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We report room-temperature pulsed up-conversion laser oscillation in Er-doped $LiYF_4$ and KYF_4 at 551 and 562 nm, respectively. In both crystals laser oscillation is observed on the $^4S_{3/2}$-$^4I_{15/2}$ ground state transition. Excitation was provided by a tunable flashlamp-pumped Ti:sapphire laser in the spectral region around 810 nm. Additional pumping with a continuous wave krypton ion laser at 647 nm was beneficial to both lasers. Laser action has also been observed in Er-doped $Y_3Al_5O_{12}$ on the same transition.

The advent and rapid improvement of laser diodes in the infrared and red spectral regions has caused new interest in the development of up-conversion lasers, which may provide compact "all solid-state" laser sources in the blue and green spectral ranges. Visible up-conversion lasing at room temperature has already been demonstrated in Tm-doped crystals[1,2] and in various rare-earth-doped fluorozirconate fibers (e.g., Ref. 3). However, up to now visible up-conversion lasers in Er-doped crystals required cryogenic temperatures, which clearly limited their applications.[4,5] Only under direct excitation laser oscillation has been achieved.[6] We now report efficient pulsed green up-conversion lasing in Er-doped crystals at room temperature. In our opinion the Er^{3+} ion is a very attractive candidate for diode pumped up-conversion lasers, because it offers various ground and excited state transitions near 800 and 970 nm, where high power laser diodes are available (see also, Ref. 7).

The relevant part of the energy level scheme of Er^{3+} with respect to the laser experiment is shown in Fig. 1. The ground state absorption (GSA) processes and the excited state absorption (ESA) characterizing the pumping scheme are also shown. As pump sources a continuous wave krypton ion laser operating at 647 nm and a flashlamp pumped Ti:sapphire laser could be used simultaneously. In principle both lasers could be replaced by diode lasers for an all solid-state device.

In the first step the krypton laser and/or the Ti:sapphire laser are exciting the short living $^4F_{9/2}$ and $^4I_{9/2}$ states of the Er^{3+} ion, respectively. From these levels the excitation rapidly decays into the metastable $^4I_{11/2}$ level and subsequently to the metastable $^4I_{13/2}$ level. ESA transitions near 800 nm originate from both metastable levels. Additionally, high populations of the metastable levels bleach the GSA at the green laser transition. Note that for 1% Er concentration the GSA at the Ti:sapphire wavelength (around 800 nm) is very weak.

In the second step, ESA at the Ti:sapphire wavelength populates the upper laser level $^4S_{3/2}$ of the green laser transition. From highly resolved ESA measurements we conclude that at a wavelength of 810 nm, where the best results were obtained, the ESA mainly originates from the $^4I_{11/2}$ level.

The experimental setup is presented schematically in Fig. 2. A dielectrically coated mirror ($M1$) combined the pump beams of the Ti:sapphire and the krypton ion laser. The pulse width of the flashlamp pumped Ti:sapphire laser was about 50 μs. With a birefringent filter the wavelength could be tuned to ground state and excited state transitions of the Er^{3+} ion near 800 nm. The emission bandwidth of about 5 nm of the Ti:sapphire laser was comparable to that of high power laser diodes. In order to obtain a low threshold, a near concentric resonator with $r=5$ cm mirrors was used. To increase the absorbed pump energy, the output coupler was highly reflecting at both pump laser wavelengths. With this setup we achieved pulsed laser oscillation on the $^4S_{3/2}$-$^4I_{15/2}$ ground state transition in Er(1%):$LiYF_4$(YLF), Er(5%):YLF, Er(1%)KYF_4 (KYF), and in Er(0.5%):$Y_3Al_5O_{12}$(YAG). To our knowledge this is the first time that laser action on this transition has been reported in Er:KYF at all. The results are presented in Figs. 3 and 4. In both crystals lasing occurred in π polarization, at 551 nm for YLF and 562 nm for KYF. Using both pump beams, a maximum output energy of 0.95 mJ has been achieved with the 6.9-mm-long Er(1%):YLF sample, which absorbed only 15% of the Ti:sapphire radiation. Pumping with the Ti:sapphire laser alone yielded a maximum output energy of 0.57 mJ and a slope efficiency of almost 20% (see Fig. 3). With an output coupling of 8%, 34%, reabsorption losses per roundtrip, and an emission cross section of 2×10^{-20} cm^2 (Ref. 6), a

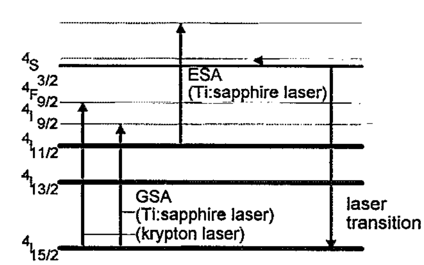

FIG. 1. Energy level diagram of the Er^{3+} ion (schematically) and pumping scheme.

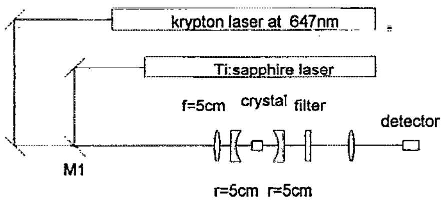

FIG. 2. Setup of the up-conversion laser experiment.

population of about 10% can be estimated for the upper laser level $^4S_{3/2}$ at threshold. On the other hand, this population can be obtained by a simple rate equation model for the pump process, taking into account the GSA and ESA transitions at the Ti:sapphire wavelength. With a measured ESA cross section of 0.5×10^{-20} cm^2, a GSA cross section of 0.05×10^{-20} cm^2, a pump energy of 10 mJ incident on the crystal, a pump spot size of 10^{-4} cm^2, and a pump pulse width of 50 μs, an upper laser level population of 11% is obtained at the end of the pump pulse in agreement with the above estimation. The main role of the krypton laser is to populate the metastable $^4I_{11/2}$ level, where the ESA transition used for pumping originates. Without the krypton laser, the Ti:sapphire laser has to populate this level via the weak GSA transition before the ESA process can efficiently populate the upper laser level and laser oscillation can start.

In the Er(1%):YLF crystal we observed simultaneous lasing at 850 nm on the $^4S_{3/2}$-$^4I_{13/2}$ transition in spite of an output coupling of more than 80% through each mirror. Both laser transitions originate from the same upper laser level. Therefore, suppression of the 850 nm laser emission may increase the efficiency of the green laser transition.

In order to obtain maximum output energy we had to tune the Ti:sapphire laser close to the maximum of the ESA. This confirms that at low Er concentrations ESA is the main pump process. With increasing Er concentration the "true" up-conversion process ($^4I_{11/2}$,$^4I_{11/2}$ $\rightarrow$$^4F_{7/2}$, $^4I_{15/2}$) becomes more effective, but, due to cross relaxation, the upper laser level lifetime rapidly decreases.

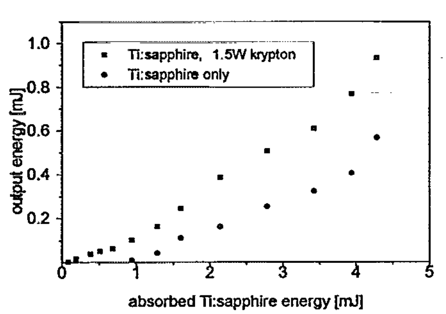

FIG. 3. Output energy of the Er(1%):YLF laser, λ(Ti:sapphire):810 nm, 8% output coupling, the inset shows the power emitted by the krypton laser at 647 nm.

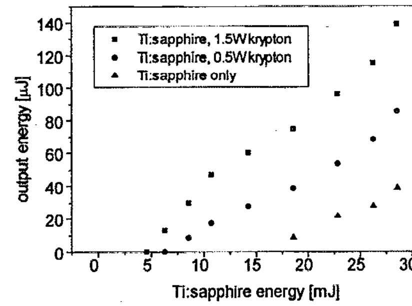

FIG. 4. Output energy of the Er(1%):KYF laser, λ(Ti:sapphire):812 nm, 16% output coupling, the inset shows the power emitted by the krypton laser at 647 nm.

The 7.3-mm-long Er(1%):KYF crystal absorbed only a few percent of the Ti:sapphire laser radiation. As it was difficult to measure the absorbed pump energy, we decided to plot the energy of the Ti:sapphire laser incident on the crystal in Fig. 4. The weak absorption is probably the main reason for the low output energy of the Er:KYF laser.

The output energy of the Er:YAG laser at 561 nm was much lower in comparison with the fluorides and decreased even further after the first few shots. We believe that the inferior performance of YAG can only partly be attributed to the shorter upper laser level lifetime—15 μs in Er(1%):YAG compared to 400 μs in Er(1%):YLF. Note that the pump pulse lasted only 50 μs. There are indications that parasitic ESA at the laser wavelength due to the $^4I_{13/2}$-$^2H_{9/2}$ transition may reduce the efficiency of green Er-doped lasers.[8]

In conclusion, we have demonstrated pulsed green up-conversion lasing in Er-doped YLF, KYF, and YAG at ambient temperature for the first time. With the Er(1%):YLF sample an output energy of 0.95 mJ has been achieved. Pumping only with the Ti:sapphire laser yielded a slope efficiency of almost 20%. From recent ESA measurements we expect that the performance of these lasers can be further improved by pumping around 970 nm.

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