

784-nm amplified spontaneous emission from Tm³⁺-doped fluoride glass fiber pumped by an 1120-nm fiber laser

Guanshi Qin, Shenghong Huang, Yan Feng, A. Shirakawa, and Ken-ichi Ueda

Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Tokyo 182-8585, Japan

Received August 20, 2004

We report 784-nm ($^1G_4 \rightarrow ^3H_5$ transition) amplified spontaneous emission (ASE) from Tm³⁺-doped fluoride (ZrF₄-BaF₂-LaF₃-AlF₃-NaF) glass fiber pumped by an 1120-nm fiber laser. To our best knowledge, this is the first report of 784-nm ($^1G_4 \rightarrow ^3H_5$ transition) ASE in a Tm³⁺-doped fluoride fiber laser. Its effects on a 480-nm ($^1G_4 \rightarrow ^3H_6$ transition) blue laser were also discussed. © 2005 Optical Society of America
 OCIS codes: 140.3510, 140.5680.

Since the first report of the blue upconversion laser in a Tm-doped ZrF₄-BaF₂-LaF₃-AlF₃-NaF (ZBLAN) glass fiber,¹ ultraviolet and visible upconversion fluoride glass fiber lasers have attracted much attention because they have a wide range of applications, including high-density optical data storage, all-color displays, undersea communications, and biomedicine. Up to now, visible upconversion fluoride (doped with Tm³⁺, Pr³⁺, Er³⁺, Ho³⁺, and Yb³⁺ ions) glass fiber lasers have been obtained.²⁻¹¹ Sanders *et al.*² reported a laser-diode-pumped 106-mW blue upconversion laser in Tm³⁺-doped ZBLAN fiber. Zellmer and co-workers^{9,10} demonstrated red, green, and blue upconversion lasers in Pr³⁺ and Yb³⁺ codoped ZBLAN fibers. At present, high-power (>1-W) visible, and especially blue, upconversion fiber lasers are the next objective of researchers. Among the above-mentioned fluoride fibers, the efficiency of blue lasers in Tm³⁺-doped ZBLAN fiber is the highest by as much as 31.7%.³ But the existence of the photodegradation effect in Tm³⁺-doped ZBLAN fiber at high pump power limits the enhancement of the output power of blue lasers.¹²⁻¹⁵ Therefore study of these effects, including photodegradation and other unexpected phenomena, is necessary and valuable for the optimization of blue upconversion fiber lasers.

In this Letter we report a new phenomenon in Tm³⁺-doped ZBLAN fiber, i.e., 784-nm ($^1G_4 \rightarrow ^3H_5$ transition) amplified spontaneous emission (ASE) from Tm³⁺-doped fluoride glass fiber pumped by an 1120-nm fiber laser. To our best knowledge, this is the first report of 784-nm ($^1G_4 \rightarrow ^3H_5$ transition) ASE in Tm³⁺-doped fluoride fiber laser. Its effects on a 480-nm ($^1G_4 \rightarrow ^3H_5$ transition) blue laser are also discussed.

In our experiments the pump laser was a Raman fiber laser operating at 1120 nm, pumped by a 106-nm Yb³⁺-doped fiber laser, which is similar to a previous report on an 1178-nm Raman fiber laser.¹⁶ A simple Fabry-Perot cavity was adopted that was composed of a fiber Bragg grating (FBG1, with reflectivity at 1120 nm larger than 99%), gain fiber, and a second FBG (FBG2, with reflectivity of 15%). The FBG mirrors were fabricated on a Flexcor-1060 fiber. The Raman gain medium was

a phosphorous-doped single-mode optical fiber with 12 mol.% of P₂O₅ with a refractive-index difference of 0.0107. The pumping source was an Yb-doped double-clad fiber laser (PYL-8M) with continuous-wave 8-W, 1064-nm single-mode output, and its out pigtail was a Flexcor-1060 single-mode fiber with a core diameter of 6 μm. With the maximum current of 1.55 A, we obtained output power of 4 W at 1120 nm.

The commercial Tm-doped fluoride fiber (KDD Fiberlabs, Japan) that we used had a TM concentration of 1000 parts in 10⁶ (by weight), a numerical aperture of 0.25, and a core diameter of 3.3 μm, corresponding to a cutoff wavelength of 1140 nm. A fiber length of 2.8 m was used for all the experiments. Both fiber ends were cut by a FK-11 fiber cleaver. We launched 1120-nm pump light into the fiber core through a pair of aspheric lenses. Tests with a short fluoride fiber (10 cm) showed that the launch efficiency, defined as launched power divided by power incident on the lens, was ~40%. The output spectrum of the fiber end and the launched power were measured with an AQ-6315A optical spectrum analyzer (ANDO, Japan) and a Labmaster optical powermeter (Coherent, Santa Clara, California). All the measurements were made at room temperature.

Figure 1(a) shows the upconversion emission spectra of the fluoride glass fiber at different pump powers. Emissions in the visible and near-infrared range come from the following transitions: $^1D_2 \rightarrow ^3F_4$ (~450 nm), $^1G_4 \rightarrow ^3H_6$ (~474 nm), $^1G_4 \rightarrow ^3F_4$ (~647 nm), $^1G_4 \rightarrow ^3H_5$ (~784 nm), and $^3H_4 \rightarrow ^3H_6$ (~810 nm). It is evident that the emissions at 474, 647, and 784 nm come from the same excited state, 1G_4 . The upconversion mechanism in Tm³⁺-doped fluoride glass fiber excited at 1120 nm has been investigated widely,¹⁷ as shown in Fig. 1(b). First, by excitation with an 1120-nm laser, the electrons at the ground state were promoted to the 3H_5 level. Through multiphonon nonradiative relaxation they populated the 3F_4 level, then the 3F_3 level, the 3H_4 level, and the states 1G_4 and 1D_2 . From Fig. 1(a), one can see that the emission at 784 nm ($^1G_4 \rightarrow ^3H_5$ transition) grows faster than at 647 and 474 nm with increasing pump power. As was mentioned above as evidence, three emissions come from the same upper state, 1G_4 . But why did

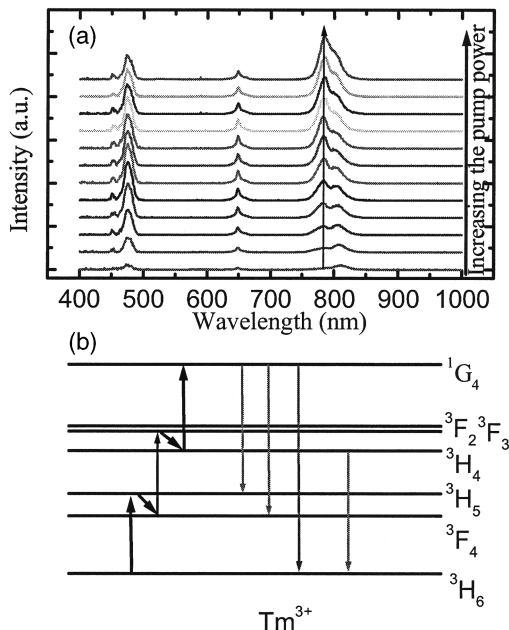


Fig. 1. (a) Upconversion emission spectra of fluoride glass fiber at different pump powers. (b) Upconversion mechanism in Tm^{3+} -doped fluoride glass fiber excited at 1120 nm.

the branching ratio of the $^1G_4 \rightarrow ^3H_5$ transition change with increasing pump power? As is known, ASE can alter the effective branching ratio from a single level to several others.^{18,19} Another effect should be considered for the change of the branching ratio, i.e., the enhancement of the loss in the short-wavelength range caused by photodegradation.¹⁴ To clarify the mechanisms of the change of the branching ratio, we carried out the following experiments.

The intensity dependence of the upconversion emissions on the pump power was measured, as shown in Fig. 2(a). In the initial stage three upconversion emissions grow with increasing pump power, which is a general description of three-photon upconversion processes. Subsequently, 474- and 647-nm emissions decrease; however, 784-nm emissions still increase, which agrees with the description given above. Figure 2(b) gives the width dependence of three upconversion emissions on the pump power. For 474- and 647-nm emissions the widths remain constant with increasing pump power, whereas that of the 784-nm emission decreases. These results confirm that 784-nm ASE exists in Tm^{3+} -doped fluoride glass fiber. In addition, we also observed 810-nm ASE (data not shown).²⁰

From the loss spectrum and wavelength of emission of the ZBLAN glass fiber (data not shown), the loss at 647 nm is nearly the same as that at 784 nm. So if the enhancement of the loss in the short-wavelength range caused by photodegradation were the main reason for the change of the branching ratio, the branching ratio of 647-nm emission would be enhanced by increasing the pump power. Figure 3 presents the branching ratio dependence of three emissions on the pump power. The negative result excludes photodegradation from the mechanism to cause the change of

the branching ratio. On the other hand, when we measured the upconversion spectra at a certain pump power (up to 1.55 A), repeated measurements showed that the upconversion emissions did not diminish with time. This result also indicates that photodegradation does not exist in our experimental conditions. So we believe that the existence of 784-nm ASE is the main reason for the change of the branching ratios from 1G_4 to 3H_5 , 3F_4 , and 3H_6 .

We also performed blue fiber laser experiments. Two mirrors, one with high reflectivity at 474 nm, and an output coupler that varied from 99% to 60%, were butted with the fiber ends. Although we tried to obtain a blue upconversion laser, no blue laser was observed. In addition, with increasing pump power, a final diminishing of blue upconversion luminescence from the outer wall of ZBLAN fiber was visible to our naked eyes, which is similar to the results given above, as shown in Fig. 2(a). As the launched power was as much as 1.8 W, we observed 784-nm upconversion laser (data not shown) in the present fiber butted with

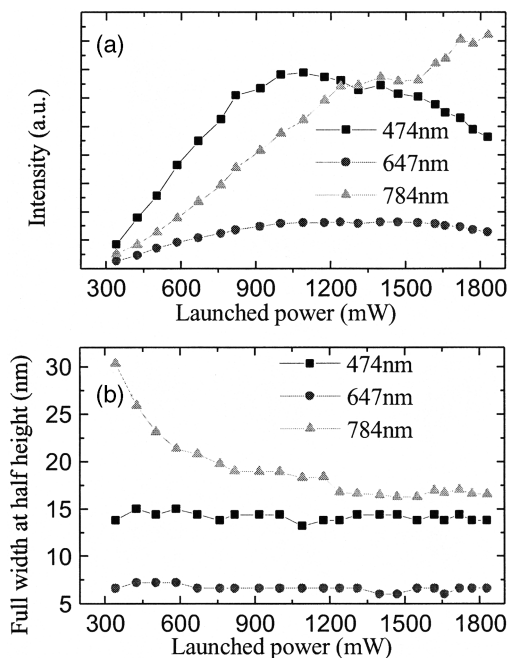


Fig. 2. (a) Intensity dependence of upconversion emissions on pump power. (b) Width dependence of three upconversion emissions on pump power.

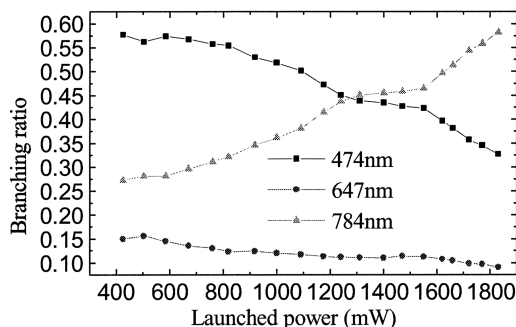


Fig. 3. Branching ratio dependence of three emissions on pump power.

two mirrors, one with high reflectivity at 474 nm, and an output coupler with 80% reflectivity at 474 nm. We measured the reflectivity at 784 nm of these two mirrors, both with 40% reflectivity at 784 nm.

Generally, the stimulated-emission cross section of the ${}^1G_4 \rightarrow {}^3H_6$ transition is larger than that of the ${}^1G_4 \rightarrow {}^3H_5$ transition in Tm^{3+} -doped ZBLAN glass fiber. But why can 784-nm lasing be obtained in the present high-loss cavity but not 474-nm lasing in the low-loss cavity? From the loss spectrum and wavelength of emission of the ZBLAN glass fiber, the internal loss at 474 nm of undoped ZBLAN fiber is larger than that at 784 nm. For different commercial ZBLAN fibers, the loss spectrum and wavelength of emission are different. If the internal loss at 474 nm of a fiber is large enough to cut off the net gain of the ${}^1G_4 \rightarrow {}^3H_6$ transition, as with the fluoride fiber we used, one cannot obtain blue upconversion lasing. In this case, for 784-nm emission, because of the low internal loss of ZBLAN fluoride fiber, the net gain can be obtained. With increasing pump power, 784-nm lasing can be obtained.

Note that, for low-loss ZBLAN fiber, although a blue upconversion laser can be obtained, the competition between the ${}^1G_4 \rightarrow {}^3H_5$ and ${}^1G_4 \rightarrow {}^3H_6$ transitions is still detrimental to optimization of a blue upconversion laser. Fabrication of fluoride fiber with ultralow loss at 474 nm can inhibit 784-nm ASE and optimize blue upconversion fiber lasing. For operation of a blue fiber laser with ultralow loss in 474-nm fluoride fiber, both the input and the output mirrors should be high transmission at 784 nm by use of coating technology that can inhibit 784-nm lasing and further optimize the blue upconversion fiber laser.

The effects of the length of ZBLAN glass fiber on 784-nm ASE were investigated. When we shortened the length of the fiber (~ 80 cm), 784-nm ASE was still observed. In comparison with that in the 2.8-m-long fiber, 784-nm ASE became weak at the same launched power. But shortening the fiber can also decrease the net gain of 474-nm emission. Selection of the fiber length might be important for optimization of a blue upconversion fiber laser. For different commercial fibers, the appropriate length should be different because of the different loss spectra and wavelengths of emission.

In summary, we have observed 784-nm (${}^1G_4 \rightarrow {}^3H_5$ transition) amplified spontaneous emission (ASE) from Tm^{3+} -doped fluoride (ZBLAN) glass fiber pumped by an 1120-nm fiber laser and investigated its effects on a blue upconversion laser. From our experimental results, 784-nm ASE is detrimental to the optimization of blue upconversion fiber lasing. Fabrication of flu-

oride fiber with ultralow loss at 474 nm can inhibit 784-nm ASE and optimize blue upconversion fiber lasing. For operation of a blue fiber laser, both the input and the output mirrors should be made highly transmissive at 784 nm by use of coating technology that can inhibit 784-nm lasing and further optimize blue upconversion fiber lasing.

This work was partly supported by the 21st Century Center of Excellence Program of the Ministry of Education, Culture, Sports, Science and Technology of Japan. G. Qin's e-mail address is gsqin@yahoo.com.

References

1. J. Y. Allain, M. Monerie, and H. Poignant, *Electron. Lett.* **26**, 166 (1990).
2. S. Sanders, R. G. Waarts, D. G. Mehuys, and D. F. Welch, *Appl. Phys. Lett.* **67**, 1815 (1995).
3. S. G. Grubb, K. W. Bennett, R. S. Cannon, and W. F. Humer, *Electron. Lett.* **28**, 1243 (1992).
4. R. Paschotta, N. Moore, W. A. Clarkson, A. C. Tropper, D. C. Hanna, and G. Maze, *IEEE J. Sel. Top. Quantum Electron.* **3**, 1100 (1997).
5. D. S. Funk, J. G. Eden, J. S. Osinski, and B. Lu, *Electron. Lett.* **33**, 1958 (1997).
6. H. M. Pask, A. C. Tropper, and D. C. Hanna, *Opt. Commun.* **134**, 139 (1997).
7. D. M. Baney, G. Rankin, and K. W. Chang, *Appl. Phys. Lett.* **69**, 1662 (1996).
8. T. Sandrock, H. Scheife, E. Heumann, and G. Huber, *Opt. Lett.* **22**, 808 (1997).
9. H. Zellmer, P. Reidel, and A. Tunnermann, *Appl. Phys. B* **69**, 417 (1999).
10. H. Zellmer, P. Riedel, M. Kempe, and A. Tunnermann, *Electron. Lett.* **38**, 1250 (2002).
11. M. Zeller, H. G. Limberger, and T. Lasser, *IEEE Photon. Technol. Lett.* **15**, 194 (2003).
12. P. R. Barber, R. Paschotta, A. C. Tropper, and D. C. Hanna, *Opt. Lett.* **20**, 2195 (1995).
13. P. Laperle, A. Chandonnet, and R. Vallée, *Opt. Lett.* **20**, 2484 (1995).
14. I. J. Booth, J.-L. Archambault, and B. F. Ventrudo, *Opt. Lett.* **21**, 348 (1996).
15. P. Laperle, A. Chandonnet, and R. Vallée, *Opt. Lett.* **22**, 178 (1997).
16. S. Huang, Y. Feng, A. Shirakawa, and K. Ueda, *Jpn. J. Appl. Phys.* **42**, L1439 (2003).
17. R. Paschotta, P. R. Barber, A. C. Tropper, and D. C. Hanna, *J. Opt. Soc. Am. B* **14**, 1213 (1997).
18. B. Li, G. Williams, S. C. Rand, T. Hinklin, and R. M. Laine, *Opt. Lett.* **27**, 394 (2002).
19. G. Qin, W. Qin, C. Wu, S. Huang, D. Zhao, J. Zhang, and S. Lu, *Opt. Commun.* **242**, 215 (2004).
20. M. L. Dennis, J. W. Dixon, and I. Aggarwal, *Electron. Lett.* **30**, 136 (1994).