62-W cw TEM_{00} Nd:YAG laser side-pumped by fiber-coupled diode lasers

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Received September 20, 1995

We describe the laser performance and thermal properties of side-pumped Nd:YAG rod lasers that use fiber-coupled diode lasers as pump sources. Utilizing a nearly homogeneous pump light profile, we realize an output power of more than 60 W in TEM_{00} mode operation with optical-to-optical efficiencies of more than 25%. In multimode operation, optical slope efficiencies of more than 46% are observed.

Diode-pumped solid-state lasers operating at high cw power levels are attractive sources for various applications in materials processing and nonlinear frequency conversion. The most efficient high-power laser systems are realized in end-pumped configurations.[1,2] However, end-pumped single laser head configurations are not scalable to TEM_{00} mode output powers beyond 30 W.[1,3] Therefore transverse excitation has to be applied for an appropriate power scaling.

Commonly, bare diode laser arrays are used as pump sources in side-pumped systems that fulfill certain requirements in terms of reliability and efficiency.[4–9] However, the laser head design of these systems is highly sophisticated. Diode lasers, focusing optics, electrical connectors, and coolants for the diode lasers have to be placed in the laser head. As a result, it is mechanically complicated to replace single diode lasers in the pump assembly. Further, because of the large-sized dimensions of the linear diode laser arrays, power scaling by increasing the pump power per rod length is difficult to realize. All these complications can be avoided by use of fiber-coupled diode lasers. There is only a bundle of optical fibers attached to the laser head. This permits a nearly free adjustment of the pump light distribution inside the laser active medium and linear pump power densities of several hundred watts per centimeter.

For side-pumped slab laser systems using fiber-coupled diode lasers, the TEM_{00} mode output powers are now limited to approximately cw 40 W.[10] The slab laser geometry reduces thermally induced effects, but, in general, asymmetric and astigmatic output beams are produced. Further mounting and fabrication of slab crystals are difficult and expensive. Therefore we decided to use rod lasers side-pumped by fiber-coupled diode lasers within a simple design and small laser head size. Utilizing uniform pump light distributions, these side-pumped rod lasers permit high output powers with excellent beam quality. In this Letter we report the operation of diode-pumped Nd:YAG rod lasers at TEM_{00} mode output powers of more than 60 W cw.

The experimental setup of the rod laser system is shown in Fig. 1. The pump arrangement permits linear pump power densities up to 150 W/cm, considering the effectively pumped rod length of 32 mm. The Nd:YAG rod (length 56 mm, diameter 4 mm, Nd-doping level 0.9 at. %) has a polished barrel that reduces the scattering losses for the pump light. The end faces of the rod are antireflection coated at 1064 nm. For direct water cooling the laser rod is mounted inside a flow tube, which is antireflection coated at 808 nm. The optical pump source consists of fiber-coupled diode lasers (Jenoptik Laserdiode) with a nominal output power of 10 W each at 808 nm. The pump radiation is delivered via fibers to the Nd:YAG laser head. The optical quartz fibers have a core diameter of 800 μm, a total diameter of 1.5 mm, and 0.22 N.A.

Each pump module consists of 16 fibers (see Fig. 1). The fibers are mounted side by side with a spacing of 0.5 mm. The pump modules are arranged in a threefold symmetry around the laser rod, giving a total available pump power of approximately 370 W. The diode laser radiation directly irradiates the laser rod without any additional focusing optics. The spacing d_{f-f} (see Fig. 1) between the fiber ends and the flow tube can be varied from 0.5 and 20 mm.

For sufficient absorption of the diode-laser radiation, pump light reflectors are mounted around the rod.[11] Nearly 340 W of the total pump power are absorbed because of the double pass of the radiation in the laser rod.

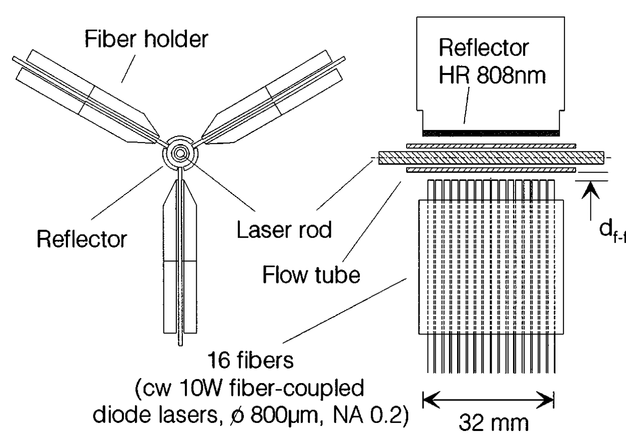

Fig. 1. Laser head side-pumped by fiber-coupled diode lasers. The linear pump power density is 150 W/cm.

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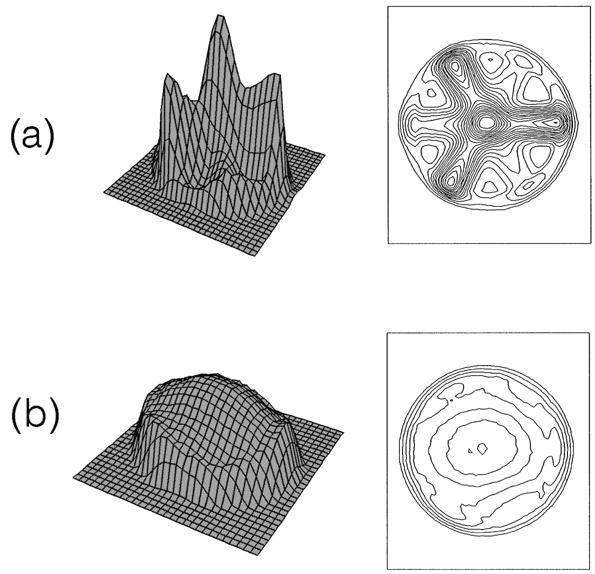

Fig. 2. Measured pump light distributions for fiber-to-flow-tube spacings of (a) 1 mm and (b) 13 mm.

To minimize the thermally induced effects for efficient TEM_{00} mode operation we investigated the pump light distribution in the laser rod by imaging the fluorescence at 1064 nm onto a CCD camera for different fiber-to-flow-tube spacings. For these measurements, only a small cross section in the laser rod was excited by three fiber-coupled diode lasers. To determine the influence of the pump light distribution on thermo-optical effects, we measured the focal length of the thermally induced lens while the Nd:YAG laser operated in an asymmetric, flat–flat resonator. We evaluated the focal length by varying the position of one resonator mirror and determining the separation between the mirror and the principal plane inside the laser rod when the output power significantly decreases. This separation corresponds to the focal length. Figure 2 depicts the pump light distributions for two fiber-to-flow-tube spacings. Short fiber-to-flow-tube spacings cause inhomogeneous pump light distributions with a high gain on the center axis of the rod. While a pump power of 370 W is applied, a focal length of ~14 cm is measured for a 1-mm distance between fiber ends and the flow tube. The focal length is increased to 21 cm for a spacing of 13 mm. This reduction of thermally induced effects is due to a more uniform pump power deposition for greater fiber-to-flow-tube spacings and to the resulting almost parabolic temperature distribution inside the laser rod.

Despite the large fiber-to-flow-tube spacings the normalized fluorescence intensity at 1064 nm and the laser output power in multimode operation stay nearly constant. Figure 3 shows the multimode output power as a function of the fiber-to-flow-tube spacing. For small spacings the output powers are low because of high thermally induced optical aberrations. A maximum multimode output power of more than 160 W cw and an optical slope efficiency of 46% are obtained for a pump power of 370 W, corresponding to a spacing of 7 mm. The observed efficiencies are comparable with those obtained for end-pumped systems.[1]

Because of the reduced thermally induced effects, large fiber-to-flow-tube spacings are preferable for high beam quality and TEM_{00} mode operation. Unlike for earlier end-pumped systems,[1] no additional components for correction of thermal distortion, such as intracavity aspheres, have to be inserted into the resonator, because the profiles of the temperature distribution and the optical path difference are nearly parabolic. For efficient and reliable TEM_{00} mode operation we designed linear flat–flat, dynamically stable resonators for a focal length of 21 cm (fiber-to-flow-tube spacing 13 mm) that are stable against both focal-length fluctuations and misalignment.[12] As a consequence, the highly reflective mirror is placed at a distance of 78 cm from the principal plane of the laser rod; the output coupler is 22 cm from the other principal plane. This configuration yields a TEM_{00} mode spot size of approximately 1.4 mm inside the laser rod. The mode spot size is nearly constant for pump power variations of $\pm 10\%$. When this resonator is applied it is not necessary to use any aperture for suppressing higher-order modes. At a pump power of 370 W a TEM_{00} mode output power of more than 62 W cw is generated, which to our knowledge is the highest reported TEM_{00} mode output power for a single laser rod. The corresponding optical-to-optical efficiency is 17%. The beam parameter product is measured with a laser beam analyzer and is less than 1.2 times diffraction limited.

Further theoretical investigations of high-power TEM_{00} mode operation indicate that uniformity of the pump light distribution and the applied pump power density are key points for an enhanced efficiency. The excitation of a laser rod from many sides leads to a more homogeneous pump light distribution, so optical aberrations are minimized. Moderate linear pump power densities also favor efficient TEM_{00} mode operation. The average temperature inside the laser rod is reduced, yielding a negligible population of the lower laser level. Further, because of the temperature dependence of the thermal conductivity in Nd:YAG, low average temperatures are important if we wish to approach a nearly parabolic temperature distribution,[13] which results in minimal aberration-related losses and permits a larger spatial overlap between the TEM_{00} mode and the pumped volume. As a

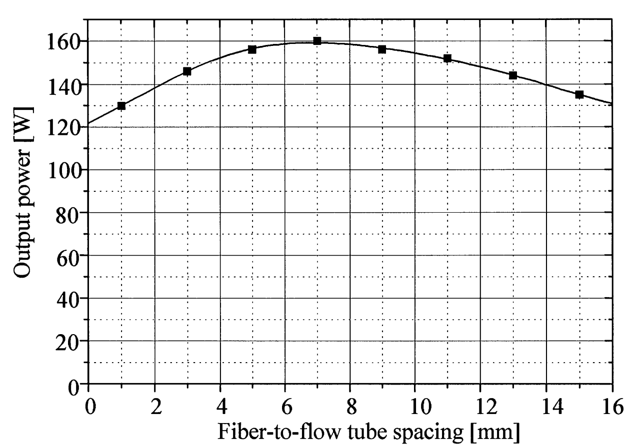

Fig. 3. Multimode output power from the cw diode-laser-pumped Nd:YAG laser versus fiber-to-flow-tube spacing at a pump power of 370 W.

consequence, in a fivefold pump scheme with 13-mm fiber-to-flow-tube spacing, optical-to-optical efficiencies of more than 25% in TEM_{00} mode operation are realized. This corresponds to an output power of 61 W with 240 W of pump power and 120 W/cm of linear pump power density.

With the assumption of uniform pump light distributions, multimode output powers of these rod laser systems near 1000 W cw seem to be possible. To evaluate the power scaling possibilities, fiber-coupled diode lasers with pump powers of more than 2000 W will be applied in our systems currently under development. Power scaling in TEM_{00} mode operation will probably be limited by strong thermal lensing at pump powers of more than 500 W and by the resulting sensitivity of the resonator to pump power variations. Therefore TEM_{00} mode output powers for a single laser rod in the range 100–150 W will be achievable. For further power scaling two laser head configurations have to be considered.

In summary, a diode-laser side-pumped 160-W cw Nd:YAG laser with an optical slope efficiency of 46% and an overall electrical efficiency of more than 8% has been demonstrated. Although the losses owing to the coupling of diode-laser radiation into optical fibers have to be considered, the efficiencies have been substantially increased compared with those for the previously reported side-pumped Nd:YAG laser.[4] The enhanced efficiencies are even more evident for TEM_{00} mode operation. Output powers of more than 60 W have been described, with an optical-to-optical efficiency of more than 25%. Uniform pump light distributions, moderate linear pump power densities near 100 W/cm, and increased laser rod cooling can significantly improve the laser performance in TEM_{00} mode operation. These devices are well suited for efficient second-harmonic generation with expected output powers of several tens of watts in diffraction-limited beam quality. Investigations now in progress have delivered cw output powers of more than 10 W at 532 nm.

This research was supported by the German Ministry of Science, Education, Research and Technology under contract 13 N 6361.

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