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# $Er^{3+}$:YLiF$_4$ continuous wave cascade laser operation at 1620 and 2810 nm at room temperature

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For the first time cw, cascade lasing was demonstrated in 1% Er doped yttrium lithium fluoride (YLF) at room temperature at both 1620 and 2810 nm. In addition, cw lasing in Er[1%]:YLF at 1640 nm and in Er[5%]:YLF at 2810 nm at room temperature is reported for the first time in material of such low concentration.

Laser emission between the $^4I_{11/2}$ and $^4I_{13/2}$ states of heavily doped Er:YLF was demonstrated to occur at 2810 nm[1] and later on wavelengths from 2660 to 2850 nm.[2] The same transition in heavily doped Er:YAG was observed at 2940 nm.[3] Previously, cw $Er^{3+}$ lasing near 1600 nm at room temperature was demonstrated in YAG and YGG.[4] Several suggestions for cascade laser operation were made.[5–7] In Tm,Ho:YLF cascade lasing was observed.[8,9] In the present letter cw-laser emission from 1% doped Er:YLF at 2810 and 1620 nm was observed at room temperature using the $^4I_{11/2}$–$^4I_{13/2}$ and the $^4I_{13/2}$–$^4I_{15/2}$ transitions (Fig. 1). Clearly, the lower level of the 2810 nm transition is the upper level of the 1620 nm transition. However, lasing involving the former transition required high dopant concentration while lasing in the latter required low concentration. At high concentrations upconversion processes between two excited Er ions in the $^4I_{13/2}$ levels favor the 2810 nm transition. The 1600 nm transition, however, only lases at low Er concentrations because of its quasi-4 level nature resulting in reabsorption at room temperature. The combination of a low concentration of $Er^{3+}$ ions and the YLF host enabled cascade lasing at room temperature at both 1620 and 2810 nm. The fact that the lifetime of both the $^4I_{11/2}$ and the $^4I_{13/2}$ levels of $Er^{3+}$ in YLF are comparable, 2.9 and 10 ms,[10] respectively, is thought to make this result possible. In comparison, the corresponding lifetimes in Er:YAG are 0.1 and 6.5 ms.

The Er:YLF rod used had an atomic concentration of 1% and was coaxially pumped by a krypton ion laser operating at 647 nm in the initial experiment and by a Ti:sapphire laser operating at 972 nm in subsequent work. The pumped length was 6.9 mm along the crystal's *a* axis. The laser resonator was a nearly concentric cavity formed by one 5 cm and one 10 cm radius mirror with high reflectivity at 1620, 2660, and 2810 nm. The laser radiation was analyzed with the aid of a 1/4 m monochromator employing a 300 grooves/mm grating blazed at 2000 nm and an InSb detector cooled to 77 K in the first experiment. More recently, an InAs diode attached to a lock-in amplifier was used to detect the laser signal. Signals from this detection apparatus were monitored with an oscilloscope (Tektronix Model 2440) and stored in a computer.

Figure 2 is evidence of simultaneous cw operation at both 2810 and 1620 nm. It also shows the temporal wave form of each wavelength while lasing. A mechanical chopper was used to reveal the appearance of the first laser pulse at 2660 nm (upper trace). After the lower Stark level of the 2660 nm transition is filled, the laser operation shifts to the longer laser wavelength at 2810 nm. When this transition is in steady state operation, the 1620 nm transition starts to lase (lower trace). Because the 1620 nm laser is near threshold, its lasing starts approximately 10 ms after the onset of pumping.

Figure 3 shows the output-vs-input power curve for all wavelength operation in cw mode (without chopping). The pump laser was focused with a 5 cm lens and the resonator employed the mirrors described above. From the definition of slope efficiency, the mirror transmissions, and the measured slope efficiency, we calculate the cavity losses at 2810 nm to be 6%. The threshold for the 2810 nm wavelength could not be measured directly because the krypton laser pump source could not stabley emit at very low power, but is estimated to be 20 mW based on the definition of threshold for the resonator used in this case.

The threshold for the 1620 nm wavelength is estimated to be 200 mW of absorbed pump power. Unfortunately, the maximum pump power of the krypton pump laser corresponded to about 230 mW of absorbed power. The slope efficiency is about 0.4% for the 2810 nm transition alone

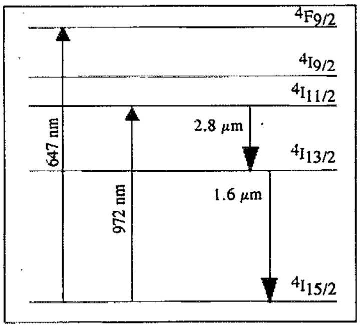

FIG. 1. Erbium-energy-level diagram.

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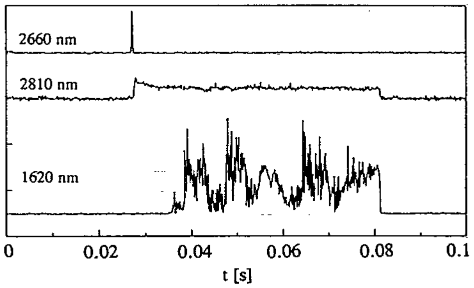

FIG. 2. Cascade laser activity is shown. After an initial laser pulse at 2660 nm the 2810 nm transition starts to lase. With a delay of approximately 10 ms the 1620 nm laser appears and both transitions lase simultaneously. The intensity for each wavelength is shown in arbitrary units.

and about 1.3% for both wavelengths lasing simultaneously (Fig. 3). The ratio between the 2810 and 1620 nm laser output power is estimated from the oscilloscope traces to be about 12:1. As cascade lasing begins, the increase in lasing efficiency is due to the rapid depletion of the lower level population of the 2810 nm transition by the onset of lasing at 1620 nm.

Excitation at 972 nm with the Ti:sapphire laser pumps directly into the upper laser level of the 2810 nm transition ($^4I_{11/2}$) thereby minimizing the quantum defect compared to pumping at 647 nm. Also, no initial lasing of the 2660 nm transition occurs in this case. When the pump light is chopped Fig. 4 shows the wave forms observed at 2810 nm without and with cascade lasing as well as the 1620 nm wave form. In this case the pump laser was focused with a 6.5 cm focal length lens and the same mirrors as mentioned above formed the resonator. Note the increase in 2810 nm output when cascade lasing takes place. The thresholds are 10 mW for the 2810 nm and 90 mW for the 1620 nm transition.

Lasing at 1640 nm without cascade lasing occurred for 1% doped Er:YLF using krypton ion laser pumping at 647 nm at room temperature. The experimental conditions were as described above for krypton laser pumping except that the mirrors were coated for 1640 nm only. The slope efficiencies were 0.3%, 1.2%, and 0.6% for output couplers with transmittance of 0.1%, 1.6%, and 2.6% at 1640 nm, respectively. Similarly, the thresholds were 50, 70, and 95 mW. The 1640 nm laser emission takes place between the lower $^4I_{13/2}$ and the upper $^4I_{15/2}$ Stark level. While cascade lasing, this transition involves either a higher $^4I_{13/2}$ or a lower $^4I_{15/2}$ Stark level or both, and shifts the wavelength to 1620 nm. In the case of cascade lasing it might be possible that the $^4I_{13/2}$ multiplet is not in total thermal equilibrium because the 2810 nm transition selectively populates a specific higher Stark component of the multiplet. Such a situation would favor an operation of the $^4I_{13/2}$–$^4I_{15/2}$ transition at shorter wavelength than when operated with no cascading. Since the same laser crystal was used in both experiments, reabsorption is not considered a likely cause of the different laser wavelengths. However, it is also possible that the ground state multiplet is involved. The cascade laser increases direct pumping of the $^4I_{13/2}$ level while the direct radiative rates $^4I_{11/2}$–$^4I_{15/2}$ are reduced. This enhances ground state depletion and may cause the cascade laser to terminate in a lower Stark component of the ground state multiplet.

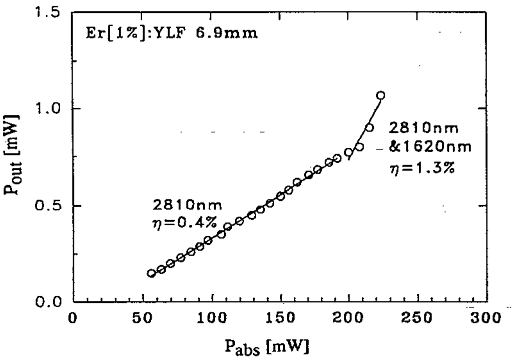

FIG. 3. The output-vs-input power curve for Er[1%]:YLF for 647 nm krypton laser excitation is given. In the first part of the curve the output power is related to the 2810 nm transition. During cascade lasing (the right side of the curve), the measured output power is the sum of that for both wavelengths.

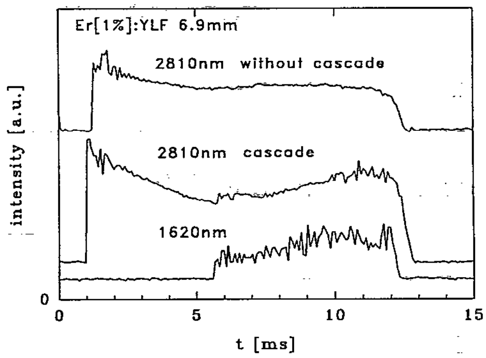

FIG. 4. Wave forms without and with cascade lasing at 2810 and 1620 nm for Er[1%]:YLF are shown. The rod was pumped with a mechanically chopped Ti:sapphire laser at 972 nm. The 1620 nm transition starts to lase after a delay of approximately 5 ms. Note that the 2810 nm power is higher when compared during cascade lasing than when operating alone.

Lasing in Er:YLF samples with lower doping concentration has been investigated previously.[11–13] However, to our knowledge, this is the first time that cw lasing at 2810 nm at room temperature is reported for a doping concentration as low as 5%. The output-vs-input power curve for the 2.2-mm-long Er[5%]:YLF rod lasing at 2810 nm pumping with 647 nm krypton laser is shown in Fig. 5. Because of the more efficient pump process in the $^4I_{11/2}$ level the slope efficiency is higher (1.6% as compared to 1.1%) and the threshold (15 mW as compared to 20 mW) is lower for the 972 nm excitation.

Simultaneous, cascade lasing is reported at both 2810 and 1620 nm at room temperature in 1% doped Er:YLF for 647 and 972 nm excitation. It is expected that the slope efficiencies can be improved with optimized cavity mirrors and rod lengths. Furthermore, Er:YLF rods with even lower concentrations should favor the 1620 nm transition and result in better performance. Lasing in Er[1%]:YLF at

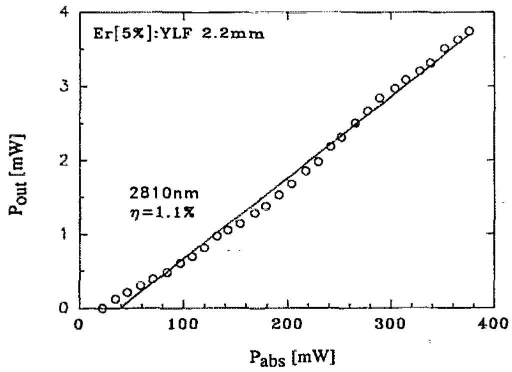

FIG. 5. Output-vs-input power curve for Er[5%]:YLF operating at 2810 nm pumped with 647 krypton laser excitation.

1640 nm and in Er[5%]:YLF at 2810 nm has been demonstrated.

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