Compact, diode-side-pumped Nd^{3+}:$YLiF_4$ laser at 1053 nm with 45% efficiency and diffraction-limited quality by mode controlling

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We demonstrate what we believe to be the highest efficiency obtained to date in a transversely diode-pumped Nd^{3+}:$YLiF_4$ slab laser operating at 1053 nm. The compact 11-cm-long laser cavity configuration is based on total internal reflection of the intracavity beam at the pump facet of the gain crystal to improve the overlap with the pump radiation. Multimode operation with 9.5 W of output power and an efficiency of 45% is obtained for 21 W of pump power in a single-pass configuration. Using a second pass through the crystal and a new mode-controlling technique, the beam quality is improved to the diffraction limit with 6.9 W of output power and 33% of optical-to-optical efficiency. © 2009 Optical Society of America

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Diode-pumped solid-state lasers are devices that have several key advantages such as compactness, efficiency, and a long lifetime. Longitudinal pumping schemes show some restrictions with respect to power scaling of the TEM_{00} mode owing to thermal effects caused by the high pump energy densities such as very short thermal lenses and crystal fracture. This has initially led to a certain decrease of the usage of fluoride crystals such as $YLiF_4$ owing to their low fracture limit, in spite of their excellent thermo-optical and energy-storage characteristics. As a result, crystals with high fracture limit, such as vanadates, have become increasingly employed as laser materials. Nd^{3+}:$YLiF_4$ has natural birefringence that eliminates thermal depolarization and very weak thermal lensing, owing to a combination of negative temperature dependence of the refractive index and positive crystal expansion, which contributes to a high-quality output beam [1]. Recently, a very high cw power and diffraction-limited output has been obtained in a longitudinally pumped slab design [2]. Nd^{3+}:$YLiF_4$ is a uniaxial crystal that has two principal lasing transitions at 1047 nm (π) and at 1053 nm (σ), corresponding to the polarizations parallel and perpendicular to the crystal c axis, respectively. Although the 1053 nm transition has a 33% lower gain, it also has the advantage of a weaker thermal lens [3], with a dioptric power 2.3 times smaller than that for the 1047 mm transition. Using a side-pumping configuration, the pump power can be increased before the onset of crystal fracture, but this configuration has poorer overlap between pump beam and intracavity beam. Dergachev *et al.* have developed a side-pumped Nd^{3+}:$YLiF_4$ laser design with a multipass slab technique and 806 nm diode bars to get uniformly distributed pump absorption inside the crystal [4]. They have been able to obtain as much as 30 W of TEM_{00} mode for 64 W of cw pump power, resulting in 47% optical efficiency at the 1047 nm transition. Using the same configuration at 1053 nm, they have obtained 20 W of cw output power for 64 W of pump power, resulting in 31% optical efficiency.

In this Letter we describe a cavity design that uses the high inversion density located in a shallow region near the pumped surface and takes advantage of the 1053 nm transition to benefit from the weaker thermal lens. A similar configuration that also uses one total internal reflection at the pump face was proposed for the first time by Bernard and Alcock using a grazing incidence configuration [5] in a high gain crystal. This resonator was dubbed the bounce resonator. Using Nd:YVO_4 together with this configuration, Minassian *et al.* achieved 68% of optical-to-optical efficiency in multimode operation and 58% efficiency in fundamental mode using an asymmetric cavity geometry [6].

In our configuration, the a-cut crystal's c axis was orientated parallel to the diode polarization to access the higher absorption cross section of the π polarization and pumped at the highest absorption peak corresponding to 792 nm. The gain medium consisted of a homegrown Nd^{3+}:$YLiF_4$ slab of $14\ mm \times 13\ mm \times 3\ mm$ with a dopant concentration of 0.8 mol. %. Owing to the much smaller absorption coefficient ($8\ cm^{-1}$) when compared to Nd:YVO_4, grazing incidence at the pump facet is not necessary to achieve good overlap with the pump radiation permitting the use of Brewster angle at the entrance of the beam into the crystal to minimize reflection losses. This also creates an efficient selection mechanism for the 1053 nm laser transition without the need for any other intracavity wavelength selective device.

The crystal was side pumped by a 20 W TM polarized diode bar thermally tuned to operate at 792 nm. Heat was removed from the crystal by thermally contacting only one of the larger slab faces to a water-cooled copper heat sink. For these reasons, the laser

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was operated with up to 16.5 W of pump power in continuous mode, while higher powers of up to 21 W at the crystal pump facet were obtained in a low duty cycle of 7% with 2 ms of pump pulse duration. The diode beam was focused into the crystal by a $f=2.5$ cm spherical lens, resulting in a spot size of 4.2 mm $\times 97$ μm in the horizontal and vertical directions, respectively.

In the first setup, a hemispherical cavity with a 30 cm radius of curvature high reflector mirror and a flat output coupler with 7% transmission was used [Fig. 1(a)]. This cavity was extremely compact with less than 11 cm overall length. The laser presented an output power of 9.5 W for a pump power of 21 W, resulting in 45% optical-to-optical efficiency and 49% slope efficiency [Fig. 2(a)]. The output beam quality was multimode with M^2 of 61.0×1.65 in the horizontal and vertical directions, respectively [Fig. 3(a)].

To achieve TEM_{00} mode, we analyzed the transverse-mode behavior in the side-pumped bounce resonator. The onset of higher-order mode oscillation occurs when [7]

$$\int \frac{s_0 r}{1+S_0 c s_0}\mathrm{d}V = \int \frac{s_N r}{1+S_0 c s_0}\mathrm{d}V, \qquad (1)$$

where s_0 and s_N are the normalized distribution functions of the photon density of the TEM_{00} and higher-order mode, respectively, and r is the distribution function of the normalized pumping rate. S_0 is the total photon number in the TEM_{00} mode normalized to the saturation flux, $I_S=(\sigma_e \tau_f)^{-1}$, c is the speed of light, σ_e is the emission cross section, τ_f is the fluorescence lifetime, and $\mathrm{d}V$ integrates over the pumped volume of the crystal. To apply this equation, an important and necessary condition is that the TEM_{00} mode oscillates before all other modes even in the absence of more losses for higher-order modes. This is the case for the side-pumped bounce oscillator. A simple analytical relation was obtained for the threshold pump powers $P_{th,00}$ and $P_{th,10}$ of the TEM_{00} and TEM_{10} mode, respectively, of this specific resonator design by setting $S_0=0$ in Eq. (1), which is shown in Fig. 2(b),

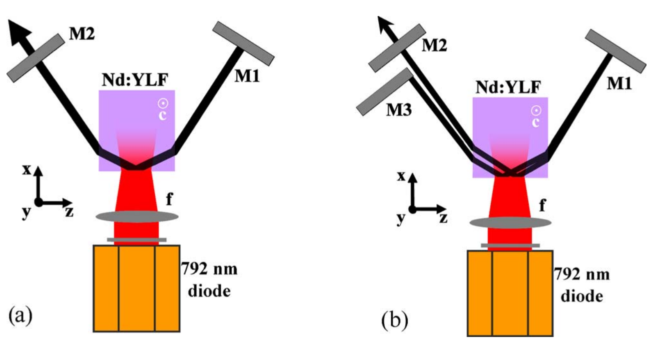

Fig. 1. (Color online) Schematic of the (a) single-bounce and (b) double-bounce cavity resonator configuration. The focal length of the spherical lens f is 2.5 cm, M1 is a curved folding mirror, M2 is a plane output coupling mirror, and M3 is a flat high reflector.

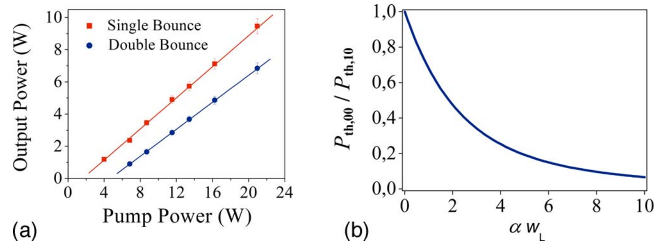

Fig. 2. (Color online) (a) Output power versus diode pump power for single- and double-bounce configurations. (b) Threshold pump power of the TEM_{00} mode divided by the threshold pump power of the TEM_{10} mode for different products of absorption coefficient times laser beam radius at pump facet measured in the x direction.

$$\frac{P_{th,00}}{p_{th,10}} = \frac{\int s_1 r \mathrm{d}V}{\int s_0 r \mathrm{d}V} = 1 + \frac{\alpha^2 {w_x}^2}{4} - \frac{\alpha w_x}{\sqrt{2\pi}} \times \exp\left(-\frac{\alpha^2 {w_x}^2}{8}\right)\left(1-\mathrm{erf}\left[\frac{\alpha\cdot w_x}{2\sqrt{2}}\right]\right)^{-1}, \qquad (2)$$

where erf is the error function, s_1 is the normalized distribution function for the TEM_{10} mode, α is the absorption coefficient of the crystal, and w_x is the mode's beam radius along the pump direction (x axis in Fig. 1) and where we have used the approximation of a negligible small grazing incidence angle and equal losses for both modes. Equation (2) is a function of $\alpha\cdot w_x$, which states that the higher the absorption coefficient or the larger the mode in the pump direction the better the overlap of the TEM_{00} with the inversion and the harder it gets for the TEM_{10} to start oscillating. As seen in Fig. 2(b), in the single bounce resonator the TEM_{00} will always start lasing before the higher-order mode.

The effective absorption coefficient of our crystal was 2.8 cm^{-1} as calculated from the overlap integral with the measured diode spectra at 22°C (emission at 792 nm). The mirror with 30 cm radius of curvature generated a beam radius of 0.45 mm in the pump direction inside the crystal, taking into account the Brewster angle at crystal entrance and the incidence angle at the pump facet, which are both 56°. The corresponding beam waist radius outside the crystal is 0.26 mm close to the entrance facet. Using Eq. (1), we calculated that a beam waist radius of at

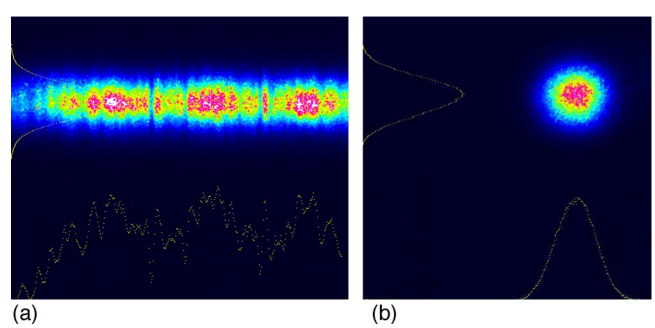

Fig. 3. (Color online) Output beam profiles without using any focusing lens. (a) Highly multimode output of the single-bounce resonator. (b) Diffraction-limited output of the double-bounce resonator.

least 1.3 mm at the crystal would be necessary to maintain TEM_{00} mode operation up to a pump power of 21 W. This can be achieved by cylindrical cavity optics, which generally imply in difficult alignment and additional losses. Instead, we choose a new approach: a double-pass configuration with two total internal reflections at the pumped facet was employed, increasing the overlap between the lowest-order mode and the pump inversion. This effectively decreases the available inversion for higher-order modes if beam diameter and separation of both beams are correctly adjusted.

The double-bounce resonator was mounted by adding a third mirror to the previous cavity [Fig. 1(b)]. This configuration has the advantage of being very simple and compact (same cavity length as in the first setup), with only three mirrors. Using a folding mirror with 50 cm radius of curvature, a flat output coupler with 15% transmission and a flat high reflector mirror, the system was able to produce 43% of optical-to-optical efficiency in the TEM_{30} mode. Although there was an immediate increase in beam quality at almost no expense of efficiency, the calculated beam waist radius of 0.3 mm proved to be still too small to avoid higher-order mode oscillation at high pump powers of up to 21 W.

Fundamental mode oscillation was extracted increasing the TEM_{00} mode beam waist radius to 0.48 mm by using a folding mirror with 3 m radius of curvature [Fig. 3(b)]. With a 10% transmission output coupler the laser presented 6.9 W output power for 21 W of input pump power, which results in 33% optical-to-optical efficiency and 42% slope efficiency, which remains higher than the best data reported to date in the literature [4]. The laser presented an excellent beam quality of M^2 of 1.16×1.05 in the horizontal and vertical directions, respectively. TEM_{00} mode operation was obtained at the maximum output power of the cavity and for separations between both beams ranging from 1.5 to 2 mm inside the crystal. Outside this range, a less efficient, low-order multimode operation was observed. This shows that the second pass through the crystal needs to occur at a specific separation from the first beam, which is large enough to increase the overall width of both beams together to a point where there is not enough gain left farther inside the crystal for the next higher mode to oscillate. On the other hand, if the separation is too large, sufficient gain remains between both beams permitting the next higher-order mode to oscillate. We did a Findlay–Clay analysis that resulted in 2.2% cavity losses, similar to the 2.1% observed in the single bounce configuration. This also demonstrates that the fundamental mode was not obtained with the insertion of additional losses. The lower efficiency can be explained by a poorer overlap with the pump region owing to the bigger mode size introduced by the larger radius of curvature of the folding mirror.

In summary, we have demonstrated what we believe to be the highest efficiency to date in multimode and TEM_{00} mode operation of a diode-side-pumped $Nd^{3+}:YLiF_4$ resonator operating at 1053 nm obtaining 45% and 33%, respectively, using a simple and very compact cavity design. In contrast to other bounce resonators, this cavity achieves good overlap between TEM_{00} and pump inversion by employing neither a telescopic resonator nor cylindrical intracavity optics but a novel resonator design based on mode controlling.

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