Properties of Diode Laser Pumps for High-Power Solid-State Lasers

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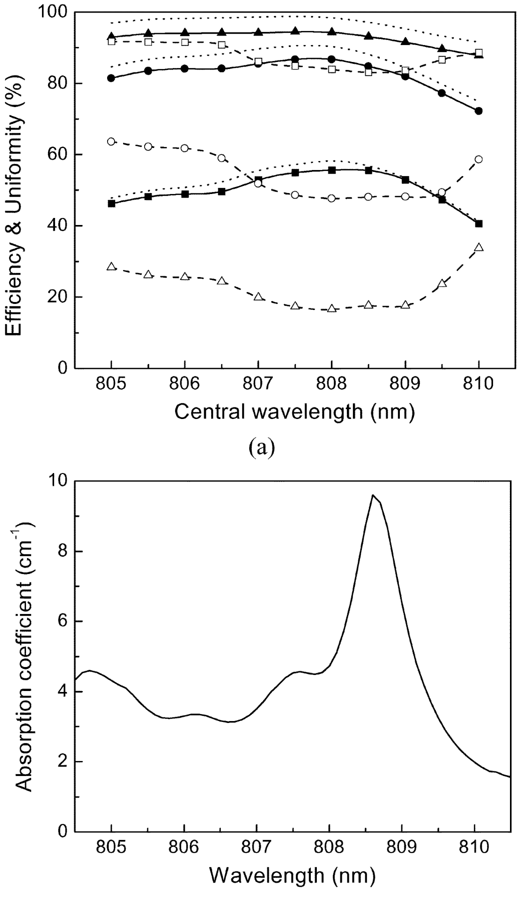
***Abstract*—Diode lasers used to pump high average power solid-state lasers typically have broad spectral width so that most of the pump light is not at the peak of the gain medium's absorption feature. However, the long absorption length in these lasers enables even weakly absorbed light to pump efficiently. The result is that high absorption efficiency and improved pump distribution uniformity are possible when using realistic pump diodes. In addition, both quantities are nearly independent of the pump center wavelength.**

***Index Terms*—Diode-pumped lasers, energy transfer, laser spectroscopy, Nd:YAG lasers, optical pumping, solid-state lasers, Yb:YAG lasers.**

DIODE laser pumped solid-state lasers have been considered, developed and sold for a number of years. In general, these have been either small, low power lasers or side pumped rod-shaped lasers with short paths available in which the pump light could be absorbed. As a result, there has been a concentrated effort to prepare pump sources with narrow lasing spectra or find gain media with wide absorption features. In this paper, we evaluate the use of realistic diode laser pump sources in high average power solid-state lasers. In particular, we examine the results of edge pumping [1] neodymium or ytterbium doped yttrium aluminum garnet (Nd:YAG or Yb:YAG) slab-shaped lasers capable of several kilowatts of output power. The conclusion we reach, that high efficiency and good uniformity are possible using broad spectrum pump diode sources, are applicable to other high average power lasers with long absorption paths such as edge pumped disks and fiber lasers. Our results also provide guidance to diode laser and diode array manufacturers supplying pump sources for high average power lasers.

An edge-pumped slab-shaped laser is one in which pump light enters the slab through each of the mid sized faces, cooling takes place on the two large faces and laser light travels a zigzag path between the large faces to pass through the smallest faces [1]. To obtain high average power performance from such a device the ratios of the width to thickness and length to thickness must both be large (e.g., >10). For good cooling and minimal thermal gradient-induced stress, the thickness must be kept small. Thus, we have previously reported on Yb and Nd:YAG slabs with dimensions 1×16 or 19×80 mm that could reasonably be expected to produce outputs of 3 kW or more [2]. When edge pumping such a slab as described above the absorption length is $\geq$ 16 mm.



(a)

(b)

Fig. 1. (a) Absorption efficiency and uniformity as a function of central wavelength of the pump laser diodes for different concentrations of Nd^{3+} ions in a room temperature, edge pumped, $1 \times 19 \times 80$ mm YAG slab. The diode array was assumed to have the 3-nm FWHM spectral bandwidth measured for a 160-W array in our lab. The squares are for 0.1%, the circles for 0.3%, and the triangles for 0.6% Nd:YAG. The solid lines and filled symbols show the absorption efficiency while the dashed lines and open symbols show the uniformity both calculated using ASAP. The dotted curves show the absorption efficiency calculated using (3). (b) The absorption spectrum of 1% Nd:YAG at room temperature near 808.5 nm.

Pump light with wavelength at the peak of the gain medium's absorption feature will, according to Beer's law, be strongly absorbed near the faces through which it enters the slab. Light with wavelengths differing from the peak absorption will be absorbed but further within the volume of the slab. Both types of light can be efficiently absorbed if the distance available for absorption is long enough—it is the product of absorption coefficient times absorption length that determines how much light is absorbed not the absorption coefficient alone. Furthermore, since different wavelengths are absorbed in different places in the slab

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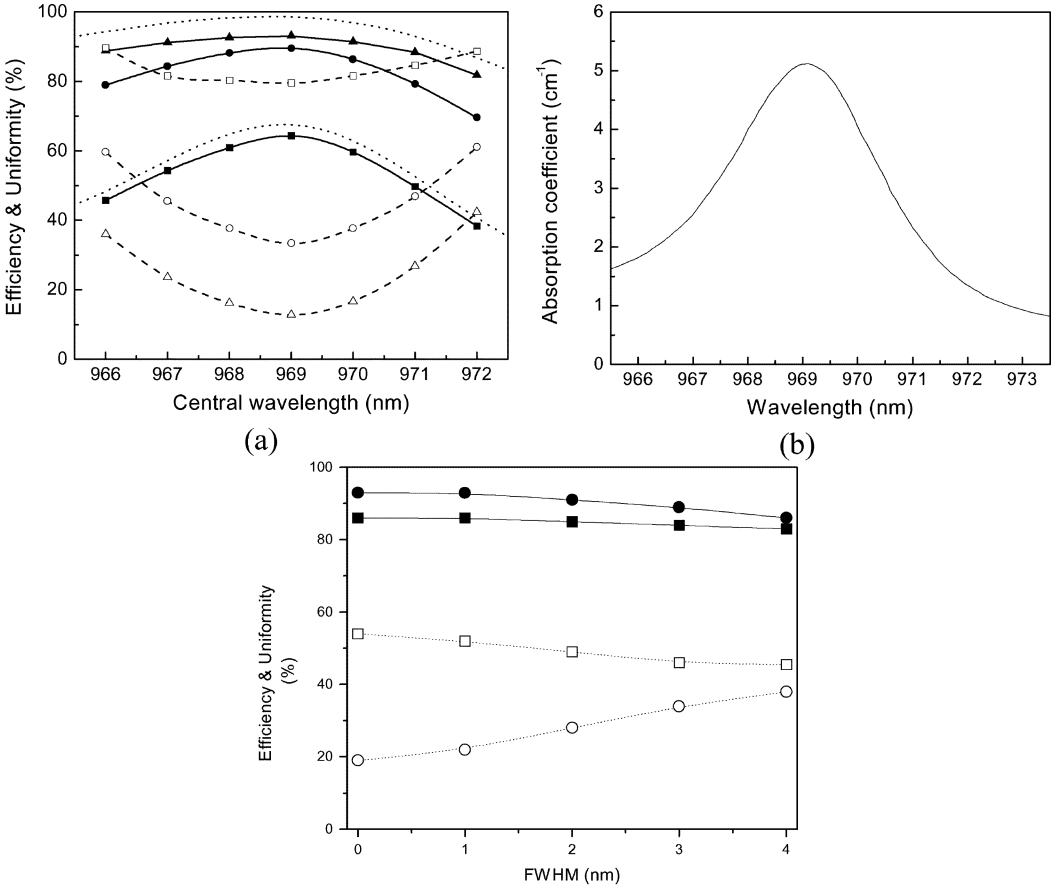

(a) (b)

(c)

Fig. 2. (a) Absorption efficiency and uniformity as a function of central wavelength of the pump laser diodes near 969 nm for different concentrations of Yb^{3+} ions in a room temperature, edge pumped, 1 × 16 × 80 mm YAG slab. The squares are for 1.0%, the circles for 3.0%. and the triangles for 5.0% Yb:YAG. The solid lines and filled symbols show the absorption efficiency while the dashed lines and open symbols show the uniformity both calculated using ASAP. The dotted curves the absorption efficiency calculated using (3). (b) The absorption spectrum of 5 at.% Yb:YAG at room temperature near 969 nm. (c) The efficiency and uniformity for the same slab as a function of diode pump source bandwidth. The solid squares indicate efficiency and the open squares the uniformity for a pump source centered at 967 nm, the solid circles indicate efficiency, and the open circles the uniformity for a source centered at 969 nm.

the distribution of absorbed pump power will be more uniform than if the pump source produced a single-wavelength output. In this paper, we follow the definition of absorbed pump power uniformity given in [1] as the ratio of the pump power absorbed at the center of the slab to that absorbed just inside the input faces.

A simple analytic model for the pump absorption efficiency with a broadband source is instructive. It applies rigorously only to the case of pumping with a plane wave of light and so serves as an upper limit on efficiency that can be obtained since real diode sources are not sources of plane wave light. Let the pump power at the input surface be $P_{\text{in}} = P_0 p(\lambda)$ where P_0 is the total incident power and the spectral weighting function, $p(\lambda)$, is normalized according to

$$\frac{\int\limits_{\lambda_1}^{\lambda_2} p(\lambda) d\lambda}{\int\limits_{\lambda_1}^{\lambda_2} d\lambda} = 1. \tag{1}$$

Applying Beer's law of attenuation, we find that the fraction absorbed at any wavelength is

$$\eta(\lambda) = p(\lambda) - p(\lambda)\exp(-\alpha(\lambda)l) \tag{2}$$

where $\alpha(\lambda)$ is the absorption coefficient, and l is the path length over which the absorption takes place. To find the total fraction absorbed, we calculate

$$\begin{aligned}\eta &= \frac{\int_{\lambda_1}^{\lambda_2} \eta(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} d\lambda} \\ &= \frac{\int_{\lambda_1}^{\lambda_2} p(\lambda) d\lambda - \int_{\lambda_1}^{\lambda_2} [p(\lambda)\exp(-\alpha(\lambda)l]\, d\lambda}{\int_{\lambda_1}^{\lambda_2} d\lambda} \\ &= 1 - \frac{\int_{\lambda_1}^{\lambda_2} [p(\lambda)\exp(-\alpha(\lambda)l]\, d\lambda}{\int_{\lambda_1}^{\lambda_2} d\lambda}.\end{aligned} \tag{3}$$

When $p(\lambda)$ and $\alpha(\lambda)$ are both known, (3) can be used to estimate the absorption efficiency for the pump source-gain medium combination in question. However, as mentioned above, the pump light is not a plane wave, and we also want to find the uniformity of the distribution of the absorbed pump power. Thus, we used the nonsequential ray tracing program, ASAP, to calculate both quantities for Nd:YAG and Yb:YAG lasers.[1]

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[1] ASAP is an optical programming language produced by Breault Research Organization.

We measured the output spectrum of a 160-W diode laser array nominally designed for operation near 808 nm. The full width at half maximum (FWHM) was 3 nm, and 11 wavelengths were selected to approximate this spectrum. One wavelength was placed at the center of the measured spectrum (e.g., half the total power was at longer and half at shorter wavelengths), and the others were given weights according to the relative strength of that wavelength in the spectrum. ASAP was then used to compute both the absorption efficiency and uniformity of the absorbed power distribution for each of these wavelengths according to the known absorption spectrum of Nd:YAG near 808 nm. It does so by tracing the propagation with absorption of many rays through the gain medium taking into account the divergence of the diodes, total internal reflections of the pump light inside the slab, and keeping track of rays that the leave the slab. The results for the several wavelengths were then added to find the overall efficiency and uniformity.

Fig. 1(a) shows the absorbed pump power efficiencies and uniformities calculated for a diode array having the spectrum described above versus the central wavelength of the array for a room temperature, 1 × 19 × 80 mm slab of Nd:YAG with the indicated doping concentrations. We note that the absorption spectrum of Nd:YAG in this spectral region, shown in Fig. 1(b), is made up of a number of narrow features yet the absorbed pump power efficiency is nearly independent of the center wavelength of the pump source. Similarly the uniformity is nearly independent of center wavelength. Pumping with a narrow spectrum pump source would result in an efficiency versus diode center wavelength plot that traced out the absorption spectrum in Fig. 1(b). Pumping with center wavelength above 810 nm would result in having too much of the pump light outside the absorption band and not absorbed at all.

Consideration of Fig. 1(a) indicates that with very little loss of efficiency one could gain significantly in uniformity by pumping with center wavelengths below 806.5 nm. Note that this wavelength is not at the peak of the absorption but actually at a minimum in the absorption spectrum. Even so, enough of the pump light is at wavelengths that are absorbed, and the length for absorption is long enough that high absorption efficiency results.

Fig. 2(a) shows the absorbed pump power efficiencies and uniformities versus the central wavelength of the pump diode array for a 1 × 16 × 80 mm slab of Yb:YAG with the indicated doping concentrations. Since we did not have a 969-nm array to measure, we treated the diode spectrum as a Gaussian-shaped function with FWHM = 3 nm and again used 11 wavelengths to approximate it for the ASAP calculations. We note that the absorption spectrum of Yb:YAG in this spectral region, shown in Fig. 2(b), is a narrow feature peaked at 969 nm, yet the absorption efficiency using a broad spectrum pump source is nearly independent of the diode center wavelength. Further evidence for the role of pump bandwidth in efficiency and uniformity is shown in Fig. 2(c) where it is clear that these two quantities do not vary very much as the bandwidth of the pump source changes from 0, a single-frequency pump, to 4 nm. Fig. 3(a) shows the efficiency and uniformity versus central wavelength when the Yb:YAG slab above is pumped near 941 nm with an array having spectral bandwidth = 3 nm FWHM. The absorption in this spectral range is shown in Fig. 3(b), and together with the broad spectral width of the diode spectrum it results in the nearly constant absorption efficiency calculated. Figs. 2 and 3 were obtained for room temperature Yb:YAG.

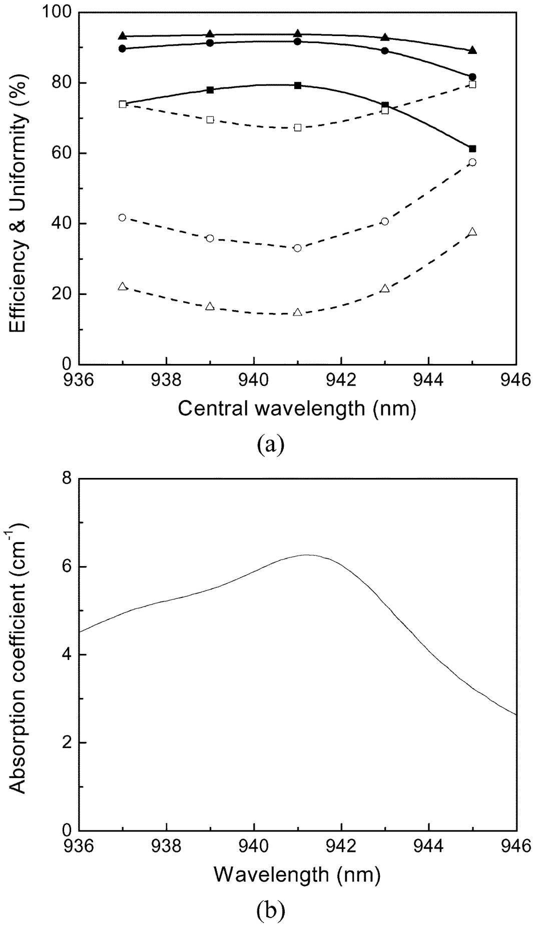
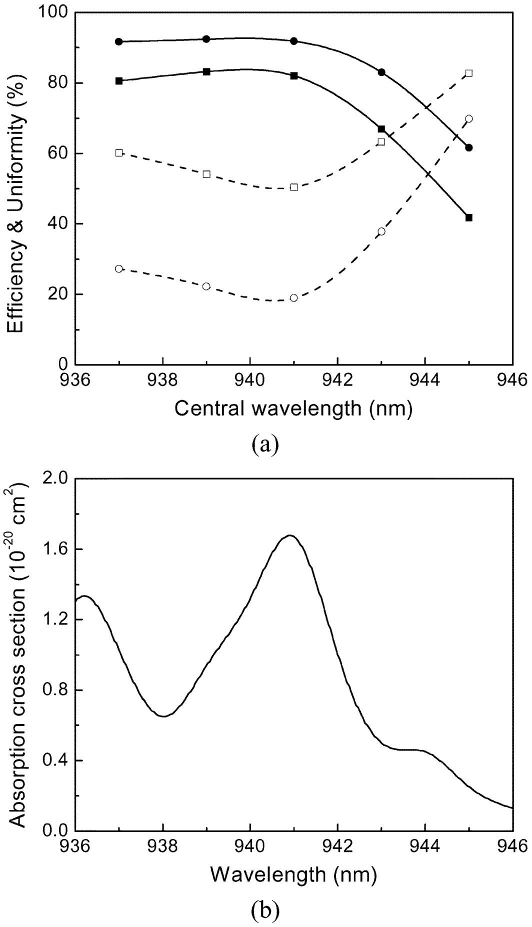


Fig. 3. (a) Absorption efficiency and uniformity as a function of central wavelength of the pump laser diodes near 941 nm for different concentrations of Yb $^{3+}$ ions in a room temperature, edge pumped, 1 × 16 × 80 mm YAG slab. The squares are for 1.0%, the circles for 2.0% and the triangles for 3.0% Yb:YAG. The solid lines and filled symbols show the absorption efficiency and the dashed lines and open symbols show the uniformity both calculated using ASAP. (b) The absorption spectrum of 5 at.% Yb:YAG at room temperature near 941 nm.

In Fig. 1(a), the dotted curves are the efficiencies calculated using (3) for the three concentrations of Nd^{3+} dopant considered. In Fig. 2(a), the dotted curves are the efficiencies calculated using (3) for the 1% and 5% Yb^{3+} doped crystals. We note that the results are close to those obtained using ASAP suggesting that (3) can serve as a good guide to determining an upper limit on the pump absorption efficiency.

Fig. 4(a) is a plot of absorption and uniformity versus pump center wavelength near 941 nm using an array with spectral bandwidth = 3 nm FWHM when the Yb:YAG is cooled to ~77 K. At this temperature, the 969-nm feature is too narrow to be used in pumping the Yb^{3+} ions, and so one must pump near 941 nm. The 941-nm absorption spectrum at 75 K is given in Fig. 4(b) [3] showing that it is composed of several distinct features as is that of Nd:YAG at room temperature [see Fig. 1(c)]. As a result, the absorption efficiency and uniformity at pump center wavelengths below 941 nm are nearly constant. If the pump center wavelength were higher than 941 nm, too much of the pump light would fall outside the absorption band and would not be absorbed.

The results in Figs. 1–4 show that the uniformity as defined in [1] and used in this paper decreases with increasing efficiency. This is clearly demonstrated in the concentration dependence of



(a)

(b)

Fig. 4. (a) Absorption efficiency and uniformity as a function of central wavelength of the pump laser diodes near 941 nm for different concentrations of Yb^{3+} ions in a 75 K, edge pumped, $1 \times 16 \times 80$ mm YAG slab. The squares are for 1.0% and the circles for 2.0% Yb:YAG. The solid lines and filled symbols show the absorption efficiency, and the dashed lines and open symbols show the uniformity both calculated using ASAP. (b) The absorption spectrum of 5 at.% Yb:YAG at 75 K near 941 nm from [3].

the two quantities. At a given center wavelength, the efficiency increases with concentration while the uniformity decreases. Increasing the concentration increases the absorption coefficient at all wavelengths and makes the wavelengths that were weakly absorbed in a low concentration sample strongly absorbed in one with high concentration. This obviates the benefits of the broadband pump source. However, it also suggests that significant uniformity improvement should be possible while retaining high absorption efficiency in samples with concentration that increases from the pump entrance edge to the center of the pumped medium. Such a graded concentration material is possible in crystalline ceramic materials [4].

We have shown that it is beneficial to have broadband pump sources for high-power solid-state lasers that have long absorption paths. This result applies to slab- and disk-shaped bulk lasers and to fiber lasers pumped along their lengths. Consideration of the pump spectrum together with the absorption spectrum and geometry of the gain medium is essential in designing an efficient laser that has good beam quality. It is unwise to seek a narrowband pump source for such an application, and it is not necessary to demand that all the pump source diodes emit light centered at exactly the same wavelength. This relaxes constraints on diode bar and array manufacturers concerning the center wavelength of their emitters.

An engineering outcome of the conclusion that the center wavelengths of the emitters can be different is that the constraint on the diode laser array cooling system to achieve absolute diode temperature uniformity can also be relaxed. The temperature dependence of diode laser wavelength is well known. If exact center wavelength uniformity were required to achieve a desired efficiency and uniformity, then all emitters would have to be identical and kept at exactly the same temperature. As is clear from the results of this paper, such a requirement is unnecessary. Some degree of temperature uniformity is necessary, however, to avoid large, stress-inducing thermal gradients that will cause diode bars to fail.

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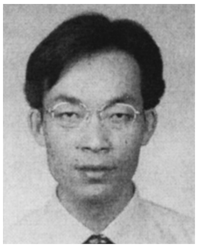

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