Journal of Russian Laser Research, Volume 23, Number 3, 2002

A COMPACT PULSED HF LASER BASED ON AN AUTO-WAVE PHOTON-BRANCHED CHAIN REACTION

R. R. Letfullin

Samara Branch of the P. N. Lebedev Physical Institute, Russian Academy of Sciences, Novosadovaya Str. 221, Samara 443011, Russia
e-mail: renat@fian.smr.ru

Abstract

Huge energy gain is detected theoretically in a pulsed chemical laser-amplifier based on a photon-branched chain reaction initiating in a gaseous disperse medium composed of H_2–F_2–O_2–He and Al particles by focused external infrared radiation. It is shown that this effect is observed due to the other optical effect of diffractive multifocal focusing of the input radiation on a certain type of bicomponent optical system coupled structurally with the input mirror of an unstable telescopic laser cavity. Such a relatively simple bicomponent diffraction system, consisting of two plane screens with circular apertures on a given optical axis, enables one to focus the input beam without using classical refraction elements such as lenses and prisms. The focusing of the input signal ensures the minimization of the initially excited volume of the laser active medium and the appropriate sharp lowering of the necessary energy of the input pulse up to $\sim 10^{-6}$ J. This enables the laser system to reach a high value of the energy gain of 10^9. The huge laser energy gain allows us to use a master oscillator in the form of a small microjoule laser powered by an accumulator, and consequently makes it possible to construct a completely self-contained compact pulsed chemical HF-laser.

Keywords: diffractive focussing of radiation, bicomponent diffracting system, chemical lasers and amplifiers, photon-branched chain reaction, auto-wave amplification regime, self-contained compact laser.

1. Introduction

All the pulsed chemical lasers created to the present time have a common deficiency – the necessity to have an external power source for initiation of the reaction. The ideal chemical laser is a self-contained source of coherent radiation, for which no additional energy source is required, or such energy is insignificantly small.

The metastable mixture of reactants used in pulsed chemical lasers is removed from its equilibrium condition by an external initiating effect. Unfortunately, the energy of such an external source is comparable to the energy of the output laser radiation, which limits the scaling of the laser. The creation of pulsed chemical lasers working without external power sources, i.e., self-contained chemical lasers of an impulse operation, would be a radical improvement over existing systems.

The solution of this problem for the pulsed chemical HF-laser can be found within the framework of a photon-branched chain reaction (PBCR) of fluorine with hydrogen in a two-phase active medium [1–8], i.e., a medium containing the working gas and ultradispersed passive particles of metal. These particles are evaporated under the action of an external laser radiation, resulting in the formation of free metal

Preprint No. 6 of the P. N. Lebedev Physical Institute, Moscow (2001).

 1071-2836/02/2303-0252$27.00

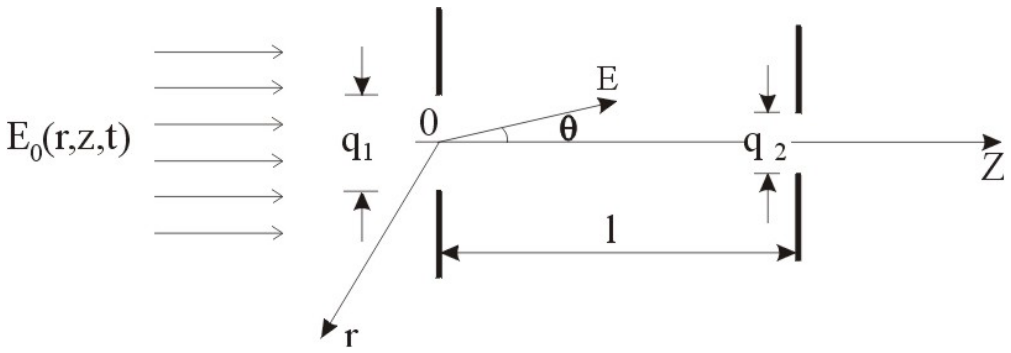

Fig. 1. Geometry of the bicomponent diffraction system consisting of two definitive plane screens with axial circular apertures of diameters q_1 and q_2, where L is the distance between the screens.

atoms and the ignition of a PBCR. Numerical studies and experiments first justified the idea. Recent experiments [9] have demonstrated the stability of a fluorine-hydrogen mixture with an injected highly-dispersed metal component (Al particles with radius $r_0 = 0.2 - 1$ μm in a concentration $N_0 \sim 10^5$ cm^{-3}) against spontaneous self-inflammation, showing that a chain reaction can be initiated by evaporating such particles by IR laser radiation. The kinetic models and wave optics of the laser have been used for calculations on both oscillators and amplifiers based on the PBCR [1–8].

A PBCR is accompanied by directional energy evolution, and under some conditions such a reaction is capable of self-propagation along a certain direction. This property has made it possible to propose in [2] a new dynamic regime of amplification of laser radiation through a multipass optical scheme. In [2–8] it has been shown that a laser-chemical reaction is initiated by an input pulse in a narrow paraxial cylindrical zone and then spreads spontaneously throughout the volume of the active medium as self-supporting cylindrical zones of photon branching. The self-supporting cylindrical zones of photon branching formed by a multipass unstable telescopic cavity can be considered as amplification cascades (zones) nested within each other. This auto-wave regime makes it possible to achieve a much stronger ($\sim 10^3$) [2] amplification of the energy of a pulse compared with the single-pass regime (≤ 10) [19].

The possibility of the energy gain increasing in an auto-wave amplification mode is far from being realized. In [3–8], the first attempt at reaching a superhigh value of the energy gain was undertaken with focusing of the initiating wave due to its diffraction on the input aperture which couples the laser amplifier to the master oscillator. Recently we have shown [10–18] for the first time that when a plane or spherical wave illuminates a certain type of bicomponent optical system, consisting of two plane screens with circular apertures on a given optical axis (see Fig. 1), a diffractive multifocal focusing of radiation (DMFR) effect can appear. Here, the diffraction picture in the focal planes represents the circular nonlocal bands of a Fresnel zone with a bright narrow peak at the center, whose intensity can exceed by six to ten times the value of the incident wave intensity. The detected optical effect is observed over a wide range of wavelengths, $\lambda = (0.4 - 10^3)$ μm, and ratios of the aperture diameters $d_1 \geq 2d_2 = (25 - 1000)\lambda$, and it is also insensitive to changes in the medium of the wave propagation. For large diameters of the input holes, $d_1 = 2d_2 > 100\lambda$, or for wavelengths in the radiofrequency region of the spectrum, the bicomponent diffraction system acts like a long-focus lens with a high-intensity Gaussian distribution of radiation, at times exceeding the initial intensity, persisting at large distances [$z = (1 - 100)$ cm] from the diffraction system [10–18].

In the present paper we offer to initiate high-power HF-lasers and amplifiers based on a PBCR by an

external power radiation, which is focused by the proposed bicomponent diffraction system. The effect of diffraction focusing ensures the minimization of the initially excited volume of a laser active medium up to some value V_{in} and appropriate sharp lowering of the necessary energy of the input pulse E_{in}. This enables the HF-laser system to reach a large value of the energy gain that allows us to use a master oscillator in the form of a small laser powered by an accumulator, and consequently, makes it possible to construct a completely self-contained pulsed chemical HF-laser. Thus, the giant energy amplification under the condition of the external input signal focusing gives the pulsed chemical HF-laser two important properties – autonomy and compactness. This present work is devoted to the analysis of these properties. In regard to the compactness, we shall examine the possibility of linear size minimization of the main laser units: cavity, master oscillator, power source, system of gas cylinders, etc. We carry out a numerical optimization of the active two-phase medium parameters and examine the characteristics of the focused external signal and geometric sizes of the unstable telescopic cavity, with the purpose of reaching the limiting-high-output energy in a pulsed HF-laser system of rather small size in a self-contained generation regime.

2. Laser-Chemical Kinetics of the Laser-Amplifier Based on a Photon-Branched Chain Reaction

Below we present the kinetic scheme describing the basic processes occurring in an active mixture of a HF-laser with finely-dispersed aluminum particles, along with the elementary process rate constants [1, 8]. Under the action of external IR laser radiation of a certain intensity, the aluminum particles are evaporated

$$\mathrm{Al}_s + n\hbar\omega \rightarrow \mathrm{Al}_g, \tag{1}$$

where n is the number of photons with the energy $\hbar\omega$ and the index s refers to the solid phase and g to the gaseous phase.

The metal vapor thus formed reacts with fluorine to yield the free F atoms by the reaction

$$\mathrm{Al}_g + \mathrm{F}_2 \xrightarrow{k_{13}} \mathrm{AlF} + \mathrm{F}, \tag{2}$$

$$k \approx 10^{15}\ \mathrm{cm}^3/\mathrm{mole{\cdot}s},$$

where k is the rate constant of the reaction. The free fluorine atoms (active centers) initiate the chain reaction:

$$\mathrm{F} + \mathrm{H}_2 \xrightarrow{\alpha_v k_1} \mathrm{HF}(v) + \mathrm{H}_2, \tag{3}$$

$$k_1 = 1.62 \cdot 10^{14} \exp(-1600/RT)\ \mathrm{cm}^3/\mathrm{mole{\cdot}s},$$

$$\alpha_1 = 0.17,\ \alpha_2 = 0.56,\ \alpha_3 = 0.27.$$

$$H + F_2 \xrightarrow{\beta_v k_2} \mathrm{HF}(v) + \mathrm{F}, \tag{4}$$

$$k_1 = 1.2 \cdot 10^{14} \exp(-2400/RT)\ \mathrm{cm}^3/\mathrm{mole{\cdot}s},$$

$$\beta_1 = 0.04,\ \beta_2 = 0.04,\ \beta_3 = 0.08,\ \beta_3 = 0.08,\ \beta_4 = 0.12,\ \beta_5 = 0.26,\ \beta_6 = 0.33,\ \beta_7 = 0.13.$$

The kinetic scheme includes also the following reactions:
Recombination of atoms:

$$\mathrm{F} + \mathrm{F} + \mathrm{M} \xrightarrow{k_3} \mathrm{F}_2 + \mathrm{M}, \tag{5}$$
$$k_3 = 10^{14} T^{0.5} \text{ cm}^6/\text{mole}^2\cdot\text{s};$$

$$\mathrm{H} + \mathrm{H} + \mathrm{M} \xrightarrow{k_4} \mathrm{H}_2 + \mathrm{M}, \tag{6}$$
$$k_4 = 10^{18} T \text{ cm}^6/\text{mole}^2\cdot\text{s};$$

$$\mathrm{H} + \mathrm{F} + \mathrm{M} \xrightarrow{k_5} \mathrm{HF} + \mathrm{M}, \tag{7}$$
$$k_5 = 10^{18} T \text{ cm}^6/\text{mole}^2\cdot\text{s};$$

Vibrational-transitional relaxation of excited HF molecules:

$$\mathrm{HF}(v) + \mathrm{M} \xrightarrow{k_6^M} \mathrm{HF}(v-1) + \mathrm{M}, \tag{8}$$

$$\begin{aligned}
k_6^{\mathrm{M}} &= v k_{1,0}^{\mathrm{M}}, \\
k_{1,0}^{\mathrm{F}} &= 9\cdot 10^8 T^{1/3} \text{ cm}^3/\text{mole}\cdot\text{s}, \\
k_{1,0}^{\mathrm{H}} &= 64.1\, T^{3.51} \exp(3946/T) \text{ cm}^3/\text{mole}\cdot\text{s}, \\
k_{1,0}^{\mathrm{HF}} &= (5\cdot 10^7 T^{1.3} + 10^{16} T^{-1.43}) \text{ cm}^3/\text{mole}\cdot\text{s}, \\
k_{1,0}^{\mathrm{F_2}} &= 8\cdot 10^{-4} T^4 \text{ cm}^3/\text{mole}\cdot\text{s}, \\
k_{1,0}^{\mathrm{H_2}} &= 1.7\cdot 10^6 T^{1.77} \text{ cm}^3/\text{mole}\cdot\text{s};
\end{aligned}$$

Vibrational-vibrational energy exchange:

$$\mathrm{HF}(v) + \mathrm{HF}(v') \xleftrightarrow{k_7} \mathrm{HF}(v+1) + \mathrm{HF}(v'-1), \tag{9}$$

$$\begin{aligned}
k_7 &= (v+1) v' k_{0,1;1,0}^{\mathrm{HF-HF}}, \\
k_{0,1;1,0}^{\mathrm{HF-HF}} &= 1.5\cdot 10^{13} \text{ cm}^3/\text{mole}\cdot\text{s};
\end{aligned}$$

$$\mathrm{HF}(v) + \mathrm{H_2}(v') \xleftrightarrow{k_8} \mathrm{HF}(v+1) + \mathrm{H_2}(v'-1), \tag{10}$$

$$\begin{aligned}
k_8 &= (v+1) v' k_{0,1;1,0}^{\mathrm{HF-H_2}}, \\
k_{0,1;1,0}^{\mathrm{HF-H_2}} &= (k_{1,0;0,1}^{\mathrm{HF-H_2}}) \exp\left[(\theta_v^{\mathrm{H_2}} - \theta_v^{\mathrm{HF}})/T\right] = 9\cdot 10^{11} \text{ cm}^3/\text{mole}\cdot\text{s};
\end{aligned}$$

Vibrational-transitional relaxation of excited $\mathrm{H_2}$ molecules:

$$\mathrm{H_2}(v) + \mathrm{M} \xleftrightarrow{k_9^{\mathrm{M}}} \mathrm{H_2}(v-1) + \mathrm{M}, \tag{11}$$

$$k_9^{\mathrm{M}} = v k_{1,0}^{\mathrm{H_2-M}},$$

$$k_{1,0}^{\mathrm{H_2-H_2}} = 10^{-3} T^{4.3},$$

$$k_{1,0}^{\mathrm{H_2-HF}} = k_{1,0}^{\mathrm{H_2-H}} = k_{1,0}^{\mathrm{H_2-F}} = k_{1,0}^{\mathrm{H_2-F_2}} = k_{1,0}^{\mathrm{H_2-Ar}} = 2.5\cdot 10^{-4} T^{4.3};$$

Chain termination on oxygen:

$$\begin{aligned} &\mathrm{H} + \mathrm{O_2} + \mathrm{M} \xrightarrow{k_{10}} \mathrm{HO_2} + \mathrm{M}, \\ &k_{10} = 10^{22}/T^2 \ \mathrm{cm^6/mole^2 \cdot s}; \end{aligned} \tag{12}$$

Thermal dissociation:

$$\mathrm{F_2} + \mathrm{M} \xrightarrow{k_{11}} 2\mathrm{F} + \mathrm{M}, \tag{13}$$

$$k_{11} = 1.38 \cdot 10^{13} \exp(-31120/RT) \ \mathrm{cm^3/mole \cdot s};$$

$$\mathrm{H_2} + \mathrm{M} \xrightarrow{k_{12}} 2\mathrm{H} + \mathrm{M},$$

$$k_{12} = 8.1 \cdot 10^{16} \exp(-103240/RT) \ \mathrm{cm^3/mole \cdot s};$$

$$\mathrm{HF} + \mathrm{M} \xrightarrow{k_{13}} \mathrm{H} + \mathrm{F} + \mathrm{M}, \tag{14}$$

$$k_{13} = 1.13 \cdot 10^{19} T^{-1} \exp(-13400/RT) \ \mathrm{cm^3/mole \cdot s};$$

Stimulated emission of radiation:

$$\mathrm{HF}(v) + \hbar\omega_{v,v-1} \longleftrightarrow \mathrm{HF}((v-1) + 2\hbar\omega_{v,v-1}. \tag{15}$$

The chain branching process

$$\mathrm{H_2}(v) + \mathrm{F_2} \rightarrow \mathrm{H} + \mathrm{HF} + \mathrm{F} \tag{16}$$

is disregarded because it is slow on the time scale of the coherent radiation pulse duration.

3. Mathematical Model of a HF-Laser Based on a Photon-Branched Chain Reaction

The processes (1)–(16) are described by the relatively simple mathematical model of the HF-laser [1–8], which includes the most important physicochemical kinetic features [1] and wave electrodynamics of the laser [2–8]. This makes it possible to calculate the output energy of coherent radiation, the pulse duration, the electromagnetic field distributions of the coherent radiation inside and outside the cavity, the chemical and engineering efficiencies of the laser, and the structural parameters of HF-laser oscillators and amplifiers.

The initiation of a PBCR in an active medium of a H_2–F_2-laser-amplifier containing passivated fine aluminium particles covered by an oxide film with a thickness ∼5–10 nm occurs by the mechanism (1)–(16). The formation of active centers of the reaction chain, diffusing into the medium, is thus possible around each fine particle in the IR-laser radiation field. The distribution of free atoms in the active volume can become sufficiently homogeneous in a time τ_h, which is limited to the duration of the chemical laser process (∼1 μs), provided the condition $R_{\mathrm{av}} \leq 2R_{\mathrm{diff}}$ is satisfied. Here, R_{av} is the average distance between the particles, and $R_{\mathrm{diff}} \sim \sqrt{D\tau_h}$, where D is the diffusion coefficient of the active centers in the laser medium. This sets the lower limit to the required concentration of disperse particles as $N_0 \sim 1/R_{\mathrm{ev}}^3$.

The kinetic equation describing the formation of active centers of a chain can be written in the approximation of quasisteady-state concentrations of the F and H atoms:

$$\frac{dn_a}{dt} = 4\pi r_0^2 \frac{dr_0}{dt} \frac{\rho_0}{m_{\rm Al} N_{\rm A}} n_{\rm Al} + W - \beta n_a. \tag{17}$$

This reduces greatly the number of iterations required in the numerical integration of the system of kinetic equations at each spatial step h_z along the direction of propagation of the electromagnetic wave undergoing amplification. Here, $n_a = n_{\rm F} + n_{\rm H}$ is the total concentration of the active centers; r_0 and ρ_0 are the radius and density of Al particles; $n_{\rm Al}$ and $m_{\rm Al}$ are the concentration of atoms and atomic mass of aluminum; and $N_{\rm A}$ is Avagadro's number. Within the quasisteady-state approximation, the rates of both chain stages (3)–(4) are identical, i.e., $k_1 n_{\rm F} n_{\rm H_2} = k_2 n_{\rm H} n_{\rm F_2}$, i.e., where the balance between the concentrations of the fluorine and hydrogen atoms is fixed: $n_{\rm F}/n_{\rm H} = \mu$. The time necessary to establish quasistationary concentrations of the active centers over a broad interval of the initial parameters (pressure, mixture composition, initial temperature) is much less than the time of burn-out of combustible or loss of active centers of a chain in three-body collisions, which allows us to use the above approximation to account for the chemical kinetics.

The first term in Eq. (17), $4\pi r_0^2 \frac{dr_0}{dt} \frac{\rho_0}{m_{\rm Al} N_{\rm A}} n_{\rm Al}$, takes into account the nucleation of active centers of the chain as a result of the interaction of F_2 molecules with evaporated Al atoms. The second term, W, describes the formation of the active centers for the dissociation of molecules, and the last term, βn_a, is the rate of loss of the centers.

Laser heating and evaporation of the disperse component are described within the approximation of free molecular flow, which is valid for particles whose size does not exceed the mean free path of molecules in the laser mixture:

$$\begin{aligned} 4\pi r_0^2 \frac{dr_0}{dt} \rho_0 &= -\eta 4\pi r_0^2 \bar{V}_s(T_s) \rho_s(T_s)\,, \\ \frac{4}{3}\pi r_0^3 \rho_0 C_s \frac{dT_s}{dt} &= \sigma_{\rm abs} I - (T_s - T_g) \sum_{\rm M} C_{\rm M} 4\pi r_0^2 n_m \bar{V}_{\rm M}(T_g) + L_{\rm evap} 4\pi r_0^2 \frac{dr_0}{dt} \rho_0. \end{aligned} \tag{18}$$

Here, C_s and $L_{\rm evap}$ are, respectively, the specific heat and the heat of evaporation of aluminum; I is the radiation intensity inside the cavity; $\sigma_{\rm abs}$ is the cross section of absorption of laser radiation by an Al particle; T_s and T_g are the temperatures of the aluminum particles and the laser-active medium, respectively; $C_{\rm M}$, $\bar{V}_{\rm M}$, and $n_{\rm M}$ are, respectively, the molar specific heat, average velocity, and concentration of molecules of the $M^{\rm th}$ component of the laser mixture; η is the accommodation coefficient; $\bar{V}_s$ is the average velocity of the vapor molecules; and $\rho_s(T_s)$ is the saturated vapor density of aluminum at T_s.

Vibrational excitation of HF(v) molecules and their quenching can be described within the framework of the equivalent two-level scheme [1], where the many vibrational levels of HF(v) are simply replaced by two: an upper and a lower level with the population n_u and n_l, respectively. The power of the radiation generated by the $(u, j-1) \to (l, j)$ laser transition is then equal to the total power emitted as a result of all the vibrational transitions (j is the rotational quantum number). The equations for the populations n_u and n_l are

$$\begin{aligned} \frac{dn_u}{dt} &= W_u - \frac{P_L}{\hbar\varpi_{ul}} - G_{VT}^{\rm HF-M} - G_{VV}^{\rm HF-H_2}, \\ \frac{dn_l}{dt} &= W_l + \frac{P_L}{\hbar\varpi_{ul}} + G_{VT}^{\rm HF-M} + G_{VV}^{\rm HF-H_2}, \end{aligned} \tag{19}$$

where W_u and W_l are the rates of pumping of the laser molecule to the upper and lower levels; $G_{VT}^{\mathrm{HF-M}}$ and $G_{VV}^{\mathrm{HF-H_2}}$ are the rates of the vibrational-translational and vibrational-vibrational relaxation processes, and P_L is the specific power of the generated laser radiation at the frequency w_{ul}.

The rate of pumping W_u of HF molecules to the upper level is governed by the chain reaction (3)–(4):

$$W_u = k_1 \frac{\mu n_a}{\mu+1} n_{\mathrm{H_2}} + k_2 \frac{n_a}{\mu+1} n_{\mathrm{F_2}}\,, \tag{20}$$

where $\mu = n_{\mathrm{F}}/n_{\mathrm{H}}$. The rate of pumping of HF molecules to the lower level is determined by the vibrational-translational relaxation of HF(v),

$$\mathrm{HF}(v) + \mathrm{M} \xrightarrow{k_3^{\mathrm{M}}} \mathrm{HF}(v-1) + \mathrm{M},$$

where

$$k_3^{\mathrm{HF-M}}(v) = v^{2.3} k_{1,0}^{\mathrm{HF-M}}, \quad k_{1,0}^{\mathrm{HF-F}} = 1.6 \cdot 10^{13} \exp(-1350/T_g)\,,$$

$$k_{1,0}^{\mathrm{HF-H}} = 1.8 \cdot 10^{12} \exp(-350/T_g)\,, \quad k_{1,0}^{\mathrm{HF-H_2}} = 1.6 \cdot 10^4 T_g^{2.28}\,,$$

$$k_{1,0}^{\mathrm{HF-F_2}} = 7.7 \cdot 10^{-7} T_g^5\,, \quad k_{1,0}^{\mathrm{HF-HF}} = 4.2 \cdot 10^{14}/T_g + 3.5 \cdot 10^5 T_g^2\,,$$

$$k_{1,0}^{\mathrm{HF-O_2}} = 1.54 \cdot 10^{-6} T_g^5\,, \quad k_{1,0}^{\mathrm{HF-He}} = k_{1,0}^{\mathrm{HF-O_2}}\,,$$

and by the processes of thermal dissociation,

$$\mathrm{HF} + \mathrm{M} \xrightarrow{k_4^{\mathrm{M}}} \mathrm{H} + \mathrm{F} + \mathrm{M}\,,$$

where $k_4^{\mathrm{M}} = \frac{1.13 \cdot 10^{19}}{T_g} \exp(-67000/T_g)$. Here, the temperature of the gas mixture is expressed in Kelvin, and the rate constants are in cm^3/mole·s. Then for W_l we have

$$W_l = \frac{\mu n_a}{\mu+1} \frac{n_a}{\mu+1} \sum_{\mathrm{M}} k_3^{\mathrm{M}} n_{\mathrm{M}} - n_{\mathrm{HF}} \sum_{\mathrm{M}} k_4^{\mathrm{M}} n_{\mathrm{M}}\,. \tag{21}$$

With allowance for anharmonicities of oscillations of the HF molecule, the expression for the rate of VT relaxation takes the form [1]

$$G_{VT}^{\mathrm{HF-M}} = G_{VT}^{\tilde{a}} \sum_{v=1}^{6} c_v a^v \Big/ \sum_{v=1}^{6} v a^v\,, \tag{22}$$

where $G_{VT}^{\tilde{a}} = \sum\limits_{\mathrm{M}} k_{1,0}^{\mathrm{HF-M}} n_{\mathrm{M}} n_u$ is the rate of VT relaxation for HF simulated as a harmonic oscillator, $c_v = k_{11}^{\mathrm{HF-M}}(v) \Big/ k_{11}^{\mathrm{HF-M}}(v) k_{1,0}^{\mathrm{HF-M}}$, and $a = n_u\,/n_u n_l$. The rate of vibrational exchange between the molecules HF and H_2 is described by the expression

$$G_{VV}^{\mathrm{HF-H_2}} = k_{1,0} n_{H_2} n_{\mathrm{HF}} \left[\varepsilon_{\mathrm{HF}}(\varepsilon_{\mathrm{H_2}}+1)\exp(-290/T_g) - \varepsilon_{\mathrm{H_2}}(\varepsilon_{\mathrm{HF}}+1)\right], \tag{23}$$

where ε_{H_2} and ε_{HF} are, respectively, the average numbers of vibrational quanta of H_2 and HF. Within the framework of a two-level model, $\varepsilon_{HF} = \varepsilon_1 n_u / n_{HF}$, where ε_1 is the average number of vibrational quanta acquired by the HF molecule in the elementary act of chemical pumping. In the general case, $\varepsilon_1 = \beta_1 + (1 + w_2/w_1)\beta_2 + \ldots + (1 + w_2/w_1 + \ldots + w_R/w_1)\beta_R$, where $w_1, \ldots, w_R$ are the frequencies of the transitions $v \to (v-1)$, and $\beta_1, \ldots, \beta_R$ are the probabilities of pumping on a given level. Here, ε_1 was taken as 3.45. Equations (17)–(23) are considered together with the relaxation equation for the H_2 molecule:

$$\frac{d\varepsilon_{H_2}}{dt} = k_{1,0}^{HF-H_2} n_{HF} \left[\varepsilon_{HF}(\varepsilon_{H_2} + 1)\exp(-290/T_g) - \varepsilon_{H_2}(\varepsilon_{HF} + 1)\right] - \varepsilon_{H_2} \sum_{M} k_{1,0}^{H_2-M} n_M. \tag{24}$$

As the rate constants of the processes occurring in a laser medium depend on mixture temperature, the above equations should be supplemented by the equation of thermal balance defining the gas temperature:

$$\sum_{M} C_M n_M \frac{dT_g}{dt} = \sum_i q_i Q_i + R\left[\theta_v^{HF} G_{VT}^{HF-M} + \theta_v^{H_2} G_{VT}^{H_2-M} + (\theta_v^{HF} - \theta_v^{H_2}) G_{VV}^{HF-H_2}\right], \tag{25}$$

where q_i and Q_i are, respectively, the thermal effect and rate of the ith reaction, $\theta_v^{HF} = 5725$ K and $\theta_v^{H_2} = 5991$ K are the characteristic vibration temperatures of the HF and H_2 molecules, and R is the universal gas constant.

The specific power P_L of the laser radiation generated as a result of the $(u, j-1) \to (l, j)$ transition is described by the following expression deduced on the basis of the two-level model:

$$P_L = \hbar w_{ul} \frac{2j+1}{4j}\left[\frac{n_u}{M_{j-1}\tau} - \frac{2j-1}{2j+1}\frac{n_l}{M_j\tau}\right]. \tag{26}$$

Here, $M_j\tau$ is the collective relaxation time from all the levels in the rotational reservoir model [1] into the given level j, where M_j is a dimensionless coefficient multiplying the characteristic rotational relaxation time τ. Calculations show τ to be given by $\tau = (\pi\Delta\nu_L)^{-1}$, where $\Delta\nu_L = \sum \gamma_M P_M$ is the homogeneous half-width of the HF line, and P_M is partial pressure of the Mth component. Here, $\gamma_{H_2} = \gamma_{O_2} = 0.02$ cm^{-1}atm^{-1}, $\gamma_{F_2} = 0.035$ cm^{-1}atm^{-1}, $\gamma_{HF} = 0.09$ cm^{-1}atm^{-1}, and $\gamma_{He} = 0.0055$ cm^{-1}atm^{-1}. The power density can affect the gain of the active medium $\alpha(t)$ through the relation $P_L = \alpha(t)\, I(r)$,where the intracavity distribution of intensity $I(r)$ is determined by the solution of the wave equation with the given boundary conditions on the mirrors.

4. Wave Optics of a Laser-Amplifier

The calculations relating to this laser were carried out by adopting an electrodynamic approach based on the solution of the wave equation in the parabolic approximation [2–8]. We considered the case of a confocal telescopic cavity with spherical mirrors (Fig. 2). Based on the exact Mie diffraction theory, we took into account the amplitude-phase modulation of the electromagnetic field by inhomogeneities of the active medium, i.e., by disperse particles introduced into the chemical mixture in the laser, and also by inhomogeneities which appear as a result of photothermal changes in the refractive index of the medium.

We assumed that the total electromagnetic field in the laser can be represented by the sum of plane and spherical waves propagating in opposite directions: $E(r,z) = E^+(r,z) + E^-(r,z)$. If $E^{\pm}(r,z) =$

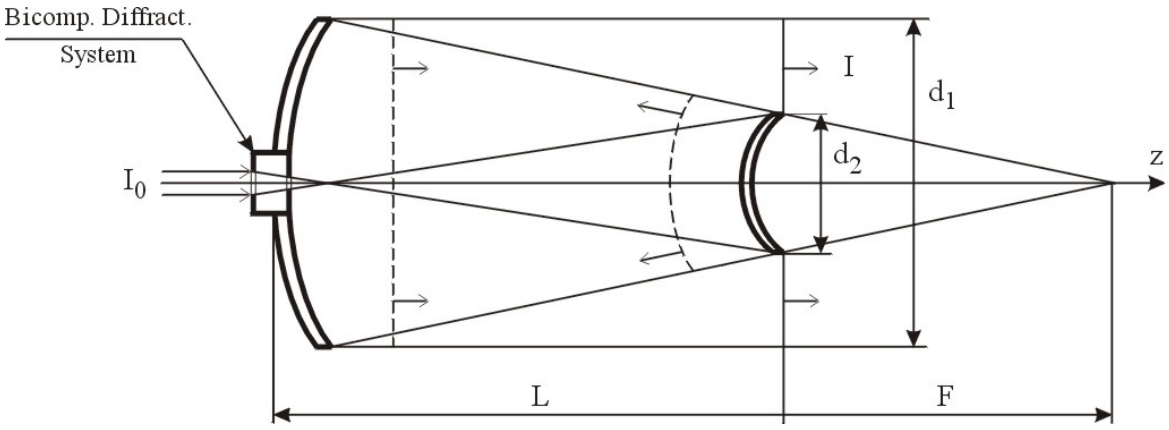

Fig. 2. Basic design of a laser-amplifier with a bicomponent diffraction system coupled structurally to an unstable telescopic cavity: $d_{1,2}$ are the diameters of the cavity mirrors, L is the cavity length, and F is the focal length of the output mirror.

$\varepsilon^{\pm}(r,z)\cdot\exp[i(\omega_{ul}t\mp\hat{k}z)]$, the intracavity intensity I can be expressed in terms of slowly varying complex amplitudes $\varepsilon^{\pm}(r,z)$ of the fields as

$$I=\frac{1}{240\pi}\left|\varepsilon^{+}(r,z)+\varepsilon^{-}(r,z)\right|^{2}, \tag{27}$$

where I is in W/cm^2 and $\varepsilon^{\pm}(r,z)$ is in V/cm. It is possible to go over to steady-state amplitudes in such a pulsed system because the time for a round trip through the cavity, $\tau_c=2L/c$ (where L is the cavity length and c is the velocity of light), is much shorter than the characteristic times of the chemical reactions in the active medium of the laser.

The propagation of a plane wave in a cavity of cylindrical symmetry is described by the parabolic wave equation

$$2i\hat{k}(\tilde{m})\frac{\partial\varepsilon^{+}(r,z)}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial\varepsilon^{+}(r,z)}{\partial r}\right]=0, \tag{28}$$

where $\hat{k}(\tilde{m})$ is a complex wave vector dependent on the refractive index $\tilde{m}$ of the medium. The parabolic wave equation for finding the field amplitude of the spherical wave can be written in terms of the spherical system of coordinates (r,θ,φ) as

$$2i\hat{k}(\tilde{m})\frac{\partial\varepsilon^{-}(r,z)}{\partial r}+\frac{1}{r^{2}\sin(\theta)}\frac{\partial}{\partial\theta}\left[\sin(\theta)\frac{\partial\varepsilon^{-}(r,z)}{\partial\theta}\right]=0. \tag{29}$$

If a medium contains N_0 monodisperse scattering and absorbing particles per unit volume, the attenuation and retardation of the wave are described by a complex wavevector which, in accordance with the Mie diffraction theory [24], can be expressed in terms of the complex refractive index of the medium as

$$\hat{k}(\tilde{m})=i\left[\frac{2\pi NS(0)}{\tilde{m}-1}\right]^{1/3}. \tag{30}$$

Here, $S(0)=\frac{1}{2}\sum\limits_{l=1}^{\infty}(2l+1)(a_l+b_l)$ is the amplitude function describing the scattering of an electromagnetic wave by a particle when the scattering angle is zero; $\tilde{m}=m_0/m_1$ is the relative value of the refractive

index of the medium; and $m_0 = n_0 - i\chi_0$ and $m_1 = n_1 - i\chi_1$ are the complex refractive indices of the particle material and of the gas, respectively. The Mie coefficients a_l and b_l contain the characteristics of the gaseous disperse medium and are calculated through a cylindrical Bessel function of the first kind $\psi_l(y)$ and a Hankel function of the second kind $\xi_l(\rho)$, both with half-integral indexes:

$$a_l = \frac{\psi_l'(y)\psi_l(\rho) - \tilde{m}\psi_l(y)\psi_l'(\rho)}{\psi_l'(y)\xi_l(\rho) - \tilde{m}\psi_l(y)\xi_l'(\rho)}\,, \quad b_l = \frac{\tilde{m}\psi_l'(y)\psi_l(\rho) - \psi_l(y)\psi_l'(\rho)}{\tilde{m}\psi_l'(y)\xi_l(\rho) - \psi_l(y)\xi_l'(\rho)}\,. \tag{31}$$

Here, $\rho = 2\pi r_0/\lambda$ is the Mie parameter; and

$$y = 2\pi r_0 n_0/\lambda, \qquad \psi_l(u) = (\pi u/2)^{1/2} J^{(1)}_{l+1/2}, \qquad \xi_l(u) = (\pi u/2)^{1/2} H^{(2)}_{l+1/2}, \qquad \psi_l' = d\psi_l(u)/du.$$

Amplitude-phase modulation of the electromagnetic field by thermal inhomogeneities of the medium is induced by photothermal changes in the refractive index of the disperse component when it is laser-heated to the phase transition temperature. This modulation is also described by the amplitude scattering function, which in general is a function of the temperature T_s of the solid particles. Empirical approximations to the temperature dependence of the refractive index, $\tilde{m}(T_s)$, can be used in conjunction with the Mie theory formulas to calculate the temperature dependences of the amplitude scattering function $S(0, T_s)$ of the disperse medium. The amplifying properties of the active medium are taken into account at each iteration step h_z along the path of propagation of the electromagnetic wave. This is done via the gain α defined through the equation

$$\varepsilon^{\pm}(z + h_z, r) = \varepsilon^{\pm}(z, r) \cdot \exp(\alpha h_z\,/2)\,. \tag{32}$$

The gain $\alpha(t) = \alpha(z\,/c)$ is found by solving simultaneously the system of equations describing the chemical kinetics, (1)–(16), and laser-level populations, (17)–(26).

The mutual transformation of plane and spherical waves in the cavity, and the presence of an input control signal in the region of the coupling aperture, are taken into account by the boundary conditions on the mirrors:

$$\begin{aligned} \varepsilon^{+}(r = \infty, z) &= \varepsilon^{-}(\theta = \pi/2, r) = 0\,, \\ \varepsilon^{+}(r, 0) &= \varepsilon^{-}(r, \theta)R_1 + \varepsilon_f(r) \qquad \text{for} \quad z = 0, \\ \varepsilon^{-}(0, \theta) &= \varepsilon^{+}(r, L)R_2 \qquad\quad \text{for} \quad z = L. \end{aligned} \tag{33}$$

Here, R_1 and R_2 are the reflection coefficients of the first and second mirrors, respectively. In view of the continuity of the boundary conditions for the wave equations (14) and (15), the reflection coefficients of the mirrors are approximated by exponential functions of the type $R_{1,2} = \exp[-(r - r')^s\,/r_s]$, , where $r' = 0.65r_m$, $r_s = (r_m - r')^s/ln(4/3)$, $s = 8$, and $s = 2r_m$ is the diameter of the mirror or aperture. The focused input signal $\varepsilon_f(r)$ is obtained due to diffraction of the plan wave from the master oscillator on the proposed bicomponent diffraction system coupled structurally to an unstable telescopic cavity (see Fig. 2). The formulation of the problem of diffraction of a plane wave on two axial holes (with diameters q_1 and q_2) is similar to that of diffraction of a wave on the cavity mirrors, Eqs. (27)–(29), with corresponding boundary conditions on the bicomponent diffraction system [2–8]:

$$\begin{aligned} \varepsilon_f(r, z)\,|_{z=0} &= \varepsilon_0 P_1(r)\,, & \varepsilon_f(r, z)\,|_{z=l} &= \varepsilon_f(r, l)P_2(r)\,, \\ \varepsilon_f(r, z)\,\big|_{|z|\to\infty} &= \varepsilon_f(r, z)\,\big|_{|r|\to\infty} = 0\,, & \varepsilon_f(r, z)\,\big|_{|z|\to\infty} &= \varepsilon_f(r, z)\,\big|_{|r|\to\infty} = 0\,, \\ P_1(r)\,\big|_{|r|<q_1/2} &= 1\,, & P_2(r)\,\big|_{|r|<q_2/2} &= 1\,. \end{aligned} \tag{34}$$

Here, l is the distance between the screens of the bicomponent diffraction system. The factors of screen passage $P_{1,2}(r)$ are approximated by the exponential functions [2–8]. The result is a closed system of equations (17)–(34) describing the electrodynamic and laser-chemical processes in the active medium of a pulsed H_2-F_2 laser-amplifier on the PBCR in an unstable telescopic cavity, initiated by focused input signal.

5. Discussion of Results

The wave approach for the description of a pulsed chemical HF-laser amplifier based on a PBCR in an unstable telescopic cavity enables the detection of interesting optical effects in an active two-phase medium of H_2-F_2-O_2-He and Al particles, and also the new properties of the laser. These effects, the optimal parameters and the output performances of the laser, and also some characteristics of the active medium are presented in Table 1, where the results of numerical accounts, both reported earlier in [2–18, 20, 21, 23] and obtained in this present work, are reviewed below.

In particular, an analysis of the aerosol optics and the laser-chemical kinetics of a PBCR is used in [2–8] to determine the range of maximum permissible parameters of the disperse component capable of supporting the operation of a pulsed chemical HF-laser with a two-phase active medium with particle radius $r_0 = 0.09 - 0.4$ μm and particle concentration $N_0 = 10^9 - 10^7$ cm^{-3} (see Table 1). In this range of aerosol parameters, the lifetime of the active medium of the HF-laser with the dispersed Al particles is governed by the coagulation, precipitation, and electrostatic scattering of particles occurring in the time range of $\sim 10^3$ s [20, 21] (Table 1).

We have also assumed that the plane electromagnetic wave from an external IR laser source is focused by a bicomponent diffraction system in a narrow Gaussian beam, whose intensity in the focal volume is $I_f = 3$ MW/cm^2. The optical breakdown of a chemically-active aerosol at the wavelength of the generated radiation ($\lambda_g = 3.3$ μm) is characterized by the threshold intensity $I_{\text{thr}} \approx 10^{10}$ W/cm^2 [23]. The focusing of the initiating radiation should occur at a small distance from the input mirror of a cavity, exactly equaling the distance at which the first Fresnel zone is opened for a given diameter $d = q_2$ of the output aperture of bicomponent diffraction system, $z_f = d^2/(4\lambda)$. Then, through this diameter d we can connect the focal length z_f with the geometric parameters of an unstable telescopic cavity, $N_p = \ln(d_2/d)/[ln(1 + L/f) + 2]$, where N_p is the number of beams passing into the cavity, L is the cavity length, and d_2 and F are the diameter and focal length, respectively, of the cavity output mirror. Here, the square brackets mean selection of the whole part of a number. The above supposition links the focusing properties of a bicomponent diffraction system with the parameters of a cavity, so that the problem of an initiating radiation introduced into the cavity through a coupling aperture becomes optically self-consistent.

The diameter, d, of a coupling aperture with the master oscillator satisfies the condition $d \sim 3d_f$, where d_f is the focal spot diameter. Thus, the value of d changes for each new value of d_f, and consequently, the value of the input energy E_{in} required for ignition of the PBCR in the small focal volume varies as well: $E_{\text{in}} = I_f(\pi d_f^2/4)\tau_{\text{in}}$. The pulse duration of the input signal, τ_{in}, was selected so that the enclosed energy in the focal volume, $V_f \sim 10^{-7}$ cm^3, was enough for evaporation of the particles of aluminum for the initiation of the PBCR and, in the end, for generation of the laser. Calculations [2–8] show that at a given intensity in the field at the focal point, the threshold value τ_{in} for a master oscillator generating radiation is 250 ns for the selected composition of the active laser mixture containing disperse Al particles.

TABLE 1. Main Properties and the Parameters of the HF-Laser-Amplifier Based on a PBCR

Observed effects and properties of the laser	Calculated optimal laser parameters	Output characteristics	Notes
Effect of auto-wave spreading of a PBCR throughout the volume of the active medium as self-supporting cylindrical zones of photon branching.	Ratio of the reagents as $H_2:F_2 = 1:2$. The range of general pressures of the mixture is P=(1–2.3) bar	E_{out}=1.5×2.3 kJ; E_{sp}=(200–730) J/L; $P_{max} \sim 10^{11}$ W.	It is possible to initiate a PBCR into an initial small focal volume of an active two-phase medium by focused external IR radiation.
Effect of giant laser energy gain of $k_{amp} = E_{out}/E_{in} \sim 10^9$, where E_{out} and E_{in} are the output and input energies, respectively.	Range of Al particle radius and concentration, respectively: $r_0 = (0.09 - 0.4)$ μm and $N_0 = (10^9 - 10^7)$ m^{-3}.	$\tau^L \approx 800$ ns, $\tau^L_{1/2} = 100$ ns.	The lifetime of the active medium of a HF-laser with dispersed Al particles is governed by the coagulation, precipitation, and electrostatic scattering of particles, which amounts to $\sim 10^3$ s.
Autonomous generation: a self-contained laser can be initiated by a small submicrojoule master oscillator powered by an accumulator.	Performances of the master oscillator: input signal intensity, $I_0 = 10^5$ W/cm^2; energy of input pulse $E_{in} = 10^{-6}$ J; duration of initiating pulse is $\tau_{in} = 250$ ns.	$k_{amp} = E_{out}/E_{in} \approx (10^4 - 10^9)$.	The optical breakdown of the chemically-active aerosol at the wavelength of the generated radiation ($\lambda_g = 3.3$ μm) is characterized by the threshold intensity $I_{thr} = (1-3) \cdot 10^{11}$ W/cm^2.
Property of compactness, which is determined by the minimal performances of the main laser units: linear sizes of the cavity, $\sim 13 \times 14 \times 14$ cm; energy of the master oscillator, $E_{in} = 10^{-6}$ J; and initially excited volume, $V_{in}^{min} = 10^{-7}$ cm^3. The volume of the active medium is $\sim 2L$.	Geometric parameters of an unstable telescopic cavity: number of passes, $N_p = 4$; range of cavity lengths, 13–50 cm; range of magnification coefficients, $\beta = 1.5 - 2$; diameter of the coupling aperture, $d \leq 3$ mm.	The profile of the output pulse in the near-field zone is a torus, and in the far-field zone the profile is Gaussian.	

Here, r_0 and N_0 are the radius and concentration of the dispersed particles; I_0 and τ_{in} are the intensity and duration of the initiating radiation; E_{out} and E_{sp} are the full (i.e., for the whole volume of the laser active medium) and specific (i.e., per unit volume) energies of the output pulse of radiation; P_{max} is the maximum power of generation; k_{amp} is the energy gain factor; τ^L is the duration of the output pulse; $\tau^L_{1/2}$ is the output pulse duration at half of the maximal power; and I_{thr} is the threshold intensity for optical breakdown of the active medium.

The optimal laser variant was found to have a four-pass unstable telescopic cavity of length $L = 49.5$ cm [2] when the diameter of the first mirror is $d_1 = 14$ cm and that of the second mirror $d_2 = 5.98$ cm and the focal length of the second mirror is $F = 53$ cm. In our calculation we assumed that the cavity is filled with a high-energy-capacity working mixture, with the composition H_2:F_2:O_2:He = 166:334:40:210 torr, containing fine passivated aluminum particles of radius $r_0 = 0.2$ μm and a concentration $N_0 = 1.3 \cdot 10^8$ cm^3. External focussed IR radiation of wavelength $\lambda_{\text{in}} = 3.3$ μm, identical with the wavelength λ_g of the output radiation, was assumed to enter the laser through a central coupling aperture in the input cavity mirror.

Let the plane electromagnetic wave from an external IR laser source (Fig. 3a) be focused by a bicomponent diffraction system in a narrow Gaussian beam (Fig. 3b), whose intensity in the focal volume is $I_f = 3$ MW/cm^2. Here, the diffraction picture in the focal plane represents the circular nonlocal bands of the Fresnel zones with a bright narrow peak at the center, whose intensity can exceed by six to ten times the value of the incident wave intensity. Calculations show that the focusing of the initiating radiation should occur at a small distance from the input mirror of a cavity, exactly equaling the distance at which the first Fresnel zone is opened for a given diameter d of the coupling aperture, $z_f = d^2/4\lambda$. Further wave propagation is accompanied by a slow monotonic decrease of the intensity due to diffractive spreading of the wave and the onset of a Gaussian distribution of the radiation intensity. The intensity distribution of a diffracted field formed by a bicomponent diffraction system at the far zone (on the output mirror) is similar to a Fraunhofer diffraction picture.

Figures 3c, d, e, f show the characteristic stages of evolution of an auto-wave PBCR and lasing inside an unstable telescopic cavity. We can clearly see how the ring-shaped zones, formed by the paths of the rays inside the cavity, are gradually filled with the electromagnetic field. The radiation intensity in each zone is higher than the input signal intensity, indicating initiation and self-propagation of a PBCR throughout the cavity. The mechanism of initiation of the PBCR and the auto-wave regime of its propagation are discussed below.

Heating of the disperse Al particles in the focal volume to their melting point during $t = \tau_{\text{in}}$ results in the evaporation of aluminum atoms from the surface, and these atoms react with F_2 molecules in a fast reaction (2), which is accompanied by the formation of free F atoms. A chain reaction (3)–(4) is initiated, whose product is in the form of HF molecules with excited vibrational levels. The radiation is amplified in the first zone, formed by input radiation. The new irradiated photons in the focal volume propagate in the solid angle 4π of the space, but only part of them have participated in the generation of the output radiation. At the initial stage the density of new irradiated photons is not enough for heating the layers of the active medium, close-fitting to the focal volume, and the radiation cannot be amplified there. Thus, the amplification of the radiation is observed only in the channel of input signal propagation, where the laser – chemical reactions are ignited. Figure 3c shows the structure of the steady-state field, which is formed by multiple reflections from the mirrors in the central (first) cavity zone.

The amplified radiation tends to increase the efficiency of heating of the laser active medium and independently ignites the auto-wave PBCR in the whole cavity volume. As a result of the self-propagation of the PBCR the second, third, and fourth cavity zones become filled with radiation (Fig. 3d) at essentially the same time. This time duration for the formation of radiation in these zones is less than that for the first zone formation, because the radiation passing through these zones is stronger than the initial radiation.

The further process of laser generation is represented in Fig. 3d and e. We can see that the development of the auto-wave PBCR is accompanied by the formation of a radiation valley in the central (first and second) zones. This means that the active mixture in the central zones gradually burns out and loses its

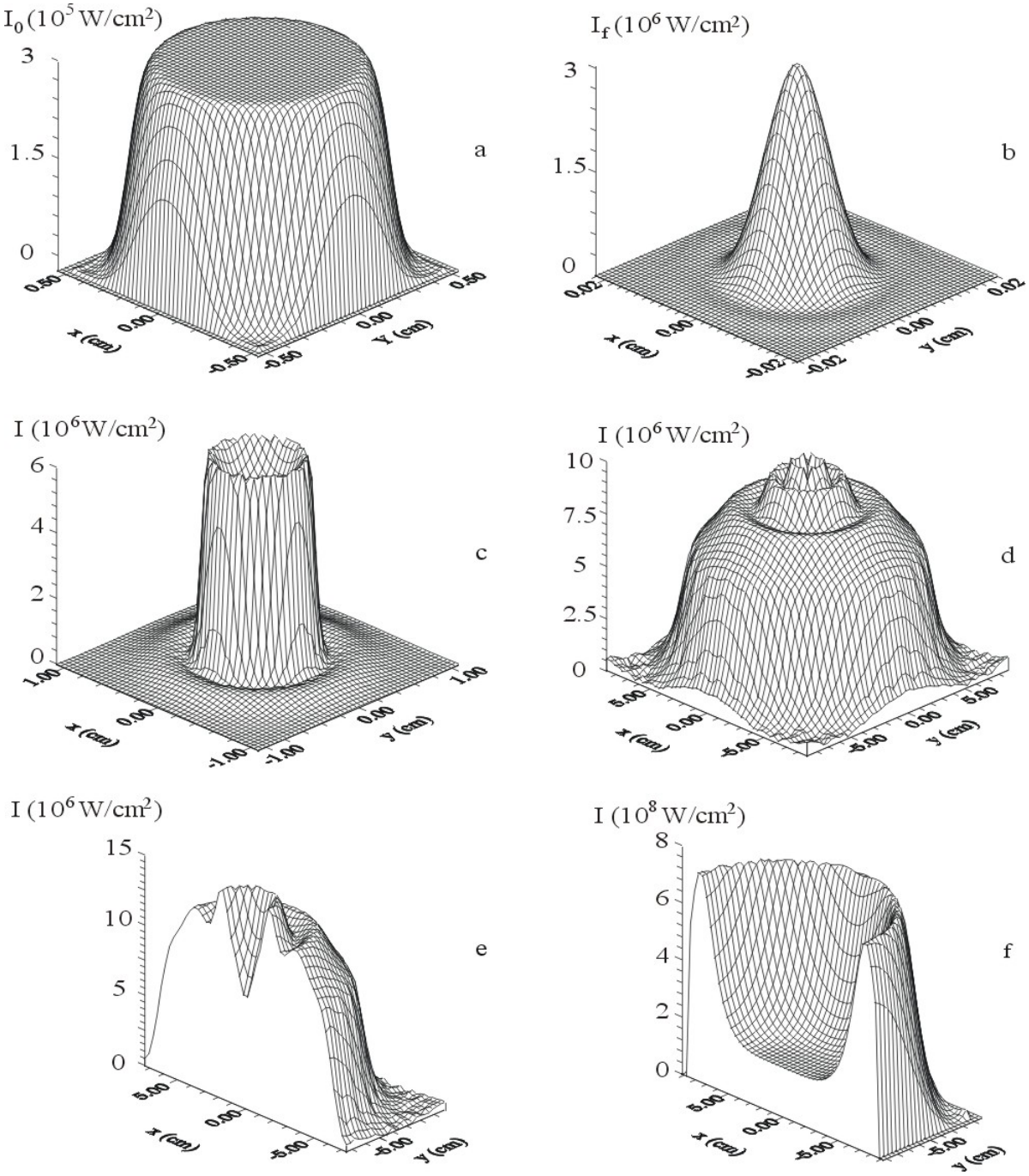

Fig. 3. Space distributions of the intensities of the initial plane wave (a) and input focused wave (b) and intracavity intensities of radiation in the first (c), second, third, and fourth (d), third and fourth (e), and fourth (f) cylindrical zones of photon-branching.

TABLE 2. Output Characteristics of a Laser-Amplifier with a Four-Pass Unstable Telescopic Cavity

d_f, mm	E_{in}, J	E_{out}, J	E_{sp}, J/L	τ_l, ns	k_{ampl},	Curve # in Fig. 3
0.01	$5.891{\cdot}10^{-7}$	2292.04	300.8	884.5	$3.89{\cdot}10^{9}$	—
0.015	$1.473{\cdot}10^{-5}$	2082.9	273.35	892.64	$1.41{\cdot}10^{8}$	—
0.03	$5.892{\cdot}10^{-5}$	2268.3	297.68	882.76	$3.85{\cdot}10^{7}$	—
0.05	$1.325{\cdot}10^{-4}$	2160.0	283.0	884.0	$1.63{\cdot}10^{7}$	5
0.1	$5.3{\cdot}10^{-4}$	2173.16	285.2	886.1	$4.1{\cdot}10^{6}$	—
0.2	$2.121{\cdot}10^{-3}$	2176.57	285.64	882.76	$1.03{\cdot}10^{6}$	—
0.33	$5.892{\cdot}10^{-3}$	2121.02	278.35	882.96	$3.6{\cdot}10^{5}$	4
0.53	$1.503{\cdot}10^{-2}$	2210.11	290.0	858.0	$1.47{\cdot}10^{5}$	2
0.67	$2.358{\cdot}10^{-2}$	2075.16	272.33	850.0	$8.8{\cdot}10^{4}$	1
1.0	$5.303{\cdot}10^{-2}$	1739.3	228.25	861.0	$3.28{\cdot}10^{4}$	3

The cavity is filled with a working mixture of composition H_2:F_2:O_2:He = 166:334:40:210 torr containing fine aluminum particles of radius $r_0 = 0.2$ μm in a concentration $N_0 = 1.3 \times 10^8$ cm^{-3}, initiated by a focused IR pulse of duration $\tau_{\text{in}} = 250$ ns and intensity $I_f = 3$ MW/cm^2 on a focal spot of diameter d_f. Here, τ_l is the duration of the laser pulse, and E_{sp} is the specific output energy.

amplifying properties. However, in the following (third and fourth) zones, the mixture is not completely depleted, which accounts for the smooth variation of the radiation intensity from one zone to the next. Finally, at the fourth stage the powerful amplified radiation fills the whole ring volume of the cavity, and the structure of this radiation is shown in Fig. 3f.

The results of numerical calculations of the output characteristics of this laser obtained for various diameters of the focal spot are listed in Table 2 and also presented in Figs. 4 and 5. In these calculations, the diameter of the focal volume was varied over the range $d_f = 15$ μm–1 mm.

Table 2 and Fig. 4 reveal small oscillations in the output energy E_{out} and maximum value of the generated power $P_{\max}$ over the range of values $E_{\text{out}} \sim (2075-2268)$ J and $P_{\max} \sim (6.865-7.486{\cdot}10^{10})$ W, respectively, as d_f is varied. These oscillations appear, firstly, because of the influence of boundary diffractive effects of the input field on the bicomponent diffraction system, i.e., the output field "senses" wave perturbations at the input to the laser-amplifier. Variation of the diameter of the focal spot automatically alters the value of d and the initial conditions for the diffraction of the input wave, so that the focusing of this wave occurs at different initial distances from the aperture. Consequently, the initially-excited volume of the active medium $V_{\min}$ changes, which results in oscillations of E_{out} and $P_{\max}$: $E_{\text{out}} \approx \frac{V_L}{V_{\min}} E_{\text{in}}$, where V_L is the total cavity volume. Secondly, the expansion of d increases the energy lost directly in the aperture on reflection from the input mirror. For the maximum aperture diameter $d \approx 3$ mm ($d_f = 1$ mm) the energy losses become significant, resulting in a sharp drop of both the output energy, up to the value $E_{\text{out}} \sim 1700$ J, and the power of laser generation (curve 3 in Fig. 4).

However, it is necessary to note that the oscillations of the output energy E_{out} and maximum laser

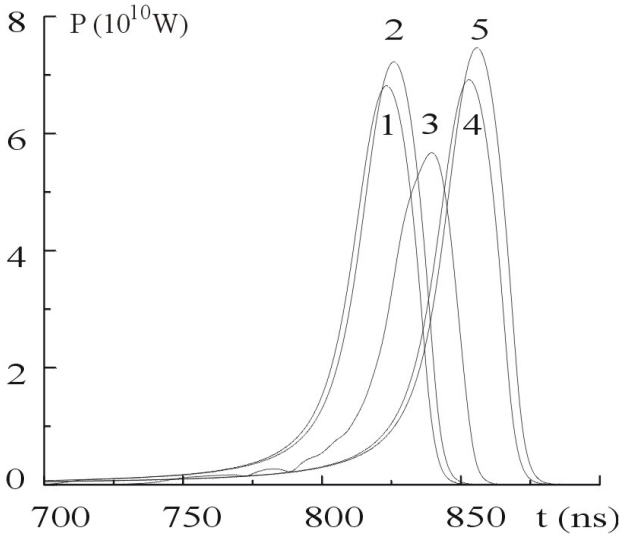

Fig. 4. Time dependences of the output power P of a laser-amplifier, calculated for various diameters of the focal spot (Table 2).

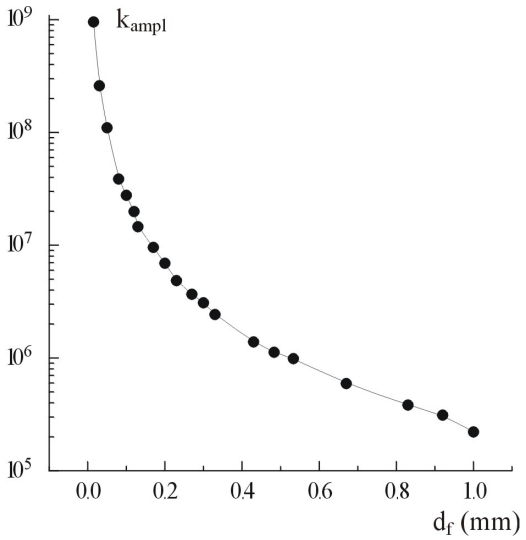

Fig. 5. Calculated dependences of the energy gain k_{ampl} on the diameter of the focused input radiation for a working mixture with the composition H_2:F_2:O_2:He = 166:334:40:210 torr containing fine aluminum particles of radius $r_0 = 0.2$ μm in a concentration $N_0 = 1.3 \cdot 10^8$ cm^{-3}.

power $P_{\max}$ do not exceed 10%, indicating that the output field depends weakly on the focal spot dimensions. This is explained by an auto-wave regime of amplification, when a PBCR is initiated in a small volume and then spreads out of this minimal volume spontaneously, without external power sources, to subsequently fill the whole volume of the laser. The output pulse duration τ_L obtained in the auto-wave lasing regime for the characteristics of the laser-amplifier given above is approximately constant at a value of ∼800 ns (Table 1).

A stronger exponential dependence on the conditions of focusing is observed for the energy gain k_{ampl} (see Fig. 5). The acute focusing of the input signal ensures minimization of the initially-excited volume of the laser active medium $V_{\min}$ and, accordingly, reduces dramatically the required energy of the input pulse from the master oscillator, right down to the microjoule level (see Table 2). Thus, the focusing of the input signal and the auto-wave regime of the PBCR propagation over the whole volume of the laser make it possible to reach an extremely high energy gain $k_{\text{ampl}} \approx 10^9$. This result is remarkable because it allows us to use a master oscillator in the form of a small microjoule laser powered by an accumulator. The huge energy gain should thus make it possible to construct a self-contained compact powerful laser, which can be initiated by a very weak source signal.

The high-energy storage of a fluorine-hydrogen mixture, in combination with the detected effects of an auto-wave PBCR spreading and the giant laser energy gain, enable us to obtain a high output energy from the rather small volumes of the HF-laser active medium. In Table 3 and Fig. 6 the results of the parametrical research of the output energy performances of the considered laser-amplifiers are represented for the various geometric parameters of the cavity, the characteristics of the dispersed component, the general pressures, and the composition of the working laser mixture. We see that due only to the optimization of the dispersed component parameters r_0 and N_0, it is possible to increase by 60% the specific output energy E_{sp} (i.e., output energy per unit volume of the laser active medium) from 195 J/L to 313 J/L (see Table 3). This allows a reduction of the length of the cavity by half in comparison with the initial value (from $L \approx 50$ cm to $L \approx 25$ cm), saving then a large amount of the full output energy (i.e., for the whole volume of the laser active medium) in a pulse, $E_{\text{out}} \sim (1200 - 1500)$ J.

A further increase of the output specific energy E_{sp} by 2–2.5 times is possible due to the rise in the pressure (P) of the laser working mixture up to 2–2.3 bar (see Table 3). The specific output energy ∼737 J/L ($P = 2.3$ bar) allows us to obtain the same output energy in a pulse for the length of an unstable telescopic cavity only at ∼13 cm. At such a cavity length and with the autonomy of generation, the laser becomes a small compact device which is capable of "shooting" pulses with $E_{\text{out}} \sim 1.5$ kJ (Fig. 7).

We should note that the proposed compact scheme of the laser in Fig. 7 is rather simplified. It does not contain a number of technical devices associated, for example, with neutralizing the spent gases, guarding the mirrors, clearing the cavity, etc., which will lead to an increase in the overall performance of the laser. Nevertheless, our parametric research has allowed us to find the minimal performances of the main laser units – linear sizes of the cavity, energies of the master oscillator and its power source, and the system of gas cylinders – and also to obtain the optimal composition of the reactants and the pressure of the laser working mixture. Thus, due to the increase in the general pressure of the working gases, up to $P = 2.3$ bar, the optimization parameters of the dispersed component (Al particles with radius $r_0 = 0.09$ μm and concentration $N_0 = 1.4 \cdot 10^9$ cm^{-3}), and the composition of the working mixture, the HF-laser ensures an output energy up to ∼1.5 kJ in a pulse from a rather small volume ∼2L of the active medium.

We have calculated also the space distributions of the output radiation intensity of the compact laser in the near- and far-field zones. Figure 8 gives the transverse distributions of the field intensity for a laser with minimal length of the unstable telescopic cavity, $L = 13$ cm, at various distances z from the output mirror. It is evident from Fig. 8a that the profile of the output pulse in the near-field zone is a torus with maximum output intensity $I_{\text{out}} = 6 \cdot 10^8$ W/cm^2. With increase in the distance z, the field is gradually concentrated near the axis (Fig. 8b and c)) to form a beam which is 2 cm in diameter due to diffraction processes. The diffractive focusing of the wave is accompanied also by a growth in the radiation intensity

TABLE 3. Results of Parametric Studies of the Output Energy Performances of the HF-Laser-Amplifier Presented for Various Geometric Parameters of the Cavity, Characteristics of the Dispersed Component, General Pressures, and Composition of the Working Laser Mixture

L, cm	Cavity parameters, cm			R_0, μm	N_0, 10^8 cm^{-3}	P, bar	Composition of the mixture $H_2 : F_2 : O_2 : He$, torr	I_0, MW/cm^2	τ_{in}, ns	E_{out}, J	E_{sp}, J/L	P_{max}, 10^{10} W	τ_L, ns
	D_2	F	β										
49.5	5.98	53	1.93	0.2	1.3	1.0	76:228:23:578	5	150	1.85	194.9	1.5	737
							166:334:40:210	3	250	2.210	290	7.3	858
33	8	69.5	1.48	0.2	1.3	1.0	76:228:23:578	5	150	1.190	234.26	2.22	671
26.4	8.88	76.1	1.35	0.9	14	1.0	76:228:23:578	5	150	1.271	312.76	1.99	564
						2.0	200:800:100:420	5	120	2.539	624.8	5.18	547
						2.3	250:1000:100:420	5	120	2.554	628.5	5.49	599
13.2	10.4	89.3	1.15	0.09	14	2.3	250:1000:100:420	5	120	1.497	736.72	3.21	590

A focused IR pulse initiates the laser. Here, L is the length of the cavity with input and output mirrors of diameters $d_1 = 14$ cm and d_2, respectively, F is the focal length of the output mirror, β is the magnification coefficient of a cavity, and P is the general pressure of the working mixture H_2:F_2:O_2:He.

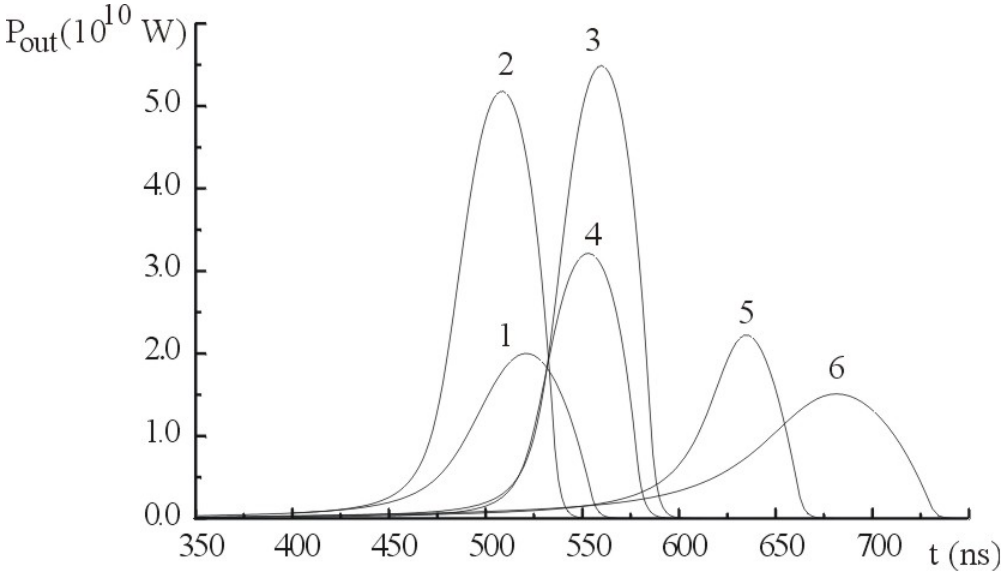

Fig. 6. The time dependences of the output power P_{out} of the HF-laser-amplifier, calculated for the different geometric parameters of the cavity and general pressures of the laser working mixture: 1) $L = 26.4$ cm, $P = 1$ bar, 2) $L = 26.4$ cm, $P = 2$ bar, 3) $L = 26.4$ cm, $P = 2.3$ bar, 4) $L = 13.2$ cm, $P = 2.3$ bar, 5) $L = 33$ cm, $P = 1$ bar, and 6) $L = 49.5$ cm, $P = 1$ bar.

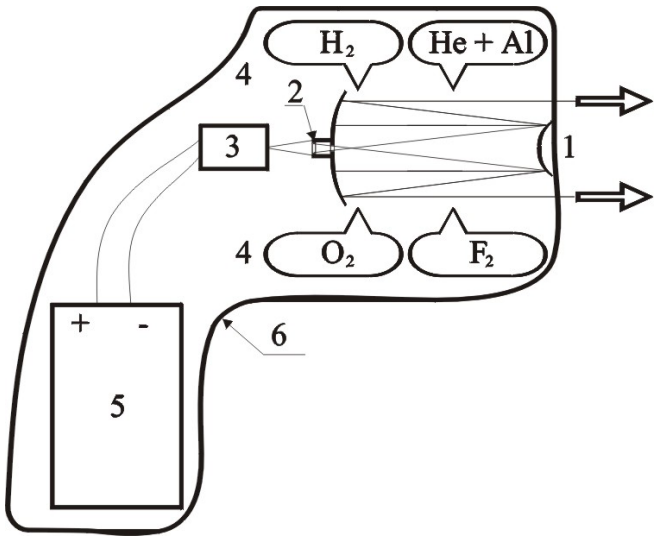

Fig. 7. Simplified basic design of the compact self-contained HF-laser-amplifier: 1) unstable telescopic cavity, 2) bicomponent diffraction system, 3) master oscillator, 4) system of gas cylinders, 5) accumulator, and 6) casing.

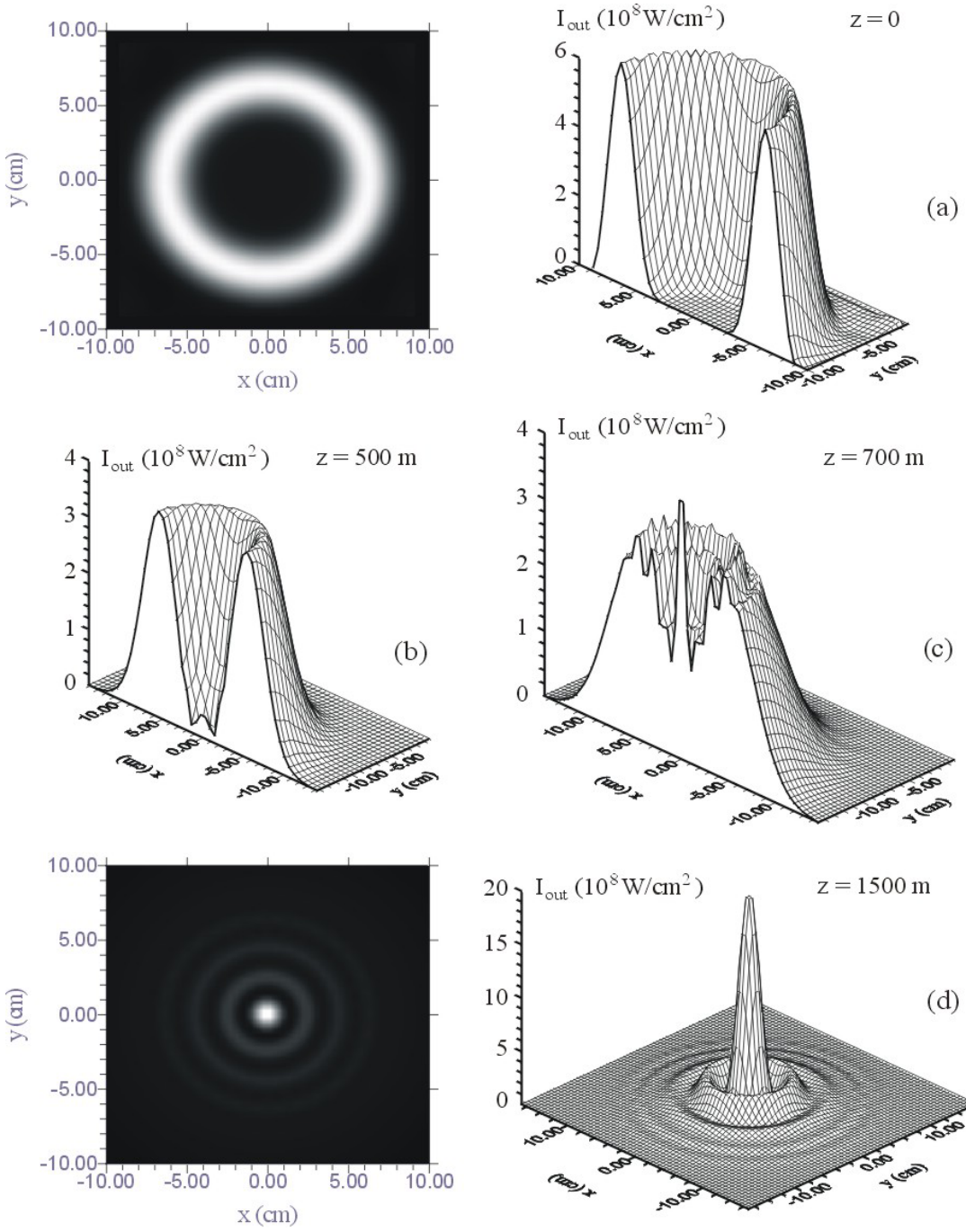

Fig. 8. Transverse distributions of the output radiation intensities at the distance $z = 0$, i.e., immediately behind the output mirror (a), at $z = 500$ m (b), at $z = 700$ m (c), and at $z = 1500$ m (d) from the laser.

at the center of the diffraction picture. At a distance $z = 1500$ m, this exceeds by 3.5 times the value of the output intensity in the near-field zone, leading to the magnitude $I_{\text{out}} \approx 2 \cdot 10^9$ W/cm^2. Further propagation of the wave is accompanied by a slow monotonic drop of its intensity due to diffractive spreading and development of a Gaussian distribution of the radiation intensity in the far-field zone.

6. Conclusions

As an example of the prospective application of the DMFR effect, in the present paper we propose to initiate high-power HF-lasers and amplifiers by an external power radiation that is focused by the proposed bicomponent diffraction system. A parametric study of a pulsed chemical laser on a PBCR initiating in a gaseous disperse medium composed of H_2-F_2-O_2-He and Al particles by focused external IR radiation has been conducted. We see that both the observed effects of auto-wave spreading of a PBCR under the condition of external signal focusing and the effect of a large laser energy gain of 10^9 give the pulsed chemical HF-laser the important properties of autonomy and compactness. We have determined the minimal performances of the main laser units – linear sizes of the cavity, energies of the master oscillator and its power source, and the system of gas cylinders – and have also obtained the optimal composition of the reactants and the pressure of the laser working mixture. We see that at the general pressure of the working gases of $P = 2.3$ bar, the optimal parameters of the dispersed component (Al particles with radius $r_0 = 0.09$ μm and concentration $N_0 = 1.4 \cdot 10^9$ cm^{-3}), and the composition of the working mixture, the HF-laser ensures an output energy up to $\sim$1.5 kJ in a pulse from a rather small volume $\sim 2L$ of the active medium. A specific design is proposed for a self-contained compact pulsed HF-laser with small linear sizes of an unstable telescopic cavity ($\sim 13 \times 14 \times 14$ cm, where 14 cm is the diameter of the input (large) mirror), which can be initiated by a small submicrojoule master oscillator powered by an accumulator. Wave studies of the spatiotemporal behavior of the output laser radiation show that the profile of the output pulse in the near-field zone is a torus, and in the far-field zone the profile is Gaussian.

References

1. N. G. Basov, A. S. Bashkin, V. I. Igoshin, et al., *Chemical Lasers*, Springer-Verlag, Berlin (1990).
2. V. I. Igoshin and R. R. Letfullin, *Kvantovaya Élektron.*, **27**, 487 (1997).
3. V. I. Igoshin and R. R. Letfullin, *Kvantovaya Élektron.*, **29**, 37 (1999).
4. R. R. Letfullin and S. P. Sannikov, *Kvantovaya Élektron.*, **29**, 43 (1999).
5. V. I. Igoshin and R. R. Letfullin, *Kvantovaya Élektron.*, **30**, 1049 (2000).
6. R. R. Letfullin and T. F. George, *J. Appl. Phys.*, **88**, 3824 (2000).
7. R. R. Letfullin and T. F.George, *Appl. Phys.* B, **71**, 813 (2000).
8. R. R. Letfullin, V.I. Igoshin, and T. F. George, "Pulsed Chemical Laser on Photon–Branched Chain Reaction," in: *Modern Topics in Chemical Physics*, Research Signpost (2002).
9. M. A. Azarov, V. A. Drozdov, V. I. Igoshin, et al., *Kvantovaya Élektron.*, **27**, 953 (1997).
10. R. R. Letfullin, "Bicomponent diffraction system for focussing of radiation. 1. Theory," Preprint No. 4 of the P. N. Lebedev Physical Institute, Moscow (2000).
11. R. R. Letfullin and T. F. George, *Appl. Opt.*, **39**, 2545 (2000).
12. R. R. Letfullin and O. A. Zayakin, "Bicomponent diffraction system for focussing of radiation. 2. Experiment," Preprint No. 29 of the P. N. Lebedev Physical Institute, Moscow (2000).

13. R. R. Letfullin, Preprint No. 30 of the P. N. Lebedev Physical Institute, Moscow (2000).
14. R. R. Letfullin O. A. Zayakin, and T. F. George, in: A. V. Kudryashov and A. H. Paxton (eds.), *Laser Resonators IV (Photonics West 2001: High-Power Lasers and Applications), Proc. SPIE*, **4270**, 163 (2001).
15. R. R. Letfullin and O. A. Zayakin, *Kvantovaya Élektron.*, **31**, 339 (2001).
16. R. R. Letfullin, O. A. Zayakin, and T. F. George, *Appl. Opt.*, **40**, 2138 (2001).
17. R. R. Letfullin and O. A. Zayakin, *J. Russ. Laser Res.*, **23**, 149 (2002).
18. R. R. Letfullin and T. F. George, *Fiber Integr. Opt.*, **21(2)**, 145 (2002).
19. V. I. Igoshin and S. Yu. Pichugin, *Kvantovaya Élektron.*, **13**, 267 (1983).
20. R. R. Letfullin, K. G. Melihov, V. I. Igoshin, and L. A. Mitlina, *Kvantovaya Élektron.*, **25**, 911 (1998).
21. N. Bekrenev, V. I. Igoshin, R. R. Letfullin, and K. G. Melihov, *Kvantovaya Élektron.*, **24**, 227 (1997).
22. N. V. Karlov, *Lectures on Quantum Electronics* [in Russian], Nauka, Moscow (1983).
23. V. I. Igoshin, R. R. Letfullin, and S. Yu. Pichugin, *Proceedings of the P. N. Lebedev Physical Institute* [in Russian], Nauka, Moscow (1993), Vol. 217, p. 146.
24. H. C. van de Hulst, *Light Scattering by Small Particles*, Wiley, New York (1957).