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LASER CAVITY WITH A GRADUALLY EXPANDING RADIATION BEAM IN THE ACTIVE MEDIUM

Subject and Purpose. *Increasing the operational efficiency of laser generators and the amount of their radiated power is an important task in laser development, which can be approached to in a number of alternative ways. The present work has been aimed at increasing the efficiency of energy exchange between the active medium and the laser radiation by way of optimizing the radiated intensity distribution over the entire active volume within the resonant cavity of a novel structure.*

Methods and Methodology. *A model for the process of radiated power amplification in the laser cavity has been considered. Losses within the cavity have been analyzed, as well as possibilities for improving the efficiency of energy transfer from the gain medium to the laser radiation. The importance of optimizing the density of laser radiation in the gain medium is substantiated, and the main problems that might arise clearly identified. The task of increasing the cross-section of the radiation beam being amplified in the active medium has been formulated, and a concept suggested for solving the problem through modification of the telescopic resonator's optical scheme.*

Results. *A novel configuration has been suggested for the laser resonator, where the radiated beam is expanded in width over two stages of counter propagation. Nonlinear regimes of increasing the beam cross-section in the resonator have been analyzed and recommendations formulated for selecting dimensions of the resonator and geometry of the mirrors, depending on the amount of amplification in the active material. Fragmentation of the output mirror is proposed as a means for feedback optimization, with account of diffraction-caused divergence of the radiation. As has been found, field-exciting elements can be placed inside the active medium. Recommendations are developed as for practical application of the scheme proposed in lasers of a variety of frequency ranges.*

Conclusions. *Application of laser resonators of the design considered opens up new possibilities for increasing the efficiency of lasers and their radiated power.*

Keywords: *laser resonator, active medium, laser radiation, efficiency.*

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Introduction

An important task in the development of lasers, as well as of any generators, is to increase their efficiency, thus increasing the output power of the radiation. There are many different ways for achieving these goals — because of the wide variety of existing types of lasers, ranges of the frequencies generated, output power levels, sizes and varieties of resonant systems, and features of the gain media employed.

Universal methods are known that are suitable for increasing the efficiency of amplification in any active medium, of which latter there is a wide variety, too[1]. One of the methods is based on providing a uniform distribution of laser radiation throughout the volume of the active medium. It is desirable that the active material should not involve zones inaccessible for laser radiation, because those are the zones where the energy of the active material cannot be converted into radiated energy. This condition can be easily provided for in the well-known Fabry–Perot resonator [2]. Whereas, some problems might arise, for example, with confocal resonators, in which the radiation is concentrated near the axis [3]. In order to achieve a maximum efficiency of converting the energy of the active material into laser radiation, it is not sufficient to just fill the entire active volume with the radiation but is rather necessary to ensure an optimized intensity distribution of the laser radiation throughout the volume. Should the radiation intensity be in excess of a certain level, then kind of a saturation effect could occur, such that amplification in the active material would be decreased. Otherwise, in case the intensity of the laser radiation were very low, not all of the energy pumped in could be used efficiently. Therefore, ensuring an optimal intensity of laser radiation throughout the volume of the active material is an important condition for obtaining a high amplification efficiency for the laser radiation, and, as a consequence, an increased output power of the laser [4]. Partially, the problem can be solved by providing an optimal feedback. Note the radiation intensity to decrease abruptly when arriving at an output mirror or another coupling element. Meanwhile, in order to obtain a maximized gain it is necessary that the radiation intensity be optimized all the way through the active material. So far, this condition cannot be ensured in the currently existing laser cavities [5, 6]. Apparently, there is a need for developing laser resonators of novel designs. The aim of this work is to increase the efficiency of converting the energy contained in the active material into that of laser radiation by optimizing the radiative intensity throughout the active volume, using a resonant cavity of a novel (modified) structure.

1. Prospects for increasing the efficiency of lasers

Opportunities for improving the efficiency can be identified through a detailed analysis of energy conversion processes in the Fabry–Perot laser resonator (Fig. 1).

The resonator is formed by two planar mirrors (see Fig. 1, *a*). One of them is opaque, while the other, which is at the output, is partially transparent. The active element is located between the mirrors. The change in the radiation intensity that occurs over two passes through the resonator during its steady operation is shown schematically in Fig. 1, *b*). A certain part of the radiation (denoted I_0) is reflected from the output mirror back into the resonator. While passing through the resonator sections which are not filled with an active material the radiation is not amplified. On the contrary, it gets somewhat weakened. Also, radiation intensity losses occur at both mirrors. Therefore, sizes of the resonator sections not occupied by the active material need to be minimized, and both the ohmic and the diffractive losses at the mirrors must be reduced to increase the laser efficiency.

After two consecutive passes through the resonator the radiation arrives at the output mirror once again. Here, part of the radiation is extracted from the resonator, while the other part gets reflected back into it, thus providing a feedback. A maximized efficiency of the laser can only be obtained with an optimal ratio of these two parts of the radiation. The main factors influencing this ratio are amplifiication properties of the active material, length of the resonator and the amount of losses therein. A smooth and equable introduction of pump energy into the active material allows ensuring uniformity and high amplifying properties of the latter.

An important condition for ensuring an effective amplification of the laser radiation consists of maintaining its intensity at an optimal level along the entire path through the active material. The radiation

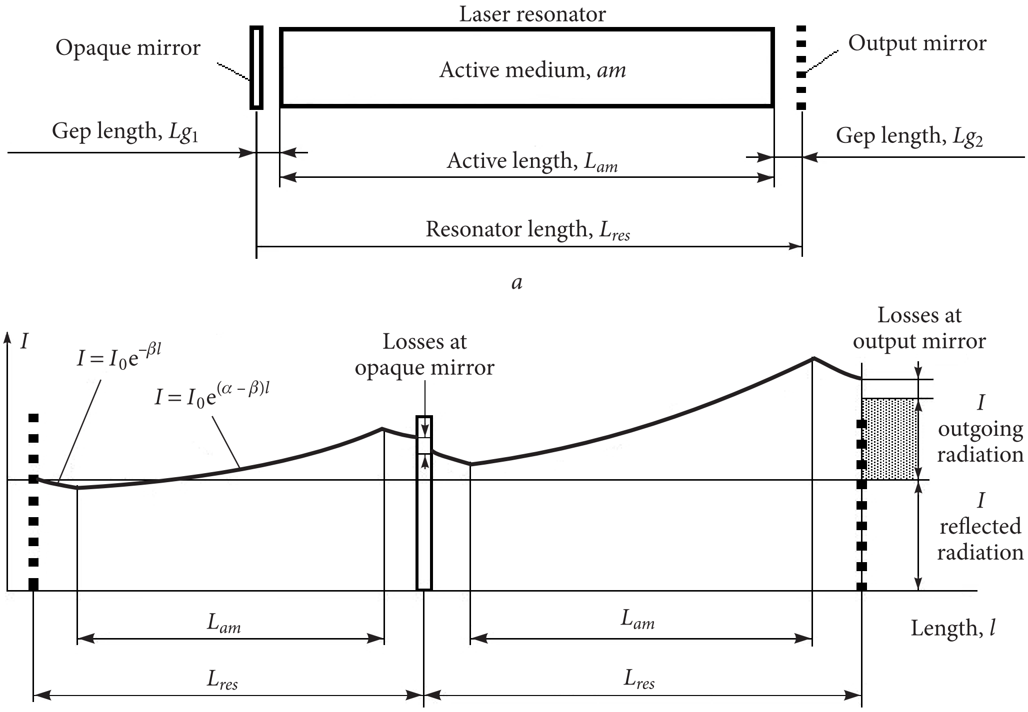

Fig.1. Structural model of the laser resonator (*a*), and variations of the laser radiation intensity *I* in the direction *l* (*b*)

intensity should not exceed the threshold value causing saturation [4, 7], lest the gain would decrease. Still, the radiation intensity should not be too low, such as to prevent the energy contained in the active substance from being used effectively (and, instead, be partially spent on some spurious spontaneous radiation). The maximum amplification efficiency can be achieved only at an optimal level of laser radiation intensity, at the edge of saturation effect [4, 7, 8].

In case both the active element and the laser beam in it are characterized by constant cross section areas (Fig. 1), it proves impossible in principle to ensure an optimal radiation intensity along the entire length of the resonator. Indeed, the intensity is constantly growing over every two passages through the active substance. An intensity close to optimum can only be achieved over some individual section of this path. The ratio between the length of this section and the total path traveled by the radiation as a result of two consecutive passes can be diminished through reducing the resonator length. Yet in that case the effect of radiation losses on the mirrors may increase. Although these losses are small, they occur at every pass. Consequently, a contradiction arises which cannot be eliminated for the resonator geometry considered.

The energy of the active substance would be used most efficiently if the cross section of the laser beam in the resonator, as well as the cross section of the active element on its path, both increased in proportion to the growth rate of the laser radiation power. In other words, the radiation intensity should remain at a certain optimal level. In that case, a uniformly maximized amplification would be ensured in each part of the active medium, providing for a maximum use of its energy, while never crossing the limits of saturation.

An approach of kinds toward optimizing the radiation density is implemented in the well-known confocal laser resonator of unstable positive type, commonly known as telescopic [4, 8]. The resonator consists of a concave and a convex mirror with a focal point in common (Fig. 2). In this case, the focus for the convex mirror is imaginary. The convex mirror is of a smaller diameter. Radiation is output from such a resonator past the convex mirror, in the form of a parallel beam of annular cross section.

The advantage of such a laser resonator is that the radiation traveling from the convex toward the concave mirror propagates as a smoothly expanding beam. Moreover, the farther each of the beam fragments is "shifted" from the resonator axis, the larger

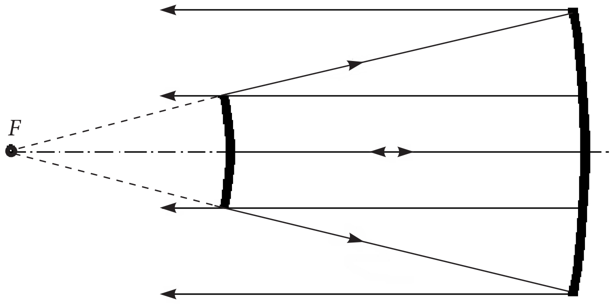

Fig. 2. Telescopic resonator

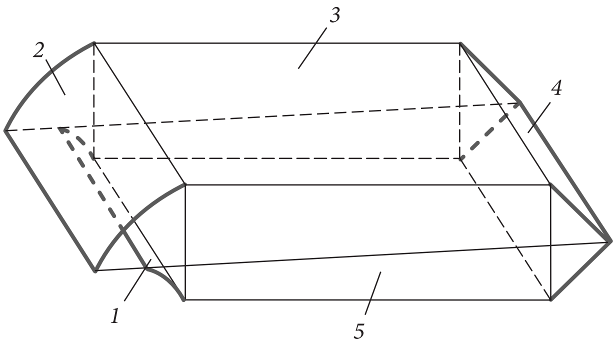

Fig. 3. Scheme of a laser cavity with a smooth expansion of the radiation beam cross section

gets its angle of expansion. This character of beam expansion is well correlated with the exponential growth of the radiation intensity in the active material (denoted *1* in Figs. below). Therefore, it becomes possible to obtain, by properly selecting the geometry of the mirrors, the allegedly optimum level of intensity for the active substance that has been used. This permits achieving a nearly maximum energy efficiency of the active material throughout the specific passage of radiation through the resonator. However, on the way back (from the concave toward the convex mirror) the radiation propagates in the form of a parallel beam, which does not allow obtaining a high gain during this passage. In addition, the efficiency of the first passage is somewhat reduced by the fact that only a part, rather than the entire volume of the active material, is involved in amplifying the radiation intensity. Another advantage of the resonator is that the radiation leaves it in the form of a parallel beam. Meanwhile, the output beam is characterized by an annular cross section, which may be considered a disadvantage. Still, despite all the shortcomings, such resonators are in use, owing to their increased efficiency. Work on their improvement is continued [9—13]. However, no fundamental changes have been introduced into the structure, such that could make it possible to achieve beam expansion in both of the opposite-directed passages. Therefore, a radiation intensity optimized over the entire volume of the active medium could not be achieved.

2. General structure and operating principle of the laser resonator with an expanded cross section of the radiation beam

The optical principles suggesting solution to the problem of creating a smoothly expanding radiation beam have been analyzed. A fundamentally new structure and lay-out of the resonator have been proposed [14], which provide for a smooth expansion of the laser beam's cross section during its passages through the active medium. The general structure of the resonator is shown in Fig. 3, while Fig. 4 illustrates the ray trajectories in it.

The resonator involves a convex cylindrical mirror *1* and a concave cylindrical mirror *2*, both located at the same face of the active element *3* which has a rectangular cross section. The dihedral reflector *4* is located on the opposite face of the active element *3*. That reflector consists of two rectangular planar mirrors making a 90° angle. The surface generatrices of cylindrical mirrors *1* and *2* are parallel to the dihedral edge of reflector *4*. The rectilinear edges of cylindrical mirrors *1* and *2* are adjacent to opposite edges of the end face of active element *3*. The tangent planes that can be drawn through these edges to cylindrical surfaces of mirrors *1* and *2* form a 90° angle between themselves and a 45° angle with the end face of the active element. The other rectilinear edges of each cylindrical mirror lie either within [the imaginary] plane *5* or at some distance from it. Plane *5* could be drawn through the crease of the dihedral reflector *4* at an angle φ (Fig. 4) to the side face of the active element *3*, which is adjacent to the convex mirror *1*. The angle φ determines the geometric divergence of rays in the active medium and is chosen with account of amplifying properties of the latter. The higher the amplification rate in the active material, the greater expansion of the radiation beam's cross section is required for obtaining a maximized efficiency. Hence, the greater should be the magnitude of the angle φ which ensures formation of a divergent laser beam in the resonator (Fig. 5). Moreover, it should be taken

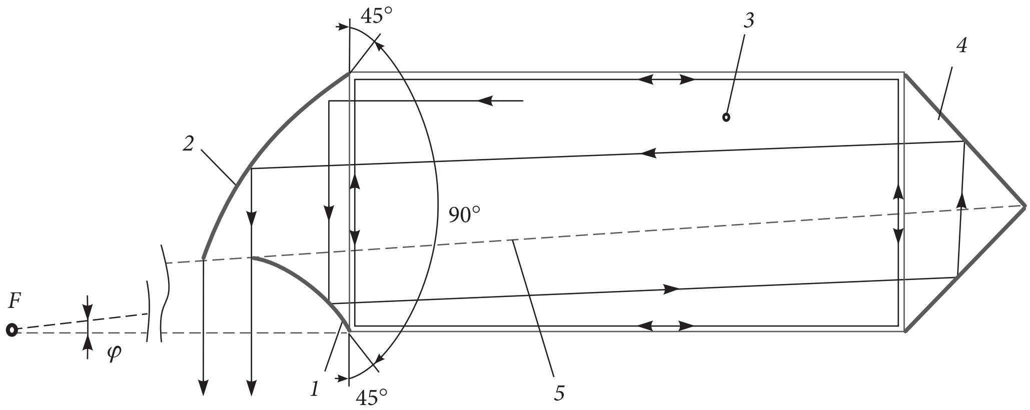

Fig. 4. Path of rays in a laser cavity with smooth expansion of the radiation beam cross section

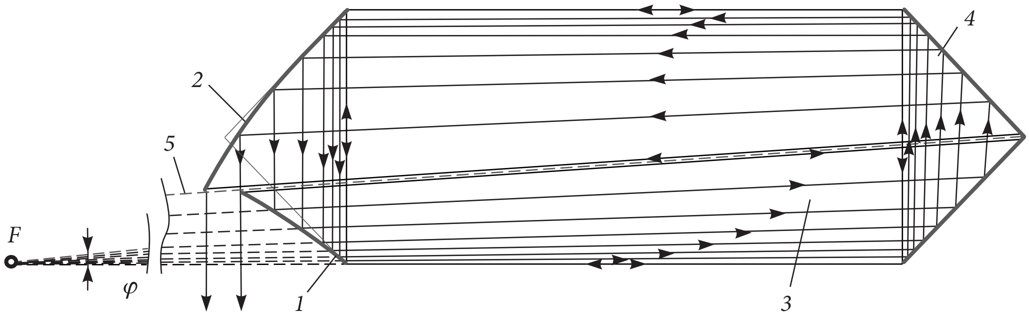

Fig. 5. Formation of a divergent laser beam in the resonator

into account that the angle φ is not such of geometric divergence of the rays. The angle of geometric divergence is smaller than the angle φ, and is not of the same magnitude over the resonator volume. The angle of geometric divergence increases after each consecutive passage of the radiation toward the exit from the resonator. The characteristic behavior of the beam's cross section is close to the exponential law obeyed by the growing radiation intensity in an active material.

The guides of the cylindrical mirrors *1* and *2* represent the parts of a parabolic surface which provide for satisfaction of the conditions as follows. All the rays directed toward the surface of the concave mirror *2* which are parallel to the end face of the active element *3* and perpendicular to the top of the dihedral reflector *4*, are directed, upon reflection from the concave mirror *2* and then from the faces of the rectangular mirror *4*, toward the focal line F of the optical system (Fig. 5). The rays traveling in the opposite direction (toward the convex mirror *1*) behave as if divergent from the focal line *F* upon reflection from the mirror *1*. The focal line is in fact formed by intersection of the separating plane *5* with continuation of the lower face of active element *3*. Note all the rays reflected from mirror *2* to be parallel to one another. This makes it possible to extract radiation from the resonator in the form of a parallel beam.

Calculations of the surface form of cylindrical mirrors *1* and *2* should be made with account of diffractional properties of the radiation involved. The reason is that the diffraction-caused divergence of the beam is responsible for certain corrections in the geometry of the beam path through the resonator. The effects will be especially significant in the terahertz frequency range where the diffraction-produced divergence of laser radiation is quite significant. Consequently, to implement a high-quality profile of the mirror it may prove necessary to take into account, along with the gain factor due to the active material, also the radiation wavelength relative the geometric dimensions of the resonator [16]. This is a rather complex problem which can be solved with the aid of computer simulation.

The physics of the processes occurring in a laser cavity with a smoothly expanding cross section of the radiation beam is as follows. The active element *3* is excited by any of the known methods, as

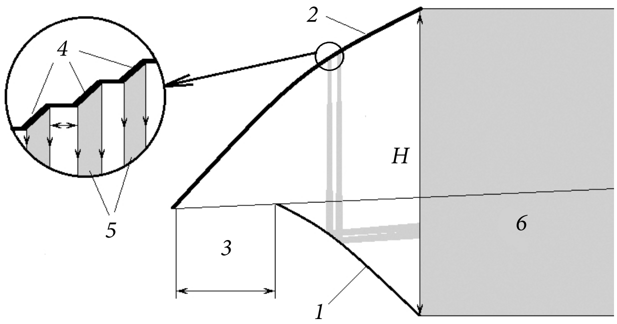

Fig. 6. Stepped surface of the concave cylindrical mirror

a result of which radiation is generated. The set of mirrors *1*, *2* and *4* shape the laser radiation up. The generation conditions in the near-surface part of the active element *3* are similar to such in the ring laser. The amplification process is almost the same for oppositely directed radiation beams that are reflected from edge zones of mirrors *1*, *2* and *4* adjacent to active element *3*. The laser beam expansion is minimal throughout this near-surface zone, occurring almost exclusively as a result of diffraction. The laser-conditioned generation can occur in the standing wave regime. This near-surface zone of the active element *3* can be considered as the zone of formation of coherent radiation. Owing to diffraction effects and correctly chosen geometry of the mirrors, the laser-produced radiation is "shifted", with each passage through the near-surface zone, into the middle part of the active element *3* and toward plane *5*. The geometry of the mirrors is arranged so that "shifted" inwardly is only the radiation propagating from the convex mirror *1* toward the rectangular mirror *4* and then from mirror *4* to the concave mirror *2*. The geometry of the mirrors prohibits the radiation of the opposite direction from being deflected into the active element *3*. The cross section of the radiation beam shifted into the active element *3* expands with each consecutive passage. The closer the radiation "shifts" toward plane *5*, the larger gets the beam's angle of expansion. The maximum expansion of the radiation beam is the greater, the larger the magnitude of the angle φ. The radiation reflected from the concave mirror *2* takes the form of a parallel beam, and part of it (which is closer to plane *5*) leaves the resonator past the edge of the convex mirror *1*. Thus, the output laser beam has a nearly rectangular cross section, characterized by a parallel arrangement of the beams in it.

The smooth shape of the profiles of mirrors *1* and *2* does not allow fulfilling all the conditions for optimizing the expansion of the radiation beam, while still providing for an optimal feedback. Therefore, it is advisable to assume a stepped surface for the concave cylindrical mirror *2* (Fig. 6). This makes it possible to change the size of mirror *2* in the axial direction of the resonator, regardless of the angle of expansion of the beam cross section. This permits varying the gap *3* between mirrors *1* and *2* and changing the amount of feedback over a wide range, regardless of possible dependence upon the angle of expansion of the radiation beam. The stepped surface of mirror *2* may consist of individual reflective fragments (bands) *4*. These fragments can be in the form of parabolic sections, or spherical sections of a variety of curvatures. These fragments can also be straight sections with different angles of inclination. The size of the reflective fragments a and the distance between them may vary, depending on specific conditions. The choice of distances between reflecting fragments must be made, based on the amount of feedback in the resonator which is dependent on the size of gap *3* between mirrors *1* and *2* (Fig. 6). The phases of the waves reflected from neighboring fragments of the reflecting surface of mirror *2* must coincide if the resonator operates in a single-frequency mode, which is typical for terahertz lasers. To do this, it is necessary that the distance a between adjacent fragments of the reflecting surface of mirror *2* (Fig. 6) be a multiple of the radiation wavelength. The choice of reflecting fragment sizes and distances between them should be made with account of the ratio between the radiation wavelength and size of the resonator. It is desirable that the adjacent radiation bands (denoted *5*) that undergo reflection from the stepped mirror *2* were transformed, owing to diffraction-produced divergence, into a relatively uniform radiation flux while traveling from mirror *2*, then past mirror *1* toward the active material *6*. For this, the relation must be satisfied:

$$a \le h \times \operatorname{tg} \vartheta,$$

where a is the distance between adjacent reflecting fragments of the stepped mirror *2*; h is the resonator height; ϑ is the angle of divergence of the laser beam as reflected from an individual fragment of the reflecting surface of mirror *2*.

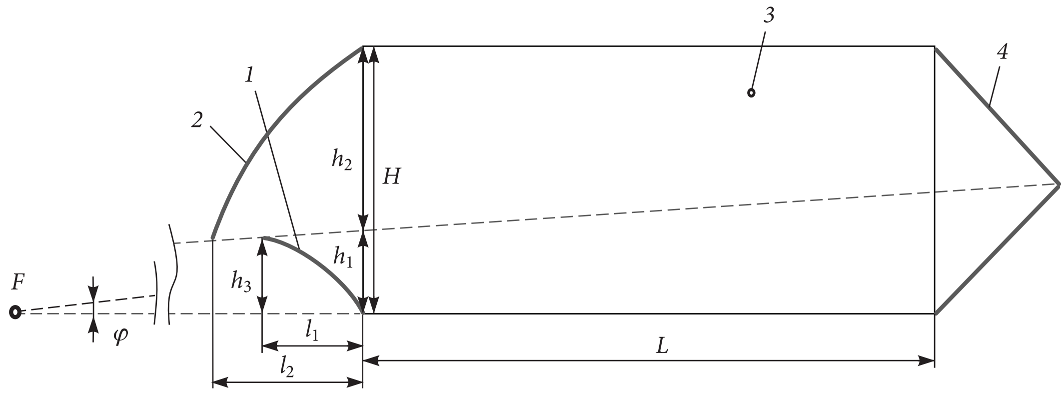

Fig. 7. Principal geometric parameters of the resonator

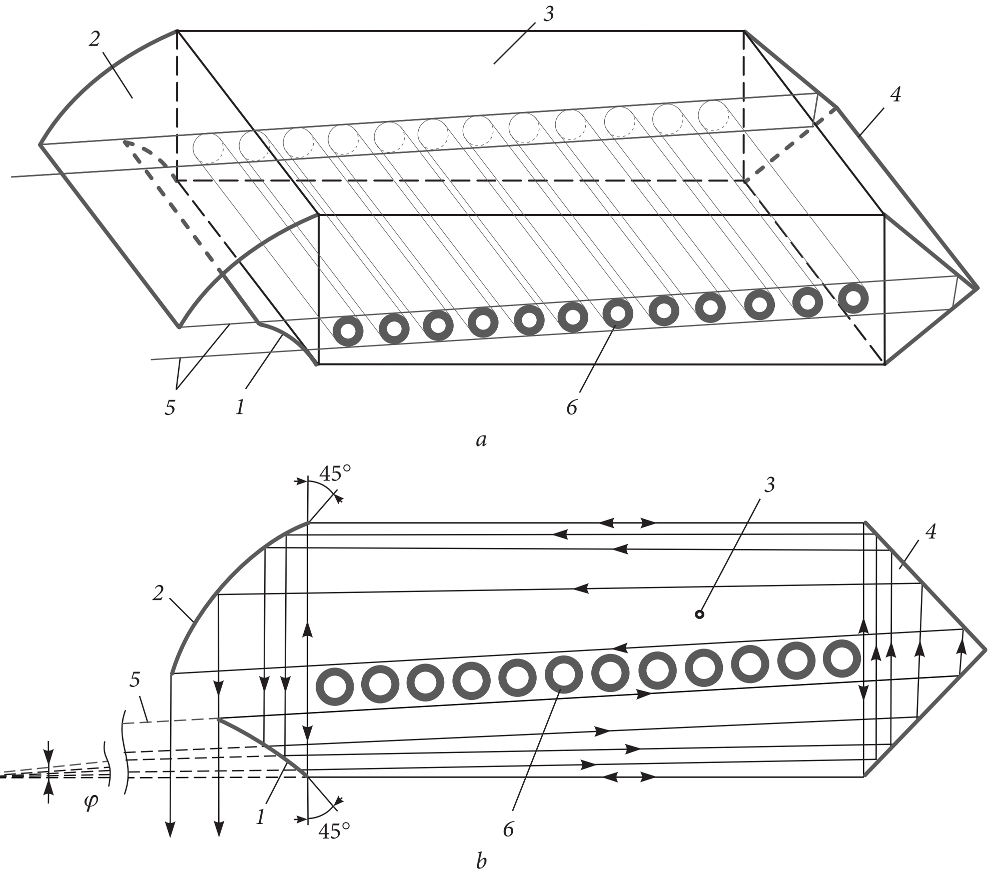

Fig. 8. Laser resonator with a smooth expansion of the radiation beam's cross section: pumping elements (*a*) inside the active material, and ray trajectories (*b*)

When using stepped mirrors, the smooth expansion of the radiation beam cross section is accompanied by discretized expansion upon reflection from the stepped mirror *2*. This must be taken into account when optimizing the beam expansion in the resonator.

The calculation of feedback and expansion of the radiation beam cross section in the resonator is based on the main geometrical parameters of the resonator (Fig. 7). Moreover, the basic parameters are: the initially set angle φ, which determines the geometric divergence of rays in the resonator; the length of the active element — L; height H of the active element, and vertical size h_3 of the cylindrical mirror. Among the important parameters to determine the feedback in the resonator also are horizontal dimensions of the convex cylindrical mirror *1* (l_1) and of the concave cylindrical mirror *2* (l_2). The remaining dimensions can be derived from these basic parameters.

The expansion of the cross section of the radiation beam in the resonator can be characterized by the coefficient of increase in the beam's cross section — *M*. This coefficient shows how many times the total beam cross section increases in two passes in the resonator — on the way from the entrance to the active substance *3* from the side of the convex mirror *1* to the exit from the active substance towards the concave mirror *2* (Fig. 7).

$$M = h_2 / h_1 ,$$

where h_1 is the vertical size of the laser beam at the entrance to the active substance from the side of the cylindrical mirrors, h_2 is the vertical size of the laser beam at the exit from the active substance in the direction of the cylindrical mirrors.

In calculations, it is advisable to use the basic parameters of the resonator:

$$h_2 = h_1 + (2L + H)\,\mathrm{tg}\,\varphi,$$

$$h_1 = h_3 + l_1\,\mathrm{tg}\,\varphi,$$

then

$$M = \frac{\left(h_3 + l_1\,\mathrm{tg}\,\varphi\right) + (2L + H)\,\mathrm{tg}\,\varphi}{h_3 + l_1\,\mathrm{tg}\,\varphi}.$$

The feedback in the resonator is characterized by the coefficient *K* representing the share of radiation extracted from the resonator, namely:

$$K = \frac{l_2 - l_1}{l_2}.$$

In the considered resonator, the radiation is reflected four times from the mirrors during two opposite passes through the active substance. Consequently, the losses on the mirrors are higher than those of resonators of comparable length with two mirrors. However, these losses can be compensated by increasing the resonator length. After all, with an increase in the length of the resonator under consideration, the efficiency of using the energy of the active substance does not decrease (in contrast to resonators without expansion of the beam cross section). However, an increase in the length of such a resonator entails an increase in its cross section. This is especially true for resonators with a large expansion of the beam cross section. At the same time, attention should be paid to ensuring the uniformity of the pumping of the internal zones of the active substance.

The active element can be pumped in various ways. The pump elements can be placed at the outer boundaries of the active element. The scheme of the resonator under consideration allows this to be done with little modification. To do this, it is necessary to change dimensions of cylindrical mirrors *1*, *2* and their location relative to the top of the dihedral reflector *4*, as shown in Fig. 8. As a result, a zone free from radiation appears in the resonator. This zone is limited by two parallel planes *5* passing through the edges of cylindrical mirrors (Fig. 8). The lower plane passes through the focal line *F*. Additional pumping elements *6* can be placed in this free zone. Sufficient energy supply of the active substance in this area favorably affects the efficiency of the laser.

The use of additional internal excitation elements might be necessary for improving the homogeneity of the active material in resonators of a relatively large cross section area.

Conclusions

A new scheme of the laser resonator has been proposed. This resonator provides an increase in the efficiency of converting the energy of the active material into the energy of laser radiation by way of optimizing the intensity of laser radiation throughout the active volume. The main advantage of the geometry implemented in the new resonator is the smooth manner of expanding the laser beam's cross section during either of its oppositely directed passages through the active material. As a result, the radiation is evenly distributed over the entire active volume and extracted from the resonator in the form of a parallel beam of a nearly rectangular cross section. The smooth expansion of the radiation beam's cross section allows obtaining an optimum radiation intensity in the active material. This permits to efficiently use the energy contained in the active material, while avoiding saturation effects.

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ЛАЗЕРНИЙ РЕЗОНАТОР З ПОСТУПОВИМ ЗБІЛЬШЕННЯМ
ПЕРЕРІЗУ ПУЧКА ВИПРОМІНЮВАННЯ В АКТИВНІЙ РЕЧОВИНІ

Предмет і мета роботи. Підвищення ефективності роботи лазерів і потужності їх випромінювання є важливою задачею, до вирішення якої можна підійти кількома альтернативними шляхами. Ця робота спрямована на посилення енергообміну між активним середовищем і лазерним випромінюванням шляхом оптимізації розподілу інтенсивності випромінювання по всьому активному об’єму в лазерному резонаторі модифікованої конфігурації.

Методи і методологія. Розглянуто енергетичну модель процесу посилення випромінювання в лазерному резонаторі. Проаналізовано втрати в резонатора, а також можливості підвищення ефективності передачі енергії від активної речовини до лазерного випромінювання. Обґрунтовано важливість оптимізації інтенсивності лазерного випромінювання в активній речовині та визначено проблеми, які при цьому виникають. Сформульовано задачу поступового збільшення поперечного перерізу пучка випромінювання, яке посилюється в активній речовині, та запропоновано концепцію її вирішення шляхом модифікації оптичної схеми телескопічного резонатора.

Результати. Розроблено нову конфігурацію лазерного резонатора, в якому переріз пучка лазерного випромінювання поступово збільшується на обох зустрічних шляхах. Проаналізовано нелінійний режим збільшення перерізу пучка в резонаторі та сформульовано рекомендації щодо вибору розмірів резонатора і геометрії дзеркал залежно від величини підсилення в активній речовині. Запропоновано фрагментацію вихідного дзеркала як засіб оптимізації зворотного зв’язку з урахуванням дифракційного розходження випромінювання. Виявлено можливість розміщення додаткових елементів збудження всередині активної речовини. Розроблено рекомендації щодо практичного застосування запропонованої схеми в лазерах різних частотних діапазонів.

Висновки. Застосування лазерних резонаторів розглянутої конфігурації відкриває нові можливості для підвищення ефективності лазерів і потужності їх випромінювання.

Ключові слова: *лазерний резонатор, активна речовина, лазерне випромінювання, ефективність.*