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Basic trends in the development of diode-pumped solid-state lasers

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Abstract**.** **Solid-state lasers of a new generation – diode-pumped solid-state lasers (DPSLs) are considered. The outlook for their further development is analysed. It is shown that in fact all the parameters of DPSLs are superior to those of flashlamp-pumped lasers.**

Keywords: *solid-state lasers, diode pumping, laser parameters.*

1. Introduction

Modern solid-state lasers are extensively used in fundamental physics, for example, they are used for studying nonlinear and parametric processes in the interaction of radiation with matter and for investigating the properties of matter in superstrong electromagnetic fields; in the development of methods for generation of X-ray radiation and γ radiation; in very precise measurements performed in various fields of physics; the development of new optical standards, etc.

Solid-state lasers are also extensively used in technology. Today we can speak about laser instrument making and laser technologies as about independent technology fields. Modern solid-state lasers and devices based on these lasers are applied in optical communication and navigation systems, laser medicine and biotechnologies, metallurgy and military technologies, geodesy and cartography, in the environment monitoring, and other fields of science and technology.

In this connection the development of efficient solid-state lasers of a new generation, the extension of their functional possibilities and the methods for controlling their lasing regimes is still an urgent problem. The solution of this problem will provide a substantial progress in most of the above-mentioned fields.

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2. Solid-state lasers of a new generation

Considerable recent advances in the physics of solid-state lasers are related to the development and studies of a new generation of these lasers – diode-pumped solid-state lasers (DPSLs). The progress in this field of laser physics was achieved due to

(1) the use of narrow-band semiconductor radiators for pumping solid-state lasers, which resulted in a substantial increase in the lasing efficiency and in a decrease in thermal loads in active elements;

(2) the use of monolith and semimonolith designs, which combine in one element an active medium, an optical cavity, and (in some cases) control elements, resulting in turn in a considerable improvement in the output radiation stability;

(3) the use of new active media, among which the media possessing large gains and nonlinear-optical media should be distinguished, which extended the functional possibilities of solid-state lasers;

(4) the high reliability and long operating life of semiconductor radiators.

Of great importance is also the introduction of new technologies, such as the use of distributed domain structures (DDSs), phase conjugation (PC), distributed Bragg reflectors (DBRs), highly selective dielectric coatings, phased semiconductor radiators, etc, which significantly simplify solutions of many technological problems.

Solid-state lasers of a new generation drastically differ from their precursors, conventional flashlamp-pumped solid-state lasers. The efficiency of DPSLs is almost an order of magnitude greater than that of conventional lasers. A distinctive feature of DPSLs is their high temporal and frequency stability. Note that the use of virtually inertialess semiconductor radiators for pumping makes it possible to realise easily mode locking and fast feedback, which facilitates the stabilisation of the output radiation parameters of DPSLs.

DPSLs have a small size and in most cases (at average powers up to 1 W) do not require water cooling. This makes them very promising for a variety of applications. In addition, a high reliability of semiconductor radiators and their long operating life, which exceeds, as a rule, 10^4 h, also facilitate extensive applications of these lasers.

The development, fabrication, and studies of DPSLs occur so rapidly in the last years that even scientific papers cannot timely reflect a real progress in this field of laser physics. In this connection, the analysis of further developments in this field is quite important. The aim of this review is to describe the basic lines and trends in the development of a new generation of solid-state lasers.

A variety of applications of solid-state lasers put forward different (often incompatible) requirements to the output parameters of these lasers. Indeed, the most important parameters of lasers used in metrology, laser spectroscopy, precision measurements, and in Doppler measuring systems are the stability of cw lasing, single-mode and single-frequency lasing, an extremely narrow emission spectrum, the high spatial and time coherence, and a low noise level. At the same time, a high output power is not very important for such lasers.

Lasers used in medicine, military technologies, various technological processes, and in some other fields should provide first of all a stable repetitively pulsed regime at the average output power of the order of several tens of watts.

Finally, technological lasers should have a high output power of the order of several hundreds of watts and a high efficiency. In this case, as a rule, single-mode, single-frequency emission is not required.

The basic trends in the development of DPSLs are determined by their practical applications. First, this is the improvement of the DPSL design and schemes for their pumping and, second, the extension of functional possibilities of these lasers. The latter includes, for example, the development of tunable lasers, lasers with frequency self-doubling and variable polarisation of emission. It is also important to create DPSLs that can operate in various specific regimes such as periodic Q-switching and mode locking, self-modulation and travelling-wave modes in solid-state ring lasers, and some other regimes.

Note, however, that the realisation of different lasing modes in DPSLs, as a rule, does not require new technological solutions compared to those used in flashlamp-pumped lasers. Therefore, here we will consider only the developments in the field of solid-state lasers with semiconductor pump (mainly cw lasers), which are related to the improvement of their design and the extension of their functional possibilities.

First we consider briefly several general questions concerning the use of narrow-band laser diodes for pumping solid-state lasers.

3. Basic optical pumping schemes

In a DPSL, the broadband and strongly astigmatic emission from a semiconductor laser is converted to the radiation of a solid-state laser emitted, as a rule, in the fundamental transverse TEM_{00} mode. A solid-state laser can be pumped by one or several independent semiconductor lasers (laser diodes) or semiconductor laser linear or two-dimensional arrays. Advances in the manufacturing of highly efficient DPSLs were achieved due to a considerable progress in the development of highly efficient semiconductor lasers and laser arrays.

The maximum output cw power of a modern semiconductor laser with the width of the $p-n$ junction equal to 100 μm (which determines the minimum possible cross section of the laser beam) is ~ 10 W. Much greater powers acieving several kilowatts can be obtained using laser linear or two-dimensional arrays, which contain from several tens or several thousands laser diodes, respectively.

Emission from a laser diode can be focused into a spot of diameter ~ 0.1 mm. This allows one to decrease a minimum volume of the active medium required for lasing almost by four orders of magnitude (from 10^{-1} to 10^{-5} cm^3), thereby opening up unlimited possibilities concerning miniaturisation of lasers and the reduction of the pump power. An example of the implementation of such possibilities is a laser whose active element represents a sphere of diameter of a few micrometers (see section 6).

An important factor determining the efficiency of DPSLs is the efficiency of 'transport' of the pump radiation into an active element. The main difficulty here is caused by a strongly different divergence of emission from laser diodes in perpendicular planes, which hinders the use of spherical optical elements for focusing pump radiation.

The most efficient (and most widespread) is the use of laser diodes whose emission is outcoupled with the help of fibres. In addition, the pump radiation is often focused using spherical optical elements and prisms. When pumping is produced by diode arrays, radiation is focused with the help of special fibre splitters or conical radiation concentrators, which allow one to transport the pump radiation to a required region with minimum losses.

At present there are several somewhat different optical schemes for pumping solid-state lasers using semiconductor radiators (see, for example, Refs [1 – 11]). These schemes can be divided into two large groups: schemes with longitudinal (front) pumping (through ends) (Fig. 1) and with transverse pumping (Fig. 2).

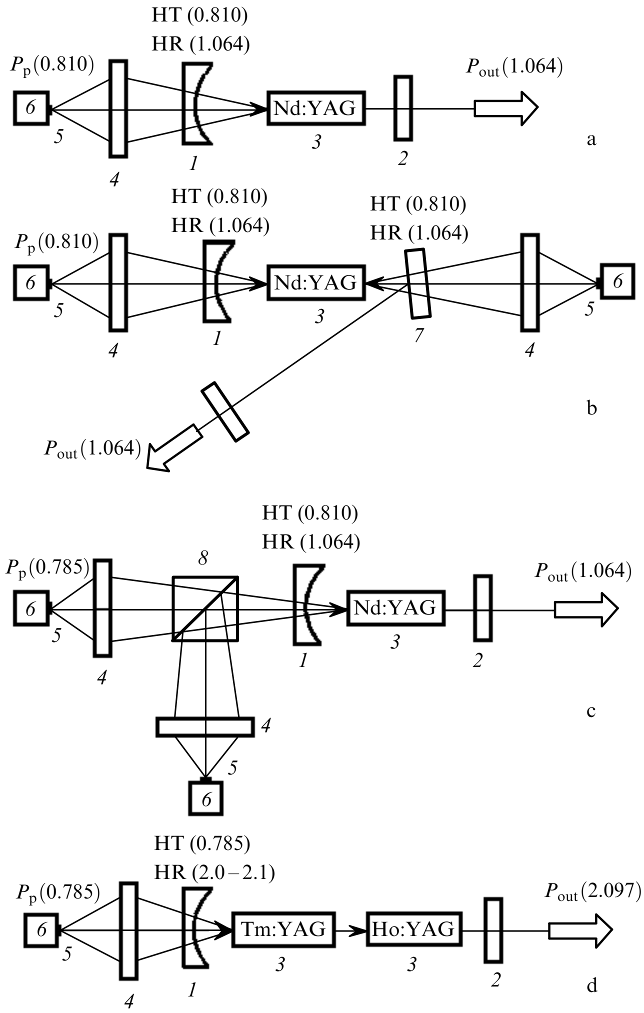

Figure 1. Basic longitudinal pumping schemes: classical longitudinal pumping (a); two-sided pumping (b); pumping by two semiconductor lasers (c); and pumping with the intracavity conversion of the pump wavelength (d). (*1*) Highly reflecting cavity mirror (which is often deposited directly on the end of the active element); (*2*) output cavity mirror; (*3*) active element; (*4*) microobjective; (*5*) laser diode; (*6*) thermostat; (*7*) additional selective mirror; (*8*) mixing polarisation cube. Hereafter, HR and HT denote high reflectivity and transmission of dielectric coatings of some laser elements. In parentheses the wavelengths are indicated in micrometers.

In the first case (Fig. 1), the direction of the pump beam P_p coincides with that of the laser beam, thereby providing the possibility of a spatial matching of the volumes of the generated mode and the excited region. This ensures the

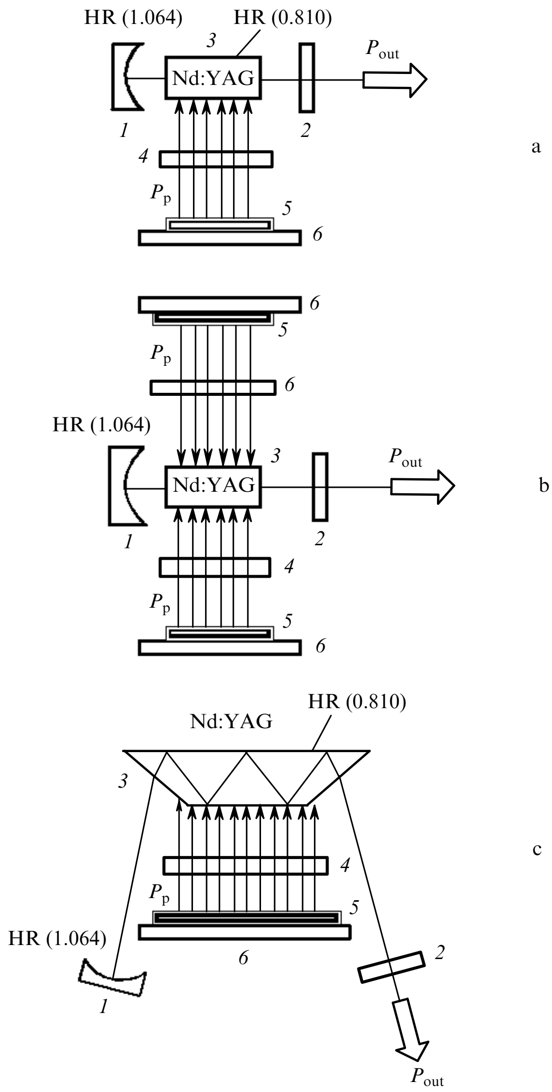

Figure 2. Basic transverse pumping schemes: one-sided pumping (a); two-sided pumping (b); and excitation of a slab element (c). (*1, 2*) Highly reflecting and output cavity mirrors; (*3*) active element; (*4*) cylindrical lens; (*5*) semiconductor array; (*6*) thermostat.

efficient use of the pump power, and such schemes allow one to obtain the maximum efficiency of conversion of the pump radiation into stimulated emission.

Solid-state lasers with longitudinal pumping have a rather high efficiency, however, their output power P_{out} is restricted by the size of the lasing volume of the active element and the pump power. This problem can be solved by using several semiconductor lasers, which can be either combined with the help of fibres or a prism system or used independently for pumping different regions of the active element. Because in the latter case, the effective volume of the active element can be increased, this case is preferable.

The absorption coefficient of the most widespread active media at the pump wavelength is of the order of several inverse centimetres. Therefore, the length of the active element at which $\sim$90 % of the pump power is absorbed is as small as 3 – 5 mm. In microlasers, active media often used in which the absorption coefficient at the pump wavelength amounts to several tens of inverse centimetres and the pump radiation is completely absorbed at the length less than 1 mm.

The longitudinal pumping is the most efficient in comparatively low-power (output power up to 1 W) highly stable miniature DPSLs. In this case, to obtain the high efficiency, one should solve a difficult problem of the formation of the spatial profile of the pump radiation. The matching of a cylindrically symmetrical volume of the TEM_{00} mode with a strongly astigmatic output beam of a laser diode requires the use of an anamorphous optical system containing cylindrical lenses or prisms. The most efficient method for matching the beams is the use of laser diodes with fibre outcouplers. This method allows one to combine many laser diodes into a single pump source using one branched fibre [12, 13].

A specific highly efficient multistage scheme of longitudinal pumping was implemented in paper [14]. In this scheme, a 2.097-μm Ho:YAG laser was pumped by an auxiliary 2.013-μm Tm:YAG laser (pumped by a laser diode), which was placed inside the Ho:YAG laser cavity.

The efficiency of longitudinal pumping decreases with increasing power of a DPSL because to obtain high output powers, active elements of a large volume are required whose longitudinal pumping is hindered. Indeed, at high powers the longitudinal pumping cannot provide the pumping of the active element over its entire length, which results in a number of negative effects: a strong local heating of the active element, the appearance a thermal lens in it, and induced birefringence.

The transverse pumping lacks these drawbacks and can be used in the case of long active elements. Its main disadvantage is an incomplete matching of the excited volume of the active element with the volume of lasing modes, resulting in a lower lasing efficiency. Nevertheless, when high output powers are required, the transverse pumping becomes not only preferable but the only possible.

One of the problems encountered in the development of transversely pumped high-power solid-state lasers is the provision of the efficient heat removal from the active medium. Note that just the necessity of efficient heat removal determines the design features of these lasers.

4. Most widespread active media for DPSLs

The semiconductor lasers can be used in principle for pumping almost any solid-state lasers because absorption bands of most active media doped with rare-earth ions lie in the spectral region from 0.7 to 1.3 μm, where laser diodes efficiently emit powerful radiation. The number of active media in which lasing was obtained upon pumping by laser diodes exceeds several tens (see, for example, Refs [1, 15, 16]). Consider some most promising active media that are widely used in modern DPSLs.

$Nd^{3+}:Y_3Al_5O_{12}$ (Nd:YAG) single crystals are most popular among the DPSL active elements. Lasers based on these crystals produce emission at 0.946 [17], 1.06 [18], 1.12 [19], 1.3 [20], and 1.44 μm [21] at room temperature. The wide application of Nd:YAG crystals is explained by a fortunate combination of their good luminescence parameters and sufficiently strong absorption bands located in the spectral region that is convenient for pumping between 0.808 and 0.812 μm with a high optical homogeneity of these crystals and their excellent operating parameters (high heat conductivity, low thermal expansion, high hardness, etc.).

The YAG crystals doped with other rare-earth elements are gaining increasing importance in the last years [22–26]. In particular, Yb:YAG crystals emitting at 1.029 μm with the quantum efficiency of up to 89 % upon pumping at 0.97 μm are the most promising for the development of high-power cw lasers [26].

The necessity of building ecologically safe lasers emitting in the spectral range between 2 and 3 μm stimulated extensive studies on the development of efficient lasers based on Er^{3+}, Ho^{3+}, and Tm^{3+} ions [22–25].

The $Nd^{3+}:KGd(WO_4)_2$ crystals represent a certain interest for the fabrication of miniature DPSLs. These crystals belong to low-threshold active media, which have a high efficiency at low pump powers. Their advantage is a weak concentration quenching, which allows one to use high activator concentrations [27].

The $Nd^{3+}:YVO_4$, $Nd^{3+}:GdVO_4$, and $Nd^{3+}:GdWO_4$ lasers are also used for the manufacturing of miniature chip lasers [28–31]. The cross sections for the operating transitions and absorption cross sections of these crystals at the pump wavelength are greater than those for a Nd^{3+}:YAG crystal, and they also have broader absorption bands (see Table 1).

Table 1.

Parameters of the active medium	Nd:YAG	$Nd:YVO_4$	$Nd:GdVO_4$
Effective cross section for the stimulated transition at 1.064 $\mu m/10^{-19}$ cm^2	2.8	15.6	7.6
Absorption coefficient/cm^{-1}	7.6	40.7 ($E\|\|C$) 10.5 ($E\perp C$)	74 ($E\|\|C$) 10.6 ($E\perp C$)
Absorption bandwidth/cm^{-1}	2.5	8.7 ($E\|\|C$) 15 ($E\perp C$)	3.2 ($E\|\|C$)
Thermal diffusivity/ W m^{-1} K^{-1}	13	5.1	12.3

The $YLiF_4$ (YLF) crystals are also of great interest for some applications [32–34]. Due to their high transparency in the UV and IR spectral regions, they produce lasing in a broader spectral range. The YLF crystals doped with Nd^{3+} ions emit at 1.047 and 1.053 μm and doped with Er^{3+} or Ho^{3+} ions they emit at 1.6 or 2.06 μm, respectively.

The lifetime $T_1 = 480$ μs of the upper lasing level in Nd:YLF crystals is longer than that in a Nd:YAG crystal, which provides their more efficient pulsed lasing. The high heat conductivity of these crystals and a weak temperature dependence of their refractive index result in a better stability of cavity parameters in a broad range of output powers. Finally, the lasing wavelength coincides with the wavelength corresponding to the maximum of the gain of phosphate glasses, which permits the use of a Nd:YLF laser as a master oscillator in high-power phosphate glass laser systems [35].

A $Nd^{3+}:YAlO_3$ crystal is also widely used as a laser crystal emitting at 1.079 μm [36, 37].

Crystals possessing a broad luminescence band, which can produce mode-locked femtosecond pulses, attract great recent interest. These crystals include $Cr^{3+}:LiSrAlF_6$ (Cr:LiSAF), $Cr^{3+}:LiCaAlF_6$ (Cr:LiCAF), $Cr^{4+}:Mg_2SiO_4$ (forsterite) and others [38–40].

Nonlinear-optical active media are very promising for intracavity frequency self-conversion in solid-state lasers upon harmonic generation and SRS [41–46]. Among nonlinear-optical crystals used for this purpose are $Nd^{3+}:LiNbO_3$ [41, 42], $Nd^{3+}:YAl_3(BO_3)_4$ [43, 44], and $Nd^{3+}:Ce_{1-x}Cd_xSc_3(BO_3)_4$ [46]. Glasses of various types doped with rare-earth ions ($Nd^{3+}, Er^{3+}, Yb^{3+}$, and others) are also extensively used and, in particular in fibre lasers [47–49].

Thermal stabilisation of the elements of diode-pumped lasers consists in the maintaining of the temperature of the laser diode required for the matching of its emission wavelength to the absorption band of the active element and in the thermal stabilisation of the active element itself. The former problem is solved using well-developed conventional methods. The thermal stabilisation of active elements is also usually not complicated, although highly stable single-frequency lasers require a rather high accuracy of the temperature control (~0.01 K).

A wide use of semiconductor pumping stimulates the search and development of new active media for chip lasers, which should satisfy the stringent requirements, such as a low lasing threshold, the possibility of using active ions at high concentration, a high optical quality of crystals, a high heat conductivity, low thermal expansion, and the presence of nonlinear and magnetooptical properties.

5. Single-frequency chip lasers

5.1 Linear chip lasers

Monolith linear chip lasers represent short (of length from 0.1 to 5 mm in the lasing direction) rods with flat or spherical ends. Such lasers are pumped, as a rule, longitudinally. On one of the crystal ends, through which the pumping is performed, a selective mirror is deposited, which is highly reflecting at the lasing wavelength and is transparent at the pump wavelength. Another crystal end has an output mirror deposited on it. The pump radiation is focused with a microobjective inside an active element.

The output cw power of such lasers can achieve several watts. The peak power of *Q*-switched chip laser achieves 600 kW for the pulse energy ~5 mJ.

In most cases, it is important to obtain lasing in the fundamental transverse TEM_{00} mode. The selection of transverse modes in longitudinally pumped monolith lasers can be produced by a proper choice of the cavity design and by a special formation of the pump-beam caustic. The problems of optimisation of the longitudinal pumping were discussed in detail in Refs [50–52]. Note the optimal cross section of the region being pumped should be close to the cross section of the caustic of the fundamental mode in the cavity [53]. For tight focusing of the pump beam, higher-order Laguerre–Gaussian modes can be predominantly excited.

The selection of longitudinal modes for producing single-frequency lasing in linear chip lasers is a rather complicated problem. This is explained by a large (compared to the intermode spacing) width of a homogeneously broadened gain line of typical solid-state lasers. For example, the width of the gain line in a Nd:YAG laser is ~180 GHz, whereas the intermode spacing does not exceed, as a rule, 10–15 GHz. For this reason, it is necessary to use special selectors for producing single-frequency generation in linear chip lasers.

However, because it is impossible to introduce selective elements into the cavity of monolith chip lasers, the main method for producing single-frequency lasing is the reduction of the longitudinal size of the cavity. To achieve stable single-mode generation in linear chip Nd:YAG lasers, the cavity length should not exceed 200–300 μm [55]. In the case of longer cavity lengths, single-frequency lasing can be achieved when the pump power only slightly exceeds the threshold.

To obtain a high output power in linear chip lasers with short cavities, it is reasonable to use either media containing active centres at high concentrations or media with high absorption cross section at the pumping wavelength [56, 57]. In such media, single-frequency lasing can be obtained due to competition between longitudinal modes [58].

A classical example of a monolith linear chip laser is a laser with mirrors deposited directly on the crystal ends [59]. The active element of this laser made of a high-quality $Nd:YVO_4$ crystal has a square cross section with a side of 3 mm. One of the crystal ends is flat and another is spherical, with the radius of curvature of 10 cm. The flat end is covered by a selective coating with a high reflectivity at the lasing wavelength (1.06 μm) and a low reflectivity at the pump wave-length (0.808 μm). The cavity (active element) length is 1.5 mm. The laser produces several tens of milliwatts of cw emission in the fundamental transverse TEM_{00} mode. The differential efficiency of such chip lasers achieves 57 % – 58 %. If the active element is made of a Nd:Cr:YAG crystal, which plays simultaneously the role of a saturable absorber, the laser can operate in the *Q*-switching mode [60].

At present, active crystals operating both according to the four-level and three-level schemes are used in linear chip lasers. In the latter case, it is necessary to provide the conditions when the pump intensity on the output end of the crystal represents a substantial fraction of the pump intensity on the input end. This is explained by the necessity of producing the population inversion over the entire length of the active element, because, otherwise, the losses at the lasing wavelength drastically increase.

5.2 Ring chip lasers

The possibility of obtaining a sufficiently stable single-frequency generation in linear chip lasers is restricted by a spatially inhomogeneous burning of the population inversion during generation, which is inherent in these lasers. For this reason, ring travelling-wave lasers are the most promising for producing a stable single-frequency lasing [61].

Travelling-wave ring lasers can be divided according to their design into three groups: conventional ring lasers consisting of discrete elements [62, 63], monolith [64–68], and semimonolith ring chip lasers [69–71].

Cavity mirrors in lasers of the first group are, as a rule, separate elements, and an active element itself is often used as a nonreciprocal optical rotator. Reciprocal optical rotation in ring lasers can be obtained by using a nonplanar cavity [72]. A drawback of ring lasers consisting of discrete elements is their poor stability (the relative instability of the emission intensity is ~1 % and that of the frequency is 10^{-8}) caused by an insufficient rigidity of the construction.

From the point of view of stability, a monolith design of a chip laser has the best parameters. A monolith ring chip laser represents a complex polyhedral prism (Fig. 3) cut from an optically homogeneous single crystal (more often from Nd:YAG). In this laser, the same element plays the role of the active medium, reciprocal and nonreciprocal optical rotators, and the optical cavity. The configuration of this element chosen so that the existence of a ring cavity (flat or nonplanar) is provided by total internal reflections from the element faces and by a partially transmitting mirror deposited on one of its faces. To provide the cavity stability, one of the prism faces has a spherical surface on which a selective mirror is deposited, which has a high reflectivity at the lasing wavelength and is highly transparent at the pump wavelength. The chip laser is pumped through this mirror (Fig. 3).

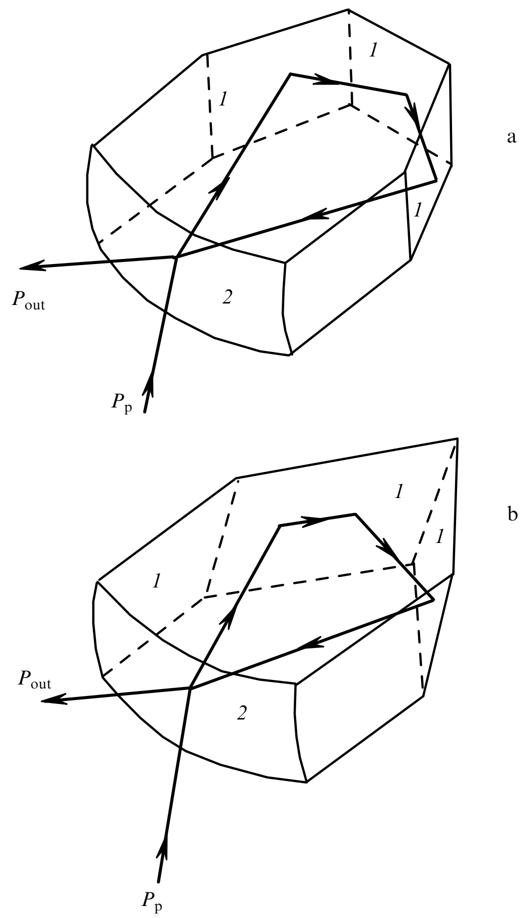

Figure 3. Principal schemes of some monolith ring chip lasers with flat (a) and nonplanar (b) cavities: (*1*) faces of total internal reflection; (*2*) selective mirror.

The magnetic field ***H*** applied to the active medium causes nonreciprocal optical Faraday rotation. The nonplanar ring cavity serves as a reciprocal optical rotator. It is the combination of the reciprocal and nonreciprocal optical rotators with the polarisation-anisotropic output mirror that provides unidirectional lasing.

The development of highly stable single-frequency ring chip lasers requires a detailed working of all laser elements. To obtain the maximum stability and minimum width of the laser line, it is necessary to reduce maximally the optical coupling between the pump source and the monolith element, as well as between the active element and a detector. The presence of such couplings and their instability result both in fluctuations of the spectrum and the emission intensity of the laser diode and in fluctuations of the coupling coefficients between counterpropagating waves in the ring chip laser itself [73]. The effect of these couplings can be reduced using an additional selective mirror and optimal focusing of the pump beam on the spherical surface of the active element [74].

A Nd:YAG ring chip laser with optimised parameters produces 60 mW of cw single-frequency emission at 1.06, 1.319, and 1.338 μm at the magnetic field strength H = 100 Oe [75]. One of the necessary conditions for optimisation of unidirectional lasing is a proper choice of the parameters of a partial polariser, i.e., of optimal reflectivities of the mirror for s and p polarisations. This problem was analysed, for example, in paper [72].

Note that along with ring lasers operating in the travelling-wave mode, ring lasers operating in the stable two-directional lasing mode are also widely applied. In the latter case, the self-modulation regime of the first kind is the most interesting [76].

Of practical interest is also the use of phase anisotropy, which takes place in a ring nonplanar cavity even in the absence of the magnetic field. This anisotropy results in the frequency splitting for right- and left-polarised waves, which can amount to several hundreds of kilohertz at $H = 0$ [72]. The dependence of the frequency splitting of the magnetic field can be used for tuning chip lasers [64].

A system consisting of a highly stable, monolith, single-frequency (as a rule, ring) chip laser and a power amplifier is the most convenient for producing single-frequency output powers of several tens of watts [77], whereas to obtain output powers up to 10 W, it is preferable to use conventional ring lasers consisting of discrete elements, which are longitudinally pumped by a high-power laser diode [78].

A monolith chip laser can be tuned by producing and controlling mechanical stresses in the active element itself [79–81]. The tuning range in a static regime can achieve 100 MHz [80] and upon resonance excitation of stresses, several tens of gigahertz [79, 81]. In Ref. [82], the possibility of tuning of a ring chip laser by a magnetic field is reported.

Another method of tuning of chip lasers is based on the modulation of the pump power [83]. This method offers a number of advantages over conventional methods (piezooptical, electrooptical or acoustooptical) because is does not require a large controlling power (or voltage), the use of complicated electronic circuits, the introduction of additional elements inside the cavity or the use of special mechanical details. The method is based on the variation in the temperature of the active element, resulting in the change in the proper frequency of the laser cavity.

Summing up the properties of monolith, single-frequency, ring chip lasers, we emphasise once more that it is these lasers that produce extremely narrow instantaneous emission linewidths close to the theoretical limit determined by the Shawlow–Townes formula [84].

The long-term stability of emission from monolith chip lasers is restricted mainly by the instability of their temperature regime. The problem of long-term stability can be solved by locking the emission frequency of the chip laser to the frequency of a standard whose parameters only weakly depend on the environment [85–89]. The interesting method of stabilisation of the emission frequency of the chip laser is its cooling to liquid nitrogen temperature [90].

5.3 Semimonolith ring lasers

The second line of investigations, which seems quite promising, is the creation of ring chip lasers with a composite cavity [69–71]. Although such cavities will be, naturally, less rigid than monolith lasers, they can feature a better thermal stability (when two materials with different thermooptical properties are used). Chip lasers consisting of two or three rigidly connected elements possess greater functional possibilities. The designs of such lasers are shown in Fig. 4.

Semimonolith ring lasers can be tuned using piezoelectric transducers [69, 70]. The ratio of losses for counterpropagating waves in such lasers can be easily optimised, which is necessary for producing powerful unidirectional single-frequency lasing.

In Ref. [71], 155 mW of single-frequency output power was obtained from a semimonolith Nd:YAG laser pumped by 1.2 W and tunable within 2 GHz. The laser linewidth measured by heterodyning emission from two identical lasers was lower than 100 kHz during measurements for 20 ms. A semimonolith chip laser shown in Fig. 4c can be tuned even over a broader range of 13.5 GHz [69]. Such a broad tuning range was achieved by using two elements in the laser design, the air gap between them being controlled with the help of piezoelectric.

Ring lasers with a cavity formed by the active element, which has Brewster ends whose planes are located at an angle of 1.5° to each other, and by two selective mirrors (see Fig. 5 in Ref. [91]) also belong to lasers of this type. The travelling-wave mode is provided by the application of a

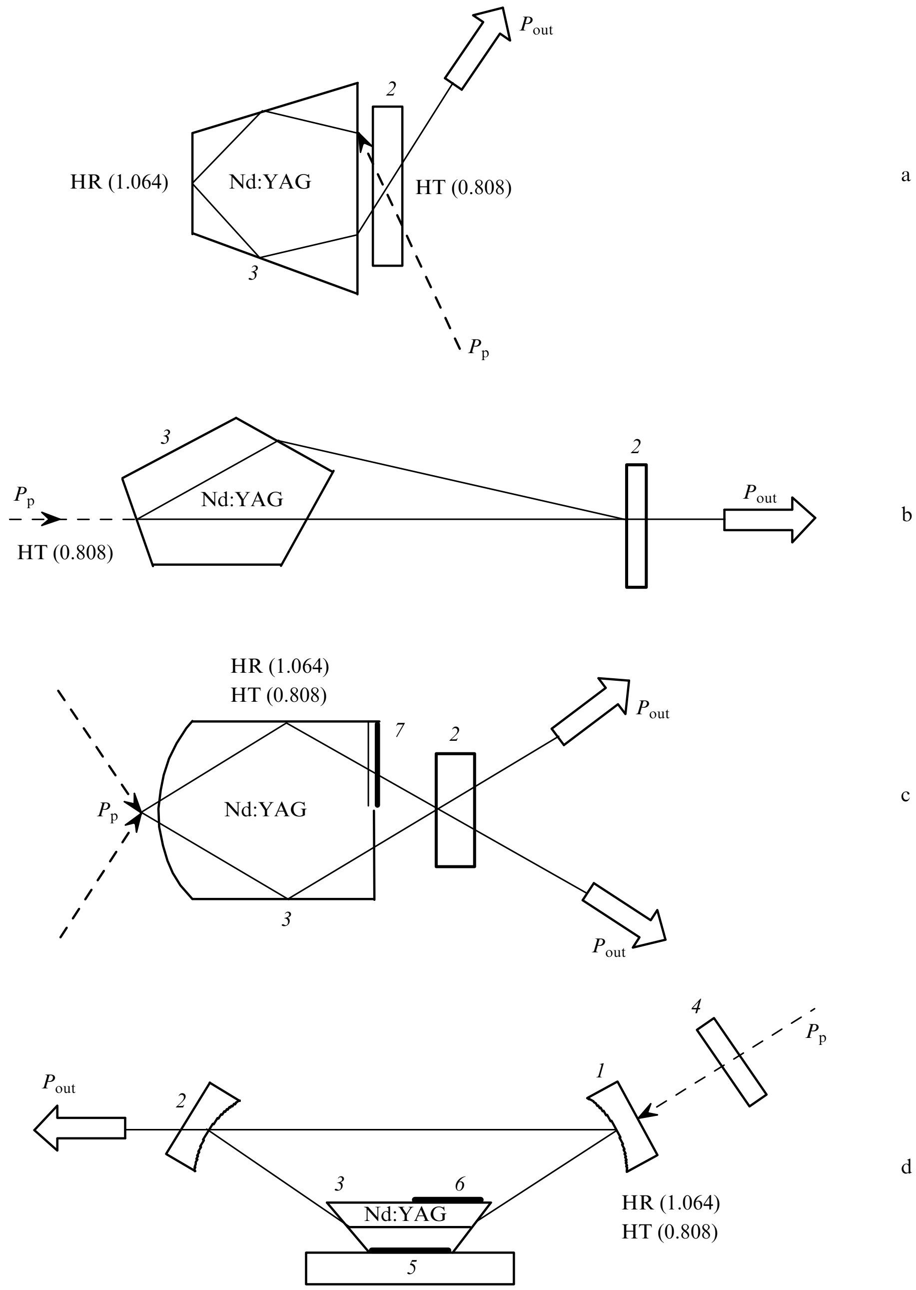

Figure 4. Principal schemes of semimonolith ring lasers: (*1, 2*) highly reflecting and output mirrors; (*3*) active element; (*4*) microobjective; (*5*) thermostat; (*6*) permanent magnet; (*7*) partial polariser.

longitudinal magnetic field to the active element (Nd:YAG). The advantage of such a design is a minimal number of elements and the possibility to change rapidly the lasing wavelength (from 1.064 to 1.319 μm) because the laser has no intracavity elements with antireflection coatings.

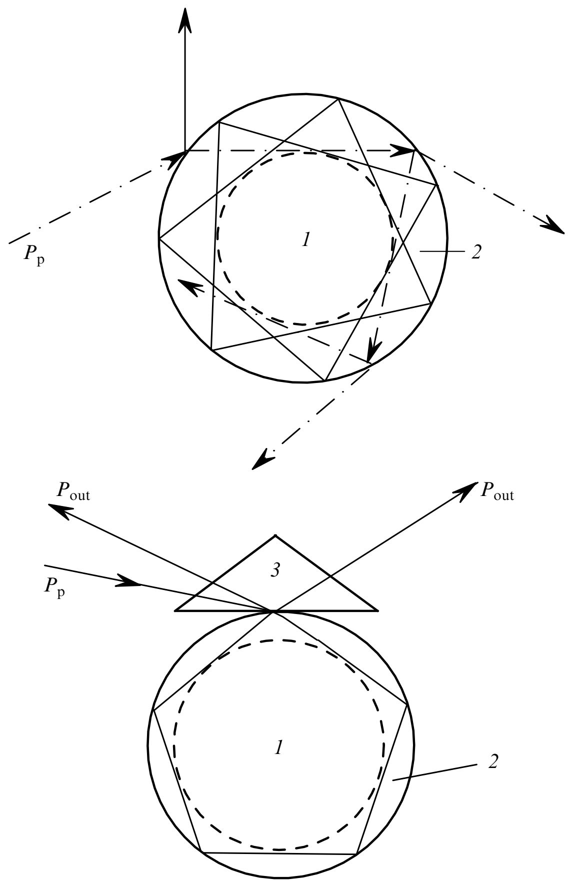

Figure 5. Principal pumping schemes for spherical lasers: (*1*) microsphere; (*2*) region in which the inversion is produced; (*3*) glass (quartz) prism.

6. Microsphere lasers

Microsphere solid-state lasers (spherical lasers) gained wide acceptance in the last years [92–97]. The active element of such a laser is a sphere of a small diameter (from fractions of millimetre to a few millimetres) made of a doped glass or single crystal. The optical feedback required for lasing is provided by total internal reflection from the sphere surface (Fig. 5). In this case, lasing is taking place at 'whispering gal-lery' modes [97].

These lasers have an extremely small size and a high cavity Q factor, which achieves $\sim 10^8 - 10^9$. In addition, they are characterised by a very low lasing threshold, which can be as low as a few nanowatts [98]. This permits the creation of a microlaser operating at liquid helium temperature, which contains only several (!) active ions.

Spherical lasers can be pumped by a focused pump radiation by two methods (Fig. 5). In the first case, the pump beam is directed to the sphere at an angle to the tangent and enters the sphere after refraction, by passing inside it in the plane containing the sphere centre and the wave vector of the pump wave. In this case, the excited region has the form of a torus. In the second case, a prism is pressed against the sphere, and the focused pump beam enters the sphere at the contact point. The direction of the pump beam inside the sphere (and, therefore, the position of the excited region) can be varied by changing the direction of the incident pump beam. In this case, it is sufficient simply to provide total internal reflection not only for the lasing wave but also for the pump wave. The active region is also toral in this case.

Depending on the pumping conditions, the generation of a spherical laser can occur either at one mode or simultaneously at several linearly polarised modes, their polarisation vectors being parallel or perpendicular to the pumping plane.

A special feature of the radiation dynamics of a spherical laser is the fact that the rate of spontaneous emission inside a high-Q microsphere is more than 10^3 times exceeds this rate in a free space. This changes the type of relaxation processes, resulting in the involvement of new transitions in the Nd^{3+} ion in lasing [97].

Unlike lasers with a cylindrical symmetry emitting, as a rule, at Gaussian modes, spherical lasers can emit at modes of other types (depending on the type of pumping) [99]. A great interest in microsphere lasers is caused by the possibility to use them in fundamental experiments in the field of quantum electrodynamics.

7. Average-power solid-state lasers

7.1 Methods for improving radiation quality

Consider now the principles of the design of DPSLs having an average output power of several tens of watts. To produce the high output power in such lasers, large volumes of the active medium should be excited. In this case, despite a high efficiency of diode pumping, a simple enhancement of the pump power by using longitudinal pumping (see Fig. 1) is inefficient because of the local absorption of the pump radiation, resulting in the appearance of parasitic thermal effects. In the case of cw lasers with output powers exceeding 10 W, the problem of heat removal from the active element becomes very important. The matter is that the active element heating results not only in the increase in the lasing threshold but also impairs the quality of the output radiation due to the lens effect, induced birefringence, and excitation of transverse modes.

The quality of the output laser radiation is usually characterised by the parameter $M^2 = 2N + 1$ (where N is the number of the highest-order transverse lasing mode). This parameter gives the ratio of the divergence of the output beam to the diffraction-limited divergence. A high quality of the beam (small value of M^2) can be obtained by optimising the laser design and substantially reducing thermal effects in the active medium, resulting either in a complete elimination of the thermal lens effect or its compensation.

The latter requirement can be fulfilled, if, for example, a thermal flow is collinear to the direction of the laser beam in the active medium. This is achieved in the laser design with an active element in the form of a thin disc, which is cooled from one or both sides (disc lasers). The detrimental thermal effects can be reduced by pumping the entire volume of the active medium more or less uniformly, which is the case in the so-called slab lasers. Of course, high-quality output radiation is achieved when lasing occurs in the fundamental transverse mode.

The single-frequency highly stable lasing with high output powers (tens of watts) can be usually produced in systems consisting of a master oscillator and a high-power laser amplifier [98, 99]. As master oscillators, highly stable ring chip lasers with output powers from 100 to 400 mW are used in most cases.

7.2 Lasers with several active elements

The use of longitudinal semiconductor pumping in lasers with output powers above 10 W resulted in the development of new designs of optical cavities allowing the simultaneous employment of several pump sources for excitation of different regions of the active medium.

A simplest is the design in which an active element is excited from two ends (see Fig. 1), which provides a more uniform excitation of the active element and a more uniform thermal load [100]. An original design, which provides greater output powers (compared to a simplest design), uses a cavity containing two active elements, which are often divided by a phase plate [101].

A laser design based on the use of z-like sections is even more efficient (Fig. 6). As a example, the design of a 1.06-μm $Nd:YVO_4$ laser is shown, which is pumped by four 20-W, 0.81-μm diode arrays with fibre concentrators of diameter 1.1 mm [102]. Such a design provides high-quality output radiation ($M^2 = 1.1$) of quite high power. This is achieved because the pumping scheme minimises thermal aberrations, phase distortions, and thermal focusing, which are inherent in longitudinally pumped high-power lasers. The output power of the laser in the fundamental TEM_{00} mode is 35 W ($M^2 = 1.1$) for the pump power 56.5 W. The optical efficiency of the laser is $\sim 62\,\%$ and its quantum efficiency is 94 %.

To reduce local thermal loads in the active element and to obtain the high-quality output, the so-called folded internal cavity can be used [31, 103]. In this case, an active element is made in the form of a prism with selective mirrors deposited on its faces, which provide the multiple passage of

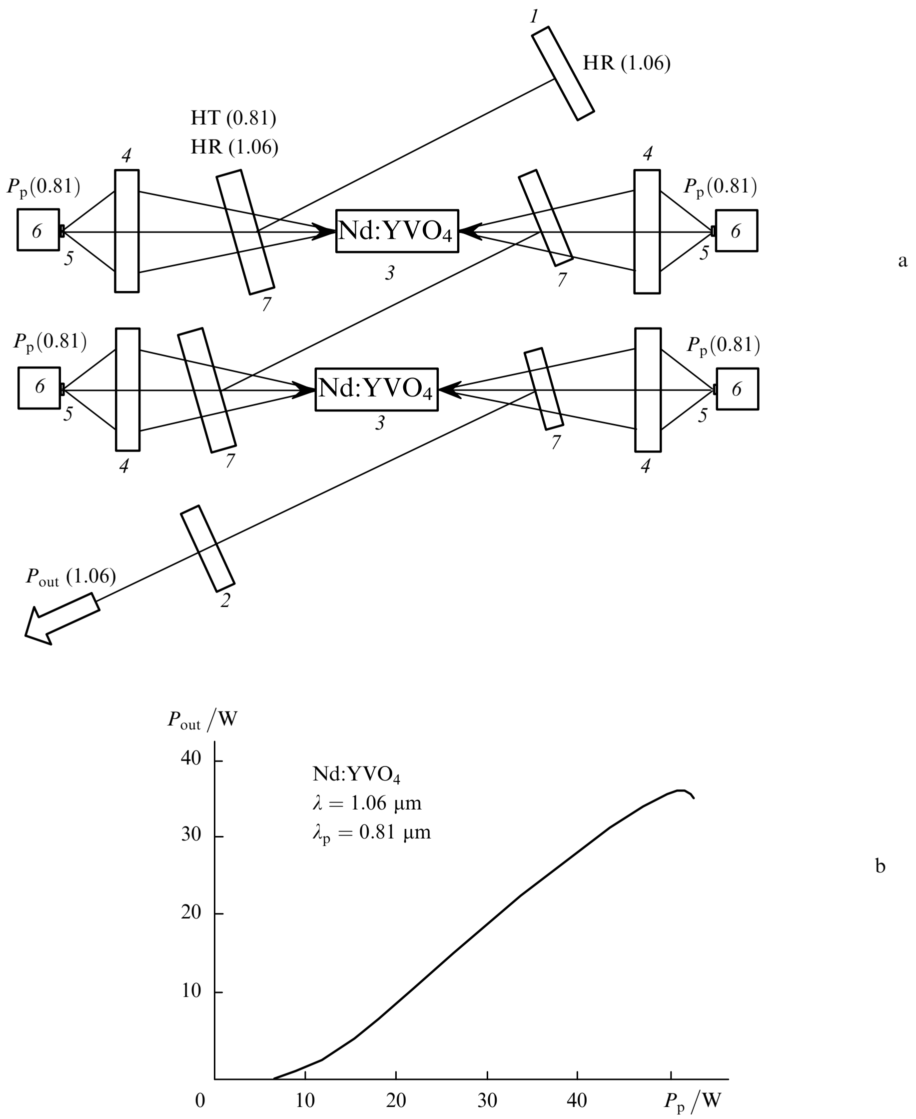

Figure 6. Principal scheme of a DPSL consisting of two *z* sections (a) and the typical dependence of the cw output power *P* of the Nd : YVO_4 DPSL with $M^2 < 1.1$ on the pump power P_p (b): (*1, 2*) highly reflecting and output mirrors; (*3*) active element; (*4*) microobjective; (*5*) laser diode; (*6*) thermostat; (*7*) deflecting mirror.

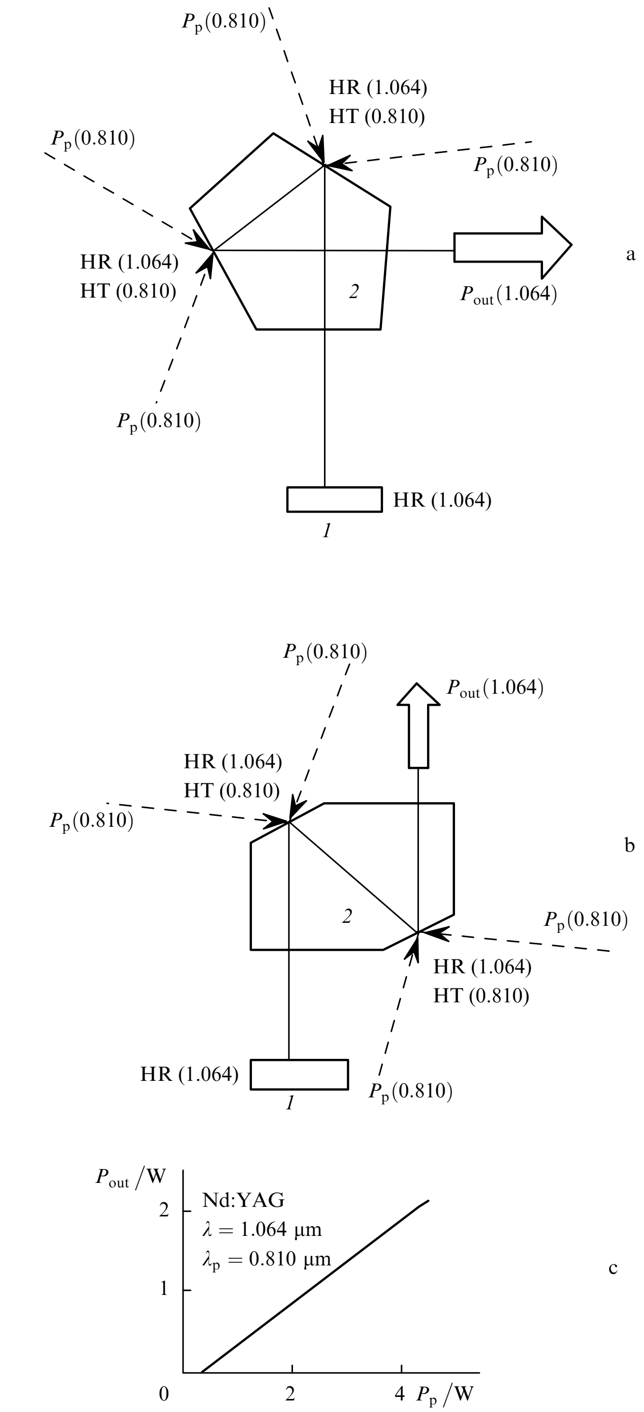

Figure 7. Principal schemes of DPSLs with folded cavities (a, b) and the typical dependence of the cw output power P_{out} of the Nd:YAG DPSL on the pump power P_p (c): (*1*) highly reflecting cavity mirror; (*2*) active element.

radiation inside the prism and longitudinal pumping from different sides (Fig. 7). Such a DPSL design is identical to the above scheme with several active elements.

7.3 Slab lasers

Slab lasers have received wide acceptance in the development of average-power DPSLs [104–106]. The active element in such lasers has a rectangular cross section, and radiation propagates in it along the zigzag path and experiences total internal reflection from flat faces of the active element or is reflected from highly reflecting coatings deposited on the faces.

Upon the transverse pumping of slab lasers with a rectangular cross section of the active element, the pumping can be accomplished in the plane of the zigzag path of the radiation beam by two methods: from the side face of the slab laser or from its end (Fig. 8). The latter variant is preferable for high-power lasers because the active element can be cooled comparatively easily: the area of the contact with a cooler can be sufficiently large in this case (the active element is usually placed between two copper coolers from which heat is removed by a liquid coolant). The output power of a slab laser can achieve several hundreds of watts.

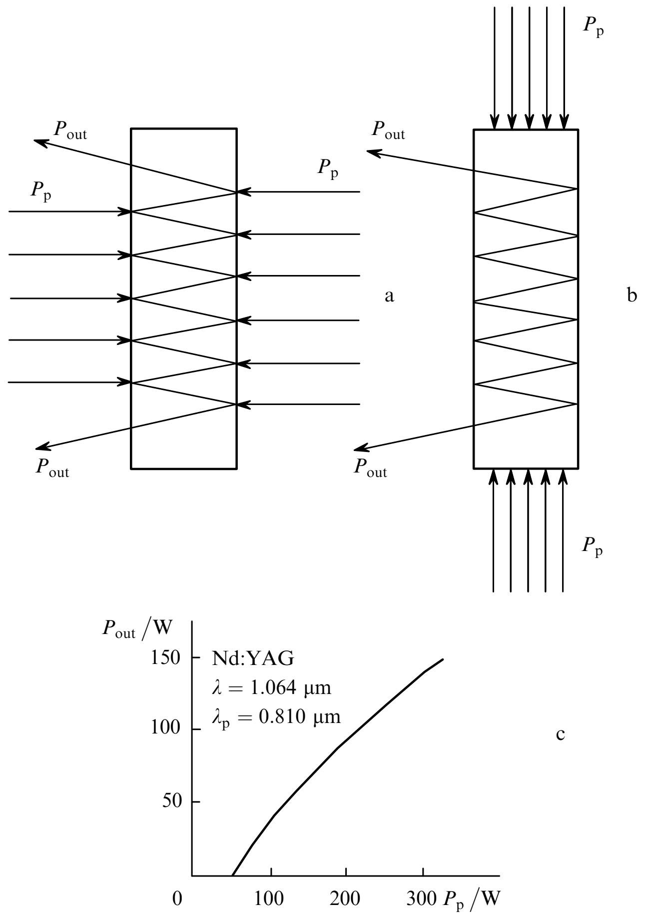

Figure 8. Principal pumping schemes for slab lasers (a, b) and the typical dependence of the cw output power P_{out} of the Nd:YAG slab laser on the pump power P_p.

The advantage of slab lasers is that the distribution of the mechanical stress inside the active element, which reflects the distribution of thermal loads, proves to be more uniform and provides the reduction of thermally induced birefringence. In addition, a zigzag path of the laser beam provides the uniform excitation of the active element, thereby minimising the thermal lens effect [104].

Of interest is the laser design [105] that combines the properties of the ring and slab lasers. This laser is intended for using in a setup for the search for gravitational waves. Therefore, along with a high output power, the laser should provide an extremely narrow emission linewidth and a low intrinsic noise level. The laser contains a minimum number of elements, and the heat is removed from both sides of the slab. The temperature of the active element is maintained with an accuracy of ± 5 mK with the help of a Peltier thermostat. The relative emission linewidth of the laser is $\Delta v / v \sim 10^{-16}$.

7.4 Disc lasers

Undesirable effects caused by the uniform density of the pump power in active elements of DPSLs can be also eliminated by using disc elements [106, 107]. One of the possible laser designs with a disc cavity in shown in Fig. 9 [107]. The active element is pumped by 25 laser diodes with fibre outcouplers combined in one bundle. The power of each laser diode at the fibre output is 1.2 W. Pump radiation is directed on the active element with the help of four spherical mirrors of diameter 38 mm and the radius of curvature $r = 51$ mm and one flat mirror.

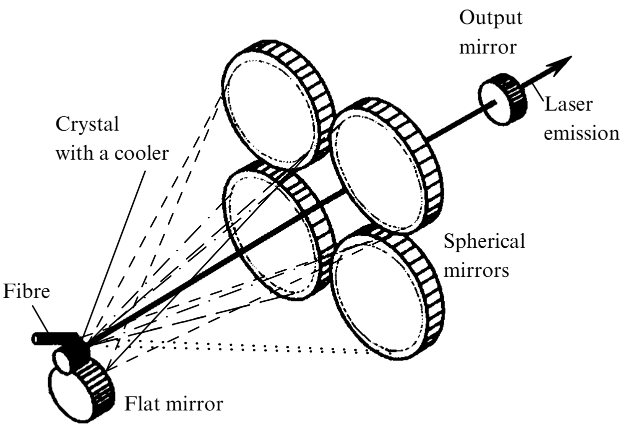

Figure 9. Scheme of a laser with a disc cavity [107].

The active element (a YAG crystal doped with 8 % of Yb^{3+}) made in the form of a disc of thickness 0.4 mm is placed inside the cavity formed by a spherical mirror ($r = 50$ cm) and a mirror deposited on the rear end of the active element. The system of mirrors provides eight transits of the pump beam through the active element. The pump-beam diameter (and, therefore, the diameter of the cross section of the lasing mode caustic) can achieve several millimetres, providing sufficiently high output powers. The active element is cooled with the help of a copper cooler attached to it. The output radiation from this laser at the 18.8-W pump power (the temperature of the active element was 203 K) had the diffraction-limited divergence and power of 9.5 W, which corresponds to the optical efficiency 50.5 % and the differential efficiency 66.5 % [106].

More powerful (with powers up to 300 W) cw Yb:YAG disc lasers, in which similar pumping was used, are described in paper [107]. Note that a high width of the gain line in a Yb:YAG crystal and efficient cooling of the active element provide continuous tuning of this laser from 1.018 to 1.053 μm using a selective intracavity filter.

8. High-power solid-state lasers

In the last decade, a great progress was achieved in the fabrication of dioded-pumped high-power Yb:YAG lasers. The cw power of such lasers exceeds now 5 kW [108 – 110]. These advances were achieved mainly due to excellent thermomechanical properties of garnet matrices doped with Yb^{3+}. Indeed, garnets doped with ytterbium [Yb : YAG, $Yb^{3+} : Lu_3Al_5O_{12}$(Yb : LuAG)] are characterised by the lowest thermal release upon narrow-band excitation of the active medium, which minimises detrimental thermal effects (the appearance of thermal lenses and birefringence).

One of the main advantages (Table 2) of ytterbium lasers over Nd:YAG lasers is the closeness of their absorption and luminescence bands. The Yb:YAG laser emitting at 1.029 μm is pumped at 0.941 μm. As a result, only 11 % of the pump power is converted to heat, whereas in the Nd:YAG laser pumped at 0.81 μm and emitting at 1.064 μm, this value amounts to 37 %.

Table 2. [26].

Parameters of the active medium	Yb:YAG	Nd:YAG
Pump wavelength/μm	0.941	0.808
Absorption band/nm	18	2
Absorption cross section/10^{-20} cm^2	0.77	6.7
Emission wavelength/μm	1.029	1.064
Emission cross section/10^{-20} cm^2	2.1	28
Lifetime of the operating level/ms	0.95	0.23
Saturation energy/J cm^{-2}	9.2	0.67
Saturation intensity/kW cm^{-2}	9.7	2.9

A broad absorption band in Yb:YAG crystals provides a weak sensitivity to the pump wavelength. Another advantage of the high-power Yb:YAG laser is a higher saturation intensity (compared to the Nd:YAG laser), which allows the use of active elements of a small diameter (several millimetres).

One of the optimal pumping schemes for obtaining maximum output cw powers is the scheme in which a cylindrical active element is pumped from different sides by diode arrays (matrices), as shown in Fig. 10a. The number of pump sources can be varied from two to eight. In Ref. [110], a cw Nd:YAG laser pumped from five sides by ten diode arrays is described. The active element of diameter 8 mm and length 118 mm was placed inside a transparent tube through which coolant was flowing. The tube had an antireflection coating at the pump wave of 0.807 μm. The radiation from diode arrays was focused by cylindrical lenses inside the active element. The pump power linear density was 380 W cm^{-1}. The output parameters of the laser consisting of two identical blocks are shown in Fig. 10b. The laser cavity length was 400 mm and the reflectivity of the output mirror was 70 %.

The results of the study of a Yb:YAG laser emitting 1080 W in the fundamental transverse mode are reported in Ref. [111]. The laser has two active elements, which are divided by 90° quartz optical rotator for compensation for birefringence.

Even greater output powers were obtained in a multisectional laser. A three-sectional DPSL emitting 5.1 kW with the efficiency 20.5 % is described in Ref. [112]. The Nd:YAG active elements of diameter 8 mm and length 200 mm were used in this laser. Each section was pumped from three sides by 1.5-kW diode arrays. As active elements in high-power cw lasers, along with Yb:YAG other crystals doped with Yb^{3+} ions can be used (for example, $Yb^{3+} : Sr(PO_4)_3F$, $Yb^{3+} : BaCaBO_3F$, and $Yb^{3+} : U_5Al_5O_{12}$).

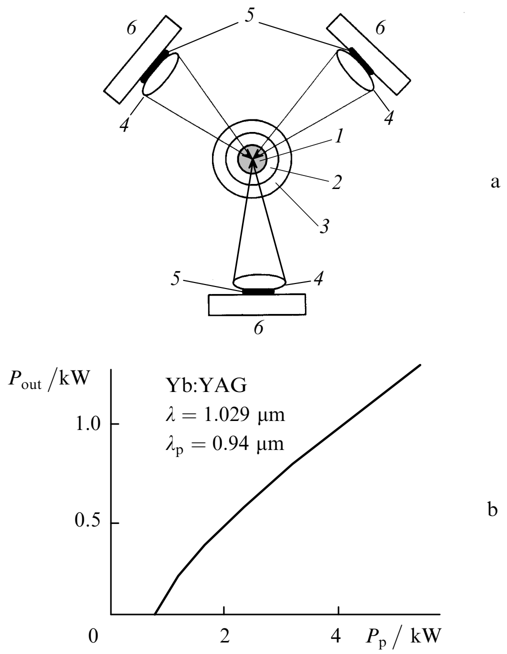

Figure 10. Principal scheme explaining the design of a high-power DPSL (section by a plane perpendicular to the cavity axis) (a) and the dependence of the output power of the Yb:YAG DPSL on the pump power (b): (*1*) active element; (*2*) cooling liquid; (*3*) transparent tube; (*4*) cylindrical lens; (*5*) semiconductor arrays; (*6*) thermostat.

Obviously, it is impossible to obtain high output powers without the efficient cooling of the active element. In the case of transverse pumping, cooling, as a rule, is performed using a coolant flowing through a transparent tube in which the active element is placed.

9. Fibre lasers

The development and fabrication of diode-pumped fibre lasers, which can be also classified as DPSLs, is another rapidly developing field of investigations [47–49, 113–117]. These lasers are extensively used in optical communication. The active element of such lasers is a fibre with a core doped with rare-earth ions ($Nd^{3+}, Er^{3+}, Yd^{3+}$, etc.).

Fibre lasers can be pumped by two methods. In the first case, the pump radiation is injected directly into the fibre core, while in the second case (when double-cladding fibres are used), the pump radiation is injected into an external, reflecting cladding and, undergoing total internal reflection from this cladding, propagates in the inner cladding and the fibre core. During its propagation, the pump radiation is efficiently absorbed by active ions, providing, in the case of feedback produced by the optical cavity, the conditions for lasing inside the fibre core, whose diameter can vary from several units to several hundreds of micrometres.

There are several designs of optical cavities for fibre lasers. For example, cavity mirrors are deposited directly on the polished ends of the fibre or conventional dielectric mirrors can be used as reflectors, which are matched with the fibre with the help of microobjectives. However, the use of Bragg mirrors (Bragg gratings) proved to be the most efficient. Bragg mirrors are recorded directly inside the fibre and have a high reflectivity at fixed wavelengths.

Advances in the development of fibre lasers are related in a great degree to new technologies of fabrication of fibres with minimum losses at the lasing wavelength and of fibres providing the efficient nonlinear conversion of the pump radiation into Stokes components.

Also, very promising is the multifunctional use of the elements of a fibre laser (combination of Bragg reflectors with the active medium, of a mode-locker with the pump source, inclusion of the pump source into the cavity (see, for example, Refs [115, 116]), which is now widely accepted.

At present, the output power of cw fibre lasers doped with $Nd^{3+}, Yb^{3+}, Er^{3+}$, and other ions amounts to several tens of watts. As an example, Fig. 11 shows the design of a ytterbium-doped fibre laser [115]. The active fibre manufactured by the MCVD method has the active core of diameter 5 μm and the inner cladding with the square cross section with side 120 μm. The pump radiation was completely absorbed in the fibre cladding at the cavity length $L = 16$ m. The external cladding was made of silicon rubber, whose refractive index provided the input numerical aperture of 0.38–0.4 for the pump radiation, giving the pump efficiency ~96 %.

The laser cavity was formed by a Bragg grating with the reflectivity $R = 99$ % and the output end of the fibre ($R = 4$ %). The pumping was performed by a 10-W, 0.978-μm semiconductor laser with the fibre outcoupler of a diameter of 250 μm. Optical losses at the outcoupler–active fibre splicing did not excedd 0.2 dB. The differential efficiency of the fibre laser was 83 % and its quantum efficiency was 90 %.

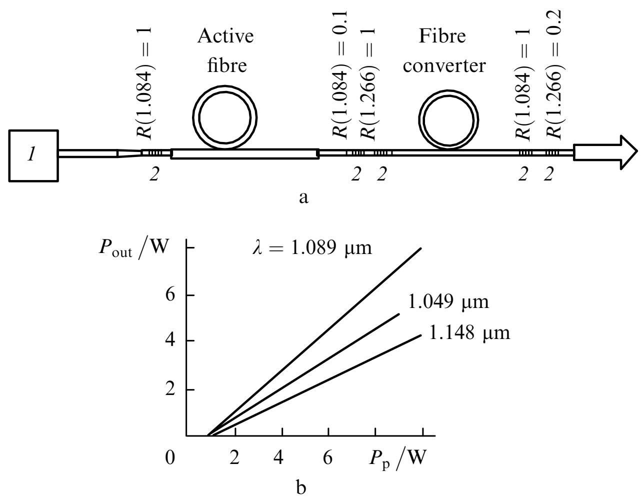

Figure 11. Principal scheme of a fibre laser with an intracavity SRS converter (a) and the dependence of its output parameters of the laser on the different resonance wavelengthes on the pump power (b) [115]: (*1*) semiconductor radiator; (*2*) Bragg gratings; (*R*) reflectivity.

10. Extension of functional possibilities of DPSLs

The use of diode pumping opens up a variety of the possibilities in the field of development and fabrication of modern highly efficient lasers of a new generation. The fabrication of miniature, highly stable and reliable cw lasers having a long operating life, *Q*-switched and mode-locked lasers, generators of optical harmonics, frequency converters, and other laser devices becomes urgent.

10.1 Q-switching

Along with solid-state cw lasers, Q-switched solid-state lasers have a variety of applications. Although Q-switching in DPSLs does not virtually differ from Q-switching in conventional flashlamp-pumped lasers, the use of diode pumping provides a substantial progress in this case.

Q-switching in a DPSL is performed in the same way as in conventional lasers by using saturable absorbers, acousto-optical and electrooptical switchs. Due to a small length of the DPSL cavity, extremely short pulses can be rather easily produced by using saturable absorbers.

Sufficiently powerful compact Q-switched DPSLs can be manufactured by using Cr:YAG crystal as a saturable absorber. In this case, 1.5-mJ nanosecond pulses can be produced (see, for example, Refs [118–120]). The use of active media providing self-Q-switching is very promising. For this purpose, for example, $Cr^{4+}:Nd^{+}:YAG$ crystals can be used [60].

Virtually all known active crystals can be used as active media for DPSLs. To obtain Q-switching, it is desirable to use crystals with the long lifetime T_1 of a metastable level. Note $Yb^{3+}:Sr_5(PO_4)_3$ among such crystals [121, 122]. The advantage of this crystal (especially for the lasing wavelength 0.985 μm) is the closeness of the emission and pump (0.9 μm) wavelengths, which provides the high quantum efficiency equal to 0.91 [123].

Therefore, all the advantages of diode pumping (the possibility of fabrication of miniature highly stable lasers, their high efficiency, high radiation quality (small M^2), the absence of cooling problems, high reliability, and a long operation life) are completely realised in Q-switched DPSLs.

In addition, the use of diode pumping in such lasers gives them some new advantages, in particular, the manufacturing solid-state lasers with extremely short cavities ($L < 1$ cm). In this case, it is possible to produce short emission pulses of duration 1–2 ns using passive Q-switching. A weak heat release in the active elements of DPSLs facilitates lasing with high pulse repetition rates in the repetitively pulsed ('machine-gun') regime.

A high quality of radiation from Q-switched lasers, which is difficult to obtain in flashlamp-pumped lasers, is important for a number of practical applications.

The spatial homogeneity of pumping of the active medium and lower thermal loads permit the fabrication of Q-switched DPSLs for which $M^2 = 2.4$ for an average output power of 183 W and a pulse repetition rate of 5 kHz [124]. The high efficiency of Q-switched DPSLs opens up wide prospects for their application in thermonuclear fusion facilities [125–127]. This stimulated interest in the development of DPSLs producing extremely high-power pulses.

At present a DPSL setup is manufactured which produces 10-J pulses with a pulse repetition rate about of 10 Hz [128]. This setup consists of a 1.053-μm Q-switched $Nd^{3+}:LiYF_4$ master oscillator, an eight-pass slab preamplifier, and a main amplifier made of a glass active element of size 523 mm × 119 mm × 20 mm doped with Nd^{3+} ions, which operates at 1.053 μm and is pumped by 200-kW laser diode arrays at 0.803 μm. The pump power density is 2.6 kW cm^{-2} at the pump pulse duration of 0.25 ms.

The laser system emits 10-J, 20-ns pulses. The divergence of the output radiation is only twice the diffraction limit ($M^2 = 2$). This setup is a scalable prototype of a laser facility (laser driver) intended for producing 4-MJ pulses required for thermonuclear fusion studies [129].

10.2 Mode locking

The use of diode pumping stimulates the further development and practical applications of mode-locked solid-state lasers. Diode pumping permits the fabrication of small-size highly stable lasers emitting pulses of duration from tens of picoseconds to several femtoseconds [130–135].

An extremely small time lag of diode sources allows one to realise easily forced mode locking in DPSLs (including mode locking in fibre lasers) by directly modulating the pump radiation at the intermode beat frequency.

Note that in the last years mode locking is often obtained using mirrors with a semiconductor nonlinear absorber deposited on them. This significantly simplifies the laser design and enhances its reliability and operating life [134].

One of the fields in the physics of solid-state lasers, where advances were achieved due to diode pumping, is the generation of ultrashort pulses with a repetition rate of several tens of gigahertz [130, 131]. For example, in Ref. [136], a $Nd:YVO_4$ laser is described which produces 6-ps pulses with a pulse repetition rate of 59 GHz. The laser contains an active element of length 1.15 mm with a selective mirror deposited on its spherical end. The flat end of the active element covered by an antireflection coating is in contact with an $In_{0.25}Ga_{0.75}As/GaAs$ semiconductor saturable absorber. The saturation energy density for this nonlinear absorber is ~ 100 μJ cm^{-2}. For the 550-mW pump power, an average output power of the mode-locked laser is 28 mW and the energy of an ultrashort pulse is 1.7 pJ. Fibre lasers also can produce mode-locked ultrashort pulses with a high (gigahertz) repetition rate [137].

Standard femtosecond lasers emit ultrashort pulses with the peak power of the order of several hundreds of kilowatts and a pulse repetition rate of ~ 100 MHz. The use of multipass cavities allows one to reduce the pulse repetition rate to 15 MHz and to increase the peak power of ultrashort pulses up to 0.5 MW in lasers with Kerr mode locking [138].

Lasers with intracavity delay lines, which substantially increase the effective cavity length, can produce ultrashort pulses with even greater peak powers [139]. In this case, the energy of ultrashort pulses and their peak power are increased almost by an order of magnitude, the pump power being fixed.

The use of intracavity optical delay lines was demonstrated in paper [140] where the $Ti^{3+}:Al_2O_3$ laser was studied, which produced 0.8-μm, 23.5-fs pulses with a peak power of 0.9 MW and a pulse repetition rate of 7.2 MHz. Mode locking in this laser was obtained in a Kerr-lens cavity. Various methods of longitudinal mode locking in solid-state lasers are considered in detail in Ref. [141].

10.3 Tunable cw lasers

Remarkable advances have been also achieved in the use of diode pumping in tunable lasers (see, for example, Refs [142–144]) The application of active media with broad luminescence band Cr:LiCAF, Cr:LiSAF, $Ti^{3+}:Al_2O_3$, $Cr^{4+}:Mg_2SiO_4$ in combination with diode pumping is promising for the manufacturing of small-size highly stable DPSLs, which can be tuned in a broad spectral range.

Diode pumping can be used both for direct pumping of active media of tunable lasers, which requires a sufficiently high power in the TEM_{00} mode, and for pumping a cw solid-state laser whose single-mode radiation is then directly used for pumping the tunable laser.

10.4 Generation of harmonics and frequency conversion

The devise of radiation frequency converters (generators of harmonics, parametric oscillators, SRS converters, generators of sum and difference frequencies) is an independent, also rapidly developing field in laser physics and technology. We will not consider here conventional devices for frequency conversion in a separate nonlinear element, which is placed either inside the cavity or outside it. We briefly discuss only the possibility of frequency self-conversion in DPSLs. This can be performed by using nonlinear-active media in these lasers, which provide not only lasing but also the efficient frequency self-conversion of the laser emission directly in the cavity [145–147].

Note that frequency self-conversion (in particular, frequency self-doubling in miniature chip lasers) has specific features compared to frequency conversion in conventional lasers consisting of discrete elements, in which the optimisation of parameters of a nonlinear element presents no problems. In this connection, of special importance is the optimisation of the parameters upon frequency self-doubling in miniature lasers, which is achieved using the so-called double cavities, i.e, cavities that have a high quality not only at the lasing frequency but also at the second harmonic frequency [148].

Frequency self-conversion occurs most efficiently in active elements where distributed domain structures have been purposely created. The use of these structures substantially facilitates the achievement of phase matching during generation of harmonics and SRS. Phase matching in a $Nd^{3+}:LiNbO_3$ chip laser was observed, for example, in [149].

Another promising line of studies is the development of DPSLs in which frequency self-doubling and summation occur simultaneously. Such processes take place, for example, in a $Nd^{3+}:BaNaNb_5O_{15}$ laser [150]. Studies in this field are closely related to a search for and synthesis of new nonlinear-optical active crystals. The use of SRS in the active element of a DPSL seems very promising.

Frequency self-conversion occurs most efficiently in fibre lasers (see, for example, Refs [115]). This is explained by a small cross section of the fibre and, hence, a high power density in it. The radiation frequency of fibre lasers can be efficiently transformed by means of SRS converters [115]. The conversion is especially efficient in ytterbium-doped fibre lasers coupled to SRS converters based on phosphosilicate fibres (the Raman shift in these fibres is 1330 cm^{-1}). The output parameters of such a laser are shown in Fig. 11 [115].

From the point of view of producing high-quality emission, it is important to use adaptive laser cavities [151, 152]. It seems that the most promising is the development of self-adaptive cavities in which self-correction of intracavity aberrations takes place. The possible design of a laser with the self-adaptive cavity is discussed in Ref. [152] where a cw $Nd:YVO_4$ laser is described, which produces 7 W of a single longitudinal mode output.

11. Conclusions

At present the development of diode-pumped solid-state lasers consists in the improvement of the design and optimisation of output parameters of

(1) highly stable, single-frequency, monolith, miniature linear and ring lasers;
(2) whispering-gallery mode microlasers;
(3) slab lasers with power of several tens of watts;
(4) lasers with an output power of more than 1 kW;
(5) frequency self-conversion lasers;
(6) fibre lasers, including Raman lasers.

The extension of the functional possibilities of DPSLs, such as tuning of lasers and the lasing frequency stabilisation by means of an external standard, are also important. The development of laser systems containing intracavity nonlinear-optical elements for frequency conversion (generation of harmonics and Stokes and anti-Stoked components upon SRS, etc.) is an independent field of research.

Of great importance for the development of DPSLs is a search for new highly efficient active media, including nonlinear and magnetooptical media, as well as media doped with active ions at high concentrations, which provide high gains.

The use of diode pumping substantially enhances the efficiency and stability of lasing, drastically reduces the size and energy consumption of solid-state lasers operating in various regimes: mode locking and Q-switching, intracavity frequency doubling and self-doubling, intracavity frequency conversion, parametric processes, SRS and SBS.

The experience acquired in the development and applications of various DPSLs shows that the longitudinal pumping is preferable for moderate-power single-frequency solid-state lasers. In this case, the pumped volume of the active medium can be efficiently matched with the volume of the TEM_{00} cavity mode and the length of the active medium can be chosen to provide complete absorption of the pump power, resulting in the maximum possible lasing efficiency.

Monolith ring lasers provide extremely low levels of quantum fluctuations of radiation, which are very close to the theoretical limit.

At present, monolith ring lasers with optically homogeneous active media are well studied. However, the use of uniaxial and biaxial active elements in such lasers is of great interest.

Of special interest is the study of the possibility of controlling phase shift during total internal reflection in monolith chip lasers, which can be achieved by applying special dielectric coatings changing the phase shift upon total internal reflection. It is also interesting to study the possibility of using mirrors with magnetooptical properties (using the magnetooptical Kerr effect).

Another recent field is the magnetooptical study of solid-state lasers (especially, ring lasers) [153, 154].

Two basic directions in the development of high-power DPSLs with output powers of several tens of kilowatts and more can be distinguished: the fabrication of high-power laser systems and the manufacturing of laser systems using a master oscillator with the subsequent amplification of its radiation. The choice of one or another direction is determined by such factors as the required mode composition of the output radiation, the maximum output power, the frequency and amplitude stability of the output radiation, the spatial coherence and spatial profile of the output beam.

Let us sum up the review. One can boldly claim that the use of diode pumping represents a new stage in the development of laser physics and technology. Note that DPSLs, along with their advantages, are also highly reliable and have much longer operating life than conventional lasers.

At present, single-frequency DPSLs with output powers up to 100 mW completely replaced conventional flashlamp-pumped lasers. In the near feature, microminiature solid-state lasers will be manufactured whose size will be only slightly larger than that of diode lasers.

DPSLs producing the cw output power up to 1 kW also have significant advantages over flashlamp-pumped lasers. These are a better quality of the output radiation, a lower heat release, a simpler cooling system, a significantly higher stability, a lower intrinsic noise, and a longer operating life. The efficiency of these lasers is several times higher than that of conventional lasers.

DPSLs with the output power of several tens of watts also are replacing conventional flashlamp-pumped lasers from science and technology. Such DPLSs are already commercially available.

At present, DPSLs producing above 5 kW of cw radiation are manufactured. Wide applications of these lasers are somewhat restricted by high cost of diode arrays. However, it is reasonable to suppose that this only temporary circumstance. Mode-locked DPSLs are already widely used in laboratories.

Diode pumping will be certainly used in the near future in Q-switched solid-state lasers at output pulse energies up to several joules.

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