150 mW unsaturated output power at 3 μm from a single-mode-fiber erbium cascade laser

M. Pollnau,[a] Ch. Ghisler, G. Bunea,[b] M. Bunea,[b] W. Lüthy, and H. P. Weber
Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

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We report on an erbium cascade laser in a fluorozirconate fiber. Lasing on the transition $^4I_{11/2}\rightarrow{}^4I_{13/2}$ at 2.71 μm is supported by colasing on the transition $^4S_{3/2}\rightarrow{}^4I_{9/2}$ at 1.72 μm. This recycles the excitation that is lost via excited-state absorption and avoids the saturation of the output power. Threshold at 2.71 μm is 33 mW launched pump power at 791 nm. The measured slope efficiency of 22.6% is relatively close to the 29.1% stokes-efficiency limit. An output power of 158 mW is obtained, limited only by the 1.43 W power available from the Ti: sapphire pump laser. Output power is 15 and slope efficiency 2.5 times higher than reported in previous publications. © *1995 American Institute of Physics.*

Erbium-doped fluoride fibers are promising candidates for the construction of compact and efficient all-solid-state laser sources. The guiding of pump and laser beam through the fiber core results in a perfect overlap between the two beams and allows for a low laser threshold and high efficiency. The continuously rising interest in the 3 μm erbium laser is evoked by applications in medicine, especially in surgery.[1] For these applications a powerful fiber-laser source would be most suitable. The 3 μm erbium fluorozirconate fiber, however, exhibits a slope efficiency below 10% and saturates at a low output power in the range of 10 mW[2–5] depending on dopant concentration and pump wavelength. This saturation behavior has been previously addressed to ground-state bleaching.[6]

We have analyzed the saturation effect in computer simulations and experiments.[7,8] In this letter we report on an unsaturated continuous-wave cascade laser at 1.72 and 2.71 μm on the transitions $^4S_{3/2}\rightarrow{}^4I_{9/2}$ and $^4I_{11/2}\rightarrow{}^4I_{13/2}$. In an erbium-doped single-mode fiber an output power of 158 mW at 2.71 μm is achieved, limited only by the maximum power available from the pump laser. A slope efficiency of 22.6% versus launched pump power is measured. The output power is fifteen times higher and the slope efficiency is 2.5 times larger than reported in previous publications.[2–5]

The laser cavity consists of a fluorozirconate fiber (Le Verre Fluoré). In two different experiments (see Table I), fibers doped with 1000 and 5000 ppm mol Er^{3+} ions, respectively, are investigated. The fibers have a core diameter of 6.5 μm, N.A.=0.156, a cutoff wavelength of 1.3 μm, and are, therefore, single mode at both the 2.71 and 1.72 μm wavelengths. The fibers are cw pumped with an Ar^+-laser-pumped Ti:sapphire laser that provides a maximum power of 1.43 W at the pump wavelength 791 nm. The overall coupling efficiency of the pump power into the fiber is 56%, including the mirror transmission at the pump wavelength. The mirrors are butt-coupled to the fiber ends. They were specially manufactured at our institute to decrease the threshold of the $^4S_{3/2}\rightarrow{}^4I_{9/2}$ laser transition at 1.7 μm[9] and to suppress competitive lasing on the $^4S_{3/2}\rightarrow{}^4I_{13/2}$ transition at 850 nm,[10] which has a large emission cross section. Therefore, the mirrors have a high reflectivity at 1.7 μm and a high transmission at 850 nm (see Table I). The transmission on the order of 70% at 2.7 μm for input and output mirrors is not optimized for maximum output power at 2.7 μm. Investigations in a similar arrangement[5] showed that owing to strong fiber losses, a low mirror reflectivity combined with high single-pass gain lead to the highest output power at 2.71 μm.

Figure 1 displays the energy-level scheme of Er^{3+} in fluorozirconate fibers. The Er^{3+} ions are excited via ground-state absorption (GSA) at 791 nm to the $^4I_{9/2}$ level and fast multiphonon relaxation leads to the population of the $^4I_{11/2}$ upper level of the 2.71 μm transition. Although the lifetime of the $^4I_{11/2}$ level is smaller than the lifetime of the $^4I_{13/2}$ level, cw population inversion between the $^4I_{11/2}$ and $^4I_{13/2}$ multiplets is established due to the large branching ratio for the $^4I_{11/2}\rightarrow{}^4I_{15/2}$ transition.[11,12] Gain on this transition leads to 2.71 μm lasing. Excited-state absorption (ESA) from the $^4I_{13/2}$ level into the $^2H_{11/2}$ level[13] and subsequent thermal relaxation efficiently populate the $^4S_{3/2}$ level. This is a strong

TABLE I. Experimental data for the two experiments performed. Slope efficiencies are given for the 2.71 μm laser only. Slope efficiency 1 is measured in the range between the thresholds of 2.71 μm lasing and 1.72 μm lasing, slope efficiency 2 in the cascade-lasing regime.

	Experiment 1	Experiment 2
Fiber data		
Length	0.78 m	4.8 m
Dopant conc.	5000 ppm mol	1000 ppm mol
Mirror data		
791 nm pump	T=85%	T=84%
850 nm laser	R=12%	R=10%
1.72 μm laser	R=94%	R=99%
2.71 μm laser	R=25%	R=32%
Laser data		
2.71 μm threshold	88 mW	33 mW
1.72 μm threshold	250 mW	120 mW
2.71 μm slope eff. 1	2.6%	7.6%
2.71 μm slope eff. 2	18.3%	22.6%

[a]Electronic mail: pollnau@iap.unibe.ch
[b]On leave from the Institute of Microtechnology-Bucharest, P.O. Box 36-160, Bucharest-70225, Romania. Electronic mail: gabib@zeus.imt.ro

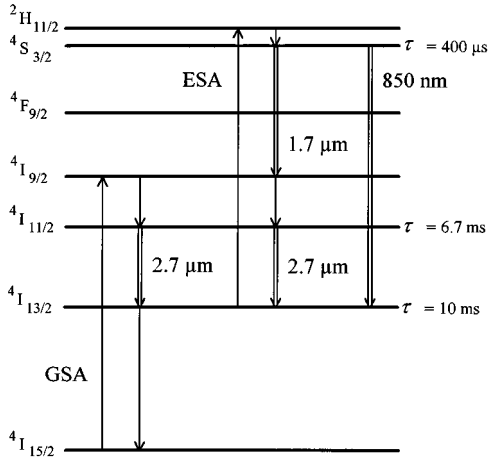

FIG. 1. Energy level scheme of erbium in fluorozirconate fibers indicating the two loops that drive the 2.71 μm laser transition: lower loop with GSA $^4I_{15/2}\rightarrow{}^4I_{9/2}$, multiphonon relaxation to $^4I_{11/2}$, laser transition $^4I_{11/2}\rightarrow{}^4I_{13/2}$ at 2.7 μm, fluorescence decay to $^4I_{15/2}$, and upper loop with ESA $^4I_{13/2}\rightarrow{}^2H_{11/2}$, thermal relaxation to $^4S_{3/2}$, laser transition $^4S_{3/2}\rightarrow{}^4I_{9/2}$ at 1.7 μm, multiphonon relaxation to $^4I_{11/2}$, laser transition $^4I_{11/2}\rightarrow{}^4I_{13/2}$ at 2.7 μm. Possible competitive colasing on the transition $^4S_{3/2}\rightarrow{}^4I_{13/2}$ at 850 nm is also indicated.

loss channel for the four-level laser loop $^4I_{15/2}\rightarrow{}^4I_{9/2}\rightarrow{}^4I_{11/2}\Rightarrow{}^4I_{13/2}\rightarrow{}^4I_{15/2}$. Competitive colasing at 850 nm on the transition $^4S_{3/2}\rightarrow{}^4I_{13/2}$ is responsible for the saturation of the 3 μm laser output,[7] because the strong 850 nm transition is efficiently fed by the ESA and directly populates the lower laser level of the 2.71 μm transition. However, even without 850 nm lasing, the 2.71 μm laser would saturate, because a large fraction of the Er^{3+} ions is excited to the $^4S_{3/2}$ level and would remain there if no laser transition starts from this level.[7] Only cascade lasing on the loop $^4I_{13/2}\rightarrow{}^2H_{11/2}/{}^4S_{3/2}\Rightarrow{}^4I_{9/2}\rightarrow{}^4I_{11/2}\Rightarrow{}^4I_{13/2}$ can suppress the 850 nm line and simultaneously recycle the energy from the $^4S_{3/2}$ level. As the ESA cross section has twice the value of the GSA cross section,[7] the laser operates to a considerable fraction in the upper-loop cascade regime.

The input-output curves for the 2.71 μm laser are shown in Fig. 2. For the 1000 ppm mol fiber and with higher mirror reflectivity at 1.7 μm (see Table I, experiment 2), the threshold for the 2.71 μm laser is 33 mW pump power launched into the fiber core. Below the onset of 1.72 μm colasing at a threshold of 120 mW, the slope efficiency is 7.6%, which is comparable to previous experiments without cascade lasing.[2–5] The slope efficiency at 2.71 μm increases considerably to 22.6% due to the recycling of energy from the $^4S_{3/2}$ level when the 1.72 μm laser sets on. The measured slope efficiency is relatively close to the stokes-efficiency limit of $h\nu_{\text{laser}}/h\nu_{\text{pump}}=29.1\%$. The smaller slope efficiency obtained in experiment 1 is mainly an effect of the dopant concentration.[5] Output powers at 2.71 μm of 112 mW from the rear fiber end and 46 mW from the input fiber end are achieved. The output power of 158 mW at 2.71 μm obtained from both fiber ends can be expected to be emitted from the rear fiber end alone if the incoupling mirror has a reflectivity of >99% at 2.71 μm. The output power is only limited by the maximum power of 1.43 W available from the Ti:sapphire pump laser at 791 nm. The values obtained for the output power and slope efficiency make this fiber laser comparable to the most efficient transversally single-mode erbium crystal lasers reported so far.[14]

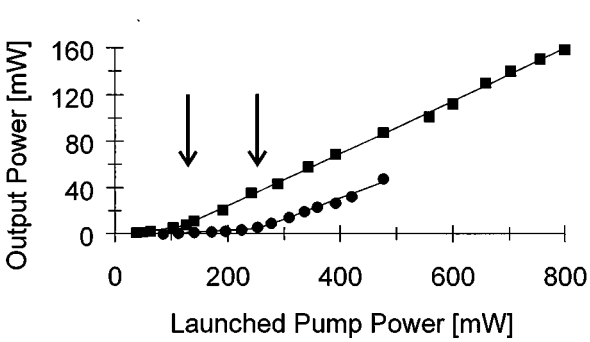

FIG. 2. Input-output curve for the 2.7 μm laser transition. Circles denote the curve for experiment 1, squares the curve for experiment 2 (see Table I). The indicated output power is the sum of the output powers measured at both fiber ends. Arrows indicate the threshold for the 1.7 μm laser and the onset of cascade lasing in the different experiments.

The 1.7 μm laser has a maximum output power of 9 mW with mirror reflectivities of 94% at 1.72 μm. When using the mirrors which 99% reflectivity, the threshold for the 1.72 μm laser is reduced. The recycling of energy starts at a lower pump power, which enhances the overall efficiency of the 2.71 μm laser. The maximum output power at 1.72 μm decreases to <1 mW. 850 nm colasing is suppressed by reducing the threshold for 1.72 μm with high-reflectivity mirrors at this wavelength, and by maintaining a high threshold for the 850 nm laser due to a high mirror transmission. With well-aligned mirrors, no colasing at 850 nm is observed. When the mirrors are slightly misaligned, the threshold for the 1.7 μm line increases, strong lasing at 850 nm is observed instead, and the output power for the 2.71 μm laser decreases to the 10 mW value obtained without cascade lasing.

In conclusion, we have achieved an output power of 158 mW at 2.71 μm from an erbium-doped single-mode fluorozirconate-fiber cascade laser working on the transitions $^4I_{11/2}\rightarrow{}^4I_{13/2}$ and $^4S_{3/2}\rightarrow{}^4I_{9/2}$. The threshold for the 2.71 μm transition is 33 mW with a slope efficiency of 22.6% in the cascade lasing regime, which is relatively close to the stokes-efficiency limit of 29.1%. The output power is limited only by the pump power available from the Ti:sapphire laser. This represents the removal of the saturation effect observed so far in the erbium 3 μm fiber laser and makes this laser able to compete with the most efficient erbium 3 μm crystal lasers.

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