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Efficient multiple-longitudinally diode laser pumped Nd: YAG slab laser

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The operation of an eightfold longitudinally diode laser pumped 1.06 μm cw Nd: YAG slab laser is demonstrated. The 809 nm diode radiation is focused through a dichroic coating into each laser channel starting from the reflection points of the 1.06 μm beam in the slab crystal. At an absorbed pump power in the crystal of 2830 mW a maximum cw TEM_{00} output of 1075 mW was achieved with a corresponding slope efficiency of 42.5%.

1. Introduction

Conventional flashlamp pumped Nd: YAG lasers allow optical efficiencies in the range of a few percent [1]. Due to the improved spectral and geometrical overlap of diode pumped solid state lasers [2] much higher efficiencies can be obtained. Recent improvements of diode lasers in view of output powers and operational lifetimes [3] encourages the development of high power diode pumped solid-state lasers. The present research activities are concentrated on three different pump geometries.

High power output in the range of kW is possible with transversally pumped rod or slab systems in multimode operation. An optical slope efficiency of 54% for a pulsed system in multimode operation has been reported in [4]. In the fundamental mode the efficiency is much lower because of the poor mode matching of pump and laser beam.

In contrast highly efficient conversion to fundamental mode radiation can be realized with end-pumped systems due to excellent spatial mode matching. A slope efficiency close to the quantum limit has been achieved in [5]. In [6] a 15 W cw Nd: YAG laser pumped by four 10 W diode lasers was demonstrated. With this geometrically multiplexed end-pumped rod an optical slope efficiency of 60% was measured in multimode operation. In the fundamental mode the highest output power decreased to about 6 W. However, scaling possibilities of these configurations are limited as only a small number of pump sources can deposit their energy within the desired volume of the laser rod [5].

Longitudinally scaled multiple end-pumped systems promise to be a successful approach to achieving higher output powers in fundamental mode. At the present time there exist basically two concepts of scaleable high power laser systems with high efficiencies.

In one configuration the gain medium is divided into several discs [7]. With this arrangement a slope efficiency of 34% has been achieved. The mechanical complexity of this system prevents a precise alignment of the discs, which is essential to achieve high efficiencies [8].

The other concept is a longitudinally multiple end-pumped slab laser. In one approach a slab crystal was *quasi* longitudinally-pumped by three 10 W diode bars in a tightly folded

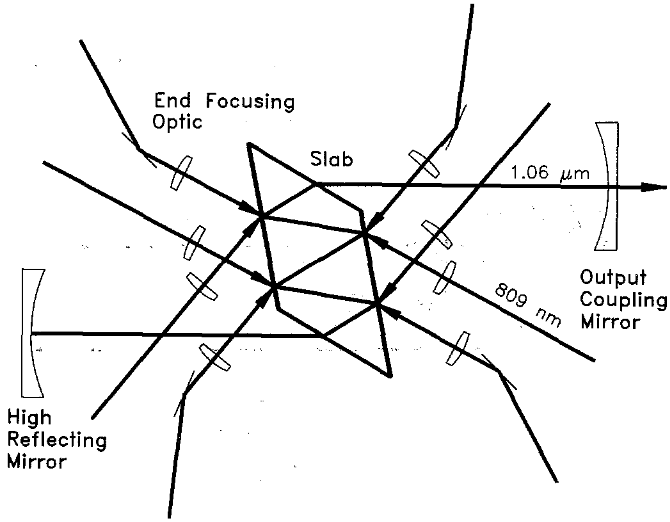

Figure 1 The slab configuration. The coated surfaces (length 29 mm) are highly transmitting (>95%) for the 809 nm pump wavelength and highly reflective (>99.95%) for the 1.06 μm laser beam. To minimize reflection losses the other two surfaces (length 23 mm) are cut in Brewster's angle relative to the resonator axis. For technical reasons four of the 809 nm pump beams are diverted 34° by a mirror.

resonator [9]. A maximum TEM_{00} output of about 10 W was achieved with an incident pump power of 27 W. With a threshold of 3 W this resulted in a slope efficiency of 42%.

In another experiment [10] a four-times diode pumped system has been presented. At the reflection points of the 1.06 μm beam both channels are pumped. The diode radiation is focused into the channel by farfield imaging. An output power of 675 mW TEM_{00} was measured at a diode power of 2 W, the achieved slope efficiency amounted to 40%. This system was a low scale model for basic investigations.

However, all these multiple longitudinally pumped systems were at most pumped by four diodes [9, 10], or the handling was unpractical [7]. To obtain higher power with good efficiencies the total incident power has to be scaled. This can be realized either by increasing the output power of the diodes, or by increasing the number of pump sources. As a step to higher power we demonstrate the scaleability of the system mentioned in [10]. This is realized by increasing the number of reflection points of the 1.06 μm beam in the slab up to four. Compared to [10] the number of pump sources is doubled and twice as much incident pump power is available.

We also present some basic calculations of beam divergence and power extraction efficiency. The results are compared with the experimental values. Operation of this system gives insight into the laser characteristics and adjustment requirements of the eightfold longitudinally diode pumped slab geometry.

2. Experimental set-up

The experimental arrangement is shown in Fig 1. Two sides of the slab crystal are cut in Brewster's angle to minimize reflection losses. The other two sides are coated with a recently developed new dichroic coating with minimized reflection loss of the 1.06 μm laser beam. This coating is highly reflective (>99.95%) for the π-polarized 1.06 μm laser beam and highly transmitting (> 95%) at the σ-polarized 809 nm pumping wavelength. The 1.06 μm laser beam is reflected twice on each coated surface. At each reflecting point the beam is pumped in both directions by 809 nm diode lasers. We therefore obtain an eight times longitudinally diode pumped slab laser. This configuration allows a compact set-up.

We used Siemens diode lasers SFH 48 E1 as pump sources, with a specified output power of 500 mW. A four-element containing optic was used to perform a farfield imaging of the diode radiation into the 1.06 μm laser channel. Three lenses immediately at the diode array serve to shape the pump laser emission to a beam with divergence < 2°, whereas the fourth lenses shown in the figure are used as end-focusing optics in front of the crystal. For technical reasons four of the pump beams are diverted 34° by a mirror, and the end-focusing lenses are cut on both sides. These mirrors reflect 87% of the pump beam. With all these modifications this leads to a transmission of the focusing system of 75% on average.

In comparison to [10] the crystal size was scaled up by a factor of three to attain four reflections of the 1.06 μm beam at the coated surfaces. It is a 1.1 at.% Nd^{3+} : YAG with dimensions $29 \times 17 \times 5\,mm^3$. The total path length in the crystal is 75 mm consisting of twice 10.4 mm at the end parts and three times 18.1 mm in the central parts. A path length of 9 mm is required for 99.9% absorption of the incident 809 nm pump power. Hence a complete absorption of the pump power in the crystal can be assumed. The bottom surface of the crystal is in contact with a heat sink at room temperature.

The symmetric stable type resonator was formed by two mirrors with 150 mm radius of curvature, one of them being a high reflector. Assuming Gaussian beams the calculated effective resonator length in the horizontal direction is 250 mm. As the slab crystal is positioned at Brewster's angle the corresponding value for the vertical direction is 280 mm. The effective resonator length difference of 30 mm provokes an elliptic laser mode which results in a beam waist 138 μm in the horizontal and 112 μm in the vertical direction. The corresponding divergences at half angle are 2.45 mrad in the horizontal and 3 mrad in the vertical direction. The cofocal range in the vertical direction is equal to the path length in the crystal.

3. Experimental results

3.1 Input–output

Figure 2 shows the 1.06 μm output power versus the absorbed 809 nm pump power for two different values of the output coupling transmission T. For $T = 5\%$ a maximum 1.06 μm output power of 720 mW was achieved with an absorbed diode pump power of 2.2 W in the crystal. The absorbed threshold pump power amounted to 170 mW. The linear fitted value for the slope efficiency is 36.5%. For $T = 10\%$ the output power was 830 mW at the same pump power with a slope efficiency of 42.5%. For $T = 15\%$ a slope efficiency of 42% resulting in smaller output powers was achieved. For $T = 10\%$ the achieved output power increased to 1075 mW for an absorbed pump power of 2830 mW. The deviation from linear polarization was less than 1.8×10^{-3}.

A plot of the threshold power versus output coupling for four different mirrors following [11] is given in Fig. 3. The total internal losses according to the diagram are about 5.1%. They consist of transmission losses of the 1.06 μm laser beam at the coated surface, reflection losses at the Brewster's surfaces, scattering losses in the crystal and the coating and reabsorption losses of the 1.06 μm laser beam in the crystal. A precise analysis of these different losses is given in Section 3.3.

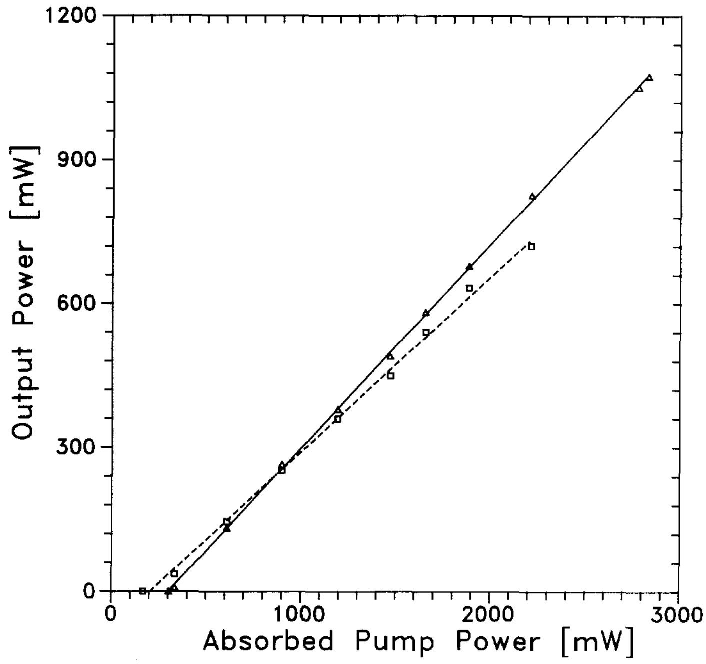

Figure 2 1.06 μm output power versus absorbed pump power for two different output coupling mirrors. For T = 5% a slope efficiency of 36.5% was achieved. The largest value of 42.5% was obtained with T = 10% (——△——) T = 10%. (—□—) T = 5%.

3.2. Beamprofile and divergence

Following [12] the derived beam divergences influenced by the mirror outside the resonator are 3.5 mrad in the horizontal and 4.4 mrad in the vertical direction. The intensity of the output beam was measured in the horizontal and vertical direction at three different distances from the resonator, with an output power of 440 mW. For each position the deviation from a Gaussian beam was less than 1%. The 1.06 μm laser beam emerges from the output coupler with a fitted half angle divergence of 2.9 mrad in the horizontal and 3.1 mrad in the vertical direction, with deviations of less than 10%. So we can say the resonator emits in a slightly elliptical fundamental mode. The beam profile at a distance of 680 mm from the middle of the resonator is given in Fig. 4.

The measured compared to the calculated divergence is 15% lower in the horizontal and 30% lower in the vertical direction, respectively. This is probably due to the thermal lensing described in [13, 14]. A detailed analysis of this influence will be the subject of a future investigation.

3.3. Losses in the crystal

The total round trip losses in the crystal amount to 5.1%. The total 1.06 μm losses at the reflection points on the coated surfaces and the Brewster reflections on the uncoated end surfaces of the slab equals 0.1% of the total internal intensity in the resonator. Scattering and reabsorption losses in the crystal bulk can be assumed to be approximately 1%. The remaining 4% of the total losses are presumably due to scattering in the coatings. To confirm this assumption four reflections in air under the corresponding angle at two coated

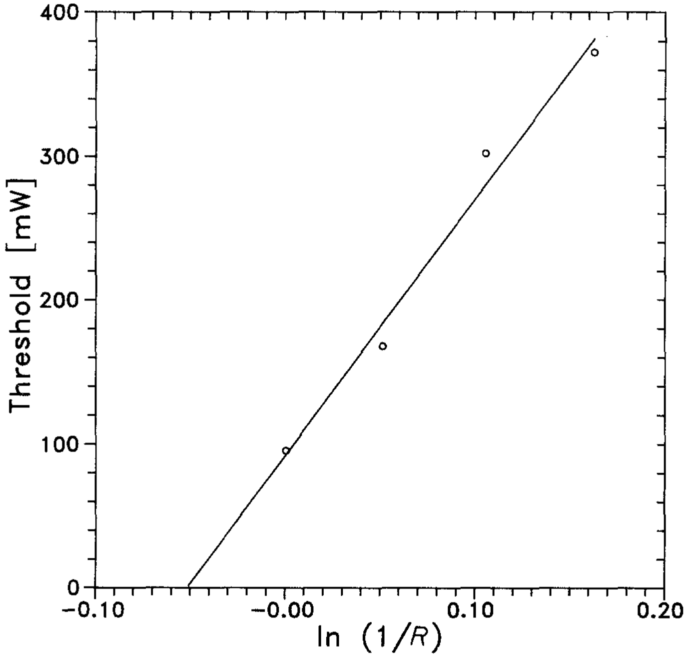

Figure 3 Absorbed threshold pump power versus ln(1/*R*). According to the diagram the total internal losses amount to 5.1%. They can be divided into scattering losses in the coating (≈4%), reflection losses on the coating (≈0.1%) and scattering and reabsorption losses in the crystal (≈1%).

surfaces have been realized with two equal crystals outside the resonator. The measured losses in the coating amounted to about 2%. So the coating produces the main part of 4% of the total internal round trip losses. By a microscopic inspection of our crystal compared with the one used in [10] our coatings revealed a large number of small spots. These spots are assumed to be scattering centres and produce losses in the coating.

4. Discussion

The maximum output power of 1075 mW was achieved for $T = 10\%$ at an absorbed input power of 2830 mW. This leads to an overall optical efficiency of 38%. The total losses in the crystal amounted to 5.1%. These values should be compared with those obtained in [10]. In this arrangement an output power of 685 mW was achieved, with an absorbed pump power of 1800 mW, corresponding to an optical efficiency of 38% with resonator losses of 1%. Following [15] and assuming a constant unsaturated gain coefficient along the path in the crystal the configurations are compared in view of power extraction efficiency. The system described in [10] theoretically would have allowed a power extraction efficiency of 0.65. The experimentally achieved value was 0.38. Therefore 58% of the theoretical value was obtained.

Due to the larger losses of 5.1% in the crystal of our eightfold pumped system the theoretical obtainable power extraction efficiency decreases to 0.55 with an optimum reflectivity of the output coupler of 0.91. In our experiment with an output coupler of 0.90, 0.38 was measured as the highest efficiency. Hence in our system 70% of the theoretically obtainable efficiency is achieved. However, in both systems at most 70% of the theoretically

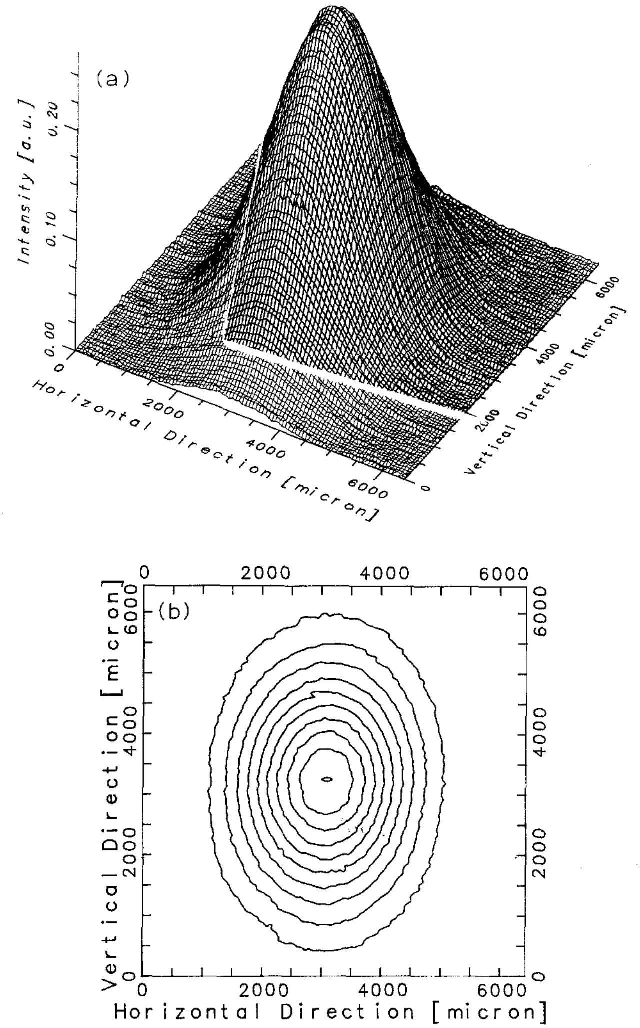

Figure 4 (a) Three dimensional plot of the beamprofile at a distance of 680 mm from the centre of the resonator. (b) Topographic plot of the same beamprofile. The step between two successive lines is 10% of the relative maximum intensity.

obtainable efficiency is achieved. Our optics perform farfield imaging and produce a convexity dip in the middle of the intensity distribution at the focus. Thus the geometrical overlap of pumped volume in the crystal and the laser mode is incomplete and only a part of the pump intensity can be transformed into output intensity of the TEM_{00} 1.06 μm laser beam. Therefore the main part of the deviation from the theoretically obtainable power extraction efficiency can be identified as incomplete spatial mode matching. A comparison between a scanned diode pump beam and a calculated fundamental mode pump beam for a single longitudinally end-pumped rod will be presented in [16]. This is a numerical simulation and confirms the difference in our results between the theoretically obtainable and the achieved efficiencies.

With the system reported in [10] a maximum output power of 675 mW at an absorbed pump power of 1.8 W was achieved with 95% efficient coupling optics. In an eightfold pumped system twice as much pump power, 3.6 W, should be available. Assuming the same resonator characteristics the output power would be 1.45 W.

In our realized eightfold pumped configuration the output power was lower because of larger losses. The main part of the resonator losses are due to the coatings on the crystal which have an excellent reflectivity but also a large number of scattering centres. This is a technical problem and better coatings with smaller scattering losses should be attainable. Also the average losses of 25.5% of the endfocusing optics could be minimized. With optimized imaging optics at least 90% of the pumping radiation should be transmittable and the largest absorbed pump power in the crystal would increase to 3.4 W. With crystal losses of 2% this would lead theoretically to a power extraction efficiency of 0.63. With the same spatial mode matching this efficiency would decrease to 0.44 resulting in a maximum 1.06 μm output power of 1.5 W, which was expected from this system.

The calculated difference in efficiency [16] and the good agreement between the theoretical and experimental values for the optimum output coupling factor in our system confirms the possibility of application of the model described in [15] as a useful approximation. Because of thermal problems in many systems the operation in the fundamental mode is limited in power [6, 14]. In our system eight pump sources deposit their energy in four different points at the crystal surface. With a maximum pump power of about 3 W and a heat removal through the bottom of the crystal, thermal effects did not disturb the fundamental mode oscillation characteristics of our system. Thermal lensing is expected to reduce the ellipticity of the beam, given by Brewster's angle entrance faces of the slab crystal. As the 1.06 μm laser emission was a reduced elliptical TEM_{00} mode, this expectation is verified.

5. Conclusions

We have shown the scalability of multiple end-pumped Nd: YAG slab lasers up to eight diode laser pump sources. The scaling did not provoke any other problems in view of alignment and thermal effects. At 2830 mW pump power a 1.06 μm laser output of 1075 mW TEM_{00} resulting in a slope effiency of 42.5% was obtained. The present system suffers from non-optimized spatial mode matching and losses in the coatings. In a future system the scaling of the pump power of the diode lasers and the corresponding thermal behaviour of the system will be investigated.

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