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# Unstable resonators of high-power chemical oxygen – iodine lasers

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*Abstract*. **Configurations of unstable resonators are considered depending on the basic parameters of a high-power chemical oxygen – iodine laser and the design of an unstable resonator is proposed which provides the compensation of the inhomogeneity of the small-signal gain downstream of the active medium, a high energy efficiency, and stability to intracavity aberrations. The optical scheme of this resonator is presented and its properties are analysed by simulating numerically the kinetics of the active medium and resonator itself in the diffraction approximation.**

***Keywords***: *chemical oxygen – iodine laser, unstable resonator, diffraction calculation of the resonator*.

## 1. Introduction

Chemical oxygen – iodine lasers (COILs) are a most promising type of gas lasers from the point of view of various practical applications. This is caused by the following factors:

(i) A high specific energy extraction allowing the construction of high-power and compact systems;

(ii) the possibility of the development of autonomous systems because the energy source is a chemical reaction;

(iii) the laser wavelength of 1.315 μm making it possible to build systems with a low angular divergence and transmit radiation through a silica fibre;

(iv) a high optical homogeneity of the active medium (AM) and, therefore, good optical quality of radiation.

However, along with these advantages, some difficulties are encountered in applications of COILs:

(i) A small wavelength results in a high sensitivity of the laser to intracavity inhomogeneities such as misalignment as well as to defects of optical elements and atmospheric turbulence;

(ii) the distribution of the gain downstream of the AM is inhomogeneous and differs from such distributions for lasers of other types;

(iii) the small-signal gain in the AM is low, which imposes certain requirements on the structure of the optical resonator.

In this connection an important problem in the development of moderate- and high-power COILs is the creation of efficient unstable resonators. The general theory of these resonators and some aspects of their realisation in COILs were considered in [1 – 3].

This problem is especially important for moderate-power COILs [4] where a high magnification factor in the resonator should be provided to improve the spatial characteristics of radiation in the case of a small gain length. In [5, 6], an attempt was made to solve this problem by using a hybrid resonator, which was stable (plane – parallel) on one plane and unstable in another plane perpendicular to the first one. This method has a number of disadvantages, for example, it is sensitive to misalignments in the plane of the plane – parallel resonator. In addition, this method does not solve completely problems related to a small duration of amplification and, hence, a low magnification factor of the resonator. The use of unstable resonators of the negative branch with the intracavity waist to compensate for intracavity inhomogeneities leads to a considerable increase in the size of the system because of necessity to move the waist outside the active medium [5].

## 2. Peculiarities of the active medium of a COIL concerning the choice of the optical resonator

Consider the peculiarities of the active medium of a COIL which should be taken into account in the development of the optical scheme of the resonator.

1. The active medium of a COIL has a comparatively low gain. Its value is determined by the concentration of active particles (excited iodine atoms), the cross section for resonance interaction with photons and the gain linewidth.

Thus, at a pressure of 2 – 3 Torr and temperature 200 K for the traditional composition of the active medium (the relative consumption of iodine is 2 % and the degree of dilution with the primary nitrogen is three [11]), the small-signal gain is $g_0 = 0.5 - 0.6$ m$^{-1}$ and the gain linewidth is mainly determined by the Doppler broadening. As the static pressure is increased, the gain increases; however, the impact broadening dominates already at $P \approx 8 - 10$ Torr. This means that the linewidth is proportional to pressure and the gain ceases to increase despite the increase in the concentration of atoms. The characteristic value of the small-signal gain measured at a high static pressure of the medium is close to 1 m$^{-1}$.

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On the other hand, the effective unstable resonator should have a high enough magnification $M$, otherwise it is very sensitive to vibrations of mirrors. In addition, the unstable resonator with the magnification factor close to unity has no considerable advantage over a multimode stable resonator in respect of the radiation divergence. This means that in the case of a low small-signal gain, the amplification length should be large enough. From the point of view of stationary lasing, the radiation intensity at an arbitrary point inside the resonator remains invariable from transit to transit. The condition of stationary lasing can be written in the form

$$\exp(2g_0L_{\mathrm{AM}}) = M^2.$$

If the magnification factor of the resonator is two, the AM length required for the appearance of lasing is $L_{\mathrm{AM}} = 1.4$ m for $g_0 = 0.5$ m$^{-1}$ and 0.7 m for $g_0 = 1$ m$^{-1}$. For a 10-kW COIL, these parameters can be achieved only by using multipass resonators.

2. The small-signal gain $g_0$ is substantially nonuniform along the flow. This is explained by the fact that the characteristic times of kinetic processes determining the development of the gain are of the same order of magnitude as the AM residence time in the resonator. As a result, the distribution of $g_0$ along the flow is approximately described by a symmetric curve with one maximum [10].

This means that a multipass resonator should have an odd number of passes along the flow because otherwise the laser beam intensity will be considerably inhomogeneous over the beam cross section.

3. A supersonic COIL has a rather high specific energy extraction per unit area of a nozzle unit (NU). Hereafter, we call the area of the NU cross section at the input to the laser resonator the NU area. The energy extraction is mainly determined by the singlet-oxygen flow circulating through the NU. This flow is determined, in turn, by pressure in a singlet-oxygen generator (SOG). Thus, in low-pressure systems at a pressure of 30 Torr in the SOG, the energy extraction is $\sim$50 W cm$^{-2}$.

A variant of gas-dynamic COILs is a high-pressure laser with an ejector NU [7]. The active medium of such a laser has the small-signal gain in the range from 0.7 to 1.0 m$^{-1}$. The theoretical specific energy extraction of lasers of this type determined by the singlet-oxygen flow through the unit area of the output NU cross section can achieve 400 W cm$^{-2}$ (this value is determined by the flow rate of oxygen in the NU; thus, at the slowing down pressure $P_0 = 30$ Torr, the NU with the geometrical expansion 1 : 2 provides the flow rate of pure oxygen equal to 3.9 g s$^{-1}$ cm$^{-2}$, which corresponds to the specific energy extraction of 400 W cm$^{-2}$ if the chemical efficiency is $\eta_{\mathrm{ch}} = 30\%$). The energy extraction achieved in practice was $\sim$200 W cm$^{-2}$ [7].

For this reason, COILs with output powers of a few tens of kilowatts have a comparatively small NU. Because the size of the resonator aperture is determined by the beam formation system, the amplification length is also defined.

Therefore, the initial parameters for the development of the optical scheme of a COIL resonator are:

(i) The nominal power;

(ii) the small-signal gain; and

(iii) the specific energy extraction per NU area.

The main project parameters of the resonator scheme are the magnification factor and the number of passes along and across the flow.

## 3. Dependence of the configuration of an unstable resonator on the basic parameters of a COIL

Let us set the magnification factor of a 10-kW COIL equal to 2.5. Because such a magnification factor provides the compactness of the laser and a weak sensitivity of the resonator to aberrations, we will perform further calculations for this value. In this case, the minimal amplification length at which the laser will still operate is $\sim$180 cm for $g_0 = 0.5$ m$^{-1}$ and $\sim$90 cm$^{-1}$ for $g_0 = 1$ m$^{-1}$. The magnification factor of the resonator providing the efficient energy extraction will be $\sim$1.7. Then, we can easily estimate the total number of transits of radiation in the resonator by using the following algorithm. Given the required power of the laser, the energy extraction, and the size of the system, we determine the NU length as the ratio of the required power to the product of the energy extraction per unit area and the system size. Then, we find the required number of transits as the ratio of the required amplification length ($\sim$180 cm for $g_0 = 0.5$ m$^{-1}$ and $\sim$90 cm for $g_0 = 1$ m$^{-1}$) to the NU length. The results of the estimates are presented in Table 1. They show, in particular, the following.

**Table 1.** Total number of transits of laser radiation in the unstable resonator.

| Aperture size/cm | Power/kW | Number of transits of radiation in the resonator | | |
|---|---|---|---|---|
| | | I | II | III |
| 3 | 10 | 3 | 6 | 11 |
| | 30 | 1 | 2 | 4 |
| | 50 | 1 | 1 | 2 |
| 4 | 10 | 4 | 7 | 15 |
| | 30 | 1 | 2 | 5 |
| | 50 | 1 | 1 | 3 |
| 6 | 10 | 5 | 11 | 22 |
| | 30 | 2 | 4 | 7 |
| | 50 | 1 | 2 | 4 |

Note: The specific energy extraction is 50, 200, and 400 W cm$^{-2}$ and the gain is 0.5, 1, and 1 m$^{-1}$ for the number of transits in the resonator presented in columns I, II, and III, respectively.

In the acceptable scheme of the resonator that can be constructed for a low-pressure 10-kW COIL, radiation performs three transits, and the aperture size is 3 cm. In this case, the NU length is $\sim$180 cm/3 = 60 cm (it is the amplification length 180 cm that corresponds to the threshold magnification factor 2.5). Such a NU can be manufactured with the transverse size of 6 cm and length 60 cm/2 = 30 cm. Then, radiation will perform two transits in the resonator along the flow and three transits across it. In this case, the total AM length along the flow is 9 cm.

Resonators with the 6-cm aperture efficiently operate in high-power COILs. Thus, a three-pass resonator (Table 2) efficiently operates with a low-pressure NU in the power range from 17 to 20 kW. The total amplification length is $\sim$180 cm, and the NU length is $\sim$180 cm/3 = 60 cm. The resonator length along the flow in such a three-pass system is 6 × 3 = 18 cm. It can be reduced by a factor of 1.5 down to 12 cm by using the Z-like resonator scheme.

**Table 2.** Parameters of the COIL resonator with the 6-cm aperture.

| Power/kW | Number of transits of radiation in the resonator | | |
|---|---|---|---|
| | I | II | III |
| 10 | 5.5 | 11 | 22.1 |
| 12 | 4.6 | 9.2 | 18.4 |
| 14 | 3.9 | 7.9 | 15.8 |
| 17 | 3.2 | 6.5 | 13 |
| 20 | 2.7 | 5.5 | 11 |
| 24 | 2.3 | 4.6 | 9.2 |
| 29 | 1.9 | 3.8 | 7.6 |
| 35 | 1.6 | 3.2 | 6.3 |
| 42 | 1.3 | 2.6 | 5.3 |
| 50 | 1.1 | 2.2 | 4.4 |
| 60 | 0.9 | 1.8 | 3.7 |
| 72 | 0.8 | 1.5 | 3.1 |

Note: For the number of transits of radiation in the resonator of a low-pressure COIL (column I), the specific energy extraction is 50 W cm$^{-2}$, the gain is 0.5 m$^{-1}$, and the amplification length is 183 cm; for a low-pressure COIL, these parameters are 200 W cm$^{-2}$, 1 m$^{-1}$, and 92 cm, respectively (column II). Theoretical limit (the number of transits in column III) is 400 W cm$^{-2}$, 1 m$^{-1}$, and 92 cm.

**Table 3.** Parameters of the resonator with the 10-cm aperture.

| Power/kW) | Number of transits in the resonator | | |
|---|---|---|---|
| | I | II | III |
| 60 | 1.5 | 3.1 | 6.1 |
| 72 | 1.3 | 2.6 | 5.1 |
| 86 | 1.1 | 2.1 | 4.3 |
| 103 | 0.9 | 1.8 | 3.6 |
| 124 | 0.7 | 1.5 | 3.0 |
| 149 | 0.6 | 1.2 | 2.5 |
| 179 | 0.5 | 1.0 | 2.1 |
| 215 | 0.4 | 0.9 | 1.7 |
| 258 | 0.4 | 0.7 | 1.4 |
| 310 | 0.3 | 0.6 | 1.2 |
| 372 | 0.2 | 0.5 | 1.0 |
| 446 | 0.2 | 0.4 | 0.8 |
| 535 | 0.2 | 0.3 | 0.7 |

Note: Same as in Table 2.

For 50 – 60-kW COILs, a single-pass resonator with a low-pressure NU of size 6 × 180 cm can be fabricated.

A three-pass resonator with a high-pressure NU is suitable for the 35-kW power level. The amplification length is ~90 cm and the NU length is ~90 cm/3 = 30 cm. Thus, we have the NU of size 6 × 30 cm. The active region length along the flow is 6 × 3 = 18 cm. The system with such parameters can be used with high-speed AMs produced in a high-pressure NU. By increasing the specific energy extraction up to 400 W cm$^{-2}$, it is possible to build efficient 70-kW laser setups with a three-pass resonator.

Such a qualitative analysis gives an interesting result for the 10-cm aperture (Table 3). In this case, the active medium prevents the manufacturing of a resonator with the number of passes along the flow more than one, so that the choice of the resonator scheme becomes virtually unambiguous.

Thus, a single-pass resonator can be successfully used in 80 – 100-kW low-pressure COILs. In this case, the size of the NU is ~10 × 180 cm. It may seem that at a higher power and a larger size of the NU it is possible to increase the magnification factor of the resonator; however, it will not necessarily improve the parameters of the laser system because the resonator mode will be poorly matched with a rectangular shape of the active volume. At a lower power, it is necessary to increase the number of passes. However, this is impossible because the length of the positive gain region downstream is limited by the kinetics of processes in the AM.

A single-pass resonator successfully operates in 150 – 220-kW high-pressure COILs with the NU of size ~10 × 90 cm. By increasing the specific energy extraction, it is possible to increase the output power of the laser system without increasing the NU size. Thus, the NU of size ~10 × 90 cm with the energy extraction equal to the theoretical limit allows one to fabricate a single-pass resonator to achieve the output power in the range from 310 to 450 kW.

The results of a more detailed analysis of the applicability of various resonator schemes are summarised in Fig. 1 where the regions of applicability of single-, three-, and five-pass schemes are presented in the aperture-power coordinates.

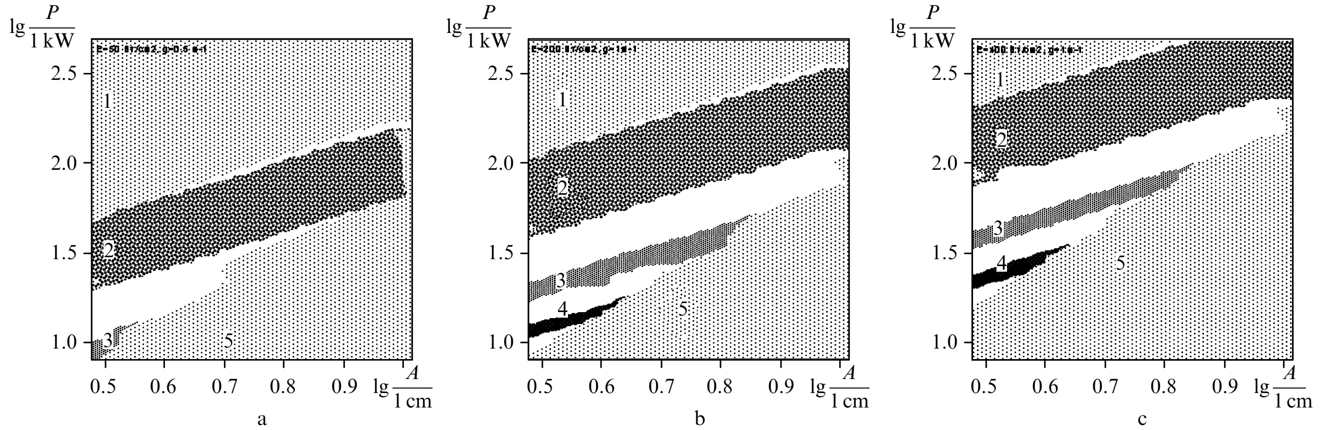


**Figure 1.** Regions of applicability of different schemes of unstable resonators for low-pressure (a) and high-pressure (b) COILs; (c) promising COIL with the specific energy extraction close to the theoretical limit (*A* is the aperture height; *P* is the laser power). Number 1 indicates regions where the AM length along the flow exceeds 10 cm (for a low-pressure COIL) or 20 cm (for a high-pressure COIL), numbers 2, 3, and 4 indicate regions where single-pass, three-pass, and five-pass schemes are applicable, respectively; number 5 indicates regions where the required AM length along the flow is smaller than 3 cm.

For low-pressure COILs (Fig. 1a), two variants of resonators exist:

(i) A three-pass resonator of the type shown in Fig. 2a. It corresponds to small region 3 in the diagram at the left bottom corner of Fig. 1a. This resonator has the aperture of size ~3 cm, the length along the flow ~9 cm, the amplification length ~180 cm [in the 'double-level' configuration (Fig. 2b), this corresponds to the NU size 6 × 30 cm], and the output power 10 kW.

(ii) A single-pass resonator with the aperture from 5 to 10 cm, which is equal to the resonator length along the flow. It has the amplification length ~180 cm, the NU height from 5 to 10 cm, and the output power from 40–50 to 100 kW. This scheme corresponds to region 2 in the diagram in Fig. 1a. It is reasonable to construct a 50-kW laser by using the 'double-level' scheme. In this case, the NU size will be ~10× 90 cm. A 100-kW laser has the NU of size 10 × 180 cm.

Note that the AM length along the flow required for the realisation of a multiple-pass resonator providing the specified output power for the given aperture size is also determined unambiguously. At the same time, this length is restricted due to the gain relaxation. Because of this, for any resonator scheme there exits a certain range of the aperture size within which this scheme can be realised. The best parameters for each of the schemes are realised when the AM length along the flow is maximal because in this case the maximum AM volume is used. Each type of lasers has its own kinetic restrictions on the AM length, which are determined by the composition and gas-dynamic parameters of the medium.

According to the above discussion, three variants of schemes are possible for high-pressure COILs (Fig. 1b):

(i) A five-pass resonator with the 3–4-cm aperture, the output power 12–13 kW, the NU size (3 – 4) × 90 cm or (6 – 8) × 45 cm and the resonator length along the flow equal to 15–20 cm. This scheme corresponds to the intersection of region 4 (region of five-pass schemes) and lower region 1 corresponding to the length along the flow exceeding 20 cm.

(ii) A three-pass resonator with the ~6-cm aperture, the NU size ~ 6 × 90 cm (or ~12 × 45 cm in the case of the double-level configuration), the resonator length along the flow ~18 cm, and the output power ~30 – 32 kW. This scheme corresponds to the intersection of regions 3 and 1.

(iii) A single-pass with the aperture above 10 cm, the NU size exceeding 10 × 90 cm, and the output power more than 150 kW.

## 4. Promising resonator for a COIL

The analysis performed above showed that the structure of the unstable resonator of a COIL should be strictly matched with the AM where, as mentioned above, the gain distribution along the flow is nonuniform and has one maximum.

We can propose the unstable resonator which takes into account these features of the AM and improves the efficiency of a COIL as a whole [8]. The resonator consists of two end spherical confocal mirrors (confocal resonator) and $2(m+n)$ (where $m = n = 1, 2, 3, ...$) plane intermediate mirrors. The plane mirrors form $2m+n-1$ two-mirror corner reflectors (two plane mirrors at an angle of 90°). The edges of $2m$ corner reflectors are perpendicular to the direction of the AM flow, while the edges of $n-1$ corner reflectors are parallel to it. Radiation in this resonator passes through the AM $(2m+1)n$ times (from one end spherical mirror to another). The number $n$ is equal to the ratio of the AM size in the direction perpendicular to the flow to the size of the laser beam aperture in the same direction, and the number $(2m+1)$ is equal to ratio of the AM size in the direction parallel to the flow to the laser beam aperture size in the same direction. The AM size in the direction perpendicular to the flow is equal to the NU height, while its size in the direction parallel to the flow is equal to the distance from the NU cut to the point where the small-signal gain is zero.

It follows from the above analysis that the value $m = 1$ (three passes along the flow) is the most acceptable for a COIL, although other value of $n$ are also possible in principle.

Figure 2 shows the principal schemes of the proposed resonator for $m = 1$ and different $n$.

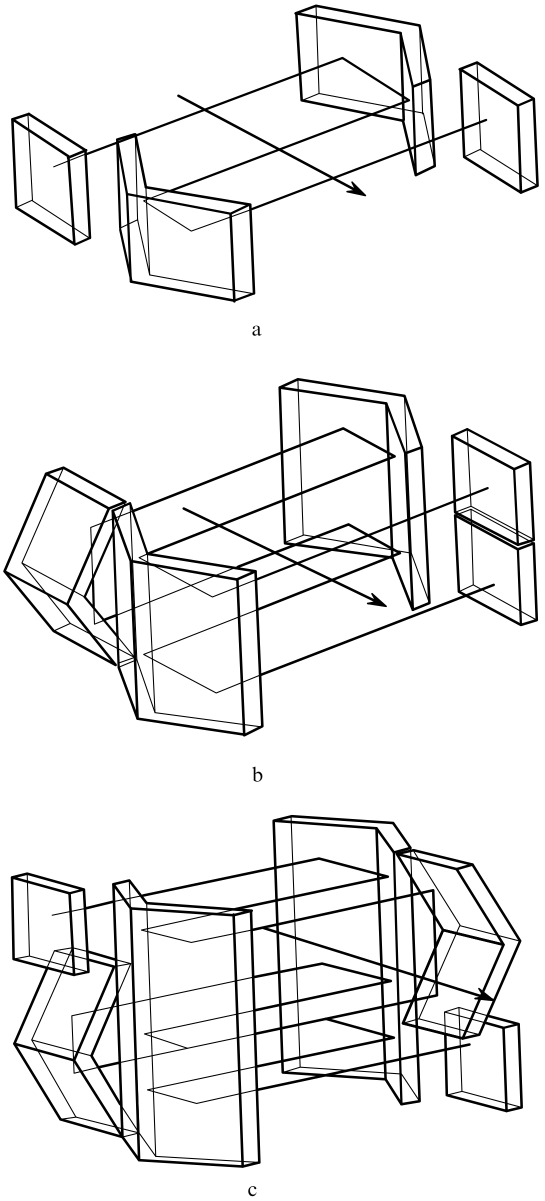


**Figure 2.** Principal schemes of the proposed resonator for $m = n = 1$ (a), $n = 2$ (b), and $n = 3$ (c). The arrow shows the direction of the AM flow from the nozzle unit.

The resonator proposed for a supersonic COIL offers a number of advantages over the known resonators:

(i) A high magnification factor due to many passes of radiation (no less than three passes in the AM).

(ii) The possibility of levelling the radiation intensity on the output mirror with the help of corner reflectors inverting the electromagnetic field, their number and positions being consistent with the gain distribution in the resonator.

(iii) A high energy efficiency because the resonator mode is optimally matched with the gain distribution in the AM: radiation turned by corner reflectors passes successively through regions with high and low gains, thereby providing efficient energy extraction.

(iv) A lower sensitivity to misalignments and vibrations due to the use of corner reflectors.

(v) Parallelism of the directions of all passes over the AM, which makes it possible to use polarisation elements in this resonator, in particular, Brewster windows.

The scheme of this resonator was developed by simulating an unstable resonator together with the AM of a COIL. Mathematical models were realised by means of a special program package.

We simulated numerically a three-dimensional unstable resonator in the diffraction approximation by the spectral method using the fast Fourier transform algorithms [9]. For this purpose, the three-dimensional calculation region of the unstable resonator was divided into separate segments limited by amplitude – phase screens along the propagation direction of radiation. All calculations were performed for a square 512 × 512 network, the central part of the network of size 256 × 256 nodes being inscribed into the AM aperture and the remaining nodes (128 on each side) representing the ‘guard region’ [9]. The active medium was divided into five identical segments. Empty regions between each of the mirrors and the corresponding AM boundary were two additional segments. This configuration of the calculation region provided the required accuracy for calculating unstable resonators under study. Spherical mirrors were replaced by quadratic phase screens located at the end of the corresponding segments.

The propagation of light in free space between the screens was described by the parabolic wave equation

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}-2\mathrm{i}k\frac{\partial u}{\partial z}=0,$$

where $k$ is the wave number and $u$ is the complex amplitude of the field.

This equation was solved by the spectral method using the fast Fourier transform algorithms.

The complex amplitude of the light wave field for each $i$th screen was multiplied by the amplitude – phase factor $A_i$ characterising the integral amplifying and aberration properties of the AM inside the segment:

$$u_i(x,y,z)=u(x,y,z)A_i(x,y),$$

$$A_i(x,y)=\exp[\mathrm{i}\varphi(x,y)]\exp[g(x,y)L_i/2],$$

where $\varphi(x,y)$ is the change in the radiation field phase after propagation of radiation through the AM segment in front of the $i$th screen [we assume that the AM is optically homogeneous and, therefore, $\varphi(x,y)=0$]; $g(x,y)$ is the gain in the AM; $L_i$ is the length of the segment in front of the $i$th screen in the propagation direction of radiation.

We calculated the propagation of the complex light wave in the forward and backward directions in the resonator to obtain the quasi-established level of diffraction losses. This procedure is described in more detail in [9].

The gain $g(x,y)$ in the AM of the COIL was determined by using a specially developed mathematical model based on the two-layer gas-dynamic model of mixing of flows containing a buffer gas with singlet oxygen and a buffer gas with iodine, on the main equations of the chemical kinetics of COILs, and on the stationary lasing equations. This model for calculating the gain is described in detail in [10].

Our calculations showed that the intensity distribution over the laser aperture for the resonator proposed is considerably more homogeneous compared to that for other schemes. In particular, Fig. 3 presents the laser radiation intensity distributions in the plane of the output mirror of the resonator and the gain distributions in the plane parallel to the output mirror and passing through the AM middle calculated for three resonator schemes (Fig. 4) under the condition that the height of the NU vane is 30 mm (Fig. 4a) or 60 mm (Figs 4b, c) and $L_{\mathrm{AM}}=370$ mm. The magnification factor for the three schemes was set equal to 1.3. The distance between the mirror is $L_{\mathrm{m}}=1$ m. The direction $y$ in Fig. 3 is perpendicular to the flow and the direction $x$ is parallel to it. The size of mirrors for resonators in Figs 4a, 4b, and 4c was 30 × 60 mm, 60 × 60 mm, and 60 × 30 mm, respectively. One can see from the diagrams that the resonator in Fig. 4c has a more uniform intensity distribution on mirrors and, therefore, in the output beam than resonators shown in Figs 4a and b. In addition, our calculations showed that this resonator provides a higher output power, all other factors being the same.

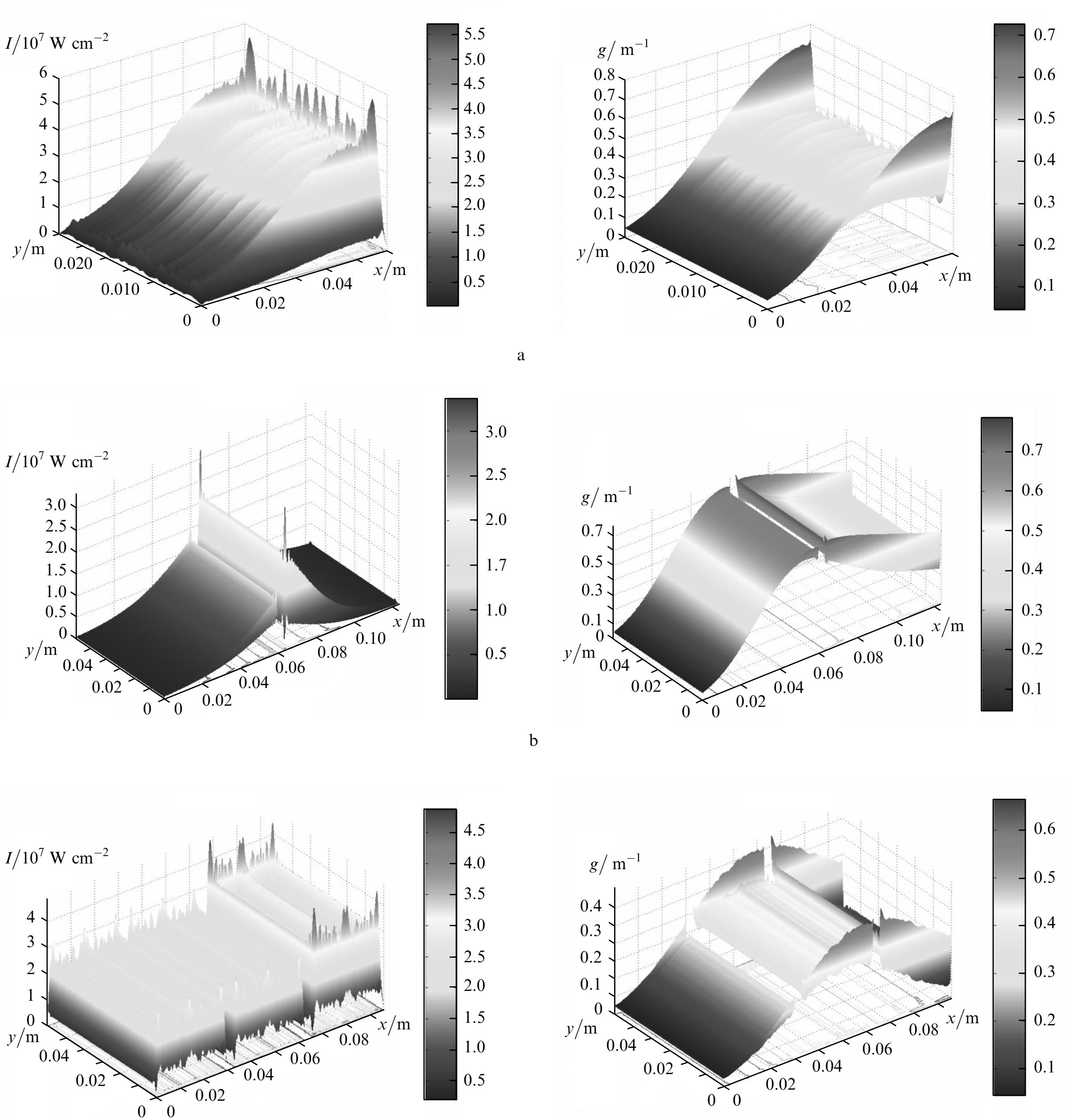
## 5. Conclusions

Let us formulate the main results of the paper:

(i) For low-pressure COILs, a resonator with an odd number of transits along the AM flow and ‘field inversion’ with the help of corner reflectors after each transit is optimal. Such a resonator provides the high energy efficiency and the uniform field over the aperture. In this case, the number of transits across the AM flow (resonator ‘levels’) is not substantial. Thus, a low-pressure NU of size 6 × 30 cm producing the AM of length 9 cm along the flow allows one to construct a resonator with the number of passes along and across the flow equal to 3 and 2, respectively. Such a resonator with the magnification factor ~1.7 provides ~ 10 kW of output power.

(ii) For the power level 30 – 40 kW, of interest is a high-pressure NU in combination with a three-pass resonator. Thus, for the 6-cm aperture, the NU of size 6 × 30 cm, and the AM length of 18 cm along the flow, a three-pass resonator with a magnification factor of 1.7 – 2 is suitable.

(iii) If the aperture size exceeds 6 cm, only single-pass resonators can be used because the resonator length along the flow is restricted by kinetic processes proceeding in the AM.

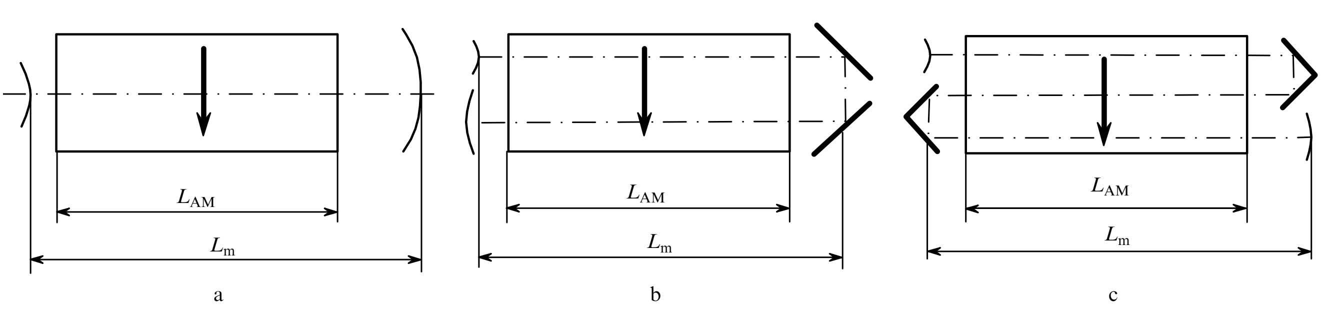


a

b

c

**Figure 3.** Intensity and gain distributions in the output mirror plane for resonator schemes presented in Figs 4a, b, c, respectively.



a

b

c

**Figure 4.** Alternative schemes of single-pass (a), Π-like (b), and new proposed (for $m = 1$ and $n = 1$) (c) COIL resonators. The thick arrow indicates the AM flow direction.

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