Three-transition cascade erbium laser at 1.7, 2.7, and 1.6 μm

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We report on an upconversion cascade laser in an erbium-doped ZBLAN fiber emitting simultaneously on the three transitions $^4S_{3/2} \rightarrow {}^4I_{9/2}$ at 1.7 μm, $^4I_{11/2} \rightarrow {}^4I_{13/2}$ at 2.7 μm, and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 1.6 μm. At moderate pump powers, the laser transition at 1.6 μm supports 2.7-μm lasing and permits a slope efficiency at 2.7 μm of 15% versus launched pump power. Above the threshold of upconversion lasing at 1.7 μm, the slope efficiency at 2.7 μm increases to 25.4%. Taking pump excited-state absorption into account, this value represents more than 90% of the theoretical slope efficiency. A transversely single-mode output power of 99 mW is achieved at 2.7 μm.

The increasing interest in 2.7–2.8-μm lasers is evoked by applications in surgery.[1,2] Erbium-doped fluoride fibers are promising candidates for the construction of compact and efficient all-solid-state laser sources emitting between 2.7 and 2.8 μm. In diode-pumped double-clad fiber systems, generally a high-brightness transversely single-mode laser output can be achieved.[3] The resulting high output intensity is favorable for the ablation process in surgery.

In earlier research, a saturation of the output power of the fiber laser owing to competitive lasing at 850 nm was observed.[4] The saturation was recently overcome in an upconversion cascade lasing regime[5] at 1.7 and 2.7 μm by energy recycling into the 2.7-μm laser process. Stringent demands on the pump intensity, however, have prevented this system from double-clad pumping with low-brightness diode lasers. Other possibilities for overcoming the saturation effect are the quenching of the lower laser level by colasing at 1.6 μm (Ref. 6) or a combination of this approach with the upconversion cascade regime of Ref. 5, which results in lasing on three transitions.

In this Letter we report on a three-transition cascade laser emitting simultaneously on the transitions $^4S_{3/2} \rightarrow {}^4I_{9/2}$ at 1.7 μm, $^4I_{11/2} \rightarrow {}^4I_{13/2}$ at 2.7 μm, and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 1.6 μm (see Fig. 1). The quenching of the lower laser level of the 2.7-μm transition is achieved by a combination of cascade lasing at 1.6 μm and pump excited-state absorption[7] (ESA). The energy accumulated in the $^4S_{3/2}$ level is recycled into the laser process at 2.7 μm by cascade lasing at 1.7 μm. A slope efficiency of 25.4% is obtained at 2.7 μm, which is, to our knowledge, the highest value reported so far for an erbium 2.7-μm fiber laser. Differences between this three-transition cascade regime and the performance of a two-transition cascade regime at 1.7 and 2.7 μm are investigated.

A fluorozirconate fiber (labeled fiber A; see Table 1) is pumped by a Ti:sapphire laser at 792 nm. The pump beam is chopped with a frequency of 10 Hz and a duty cycle of 50%. Approximately 55% of the incident pump power is launched into the fiber. This value includes a transmission of the incoupling optics of 94%, a transmission of the incoupling mirror of 84%, and an estimated coupling efficiency into the fiber of 70%. The fiber length of 1.1 m minimizes reabsorption losses on the ground-state transition and ensures high pump absorption. More than 96% of the launched pump power is absorbed in the fiber through ground-state absorption (GSA) and ESA (see Fig. 1).

The mirrors are butt coupled to the fiber ends. Mirror transmissions are 88% at 850 nm, 1% at 1.6 μm, 1% at 1.7 μm, and 68% at 2.7 μm. High transmission at 850 nm increases the threshold of the high-gain 850-nm laser. Both the 1.6- and the 1.7-μm mirror transmissions are designed for high intracavity power rather than high output power to support lasing at 2.7 μm. The mirrors could not be optimized for the

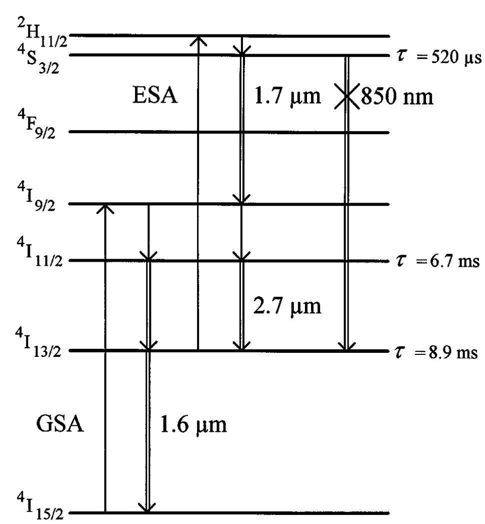

Fig. 1. Energy-level scheme of Er^{3+} in ZBLAN fiber. The system is pumped by GSA and ESA at 792 nm. Laser emission is obtained on the three transitions $^4S_{3/2} \rightarrow {}^4I_{9/2}$ at 1.7 μm, $^4I_{11/2} \rightarrow {}^4I_{13/2}$ at 2.7 μm, and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 1.6 μm. Competitive lasing at 850 nm is suppressed.

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Table 1. Parameters of the Investigated ZBLAN Fibers[a]

Parameters	Fiber A	Fiber B
Length (m)	1.1	4.8
Core diameter (μm)	6.0	6.5
N.A.	0.4	0.16
Er^{3+} concentration (parts in 10^6 mol.)	3000	1000
Slope efficiency 1	15%	7%
1.7-μm threshold (mW)	304	120
Slope efficiency 2	25.4%	22.6%

[a]Fibers are from Le Verre Fluoré. Lasing at 2.7 and 1.7 μm is obtained in both fibers; lasing at 1.6 μm is only in fiber A. Comparison of the slope efficiencies obtained at 2.7 μm: slope efficiency 1 is obtained below the threshold of upconversion lasing at 1.7 μm (i.e., lasing at 2.7 and 1.6 μm in fiber A, lasing at 2.7 μm in fiber B); slope efficiency 2 is obtained with 1.7-μm lasing.

highest 2.7-μm efficiency because the requirements at 792 nm, 850 nm, 1.6 μm, and 1.7 μm had to be matched.

The input–output characteristics of the laser are shown in Fig. 2. The threshold of 2.7- and 1.6-μm lasing is at 60-mW launched pump power. The slope efficiency at 2.7 μm is 15% in the two-transition cascade regime with 1.6-μm colasing but increases to 25.4% at the onset of 1.7-μm lasing and energy recycling into the 2.7-μm laser process above 304-mW launched pump power. The Stokes limit of the system for the pump wavelength of 792 nm is 29.3%. The theoretical limit of the slope efficiency, however, is slightly smaller than the Stokes limit, because there is a small loss owing to pump ESA from the $^4I_{11/2}$ level (not indicated in Fig. 1). Pump photons absorbed on this transition are not converted into laser photons at 2.7 μm, which decreases the quantum efficiency and reduces the limit of the slope efficiency to 27.5%.[8] The experimentally obtained value of 25.4% represents 92% of this maximum possible slope efficiency.

A transversely single-mode output power of 99 mW at 2.7 μm is achieved with 553-mW launched pump power. Above this pump-power level, an increase of the spot size of the Ti:sapphire laser as well as damage of the self-fabricated mirror coating is observed. The laser lines at 1.6 and 1.7 μm have output powers of approximately 1 mW because of the high mirror reflectance at these wavelengths. The three laser lines (see Fig. 3) are centered at 1.602, 1.716, and 2.702 μm.

These results are compared with results of a two-transition cascade regime at 1.7 and 2.7 μm, which are obtained with a different fiber (labeled fiber B; see Table 1). Several remarks are necessary: (i) The same resonator mirrors are used for both experiments. (ii) The product of the fiber length and the dopant concentration is smaller by a factor of 1.45 for fiber A; this leads to a reduced ground-state reabsorption that allows for lasing at 1.6 μm, which is not achieved with fiber B. (iii) The fraction of launched pump power absorbed in the fiber is larger than 96% in both experiments. (iv) Fiber A has improved parameters of core diameter and N.A. for better guiding of the 2.7-μm laser line.

The improved fiber parameters as well as colasing at 1.6 μm increase the 2.7-μm slope efficiency at lower pump power from 7% (fiber B) to 15% (fiber A). The 1.6-μm laser repopulates the ground state and ensures that a high fraction of pump power is absorbed on the GSA transition that feeds the 2.7-μm laser. The threshold of 1.7-μm lasing and energy recycling into the 2.7-μm laser process, however, increases from 120 mW (fiber B) to 304 mW (fiber A). This is caused by the additional depletion of the $^4I_{13/2}$ level through 1.6-μm lasing, which weakens the pump ESA from this level and decreases the excitation of the $^4S_{3/2}$ level from which the 1.7-μm laser originates.[9]

In the upconversion cascade regime with 1.7-μm lasing, the slope efficiency at 2.7 μm is increased from 22.6% (fiber B) to 25.4% (fiber A) because of the improved fiber parameters. Additional lasing on the third transition at 1.6 μm transfers population from the $^4I_{13/2}$ level to the $^4I_{15/2}$ level. Whether this influences the laser performance in the upconversion cascade regime depends on the fraction of launched pump power that is absorbed within the fiber. The ESA transition from the $^4I_{13/2}$ level has a higher absorption cross section than the GSA transition.[4] If not all the pump power is absorbed, it is potentially better to maintain the population in the $^4I_{13/2}$ level rather than to transfer it to the ground state, because then the increase in ESA exceeds the decrease in GSA.[8] In the present cases, most of the launched

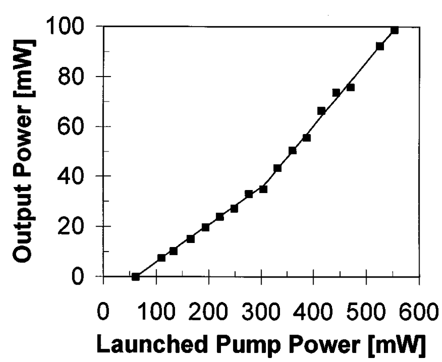

Fig. 2. Input–output curve at 2.7 μm obtained with fiber A operating in two different cascade regimes. Below 304-mW launched pump power: emission at 2.7 and 1.6 μm, slope efficiency $\eta = 15\%$. Above 304 mW: emission at 1.7, 2.7, and 1.6 μm, $\eta = 25.4\%$.

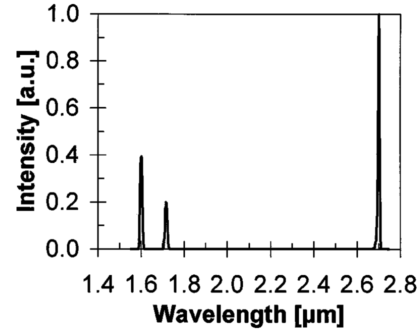

Fig. 3. Spectral behavior of the emission at 1.602, 1.716, and 2.702 μm. The intensities of the 1.6- and 1.7-μm lines are magnified by a factor of 20.

pump power is absorbed within the fiber. It is of no importance whether a pump photon is absorbed through GSA or ESA from the lower laser level. The pump photon is converted into a laser photon at 2.7 μm in both cases (see Fig. 1). Thus the 1.6-μm laser does not influence the slope efficiency in the upconversion cascade regime.

In conclusion, we have demonstrated an erbium ZBLAN fiber cascade laser operating on the three transitions $^4S_{3/2} \rightarrow {}^4I_{9/2}$ at 1.7 μm, $^4I_{11/2} \rightarrow {}^4I_{13/2}$ at 2.7 μm, and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 1.6 μm. A slope efficiency of 25.4% is achieved at 2.7 μm. This represents more than 90% of the possible slope efficiency at the pump wavelength of 792 nm. A transversely single-mode output power of 99 mW is obtained at 2.7 μm. Both the 1.7 and the 1.6-μm transitions improve the performance of the laser operating solely at 2.7 μm. Comparison with a two-transition cascade laser regime at 1.7 and 2.7 μm shows that colasing at 1.6 μm is advantageous in the low-power region below the 1.7-μm threshold but that the threshold for energy recycling into the 2.7-μm laser process through 1.7-μm lasing increases. Above the threshold of 1.7-μm lasing, the 1.6-μm laser does not influence the system. The slope efficiency at 2.7 μm in the high-power region is enhanced by improved fiber parameters.

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