3-μm cw laser operations in erbium-doped YSGG, GGG, and YAG

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We have demonstrated cw laser operation at wavelengths near 3 μm from monolithic, Er-doped YSGG, GGG, and YAG lasers by direct upper-state pumping in the 0.97-μm wavelength region with either a Ti:sapphire laser or InGaAs diode lasers. We have obtained slope efficiencies as high as 31% and, with diode-laser pumping, output powers of 0.5 W. In addition, we have demonstrated tunable single-frequency operations from Er:YAG.

Laser transitions of trivalent Er at wavelengths near 3 μm operate between the $^4I_{11/2}$ (upper) and the $^4I_{13/2}$ (lower) states. The long lifetime of the lower state impedes cw operation but is mitigated by a rapid thermalization among the lower-state Stark-split levels. Thermalization favors laser action from transitions terminating in the highest-lying Stark levels. In Er:$LiYF_4$ (YLF), cw operation should be possible solely because of thermalization.[1] Upconversion from the lower state, identified as an important factor in early studies of long-pulse, flash-lamp-pumped lasers,[2–4] also aids in establishing net cw gain for crystals with high Er concentrations.

The first true cw, 3-μm Er laser,[5] operating with the host crystal YLF, was pumped by excitation of the $^4I_{9/2}$ state at a 0.79-μm wavelength with an AlGaAs laser and produced an output power of ~180 μW, which was later improved to nearly 10 mW.[6] Direct excitation of the upper state by pumping near 0.97 μm leads to higher efficiencies than does excitation at 0.79 μm, because of reduced energy losses resulting from other deexcitation processes. Recent experiments with 0.97-μm, Ti:sapphire-pumped Er:GSGG lasers[7] have shown power outputs approaching 130 mW, with slope efficiencies of 36%, greater than the ratio of pump to laser wavelength. The high slope efficiency is attributed in part to repumping of the upper laser state by upconversion.

In the experiments discussed here we extend operation of direct-pumped 3-μm Er lasers to three new crystals and report on efficient operation with 0.97-μm, InGaAs diode pump lasers at 3-μm output power levels as high as 0.5 W. In addition, we demonstrate the first, to our knowledge, single-frequency, tunable output from a cw Er:YAG laser.

As in previous studies,[1,5–7] the laser configuration that we used was a longitudinally pumped monolithic resonator. The laser crystals were 3 mm long and 3 mm in diameter, except for the single-frequency monolith, which was 1 mm long and 1.5 mm in diameter. The flat, pump surfaces of the monoliths were coated to be highly transmitting at 0.97 μm and highly reflecting at the laser wavelength. The output surfaces were coated for nominal 99.7% reflection at the laser wavelength and were polished with convex 1- and 4-cm radii of curvature for the 3- and 1-mm lengths, respectively. Materials used for the 3-mm monoliths were 30%-doped Er:YSGG, 30%-doped Er:GGG, and 33%-doped Er:YAG. We fabricated the 1-mm monolith from 50%-doped Er:YAG in order to maintain a high level of pump absorption. Unless indicated, all data apply to the 3-mm-long monoliths.

We conducted our initial experiments using a cw Ti:sapphire laser as the pump source, focused to a 40-μm spot ($1/e^2$ radius) on the flat surface of the crystals by a 10-cm focal-length lens. We obtained power, threshold, slope efficiency and laser wavelength data for each material at 300 K. Our results are presented in Table 1, along with our measured lifetimes for the upper and lower laser states. To our knowledge, these data represent the first cw operation from Er:GGG and the first cw operation in the other hosts by direct pumping of the Er^{3+} ion. Er:YSGG typically showed the best performance of the three materials, with a slope efficiency of 31% well over threshold.

We observed laser action from the YSGG and GGG hosts at Ti:sapphire pump wavelengths ranging from 0.91 to 0.99 μm. Figure 1 shows, for the Er:YSGG laser, plots of the ratio of output power to pump power as a function of pump wavelength for pump powers near threshold (15 mW at 0.97 μm) and far over threshold (400 mW at 0.97 μm). Also shown in the figure is the absorption coefficient for the laser material; laser action occurred for absorption coefficients as low as 0.2 cm^{-1}. We find good agreement between the shapes of the laser excitation spectra and the absorption spectra, indicating that pump excited-state absorption either is wavelength independent or has a minimal effect on laser performance at the excited-state densities encountered in the monoliths.

We used two different types of strained-layer, quantum-well InGaAs diode lasers to pump the Er-doped monoliths. The first was a 50-mW, single-transverse-mode device (SDL-6302-H1); we were able to pump the GGG and YSGG crystals over threshold, using a 10-cm single-element spherical focusing lens. With 48 mW of 965-nm diode-laser power incident upon the crystals, we observed 6.1 and 8.3 mW of output power from the GGG and YSGG lasers, respectively.

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Table 1. Performance Summary of 3-μm Er Lasers at 300 K[a]

	Er:YSGG	Er:GGG	Er:YAG
Wavelength (nm)	2797	2821	2937
Output power (mW)	190 (511)	155 (293)	143 (171)
Threshold (mW)	5 (70)	7 (250)	40 (410)
Slope efficiency (%)	31 (26)	27 (19)	26 (12)
$^4I_{11/2}$ Lifetime (ms)	1.3	0.96	0.12
$^4I_{13/2}$ Lifetime (ms)	3.4	4.86	7.25
α (cm^{-1})	15	18	12

[a]Efficiency and power measurements in parentheses indicate results of diode-laser pumping; other values refer to Ti:sapphire pumping.

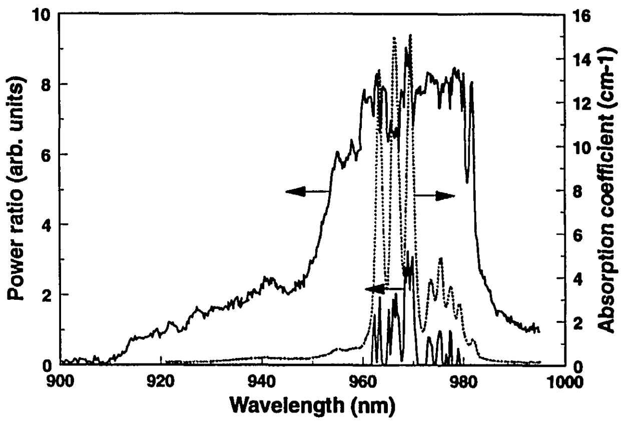

Fig. 1. Er:GGG laser excitation spectra (solid curves) for two pump levels, along with the absorption spectrum of the crystal (dashed curve).

The second diode laser was a 1-W, multimode device (SDL-6562-P1) with a 100-μm stripe width. To obtain high pump powers, we used two of the devices, oriented for orthogonal polarization and combined into a single beam with a polarizing beam cube. The individual diode laser outputs were collimated with a four-element lens ($f = 15$ mm, 18-mm aperture). An identical lens focused the combined beams onto the monoliths. Figure 2 shows the input–output curves for the three materials. Power, threshold, and efficiency data for the double-diode pumping scheme are summarized in Table 1.

We used a 0.25-m grating spectrometer to measure the emission spectrum of the Er lasers. Longitudinal modes of the 3-mm-long-crystals were spaced approximately 0.7 nm apart and were resolved by the spectrometer. The 3-mm monoliths generally operated on 3–5 longitudinal modes, with a resultant overall width of ~2.5 nm FWHM. The 1-mm-long crystal of Er:YAG, when pumped by the Ti:sapphire laser, operated on a single axial mode based on the observed spectrometer output and on the fact that a stable reading of wavelength was evident when the laser output was analyzed by a high-resolution wavemeter (Burleigh wavemeter). For the 1-mm crystal, we obtained a 40-mW threshold, a 16% slope efficiency, and 70 mW of output power for 540 mW of pump power.

We placed the 1-mm Er:YAG crystal mount on a thermoelectric cooler to determine the temperature and pump-power tuning rate of the laser wavelength, which we measured with the wavemeter to a resolution of 0.01 nm and an absolute accuracy of 0.1 nm. We observed that the monolith switched between the 2.94- and 2.83-μm laser transitions, depending on the crystal temperature and pump power. By changing both pump power and crystal temperature, we were able to tune the 2.83-μm line over a 1.9-nm range. The 2.83-μm line demonstrated a constant-pump-power wavelength tuning versus temperature relation, plotted as points in Fig. 3. The solid line in the figure is the slope predicted if tuning results entirely from the shift in the cavity mode wavelength with temperature. We calculated the slope, 0.033 nm/°C, using dn/dt and a thermal expansion coefficient of 7.3 and 7.5×10^{-6}, respectively, for the YAG host crystal. The agreement between the data and the predicted tuning rate is excellent, and the deviation from a straight line at the extremes of the temperature range may result from a shift with temperature of the transition peak wavelength. The pump-power tuning rate, for a fixed heat-sink temperature of 25 °C, was 0.004 nm/mW in the pump-power range of 300–500 mW. The two rates combined imply that the monolith temperature, in the volume occupied by the laser mode, rises at a rate of 0.10 °C/mW of incident pump power.

In analyzing our results, we estimated the expected threshold pumping level for the lasers by setting up

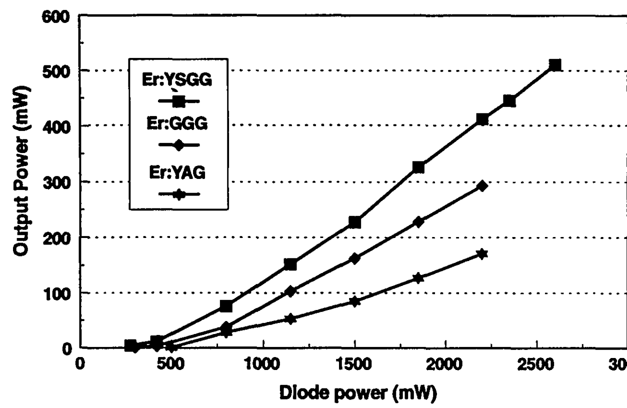

Fig. 2. Input–output curves for Er-doped monolithic lasers pumped by two 1-W diode lasers.

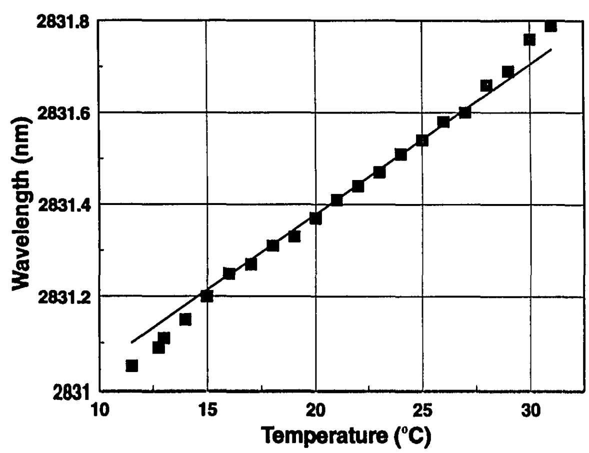

Fig. 3. Observed temperature tuning of single-frequency Er:YAG laser wavelength.

the rate equations for populations of the upper and lower laser states and finding the steady-state solutions as a function of pump rate. We included terms for upconversion from each state and, in addition, terms accounting for the finite probability that excitation arriving in the $^4I_{9/2}$ state from upconversion may cross relax and generate two excitations in the lower laser state, rather than excite the upper state after nonradiative relaxation, as discussed by Chou and Jenssen.[8] We measured the upconversion coefficients and the $^4I_{9/2}$ branching term for YSGG and employed the upconversion data of Shi *et al.*[9] for Er:YAG. After calculating the cw population densities in the upper and lower states, we determined the pumping rate needed to obtain a net gain in the laser crystal, accounting for the thermalized fraction of excitation in the appropriate upper- and lower-state Stark-split levels.

We find that pumping rates of 4×10^{21} and 2.5×10^{22} cm^{-3} are predicted to obtain net cw gain in Er:YSGG and Er:YAG at the doping levels we used in our 3-mm monoliths. We calculated the actual threshold pumping rates, W_{th}, at the crystal surface for Ti:sapphire pumping, using the formula (for a Gaussian pump)

$$W_{th} = \alpha P_{th}/(\pi w_0^2 E_p),$$

where α is the pump absorption coefficient, P_{th} is the threshold pump power, w_0 is the pump beam radius, and E_p is the energy of the (965-nm) pump photon. The values for α and P_{th} for the lasers appear in Table 1, and w_0 is 40 μm. We find that W_{th} is 7.3×10^{21} and 4.7×10^{22} cm^{-3} for Er:YAG and Er:YSGG, respectively, which in both cases is slightly less than twice the theoretical value needed to yield net gain. A more involved threshold calculation requires full accounting for the overlap between the spatial variation in gain in the laser crystal and the laser mode.

The issue of enhanced efficiency from lower-state upconversion has been discussed before.[7] The highest Er:YSGG laser slope efficiency that we observed is 88% of the quantum limit, for a system with a nominal 0.3% output coupling. We estimate the enhancement factor for both Er:YSGG and Er:YAG to be 1.6, based on the formulas in Ref. 7. This may account for the high efficiency despite the low level of output coupling.

As higher-power, higher-brightness, 0.97-μm diode-laser sources become available, we expect that higher levels of 3-μm, cw power output can be generated by Er-doped materials.

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