Laser Original**Analysis for Pumping Geometries of LD Side-pumped Solid State Lasers**

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Excited power distributions of an LD side-pumped Nd-YAG laser were examined using a geometrical model. Our calculated results were found to agree with those obtained in the experiments. The excited power distribution in a rod and the beam quality of the YAG oscillation were depending greatly on the geometrical position of the LD laser. Based on our model, multi-fold pumping geometries were also discussed.

Key Words: LD pumped YAG laser, Pumping geometry, Analysis.

1. Introduction

Since solid state lasers pumped by GaAlAs diode laser arrays have demonstrated high efficiency and high reliable oscillation, they are currently interested in constructing a compact system, including a power supplier, a coolant circulator, optics and so on. Increasing the peak power and improving the beam quality of LD pumped laser can provide wider applications of the solid state lasers with high resolutions in sensing systems. Thin wire detection using a high peak power solid state laser is one of our interested applications as well as the remote sensing. On our interested applications, high power laser means the output power level is around several watts in high repetition rate Q-switching operation mode at about 10 KHz. To our knowledge, these output levels are classified as so-called high power solid state lasers.

To produce high power output from LD

pumped solid state lasers, the pumping geometry used to couple the diode array output to the laser material must satisfy two important conditions. Efficient absorption and high beam quality. End-pumped lasers have been limited to the output at rather low power levels because of limited diode pump sources¹⁾. Side pumping is one of the most promising methods obtaining higher power coupling to the laser rod. However, it results typically either low efficiency or poor beam quality, while some works were made to generate uniform pumping distribution²⁾. Uniform pumping is not always the best way to oscillate the output with high beam quality. Some optimization of optical arrangements should be required to solve these problems.

In this work, we analyze excited power distributions in the rod using a geometrical model, based on the experimental measurements of the fluorescence from the LD side pumped Nd-YAG laser. And also we will discuss multi-fold pump-

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ing geometries.

2. Analyzing Method and Measuring the Fluorescence Patter

First we developed the simple geometrical model to analyze the excited power distribution in the rod. In this model, propagation of LD laser output through the medium are assumed to be described by usual ABCD matrices and the output power from the LD array is to be absorbed according to Beer's law. Since the LD array emits the output power with near Gaussian distributions in the X axis and also with top flat like distributions in the Y axis, simultaneously. We can deal with the pumping beam as the single Gaussian distribution in our calculations along X axis shown in Fig. 1. YAG rod are set to receive the output power of LD array laser from its wall, so called as the side pumping configuration. In this model, the YAG rod has polished walls partially covered with AR coatings and with HR coatings dependently on the part of the entrance and the opposite side of it for the front face to the LD side due to the efficient couplings to the rod.

The excited power distributions in the rod were analyzed as followed. First we calculated the beam waist as a function of the position along the propagation direction (z axis). The beam comes out from the LD array with a very small spot size, diverging its waist along the z axis,

Fig. 1 Arrangement of the YAG rod pumped with an LD array laser.

facing the YAG rod surface and then entering the rod without reflection losses. The beam is refracted in many ways before it reaches the opposite inner surface of the YAG rod, which reflects it back toward the entrance. Finally the beam goes out from the entrance surface. With ABCD matrices, various kind of optical arrangements could be available to be analyzed, consisting of some kind of lenses and so on. After completing the calculations of the beam waist in the rod, the excited power distributions are calculated. We divided the rod into small parts, for example counting them up to 1×10^5 pieces, to apply the Beer's law to calculate the absorbed power in these small fractions, because the simple Beer's law is available in the case of the uniform plane wave. When the beam expands a little bit along the propagation axis, the power density of the beam decreases, even without losses. Therefore, avoiding this apparent decreasing of the power density, the absorbed power density are calculated in the small area where the beam waist can be treated constant and then integrating the whole absorbed power in that area.

This model could also describe multi-fold pumping based on the above single LD pumping geometry, where some number of LD lasers are used as pumping sources for a YAG laser. In the case of multi-fold pumping geometries, we rotate the excited power distribution at certain angles to add to the original one, after calculating the excited power distribution using a single LD pumping configuration.

The independent parameters for the calculations at the moment are the rod diameter, the distance between the rod surface and the LD emitting tip, the absorption coefficient of the rod, the number of the LD lasers for pumping and also the azimuthal angle to the YAG rod axis for rotation. We did not take some lensing system for focusing the beam into account although

Fig. 2 Setup for measuring fluorescence patterns from the YAG rod pumped with an LD array laser.

lensing system could be considered in our model, which makes the model simple.

Second we measured the fluorescence pattern at $1.06 \mu\text{m}$ in the Nd:YAG rod with 1.1 atm.% concentration, having 4 mm in dia. $\times$ 10 mm in length. GaAlAs LD emitting the wavelength of $0.809 \pm 0.3 \mu\text{m}$ (Spectra Diode model 3490s) at max. rated output power of 10 W is used as the pumping source for Nd:YAG laser. Figure 2 shows the experimental set-up schematically. To stabilize the output wavelength of the LD array laser, we control the temperature at the emitter's tip with accuracy of about 0.1°C using Peltier devices. The fluorescence patterns are measured with CCD camera viewing from the front end of the rod located at a suitable position. Some suitable filters eliminates the images having different wavelengths such as LD's and other's. Fluorescence patterns reflect the excited distributions of Nd^{3+} ions in the rod pumped by LD lasers, those can be regarded as the excited power distribution inside the YAG rod. To prevent the image faded due to integration effects along the YAG rod axis (Y axis), we set the LD emitter as near to the front end of the rod as possible. As the images of YAG fluorescence patterns are stored in the monitoring system based on the micro

computer, we can analyze the obtained data with a commercially available image processing software in terms of the intensity distribution, the cross sectional view of the intensity and so on. Since the present monitoring system has no sufficient capability to create high resolution of the intensity distribution, we take a sensitive photograph of the image appeared on the monochromatic display. All of our measured were conducted after the system had reached to thermal steady conditions during our experiments.

3. Results and Discussions

Figures 3a and 3b show photographs of measured fluorescence patterns at $1.06 \mu\text{m}$ as a function of the distance, at 0.2 mm and at 3 mm respectively, between the LD emitting tip and the YAG surface wall. The excited power distribution changes steeply as the distance increases due to the lens effects of the outer surface of the laser rod. This tendency suggests that the laser output from the YAG laser has less beam quality, reflecting these nonuniformity in the excitation. In fact, Figure 4 shows the beam pattern of the YAG laser output pumped by the LD laser with similar pumping configurations as in the Fig. 3. Of course, because the intensity distribution of the laser output should be affected by the cavity configurations, the intensity distribution shown in Fig. 4 could not conform to the same intensity distributions of the fluorescence pattern from the YAG rod in Fig. 3. It is clear that non symmetric distribution of pumping in the rod could not make the output beam having high beam qualities. Figure 4 points out the necessity of optimizing the pumping arrangements.

Figure 5 shows calculated results using our model mentioned before with the absorption coefficient of 0.32 cm^{-1} of the YAG rod. This absorption coefficient is the one obtained

Fig. 3 Measured intensity distributions of the fluorescence from a Nd : YAG rod of 4 mm in diameter. a: LD emitter located 0.23 mm apart from the laser rod surface; b: LD emitter located 3 mm apart from the laser rod surface.

Fig. 4 Typical beam pattern of the YAG laser pumped with an LD array laser.

experimentally, which averages over the LD's emitting wavelength. This is almost the same value quoted in Ref.3. Calculated parameters are made equally to the experimental values.

Comparing excited power distributions shown in Fig. 3 with in Fig. 5, our calculated results are found to agree well with those obtained in the experiments. Modeling of the present optical coupling configuration yields a predicted absorption of about 90 % of the incident pump power by the 4 mm dia. YAG laser rod, which is in agreement with the measured one. Since the diode

power is absorbed exponentially according to Beer's law, high absorption coefficients result in reduced coupling efficiency to the fundamental laser output. A single directional pumping will result in poor pumping distributions.

To produce high beam quality of the output from the side pumped laser, the spatial distribution of the absorbed pump power in the rod should be similar to the fundamental Gaussian mode. Thus, multi-fold symmetric star shaped with a central maximum located on the axis of the YAG rod must be required. Up to now, considerable less works has been done to analyze the pumping power distribution from this point of view. Based on the experimental and theoretical results mentioned in preceding, we analyzed the pumping power distribution of 3 and 5 fold arrangements. Figures 6 and 7 show the calculated results. These figures have the same parameters for calculation except the location of LD emitter at 2 mm away from the rod surface as indicated in Fig. 3. These figures lead to the effectiveness of multi-fold pumping schemes to generate the strongly peaked excited power distribution. This, not the uniform distribution,

Fig. 5 Excited power distributions calculated in the YAG rod. a and b have the same conditions as the measured ones.

Fig. 6 Excited power distribution in the rod calculated for 3-fold arrangement.

suggests the possibility to permit efficient coupling of the pumping power to a fundamental mode.

Figure 8 shows the Gaussian fitting to evaluate the excited power distribution in the rod, where calculated conditions are the same as in Fig. 6. Symmetric top shape of the excited power

Fig. 7 Excited power distribution in the rod calculated for 5-fold arrangement.

distribution along the center of the LD incident axis are found to agree to the Gaussian shape

Fig. 8 Gaussian fitting for the excited power distribution in the rod with a half width, W_0 , ($1/e$ value) of 1.0, 0.8, and 0.5 mm as parameters. Solid lines and the dashed line show Gaussian curves and the excited power distribution, respectively. The condition of the calculation are the same as those in Fig. 6.

Fig. 9 Power distribution of the excited power integrated on the radial length from the rod axis. The parameters are the same as those in Fig. 6.

with the half width ($1/e$ value) of 0.8 mm around the rod axis. In designing the suitable cavity for this type side pumped LD geometry, we will have to adjust the cavity mode to this above value, resulting high beam output. While the excited power distributions are quite depending on the number of LD emitters, the integrated

powers as a function of the radial length from the rod axis keep the same evolution among them shown in Fig. 9. From Fig. 9, we easily obtain the half integrated power width of about 1.15 mm, which value were usually defined as the beam waist. However, we thought this definition could not be suitable for designing the cavity to produce high beam quality.

In spite of the effectiveness for oscillating high beam quality laser output from the side pumped geometry, there may be some engineering limitations such as installation of each LD lasers with narrowed tips aside when realizing these multi-fold configurations. Sequential rod arrangements like a high power YAG laser pumped by flash lamps will be able to eliminate this spatial limitations.

4. Conclusions

We analyzed excited power distributions in the rod using a geometrical model and compared theoretical results with the experimental measurements of the fluorescence from the LD side pumped Nd-YAG laser. Our calculated results were found to agree well with the experimental results. It is also clearly found that location of LD laser influences quite severely on the excitation power density in the rod and also on the beam quality of the YAG oscillation. Our model is useful for optimizing the configurations of the LD side pumped solid state laser system. Based on our studies, symmetric star shaped pumping geometries become very promising to produce high beam quality output from a LD side-pumped solid state laser. Finally we pointed out that usual definition of the beam waist using the half width from integrated power on the radial length. We will further calculate this side pumping geometry including the thermal effect in the rod and so on.

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