551 nm DIODE-LASER-PUMPED UPCONVERSION LASER

Indexing terms: Lasers and laser applications, Infrar-red sources, Semiconductor lasers

Green laser emission at 551 nm was achieved in LiYF<sub>4</sub>: <sup>3+</sup>Er by upconversion pumping with a near-infrar-red diode laser at low temperature. Using a 2 mm-long monolithic laser crystal the lasing threshold was reached with 34 mW of absorbed power from an ALGaAs diode-laser array.

There is presently much interest in the development of visible laser devices that use frequency doubling and sum-frequency mixing techniques to convert the near-infrar-red output of ALGaAs diode lasers to shorter wavelength. Upconversion excitation mechanisms are emerging as alternative nonlinear optical processes to pump solid-state lasers that oscillate at wavelengths that are shorter than those of the pump light. Using a flashlamp, Er<sup>3+</sup> glass or CW dye laser pump sources, operation of such upconversion lasers has been demonstrated at wavelengths between 380 nm and 1.28 µm at temperatures of 10–110 K. Here we report the first operation, to our knowledge, of a visible upconversion laser pumped by a semiconductor diode laser. With a miniature laser crystal of LiYF<sub>4</sub>: Er<sup>3+</sup>, 551 nm laser emission was achieved with a threshold of 34 mW of absorbed 791 nm pump power at 40 K. In addition, a laser threshold as low as 17 mW of incident power and an output power of 4.2 mW were obtained by pumping with a CW near-infrar-red dye laser.

Certain trivalent rare earth ions such as Nd<sup>3+</sup> and Er<sup>3+</sup> are attractive for upconversion laser operation since they have metastable intermediate levels which can be populated efficiently with near-infrar-red radiation. Subsequent excitation of higher lying energy levels that emit short-wavelength radiation can occur via energy-transfer upconversion or absorption.

For diode-laser pumping experiments, a 2 mm-long monolithic laser crystal of LiYF<sub>4</sub>: Er<sup>3+</sup> (1%) was fabricated by depositing mirror coatings directly onto spherically polished end faces (r = 1.5 cm). The output coupling for the 551 nm laser radiation was 0.5%. The crystal was placed in a variable-temperature helium cryostat for cooling. The output of the ALGaAs diode-laser array is used for pumping was collimated with a fast lens and the astigmatism was reduced with a cylindrical lens system. The pump light was focused into the crystal to a 1/e<sup>2</sup>-beam diameter of 60 µm. The diameter of the laser beam waist of the monolithic resonator was 40 µm. Fig. 2 shows the 551 nm output power of the upconversion laser as a function of pump power at a temperature of 40 K. The lasing threshold was reached with 34 mW of absorbed pump power. The green light radiations corresponding to the 4S<sub>3/2</sub>(5) → 4I<sub>15/2</sub>(6) transition and the near-infrar-red pump light were polarized parallel to the c-axis of LiYF<sub>4</sub>: Er<sup>3+</sup>. The TEM<sub>00</sub> laser output exhibited three longitudinal modes separated by 0.05 nm. The multimode output of the diode laser array had a spectral envelope of ~ 3 nm and the temperature was varied to tune the output spectrum to ~ 790 nm where the absorption of the pump light was a maximum. The 791 nm pump radiation is doubly resonant; with absorption from the ground state to 4I<sub>11/2</sub> and from the intermediate 4I<sub>13/2</sub> state to 2H<sub>11/2</sub>. As a result, sequential two-photon absorption contributes to excitation of 4S<sub>3/2</sub> in addition to energy-transfer upconversion.

Owing to the poor spectral overlap of the multi-mode diode-laser output and the two 0.7 nm-wide Er<sup>3+</sup> absorption lines at 789-9 and 791-6 nm, the 2 nm laser crystal absorbed only 15% of the incident pump light. As observed in earlier experiments with dye-laser pumping, the green laser output consisted of a series of pulses of ~ 200 ns duration and a repetition rate of ~ 100 kHz. Increases in the pump power lead to a shortening of the pulse length and an increase of the repetition frequency. This self-pulsing of the CW-pumped upconversion laser requires further investigation but is thought to arise from Q-switching effects caused by saturable absorption of the green laser radiation from the intermediate 4I<sub>13/2</sub> manifold. Similar effects have been observed in BaY<sub>2</sub>F<sub>4</sub>. In another set of experiments the ALGaAs diode laser was replaced by a CW near-infrar-red dye laser tuned to a strong Er<sup>3+</sup> absorption line at 797 nm. The narrow-linewidth (~ 0.1 nm) pump light was strongly absorbed (~ 80%) by the sample and resulted in efficient upconversion excitation. Fig. 3 shows the dependence of the green output power on dye-laser pump power. Upconversion lasing was obtained with 17 mW of incident pump light and an average green output of 4.2 mW was observed with 130 mW of near-infrar-red input. In spite of the nonlinear pumping mechanism, the laser output increased linearly with pump power. This is thought to arise from saturation phenomena associated with the high population of the
intermediate states of $\text{Er}^{3+}$ and the resulting depletion of the ground state. The beam diameter of the focused pump beam was of the order of 30 $\mu$m; the profile of the inversion density produced was probably even narrower owing to the nonlinear upconversion excitation mechanism. The tight waist of the dye-laser pump beam and the better match between the waists of the inversion distribution and the laser mode resulted in a much higher differential efficiency and lower pump threshold than in the case of diode-laser pumping.

A comparison of Figs. 2 and 3 suggests the use of index-guided AlGaAs diode lasers for efficient pumping of upconversion lasers since the single-mode output of these devices can be focused to a diffraction-limited beam waist and the narrow output spectrum results in efficient absorption by a short crystal of $\text{LiYF}_4 : \text{Er}^{3+}$. The use of such pump lasers should permit upconversion excitation with efficiencies comparable to those observed with the CW dye laser in Fig. 3. Index-guided AlGaAs lasers with single-frequency outputs of up to 150 mW have been demonstrated recently.\(^{10}\) The present diode-pumped 551 nm upconversion laser using a $\text{LiYF}_4$ crystal with a nominal $\text{Er}^{3+}$ concentration of 1% operated with the lowest pump threshold at 40 K. However, laser oscillation was observed at temperatures up to 90 K. Optimisation of the $\text{Er}^{3+}$ concentration together with the use of high-power, single-frequency AlGaAs diode lasers should permit efficient operation of diode-pumped upconversion lasers at temperatures beyond 100 K.

References


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