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Determination of the radiation axis position of an unstable-cavity laser

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Abstract. **Propagation of an alignment laser beam through an unstable cavity laser is numerically simulated. It is shown that the axis of the expanded beam coincides with that of the fundamental laser radiation within an accuracy of no less than 1″ even under cavity misalignment of up to 30″. Experiments on determining the position of the radiation axis of a high-power pulsed unstable cavity chemical laser and various cavity misalignments confirm the calculation results.**

Keywords: *unstable cavity, coupling aperture, radiation axis, alignment.*

1. Introduction

The employment of unstable cavities in experimental practice seems to have started since the pioneering work by A.E. Siegman [1] published in 1965. The following fast development of experimental and theoretical investigations has revealed basic properties of such cavities (see, e. g., [2]). Since that time up to now, problems of aligning unstable cavities have been attracting much attention (see, e.g., [3 – 6]). One of the main advantages of unstable cavities in high-power laser systems with a large active volume is a substantially lower attainable divergence as compared to other cavity types. However, due to small radiation divergence, the requirements to the alignment of the radiation axis of an unstable-cavity laser to a spatial coordinate system become substantially stronger. Obviously, this alignment should provide determination of the radiation axis within the accuracy of a small part of laser radiation divergence. However, little attention has been paid to this practically important problem. Note paper [7], which casually mentions possible employment of the alignment scheme described in that work for determining the axis position. In recent years, much attention has been paid (see, for example, [8, 9]) to the beam pointing due to wide employment of lasers (in probing, diagnosing and medicine). However, from our point of view, precise determination of the position of radiation axis in an unstable cavity needs further investigation taking into account specific features of such cavities.

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In a telescopic unstable cavity (such cavities are used in high-power lasers with a large volume of the active medium), the radiation axis is the line that connects the centres of curvature of both mirrors. If this line also passes through the axis of the active medium and, in addition, the focal positions of the mirrors coincide, we deal with an ideally aligned cavity. Now we may slightly incline one mirror (or both of them) in such a way that the line connecting the centres of mirror curvatures (that is, the radiation axis) would only slightly shift from the line connecting the mirror centres and from the axis of the active medium. The cavity comprising two mirrors will be still aligned, and the laser characteristics (the energy and divergence) will actually be the same [2] except for the position of the radiation axis. From this consideration follows that, once the position of the radiation axis is known, the telescopic cavity should only be adjusted for admissible coincidence of the radiation axis with that of the active medium. The present work is devoted to the problem of precision determination of the radiation axis position and alignment of telescopic cavities.

Like in [7], we will use the scheme in which an expanding light beam multiply reflects from cavity mirrors. The beam passes into the cavity through a hole of small diameter on the axis of the concave mirror (Fig. 1). After several transits across the cavity, the beam expands to the dimensions determined by the aperture of the active medium (or active diaphragms), and a more or less uniformly illuminated ring will be seen on a screen. Instead of the screen, one can use a collimator placed on the laser axis, in which case the angular shift of the beam leaving the cavity with respect to the collimator axis can be observed.

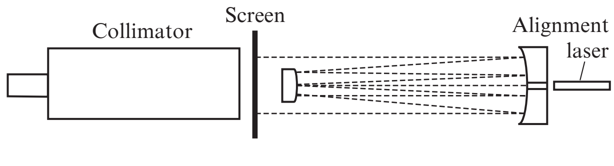

Figure 1. Scheme of the alignment laser placement.

At the first stage of experiments, it was necessary to find the admissible diameter of the hole in the concave mirror, which would not affect laser radiation characteristics. For this purpose, the radiation divergence and energy were measured under a varied diameter of the hole in the concave mirror. The holes were simulated by opaque screens that were placed near the concave mirror. Note that all experimental and calculated data in the present work refer to a pulsed chemical DF laser with an aperture of 100 mm, telescopic cavity with magnification $M = 3$, and distance between the mirrors $L = 245$ cm. A spherical mirror with a focal length of 18 m and a Pyrocam-III chamber were used to measure the divergence. Results of divergence measurements (the whole angle in which half the laser radiation energy is comprised) versus the screen diameter are presented in Fig. 2.

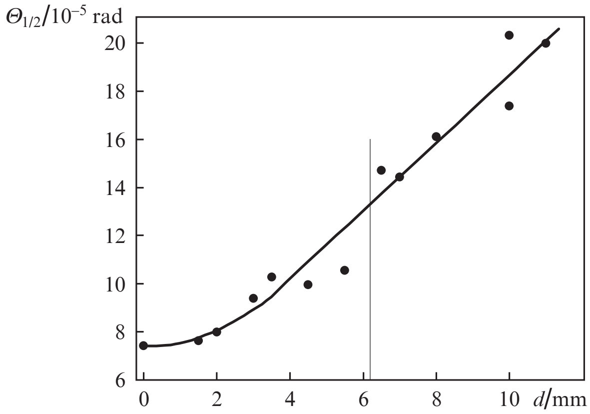

Figure 2. Divergence of laser radiation $\Theta_{1/2}$ vs. the diameter (screen) d of the hole in a concave mirror. Points correspond to experiment, solid line is approximation, and vertical line marks the diameter of the first Fresnel zone.

From general considerations of the generation development in a telescopic cavity follows that the radiation characteristics should not be affected by the hole at the axis of the concave mirror with a diameter of less than or equal to that of the first Fresnel zone $d_F = 2\sqrt{\lambda L} = 6.2$ mm and, naturally, noticeably less than the diameter of the convex mirror. From Fig. 2 one can see that the cavity is sensitive to hole diameters three–four times less than the Fresnel zone diameter; the linear growth of divergence versus the hole diameter starts from approximately $d = 3$ mm ($0.5d_F$). Interestingly, the minimal divergence in the experiment is 1.7 that of an ideal cavity, whereas the angular diameter of the first dark ring in the far-field radiation intensity distribution is 1.04 that of an ideal cavity, that is, almost coincides with the latter. In our opinion, this may be related to small-scale scattering on laser cell windows and cavity mirrors. Turning back to results in Fig. 2, one may conclude that a hole with $d = 1.5–2$ mm at the axis of the concave mirror is quite admissible. Note also that holes with diameters of up to 11 mm do not affect the laser generation energy.

Now revert to the alignment scheme (Fig. 1) and start with numerical experiments, in which the beam of an alignment laser (AL) is simulated by a large set of rays (at least 10^6) distributed over angles and AL aperture according to the values chosen for AL divergence and aperture. Transit of rays through the cavity was calculated in the frameworks of geometrical optics. Ray distribution (intensity) was determined on the screen or in the collimator focal plane from calculations. In all calculations performed, the following parameter were used: the laser beam diameter was 1.5 mm, its divergence was 10^{-3} rad, the diameter of the hole in the mirror was 2 mm, the focal length and diameter of the concave mirror were 3690 and 100 mm, respectively; the focal length and diameter of the convex mirror were 1230 and 33 mm, respectively; and the distance between the mirrors was 2460 mm (the focal points coincide). These cavity parameters correspond to magnification $M = 3$. For example, Fig. 3 presents calculation results for an ideally aligned cavity in the case of the AL placed exactly at the centre of the cavity axis (both along the radiation propagation direction and in transverse coordinates). The collimator is placed in such a way that the centre of the focal spot matches the collimator crosshair. Wings of the intensity distribution in the collimator focal zone are related to the fact that the AL rays leave the cavity having passed different number of transits depending on the initial inclination relative to the cavity axis and, thus, form groups with different angular distributions.

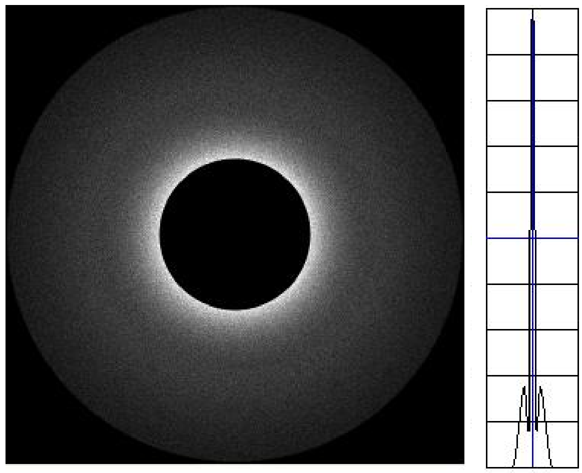

Figure 3. Example of calculation of the screen illumination intensity (left) and intensity distribution in the collimator focal zone (right; the scale is 10″).

Consider the influence of an inaccurate adjustment of the AL in the case of an ideally aligned cavity. Calculations show that inclination of the AL relative to the cavity axis of up to 60″ and transverse shifts of the laser position of up to 0.3 mm change the angle of wide beam axis inclination by 0.5″. Note that it is actually impossible to place 'inaccurately' the AL with parallel control of the screen illumination picture because it would result in obviously asymmetric illumination (Fig. 4).

This weak sensitivity of the output beam position to inaccurate placement of the AL is explained by that the shift of the AL ray from the axis in every round trip over cavity increases by a factor of M and, more important, the angle between the beam and axis reduces by the same factor. Three--four round trips over the cavity reduce the influence of AL placement inaccuracy on the output beam angle; the latter reduces by 27–81 times.

Now consider misalignment of the unstable cavity itself. It was already mentioned that in a telescopic cavity the radiation axis is the line connecting the centres of curvature of both mirrors. From this, one can easily obtain that the angle between the radiation axis of the unstable cavity and the line connecting mirror centres (the base line) is

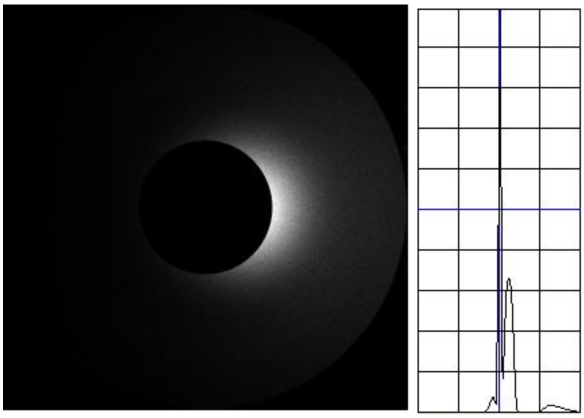

Figure 4. Example of calculation of the screen illumination intensity (left) and its distribution in the collimator focal zone (right; the scale is 10″) at inclination of the AL relative to the cavity axis of 60″.

$$\Psi = \frac{2(\beta M - \alpha)}{M - 1}, \qquad (1)$$

where β and α are the angles of inclination (misalignment) of the concave and convex mirrors relative to the base line, respectively. If the concave mirror is fixed, then the transverse shift Δ of the convex mirror will result in a change of the angle between the radiation axis and the axis of the concave mirror by

$$\Delta F^{-1} M/(M - 1), \qquad (2)$$

where F is the focal length of the concave mirror. Calculation results for the inclination angle of the output beam versus the cavity misalignment are given in Table 1. According to (2), the shifts of 0.25 and 0.75 mm from Table 1 are equivalent to the changes of the output mirror angle by 21″ and 62.9″, respectively. Comparison of the last two columns in Table 1 shows that if the angular misalignment is less than 60″ or the transverse shift of the convex mirror by a distance is below 0.75 mm, than the angle between the axis of the AL beam leaving the cavity and the radiation axis is at most 1.5″.

Table 1.

Inclination angle of the convex mirror/arcsec	Transverse displacement of the convex mirror/mm	Angular shift of the radiation axis [calculation by formulae (1) and (2)]/arcsec	Angular shift of output beam (calculation by a large set of AL beams)/arcsec
5	0	5	4.7
20	0	20	19.3
60	0	60	58.7
0	0.25	21	20.7
0	0.75	62.9	61.4

Note that it is actually impossible to align 'inaccurately' the cavity with parallel control of the screen illumination image, because this leads to obviously asymmetric illumination (Fig. 5).

Thus, placement of the AL behind a hole in the concave mirror allows one to align an unstable cavity with a high accuracy and, more important, to check the position of the axis of the unstable cavity with an accuracy of an arcsecond.

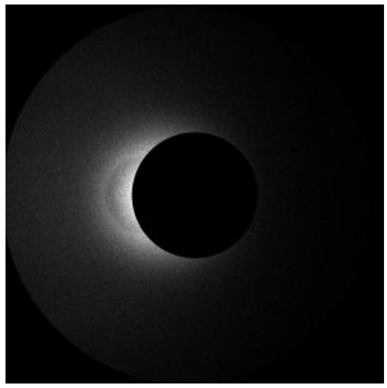

Figure 5. Screen illumination at a convex mirror inclination angle of 60″.

From formulae (1) and (2) follows that the radiation axis is tied to neither of the cavity mirrors; this axis is determined by mutual disposition of the mirrors. Position of the radiation axis can be determined by using the fact that the axis of the AL radiation beam expanded in the cross section due to multiple transits across the cavity coincides with the laser radiation axis within a high accuracy. This coincidence is explained by physics of radiation generation and evolution in an unstable-cavity laser: the radiation from near-axis domain occupies the entire cross section in several round trips across the cavity, similarly to the AL radiation.

We have verified the mentioned accuracy of matching the axes by performing the corresponding measurements with employment of a chemical pulsed DF laser according to the optical scheme shown in Fig. 6. The scheme implies passage of three optical radiation beams.

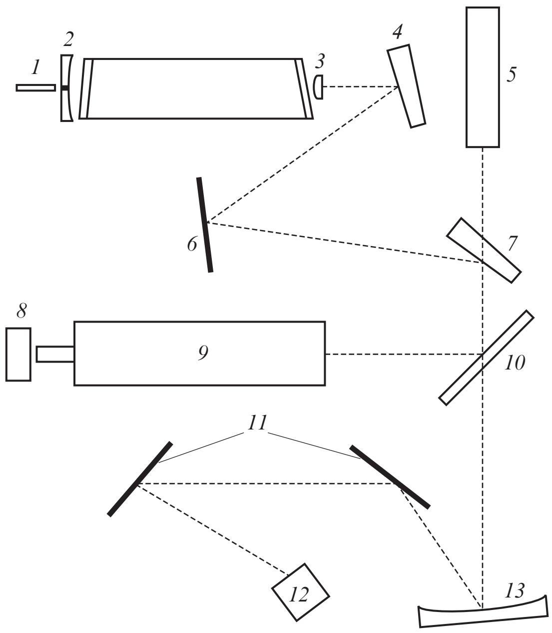

Figure 6. Optical scheme of measurements:
(*1*) AL; (*2*) concave mirror of the cavity; (*3*) convex mirror of the cavity; (*4*) wedge; (*5*) source of collimated radiation; (*6*) plane mirror; (*7*) wedge; (*8*) CCD camera; (*9*) collimator; (*10*) plane-parallel plate; (*11*) plane mirrors; (*12*) Pyrocam-III array sensor; (*13*) spherical mirror.

Beam A is the IR-laser radiation itself. It passes from the unstable cavity [mirrors (*2*) and (*3*)], reflects from the front surface of a wedge (*4*) (made of CaF_2), from a plane copper mirror (*6*) and from the first surface of a wedge (*7*) (made of CaF_2), passes through a plane-parallel plate (*10*) (made of CaF_2), reflects from a spherical mirror (*13*) with a focal length of 18 m, from two plane mirrors (*11*), and finally is detected by a Pyrocam-III sensor. Mirrors (*11*) are needed for getting a required distance from the spherical mirror to a Pyrocam-III sensor array. Beam reflections from the wedges are used to attenuate the IR laser radiation.

Beam B is the collimated radiation of a source (*5*) that has a wavelength of 0.63 μm and diameter of 50 mm. It passes through the wedge (*7*), partially (6%) reflects from the plane-parallel plate (*10*) into a collimator (*9*); in the focal plane of the latter (1000 mm), a CCD array (Spiricon SP620U) (*8*) is placed. The rest part of beam B (94%) propagates along the path of IR-radiation.

Beam C is the radiation of an alignment He–Ne laser (*1*) with a beam diameter of about 2 mm. It is coupled to the cavity axis and after three-four transits leaves the cavity in the form of a ring with diameters of 33 and 100 mm. After reflection from elements (*4*, *6*, *7*) and (*10*), this radiation passes to the collimator.

The main idea of the scheme suggested is as follows. According to the calculations discussed above, the axes of beams A and B coincide within a high accuracy; however, this fact should be experimentally verified. The CCD sensor of Pyrocam-III is insensitive to the alignement beam C that is attenuated by two wedges. Instead, the unattenuated radiation of the collimated source (beam B) passes to Pyrocam-III, and the angle between the axes of beams B and C can be exactly measured by the collimator with a CCD array. In the ideal case, the angles between the axes of beams B and C should be equal to the angles between axes of beams A and B. Results of these measurements are shown in Fig. 7. Note that the greatest angles presented in the abscissa axis were specially introduced by misaligning the cavity. In this case, as follows from our calculations, the angles between beam axes may differ by ~2″. But the average deviation of experimental points from the line corresponding to equal angles is 0.9″ at a dispersion of 5.9″. We relate this spread to the fact that, while mounting the optical scheme, we failed to meet the requirements concerning experimental measurements of angles with the accuracy of at most 1″, namely, strong adjustment of numerous cumbersome optical elements and angular stability of laser radiation (beams B and C).

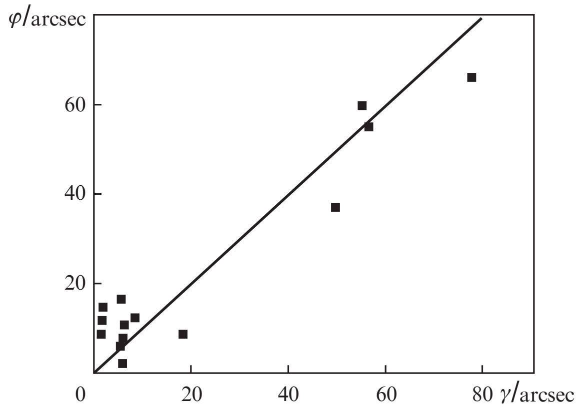

Figure 7. Angle φ between the axes of beams A and B vs. the angle γ between the axes of beams B and C. Points correspond to experiment; straight line corresponds to equal angles.

Note that it is easy to incorporate the scheme suggested for determining the position of the radiation axis of an unstable-cavity laser into any guidance system in which a sighting line is specified.

Thus, calculations and experiments show advantages of the alignment scheme considered. This scheme provides highly accurate alignment of an unstable cavity and, more important, 'shows' the position of the radiation axis of an unstable-cavity laser even in the case of imperfect cavity alignment.

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