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CONTROL OF LASER RADIATION PARAMETERS

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Enhancement of the efficiency and control of emission parameters of an unstable-resonator chemical oxygen – iodine laser

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Abstract. **The outlook is considered for the development of a high-power supersonic flowing chemical oxygen – iodine laser operating as an amplifier and controlled by radiation from a master oscillator by using an unstable resonator with a hole-coupled mirror. The influence of the seed radiation intensity, the coupling-hole diameter, the active-medium length, and the magnification factor on the parameters of laser radiation is analysed. It is shown that the use of such resonators is most advisable in medium-power oxygen – iodine lasers for which classical unstable resonators are inefficient because of their low magnification factors. The use of unstable resonators with a hole-coupled mirror and injection provides the control of radiation parameters and a considerable increase in the output power and brightness of laser radiation.**

Keywords: *unstable resonator, radiation injection, oscillator – amplifier, oxygen – iodine laser, control of laser radiation parameters.*

1. Introduction

Supersonic flowing chemical oxygen – iodine lasers (COILs) are one of the most promising sources of high-power cw laser radiation. Compared to other types of high-power lasers, first of all chemical HF – DF lasers, electric-discharge, and gas-dynamic CO_2 lasers, as well as solid-state lasers, COILs offer a number of substantial advantages. These are a high specific energy extraction, the optimal radiation wavelength providing a low diffraction divergence and the propagation of radiation through the atmosphere and optical fibres with minimal losses, as well as a high optical quality of the active medium (AM).

An important problem in the development of a COIL, as any high-power laser, is the elaboration of the optimal scheme of the optical resonator. Because the radiation of medium- and high-power COILs is used, as a rule, in the far-field (Fraunhofer) zone, the efficiency of the optical resonator and the laser as a whole is determined by the two parameters – the output power and angular divergence of radiation. The optimal combination of these parameters can be provided only in an unstable resonator.

However, a medium-power COIL (a few tens of kilowatts) has a comparatively small AM length (no more than 1 m). In this case, the small-signal gain is of the order of 0.5 m^{-1}. The advantages of the unstable resonator, namely, a low divergence of radiation and low sensitivity to intracavity aberrations, including misalignments, are manifested only for sufficiently high magnification factors ($M \geqslant 1.5$) At the same time, the above-mentioned AM parameters cannot provide such magnification factors in a single-pass resonator. This problem is specific namely for COILs in which the AM is characterised by a rather low small-signal gain and a high energy extraction.

This problem can be solved by the following methods:

(i) the use of multi-pass resonators for increasing the amplification length and producing conditions for employing an unstable resonator with the maximum magnification [1 – 3];

(ii) the use of resonators with the field rotation and compact aperture [1]; in this case, even for a small equivalent magnification, a compact emitting aperture can be obtained and, therefore, the angular divergence of radiation can be decreased;

(iii) the use of 'mixed' resonators, which are flat in one plane and unstable in the other [4, 5];

(iv) the use of an unstable resonator with the Gaussian transmission profile of the output mirror [6, 7]

Note that these methods have some disadvantages that restrict their practical applications. In particular, although multi-pass schemes offer certain advantages, their alignment is complicated due to the use of many mirrors and they have the unilluminated AM regions due to the presence of a gap between mirrors; in addition, the mirror aperture is inevitably reduced in going to the multi-pass scheme, resulting in the increase in the radiation load on mirrors. The alignment of rotating-field resonators is also complicated, and in addition, they consist of quite complex optical elements – mirrors of a special shape and corner reflectors with high requirements to the accuracy of the apex angle and the quality of reflecting surfaces. 'Mixed' resonators cannot provide a low divergence of radiation and are sensitive to aberrations because they are flat in one plane. In the case of resonators with the Gaussian profile, problems appear with the manufacturing of a high-quality coating for a mirror with a complex reflection profile at a wavelength of 1.315 μm; in addition, mirrors operating in the transmission regime are subjected to heating and thermal deformation at high radiation densities.

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An alternative variant providing a noticeable increase in the COIL efficiency as a whole can be the use of a hole-coupled-mirror unstable resonator (HCMUR). The general theory of such resonators is described in detail in [1]. It is known that the entire unstable-resonator volume can be conditionally divided into two regions: the axial region of a 'master oscillator' having the transverse size $d_{\rm F} = 2\sqrt{\lambda L_{\rm r}}$ of the first Fresnel zone of the resonator ($L_{\rm r}$ is the distance between resonator mirrors) and the amplification region occupying the rest of the resonator volume.

The axial region, where the radiation mode with energy and spatial parameters is formed, plays a special role in the unstable resonator. In this connection it is possible to affect the formation of the resonator mode by the seed radiation directed to the axial region, for example, through a hole in a highly reflecting mirror (Fig. 1). In this case, the unstable resonator will operate both as a resonator and a multi-pass amplifier.

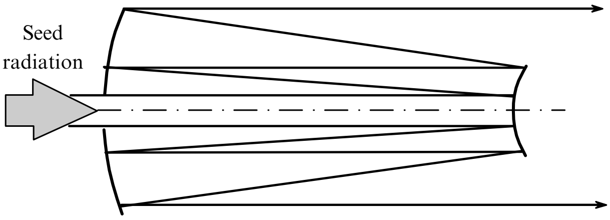

Figure 1. The HCMUR scheme.

Interest in such schemes is caused by the following reasons:

(i) The possibility of using a resonator with a large magnification factor operating efficiently due to the high-power seed radiation, which provides an increase in the laser radiation brightness and in its far-field intensity. This extends the scope of possible applications of medium-power COILs.

(ii) The possibility to control efficiently the radiation parameters of COILs, in particular, the temporal modulation of laser radiation by using a driving pulse from a master oscillator, i.e. the development of repetitively pulsed COILs. This is important for some practical applications because the repetitively pulsed laser irradiation can be preferable in a number of cases compared to cw irradiation. In this case, the magnification factor of the unstable resonator and the coupling-hole diameter can be selected so that the resonator did not generate radiation.

The main disadvantage of the HCMUR compared to the resonators described above is a more complicated design in which a master oscillator is used to produce the seed radiation.

This paper is devoted to the study of the HCMUR applied to medium-power COILs. Although such resonators have been used, in particular, in [8, 10, 11], we are not aware of the studies devoted to their use in COILs for increasing the energy efficiency of lasers measured by the far-field radiation intensity.

2. Numerical simulation method

We studied numerically the efficiency of a resonator with a hole-coupled mirror as a function of the basic parameters of the resonator. Simulations were performed by solving the wave equation by the spectral method [9] in which the three-dimensional calculation region of the unstable resonator was divided into separate segments restricted by amplitude–phase screens along the radiation propagation direction. All the calculations were performed for a square 512×512 network [the central part of the network of size 256×256 nodes fitted into the AM aperture, while the remaining nodes (by 128 from each side) formed the 'guard zone']. The active medium of the total length $L_{\rm AM}$ was divided into five identical segments. Empty regions between each of the mirrors and the corresponding AM boundary represented two more segments. This configuration of the calculation region provided sufficient calculation accuracy for the HCMUR schemes under study. Spherical mirrors were replaced by square phase screens located at the end of the corresponding segments.

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

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

where k is the wave number and u is the complex field amplitude. This equation was solved by the spectral method by using algorithms of the fast Fourier transform [9].

The complex amplitude of the light-wave field for each ith screen was multiplied by the amplitude–phase factor A_i characterising the integrated amplifying and aberration properties of the AM inside a segment:

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

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

where $\varphi(x, y)$ is the change in the radiation phase after propagation of light through a segment preceding the ith screen; $g(x, y)$ is the AM gain; and L_i is the length of the segment preceding the ith screen in the radiation propagation direction. We assume that the AM does not introduce phase distortions. The gain is determined from the relation

$$g = \frac{g_0}{1 + I/I_{\rm sat}},$$

where $g_0 = 0.5$ m^{-1} is the small-signal gain; $I_{\rm sat} = 5$ kW cm^{-2} is the saturation intensity; and I is the radiation intensity. The radiation wavelength is $\lambda = 1.315$ μm. Note that the values of the gain and saturation intensity used in simulations correspond to the COIL active medium.

The coupling hole with the seed radiation of a certain power was simulated on the resonator axis in a highly reflecting mirror. The intensity profile of seed radiation was uniform. A telescopic unstable resonator of the positive branch with square mirrors of size 5×5 cm was simulated in all calculations.

The propagation of a complex light wave in the resonator in the forward and backward directions was calculated until the quasi-stationary solution was obtained for the transverse mode of the unstable resonator.

3. Results of simulations

We studied numerically the HCMUR efficiency and its influence on the hole diameter d, the seed radiation power P_s, the resonator length L_r, the magnification factor M of the unstable resonator, and the amplification length L_{AM}. The resonator efficiency was estimated by comparing the output power and brightness of radiation from the HCMUR COIL with these parameters for a classical stable resonator.

Figure 2 illustrates the one-dimensional section of the laser intensity distribution on the output mirror of the HCMUR. One can see that the intensity is maximal in the axial region and corresponds to the seed radiation intensity. The central dip in the intensity distribution on the HCMUR axis corresponds to coupling-hole region. Radiation comes outside the hole region due to diffraction: two intensity maxima are distinctly observed on both sides of the hole region. Then, the beam 'spreads' over the HCMUR periphery due to the curvature of mirrors and diffraction, and the radiation intensity decreases despite amplification in the AM. The intensity distribution in the emitting aperture is nearly uniform, which together with the absence of phase distortions demonstrates the diffraction quality of radiation.

Figure 3 presents the dependences of the normalised radiation power on the magnification factor of the HCMUR and usual unstable resonator for different AM lengths. We assumed in these calculations that the seed radiation power P_s was 1 kW and the coupling-hole diameter d was $2.8\sqrt{\lambda L_r}$. The radiation power was normalised to the maximum power achieved for the given AM length, to which a certain optimal magnification factor of the unstable resonator corresponded.

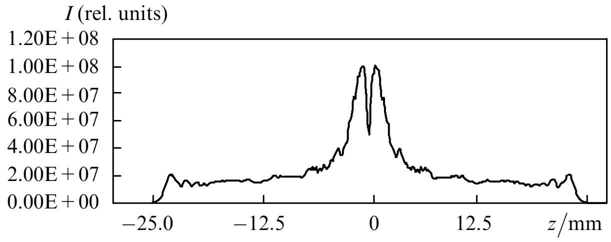

Figure 2. Radiation intensity distribution on the HCMUR output mirror for $P_s = 1$ kW, $L_r = 1.5$ m, $L_{AM} = 1.0$ m, $M = 1.5$, and $d = 2.8\sqrt{\lambda L_r}$.

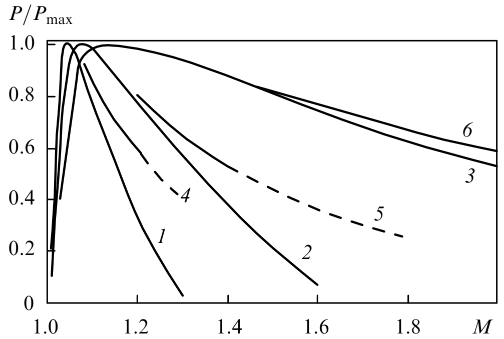

Figure 3. Dependences of the normalised radiation power P/P_{max} on the magnification factor M (P is the radiation power for the given magnification factor, P_{max} is the maximum power for the given AM for the optimal magnification) for the usual unstable resonator (*1, 2, 3*) and HCMUR (*4, 5, 6*) for $L_r = 0.5$ m, $L_{AM} = 0.5$ m (*1, 4*); $L_r = 1.5$ m, $L_{AM} = 1.0$ m (*2, 5*); $L_r = 3$ m, $L_{AM} = 2.5$ m (*3, 6*), and $P_s = 1$ kW and $d = 2.8\sqrt{\lambda L_r}$ (*4, 5, 6*).

One can see from Fig. 3 that, beginning from a certain value of the magnification factor, the HCMUR generates a higher power than a common unstable resonator does. The dependence of the power increment $\Delta P'/P_0$ on M is shown in Fig. 4. The most efficient is the use of the HCMUR in COILs with short AMs. In this case, the output power rapidly decreases with increasing M in usual unstable resonators, i.e. the acceptable magnification factors do not provide nominal output powers. For example, for $L_r = 1.5$ m and $L_{AM} = 1.0$ m, the output power for $M = 1.5$ is only $\sim 20\,\%$ of the maximum value. In this case, the use of common unstable resonators becomes inappropriate, whereas the use of the HCMUR noticeably increases the output power of the laser. In the above example for $M = 1.5$, the output power will be already almost $50\,\%$ of the maximal value, which is quite acceptable.

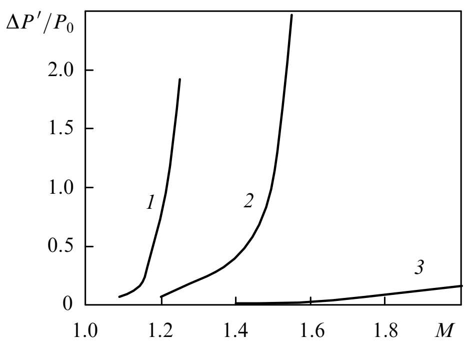

Figure 4. Dependences of the power increment $\Delta P'/P_0 = (P' - P_0)/P_0$ on the magnification factor M (P' and P_0 are the radiation powers for the HCMUR and usual unstable resonator, respectively) for $L_r = 1$ m, $L_{AM} = 0.5$ m (*1*), $L_r = 1.5$ m, $L_{AM} = 1.0$ m (*2*), and $L_r = 3$ m, $L_{AM} = 2.5$ m (*3*).

The dashed parts of the curves in Fig. 3 correspond to the situation when the HCMUR does not generate radiation in the absence of a driving pulse. It is obvious that the temporal parameters of the COIL radiation (in particular, the duration and repetition rate of laser pulses) can be efficiently controlled in this region of M values with the help of a driving radiation pulse.

The use of the HCMUR in the case of long AMs is inappropriate because a considerable complication of the laser design does not lead to the required advantage in power [see curves (*3*) and (*6*) in Fig. 3 and curve (*3*) in Fig. 4].

Our calculations showed that the HCMUR output power depends on the hole diameter d and the seed radiation power P_s. In particular, as the hole diameter decreases for a fixed power P_s, the output power increases (Fig. 5); however, the minimal diameter of the hole is restricted by the admissible radiation load on the resonator mirrors (for COIL mirrors, the admissible radiation load is 10–12 kW cm^{-2}). This behaviour is explained by the fact that, first, the diffraction divergence of the seed radiation increases and this radiation fills the resonator periphery with decreasing d (Fig. 1) and, second, the seed radiation

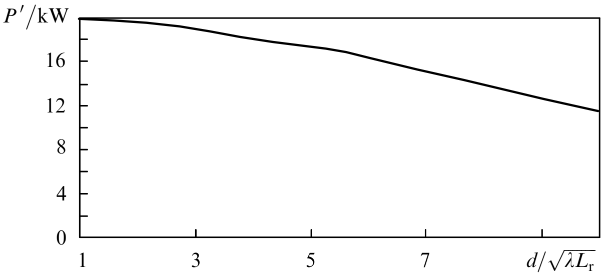

Figure 5. Dependence of the radiation power P' on the relative hole diameter $d/\sqrt{\lambda L_r}$ for the HCMUR for $P_s = 1$ kW, $L_r = 1.5$ m, $L_{AM} = 1.0$ m, and $M = 1.5$.

intensity increases; all this results in the increase in the injection efficiency. As d increases, on the contrary, the diffraction divergence of the seed radiation decreases and a great part of it returns back to the hole after a round trip in the resonator and is not involved in the formation of radiation in the unstable-resonator periphery. The seed radiation intensity I_s also decreases.

The increase in the seed radiation power leads to the increase in the output power of the HCMUR COIL (Fig. 6). However, in this case, the maximal power P_s is also restricted by the radiation resistance of mirrors. Figure 6 also shows that the output power P' first rapidly increases with increasing P_s up to $1-2$ kW and then increases slower. This is mainly caused by a simple addition of the seed power to the laser output power: one can see from Fig. 6 that, as P_s increases from 2 to 10 kW, the output power increases by 10 kW, i.e. the powers are added without the amplification effect. This suggests that there exists the optimal seed radiation power and the use of higher powers is inappropriate both from the point of view of the radiation load on mirrors and the injection efficiency. It is obvious that this optimal power depends on the AM parameters such as its length, gain, and saturation intensity.

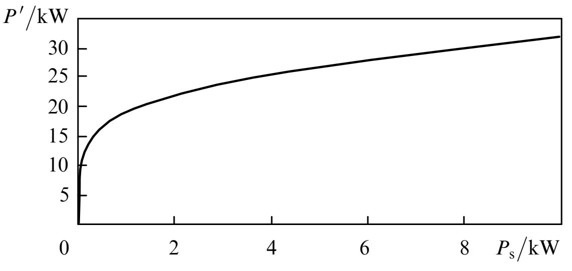

Figure 6. Dependence of the radiation power P' on P_s for the HCMUR for $d = 2.8\sqrt{\lambda L_r}$, $L_r = 1.5$ m, $L_{AM} = 1.0$ m, and $M = 1.5$.

Figure 7 presents the dependences of the output power P' and the seed radiation power on the coupling-hole diameter d for a fixed seed radiation intensity I_s. It is obvious that the dependence of P_s on the hole diameter for a fixed radiation intensity is proportional to the hole area, i.e. to d^2. The increase in the radiation power for a HCMUR for the specified parameters of the medium and resonator is close to linear.

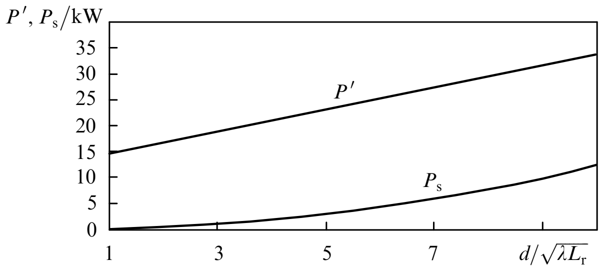

Figure 7. Dependences of the output power P' and seed radiation power P_s on the relative hole diameter $d/\sqrt{\lambda L_r}$ for the seed radiation intensity $I_s = 8$ kW cm^{-2}, $L_r = 1.5$ m, $L_{AM} = 1.0$ m, and $M = 1.5$.

The latter circumstance is explained by the following. In the geometrical approximation, the diameter d of a seed beam increases up to the output-mirror diameter after n transits in the resonator due to the geometrical magnification of an unstable resonator:

$$dM^n = D.$$

This gives the number of transits during which a particular seed photon exists in the unstable resonator:

$$n = \frac{\ln(D/d)}{\ln M}.$$

Thus, on the one hand, the seed radiation power increases with increasing the hole diameter and, on the other hand, the number of transits during which light is amplified in the resonator decreases. Due to the interaction of these factors, the rate of increase in the laser output power with increasing the coupling-hole diameter becomes lower than the rate of increase in the seed radiation power.

As mentioned above, the radiation of medium-power COILs is intended for the use in the far-field zone. In this case, the complex criterion for the unstable-resonator efficiency is the average far-field radiation intensity or the brightness J related to the laser radiation power P and divergence θ by the expression $J \sim P/\theta^2$.

The diffraction divergence of radiation of an unstable resonator is described by the expression

$$\theta = 2\frac{\lambda}{D}\frac{M}{M-1}.$$

Figure 8 shows the dependences of the parameter P/θ^2 on the magnification factor M for a conventional unstable

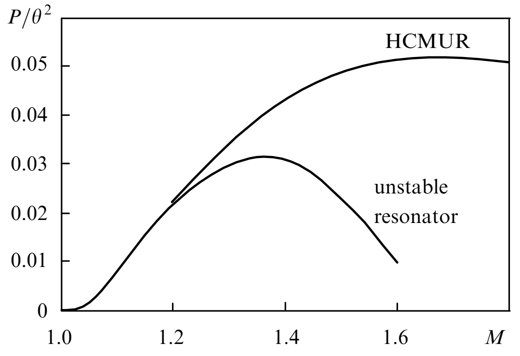

Figure 8. Dependences of the parameter P/θ^2 on the magnification factor M for the usual unstable resonator and HCMUR for $L_r = 1.5$ m, $L_{AM} = 1.0$ m, and $d = 2.8\sqrt{\lambda L_r}$.

resonator and a HCMUR. One can see that the optimal value of M (from the point of view of brightness) for the HCMUR is considerably higher that that for the conventional resonator, which reduces the radiation divergence and improves the aberration stability of the resonator. In addition, the radiation brightness for the optimal value of M for the HCMUR is also considerably higher.

4. Conclusions

Let us formulate the main conclusions of the paper:

(i) The HCMUR is a real alternative to the existing unstable resonators for medium-power cw and repetitively pulsed COILs. The use of HCMURs in master oscillator – amplifier schemes will provide the efficient control of radiation parameters and will considerably extend practical applications of medium-power COILs in the fields where the high far-field radiation intensity or spatial-temporal modulation of radiation is required.

(ii) The optimal magnification factor of the HCMUR is higher than that of a conventional unstable resonator, which reduces the sensitivity of the laser to intracavity aberrations, in particular, to the misalignment and distortions of the mirror shape, and also considerably increases the far-field radiation intensity.

(iii) The advantages of HCMURs are manifested most distinctly in medium-power lasers in which the AM length along the resonator axis does not exceed 1.5 m. The effect of using HCMURs is maximal for such lasers. The use of HCMURs in higher-power lasers does not provide advantages compared to usual unstable resonators because the optimal magnification factor for them is also high enough.

(iv) The HCMUR efficiency depends on the coupling-hole diameter and the seed radiation power. The optimal diameter of the coupling-hole is 1 – 2 diameters of the Fresnel zone of the resonator and the output power is restricted by the radiation resistance of mirrors.

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