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Advanced modifications of typical excimer laser resonators

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Abstract. In the paper proposed are some simple modifications of plane-parallel and unstable telescopic resonators the most widely used in excimer lasers. These can increase output energy, density of emission power and improve the shape of a laser beam cross-section. Physical essence of these modifications lies in formation of an optically closed zone in some part of the resonator, which prevents photons to escape. This yields in their increased concentration (the so-called 'photon concentrator') that favors discharge stabilization and shifting this zone towards a cathode where main instabilities of an electric discharge originate. In the plane-parallel cavity such a photon concentrator can be realized by application of an output window with a mirror area in the range corresponding to the cathode space. Using the scheme in our conditions we observed the increase of laser pulses emission energy by 15% and, respectively, their energy density by 44% with simultaneous decreasing the laser beam shape extent (in its cross-section) and proportional reducing a beam divergency along the diminished size. In the unstable telescopic resonator this kind of a closed zone (photon concentrator) should exist by definition and, as a rule, in a paraxial part of it. The modification proposed consists in shifting this zone towards a cathode. In our conditions this way provided the increase of laser pulse emission energy by 5% with simultaneous improvement of the laser beam shape (in its cross-section). It means shifting a shaded spot towards a border of the beam cross-section and, in such way, to its practical removal out of operating beam.

Keywords: excimer laser, plane-parallel resonator, unstable telescopic resonator, pulse emission energy, power/energy density.

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1. Introduction

Excimer lasers (EL) and complex based on them are the most powerful sources of coherent UV emission and used more and more widely in diverse spheres of human activity, namely: from fundamental investigations to newest high technologies, from medicine till environmental monitoring, etc. [1]. At the same time, along with indisputable advantages, emission of such lasers has several definite deficiencies that need investigations and improvements. The first and the most common limitation is a shape of a laser beam cross-section. For typical and the most widespread electric-discharge EL, it, as a rule, has a look of an extended rectangular with dimensions (5…10) × (20…30) mm^2 with the side ratio 1: (3…6), which is conditioned by the nature of EL active media based on transverse electric discharge in a gas volume with considerable area and length. To some extent, the above relationship between rectangular sides can serve as some characteristic of laser perfection, balance of its construction and mainly of its preionization and excitation systems. The application of promising plasma electrodes in excimer laser [2] enables one to significantly improve the ratio of beam section rectangular sides [3]. In recent years, to overcome this deficiency, excimer lasers are frequently supplemented with the so-called «homogenizers» that transform a beam with an extended-rectangular cross-section as well as non-uniform energy distribution into a beam with the round (or square) cross-section and uniform distribution of energy in it (see, for instance, [4]). But these homogenizers consist of many precise optical parts made of silica with interferential dielectric anti-reflection coatings, and therefore these are very expensive optical attachments.

The second deficiency of excimer laser emission when using the simplest plane-parallel cavity (PPC) is the large value of its divergency $\varepsilon = 10^{-2}…10^{-3}$ rad (that is poor directivity). It is a consequence of a small lifetime intrinsic to excimer molecules (1…10 ns), which corresponds to a small time of inversion existence (10…100 ns) in the excimer active medium. Thus, only the lowest emission modes formed in the course of little numbers of passes (3 to 5) in the resonator can contribute into lasing [5,6]. Besides, it is evident that divergencies of a laser beam along its width and height are proportional to the latter ones and due to this fact differ one another. These circumstances complicate both calculation and experimentation when it is necessary to focus the beam to minimum possible dimensions.

The third deficiency of EL emission produced by the simplest spectral-nonselective PPC and unstable confocal telescopic cavities (UTC) is a large width of generated line and/or complex spectral composition of laser emission [7].

EL designers work hard to overcome above deficiencies both all these together and each one separately. To illustrate the diversity of efforts applied in this direction, one can refer to author's certificate [8] where, to suggest some way of transforming a cross-section of an output beam into a round shape and energy distribution in it up to the axial-symmetric one, the author offers to screw discharge along its length using spiral (!) electrodes.

To reduce divergency, three-pass UTC are the most often used for both generating emission with small divergency as well as saving energy and emission amplification (Fig. 1a, b). But application of a classical axial-symmetric UTC causes formation of a shaded spot produced by a small mirror deposited on a resonator output optical element. This spot is situated in the very center of the rectangular beam cross-section (Fig. 1c). It is this fact that prevents both theoretical and experimental estimation of energy (power) distribution in the vicinity of the beam focus.

Using classical methods of narrowing generation lines, one can achieve decrease of their width at the cost of considerable reducing their output energy (see, e.g. [9]). Note that spectral investigations were not performed in this work.

It is possible to overcome simultaneously the second and third deficiencies by using two exactly synchronized and optically combined EL operating by the scheme «generator-amplifier». But such usage of two EL coupled is not always economically expedient and accessible to any user.

Thus, there exist several obvious objective needs that stimulated investigations of EL resonators main types, which was performed by the author and directed to improvement of EL beam geometrical characteristics and/or to a rise in pulse emission energy. Directions of these investigations were promoted by the following circumstances:

1) There exists non-coordination between a linear amplification factor of active medium, time of inversion existence and a resonator load in EL, which can be developed as a high level of reinforced spontaneous luminescence. Sometimes, this non-coordination can be weakened by reducing transmission of resonator output optical element across its whole aperture [10], which provides some positive result. Then, there arises the next question: whether it is possible to reach the same or alike result by local reducing the transmission?

2) Inherent to EL is also non-uniformity of a voltage drop in the discharge gap along its height (Fig. 2) and, as a consequence, non-uniformity of energy release distri-

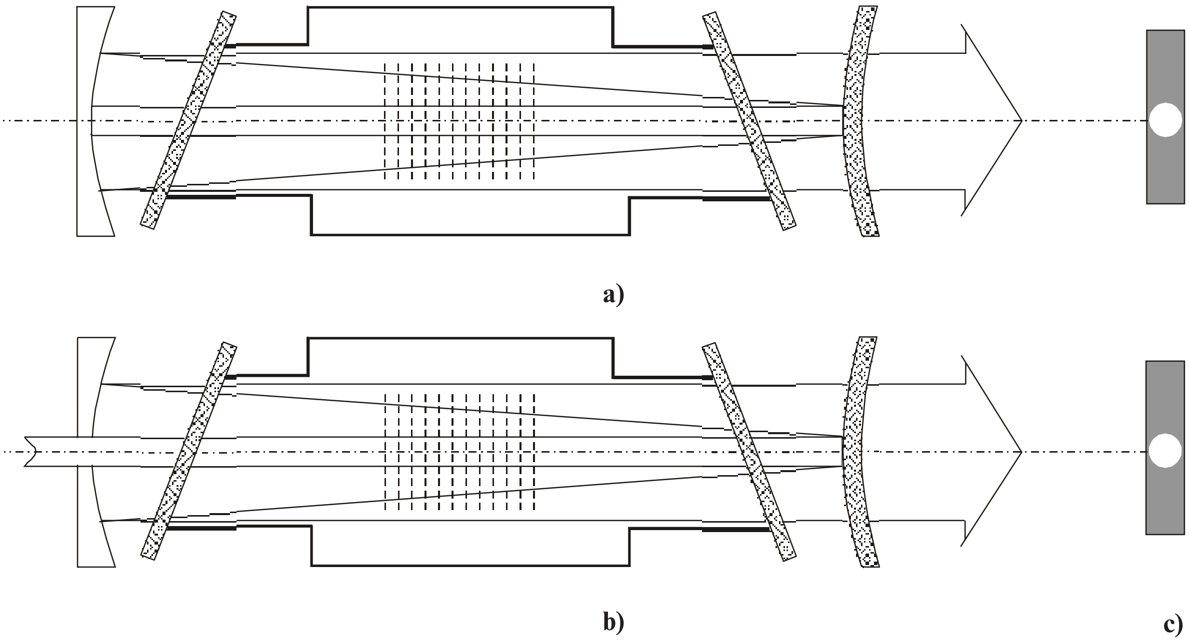

Fig. 1. Schemes of unstable telescopic resonators used for: a) generation of emission with a small divergency; b) amplification of emission with a small divergency; c) a laser beam cross-section look.

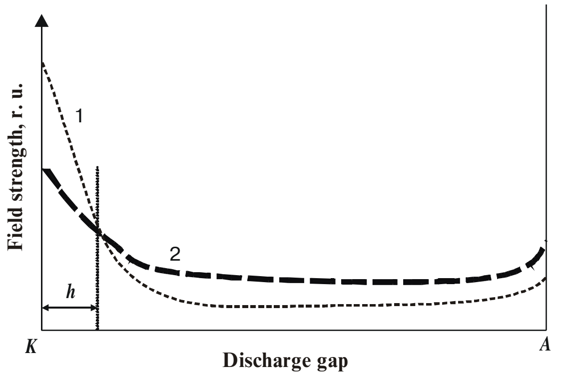

Fig. 2. Distribution of an electric field strength along the discharge gap in a plane-parallel resonator: 1 – without any additional mirror, 2 – with an additional mirror introduced into the resonator up to the distance *h*.

bution that yields in non-uniformity of output energy along the beam height. This non-uniformity can be corrected or passively used by reducing a transmission of the resonator output optical element just at the same level.

Besides, in [11] assumption was made that the photon field of a resonator plays some stabilizing role as to electric discharge what is partly evidenced in [12]. If this assumption is valid then the optically closed internal range with an increased photon concentration (photon concentrator), fixed between a back mirror and a mirror part of a resonator output optical element, should play the same stabilizing role as to electric discharge. This, in its turn, should develop in increasing energy of laser pulses.

2. Experimental details

Investigations were carried out using a typical XeCl* EL with a transverse electric discharge and spark UV pre-ionization in the construction like to that used in [13]. Electrodes for spark pre-ionization were positioned symmetrically on both sides of the cathode approximately 15 mm apart from it and 30 mm from the anode. Dimensions of the discharge (and active medium, respectively) were $500 \times 22 \times (6\ldots7)$ mm^3. The respective cross-section of the laser beam was $22 \times (6\ldots7)$ mm^2. As operating mixture HCl:Xe:He = 2:20:1500 Torr was used. An operating voltage was determined by using the thyratron IGI – 1000/25 and varied in the range of 7 up to 24.9 kV. The pulse train frequency reached 50 s^{-1}.

The laser worked in the frequency mode of 13…15 Hz. Energy of laser pulses was measured with the power meter IMO–2H that was used in the regime of mean power measurements (with the main inaccuracy ±3%, zero drift of $2{\cdot}10^{-5}$ W min^{-1} and time constant of 40 s).

The investigations were performed in three logically connected stages. First, the distribution of a generation energy along the height of the discharge gap was checked up experimentally. At this stage, the slit of 1 mm width positioned perpendicular to the discharge height, *H*, was situated just behind the output window of the PPC and displaced along the height of the discharge gap from one electrode to another (Fig. 3).

At the second stage, investigated was the PPC supplemented with an Al-mirror 1 and a silica plate 2. An additional Al-mirror 3 was introduced into the resonator beside the output silica plate at the height *h*. The possibility to introduce it from the side of any electrode keeping its parallel orientation to the main mirror 1 was provided (Fig. 4).

At the third stage, investigated was the UTC consisted of a spherical Al-mirror 1 and two output menisci 2 and 2′ with mirror discs in their centers (Fig. 5). Diameters of mirror discs, d_1 and d_2, height of active medium (electrical discharge), *H*, length of laser chamber *L*, radii of surface curvature, *r* and *R*, focal distances *f* and *F*, *M′* – magnification of active part of resonator, ratio of output beam to input seed beam diameters were deduced from simple geometric considerations [5], which is also clear from Figs 1 and 5b,c : $R/r = F/f$; $H/h = M'$; $F\text{-}f = L$. Respective values were as follows: $R = 2000$ mm, $r = 200$ mm, $F = 1000$ mm, $f = 100$ mm, $H = 22$ mm, $d_1 = 2$ mm, $d_2 = 4$ mm.

It is clear from the same geometric considerations that simple shifting the UTC axis towards one electrode is not quite correct, because of two different values of the resonator amplification factor *M′* should correspond to these two positions of the cavity axis: in the midway between electrodes and in the vicinity of one of them (Figs 5b,c). Therefore, it is necessary to choose a corresponding way of smooth (or gradual) changing the resonator amplification factor *M′*. But it is rather difficult to realize this way in practice. To overcome indicated incorrectness, the investigation of UTC was carried out in three steps:

- first, made was synchronic (with keeping their mutual resonance position) shifting both mirrors and, consequently, the resonator axis – AA-line in Fig. 5a – from

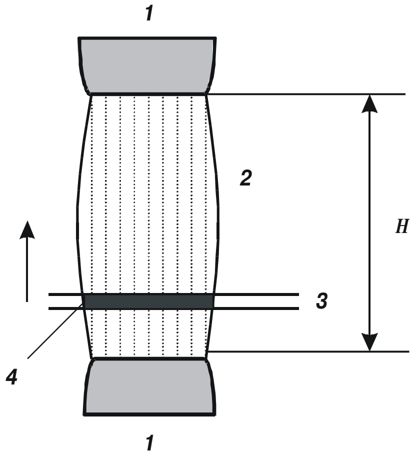

Fig. 3. The optical scheme of experiment to determine generation energy distribution along the height *H* of a laser beam cross-section (discharge gap): 1 – electrodes, 2 – discharge, 3 – slit, 4 – output beam.

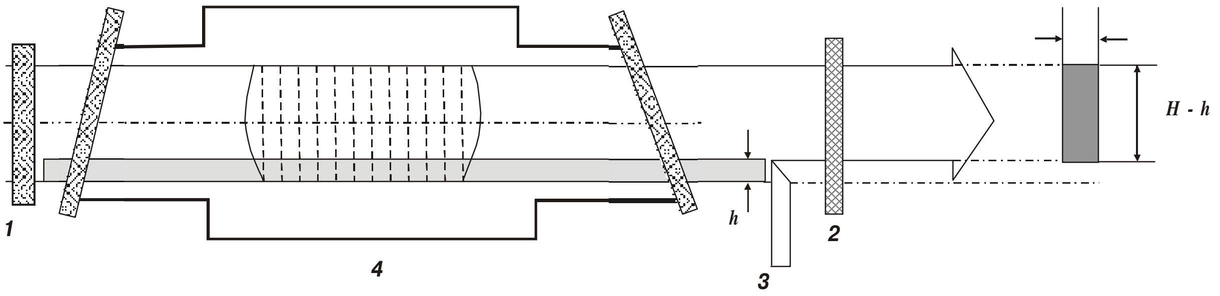

Fig. 4. The scheme of plane-parallel cavity modification: 1 – mirror, 2 – output window, 3 – additional mirror, 4 – laser chamber. *a* – beam width, *H* – initial beam height, *h* – height of additional mirror position.

their central between position electrodes (BB-line in Fig. 5) where these lines coincided (Fig. 5a) towards one of electrodes (Fig. 5b);

- second, the output meniscus 2 with the mirror having the diameter d_1 = 2 mm was replaced by the meniscus 2' with the same radius, but with central mirror of two-fold diameter d_2 = 4 mm (Fig. 5c) which changed the amplification factor from M' = 11 to M' = 5.5;

- third, using the meniscus with the latter mirror (d_2 = = 4 mm), synchronic lifting both mirrors (and the resonator axis) was fulfilled up to the central position (Fig. 5d).

3. Results and instructions for designing proposed resonator types

The distribution of generation energy along the height of a discharge gap is shown in Fig. 6. It is obvious that the density of generation energy near the anode (A) exceeds by 30% that in the vicinity of the cathode (K). Such distribution is characteristic for electric discharge ELs [14] and caused by a non-uniform (along the height) voltage drop in the discharge gap that results in non-uniform energy release and respective non-uniformity of a generation energy density.

Fig. 7 illustrates the following dependencies:

- of laser pulses relative energies versus *h*-values, i.e. displacements of the additional mirror 3 into the PPC (Fig. 4a) from the cathode side (curve 1) and the anode one (curve 2), respectively;

- of laser pulses relative energies versus the UTC axis displacement values (the line AA in Fig. 5). These values are reckoned from the mean line of an active medium (discharge) (see the line BB in Fig. 5) when moving towards the cathode within the UTC with M' = 11 (curve 3) and M'=5.5 (curve 4).

When considering results of the output obtained, it was assumed that observed changes of the output energy could be related to duration and/or time shape changes of laser pulses. To check this assumption, observations of the laser pulses time shape were carried out using standard devices FEK – 22SPU and S7-19. No changes were observed.

All dependencies are plotted in the same figure and scale in order to conveniently compare laser pulse energies when using both these cavity types and their modifications.

As seen from these figures, laser pulse energies for both cavities depend on variable parameters in very complex and non-obvious manner. For instance, with increasing the closed part of the PPC (Fig. 7, curves 1, 2) one can observe initially the increase of the output energy value, then this value reaches maximum for a definite *h*-value that is followed by decreasing values down to zero when full shutting down the outlet. Moreover, this output energy increase was more expressed while keeping the additional mirror near the cathode (K) than near the anode (A).

Taking into account advantages attained with positioning the closed zone near the cathode, which was ascertained during PPC investigations, we studied UTC in the same range near the cathode. When researching the UTC, the output energy behaves in a similar way, although its amplitude changes are less. For example, changing a PPC by the axis-symmetrical UTC with M' = = 5.5, one can raise the output energy value by 5 %, while for the UTC with M' = 11 it is practically unchanged (curves 3 and 4 in a central position, Fig. 7). Displacing the UTC axis towards the cathode one can observe some increase in the output energy, moreover, for the UTC with M' = 5.5 this increase is more pronounced (up to5%).

Abovementioned dependencies demonstrate perceptible efficiency of suggested modifications for both resonator types and analyzing them one can draw the following conclusions:

- in the case of PPC, introduction of an additional mirror from the side of a cathode up to 4 mm (this is equal to 20% of the cross-section) results in increasing the laser pulse energy by 15% with simultaneous decreasing area of the beam cross-section by 20%, which increase an emission energy density by approximately 44%. This is accompanied by effective improvement of the beam cross-section shape: its length and divergency diminish along this dimension;

- replacing PPC by axis-symmetrical UTC can cause an increase of laser pulse energy. In this case the decisive

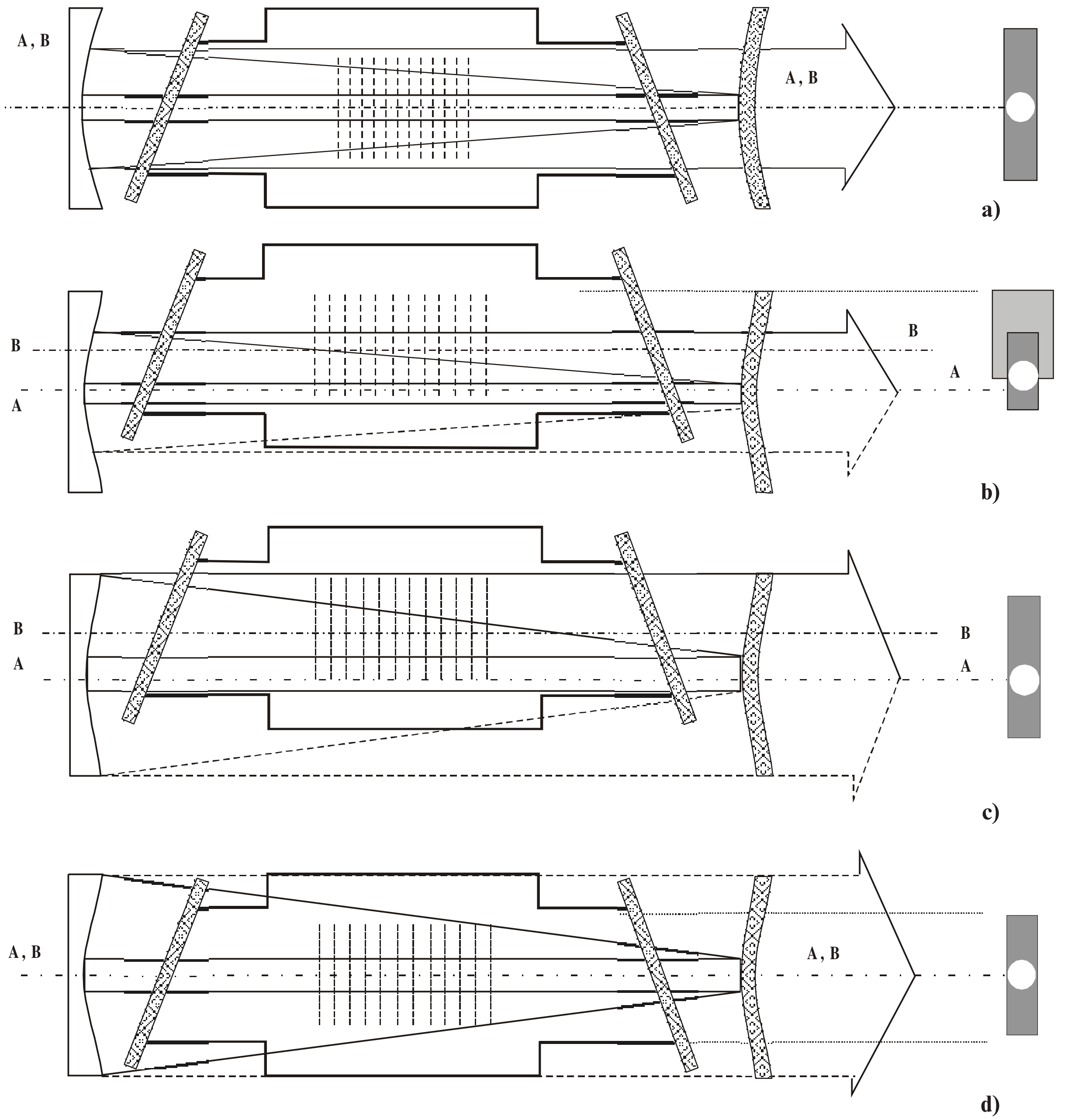

Fig. 5. The scheme of unstable telescopic resonators and the sequence of investigation steps: a – UTC with $M' = 11$; a-b – shifting the UTC ($M' = 11$) axis towards one of the electrodes; c – change of the output meniscus 2 with a mirror diameter 2 mm by the meniscus 2′ with a mirror diameter 4 mm, which results in transformation of UTC with $M' = 11$ into that with $M' = 5.5$; c-d – lifting the UTC (M'=5.5) axis up to the middle (axial relatively to electrodes) position.

role is played by the ratio of areas of the shaded spot and discharge cross-section. Eventually, it depends on the optical amplification factor M'. Moreover, this increase of the output energy can be essential and reaches its peak value at the definite M'-value that probably correlates with respective area ratio in the case of PPC. In our experiments, the energy increase was approximately 5% at M'=5.5;

- in the case of UTC at M'=5.5, the laser pulse energy increase when shifting the cavity axis towards a cathode was about 5%, i.e. insignificant. It is obvious that in this case the beam cross-section area does not change, but the shaded spot is displaced out of the beam borders.

The author believe that with reference to electric discharge, such increase can be ascribed to a stabilizing role that is played by the region of an increased photon concentration (photon concentrator) formed in the discharge. When the concentrator is present, a large voltage drop near the cathode is decreased as a result of increasing electron concentration caused by photoioni-

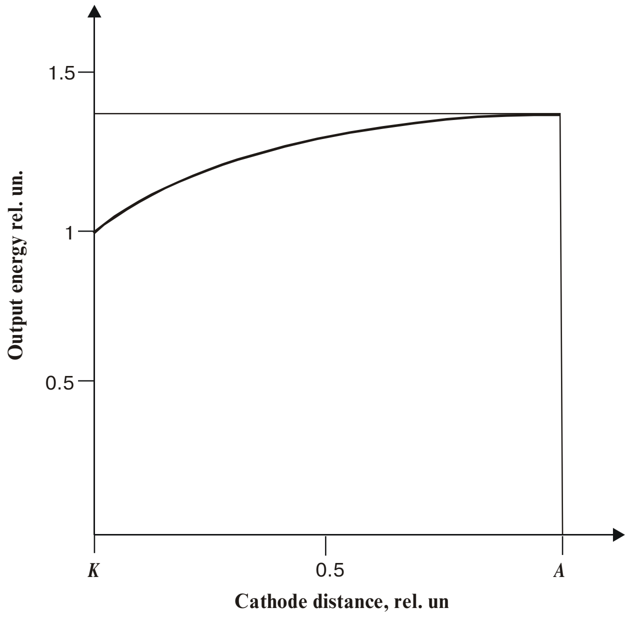

Fig. 6. Distribution of emitted energy along the laser beam height.

zation of negative Cl^- ions [15,16]. That yields in growing field strength along the main part of the discharge space (Fig. 2, curve 2), which rises energy contribution and, respectively, energy of generation. But these results as to UTC should be considered as the preliminary ones, as an accuracy of measurements using IMO-2H meter is insufficient to make a reliable conclusion.

It should be mentioned that all suggested modifications have one deficiency that lies in presence of several parasitic beams reflected from continuous metallic electrodes. Reasoning from geometrical considerations, these beams have a less number of useful passes than the main ones (as a result of weaker reflections from electrodes) and, therefore, a less energy value.

Besides, they spread at some angles to the main beams and can be easily separated with space filters. This difficulty can be avoided using perspective sectionalized electrodes (cathodes) [15] considered as the discharge-stabilizing ones or grids [16] that enable one to place a preionization source directly under the cathode. This way provides insignificant reflection, and parasitic beams will have much less energy than in our case.

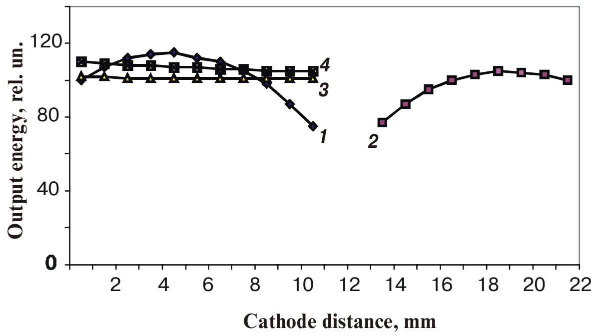

Fig. 7. Dependences of output energy on additional mirror positions within PPC (curves 1, 2) and UTC axis displacements towards the cathode (curves 3, 4).

Conclusions

Modifications of the most widely used in excimer lasers resonators – PPC and UTC – that enable one to improve emission parameters have been investigated in this work.

It is shown that formation of a photon concentrator in any region of an active medium as well as variation of its dimensions and positions relatively to a cathode are able to promote coordination of discharge and active medium characteristics, which, in its turn, can provide an increase of laser pulse energy.

In the author's opinion, suggested modifications of an EL resonator demonstrate definite advantages against the existing ones and can find their further development, improvement and application.

References

1. S.G. Anderson Review and forecast of laser markets: 1999-Part1 //*Laser Focus World*, №1, pp. 80-84 (1999).
2. V.Yu. Baranov, V.M. Borisov, Yu.Yu. Stepanov, *Electrodischarge excimer lasers,* Energoatomizdat, Moscow, 1998, pp. 33-41 (in Russian).
3. Yu.I. Stupak, M.P. Antonenko, V.V. Nesprava, N.S. Belokrinitskiy, USSR. a.c. №1552961, *Electrode system of the electrodischarge laser* (in Russian).
4. «Exitech. Advanced Laser Research» Long Hanborough, Oxford, UK, 1995.
5. Yu.A. Ananiev, *Optical resonators and laser beams.* Nauka, Moscow, 1990 (in Russian).
6. V.Ch.Belash, V.A. Kartazayev, V.L. Naumovich // *Kvantovaya elektronika,* №6, pp.68-72 (1989) (in Russian).
7. A. Luches, V. Nassisi, M.R. Perrone, E. Radiotis//*Optical Communication* №1-2, pp. 97-102 (1989).
8. A.c. JP № 61-187388
9. V.E. Peet, A.B. Treshchalov // Kvantovaya elektronika, №12, pp. 242-248 (1987) (in Russian)
10. E. Popp, W. Sajda, J. Bohnenberger, E. Bolte, F. Moller, K. Yasui, M. Tanaka, M. Kuzumoto, H. Amagasaka, A.c. DE № OS 3639580, Laser appliance
11. A.c. JP № 61-199686.
12. K.E. Oughstun, A.c. US № 4769614, *Unstable resonator with the changed Fresnel zone.*
13. V.P. Ageyev, V.V. Atezhev, V.S. Bukreyev, S.K. Vartapetov, A.N. Zhukov, V.I. Konov, A.D. Saveliev // ZhTF **56**(7), pp. 1387-1389 (1986) (in Russian)
14. V.Yu. Baranov, V.M. Borisov, Yu.Yu. Stepanov // Kvantovaya elektronika, pp.1542-1546 (1987) (in Russian)
15. V.M. Baginskiy, N.G. Basov, P.M. Golovinskiy, V.A. Danilychev, A.I. Milanich, A.M. Soroka, A.I. Shchedrin// Pis'ma v ZhTF, **11**(10), pp. 627-631 (1985).
16. V.M. Baginskiy, P.M. Golovinskiy, V.A. Danilychev, A.I. Milanich, A.M. Soroka, A.I. Shchedrin // *Kvantovaya elektronika* **13**(4), pp. 751-758 (1986).
17. Patent GDR № 297038, *Discharge chamber of excimer laser.*
18. V.V. Apollonov, G.G. Baitsur, A.M. Prokhorov, K.N. Firsov // *Pis'ma v ZhTF* **11** (20), pp. 1262 (1985) (in Russian)