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Diode-pumped solid-state lasers

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Progress in technology and construction of diode-pumped laser made in the 80's caused renewed interest in diode pumping of active media of solid-state lasers (DPSSL -Diode Pumped Solid State Laser) and next their rapid development. At present, DPSSL are commonly applied in medicine and industry.

The paper presents advantages of such excitation and significant improvement in generation efficiency, longer service life of devices, smaller dimensions of quantum generators and theirs power suppliers. Special attention is paid to the possibility of application of new active media (new neodymium doped hosts), including ytterbium (Yb) doped media, that have perfect functional parameters with diode pumping. Fundamental configurations of active media and their excitation methods are described. A "slab" type geometry used for high-power lasers is distinguished. It is shown that construction of, so-called, microlasers is possible when diodes are used as pumps of solid state lasers. Microlasers can generate strictly monochromatic radiation (i.e., generate only one longitudinal mode). These lasers can be used for rangefinder transmitters and radars with heterodyne detection – new type devices applicability range of which is difficult to predict. Microlasers can be also used as frequency and length standards. A group of fibre lasers is considered and their unusual possibilities are described, among others generation of beams of high quality (M^2 ~1) and high-power (1 kW). The examples of construction of high-power DPSSL (3.5 kW) are presented.

Keywords: diode pumped solid state lasers (DPSSL), laser diode, active materials, dopants, microlasers, fibre lasers, high power laser.

1. Introduction

Pumping of lasers with radiation of other quantum generators were started relatively early, i.e., in the 60's [1]. Lasers are the most efficient pumps for other quantum generators. Basic advantages of such pumping are:

- possibility of matching of pumping radiation spectrum to maximum of absorption band of active materials,
- possibility of matching of excited medium volume to a volume of generated modes (e.g., TEM_{00}),
- possibility of effective pumping of small-size media (microlasers, fibers),
- significantly lower heat load of a medium pumped with laser radiation compared with flash one (3–4 times),
- possibility to use short pulses pumping of very high power densities.

Diode laser pumping differs significantly from pumping with gaseous or solid-state lasers. It is also more difficult in practice because of lower luminance, larger beam divergence angle and often larger dimensions of a surface emitting excitation radiation. However, application of laser diodes as pumps for solid-state lasers was decisive for their rapid development observable during the last years.

Diode lasers dominate the other type of lasers. It results from their advantages, mainly from:

- extreme small dimensions – average dimensions of single emitter are 1×10×100 μm^3,
- the highest generation efficiency, reaching value of 70% (gaseous lasers ≈0.1%, solid state lasers ≈1%, CO_2 molecular lasers ≈ 30%),
- simple power supply $(U \approx h\nu/e)$, where U is the constant voltage of a supply source, $h\nu$ is the energy quantum approximately equal to energy gap value, e is the electron charge,
- possibility of construction of multielement matrices of emitters (fundamental method of increase in power or output energy).

Diode lasers have also some disadvantages:

- beam asymmetry (beam divergence angles of edge lasers, in parallel and perpendicular planes to a junction are not the same),
- relatively strong dependence between generated wavelength and temperature (tuning rate ≈ 0.3 nmK^{-1}),
- no possibility to store energy in the excited states, the same possibility of short pulses generation by means of losses switching (q-switching).

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Advantages of laser diodes can be noticed especially when they are used as solid-state lasers pumps.

Turning-point observed in the 80's in technology of laser diodes was decisive not only for promotion of diode lasers in relation to other lasers but it caused also return to the idea of technique of diode pumping of solid state lasers and its development. The above mentioned technological turn includes introduction of new technologies of fabrication of semiconductor structures, e.g., MOCVD (Metal Organic Chemical Vapour Deposition) and MBE (Molecular Beam Epitaxy), and first of all introduction of quantum wells constructions – SQW (Single Quantum Well) and multiple quantum wells (MQW – Multi Quantum Well) (see Fig. 1) [2].

This paper is not aimed at diode lasers but one cannot notice that development of diode lasers during last decade has changed optoelectronics and caused existence and rapid development of its new fields. Diode pumping of solid-state lasers is one of them. Diode lasers as optical pumps, similarly as diode lasers for industrial applications are not often build as single emitters. High output powers (also energies in Q-CW lasers) are obtained by making edge emitter matrices, so-called "arrays". Diode arrays can be one-dimensional, called bars or two-dimensional matrices (2-D arrays) sometimes called stacks or stack bars. Diode lasers sets (bars and stacks) have directional characteristics as single emitters. Beams are non-symmetrical and divergence angles in mutually perpendicular directions are 10° and 35°, respectively. This parameter and large transverse dimensions causes some problems in matching of pumping beam to a size and shape of active media of solid-state lasers.

Contemporary, commercial high-power diode lasers as well pumping diodes have the power up to 100 W/cm in CW lasers of linear structure and Q-CW lasers bars of the order of 250 W/cm.

The highest efficiencies are obtained from AlGaAs/GaAs and InGaAs/GaAs structures (λ ≈ 800 nm and 940–980 nm). These spectral ranges are the most important for excitation of majority commonly applied active materials of solid-state lasers, including neodymium doped hosts. Maximum powers obtained from laser diodes in various bands are shown in Table 1.

Table 1. Output powers of contemporary cw laser diodes for = 630–2000 nm.

Material	Wavelength (nm)	Single mod (mW)	100 µm aperture (W)	1 cm bar (W)
InAlGaP-GaAs	630	60	1.4	6
InAlGaP-GaAs	680	295	1.7	90
AlGaAs-GaAs	850	500	5.2	120
InGaAs-GaAs	980	1000	12.4	62
InGaAsP-InP	1300–1550	380	5.2	
InGaAsP-InP	1800–2000	30	0.5	8

At present, intensive technological works are carried out aimed at improvement of useful parameters of diode lasers, especially high-power ones. These works performed mainly within the frame of research programmes in US, Japan [3], and Germany [4] are focused on the following problems [5,6]:

- increase in power obtained from a single emitter due to increase in power of catastrophic damage of mirrors

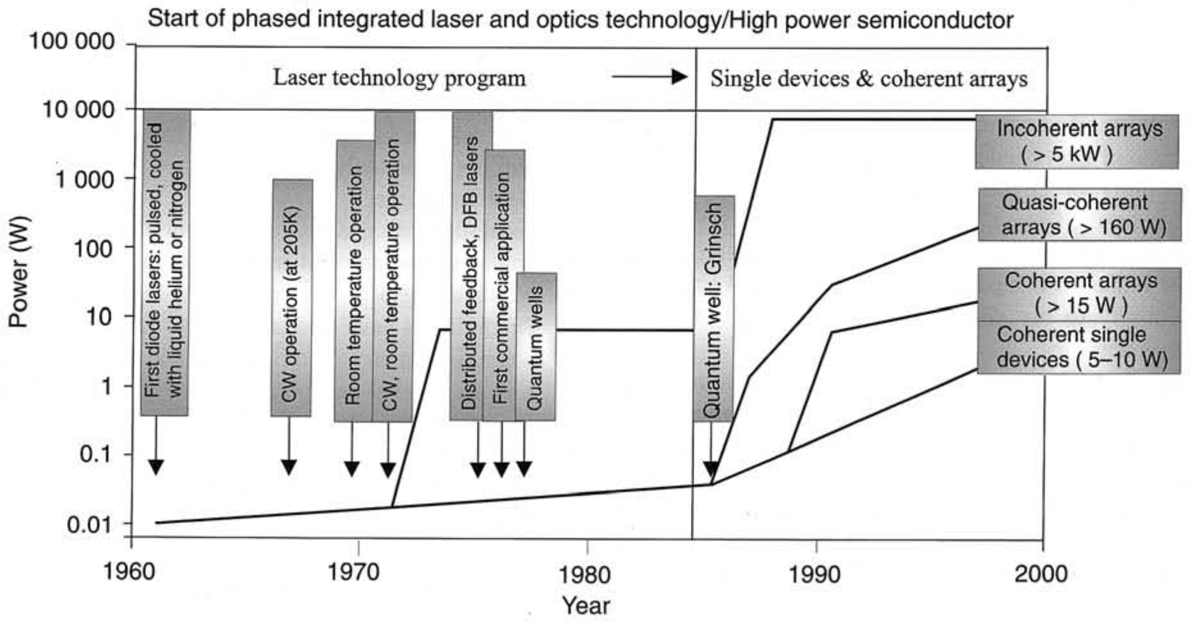


Fig. 1. Semiconductor diode laser progress (after Ref. 2).

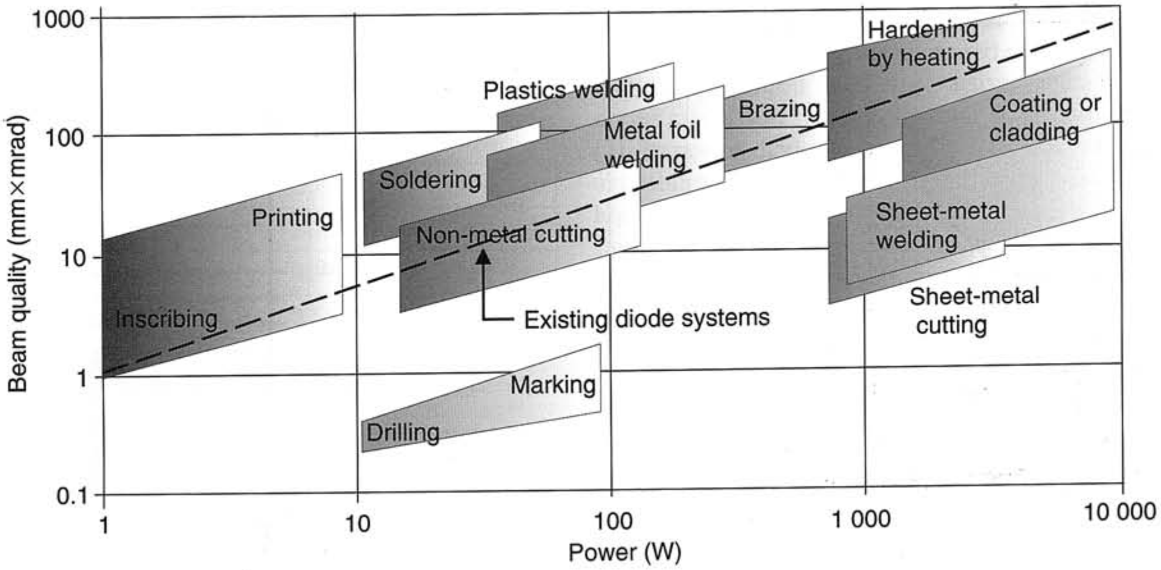


Fig. 2. Laser beam quality and power performing various material processing applications (after Ref. 8).

and degradation of laser characteristics of heat release in a structure,

- improvement in quality of beams generated by diode lasers,
- extension of lifetime of diode lasers.

From among the presented solutions conical structures can be mentioned that are known from earlier constructions MOPA (Master Oscillator and Power Amplifier). However, these structures have significantly longer lengths (~3 mm) and widths (100–500 μm) and can generate the power up to 3–6 W from a single emitter with exceptionally high-quality beam ($M^2 < 2$) [2,7].

Quality of a beam generated by high-power diode lasers is a crucial problem at the present stage of their development. This problem is related not only to laser pumps but also to other diode lasers, especially these ones devoted to industrial applications. A product of a diameter and divergence angle of a beam (unit mm×mrad is used equally with M^2 parameter to characterise quality of a laser beam) of the currently available high-power diode lasers and requirements of industrial applications are given in Fig. 2 [7,8]. As we can see, the contemporary used technologies of metal treatment need improvement in their quality of one order of magnitude.

It was accepted that diodes can be used in industry if their lifetime is about 10^4 hours. A basic factor limiting lifetime of diode lasers operating within the range of 800–840 nm is presence of aluminium in laser structure (structures of AlGaAs/GaAs type). Larger and larger number of leading in world firms manufacturing diode lasers of this spectral range change AlGaAs/GaAs structure into InGaAs/GaAs one generating also in this range and the motto "Al-free" is a symbol of up-to-date technology of diode radiation sources. A guaranteed lifetime of these sources is significant, i.e., almost twice longer (16000–20000 h).

The above information on tendency in development of diode lasers testifies that priority of diode lasers in comparison of other ones is still growing. Diode lasers seem to be good instruments to cover applications in micro- and macro- industrial technologies. Important role in this field fulfils also solid-state lasers using diode lasers as pumps.

2. Idea of diode pumping of solid-state lasers

Idea of diode pumping of solid state lasers and comparison of this method with flash pumping will be explained using Nd:YAG medium as exemplary active material. This idea is illustrated in Fig. 3 [9]. It enables us to explain also previously mentioned advantages of this pump, especially matching of radiation spectrum of a diode to absorption spectrum of active material. The level $^4F_{5/2}$, through which the neodymium ions are excited to the metastable level $^4F_{3/2}$, is its closest level. Thus, non-radiant losses connected with pumping process, i.e., medium heating, are as low as possible. Flash lamp radiation (e.g., xenon one) excites medium through all, also upper absorption levels, so the losses connected with ions transfer from these levels to $^4F_{3/2}$ metastable state are significantly higher.

The output power P_{out} of a laser as a function of the pump power P_p can be determined from the well-known relationship

$$P_{out} = \eta_s (P_p - P_{th}), \tag{1}$$

where η_s is the slope efficiency of generation and P_{th} is the threshold power.

Total efficiency

$$\eta_c = \frac{P_{out}}{P_p}, \tag{2}$$

includes both slope efficiency and threshold power of excitation.

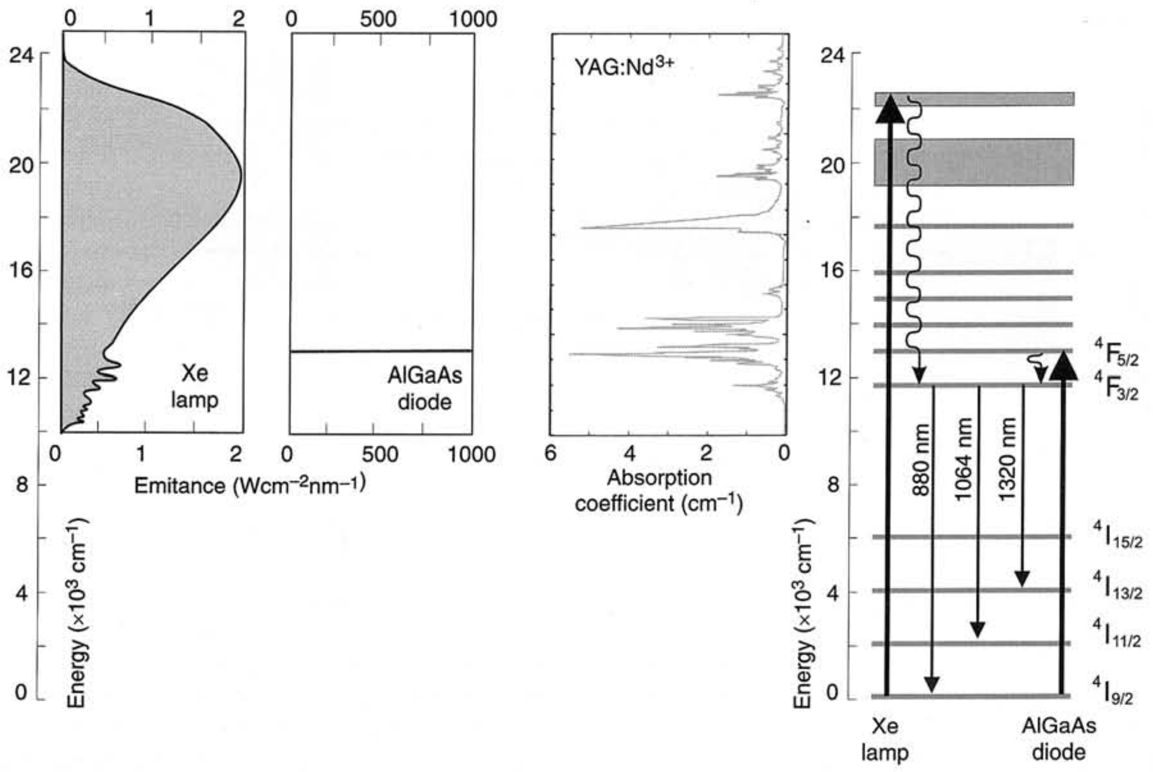


Fig. 3. Idea of diode pumping of Nd:YAG laser (after Ref. 9).

The parameters P_{th} and η_s are determined with properties of active medium and its excitation efficiency

$$P_{th} \propto A_m \frac{I_s}{\eta_{exc}} \delta, \tag{3}$$

$$\eta_s \propto \eta_{exc} \frac{\lambda_p}{\lambda_g} \frac{T}{\delta}, \tag{4}$$

where $I_s = h\nu_g / \sigma_e \tau_f$ is the saturation power, δ are total resonator losses, T is the mirror transmission, A_m is the averaged medium area, σ_e is the stimulated emission cross section, τ_f is the lifetime on upper laser level.

As it results from the above relations main output laser parameter – its output power is determined by material parameters (σ_e, τ_f), resonator losses (δ, T), averaged pump wavelength vs. generation wavelength (λ_p/λ_g), and efficiency of excitation energy transfer from pump to active material dopant (η_{exc}).

Excitation efficiency includes all losses occurring during pumping process and it is expressed as

$$\eta_{exc} = \eta_r \eta_{pro} \eta_{abs} \eta_q \eta_{ext}, \tag{5}$$

where η_r is the radiation efficiency determining part of electrical energy delivered to pump changing into radiant energy (for diode pump it is efficiency of laser diode), η_{pro} is the projection efficiency determining a part of energy radiated by a pump that reaches laser active material, η_{abs} is the absorption efficiency determining value of energy absorbed by active ions of laser medium, η_q is the quantum efficiency determining a part of excited ions reaching higher laser level, η_{ext} is the efficiency of energy extraction determining a part of energy accumulated in excited ions that is emitted as a laser radiation.

The efficiencies given in evident form in Eq. (4) are, so-called, Stock efficiency (λ_p/λ_g) and efficiency determining influence of dissipation losses of resonator (T/δ), respectively.

All parameters determining efficiency of diode pumped and lamp pumped systems are listed in Table 2. For lamp pumping the main sources of losses are connected with non-effective transfer of excitation energy from a lamp to active medium and lack of matching between emission spectrum of a pump (lamp) and absorption bands of active medium. Projection and absorption efficiencies of diode pump can be as high as 95–98 % and they are decisive on pumping superiority to lamp one. Also Stokes's factor causes significant increase in efficiency. It is relatively low for Nd:YAG pumping ($\lambda_p/\lambda_g \approx 0.76$) but it is much higher than Stokes efficiency of lamp pump ($\lambda_p/\lambda_g \approx 0.5$). For other media and diode pump this efficiency is much higher. The total efficiency (2) of lamp-pumped Nd:YAG lasers usually is of 1–3%. Diode pumping ensures significant increase in efficiency up to 8–30%, in dependence on medium geometry, method of its excitation, regime of operation, generated power, and the like [10,11].

Table 2. Main factors effecting efficiency of diode and lamp pumped lasers.

Pump source	Lamp	Diode laser
Radiation efficiency	50%	40%
Projection efficiency	35%	95%
Absorption efficiency	50%	98%
Quantum efficiency	40%	76%
Excitation efficiency	3.5%	28.3%

3. Active materials of diode-pumped lasers

Research works on a synthesis of new laser active media result in greater possibilities of application of solid-state lasers. It is related to both ions being active dopant as well as host crystals. Table 3 shows investigated and applied active ions (activators) and crystals being the hosts of solid-state lasers. Also glasses used mainly in fibre lasers are among these hosts. It should be pointed out that diode pumping significantly extended a range of used solid state active media. Lamp-pumped inefficient active media (e.g., Yb^{3+} doped media) are successfully used as diode pumped ones [7]. Range of diode pump application depends mainly on availability of adequately efficient diode lasers of enough high power. Till now, the highest efficiencies are obtained from AlGaAs/GaAs structures (band 800 nm) and InGaAs/GaAs ones (band 940–980 nm) and the most frequently used active media of solid-state lasers are these having absorption bands in this spectral range. Table 4 shows the scheme of energy levels of majority of ions used as activators of lasing media and the band in which they can be excited. Up to now, the most frequently applied materials in diode pumped lasers were neodymium doped media, especially Nd:YAG [12,13]. Table 5 presents the most important parameters of the most often used neodymium doped hosts in diode pumped lasers.

Table 3. Active media (activators and crystalline hosts) of solid state lasers.

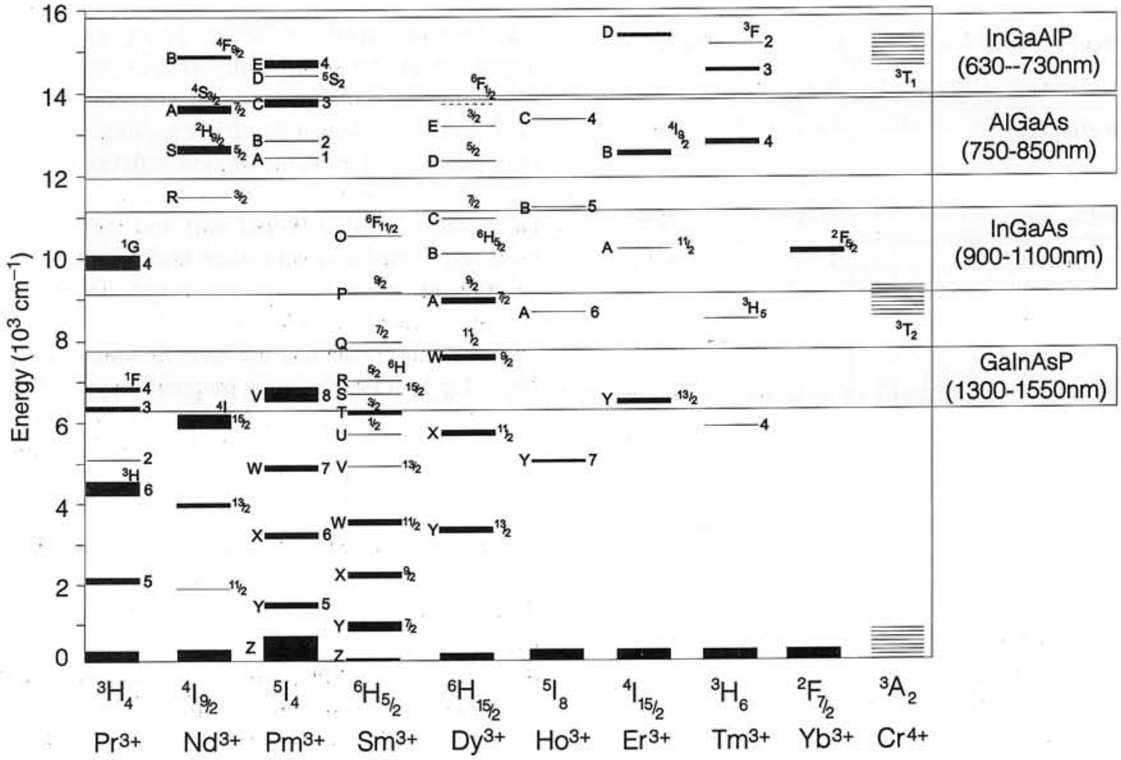
Garnets	Fluorides
$Y_3Al_5O_{12}$ (YAG)	$LiYF_4$ (YLF)
$Gd_3Ga_5O_{12}$ (GGG)	$GdLiF_4$ (GLF)
$Gd_3ScGa_5O_{12}$ (GSGG)	$Ca_5(PO_4)_3F$ (FAP)
$Y_3Sc_2Ga_5O_{12}$ (YSGG)	$(Ca_{1-x}Sr_x)(PO_4)_3F$ (SFAP)
Vanadates	Phosphates
YVO_4 (YVO)	$LiNdP_4O_{12}$ (LNP)
$Sr_5(VO_4)_3F$ (SVAP)	NdP_2O_{12} (NdPP)
$GdVO_4$ (GVO)	$LaNdMgAl_{11}O_{19}$ (LMA)
Gallates	Tungstates
$SrGdGa_3O_7$ (SGGO)	$KGd(WO_4)_2$ (KGW)
$SrLaGa_3O_7$ (SLG)	$KY(WO_4)_2$ (KYW)
$SrLaAlO_4$ (SLA)	
$La_3Ga_5GeO_{14}$ (LGG)	
$La_3Ga_5SiO_{14}$ (LGS)	
	Other
	$LaSc(BO_3)_4$ (LSB)
	$La_2Be_2O_5$ (BEL)
	$YAlO_3$ (YAP)
	Al_2O_3 (LGS), Ti:Sapphire
Activators	Forsteryt Cr^{4+}: Mg_2SiO_4
Lanthanides	Glasses
Nd^{3+} Yd^{3+} Tm^{3+} Ho^{3+} Er^{3+} Pr^{3+} Gd^{3+} Eu^{3+} Ce^{3+} Sm^{2+} Dy^{2+} Tm^{2+}	
Transition elements	Actinides
Cr^{4+} Cr^{3+} Ti^{3+} Ni^{2+} Co^{2+}	U^{2+}

Taking into consideration the $\Delta\lambda_p$ parameter, the most often used till now Nd:YAG active medium shows some disadvantages when diode pump is applied. Width of its pump absorption band ($\Delta\lambda_p \approx 1$ nm) is too small. In order to ensure high pumping efficiency, accurate regulation and temperature stabilisation of pumping diode ($d\lambda/dT \approx 0.3$ nmK^{-1}) should be ensured. It may be insufficient for pulse pump when during pump pulse temperature of junction and pump wavelength changes can exceed admissible limits. Thus, Nd:YVO_4 and Nd:$GdVO_4$ are frequently used in DPSSL that because they have not only wider absorption bands but also significantly higher pump absorption coefficient what makes them useful for microlasers construction. Nd:YVO_4 can be excited also with radiation at 880 nm filling directly higher laser level [14]. In these conditions, due to lower quantum defect there was obtained high efficiency generation, i.e., 73.3% at wavelength 1064 nm, and 51% at wavelength 915 nm. Among other new crystals doped with neodymium especially interesting is Nd:LSB (Nd:$LaSc_3$[BO_3]$_4$). LSB permits neodymium doping to be relatively high (>20%). Its pump absorption coefficient is higher than Nd:YAG one for five times wider absorption band. So, it is not sensitive to temperature drift of pump wavelength and is useful for construction of stable, high-energetic lasers, including pulse lasers.

Among others activators, the attention should be paid to Yb^{3+}, Er^{3+} and Cr^{3+} and Cr^{4+} ones. These ions can be dopants of majority of listed in Table 3 hosts including YAG [15].

Due to diode pumping ytterbium (Yb^{3+}) started to be used as sensibiliser (especially with erbium dopant) and also as individual dopant of various hosts, particularly of YAG and glasses (fibre lasers) [16]. It is the most promising active material and it is much adequate for diode pump than traditionally used neodymium doped media. In Table 6, the basic parameters (Yb:YAG and Nd:YAG) of these media are compared. Ytterbium doped medium can be pumped with InGaAs/GaAs laser diode at wavelength 940 nm and it generates wavelength of 1030 nm. The quantum defect is for it significantly lower than for Nd:YAG

Table 4. Structure of energetic levels of basic activators.



($\lambda_p/\lambda_g \approx 0.91$ for Yb:YAG and 0.76 for Nd:YAG). Moreover, it has wider absorption band of pump radiation compared with neodymium. Slope efficiencies of ytterbium lasers are extremely high and reach even 70%. So, no wonder that this material is interesting for many leading research centres that using it have obtained exceptionally high powers, up to 1 kW. The most interesting results have been obtained in LLNL [17,18]. Special construction of active rods, with undoped covers on their end-faces and concentrators of pump radiation (HLD – Hollow Lens Duct), en-

Table. 5. Important spectroscopic parameters of neodymium doped media used in DPSSL.

Active medium	λ_p (nm)	α (cm^{-1})	$\Delta\lambda_p$ (nm)	λ_g (nm)	$\Delta\lambda_g$ (nm)	σ_g (10^{-19}cm^{-2})	n	dn/dT (10^{-6}/K)	τ (μs)	% at
Nd:YAG	805 809 811	8	1	1.061 1.064 1.064	0.4 1	2.5 3.3 1.45	1.82	7–10	230	1.1
Nd:YAP	812 796 802	8	1.6	1.079 1.064	2	3.7 1.7	1.92 1.91	9.7	170	0.7
Nd:YLF	793 798 804	3	0.75	1.047 1.053	1.3 1.4	1.8 1.3	1.47 1.45	–4.3 –2	480	1
Nd:GGG	805 808 811	5	1.5	1.058 1.060 1.062	0.75 0.8 0.8	2	1.94	17.4	200–280	1–3
Nd:YVO$_4$	750 808	50	9	1.064	1	25	1.958 2.168	8.5 3.9	80–100	0.9–3
Nd:GdVO$_4$	808	78	1.5	1.063	1.3	7.6	2.17		60–90	1–2.5
Nd:LSB	808	36	5	1.063	4	1.3	1.828	4.4	70–100	5–25

sure the output powers of 430 W cw and 280 W Q-S from the rod of 2-mm diameter and 5 cm length ($M^2 < 2.4$ up to 180 W). The laser with active material composed of two such rods generates 1080 W cw with $M^2 = 13.5$ and 532 W Q-S with $M^2 = 2.5$ (Fig. 4). It seems to be far to the limit of possible parameters of these lasers if the ranges of generated powers and beam quality are concerned.

Table 6. Spectroscopic laser parameters of Nd and Yb doped YAG.

Parameter	Nd:YAG	Yb:YAG
Pump wavelength	808 nm	942 nm
Peak pump cross-section	6.2×10^{-20} cm^2	0.8×10^{-20} cm^2
Pump transition line width	1.0 nm	18 nm
Upper laser manifold lifetime	260 μs	1200 μs
Pump saturation flux	15 kW/cm^2	22 kW/cm^2
Laser wavelength	1064 nm	1029 nm
Peak laser cross-section	2.82×10^{-19} cm^2	2.0×10^{-20} cm^2
Laser transition linewidth	0.5 nm	9 nm
Laser saturation flux	2.6 kW/cm^2	8 kW/cm^2
Heating ratio χ	0.38	0.11

Concluding this short review of lasing media it should be mentioned about trivalent chromium doped materials (Cr^{3+}) that are very important for laser technique. Many of these media are used for tunable lasers, e.g., alexandrite (Cr^{3+}:$BeAl_2O_4$), Cr: LiSAF or Cr: LiSGaF. These media have wide luminescence bands (~100 nm) and with lamp pump they are frequently used for generation of very short (pico- or femto-second) pulses. Unfortunately their efficient excitation needs the sources generating wavelengths of 600–700 nm so, in the range in which contemporary available laser diodes are not efficient enough. The papers on laser diode pumped Cr^{3+} doped ions media are not mentioned to often in scientific magazines and they can be treated only as initial ones e.g., Refs. 19 and 20. Such a situation can be changed for essential increase in power of InGaAlP laser diodes (670 nm).

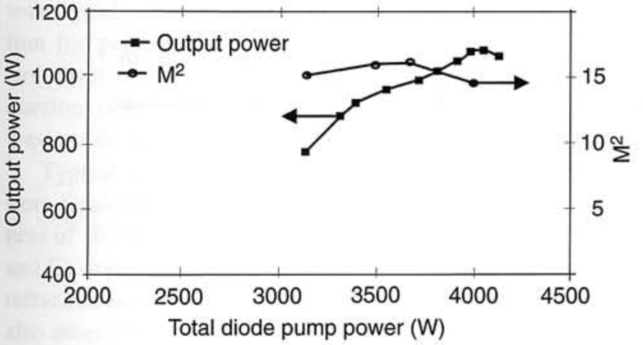


Fig. 4. Powers of diode pumped Yb:YAG lasers (after Ref. 17).

4. Configuration of active materials of diode-pumped lasers

Generally two types of scheme of active media pumping with laser diode can be distinguished: end pumping through a front surface and side pumping through a side surface [21]. If active material is shaped as a rode of circular cross-section (traditional shape taken from lamp-pumped systems), the above mentioned types of pumping can be schematically illustrated as in Fig. 5.

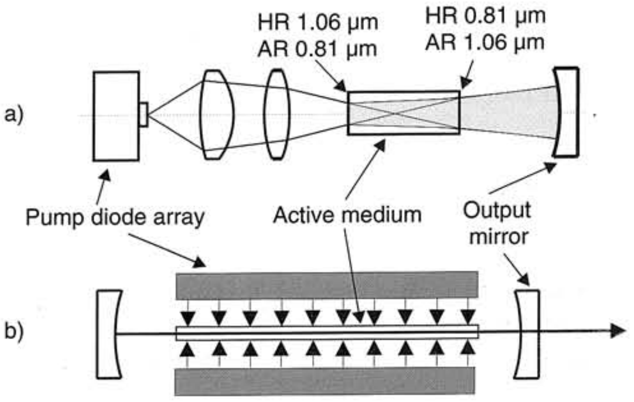


Fig. 5. Basic schemes of diode pumping: (a) end-pumping and (b) side-pumping.

End pumping is much more complicated from technical and technological point of view. It requires:

- adequate shape of pumping beam (in this case optical systems for laser diode are necessary),
- adequate layers should be deposited on the end-surfaces of active materials what ensures high transmission of pump radiation and simultaneously low resonator losses [Fig. 5(a)].

Such difficulties usually do not occur for side pumping but degree of pumping energy extraction is lower. The lasers with an end pump configuration are more efficient when side pumped systems are used in high power lasers [22]. The sets of high power pumping diodes have relatively large dimensions (e.g., 10×10 mm^2). Transformation of radiation from such large surfaces into small pumping volume (for end pumping) becomes difficult problem. Optical systems required for solution of this problem are multi--element and despite application of AR layers they can cause high losses. One of projects enabling avoiding of this difficulty is application of, so-called, lens ducts (see Fig. 6) [23]. Lens ducts have transmission exceeding 90% and they make beam much uniform in transversal surface. They can be used for end pumped rods.

Despite significantly higher efficiencies, diode-pumped active laser materials undergo rapid thermal changes [9]. Such changes especially affects the media being in form of rods with circular cross-section, particularly end pumped ones. They are heated near their axes (both from pump radiation and generation) but cooled through their sides. As a result of this effect two phenomena are observed:

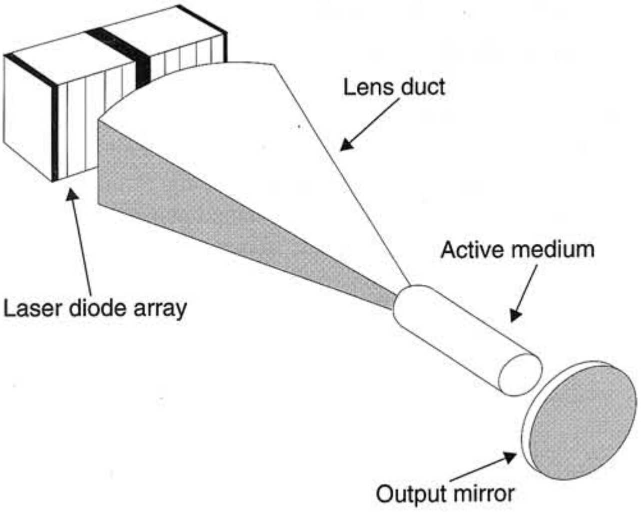


Fig. 6. Concentrator (lens duct) of pumping beam of high-power lasers (after Ref. 23).

- thermally deformed laser rod, in result of changes in its geometry and thermal dispersion of refractive index, starts to act as a lens and resonator can be out of its stability range for extreme case,
- thermal deformation generate stresses inside medium that cause changes in polarisation of transmitted radiation.

The first effect changes conditions of laser operation what in extreme case can cause generation break. The second effect is essential obstacle for generation of linearly polarised radiation or generation of short pulses by means of electrooptic q-switches. It is estimated that peak pump powers at which resonators can be out of their stability range are ~400–500 W. It ensures only about 100 W of a useful power.

Several methods for compensation of influence of thermal deformation, mainly on the output power of end-pumped lasers have been elaborated. Among them, more important ones are:

- VCR (variable configuration resonator) in which resonator is of multielement type (e.g., contains 3 active rods) with variable path for radiation of different polarisation [24],
- VRM (variable reflectivity mirror) in which the mirrors with variable profiles (e.g., Gaussian or super Gaussian) of reflection coefficient and the same wide range of resonator stability [9],
- SBS (stimulated brillouin scattering) mirror – application of a mirror with wave front reversed and compensation of beam deformation caused by defected active material [9,24],
- adding a special element to resonator compensating optical power of active material [24].

The above listed activities enable us to increase pump power up to 2 KW (useful power up to 650 W) in a single head equipped with Nd:YAG rod [24,25].

As the result of the described difficulties there is observed resignation from typical geometry of active materials in form of rods of circular cross-section. In high-power diode pumped lasers geometry of active materials "slab" type started to be dominating (Fig. 7) as well as previously known active mirrors and discs. These elements are also heated with radiation, both pump and generation one. Due to different geometry of active material, the same different distribution of deformations and stresses, their influence on beam parameters is significantly lower [9]. Especially particular becomes "slab" type geometry. It makes possible to obtain high powers with relatively high efficiency and high beam quality.

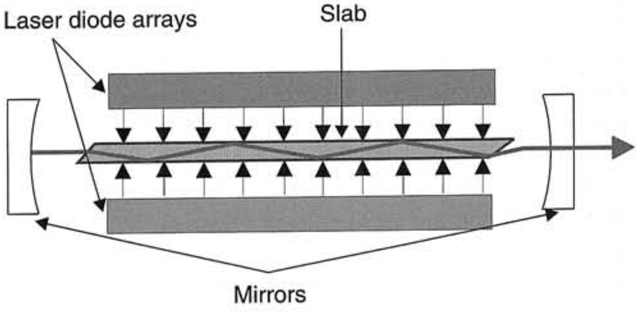


Fig. 7. Side pumped "slab-type" laser.

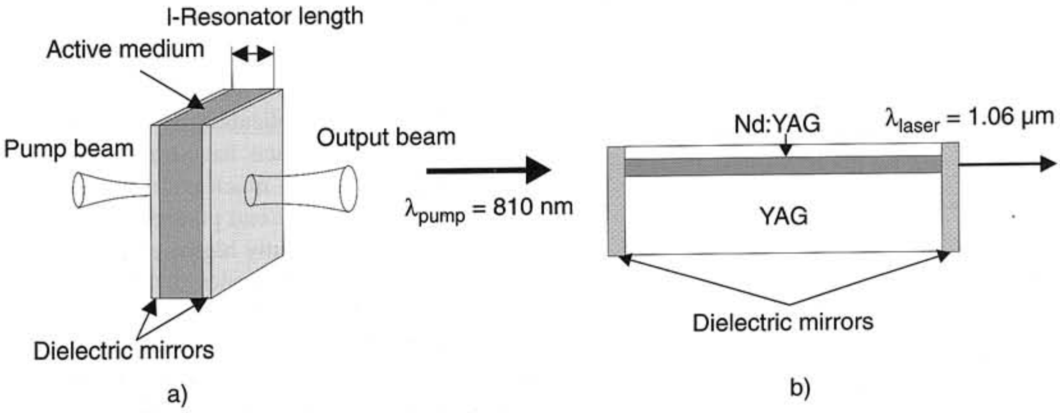


Fig. 8. Microlasers: (a) volumetric and (b) thin-layer ones.

5. Microlasers

Miniature diode-pumped solid-state lasers are called microlasers or microchips [26]. Their construction was possible due to application of diode pumping. Considering geometry of active material microlasers can be divided into volumetric and thin-layer ones (Fig. 8).

Construction of a typical volumetric microlaser is very simple. It is thin plate of active medium of dimensions about 1×1×1 mm^3 (e.g., Nd:YAG) and its polished front surfaces are deposited with resonator mirrors [Fig. 8(a)]. Such formed active material may be fixed directly to junction of AlGaAs/GaAs ($\lambda \approx 810$ nm) pumping diode. If additionally non-linear absorber (e.g., Cr^{4+}:YAG plate) is placed in a resonator, it creates nanosecond pulses generator but with nonlinear converter, (e.g., KTP) it operates as 2nd harmonic generator of Nd:YAG laser ($\lambda \approx 530$ nm).

Active media of microlasers should fulfil much more restrict criteria than other DPSSL media. Their resonators should be very short. This requirement results not only from miniaturisation needs but also because these lasers can generate monochromatic waves (generation of single longitudinal mode). Active materials of microlasers should have so high absorption coefficient of pump radiation to absorb its energy after twice pass of a laser length. For such a chosen resonator length ($l = L_{abs} \approx 2\alpha_p^{-1}$), a good characteristic of active materials of microlasers is the coefficient m [27] characterising the number of longitudinal modes existing in the gain bandwidth of the lasing transition ($\delta\nu_0$)

$$m = \delta\nu_0 \frac{n}{c\alpha_p}, \tag{5}$$

where n is the refracting index. Limiting the choice of media to neodymium doped ones, much more adequate for microlasers are vanadates (for Nd:YVO$_4$ – 1.1 at.% Nd: m = 12, Nd:YVO$_4$ – 3 at.% Nd: m = 0.3, Nd:GdYVO$_4$ – 2.5 at.% Nd, m = 0.4) or Nd:LSB (for 25 at.% Nd : m = 1.4), then Nd:YAG (for 1.1 at.% Nd: m = 2.5). Microlasers have extremely compact and miniature constructions that can generate in IR (1060 nm) continuous power of the order of hundred mW or pulses of duration 0.3 ns and energy of the order of mJ. Trend toward laser miniaturisation caused interest in thin-layer wave-guide structures and possibilities of their application for generation of optical radiation [Fig. 8(b)]. The first laser of this type was activated in 1972 [28]. Introduction of a diode pump created real possibilities of waveguide laser development and application.

Typical construction it is Nd:YAG thin layer deposited from liquid phase by epitaxy method. This layer has thickness of 10–30 µm on YAG based plate. It is additionally Lu and Ga doped in order to have adequate difference between refraction index of a layer and base ($\Delta n \geq 10^{-2}$). As dopants also other rare-earth elements (Pr, Er, and the like) or transition elements (mainly Cr, Ti) can be used.

Microlasers (both volumetric and thin layer ones) have, despite miniature dimensions and high efficiency (up to 70%), also important common property, i.e., they can generate single-frequency radiation. For volumetric lasers, this feature results from comparability of cavity mode spacing (for longitudinal modes) with the gain bandwidth for the resonator length given by

$$l \leq \frac{c}{n(A + \delta\nu_0)}, \tag{6}$$

where A is the spectral range of guaranteed single-frequency generation. For fibre lasers, such a single-frequency operation ensures the resonator with distributed feedback often used in these lasers.

Availability of cheap and simple optical generators of monochromatic waves gives possibility to develop many new fields, including metrology and telecommunication with coherent receiving. Even if for fibre telecommunication such type of communication is not clear, for rangefinders and optical radars it can be of crucial meaning. We think that we will be soon witnesses of rapid progress in works carried out in these fields.

Finally, the problem of lasers like standard frequencies used as time and length standards should be considered. Domination of He-Ne lasers, also in this application, is in danger at present. The papers have been published reporting that obtained stabilities of frequencies of signals generated by standard microlasers are constantly increasin [29,30]. Relative instability of Nd:YAG microlaser frequencies stabilised with iodine line (length of generated wave 946 nm) is $\Delta\nu/\nu \approx 2\times10^{-13}$ [30], what permits it to be a standard of optical frequency. Additionally, considering that solid-state microlasers have a very simple power-supply, a very long lifetime, and they are low-noise source, so, knowing their advantages resulting from their dimensions they can be competitive with up-to-now known and commonly used in this region – He-Ne lasers.

6. Fibre lasers

Fibre lasers belong to the family of waveguide lasers and they can operate due to diode pump. The lately observed progress in the scope of fibre lasers technology has caused that they started to be treated as a separate group of high-power lasers [11,16,31,32]. As active dopants of fibre lasers usually the following ions are used:

neodymium	(Nd^{3+})	$\lambda_g \approx$1060–1120 nm
ytterbium	(Yb^{3+})	$\lambda_g \approx$1020–1180 nm
erbium	(Er^{3+})	$\lambda_g \approx$1530–1565 nm

Fibre lasers have specific features in relation to conventional DPSSL, among them:

- high amplification,
- high efficiency and low threshold of generation due to very low resonator losses (~5 dB/km),
- diffraction limited beam (M^2 ~1),

- easy heat exchange with environment,
- high-power density in relation to pump power density.

The latter two features will be described below. Easy exchange of heat with environment, so efficiency of cooling can be estimated as a ratio of a surface through which an active element is cooled to its volume

$$\chi = \frac{S}{V}. \tag{7}$$

The ratio from Eq. (7) depends on geometry of active materials and the way of their cooling. For the rods cooled by a side surface (this group includes also fibres) $\chi_p = 2/R$, where R is the radius of an active rod (fibre).

For slabs, discs, and mirrors the active parameter of Eq. (7) depends on quantity of cooled surfaces of discs and slabs and it is equal to $\chi_d = t^{-1}$ for one cooled surface and $\chi_d = 2\ t^{-1}$ for two cooled surfaces, where t is the slab thickness. Taking into account that fibre diameter is many times lower than other dimensions of DPSSL active elements ($R_{fibre} << t < R_{rod}$) it is clear why fibre lasers have significantly better heat exchange with environment (10–100 times) than lasers of typical construction.

The second mentioned feature is connected with specific structure of active fibres of laser and the methods of its excitation. Fibre amplifiers and first lasers using this geometry of active medium were excited by introducing of pumping energy to the core from the front face or by means of directional couplers. This type of excitation meets some difficulties when single-mode fibres have to be excited with large powers (two dimensional diode array). These difficulties can be overcome using double cladding of active fibres (Fig. 9). Pump radiation is introduced into the fibre in form of cladding modes. For pump radiation, the fibre behaves as multimode fibre of numerical aperture, NA = 0.4–0.5. Introduction of pump energy to the fibre is easy, even from laser diodes of high power, directly through the fibre front or by means of fibres bundle from many diodes with fibre outputs.

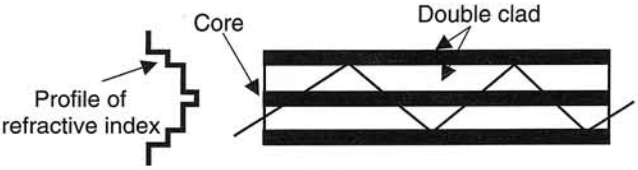


Fig. 9. Laser fibres with double cladding. Fibre parameters: core 10-15 μm, cladding 100–400 μm.

Absorption of pump energy occurs only in the core doped with active ions. It is the case as previously mentioned compression of power density of pump radiation in energy of core excitation and finally density of generation power. The compression value in the first approximation is the ratio of the cladding surface A_{cl} to the core surface A_c and for singlemode fibres it is of the order of 10^3. In reality, compression coefficient is lower because it includes also the Stokes efficiency (λ_p/λ_g) and numerical aperture (NA) and it is equal to [33]

$$M = \frac{A_{cl}}{A_c}\frac{\lambda_p}{\lambda_g}NA. \tag{8}$$

However, its value even for neodymium doped fibres (λ_p/λ_g ~0.76) is 500–700. Application of cladding modes for cores fibres excitation decreases efficient absorption coefficient of a medium and it requires longer fibres. A mechanism of radiation absorption of the particular cladding modes through centrally situated core is a very important problem. It turned out that fundamental influence on homogeneous core excitation has the shape of cross-section of a cladding. Optimal shape is not circular one. Theoretically, a rectangular shape of cross-section of cladding promises the most homogeneous absorption of pump radiation through the core. Good properties have also "D" -type and "flower" -type of the cladding (Fig. 10).

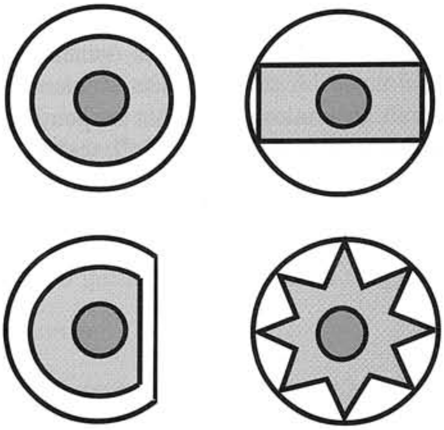


Fig. 10. Cross-sections of active fibres (after Ref. 16).

For these shapes the efficient coefficient of radiation absorption can be approximated by relationship

$$\alpha_{eff} \approx \alpha\frac{A_c}{A_{cl}}, \tag{9}$$

where α is the absorption coefficient of the core materials.

The resonators of fibre lasers can be made simply using Fresnel reflection from front surfaces of fibres. From the fibre laser (50-m length) doped with 0.5% Nd^{3+} the obtained power of 2.4 W with efficiency of 73% (counting the both outputs) [16]. The mirror R = 1 placed at one of the fibre ends decreases output power down to 1.86 W and efficiency down to 60%. As it can be seen, the value of differential efficiency of fibre lasers approaches to the Stokes efficiency that for Nd^{3+} is about 76%. For ytterbium doped fibres, the Stokes efficiency is significantly higher (≅ 91%) and relatively higher differential efficiencies are obtained (86%) [31]. In fibre lasers, also resonators with narrow-band Bragg's mirrors, made in the final

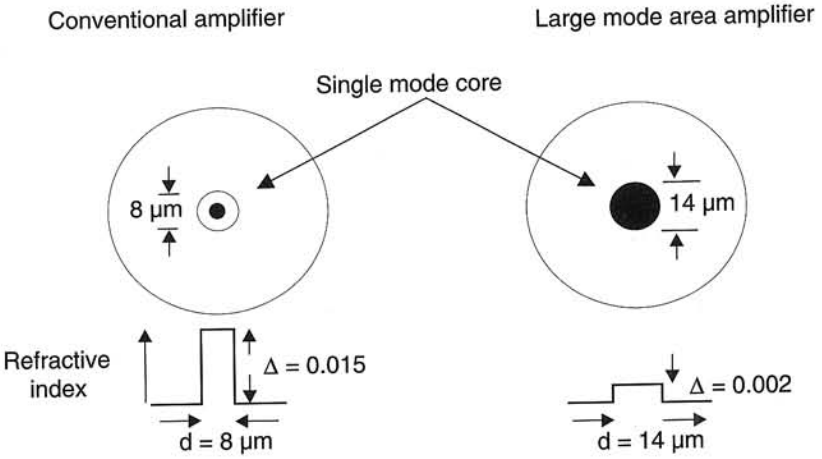


Fig. 11. Laser fibres LMA type.

parts of fibres, can be used [28]. Searching for increase in power generated from fibre lasers led to one more modification of active fibres. These fibres are known as large mode area (LMA) (Fig. 11) in which the core diameter is larger with simultaneous reduction of the difference of refraction coefficient between core and cladding.

LMA fibres ensure:

- increase in amount of dopant ions per the length unit and the same increase in the cumulated energy,
- reduction of NA – small divergence angle of a generated beam,
- doping that ensures single mode operation from multimode fibre.

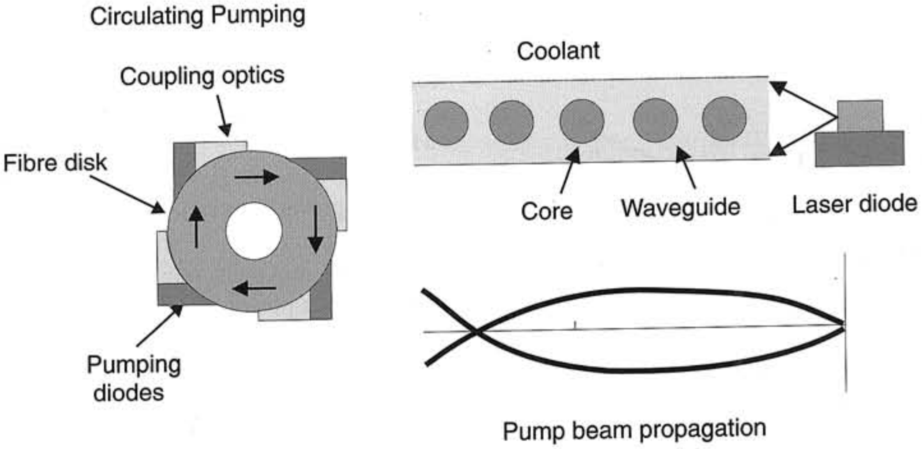


Fig. 12. High-power fibre disc laser (after Ref. 16).

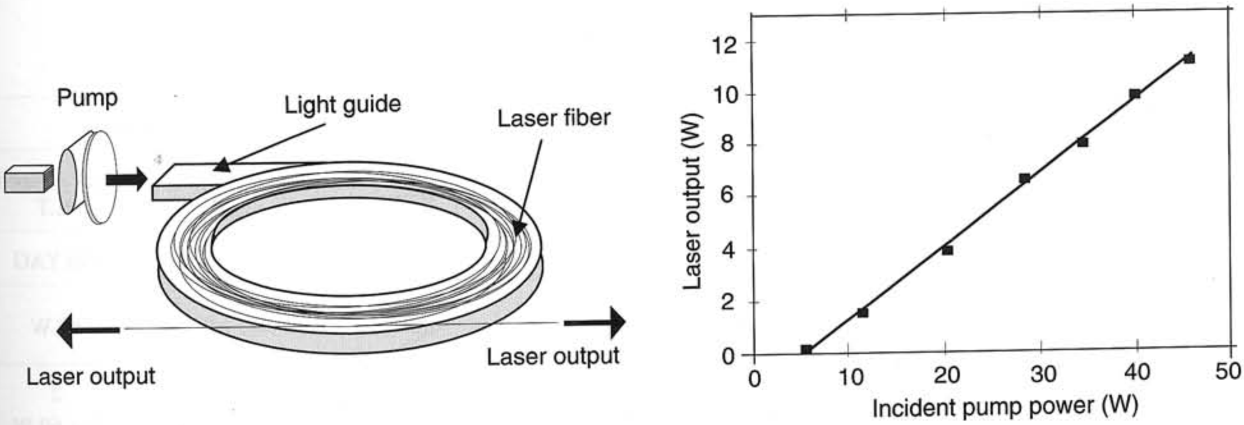


Fig. 13. First implementation of the fiber embedded structure laser concept and fiber laser characteristics corresponds to the sum of the output powers at both ends (after Ref. 35).

Investigations on high-power fibre lasers have been started recently. Despite this, the obtained results are impressive. From cw lasers the maximum powers of 50 W were obtained. Interesting construction of fibre laser was proposed in Ref. 16. It is laser which active fibre is coiled in form of disc excited radially or radially-spirally through a side surface (Fig. 12). The disc thickness is 100 μm and pumping radiation propagates in it such as in planar waveguide exciting dopant ions in a spirally coiled rod. The first implementation of the concept was presented in Ref. 32. Nd^{3+} doped silica fibre, 100 m in length, 40 μm in diameter and 125 μm cladding diameter was coiled into a ring 10 cm in diameter and next flooded in resin (Fig. 13). The pump radiation has been directed into such formed waveguide. The core absorption at 810 nm was 280 dB/m and the core background losses measured at 1200 nm was 8.4 dB/km. This system was examined with an open resonator. The fibre laser feedback was provided by Fresnel reflections from fibre ends. The obtained results show possibility of practical realisation of side pumped fibre laser. Side pumping causes significantly increase in a power concentration coefficient [expressed in Eq. (8)] of the output power in relation to pump power. It is estimated that concentration coefficient can be then even 10^9 [16]. The opinion is formulated that new constructions of fibre lasers make possible to generate significantly higher powers (up to 1 kW) and they can be used in industry, where the lasers of extremely high quality beam are required.

7. High-power lasers

Considering the aplications of diode pumped solid-state lasers [34], one can state that DPSSL lasers are commonly used in practice for scientific research and they can also play important role in industrial applications.

It is one of the reasons causing greater interest in a progress made within high-power DPSSL for industrial and medical applications. The second reason of such interest is rapid progress observed in development of diode pumped lasers and lasers generating high output powers.

Recently, great research programmes have been created, the results of which, among others, is to achieve such constructions of DPSSL's, the power values of which are enough to replace presently used CO_2 and (lamp) Nd:YAG lasers in industrial applications. Two programmes (their range and the results of investigations) are published in Refs. 3 and 4.

The main result of the programme [4] is presented ROFIN-SINAR GmbH. The basic parameters of 3.3 kW laser which are shown in Table 7 in comparison with the previously obtained results of the other leading firms.

Within the scope of generation technique the project concerns mainly DPSSL using active materials both in form of rods and slabs. Generally, increase in a generated power up the level of 10 kW with efficiency above 20% from heads of a volume smaller than 0.05 m^3 is planned. The problems of beam quality and possibility of its focusing are discussed. Regarding these, the project assumes construction of laser system of the power 1 kW and efficiency 20%, the beam of which could be focused on the surface of 50 μm in diameter. One of constructions fulfilling these requirements can be fibre laser. It is also planned to develop conversion systems of wavelengths and production of the 2nd and 4th laser harmonic of Nd:YAG laser of powers of the order of tens watts.

As far as DL are concerned, in the project elaboration of high-quality beam and power of about 40 W for fibre laser pumping is predicted [3,11,32].

A basic module (head) of a laser of typical construction with Nd:YAG active rod of length 150 mm (0.6% Nd^{3+}) is capable to generate power of about 1 kW cw and efficiency of pump power conversion 47% (total efficiency 19%). The laser consisting of four (in series situated) heads (resonator length 940 mm with output mirror of transmission 50%) generates the power of 3.3 kW for pomp power 9.4 kW (efficiency of pump power conversion 35%). Scheme of module construction and its energetic characteristics are shown in Fig. 14.

Even better results were obtained from the laser in which active material in form of a slab was used. Nd:YAG slab of neodymium ions concentration 1.05 atm % has di-

Table 7. Parameters of high-power DPSSL lasers obtained in various world research centres.

	Rod laser			Disk laser	Slab laser	
	Side pumped ROFIN	Side pumped HUGHES	End pumped LLNL	End pumped IFSW	Side pumped TRW	End pumped ILT
Laser medium	Nd:YAG	Yb:YAG	Yb:YAG	Yb:YAG	Nd:YAG	Nd:YAG
Max. output power (single laser head)	3.3 kW	950 W	450 W	350 W	3.5 kW	60 W
Beam quality (M^2)	36 P = 3.5 kW	?	6 P = 100 W	10 P = 300 W	10 P = 3.5 kW	2 P = 60 W
Efficiency P_{out}/P_{pump}	9%	24%	25%	42%	19%	50 %

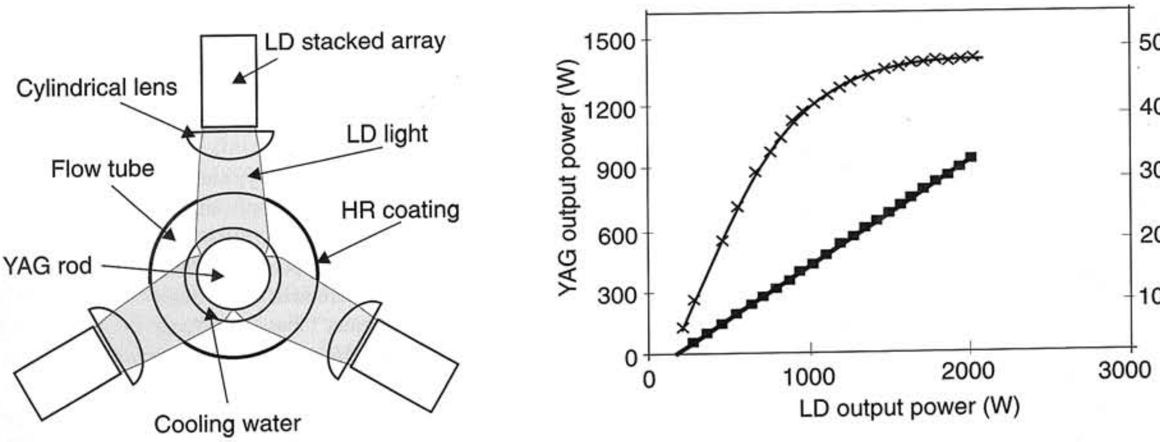


Fig. 14. Scheme of construction and output characteristic of a head with a laser rod investigated within the frame of the program "Advanced Photon Processing and Measurement Technologies" (after Ref. 33).

mensions 6×25×206 mm^3. It is pumped by two sets of laser diodes, each of them consists of 18 stacks. The stack includes 16 arrays. Nominal array average power is 240 W (regime qcw with peak power 960 W, pulse duration 400 µs, and frequency 625 Hz). The slab is pumped from both sides and head construction and Au mirrors system ensure its efficient and uniform pumping (Fig. 15). This active material situated in a resonator of output mirror transmission 47% generates an average power of about 3.3 kW (power per pulse 13 kW) with 35% conversion of pump power (total efficiency 13%). The project executors hope that this system will allow for construction of laser generating average power of 10 kW required for welding of steel plates 30 mm thick or plates of aluminium alloys of thickness 20 mm.

Progress in mastery of diode-pumped high-power solid-state lasers liven up the hope for construction of thermonuclear powers with laser initiation. The concept of laser

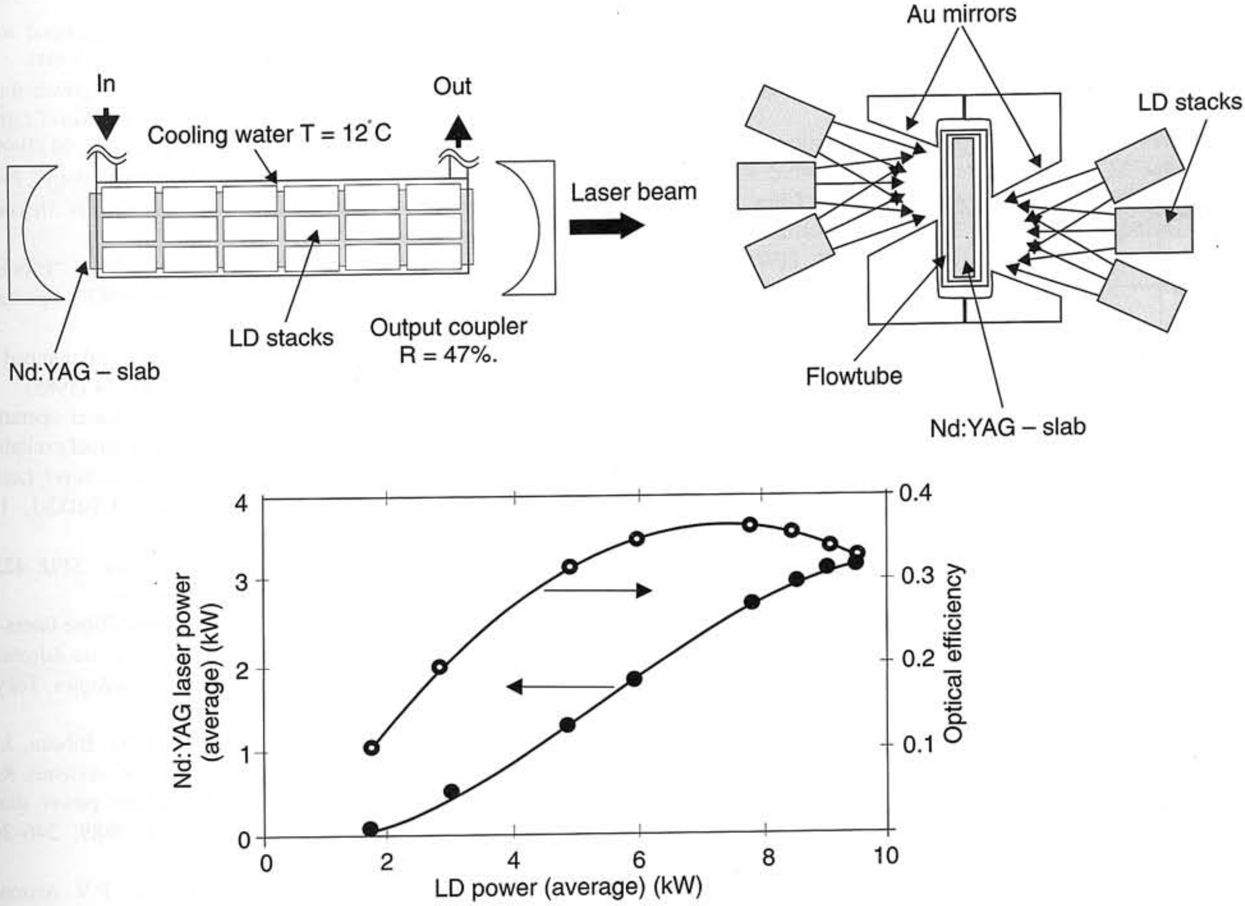


Fig. 15. Scheme of construction and output characteristic of a slab type head investigated within the frame of the program "Advanced Photon Processing and Measurement Technologies" (after Ref. 36).

microfusion is still the subject of interest of researchers, despite lost hope on application of up-to-now used lasers for its practical realisation. Maybe diode--pumped solid-state lasers allow overcoming inaccessible till now threshold of high energy per pulse and frequency of their repetition. We suppose that such a programme is carried out in Japan [38, 39] and probably also in USA.

8. Conclusions

Progress in laser diodes allows their application in industrial technologies. So far, the main obstacle was quality of beams of high-power edge semiconductor lasers. One of possible solutions is application of diode pumped solid state lasers. DPSSL have beams of good quality, enough for majority of industrial applications and moreover they have high efficiency long service life (lifetime of pumping diodes is estimated for tens thousand hours), and they can generate very high powers. The above--mentioned results on DPSSL show that these lasers can be competitive with other lasers used in industry, mainly with lamp-pumped solid-state lasers and CO_2 ones. One reason limiting their implementation is high price of pumping diodes. However, market analysis shows that their prices decrease at a rate 60% per year (Fig. 16). If this trend is constant, diode prices will be soon significantly lower than 10$ for 1 W of peak power. Then, the main obstacle in development and expansion of these lasers in main fields (industry, medicine) will disappear. We expect that diode pumped laser will be dominant in the next decade.

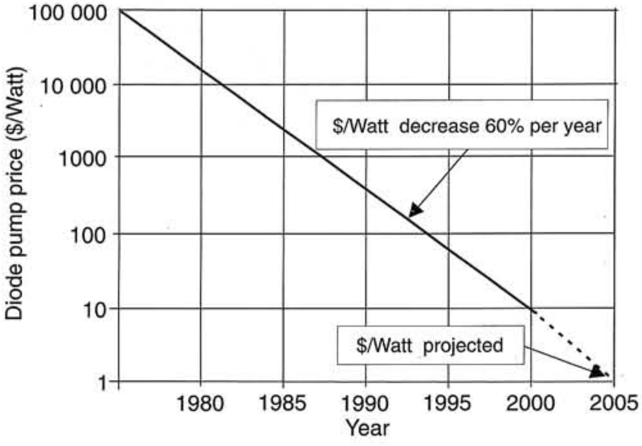


Fig. 16. Price reduction slope of the diode pumps (after Ref. 37).

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