International Journal of Optics and Applications 2012, 2(5): 72-75
DOI: 10.5923/j.optics.20120205.03

A Green Upconversion Laser with Erbium-Doped $LiLuF_4$ Crystal by 976 nm Fiber Laser Pump

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Abstract A stable fiber laser operating at approximately 976 nm peak power at a 280 ns and 1.9 W pump was used as a pumping source for an upconversion laser based on an Er 3+ :doped LiLuF4 crystal. A 548 nm wavelength and 320 mW could be achieved. In this study, we used a 976 nm low threshold average pump power fiber laser at 8 mW, which can achieve green upconversion laser output at room temperature. This system includes a high reflective coating at 552 nm+/-10 nm on the LiLuF4 crystal and a 96% reflective mirror forming a laser cavity for the 548 nm laser. Using the laser cavity setup and 976 nm fiber laser pump, low threshold pump power green erbium upconversion lasing was achieved. The two peak wavelengths of 548 nm and 537 nm are observed and the intensity changes by changing the input to 976 nm pump power.

Keywords Erbium-Doped, Green Upconversion, $LiLuF_4$ Crystal

1. Introduction

Upconversion lasers are particularly attractive because of their wide lasing wavelength range from infrared to ultraviolent[1,2] and are used in various applications, such as medical diagnosis, medical treatment, industrial machining, and full-color all-solid-state displays[3,4].

Compared with semiconductor diode lasers, with which lasing in the green wavelength region at room temperature is difficult[5], upconversion lasers are reported to enable lasing in the green wavelength region with different hosts of low phonon energy, including $LiLuF_4$, $LiYF_4$, BaY_2F_8, and ZBLAN (ZrF_4–BaF_2–LaF_3–AlF_3–NaF)[6,7]. These low phonon-energy hosts are popular in upconversion lasers because of their lower nonradiative relaxation rates and their longer lifetimes in more highly excited states. Lower nonradiative relaxation rates and longer lifetimes in highly excited states are critical in enabling a laser to overcome population inversion.

This study focuses on an upconversion laser system composed of near-infrared light sources and rare-earth-doped crystals[7]. This upconversion is a non-linear process that involves two or more low-energy excitation photons being converted into one or two high-energy photons. Particularly, erbium (Er^{3+})-doped materials are more suitable for the upconversion processes because of the unique energy level structure of Er^{3+}. By absorbing the radiation of near-infrared light, visible radiation emits from rare-earth-doped crystals. Fig. 1 shows the upconversion process. In Er^{3+}:$LiLuF_4$, for example, when pumped by a 976 nm light source, the trivalent erbium ion with multiplet $^4I_{3/2}$ is excited by two sequential steps. The first step is ground-state absorption from $^4I_{15/2}$ to $^4I_{11/2}$. The second step is an excited state from $^4I_{11/2}$ to $^4F_{7/2}$. The $^4I_{11/2}$ is the so-called intermediate level. The excited photon relaxes to $^4S_{3/2}$ then decays to a ground state with emitting visible radiation at 548 nm[8-10].

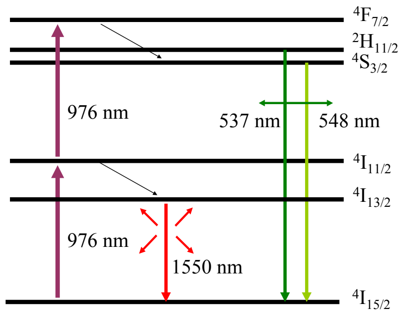

Figure 1. Energy level scheme of Er^{3+}:$LiLuF_4$ with 976nm pump laser

The upconversion excitation and emission channel are at 548 nm. Various rare-earth-doped fluoride crystals have been demonstrated in room-temperature upconversion lasing in the visible spectral range; however, laser operation could only be achieved with high pump power. This study used single-mode 976 nm pulse fiber laser pumping

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Published online at http://journal.sapub.org/optics

Er^{3+}:$LiLuF_4$ crystals to create a low-pumping power and a low-cost visible laser light.

2. Experimental Setup

As mentioned previously, lower nonradiative relaxation rates and longer lifetimes in highly excited states are critical in enabling a laser to overcome population inversion. In this study, we selected specifications of $LiLuF_4$ crystal has expected small phonon energy because the mass of Lu^{3+} ion is high, and the high lifetime of meta stable state, as shown in Fig. 2. The face of the $LiLuF_4$ crystal was prepared by using a coated mirror, which is a high transmitter of the pump wavelength (976 nm) and a high reflector of the laser wavelength (548 nm), as shown in Fig. 3.

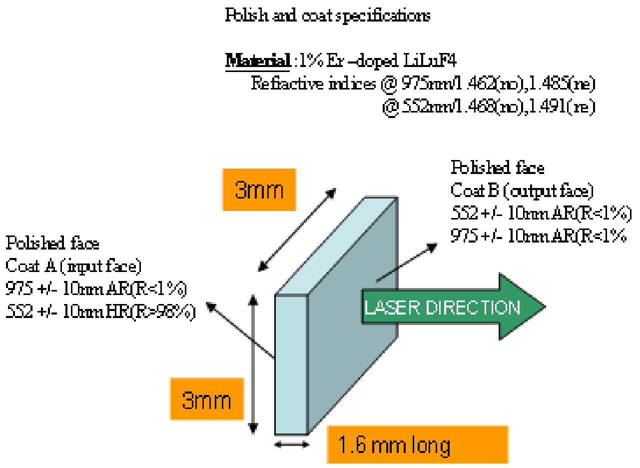

Figure 2. Polish and coating specifications of $LiLuF_4$ crystal

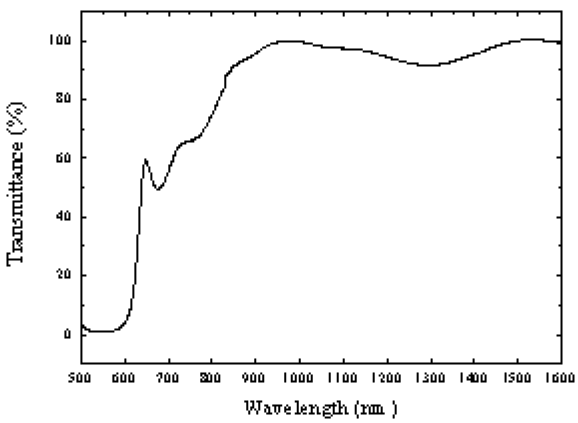

Figure 3. High reflective coating range to 548 nm on LiLuF4 crystal

Fig. 4 depicts the schematic design of the upconversion experimental setup. The 976 nm pump light with a width of 280 ns and a repetition rate of 9 kHz is collimated to the $LiLuF_4$ crystal by a lens[11]. Mirror 1 transmits highly at 1550 nm, reflects highly at 976 nm, and has a 4% transmittance for a 548 nm wavelength, as shown in Fig. 5. The coating on the $LiLuF_4$ crystal and Mirror 1 form a laser cavity for the 548 nm laser. The pump light reflects from Mirror 1 to the $LiLuF_4$ crystal results in twofold pumping and enhances the upconversion. Mirror 2 is transmits highly at 548 nm, reflects highly reflecting for 976 nm and 1550 nm wavelength as shown in Figure 6.The excited 1550 nm light leave the cavity by anti-reflector Mirror 1 and Mirror2 at 1550 nm to achieve a 548 nm single-wavelength output.

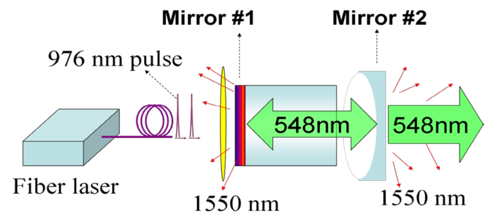

Figure 4. Experimental setup for up conversion

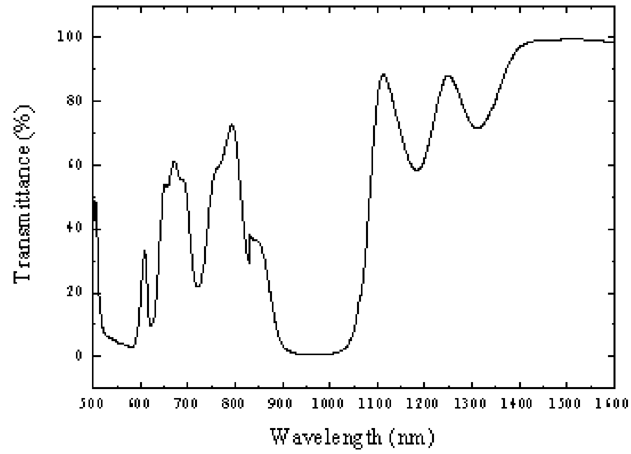

Figure 5. Mirror 1 appeared low transmittance to 548 nm laser and formed a 548 nm laser cavity with the coating on the face of $LiLuF_4$ crystal

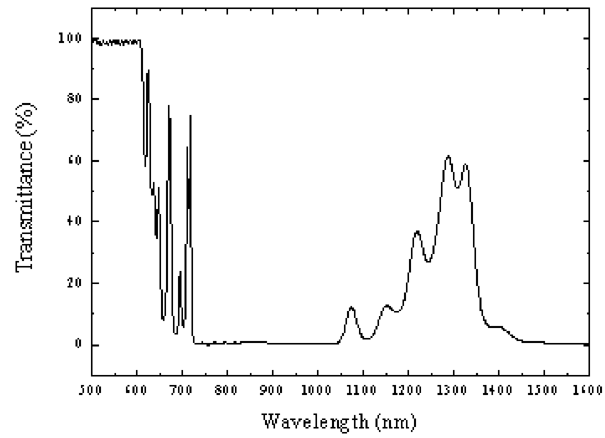

Figure 6. Mirror 2 of low transmittance to 976 nm and 1550 nm provided a 548 nm single wavelength output

3. Results and Discussion

In the laser experiment, a visible upconversion laser was used, as shown in Fig. 4. The peak wavelength was 548 nm and a spectral width of approximately 4 nm at low-threshold average pump power 25 mW and efficiency is 17 %. At 1.9 W input laser peak power, the maximum output laser peak power was 320 mW with a similar efficiency of 17 %, as shown in Figs. 7-9. The green upconversion laser is shown in Fig. 10. The spectrum peak wavelengths were 548 nm and the peak of 537 nm has a different intensity, as shown in Fig. 7.

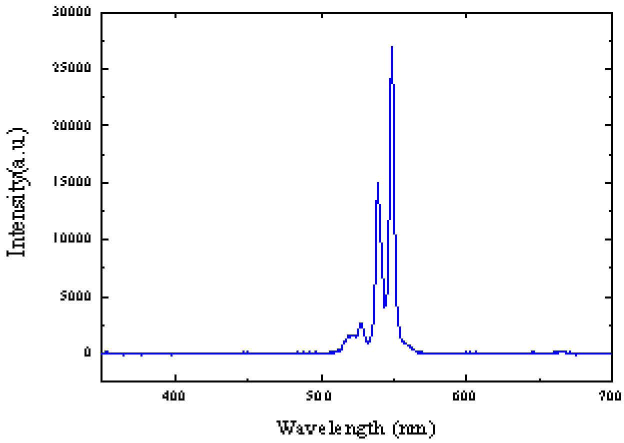

Figure 7. Maxium peak wavelength of output laser is 548 nm

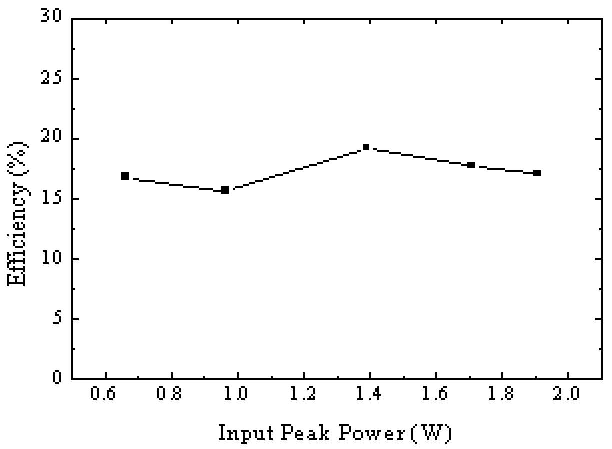

Figure 8. Efficiency of upconversion system

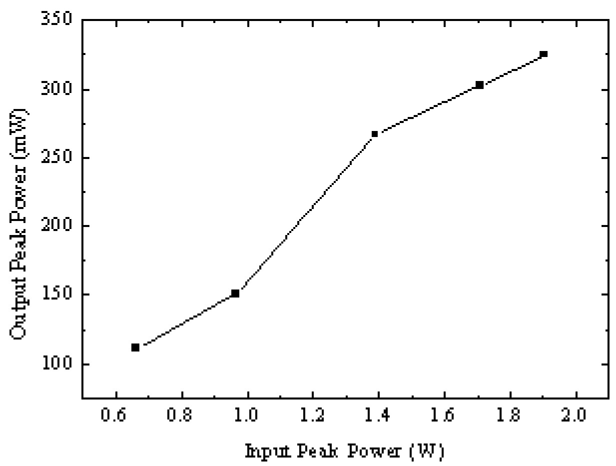

Figure 9. Input peak power at 1.9W can get max output power 320mW

In the experiment, the Er^{3+}:$LiLuF_4$ crystal was covered with bright green fluorescence. The spectrum of the fluorescence is shown in Fig. 11. The dashed line was measured by using a pump larger than the laser threshold pumping power, and the solid line was measured at less than the laser threshold pumping power. It shows solid line are fluorescence leakage and dashed light are laser and fluorescence leakage. Two peaks at 537 nm and 548 nm were observed. According to the energy level diagram of the erbium-doped fiber[10,12,13] shown in Fig. 1, these two peaks were generated by Er^{3+} ions decaying from the $^2H_{11/2}$ and $^4S_{3/2}$ states to the $^4I_{15/2}$ state. For the erbium-doped $LiLuF_4$ crystal, there are two paths for the green upconversion process. The first path is a two-stage pump-excited state absorption. First, Er^{3+} ions at the ground state absorb 976 nm of the pumping energy and excite to the $^4I_{11/2}$ state; they again absorb 976 nm of the pumping energy and are excited to the $^4F_{7/2}$ state. The second path is the energy transfer process. Some of the Er^{3+} ions decaying from the $^4I_{11/2}$ state to the $^4I_{15/2}$ state transfer their energy to other Er^{3+} ions in the $^4I_{11/2}$ state. Theese $^4I_{11/2}$ state ions then receive energy and are excited to the $^4F_{7/2}$ state. Er^{3+} ions decay nonradiatively from the $^4F_{7/2}$ state to the $^2H_{11/2}$ and the $^4S_{3/2}$ states. They return to the ground state with green emission of wavelengths of 548 nm and 537 nm[14-16]. When the pumping power exceeded the amplified threshold, the peak at 537 nm decreased. This is because the 548 nm lasing photons absorb the energy from the 537 nm nonlasing photons. The $^2H_{11/2}$ state is close to $^4S_{3/2}$ and easily transforms to the $^4S_{3/2}$ state, and the lifetime of the $^4S_{3/2}$ state is approximately 0.4 ms[17]. The $^4S_{3/2}$ -$^4I_{15/2}$ is more easily amplified than the $^2H_{11/2}$-$^4I_{15/2}$. Thus, the 548-nm emissions are amplified, whereas the 537 nm emissions are suppressed.

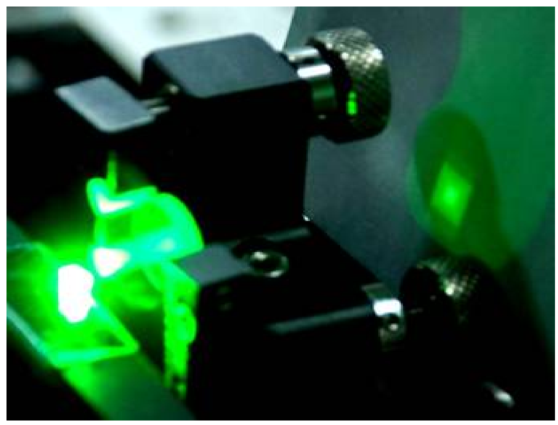

Figure 10. Visible upconversion laser by experiment setup in Figure7 is achieved

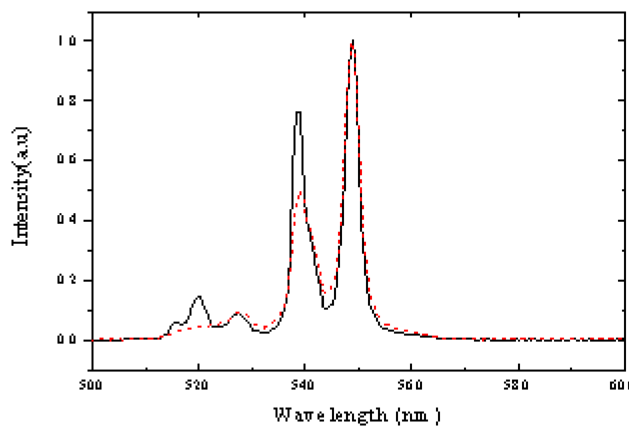

Figure 11. Fluorescence spectrum of the Erbium-Doped $LiLuF_4$ Crystal

4. Summary

In conclusion, we demonstrated a pulsed fiber laser pumping visible 548 nm upconversion laser system. The Er^{3+}:$LiLuF_4$ crystal, green emission amplification can be achieved by using a 976 nm, 280 ns pulse-pump laser and by using a mirror coating to suppress the 1550 nm laser emission. When the pumping power is lower than the laser threshold, the emission spectrum has two obvious peaks at 537 nm and 548 nm. After increasing the pumping power over the amplified threshold, the peak of 537 nm reduces and lases at 548 nm. The spectral width of 548 nm lases at approximately 4 nm. By using 8 mW input pump power, the maximum output laser peak power was 320 mW. The average efficiency of upconversion is approximately 17%.

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