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Ultrahigh energy gain in small volumes of the active medium in a laser based on an autowave photon-branched chain reaction

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Abstract. The possibility is demonstrated of initiating an autowave photon-branched chain reaction (PBCR) in an originally small focal volume of the laser active medium ($H_2 - F_2 - O_2 - He - Al$ particles) by the external IR radiation focused with a lens. It is shown that the PBCR can spread over the entire active medium of the laser with an unstable telescopic cavity, in the form of self-sustained cylindrical zones of photon branching. The autowave laser-chemical reaction initiated in the lens focus strongly reduces the required energy of the initial input pulse to 0.01 μJ, thereby providing a huge energy gain of $\sim 10^{11}$. Because of this ultrahigh gain, a small submicrojoule laser can be used as a master oscillator.

1. Introduction

All existing pulsed chemical lasers share a common drawback: the need of an external energy source to initiate the reaction. Ideally, however, the chemical laser must be an autonomous source of coherent radiation.

In pulsed chemical lasers, a metastable mixture of reagents is triggered into reaction by an external disturbance. Unfortunately, the energy of this external source is comparable to the output energy of the laser, which limits the possibility of scaling this laser. Creation of pulsed chemical lasers operating without external sources of energy, i. e., autonomous chemical pulsed lasers, could radically reduce the weight and size of these laser systems.

In the case of a pulsed chemical HF laser, this problem can be solved with the help of the photon-branched chain reaction (PBCR) between fluorine and hydrogen in a two-phase active medium [1], i. e., in a medium containing the working gas and finely dispersed passivated metal particles. The latter are then vaporised by an external laser beam, resulting in the appearance of free atoms of metal and initiation of the PBCR. This idea has been confirmed by numerical simulations and first experiments. In recent experiments [2], the stability of a fluorine-hydrogen mixture with an injected finely dispersed component (aluminium particles with a radius of $r_0 = 0.1 - 1$ μm and a concentration of $N_0 \sim 10^5$ cm^{-3}) was demonstrated with respect to spontaneous ignition, and the possibility of initiating a chain reaction by vaporising the particles with IR radiation was shown. Both lasers and amplifiers based on the PBCR have been calculated using the developed kinetic models and laser wave optics [3 – 6]. Other approaches to the building of PBCR lasers and the history of this problem are discussed in Ref. [7].

Under certain initial conditions, a photon-branched exothermic reaction can spread in a certain direction on its own. This property was used in a new dynamical regime of laser amplification in a multipass optical scheme, which was proposed in Ref. [3] and numerically substantiated in Ref. [4]. We have shown [4] that the laser-induced chemical reaction can be initiated by an external pulse in a narrow paraxial cylindrical region, and then it develops spontaneously over the entire volume in an autowave regime. The self-sustained cylindrical zones of photon branching formed by the unstable multipass cylindrical cavity can be viewed as embedded amplification cascades. The pulse energy gain in such an autowave regime is much greater ($\sim 10^3$) than a single-pass amplifier (no more than 10). In addition, in this scheme there is no danger of self-excitation of the laser even at such high gains because the medium has not been inverted initially and the energy is stored as the free energy of reagents rather than the energy of lasing transitions.

The possibilities of increasing the energy gain $k_{amp} = E_{out}/E_{in}$ (E_{in} and E_{out} are the energies of input and output pulses, respectively) in the autowave amplification regime are far from being exhausted. Earlier [5], we have numerically discovered the possibility of reaching ultrahigh gains $\sim 10^9$ by focusing the input wave as it diffracts from the orifice of coupling to the master oscillator. However, the diffraction focusing does not compress the field as efficiently as the classical refractive elements, such as lenses, prisms, etc. The radiation energy density in the focal point of a spherical lens can be thousands of times greater than the intensity of the original incident wave, whereas the diffraction focusing and the amplification by the laser active medium can produce an increase in the intensity only by a factor of 7 – 10 in the focal region.

To minimise the energy of the input pulse and maximise the energy gain, we propose in this work to initiate the autowave PBCR in a small focal volume of the active medium by an input pulse that is focused by a conventional lens. We also optimised numerically the parameters of the two-phase active medium, the characteristics of the focused external pulse, and the dimensions of the unstable telescopic cavity with the purpose of reaching ultimately high energy gains in relatively small autonomous pulsed HF lasers.

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2. Kinetics and wave optics of the PBCR-based laser-amplifier

The PBCR is initiated in the active medium of a HF laser-amplifier that contains dispersed passivated (due to the formation of an oxide film) Al particles according to the mechanism described in Ref. [1]:

$$\begin{aligned} &F + H_2 \rightarrow HF(v) + H, \\ &H + F_2 \rightarrow HF(v) + F. \end{aligned} \tag{1}$$

The active centres are produced in the fast reaction between fluorine molecules and aluminium atoms that are vaporised from the surfaces of finely dispersed particles by the external IR radiation:

$$Al + F_2 \rightarrow AlF + F.$$

The characteristic time of this reaction is less than 10^{-9} s for concentrations $n_{F_2} \geqslant 10^{19}$ cm^{-3}. We solve the chemical kinetic equations within the approximation of quasi-stationary concentrations of F and H [7]. In this case, the total number of active centres $n_a = n_F + n_H$ is given by

$$\frac{dn_a}{dt} = 4\pi r_0^2 \frac{dr_0}{dt}\frac{\rho_0 N_0}{M_{Al}} + \sum_i W_i^a, \tag{2}$$

where r_0 and ρ_0 are respectively the radius and density of Al particles and M_{Al} is the molar mass of aluminium. The first term in equation (2) describes the production of active centres of the chain in the reaction between F_2 molecules and vaporised Al atoms. The second term describes the variation in the active centre concentration due to the dissociation of molecules and the disruption of the chain in triple collisions.

Vibrational excitation of HF(v) molecules and their quenching is described by an equivalent two-level scheme [7]. In this scheme, the multiple vibrational levels of the HF(v) molecule are replaced by two levels, the upper one and the lower one, with the populations n_u and n_l, respectively, so that the power emitted on the lasing transition $(u, j-1) \rightarrow (l, j)$ coincides with the total power emitted on all vibronic transitions (here, j is the vibrational quantum number). The equations for the populations n_u and n_l have the form

$$\frac{dn_u}{dt} = W_u - \frac{P_L}{\hbar w_{ul}} - G_{VT}^{HF-M} - G_{VV}^{HF-H_2}, \tag{3}$$

$$\frac{dn_l}{dt} = \frac{P_L}{\hbar w_{ul}} + G_{VT}^{HF-M} + G_{VV}^{HF-H_2}, \tag{4}$$

Here,

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

is the rate of pumping the laser molecule to the upper level; k_1 and k_2 are the rate constants of reactions (1); $\mu = k_2 n_{F_2}/k_1 n_{H_2}$; G_{VT}^{HF-M} and $G_{VV}^{HF-H_2}$ are the rates of vibrational-translational and vibrational-vibrational relaxation, respectively; P_L is the emitted power density; and $\hbar w_{ul}$ is the photon energy in the two-level scheme [7].

The two-level model yields the following expression for P_L on the $(u, j-1) \rightarrow (l, j)$ transition:

$$P_L = \hbar w_{ul} \frac{2j+1}{4j}\left(\frac{n_u}{M_{j-1}\tau} - \frac{2j-1}{2j+1}\frac{n_l}{M_j \tau}\right), \tag{5}$$

where

$$M_j = \frac{T/Q_r}{2j+1}\exp\left[\frac{Q_r j(J+1)}{T}\right] - 1;$$

T is the gas temperature; Q_r is the characteristic rotational temperature of the HF molecule; τ is the characteristic time of rotational relaxation for a given j in the model of the rotational reservoir [7]. The power density P_L can be expressed in terms of the saturated gain $g(t) = g(z/c)$ of the laser-amplifier active medium as $g(t)I(r)$, where the intracavity intensity $I(r)$ is determined by the slowly varying complex amplitudes $\mathscr{E}^{\pm}(r, z)$ of the counterpropagating plane and spherical waves [4–6]:

$$I = \frac{1}{240\pi}\left|\mathscr{E}^{+}(r,z) + \mathscr{E}^{-}(r,z)\right|^2. \tag{6}$$

Here, I has the dimension of W cm^{-2}; $\mathscr{E}^{\pm}(r, z)$ is the dimension of V cm^{-1}; r and z are the transverse and longitudinal coordinates; and c is the speed of light. The complex amplitudes $\mathscr{E}^{\pm}(r, z)$ satisfy the wave equation, which in the parabolic approximation has the form

$$2i\hat{k}(\tilde{n})\frac{\partial \mathscr{E}^{\pm}(r,z)}{\partial z} + \Delta_{\perp}\mathscr{E}^{\pm}(r,z) = 0. \tag{7}$$

Here, $\hat{k}(\tilde{n})$ is the complex wave number describing the amplitude-phase modulation of the electromagnetic wave by inhomogeneities of the active medium; $\tilde{n}$ is the refractive index of the medium; and $\Delta_{\perp}$ is the transverse Laplacian. The initial conditions and the boundary conditions at the mirror surfaces take into account the interconversion of plane and spherical waves in the confocal unstable telescopic cavity, as well as the presence of the input control signal near the orifice of coupling to the master oscillator [4–6].

We will describe the amplification in the active medium at each small iterative step h_z in the direction z of the electromagnetic wave propagation in the following way:

$$\mathscr{E}^{\pm}(z + h_z, r) = \mathscr{E}^{\pm}(z, r)\exp(g h_z/2). \tag{8}$$

The gain $g(z/c)$ can be determined by solving simultaneously the system of chemical kinetic equations and the system of equations for the populations of the lasing levels.

3. Results and discussion

Using the wave approach, which we developed to describe the pulsed PBCR-based chemical HF laser-amplifier, and the proposed laser scheme with an unstable telescopic cavity, we discovered interesting optical effects in the two-phase active medium of the laser, as well as new properties of the laser itself (Table 1). Table 1 displays the results of the numerical calculations performed in this work and our earlier papers [4–6, 8–10].

Table 1. Main properties and characteristics of the PBCR HF laser-amplifier.

Observed effects and properties of the pulsed HF laser	Optimal parameters of the laser	Output characteristics	Comments
Autowave of a new kind: self-sustaining cylindrical zones of photon branching	Mixture $H_2 : F_2 = 1 : 2$	$E_{out} = 2292$ J, $E_{sp} = 300$ J litre^{-1}, $P_{max} = 7.6 \times 10^{10}$ W	$\tau_a \sim 10^3$ s
Huge energy gain in the case of a focused input pulse	$r_0 = 0.09 - 0.4$ μm, $N_0 = 10^9 - 10^7$ cm^{-3}	$\tau^L \approx 800$ ns, $\tau^L_{1/2} = 100$ ns	$I_{th} = (1 - 3) \times 10^{10}$ W cm^{-2}
Autonomy (the laser is initiated by a submicrojoule initial pulse from the master oscillator)	$E_{in} = 2.18 \cdot 10^{-8}$ J, $\tau_{in} = 250$ ns	$k_{amp} = 9.55 \times 10^{10}$	
Compactness	$N_p = 4, \beta = 2.41, d \leqslant 3$ mm	The output field is toroidal in the near-field zone and has a Gaussian profile in the far-field zone	

Notes: τ_{in} is the duration of the initiating pulse; E_{out} and E_{sp} are the total and specific energies of the output pulse, respectively; P_{max} is the maximum output power; τ^L is the full duration of the output pulse; $\tau^L_{1/2}$ is the duration of the output pulse at half the maximum power; I_{th} is the optical breakdown intensity of the medium; τ_a is the lifetime of the active medium with the specified properties; β and N_p is the magnification of the telescopic cavity and the number of transits of a beam inside it; d is the diameter of the input aperture.

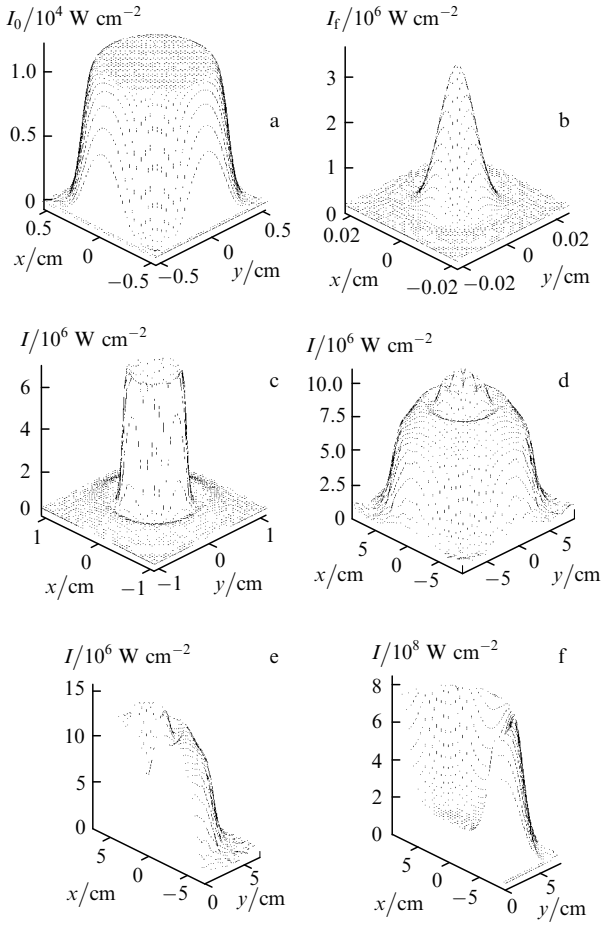

Figure 1. Spatial distributions of the intensity of the initial plane (a) and focused (b) input waves. The intensity distribution of the intracavity field in the 1st (c); 2nd, 3rd, and 4th (d); 3rd and 4th (e); and 4th (f) cylindrical zones of photon branching.

We studied a cavity that had the length $L = 49.5$ cm, the diameter of the first mirror $d_1 = 14$ cm, and the diameter of the second spherical ($f = 53$ cm) mirror $d_2 = 5.98$ cm. The cavity was supposed to be filled with the combustible working mixture $H_2 : F_2 : O_2 : He = 166 : 334 : 40 : 210$ Torr that contained passivated finely dispersed aluminium particles with the radius $r_0 = 0.2$ μm and the concentration $N_0 = 1.3 \times 10^8$ cm^{-3}. The focused IR beam from an external laser was directed to the laser-amplifier through the central coupling aperture of diameter d made in the front mirror of the cavity. The wavelength of the external laser source was $\lambda_{in} = 3.3$ μm and coincided with the lasing wavelength λ_g.

A Gaussian beam can be focused to a minimum focal radius of $r_f = \lambda/2\pi$. The focal region of approximately equal intensity has a longitudinal dimension of $2\Delta x = (4\pi/\lambda)r_f^2$ [11]. Therefore, the excited volume of the active medium $V_{in}^{min} = 2\Delta x \pi r_f^2$ can in principle be reduced to $\sim 10^{-13}$ cm^3. Physically, it is reasonable to focus into a volume that contains no less than 10 particles; then, for a concentration of $n \approx 10^8$ cm^{-3}, the minimum volume is $V_{in}^{min} \approx 10^{-7}$ cm^3, and the radius of the focused beam is $r_f = (\lambda V_{in}^{min}/4\pi^2)^{1/4} \approx 10$ μm.

The efficiency of the mechanism of the PBCR initiation is explained by the fact that the diffraction of a converging spherical wave from a small input aperture substatially affects the beam focusing. The scheme consisting of a lens and a small aperture that diaphragms the converging spherical wave provides a lower beam divergence (close to the diffraction limit) behind the focus than the focusing by a lens only. The beam cross section varies slowly in the longitudinal direction and has a waist near the focus.

In our model, the plane electromagnetic wave emitted by an external IR laser (Fig. 1a) was focused by a NaCl (or KCl) lens to a narrow beam (Fig. 1b), whose intensity in the focal region was $I_f = 3$ MW cm^{-2}. The degree of the field compression by a lens was $I_f/I_0 = 300$. For definitness, we assumed in calculations that the initiating radiation was focused at a small distance $z_f = d^2/4\lambda$ from the cavity input mirror, which was equal to the distance at which the first Fresnel zone was observed for the given diameter d of the input coupling aperture. The number N_p of transits of a beam in the unstable telescopic cavity can be written as

$$N_p = \left[\frac{\ln(d_2/d)}{\ln(1 + L/f)} + 2\right].$$

where the square brackets denote integer truncation. One can see that the focusing properties of the lens and its position are related to the parameters of the cavity. Therefore, the problem of coupling the initiating radiation to the cavity through the coupling aperture is self-consistent.

In our calculations, the diameter of the input coupling aperture was $d = 3d_f$, where $d_f = 2r_f$. The input energy E_{in} required to initiate the PBCR in the small focal volume also depended on d_f:

$$E_{in} = I_f \frac{\pi d_f^2}{4} \tau_{in}.$$

The duration of the input pulse τ_{in} was chosen so that the energy supplied to the focal volume $V_f \sim 10^{-7}$ cm^3 would be sufficient to vaporise aluminium particles for initiating the PBCR. Our calculations have shown that the threshold pulse duration of the master oscillator was 250 ns for the specified radiation intensity in the focal region.

It is interesting to consider the space-time behaviour of the intracavity field under the assumptions made above and to substantiate the possibility of initiating the autowave PBCR in a small focal region of the active medium of the laser. Figs 1c–1f show characteristic stages of the development of the PBCR and the formation of the radiation field inside the cavity. After heating dispersed Al particles in the focal region to the melting temperature during the time $t = \tau_{in}$, these particles begin to evaporate aluminium atoms, which promptly react with F_2 molecules, producing free F atoms. The chain reaction (1) starts producing vibrationally excited HF molecules, and the radiation in the first cylindrical zone intensifies. Fig. 1c shows the established field structure, formed in the central (first) zone of the cavity after multiple reflections from the mirrors.

The radiation from the first zone ignites the mixture in the whole cavity volume. As the PBCR spreads, the second, third, and fourth zones of the cavity are filled virtually simultaneously with radiation (Fig. 1d). The field forms in the second, third, and forth zones faster than in the first zone because the radiation passing through them is more intense than the input radiation.

Figs 1e and 1f show the further development of the lasing process. One can see from these figures that the development of the autowave PBCR is accompanied by the formation of a dip in the intensity profiles of the central (first and second) zones. This indicates that the active mixture gradually burns out in the central zones and loses its amplifying properties. In the fourth zone, the intense amplified radiation fills the entire circular volume of the cavity. The corresponding intensity profile is shown in Fig. 1f. Thus, using the wave approximation, we have demonstrated the possibility of initiating the autowave PBCR in an originally small focal volume of the laser active medium by an external focused IR pulse. The PBCR can then spread on its own over the entire volume of the laser active medium in the form of self-sustaining cylindrical zones of photon branching, formed in the unstable telescopic cavity.

Table 2 and Fig. 2 show the output energy characteristics of the considered laser-amplifier calculated for various focal spot diameters and the same field-compression factor $I_f/I_0 = 300$. In these calculations, the diameter of the focal volume d_f varied between 0.015 and 0.67 mm.

One can see from Table 2 that the output energy E_{out} and the maximum output power P_{max} of the laser slightly oscillate with varying d_f: $E_{out} \sim 2075 - 2268$ J and $P_{max} \sim (6 - 7.5) \times 10^{10}$W. These oscillations are caused, first, by the boundary diffraction effects that the input field experiences on the aperture. Second, as d increases, the loss of the output energy directly on the aperture increases after each reflection from the input cavity mirror. For the maximum diameter $d \approx 2$ mm ($d_f = 0.67$ mm), the energy losses on the aperture become so large that they drastically reduce the output energy E_{out} to ~ 1700 J. Naturally, the output power falls off as well.

Table 2. Output characteristics of the laser-amplifier with a 4-pass unstable telescopic cavity. The cavity is filled with the working mixture $H_2 : F_2 : O_2 : He = 166 : 334 : 40 : 210$ Torr that contains finely dispersed aluminium particles ($r_0 = 0.2$ μm, $N_0 = 1.3 \times 10^8$ cm^{-3}). The reaction is initiated by a focused IR pulse ($\tau_{in} = 250$ ns, $I_0 = 3$ MW cm^{-2}) in the focal volume with the diameter d_f. The degree of compression of the focused field I_f/I_0 was taken to be ~ 300.

d_f/mm	E_{in}/J	E_{out}/J	E_{sp}/J	τ^L/ns	k_{amp}	$P_{max}/10^{10}$ W
0.015	2.182×10^{-8}	2082.9	273.35	892.64	$9.55 \cdot 10^{10}$	6.869
0.03	8.727×10^{-8}	2268.3	297.68	882.76	$2.6 \cdot 10^{10}$	7.486
0.05	1.963×10^{-7}	2160.0	283.0	884.0	$1.1 \cdot 10^{10}$	7.124
0.1	7.854×10^{-7}	2173.16	285.2	886.1	$2.77 \cdot 10^9$	7.17
0.2	3.142×10^{-6}	2176.57	285.64	882.76	$6.93 \cdot 10^8$	7.18
0.33	8.727×10^{-6}	2121.02	278.35	882.96	$2.43 \cdot 10^8$	6.97
0.53	2.234×10^{-5}	2210.11	290.0	858.0	$9.89 \cdot 10^7$	7.3
0.67	3.49×10^{-5}	2075.16	272.33	850.0	$5.94 \cdot 10^7$	6.865

The energy gain k_{amp} also depends exponentially on the focusing conditions (Fig. 2). The tight focusing of the input pulse minimises the originally excited volume V_{in} of the laser active medium and hence greatly reduces (to a fraction of a microjoule) the minimum energy of the input pulse sufficient to initiate lasing (Table 2). Thus, due to the focusing of the input pulse and the autowave spreading regime of the PBCR, the ultrahigh energy gain $k_{amp} \approx 10^{11}$ is achieved in the active medium of the laser.

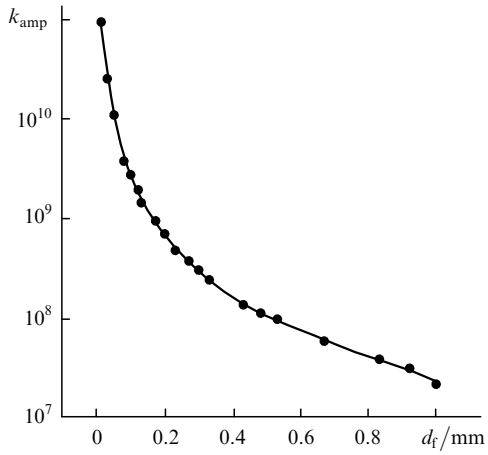

Figure 2. Calculated dependence of the energy gain k_{amp} on the diameter of the focused input pulse d_f in the case of the laser working mixture $H_2 : F_2 : O_2 : He = 166 : 334 : 40 : 210$ Torr containing finely dispersed aluminium particles of radius $r_0 = 0.2$ μm and concentration $N_0 = 1.3 \times 10^8$ cm^{-3}.

Table 3. Output characteristics of the pulsed chemical HF laser/amplifier for various values of the geometric parameters of the cavity and the total pressure p of the laser working mixture $H_2 - F_2 - O_2 - He$.

Cavity parameters				$r_0/\mu m$	$N_0/10^8\ cm^{-3}$	p/bar	Mixture $H_2:F_2:O_2:He$ content/Torr	$I_f/MW\ cm^{-2}$	τ_{in}/ns	E_{out}/kJ	$E_{sp}/J\ litre^{-1}$	$P_{max}/10^{10}W$	τ^L/ns
L/cm	d_2/cm	f/cm	β/cm										
49.5	5.98	53	1.93	0.2	1.3	1.0	76:228:23:578	5	150	1.485	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	0.09	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

This huge energy gain drastically reduces the threshold energy E_{in} of the initiating pulse to 10^{-8} J (Table 2). Therefore, a small submicrojoule laser can be used as a master oscillator and one can create an autonomous pulsed chemical HF laser-amplifier with the low-energy initiation.

The autowave lasing regime and the huge energy gain obtained upon focusing the input pulse allow one to produce coherent laser pulses with the energy of several kilojoules in a relatively small volume of the active medium of the HF laser and therefore to build very compact lasers. Table 3 and Fig. 3 present the output energy characteristics of the considered laser-amplifier that were calculated for various values of the geometric parameters of the cavity and the total pressure of the laser working mixture. These calculations show that, just by optimising the parameters r_0 and N_0 of the dispersed particles, we can increase the specific energy release E_{sp} by a factor of 1.5 from 195 to 313 J litre^{-1} (Table 3). Therefore, we can reduce the cavity length by a factor of 2 (from ~ 50 to ~ 25 cm) while preserving the high output energy ($E_{out} \sim 1200 - 1500$ J).

The specific output energy E_{sp} can further be increased by a factor of $2 - 2.5$ by increasing the pressure p of the working mixture of the laser to $2 - 2.3$ bar. The specific energy release ~ 737 J litre^{-1} allows one to obtain the above-mentioned output pulse energy in an unstable telescopic cavity that is as short as ~ 13 cm. With such a short cavity and a small battery-powered submicrojoule master oscillator, the laser becomes a compact autonomous device capable of producing pulses with the energy $E_{out} \sim 1.5$ kJ.

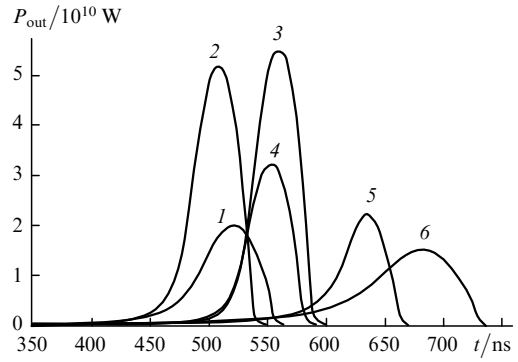

Figure 3. Time dependence of the output power P_{out} of the laser-amplifier in the case of $L = 26.4$ cm, $p = 1$ bar (*1*), $L = 26.4$ cm, $p = 2$ bar (*2*), $L = 26.4$ cm, $p = 2.3$ bar (*3*), $L = 13.2$ cm, $p = 1$ bar (*4*), $L = 33$ cm, $p = 1$ bar (*5*), and $L = 49.5$ cm, $p = 1$ bar (*6*).

4. Conclusions

We have theoretically analysed the energy properties and the space-time behaviour of the electromagnetic field in a pulsed chemical laser based on the PBCR initiated in the gas-dispersion medium $H_2 - F_2 - O_2 - He - Al$ particles by the focused external IR radiation. Within the wave approximation, we have solved the optical problem of matching the focusing properties of the lens with the geometric parameters of the unstable telescopic cavity. We have demonstrated the possibility of initiating the laser-chemical reaction in an originally small focal volume of the active medium. The reaction then spreads in the autowave regime over the entire volume of the laser in the form of self-sustaining cylindrical zones of photon branching, formed by the beam path in the unstable telescopic cavity. The initiation of the autowave PBCR by a focused external pulse drastically reduces the threshold energy of the input pulse to ~ 0.01 μJ, resulting in a huge energy gain of $\sim 10^{11}$.

The observed giant amplification of the laser energy allows one to use a small submicrojoule laser as a master oscillator and, hence, to build an autonomous pulsed chemical HF laser-amplifier. Furthermore, by increasing the specific energy release of the laser to 737 J litre^{-1} by optimising the parameters of the dispersed component (Al particles with the radius $r_0 = 0.09$ μm and the concentration $N_0 = 1.4 \times 10^9$ cm^{-3}) and increasing the pressure of the working mixture to 2.3 bar, we can obtain the output pulse energy $E_{out} \sim 1.5$ kJ in a relatively small unstable telescopic cavity ($\sim \varnothing 14 \times 13$ cm).

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References

1. Igoshin V I, Pichugin S Yu *Kvantovaya Elektron.* **10** 458 (1983) [*Sov. J. Quantum Electron.* **13** 267 (1983)]
2. Azarov M A, Drozdov V A, Igoshin V I et al. *Kvantovaya Elektron.* **24** 983 (1997) [*Quantum Electron.* **27** 953 (1997)]
3. Igoshin V I, Katulin V A, Pichugin S Yu *Trans. of XII Intern. Congress 'Laser-95'* (Munich, 1995) p. 362
4. Igoshin V I, Letfullin R R *Kvantovaya Elektron.* **24** 501 (1997) [*Quantum Electron.* **27** 487 (1997)]

5. Igoshin V I, Letfullin R R *Kvantovaya Elektron.* **26** 37 (1999) [*Quantum Electron.* **29** 37 (1999)]
6. Letfullin R R, Sannikov S P *Kvantovaya Elektron.* **26** 43 (1999) [*Quantum Electron.* **29** 43 (1999)]
7. Basov N G, Bashkin A S, Igoshin V I, Oraevsky A N, Shcheglov V A *Chemical lasers* (Berlin: Springer-Verlag, 1990)
8. Letfullin R R, Melikhov K G, Igoshin V I, Mitlina L A *Kvantovaya Elektron.* **25** 911 (1998) [*Quantum Electron.* **28** 887 (1998)]
9. Bekrenev A N, Letfullin R R, Igoshin V I, Melikhov K G *Kvantovaya Elektron.* **24** 227 (1997) [*Quantum Electron.* **27** 221 (1997)]
10. Igoshin V I, Letfullin R R, Pichugin S Yu *Trudy FIAN* **217** 146 (1993)
11. Karlov N V *Lektsii po kvantovoi elektronike* (Lectures on quantum electronics) (Moscow: Nauka, 1983)