Nd:YAG laser pumped at 946 nm

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A Nd:YAG laser crystal was pumped at 946 nm and lased at 1064 nm. This pump–lase format was investigated in order to reduce the quantum defect between the pump and laser photons as compared to other pump schemes of this material. To the best of our knowledge, this is the first realization of this scheme. A room temperature absorption coefficient and linewidth of ~0.075 cm^{-1} and ~1 nm for 1% at. Nd^{+3} concentrations were measured for the 946 nm absorption line. Those parameters impose both narrow-bandwidth pumping and a long absorption path. By increasing the laser crystal temperature above room temperature, the absorption cross sections at 946 and 938 nm increase due to enhanced thermal population of the upper energy level of the ground manifold. The possibility of exploiting this phenomenon to enhance the pump absorption is also discussed. © 2008 Optical Society of America

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A key problem in high-power solid-state lasers is the thermal load created in the lasing material. This heat causes the reduction of both the laser output power and its beam quality.

One approach to compete with the variety of heat dependent phenomena is to simply reduce the heat load itself for a given laser power by decreasing the gap between the pump and the lasing photons. Direct pumping of Nd:YAG at 885 nm and $\mathrm{Nd{:}YVO_4}$ at 880 nm, instead of the common pumping at 808 nm, are illustrations of this approach [1,2]. It should be mentioned that pumping from thermally excited Stark levels can be realized so long as the thermalization rate is higher than the pumping rate.

In this work the possibility of further reducing the quantum defect by pumping Nd:YAG from the upper component of the $^4I_{9/2}$ ground manifold directly to the upper laser level is explored. By pumping at 946 nm the quantum defect is reduced to ~11%, while the laser system preserves its "four-level" nature; namely, the lower laser level is essentially not populated at all times. Thus, the theoretical limit of the Nd:YAG laser slope efficiency using this approach is 90%, as opposed to maximum of 76% using 808 nm pumping. There are, however, two difficulties that should be addressed when considering such a scheme: narrow absorption linewidth and a low room temperature absorption coefficient.

Recent developments in the production of 9XX nm wavelength laser diodes [3], along with the demonstration of narrow linewidth external cavity diodes combined with volume Bragg gratings [4], suggest that high-efficiency, high-power, narrow bandwidth laser diodes may become readily available.

However, even if the issue of finding a suitable high-power pumping source is resolved, the low absorption coefficient sets a challenge if total absorption of the pump is desired. One way to increase the absorbed power is to ensure a long optical path of the pump photons. This can be done by using long laser crystals along with confinement of the pump light utilizing, for example, the total internal reflection (TIR) phenomena [5,6], and/or pumping in a multiple pass scheme (perhaps in a way similar to that in which thin disk lasers are pumped [7]).

Another way to increase the absorption in such a system is to raise the temperature of the laser crystal. In doing so, the upper energy level of the $^4I_{9/2}$ ground manifold becomes more populated, according to the Boltzmann distribution. Thus the absorption coefficient, which is the product of the level's population (assuming the upper laser level's population is negligible), and the absorption cross section should increase. The last statement is true so long as the thermal line broadening, which decreases the absorption cross section, is small enough. On the other hand, when considering laser operation at temperatures significantly higher than room temperature, one should bear in mind temperature dependent mechanisms that may degrade the lasing efficiency. Such mechanisms include the thermal decrease of the stimulated emission cross section, stimulated multiphonon relaxation from the upper laser level, a decrease in thermal conductivity of the laser crystal, an increase of the change of the refractive index as a function of temperature, and an increase of the thermal population of the lower laser level.

In the following we report on a 1064 nm Nd:YAG laser pumped at 946 nm. The laser output power as a function of absorbed power and the temperature dependency of the 930 to 950 nm absorption coefficient are presented. Finally, a summary and discussion conclude this Letter.

To demonstrate 946 nm pumping of a 1064 nm Nd:YAG laser, an experimental setup was constructed as depicted in Fig. 1. A Ti:sapphire beam was focused to a spot diameter of ~150 μm on a 60 mm × 2 mm × 1.6 mm Nd:YAG slab (1.1 at. %). A double pass of the pump beam was achieved by using an intracavity plano–concave mirror with radius of curvature of 500 mm that was highly transmitting (HT) for the 1064 nm radiation and highly reflective (HR) for the 946 nm radiation. The laser slab was antireflection (AR) coated for 1.06 μm on both faces. A 14 cm long resonator was formed with two mirrors—a concave back mirror ($R = 750$ mm), HR at

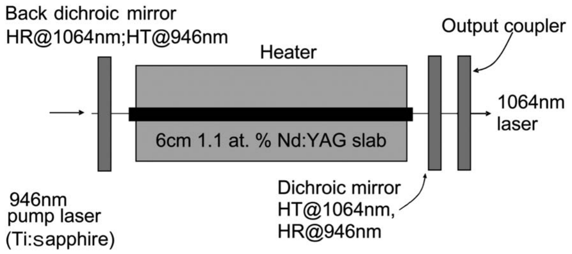

Fig. 1. Schematic of the experimental setup of the Nd:YAG resonator.

1.06 μm and HT at 946 nm; and a concave output coupler ($R = 150$ mm) with different reflectivities at 1064 nm. The calculated fundamental laser mode diameter was ~800 μm ($1/e^2$) at the surface facing the pump beam. The laser crystal was held in a cylindrical copper housing that had a small electric heater and a thermistor imbedded in it. The housing's temperature was controlled with a feedback power supply to within an accuracy of 0.5°C.

Prior to the construction of the resonators, the 930–950 nm absorption spectra of the Nd:YAG slab was measured at different temperatures using a wavelength-scanning Ti:sapphire laser (spectral width of 0.04 nm). The results are presented in Fig. 2.

The peak absorption coefficient (α_λ) and absorption linewidth ($\Delta\nu$, at FWHM) versus crystal temperature (T) are plotted in Figs. 3 and 4, respectively. The linear fit to the experimental results gives a good approximation to the peak absorption-coefficient temperature dependence within the range 27°C–180°C:

$$\alpha_{938}[1/\mathrm{cm}] = 0.06 + 6.31 \times 10^{-4} \times \mathrm{T}[°\mathrm{C}], \qquad (1)$$

$$\alpha_{946}[1/\mathrm{cm}] = 0.06 + 6.46 \times 10^{-4} \times \mathrm{T}[°\mathrm{C}], \qquad (2)$$

$$\Delta\nu[\mathrm{nm}] \approx 0.7 + 24.7 \times 10^{-4} \times \mathrm{T}[°\mathrm{C}]. \qquad (3)$$

The linewidth for both peaks was practically the same within the measurement error.

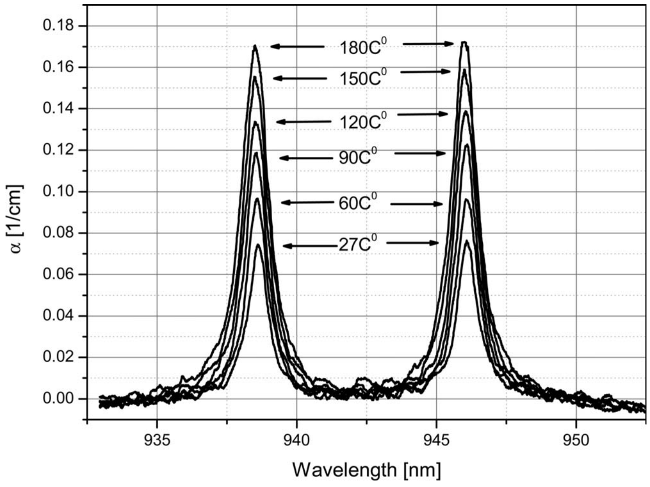

Fig. 2. Nd:YAG absorption characteristics of the $^4F_{3/2}$–$^4I_{9/2}$ transition in the vicinity of 940 nm, as a function of ambient temperature.

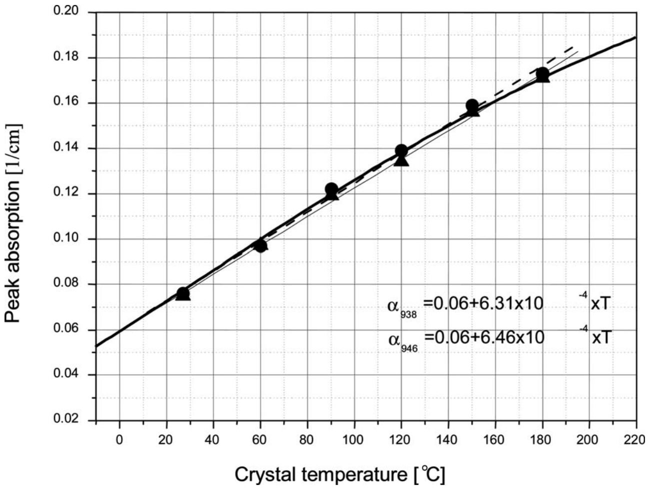

Fig. 3. Dependence of the peak absorption coefficient on ambient temperature.

Although the absorption-coefficient temperature dependency was well approximated to be linear within the temperature range of the measurements, this approximation reveals no physical insight. The absorption coefficient is expected to increase with temperature due to increasing thermal population of the upper level (N) of the ground manifold according to the Boltzmann distribution. On the other hand, temperature-dependent spectral line broadening is expected to decrease the absorption cross section (σ_{abs}) with increasing temperature. The following equation describes these effects:

$$\alpha(T_K) = \sigma_{\mathrm{abs}}(T_K) N(T_K) \propto \frac{\exp\left(-\dfrac{E_p}{kT_K}\right)}{\sum_i \exp\left(-\dfrac{E_i}{kT_K}\right)\Delta\nu}, \qquad (4)$$

where E_p is the energy of the upper energy level of the ground manifold, E_i is the energy of the ith energy level, k is the Boltzmann constant, and T_k is the temperature in degrees Kelvin.

By plugging the measured $\Delta\nu$, the energy levels of Nd:YAG, and a proportion factor (taken for 120°C),

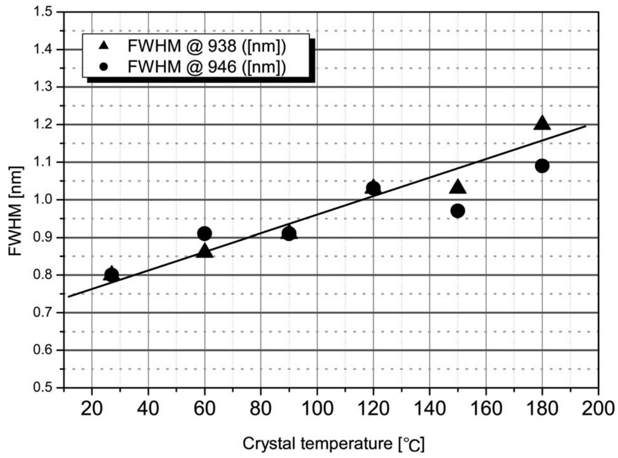

Fig. 4. Dependence of the absorption linewidth on ambient temperature.

into Eq. (4) the solid curve in Fig. 3 was constructed. As can be seen, the measured behavior is in a good agreement with Eq. (4). The absorption measurements confirmed the expected rise in absorption coefficient and line broadening as the crystal's temperature was elevated.

Figure 5 presents the results obtained for lasing at 1064 nm with different output couplers, operating the laser at room temperature (29 °C) and pumping at 946 nm. Slope efficiency of 42% was realized with a 95% transmission output coupler.

To estimate the passive losses in the crystal and resonator, a Findley–Clay analysis (Fig. 6) was conducted. The relatively high passive losses (5%), which may be due mainly to the intracavity dichroic mirror (measured to have closed to 5% reflection at 1.064 μm), explain the relatively low laser slope efficiency. To enlighten this statement, a standard four-level laser model [8] predicts a maximum slope efficiency of 0.45 when 5% passive losses, 95% output coupler, and a quantum defect of 0.11 are considered, while all other efficiency factors are taken as unity.

To summarize, pumping Nd:YAG at 946 nm and lasing at 1064 nm was demonstrated. This pumping scheme may be attractive for several reasons. In addition to the low quantum defect that causes enhancement of the lasing efficiency (up to 17% and 7% efficiency enhancement with respect to 808 and 885 nm pumping, respectively), and reduction of the thermal load (up to 60% and 38% thermal load reductions with respect to 808 and 885 nm pumping, respectively), mature and efficient laser diodes are available in this spectral range (946 and 938 nm). The slope efficiency of 42% achieved in the experimental results is far from the limit set by the quantum defect. However, Findlay–Clay analysis points toward high passive losses in the current experimental-laser resonator. A simple calculation showed that if measures are taken to reduce the intracavity losses, a very efficient laser can be expected. The low absorption coefficient will dictate the use of specific pumping configurations if diode lasers are used. Among the options is the multiple-pass configuration suggested and realized in [6]. The possibility of increasing the absorption coefficient by raising the crystal's temperature was demonstrated and discussed. It was shown that the absorption coefficient at 180 °C increases by a factor of ~2.4 as compared to the absorption coefficient at 20 °C. It is important to mention that in preliminary experiments the laser crystal lased at temperatures up to 120 °C. However, elevating the crystal temperature strongly decreased the laser performance even with respect to the pump power rather than the absorbed power. This degradation seemed to be stronger than what was expected in view of the thermal-dependent mechanisms mentioned at the beginning of this Letter. The possibility of optimizing the pump-laser scheme presented in this work by elevating the crystal's temperature should be addressed in future work.

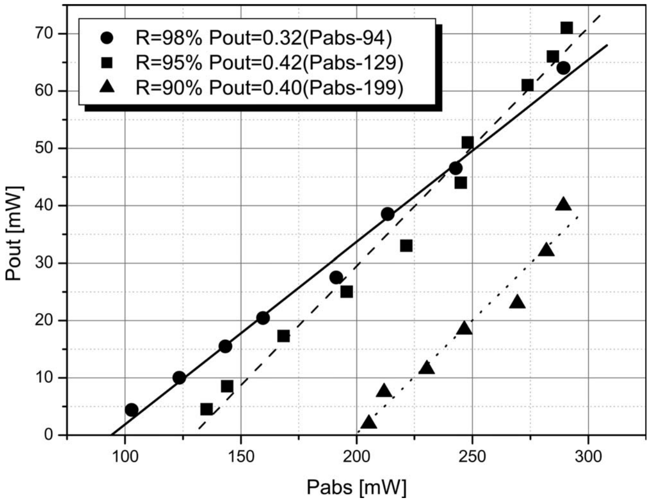

Fig. 5. Output power at 1064 nm as a function of absorbed power at 946 nm for different output couplers.

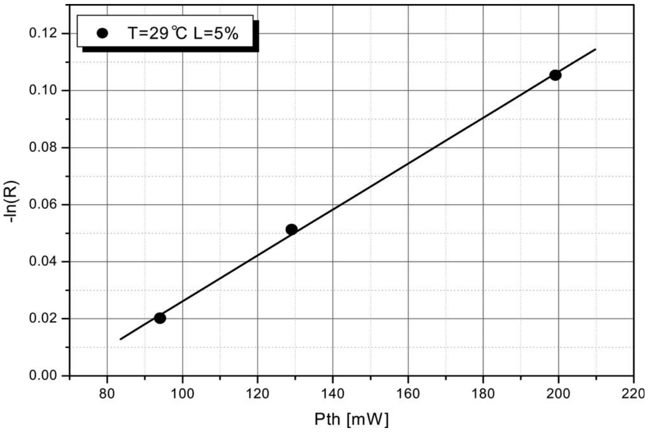

Fig. 6. Findlay–Clay analysis results obtained for laser cavity operating at various temperatures.

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