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Multi-disk: concept and realisation of a collinearly pumped multiple thin disk active medium

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***Abstract*. We analyse the concept of collinearly pumped active medium consisting of multiple thin disks (multi-disk configuration). The multiple disk design is attractive for fabrication of mid- and high-output power laser systems with a good spatial beam quality and high optical efficiency. Two approaches for realisation such multi-disk active elements are considered. Preliminary lasing experiments and numerical calculations for temperature distribution inside the lasing medium are presented.**

Keywords: *solid-state lasers, diode-pumped lasers, composite active element.*

1. Introduction

Main factor limiting the average output power of solid-state lasers is related to thermal effects in the active medium. Optimising heat removal can help to avoid this problem. One of the options that significantly increases heat removal is to use cryogenic cooling which, unfortunately, is quite complicated for most applications. Other solutions for room temperature are mainly based on a thin disk geometry with a relatively large area for heat removal or slab geometries with a zig-zag path of the laser beam, which allow compensating for thermally induced distortions.

The thin disk geometry of solid-state gain media is widely used in high-power laser oscillators and amplifiers. Main advantages of this geometry, compared to conventional geometries with end-pumped and side-pumped rods, are improved thermal management and power scalability. Apart from advantages, the thin disk geometry has its drawbacks. Commonly, in order to pump a thin laser element efficiently, use is made of an elaborate multipass (up to few tens of passes) pump system, which provides efficient absorption [1]. This is a bulky and complicated optical setup containing a parabolic mirror and prisms which requires precise assembling and alignment. Otherwise, the edge-pumped geometry can be employed but this approach suffers from lower efficiency and pump nonuniformity [2].

The power scalability of the thin disk lasers mentioned above has some certain violations. Firstly, increasing the intracavity fundamental TEM_{00} mode diameter leads to certain problems with the laser cavity stability. Efficient TEM_{00} mode generation is possible when total wave front distortions are less than $\lambda/4$. Such a requirement is extremely difficult to fulfil when the mode diameter is large. Secondly, the inherent property of the thin disk geometry is a huge difference in longitudinal and transverse gain. In certain circumstances, the transverse gain can be so high that amplified spontaneous emission (ASE) in this direction affects the laser efficiency. The origin of this difference is fundamentally related to basics of the thin disk concept [3].

The slab geometry is another well known concept for better thermal management and power scalability. Various configurations have been proposed for slab lasers [4 – 6]. The temperature profile can be relatively uniform in the two long dimensions, while the temperature gradient in the vertical direction is very strong because heat is extracted from the top and bottom faces. The zig-zag geometry causes the effects of this strong temperature gradient to be largely averaged out, but optical distortions arise from residual effects in all directions, particularly from end effects. The temperature gradient is also associated with thermally induced mechanical stress, which is typically strongest at the sides of the medium and may cause the crystal damage [7].

2. Description of a multiple thin disk active element configuration

In this paper, we offer a multiple-disk geometry which gives additional possibilities in power scaling of solid-state lasers and simplifies the pump pulse shaping system compared to the thin disk one. In essence, we use several collinearly pumped thin disks in order to simplify the pump system configuration and reduce the thermal load for an individual disk. The multiple-disk geometry is shown in Fig. 1. Each individual disk thickness is much smaller than the active area transverse dimensions. Therefore, the thermal management is similar to that of the thin disk one. The pump beam is collinear and geometrically matched in space with the generation beam. In contrast to the side-pumped geometry,

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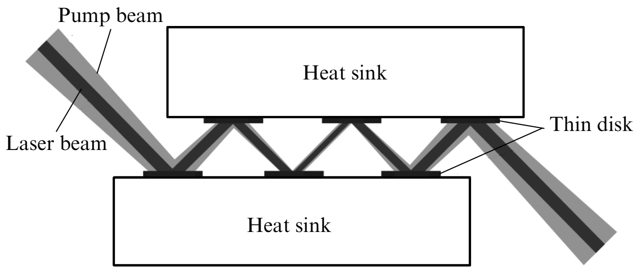

Figure 1. Geometry of collinearly pumped thin multi-disks.

the pump beam forms gaining apertures (active areas) due to which there is no need for hard apertures to maintain a fundamental transverse mode. Therefore, pump radiation is used as efficiently as in conventional end-pumped lasers. The pump scheme that we consider implies some certain requirements on the spatial quality of the pump radiation. The pump beam diameter should not necessarily have the same size and intensity distribution within all disks. If we require that pump beam radius exceeds its minimal value by K times within the length of the multiple-disk structure, then the relation between the pump beam quality M^2, the waist radius w_0, and the optical path length L has the form:

$$\frac{M^2}{w_0^2} = \frac{2\pi n}{L\lambda_p}\sqrt{K^2 - 1},$$

where n is the average refractive index of the medium and λ_p is the pump wavelength.

There are several aspects to be taken into account when choosing the number of disks. More disks lead to an increase in the gain medium volume and, hence, to stronger pump absorption and population inversion. On the other hand, the structure becomes larger and there are more stringent requirements imposed on the pump beam quality. In addition, the pump power absorbed by the disks is not equal for each active area and this difference increases with increasing number of disks.

In the case when the pump beam enters the disks from one side only, we can easily calculate that the absorbed pump power differs a lot in the first and the last disks. For example, if we have a six-disk structure and want to have the total absorption of 90 %, then the first disk will absorb 32 % of the pump power and the last one will absorb 5 % only (Fig. 2a). The situation improves when the residual pump beam is reflected back to the structure (second pass of the pump beam is realised). In this case it is needed that absorption of one disk dropped down to 18 %. Therefore, the first disk absorbs 20% and the last one absorbs 12 % of the pump power (Fig. 2b).

In order to get a more uniform pump circulation inside each individual disk, the structure should be pumped from both sides. In this case, the dependence of the absorbed pump power on the coordinate becomes symmetric and disks that absorb least of the pump power are in the middle of the structure (third and fourth disks in a six-disk structure). For the structure to absorb 90 % of the total pump power, absorption of one disk should be again 32 %, but the absorbed power in end and middle disks will be 18 % and 12 %, respectively (Fig. 2c). However, when the pump beam travels twice in the structure, the situation improves:

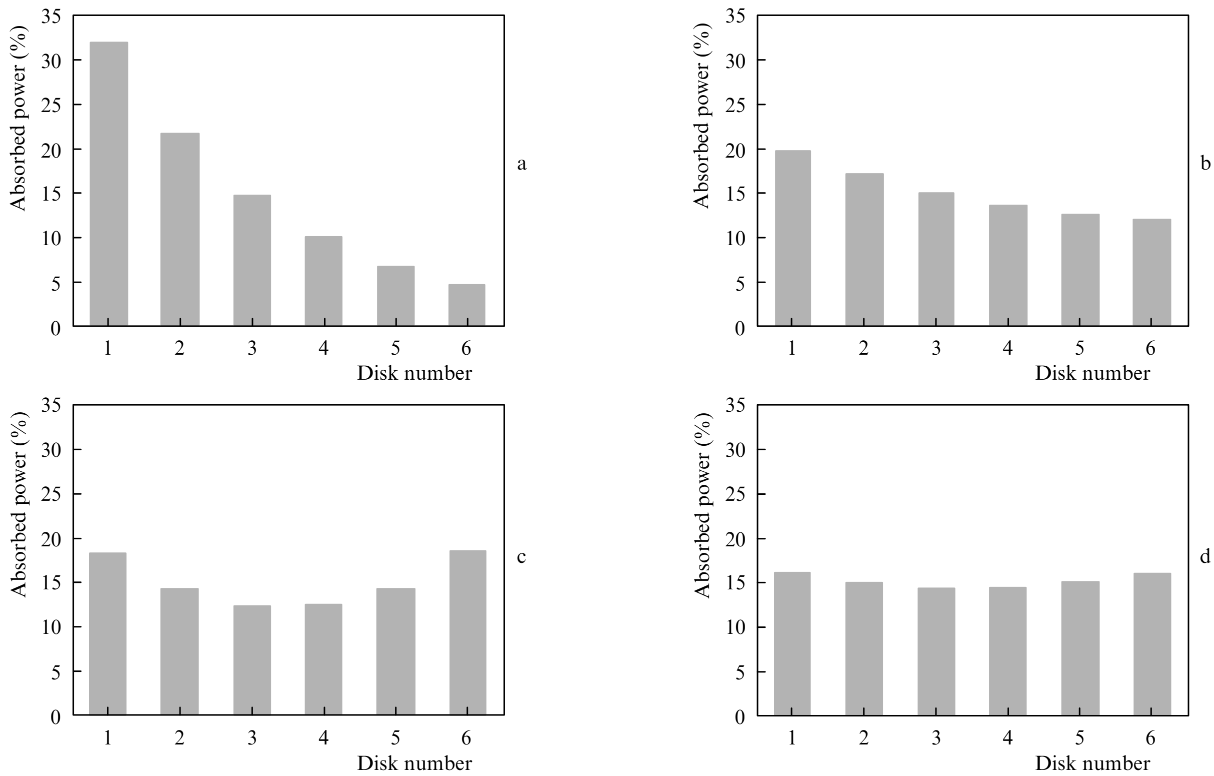

Figure 2. Variation of the absorbed pump power in each disk for different pump schemes: (a) from one end, (b) from one end with residual unabsorbed pump back reflection, (c) from both ends, (d) from both ends with residual unabsorbed pump back reflection. The total absorbed pump power in the structure in each case is 90 %.

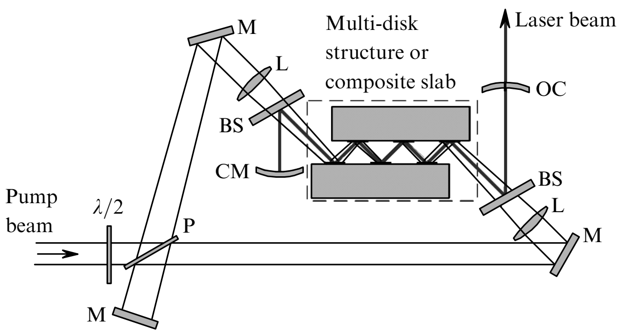

Figure 3. Scheme of a two-side pumping configuration with back reflected unabsorbed pump: (M) mirrors; (BS) beamsplitters; (L) lenses; (P) polariser; (CM) cavity mirror; (OC) output coupler; $\lambda/2$ is the half-wave plate.

the first disk absorbs 16 %, and the middle disk absorbs 14 % of the pump power (Fig. 2d). The scheme of a two-side pumping configuration with residual unabsorbed pump back reflection is presented in Fig. 3.

If we consider the dependence of the absorbed power in disks which get the least pump power on the power absorbed by one individual disk, we can see that the dependence has a maximum (Fig. 4). For different pump schemes this maximum is at different positions, which has to be taken into account. Optimal absorption for the scheme of a one-side pumping configuration with residual back reflection of unabsorbed pump (double pass) is 15 % (Fig. 4a). But in this case, more than 14 % of the pump power is not absorbed. When the active element is pumped from both sides, absorption in one disk should be 29 %; however, in this case, almost 13 % of the pump power is not absorbed (Fig. 4b). The situation is much better, if use is made of a two-side pumping configuration with residual unabsorbed pump back reflection. In that case, the optimal one-disk absorption is 22 % and only 5 % of the pump power is not absorbed (Fig. 4c).

There are two guidelines for constructing multi-disk structures. One of them is to use separate thin disks as an active resonator folding mirrors (multi-disk design), the other is to build a monolithic composite slab structure, where only thin side layers are doped (composite slab design). Both structures are optically similar but quite different in mechanical design. In this paper we study both designs.

3. Multi-disk approach

In a multi-disk structure (Fig. 1), thin crystals have antireflection coatings on one side and high reflective coatings for pump and lasing wavelengths on the cooled side. Bonding layer between coated disk and heat sink should ensure good thermal conduction.

For experimental realisation of the proposed configuration, we have chosen Nd^{3+} doped crystals for their high gain cross section compared to ytterbium crystals. Also our selection for active ions was also influenced by our demands to have a structure amplifying at a wavelength of 1064 nm. Thin disk active elements (0.5 mm in thickness) made of a YAG crystal were bonded to aluminium nitride (AlN) ceramic plates attached to heat sinks. The sol-gel technology was used for bonding the YAG crystal to a polished AlN plate. Despite poor thermal conductivity of sol-gel, good thermal conduction was obtained due to a very thin layer (about 1 μm) (Fig. 5). Crystals had dielectric high reflective coatings for 808-nm pump and 1064-nm lasing wavelengths on one side. The other side has been left uncoated. The concentration of Nd^{3+} ions was 0.6 at. %.

For lasing experiments a short resonator was built (Fig. 6). The output coupler reflectivity was 95 %. A fibre coupled laser diode emitting at 808 nm was used for pumping. The maximum output power of the laser diode with the beam waist diameter of 1.2 mm was 110 W.

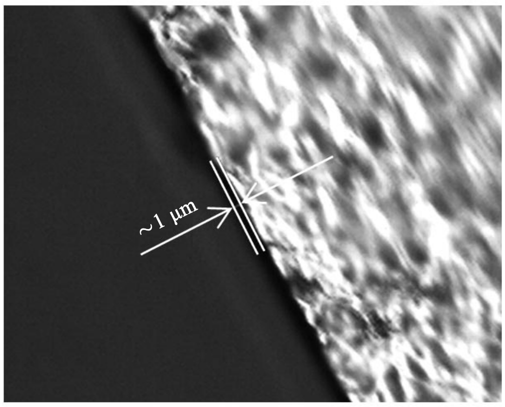

Figure 5. Photograph of the sol-gel bonding layer between the YAG crystal and AlN ceramics.

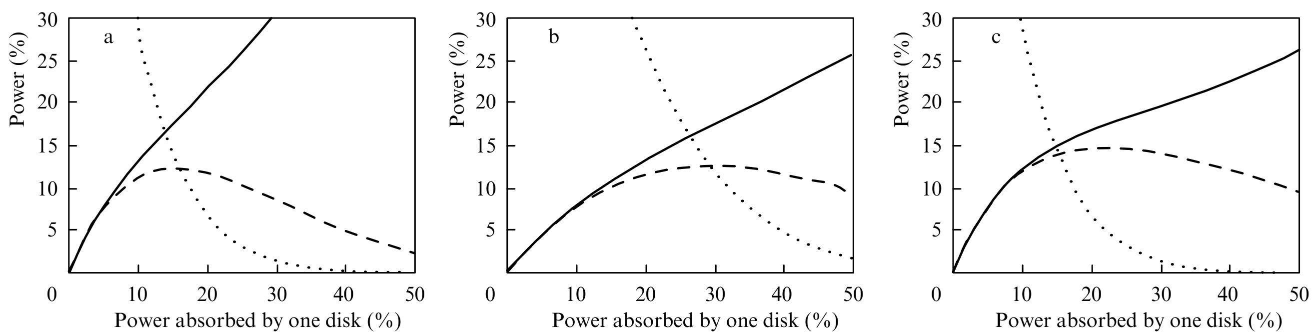

Figure 4. Power absorbed in one individual disk versus pump power absorbed in the first disk (solid curves) and in a disk, which absorbs the least power (dashed curves) in the case when (a) the structure is pumped from one side with residual unabsorbed pump back reflection, (b) the structure is pumped from both sides, (c) the structure is pumped from both sides with residual unabsorbed pump back reflection. Dotted curves show the unabsorbed pump in the structure.

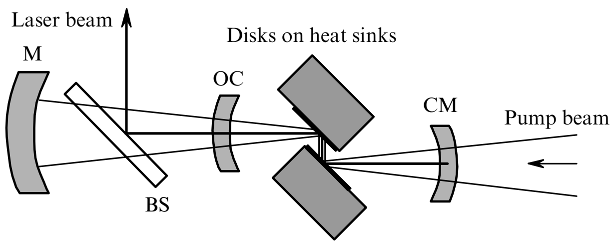

Figure 6. Optical setup of lasing experiments with disk elements: (CM) highly reflecting cavity mirror; (OC) output coupler; (BS) beamsplitter; (M) mirror reflecting pump radiation.

We performed preliminary lasing experiments with one or two disks and observed a linear increase in the output power in the case of a single pass of the pump beam through the active element (Fig. 7). In the case of a double pass of the pump beam, output power saturation was observed at high pump levels. It is important to note that the absorbed power was measured directly for a single pass of the pump beam. In the case of a double pass, the absorbed power was estimated according to the measured absorption during the first pump beam pass. We believe that the output power saturation was caused mainly by a spectral shift of laser diode emission as an unabsorbed portion of the pump beam was coupled back to the fibre. In this case, the absorption coefficient is different from that when the single pump pass configuration is used. More accurate data for a double pump pass configurations can be obtained using a fibre coupled laser diode with a Bragg grating or by isolating the reflected pump beam.

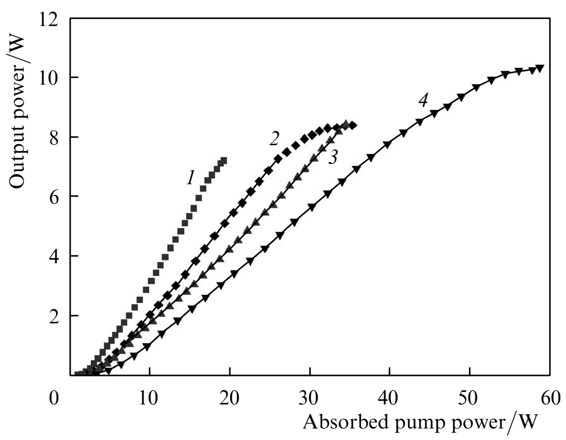

Figure 7. Output power versus absorbed pump power for different configurations with disk elements: for (*1*, *2*) one disk and (*3*, *4*) two disks in the case of (*1*, *3*) one-side pumping configuration and (*2*, *4*) one-side pumping configuration with residual unabsorbed pump back reflection.

4. Composite slab approach

The composite slab design (Fig. 8) is similar to the multi-disk design but has a monolithic form where the air gap between the active layers is filled with an undoped laser material. Such a design furnishes an opportunity to choose the bonder layer material as the monolithic structure can be sandwiched between the heat sinks. In addition, it is also possible to employ total internal reflection and abandon using reflective coatings. To avoid frustration of the total internal reflection, a low refractive index protective layer must be deposited. The total internal reflection condition in this case has the form: $\sin\beta > n_p/n_s$, here β is the internal angle of incidence; n_p is the protective layer refractive index; n_s is the slab crystal refractive index ($n_p < n_s$). For the interface between the YAG crystal and the SiO_2 layer, the total internal reflection will occur at angles exceeding 57°. Additionally, the internal angle of incidence should be chosen with some margin taking into account the pump beam angular distribution. The composite slab structure is mechanically stable and there are less stringent requirements imposed on the pump beam spatial quality due to a larger refractive index of the medium filling the gap between the active layers. The undoped filling medium also helps to reduce ASE in active regions [3]. The main disadvantage of such a design is an intricate process of composite slab manufacturing.

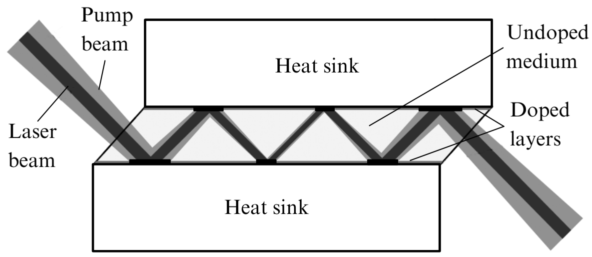

Figure 8. Geometry of a composite slab element.

Experiments were performed with a composite slab made of YAG ceramics. Active layers were 200 μm thick with Nd concentration of 2 at. %. The slab was strained between two water cooled plates. Indium foil was used as a heat conductive bonding layer. Six bounces (active regions) were realised. The composite slab was pumped from both ends (see Fig. 3). A fibre coupled laser diode emitting at 808 nm was used for pumping. The pump power up to 90 W with a beam diameter varying from 1.2 mm to 1.8 mm along z axis was launched inside the slab structure. The laser cavity was formed by a highly reflecting cavity mirror (CM) and output coupler (OC) with a reflectivity of 95 %.

Multimode continuous wave lasing experiments show a linear increase in the output power versus the absorbed pump power with the slope efficiency of 42 % (Fig. 9). It was observed that a decrease in the laser diode temperature (this detunes the pump centre wavelength from maximum absorption at 808 nm) leads to an increase in the output power. We also noticed that the output power increases if the slab is squeezed with more force between the heat sinks, thereby illustrating the importance of good heat removal. But on the other hand, the output power drops if slab is squeezed too much, which may be due to mechanical stress in ceramics.

5. Numerical simulations

The temperature distribution inside a composite slab was calculated by solving 3D steady-state heat conduction differential equation numerically using a finite element method in 'Comsol Multiphysics' software

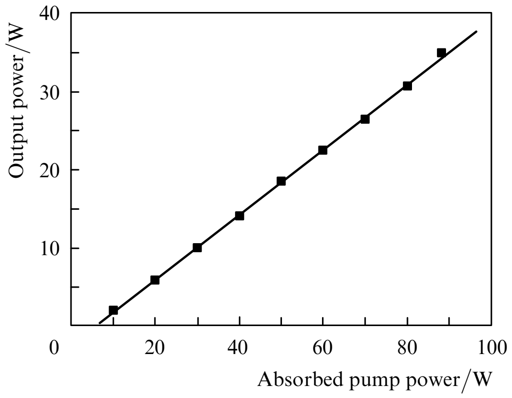

Figure 9. Output power versus absorbed pump power for a composite slab geometry.

$$\nabla^2 T(x,y,z) + \frac{Q(x,y,z)}{k} = 0, \tag{1}$$

where T is the temperature; Q is the heat source; and k is the thermal conductivity coefficient, which was assumed constant. The pump beam cross-sectional distribution was assumed hyper-Gaussian. The expression for a heat source produced by incident and reflected pump beams has the form:

$$Q(x,y,z) = \alpha\eta \frac{P}{\pi w_0^2} \left\{ \exp(-\alpha z_{\mathrm{i}}) \exp\left[-\left(\frac{x_{\mathrm{i}}^2 + y^2}{w_0^2} \right)^p \right] + \exp(-\alpha z_{\mathrm{r}}) \exp\left[-\left(\frac{x_{\mathrm{r}}^2 + y^2}{w_0^2} \right)^p \right] \exp\left(-\alpha \frac{d_{\mathrm{Nd:YAG}}}{\cos\theta} \right) \right\}, \tag{2}$$

where α is the active medium absorption coefficient; η is the power transfer efficiency (part of the absorbed pump power that generates heat); P is the pump beam power; w_0 is the pump beam half width; p is the order of the hyper-Gaussian profile; $d_{\mathrm{Nd:YAG}}$ is the thickness of active medium slab; terms z_{i}, x_{i} are the transformed coordinates for the incident pump beam; z_{r}, x_{r} are the transformed coordinates for reflected pump beam; θ is the pump beam reflection angle. The interfaces between the composite slab and cold plates are set to be in perfect thermal contact (heat flux is continuous). Outer surfaces of cold plates have constant temperature T_0. Other outside boundaries are assumed heat isolated. Pump radiation is absorbed only in doped Nd : YAG layers where all heat is generated.

Temperature distributions inside a composite slab structure have been calculated for two cases: for optimised absorption in a doped layer (Fig. 10a) and for parameters of a composite slab used in the experiments (Fig. 10b). In both cases the total pump power was 100 W, the heat sink temperature was 16 °C, and the thickness of the indium layer was 0.1 mm. Absorption coefficients have been chosen to represent optimised conditions (29 % absorption after one bounce) and twice higher absorption (49 % absorption after one bounce) to simulate the parameters of a composite slab that was used in the experiments. As would be expected, in the latter case the maximum temperature is higher (30 °C compared to 24 °C) and the difference between maximum temperatures in active zones is bigger (9 °C compared to 2 °C). It can explain why detuning of the pump wavelength (thus reducing the effective absorption) improves the laser performance. The temperature distribution around active zones should manifest itself in the form of a thermal-lensing effect which was also observed in experiments.

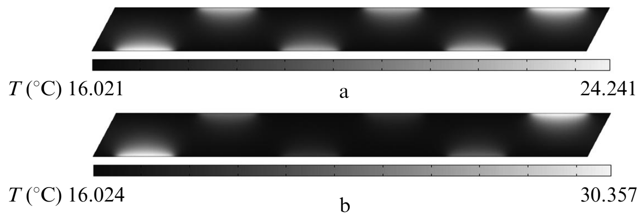

Figure 10. Temperature distribution in a composite slab under optimised conditions (a) and twice higher absorption (b). Cooler temperature and pump power are the same for both cases.

6. Conclusions

We have presented and analysed the concept of a collinearly pumped multiple thin disk active element. Two approaches to realisation of such a system have been presented. Preliminary lasing experiments with multi-disk elements have shown a linear increase in the output power except the case of a double pump beam pass configuration. Power limitation in the double pump pass configuration is caused by a spectral shift of the laser diode wavelength from the wavelength corresponding the maximum absorption by impurity ions as the unabsorbed pump beam is coupled back to the laser diode. The experiments with composite slab elements have shown high requirements imposed on cooling and need for optimisation of absorption in active layers. We have also presented numerical simulations for the temperature distribution inside a composite slab. The first experiments with multi-disk configurations have shown that this technology is promising in creating solid-state lasers with a high average output power, good beam quality and good spatial beam profile.

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