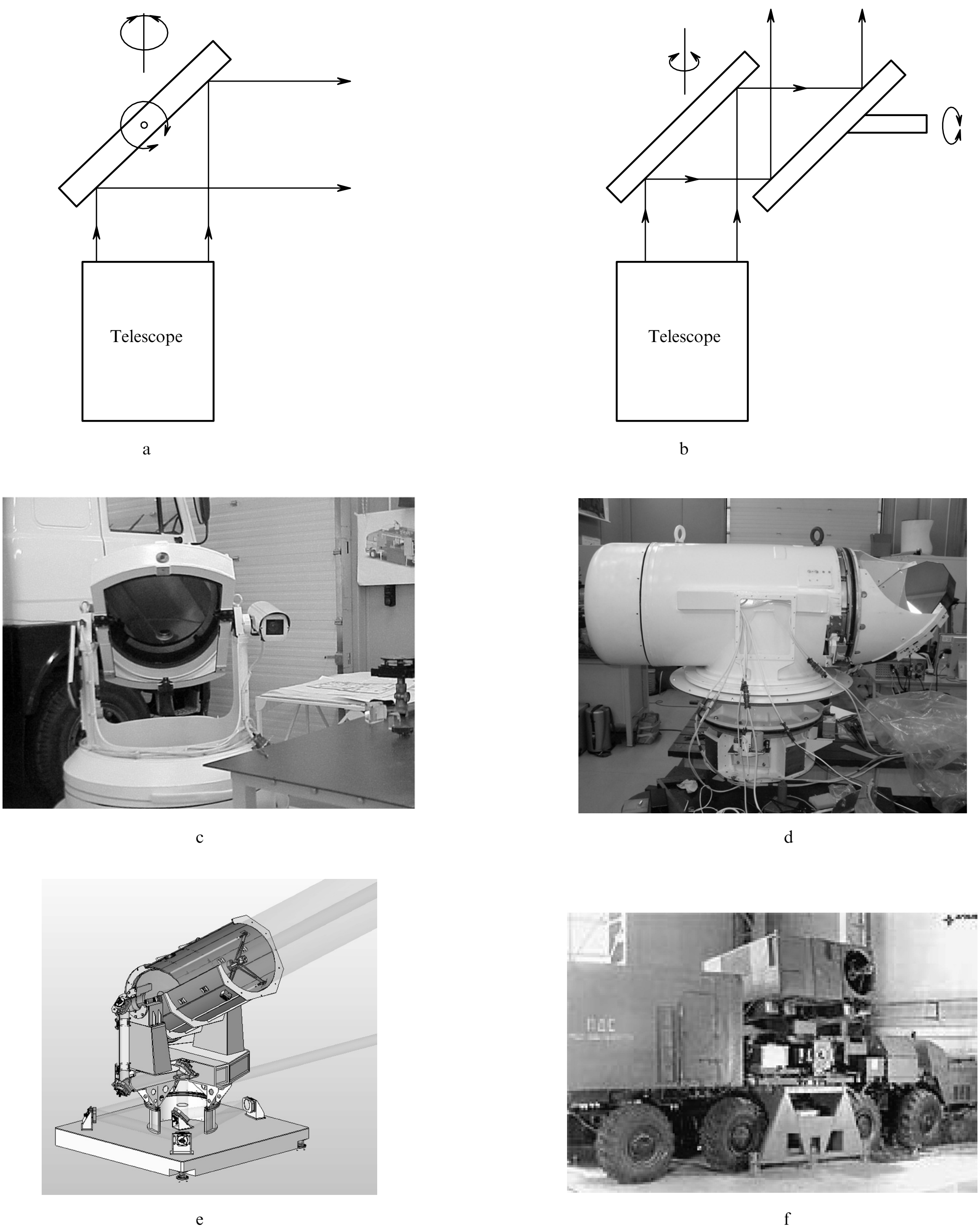
(e) diffraction-limited divergence;

(f) dynamic error in guidance control; and

(g) thermal selfaction of the beam.

Thermal blooming of the laser beam for a rapidly moving target (and/or carrier!) does not play a significant role even if the density of laser radiation approaches the threshold values.

The progress in the elemental base of the guidance systems (torque engines, optical gyroscopes, signal processors, as well as software and hardware systems for simulating and controlling the motion) make it possible to construct single-loop beam control systems with such a low *dynamic guidance error* that it no longer serves as a limiting factor. Hence a competition between laser sources is determined at



a b c d e f

Figure 9. Different versions of the scanning module and target monitoring system. Schemes of heliostat (a) and coelostat (b) with diameters of 0.5 m, and their outward appearance (c, d, respectively). Telescope in a biaxial gimbal (∅0.8 m) (e), and a mobile system for adaptive formation and precision control of a high-power laser beam [16] (f).

present by three factors: absorption and scattering in atmosphere, turbulence and diffraction divergence.

The total divergence θ is the sum of the diffraction divergence θ_d and the turbulence divergence θ_t, and takes into account the beam quality β [19]:

$$\theta^2 = \theta_\mathrm{d}^2\beta^2 + \theta_\mathrm{t}^2. \tag{8}$$

The transmission of atmosphere is defined as

$$T_\mathrm{a} = \exp(-\Gamma L), \tag{9}$$

where L is the distance from the object, and Γ is the atmospheric extinction coefficient equal to the sum of molecular and aerosol contributions to absorption and scattering.

Turbulence is defined by the expression

$$\theta_\mathrm{t} = 2 \times 2.016\lambda^{-0.2}\left(C_n^2 L\right)^{0.6}. \tag{10}$$

Table 2.

Type of system	Advantages	Drawbacks
Deflecting mirror behind the beam-shaping telescope (coelostat, heliostat)	Separation of laser-beam shaping and control functions; apertures of any shape are suitable; minimum number of high-loaded transport optics mirrors for introducing radiation into telescope; absence of restrictions on telescope height	Stringent requirements on the accuracy of positioning of controllable mirror (the required angular precision of mirror positioning is twice as high as the precision of laser beam guidance); large size of plane mirrors; stringent requirements on deflecting mirror
Rotating beam-shaping telescope	Wide angular range; moderate requirements on the accuracy of positioning of mirror systems for introducing radiation into telescope and hence on their vibration; rich technological experience of development of such systems	Large number of additional high-loaded mirrors for introducing radiation into telescope; large moment of inertia emerging during rotation of telescope; necessity of using only circular apertures

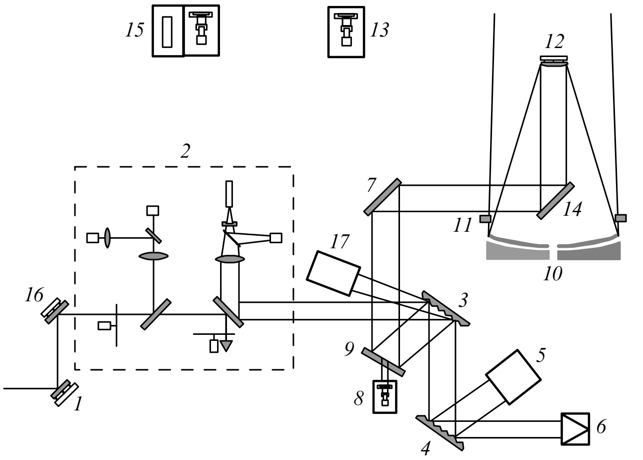


Figure 10. System of laser beam formation and control with a wavefront corrector: (*1*) mirror for introduction of a beam into the beam-formation system; (*2*) preliminary alignment block; (*3*) beam-splitting grid; (*4*) attenuating grid; (*5*) wavefront sensor; (*6*) power meter; (*7*) deflecting mirror of optical hinge; (*8*) pointing TV system; (*9*) mirror with a central orifice; (*10*) main mirror of the telescope; (*11*) autocollimating mirror; (*12*) secondary mirror of the telescope; (*13*) wide field of view TV system; (*14*) tip-tilt mirror; (*15*) rangefinder; (*16*) adaptive mirror; (*17*) wavefront sensor of radiation reflected from the operation zone.

Here C_n^2 is the structural constant of the atmosphere. The value of C_n^2 is determined by the altitude, time of the day and the geographical position [20].

The effect of all the atmospheric parameters attenuating laser radiation diminishes rapidly upon an increase in the distance from the Earth's surface. A combination of these factors depends strongly on the path geometry. We shall consider nine types of paths (Table 3).

On *horizontal sea-level beam paths*, the key role is played by the state of atmosphere and the weather, which determine the radiation attenuation. The advantage in the diffraction divergence possessed by shortwave lasers is lost on these paths on account of a strong dependence on the weather conditions.

Moreover, the 'turbulent' component of the divergence angle depends on the wavelength as $\lambda^{-1/5}$, while the diffraction divergence depends linearly on the wavelength. This means that under conditions of strong turbulence for small distances, lasers with longwave radiation have a definite advantage. For example, for low concentration of moisture, high turbulence and the presence of mist ($C_n^2 = 10^{-13}$, winter season, hazy conditions), the irradiance of the target by a CO_2 laser is even higher than by a cw CL.

However, the ever-increasing potentialities of adaptive optical systems capable of compensating the effect of atmospheric turbulence open new horizons for wavefront correction for a short-wavelength COIL also.

For *paths tilted* at angles starting from 20° – 30°, the effect of the terrestrial layer becomes insignificant and hence the advantage of shortwave lasers becomes more and more perceptible. For large distances, the limiting possibilities of radiation concentration in modern adaptive optics are determined only by diffractional divergence.

On *long vertical paths*, the diffractional divergence also plays an important role.

The surface-to-space type paths depend on weather; hence laser sources should be rather mounted in regions with a good astroclimate.

The situation changes radically for laser sources even at an altitude of 1 – 2 km above the sea level. In this case, the concentration of aerosol decreases sharply and atmospheric turbulence no longer affects the passage of the beam. For air-to-air and air-to-space paths, the dependence on weather

Table 3.

Target	Position of source		
	Surface	Air	Space
Surface	Surface-to-surface (horizontal near-surface paths)	Air-to-surface	Space-to-surface
Air	Surface-to-air (the source is located at sea level, the target is at an altitude of 1 – 2 km or more, angle of inclination of the path to the horizontal is more than 20°)	Air-to-air	Space-to-air
Space	Surface-to-space (vertical paths of more than 200 km, the source is located at sea level)	Air-to-space	Space-to-space

does not exist. The main problem in this case is the dynamic guidance error emerging due to strong vibrations of the airborne platform and turbulent flow about the output windows of the laser system (Fig. 11). The surface air layer does not have a baneful influence on radiation propagation even for paths like *air-to-surface* and *space-to-surface*.

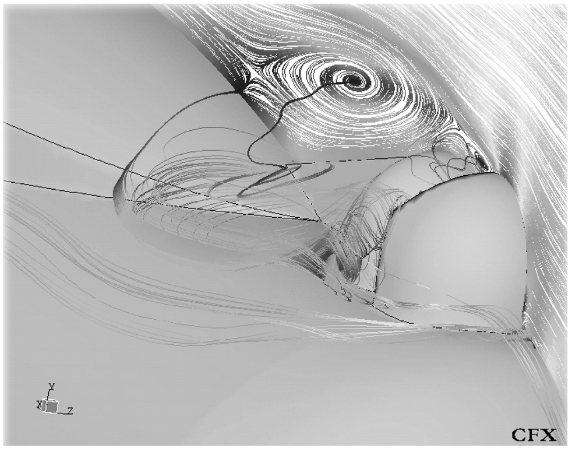


Figure 11. Pattern of turbulent flow about the output window of the airborne laser beam control system.

Indeed, the only problem in the path of propagation of high-power laser radiation is due to the surface air layer of a few hundred metres thickness. Thus, laser systems with comparatively large wavelengths may be advantageous only on horizontal near-surface paths. However, being strongly weather-dependent, a laser system working on horizontal near-surface paths may not be able to ensure the desired result at a certain instant of time irrespective of the type of laser on which it is based. This circumstance rules out the applicability of lasers on horizontal near-surface paths.

The ongoing progress aimed at improving the elemental base of the positioning systems (torque engines, gyroscopes, signal processors, as well as software and hardware systems for simulating and controlling the motion) as well as adaptive optical systems must also be taken into account. The advances made in these fields allow us to construct a single-loop beam control system instead of the two-loop systems used earlier for the same purpose. These systems have such a low dynamic error that this factor, like many other factors that seemed so important previously, is no longer considered as a serious obstacle in actual practice.

7. Parameters and potentialities of cw CL carriers

The potentialities of any new system are determined essentially by its ability to harmonise with the existing systems. For a mobile system, this means the possibility of its transportation and deployment on conventional carriers.

Preliminary design estimates of the possible mass and size parameters of autonomous mobile cw CL show that lasers with a power of several tens of kilowatts, together with the main technological systems and a certain stock of components, meet the current transport standards. This permits the deployment of lasers on existing terrestrial and air carriers used for transportation and operation of large-size equipment intended for various applications.

The new military vehicle KAMAZ-6350 ‘MUSTANG’ with an 8 × 8 wheel arrangement meets all the service requirements in urban and field conditions. The design of the vehicle envisages hooking-up of a self-sufficient container to the chassis under standard conditions of anchoring. For such a version of loading, the dimensions of the equipment being installed match with the size of a 20-foot container with a maximum load capacity of 10 tons. If required, the equipment can be installed on several trucks, e.g., in the case of a 50-kW COIL with a cryoadsorption system for recovering the waste gases (Fig. 12).

Figure 12. Assembly of a 50-kW COIL with a cryoadsorption recovery system and the beam control system.

Among the existing transport aircraft, we can mention the Russian helicopter MI-26 with the highest carrying capacity in the world, and the most popular freight carrier IL-76. These aircraft can accommodate onboard equipment whose size and weight are several times larger than the analogous characteristics of the equipment carried on land-based transport.

8. Experience of mobile laser system designing

While the projects for large cw CLs for installation on skylabs (HF laser) or aircraft (COIL) carriers have been discussed extensively, the details of development of smaller samples are much more scarce. However, the technological advances made so far promise considerable progress in this direction also.

In the familiar design of the power module of a self-contained mobile DF cw CL with an output laser beam power of 300 kW, it can be seen that the use of a high-efficiency fuel (hydrogen peroxide) leads to lower mass and size characteristics of the pressure recovery system. For example, a module of size 9 m × 3.2 m × 3 m and a total weight of 14 tons makes it possible to install the entire power section of the laser and the PRS on the chassis of a truck with 6 × 6 wheel arrangement, which is capable of carrying on a semitrailer a standard 40-foot container weighing up to 20 tons [9].

A similar semitrailer is used for mounting the power module of a 50-kW COIL (Fig. 13). The vacuum equipment of the cryoadsorption system used for recovering waste

Figure 13. Laser systems on ground-based mobile carriers.

gases increases the size of the power module as compared to the high-pressure PRS of a DF laser. It is the volume of the cryoadsorber that restricts the laser power (for an identical total operation time of 50 s). The advantage of this system is that there is no need to replenish the chemical components. The resonator of the laser has independent vibrationally isolated supports ensuring a stability of angular and spatial positions of mirrors under vibrations.

The main part of the system of laser beam formation and control is a mirror telescope with a rotating mechanism installed on a separate carrier, which also carries the dynamic stabilisation device and the adaptive optical system. The power supply to the system of formation and control is a separate self-contained generator to reduce the load on the dynamic stabilisation device.

The size of the freight bays of modern heavy-duty helicopters and aeroplanes (with not even the highest carrying capacity) is larger than even for large terrestrial carriers. For example, a 50-kW COIL can be loaded in the freight bay (of size $12\ \mathrm{m} \times 3.2\ \mathrm{m} \times 3\ \mathrm{m}$) of a MI-26 helicopter.

However, the engines of the aircraft cannot be shut down even for a short period of lasing. Hence, apart from the problems of turbulent wake, vibrations of the helicopter or aeroplane structure become a serious menace. The vibration level in these machines is much higher than in terrestrial systems, and hence the technical problems of ensuring a reliable operation of the system of formation and control of laser radiation increase manifold. These problems have already been solved successfully in the beginning of 1980s for a longwave CO_2 gas-dynamic laser. There is no doubt that these problems will also be overcome under the ABL project for a COIL mounted onboard an aircraft (or other carriers when required).

Laser systems mounted on spaceships are a matter of foreseeable future. The space applications of COILs have the most favourable prospects. This is the only one of the known high-power lasers that does not require heat removal from the structure which is a serious obstacle in the application of space systems based on high-temperature cw CLs, and even solid-state lasers [21].

The deployment of cw CLs in space removes the most ‘awkward’ problem of applying PRS for the recovery of waste gases. The traction force resulting from the discharge of these gases from the laser is compensated by the geometry of the structure. The heavy-duty Russian rocket-carriers ‘Proton’ are quite capable of launching large sections of lasers into orbit, and the scale of installation work in orbit during the construction of sky-labs should not pose any serious problems in assembling of cw CLs in space.

9. Conclusions

The experience of designing and implementing new technologies is indicative of the long duration and high cost of each stage of development, and makes it imperative to lower the risks involved in making incorrect decisions at the earliest stage of implementation of the projects.

Most of the technical problems in the implementation of specific projects of autonomous mobile cw CLs can be solved due to technological advances in the field of laser beam generation made during the last decade and the rapid progress in the development of the element base for beam pointing systems and adaptive optics for correcting the wavefront aberrations as well as modification of the software. Active research is being carried out in several directions and some of the projects are in the trial stage.

New concepts concerning the application of high-power laser systems leading to a decrease in their power and size may emerge in near future.

Global changes in international relations culminating in the formulation of new goals and new tasks may play an important role in variation and diversification of the potential targets of military laser systems. This inevitably makes the problem of ensuring mobility and self-sufficiency of such systems even more acute.

Acknowledgements. The author sincerely thanks his colleagues from ‘Laser Systems’, whose talent and dedication have contributed towards the creation of new technologies. Special thanks are due to A.V. Savin, D.N. Vasiliev, I.M. Evdokimov, and V.M. Malkov for helpful remarks and fruitful discussions in the course of preparation of the manuscript.

References

1. Boreisho A.S., Leonov A.F., Malkov V.M., Militsyn Yu.A., Moshkov V.L. *Invited Lecture at AIAA-1993 Plasmodynamics & Lasers Conf.* (Orlando, 1993) FL/ AIAA-Paper 93-3166.
2. Didyukov A.I., Kulagin Yu.A., Shelepin L.A., Yarygina V.N. *Kvantovaya Elektron.*, **16**, 892 (1989) [*Sov. J. Quantum Electron.*, **19**, 578 (1989)].
3. Boreysho A.S., Evdokimov I.M., Vasiliev D.N., Malkov V.M., Savin A.V., Strakhov S.Yu., Trilis A.V. *Proc. SPIE Int. Soc. Opt. Eng.*, **5120**, 336 (2002).
4. Boreysho A.S., Malkov V.M., Savin A.V., Vasiliev D.N., Evdokimov I.M., Trilis A.V., Strakhov S.Yu. *Kvantovaya Elektron.*, **33**, 307 (2003) [*Quantum Electron.*, **33**, 307 (2003)].
5. Boreysho A.S., Vasiliev D.N., Grenishen D.M., Evdokimov I.M., Zagidullin M.V., Nikolaev V.D., Trilis A.V. Patent No. 2182038 dated 10.05.2002 of the Russian Federation.
6. Boreysho A.S., Vasiliev D.N., Evdokimov I.M., Malkov V.M., Savin A.V., Trilis A.V. *Proc. SPIE Int. Soc. Opt. Eng.*, **5479**, 42 (2004).
7. Dauty J. *Aerokosm. Tekh.*, (2), 53 (1990).
8. *Pressure Recovery Systems (Technical Proposal)* (St. Petersburg: SIE 'Laser Systems', 2000).
9. Bashkin A.S., Beznozdrev V.N., Pirogov N.A., in *Proceedings of the Scientific-Technical Conference held at SIC 'Energomash'* (Khimki, 2001) p. 15.
10. Malkov V.M., Boreysho A.S., Savin A.V., Kiselev I.A., Orlov A.E. *Teplofiz. Aeromekh.*, **8**, 625 (2001).
11. Boreysho A.S., Kiselev I.A., Orlov A.E., Savin A.V., Shalimov V.P., Malkov V.M., Khailov V.M. *Teplofiz. Aeromekh.*, **8**, 605 (2001).
12. Hefer R. *Kriovakuumnaya tekhnika* (Cryovacuum Technology) (Moscow: Energoatomizdat, 1983).
13. Boreysho A.S., Vasiliev D.N., Evdokimov I.M., Zagidullin M.V., Ivanov V.I., Savin A.V., Smirnov A.V. Patent No. 2226622 dated 05.08.2002 of the Russian Federation.
14. Boreysho A.S., Morozov A.V., Savin A.V., et al. Patent No. 2248076 dated 23.12.2002 of the Russian Federation.
15. Boreysho A.S., Chakchir S.Ya., Konyaev M.A., Konovalov K.A., Savin A.V. *36th AIAA Plasmadynamics and Lasers Conf.* (Westin Harbour Castle, Toronto, Ontario, Canada, 2005).
16. www.raspletin.ru/production/laser/default.php
17. Alikhanov A.N., Berchenko E.A., et.al. *XI Joint Intern. Symp. «Atmospheric and Ocean Optics. Atmospheric Physics»* (Tomsk, IAO SB RAS, 2004) p. 41.
18. Kudryashov A.V., Shaml'hausen V.I. *Opt. Eng.*, **35** (11), 3064 (1996).
19. Tatarskii V.I. *Rasprostranenie voln v turbulentnoi atmosfere* (Propagation of Waves in a Turbulent Atmosphere) (Moscow: Nauka, 1967).
20. Lamberson S.E. *Proc. SPIE Int. Soc. Opt. Eng.*, **4184**, 1 (2001).
21. Scott W.B. *Aviation Week & Space Technology*, June 7, 2004, pp 57 – 59.