Diode pumping of a continuous-wave Pr^{3+}-doped $LiYF_4$ laser

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We report, for the first time to our knowledge, diode-pumped cw laser oscillation of Pr^{3+}:$LiYF_4$ in the red spectral range. The pump power is provided by a GaN laser diode emitting a maximum output power of 25 mW at a wavelength of approximately 442 nm. The Pr^{3+} laser emits 1.8 mW of output power at a 639.7-nm wavelength. Threshold pump power and slope efficiency in a nonoptimized setup are determined to be 5.5 mW and 24%, respectively.

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Trivalent praseodymium is an interesting ion for use with solid-state lasers in the visible spectral range because its energy level scheme permits several transitions in the red, orange, green, and blue spectral regions (Fig. 1). Pr^{3+}-doped fluorides, e.g., $LiYF_4$ (YLF), have been found to be promising laser materials. Visible laser emission from such materials at room temperature was demonstrated in pulsed mode under flash-lamp pumping.[1] Using several blue lines of an argon-ion laser[2] or a frequency-doubled Nd:YAG ground-state laser at 473 nm (Ref. 3) as a pumping source allowed cw laser operation to be achieved as well. All these approaches are complicated and not very efficient due to the lack of overlap between the pump wavelengths and the absorption peaks of Pr^{3+}. A new concept for efficient and compact Pr^{3+} lasers is based on the use of a frequency-doubled optical pumped semiconductor laser at 480 nm as a pumping source and was reported at the 2004 Conference on Lasers and Electro-Optics.[4]

In this Letter we report on what is essentially the most compact, to our knowledge, Pr^{3+}:YLF laser pumped directly by a blue laser diode. In general, this represents to the best of our knowledge the first GaN diode-laser-pumped solid-state laser. The laser diode provided by Nichia Corporation emits a wavelength of approximately 442 nm with a maximum output power of 25 mW at a nearly diffraction-limited beam quality ($M^2 \sim 1.1$) with respect to both axes. Figure 2 shows the room-temperature emission spectrum of the blue laser diode, indicating oscillation of many longitudinal modes. The maximum intensity is located at a wavelength of 441.9 nm. Comparing the diode emission spectrum with the absorption cross section (π polarization) of Pr^{3+}:YLF in the relevant wavelength range between 440 and 444 nm, one can see that the emission is still far from the optimum overlap to the absorption peak (Fig. 2). In principle, temperature tuning of the emission spectrum of a GaN diode is possible. However, there is a very small tuning coefficient of approximately 0.07 nm per 1 K, so tuning the spectrum close to the absorption peak would require an increase in the diode temperature of approximately 30 K. Thus we preferred the use of a comparatively long YLF crystal of 7 mm in the laser experiment to achieve a reasonable pump absorption.

From the polarized emission of Pr^{3+}:YLF the emission cross-sectional spectra could be determined. Figure 3 shows the emission in the wavelength range between 600 and 650 nm. Concerning the entire spectra in general, it could be found that the highest

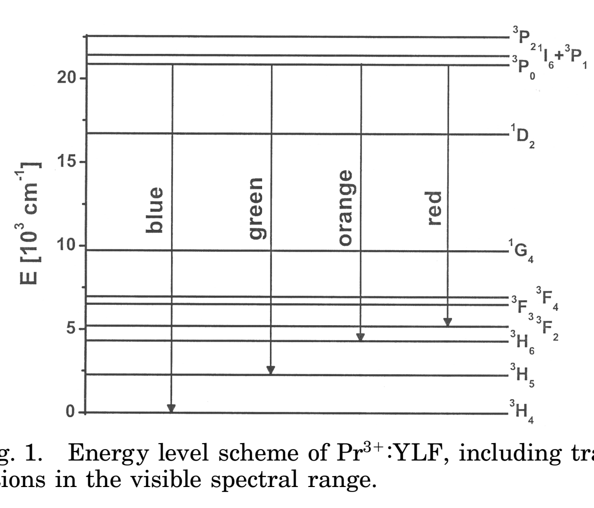

Fig. 1. Energy level scheme of Pr^{3+}:YLF, including transitions in the visible spectral range.

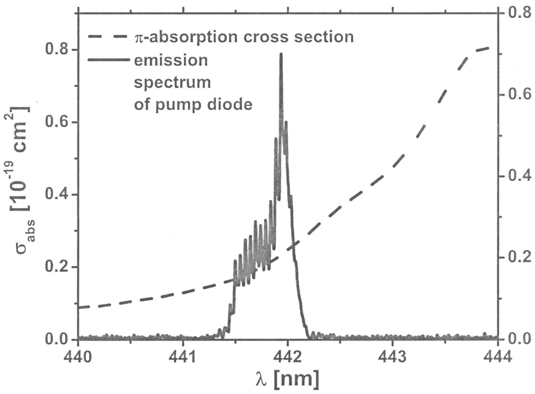

Fig. 2. Spectrum of the blue laser diode in comparison with the absorption spectrum of Pr^{3+}:YLF around 442 nm (π polarized).

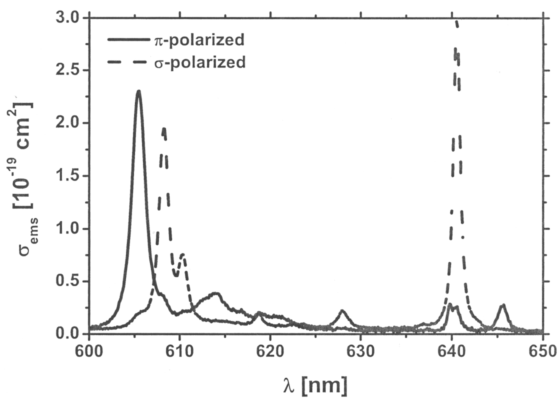

Fig. 3. Polarization-dependent emission cross-sectional spectra of Pr^{3+}:YLF in the spectral region between 600 and 650 nm.

emission cross section of 2.9×10^{-19} cm^2 is located near 640 nm in σ polarization.

Lifetime measurements of the ^3P_j manifold of Pr^{3+} were also performed by use of a short-pulse (10-ns) optical parametric oscillator as an excitation source. As an example, the decay curves of two Pr^{3+}:YLF samples of different concentrations are shown in Fig. 4. The low-concentration sample (0.1% Pr in the melt) exhibits a single exponential decay with a time constant of 51 μs. The high-concentration sample (3% Pr in the melt) exhibits a significant nonexponential behavior at the beginning of the decay curve.

It should be mentioned that the distribution coefficient of Pr^{3+} in YLF is approximately 0.1. Thus the concentration of 3% Pr in the melt corresponds roughly to 0.3% Pr^{3+} in the YLF crystal. Nevertheless, the decay curve indicates that interaction processes such as cross relaxation might already occur at comparatively low concentrations, giving rise to concentration quenching of the upper laser level. We are currently performing measurements to study the physics of such interaction mechanisms in detail. The effective time constant for the Pr(3%):YLF sample, which is used in the laser experiment, was estimated from Eq. (1) to be 38 μs:

$$\tau_{\mathrm{eff}} = \frac{1}{I_0} \int_0^\infty I(t)\mathrm{d}t\,. \tag{1}$$

For the laser experiments a nearly concentric resonator was used that consisted of two mirrors with a 5-cm radius of curvature. The input mirror was highly transmitting at 442 nm and highly reflecting at the red wavelength of the Pr^{3+} laser. The output mirror that was highly transmitting at 442 nm had a very small output coupling (<0.1%) in the red to achieve a low laser threshold. A lens of 5-cm focal length focused the blue pump beam into the 7-mm-long uncoated Pr(3%):YLF crystal. The crystal was oriented such that the pump beam was polarized parallel to the crystallographic c axis. In π polarization 60% of the pump power was measured to be absorbed by the sample. As expected from the spectroscopic measurements, laser oscillation occurs in the $^3P_0 - {}^3F_2$ transition of Pr^{3+} at 639.7 nm in σ polarization. The output-versus-input power characteristic of the red Pr^{3+} laser is shown in Fig. 5. The pump spot diameter inside the crystal was approximately 50 μm. Thus a maximum pump intensity of 1.3×10^3 W cm^{-2} could be achieved. The slope efficiency was 24% with respect to the absorbed pump power. Because of the high-Q resonator, the laser threshold could be determined to be as low as 5.5 mW of absorbed power.

Degradation of the output power of the red Pr:YLF laser of more than 20% under argon-ion laser pumping has already been reported by Sandrock *et al.*[2] for

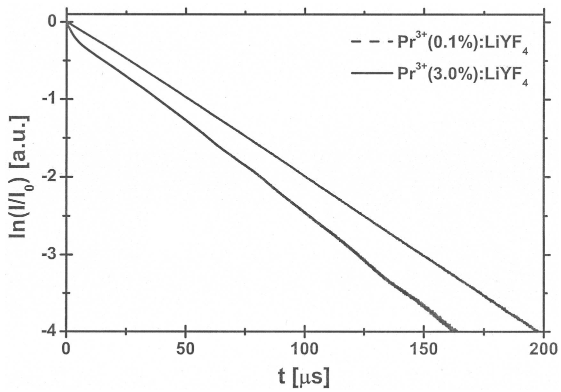

Fig. 4. Time-resolved luminescence of the ^3P_j manifold of Pr^{3+}:YLF.

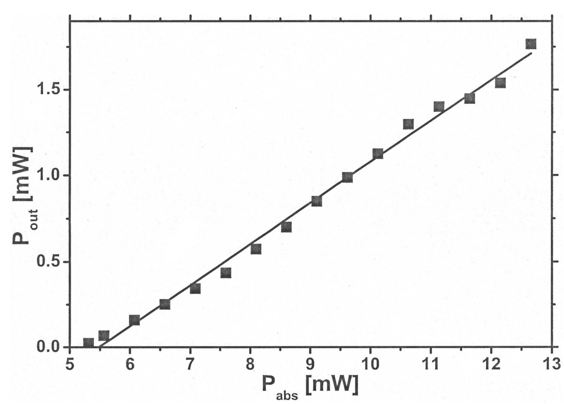

Fig. 5. Output power as a function of absorbed pump power for Pr^{3+}(3%):YLF.

an exposure time of 30 min. In comparison, no degradation of the diode-pumped red Pr:YLF laser reported in this Letter could be observed during an operation time of 6 h. However, it has to be mentioned that the maximum pump intensity of the blue argon laser was approximately 1 order of magnitude higher than that of the blue laser diode.

In conclusion, we have demonstrated, for the first time to our knowledge, direct diode pumping of a Pr:YLF laser emitting in the red spectral range at 639.7 nm. Moreover, this represents, to the best of our knowledge, the first GaN diode-laser-pumped solid-state laser.

Improvement of the laser performance can be expected by antireflection coating of the laser crystal and optimization of the resonator output coupling. Pumping the same crystal by use of a frequency-doubled optical pumped semiconductor[4] allowed the round-trip losses to be estimated by a Findlay–Clay plot to be roughly 3%/cm. However, the possible availability of GaN diode lasers with an emission maximum close to the Pr^{3+} absorption peak permits the use of shorter Pr^{3+}:YLF crystals, down to 2 or even 1 mm, connected with a substantial reduction of the crystal losses. Power scaling and operation of the Pr^{3+} laser at other wavelengths (orange or green) requires higher-power blue GaN laser diodes that can be expected to become available in the near future.

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