

Article

# Demonstration of Diode-Pumped Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> Lasers

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**Abstract:** Diode-pumped solid-state lasers using novel Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals as laser gain materials are demonstrated herein. The Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals were grown using the Bridgman method. By matching their absorption bands, continuous-wave laser operations were achieved for the first time. The Yb:LaF<sub>3</sub> laser obtained a maximum average output power of 1.19 W with dual wavelengths of 1028 nm and 1033 nm. The maximum average output power and slope efficiency of the Tm,Ho:LaF<sub>3</sub> laser were 574 mW and 18.5%, respectively. The Tm,Ho:LaF<sub>3</sub> laser exhibited two peaks at 2043 nm and 2048 nm. Both the Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals were confirmed to be laser gain materials.

**Keywords:** Yb:LaF<sub>3</sub>; Tm,Ho:LaF<sub>3</sub>; continuous-wave laser

## 1. Introduction

Diode-pumped solid-state lasers (DPSSLs) have attracted wide attention owing to their advantages including high conversion efficiency, good beam quality, long life, and compact construction [1,2]. Over the past few decades, DPSSLs have been fully developed and have been extensively applied in scientific research, medical care, industry, and other fields, and they are now still moving forward to provide more diversified applications [3,4]. For promoting the advancement of DPSSLs, a major research topic is the study of laser gain materials.

For DPSSLs, the laser gain materials are formed by incorporating active ions into host materials whose characteristics greatly affect the physical, chemical, and mechanical properties of the laser gain materials. Fluoride crystals are of particular research interest as host materials because they have distinctive properties: (i) wide wavelength-transparent areas ranging from near ultraviolet to mid-infrared; (ii) a low phonon energy, which is beneficial for reducing non-radiative relaxation; and (iii) a high damage threshold [5–8].

Yb<sup>3+</sup> ions, as representative active ions emitting near 1 μm in lasers, have been successfully used to realize tunable lasers, quasi-continuous devices, femtosecond pulse operations, and high-power systems [9–12]. Yb<sup>3+</sup> ions have a simple energy level structure: the <sup>2</sup>F<sub>7/2</sub> ground state and the <sup>2</sup>F<sub>5/2</sub> excited state [13]. Different from other rare-earth ions, Yb<sup>3+</sup> ions have no other 4f electronic states; therefore, there is no excited-state absorption or fluorescence up-conversion that has an adverse influence on laser performance. Consequently, laser systems with Yb<sup>3+</sup>-doped materials would have a

high conversion efficiency. After decades of development, Yb-doped fluoride crystals, such as Yb:CaF<sub>2</sub>, have been comprehensively reported [14–17].

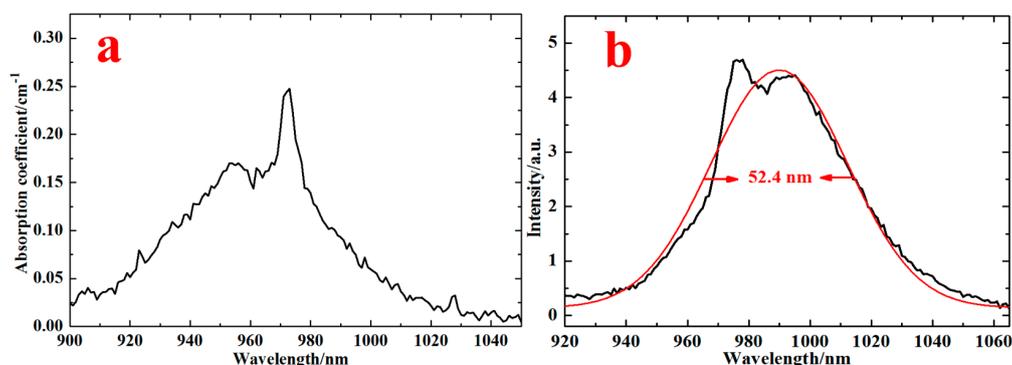
In recent years, thulium (Tm) and holmium (Ho) active ions have been investigated because of their luminescence emissions near the 2  $\mu\text{m}$  region in lasers, giving them great application potential in human eye safeness and high atmospheric transmission [18–24]. Tm and Ho co-doped materials are promising candidates to directly obtain 2  $\mu\text{m}$  region lasers with a compact structure. The around 790 nm laser diode (LD) acts as a pumped source to excite Tm<sup>3+</sup> ions, then, according to the energy transfer between Tm<sup>3+</sup> ions and Ho<sup>3+</sup> ions, Ho<sup>3+</sup> ions ultimately produce 2  $\mu\text{m}$  laser radiation [25,26]. Therefore, Tm,Ho co-doped materials could be operated as laser gain materials for the DPSSL system. Thus far, studies on Tm,Ho co-doped fluoride crystals have focused on Tm,Ho:YLF, Tm,Ho:KYF and Tm,Ho:LLF [8,19–21,27–29].

In this work, we report two novel fluoride crystal materials: Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub>. Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals are typical rare-earth-ion-doped fluoride crystals, so they possess the luminescent properties of rare-earth ions and the excellent host advantages of fluoride crystals. Moreover, La ions are of +3 valence, the same as Yb, Tm, and Ho ions; therefore, there is no charge imbalance in the process of ion doping. However, to date, Yb:LaF<sub>3</sub> crystals have not achieved laser output as solid-state laser gain materials, and Tm,Ho:LaF<sub>3</sub> crystals have not been reported [30].

Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals were prepared via the Bridgman growth method. Yb:LaF<sub>3</sub> crystals with a doping concentration of 1% had a maximum absorption coefficient of 0.25 cm<sup>-1</sup> at 973 nm. Matching the strongest absorption, Yb:LaF<sub>3</sub> continuous-wave (CW) lasers were demonstrated with a maximum average output power of 1.19 W. When the output mirror had a transmittance value of 5%, a Tm,Ho:LaF<sub>3</sub> CW laser was built and the maximum average output power was 416 mW. Employing an output mirror with a transmission value of 2%, the Tm,Ho:LaF<sub>3</sub> CW laser obtained a maximum average output power of 574 mW. The novel crystals, Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub>, were used as laser gain materials to demonstrate CW laser operations as DPSSLs.

## 2. Spectral Properties of Materials

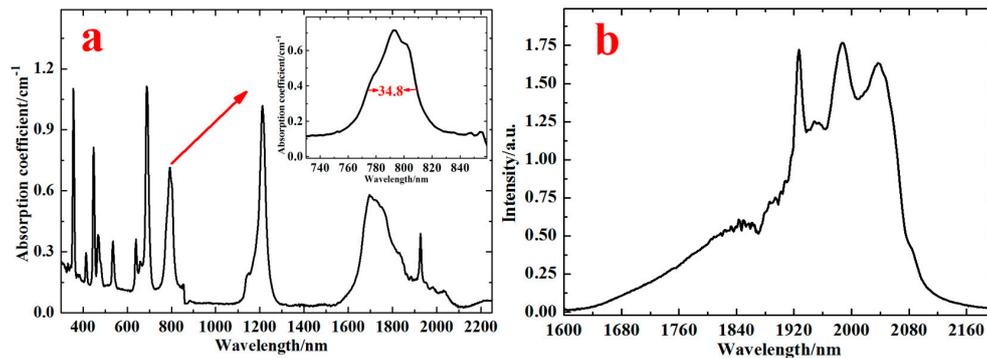
The growth method of the Yb:LaF<sub>3</sub> crystals (Pujing Company, Suzhou, Jiangsu, China) was the Bridgman method which has the advantage of inhibiting the volatilization of fluoride. The Yb:LaF<sub>3</sub> crystals with dimensions 3 × 3 × 6 mm<sup>3</sup> had a Yb doping concentration of 1%. As seen from Figure 1a, the crystals had a relatively high absorption coefficient over a wide wavelength range. The maximum absorption coefficient was 0.25 cm<sup>-1</sup> at 973 nm. Figure 1b shows the broad emission band whose full width at half-maximum (FWHM) was 52.4 nm with Gauss fitting (the red curve), revealing Yb:LaF<sub>3</sub> crystals to be a candidate for wavelength-tunable lasers.



**Figure 1.** (a) Absorption spectrum of Yb:LaF<sub>3</sub> (1 atom % of Yb); (b) emission spectrum with an 896 nm excitation source.

The Tm,Ho:LaF<sub>3</sub> materials were also prepared using the Bridgman growth method. The doping concentration was 5 atom % of Tm and 0.5 atom % of Ho ions, and the dimensions were

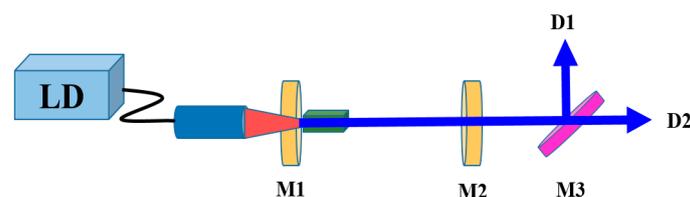
$3 \times 3 \times 10 \text{ mm}^3$ . The absorption and emission spectrum information at room temperature are shown in Figure 2. It can be seen that the Tm,Ho:LaF<sub>3</sub> materials had several peaks in the absorption spectrum. Among them, a special absorption peak is presented deliberately in the inset of Figure 2a. This peak had a center wavelength of 792.5 nm, which illustrated that the Tm,Ho:LaF<sub>3</sub> materials could be stimulated with a commercial LD. In general, LDs have the disadvantage of wavelength drift caused by changes in the LD output power and temperature. The Tm,Ho:LaF<sub>3</sub> crystals had a FWHM of 34.8 nm, so they could avoid absorption instability caused by the wavelength drift of LDs. The emission spectrum had a broad fluorescence range mainly centered at 1925–2075 nm.



**Figure 2.** Spectral information for Tm,Ho:LaF<sub>3</sub> materials: (a) absorption spectrum, (b) emission spectrum.

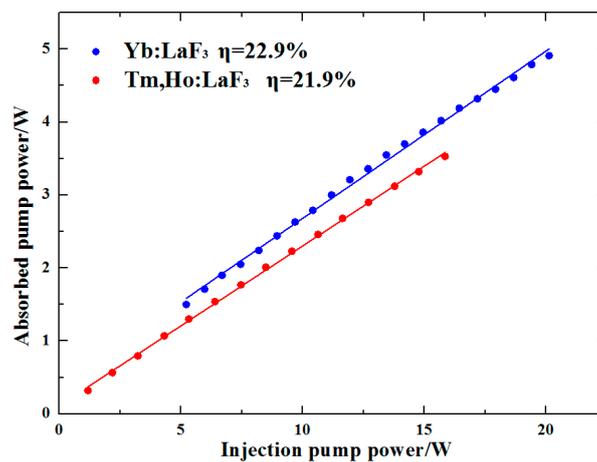
### 3. Continuous-Wave Laser Experiment Operation

The respective properties of CW lasers were researched with the Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> samples by building laser systems, which are presented in Figure 3. Two commercial LDs were used as the pump source. Matching their absorption wavelengths, an LD with a center wavelength of 974 nm was applied to the Yb:LaF<sub>3</sub> laser, and the Tm,Ho:LaF<sub>3</sub> laser was used with an LD with a central wavelength of 793 nm. The LDs both had a fiber core diameter of 200  $\mu\text{m}$  and a numerical aperture of 0.22. The pump source laser they sent was focused by a 1:1 optics coupling system. In order to effectively dissipate the heat, the Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> samples were both wrapped with indium foil and mounted in a water-cooled system where the water was maintained at 20  $^{\circ}\text{C}$  temperature. Two mirrors (M1 and M2) formed a laser cavity with a length of 35 mm. One of them (M1) had a curvature of 100 mm, and the other (M2) was a flat mirror. For the Yb:LaF<sub>3</sub> experiment, M1 was the input mirror having high transmission at the pump wavelength and high reflection at 1030–1090 nm. M2 was the output mirror, having transmission values of 1%, 2%, or 5% at 1030–1090 nm. M3 was the same type of mirror as M1 and was used to separate the pump laser and the Yb:LaF<sub>3</sub> laser. The pump laser of 974 nm was transmitted in Direction 2 (D2), and the Yb:LaF<sub>3</sub> laser was reflected in Direction 1 (D1). For the Tm,Ho:LaF<sub>3</sub> laser, M1 had high transmission at a 793 nm wavelength and high reflection at 1.9–2.1  $\mu\text{m}$ . There were two kinds of mirrors (M2) with transmission values of 2% and 5% at 1.9–2.1  $\mu\text{m}$ . M3 was a beam splitter mirror. At a 45 $^{\circ}$  angle, the 793 nm laser was reflected in D1, whereas the target laser was obtained in D2. The Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> samples were each placed near the M1 mirrors.



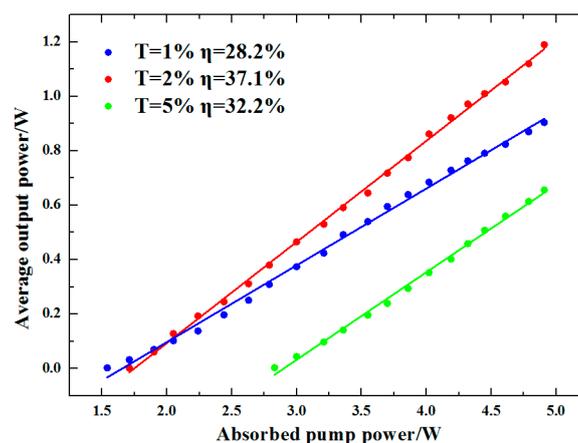
**Figure 3.** Experimental setup of the continuous-wave (CW) laser. LD: laser diode; M1 and M2: two cavity mirrors; M3: beam splitter mirror; D1 and D2: direction 1 and 2.

First, the absorption efficiency was measured for the Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals in non-lasing conditions. As shown in Figure 4, as the injection pump power was increased and the absorbed pump power was added linearly. The absorption efficiency of the Yb:LaF<sub>3</sub> crystal was found to be 22.9%, and the maximum injection pump power was 20.13 W. For the Tm,Ho:LaF<sub>3</sub> crystal, the absorption efficiency and the maximum injection pump power were found to be 21.9% and 15.85 W, respectively. Considering that a large amount of pump laser was not absorbed, the M3 mirror was used to split the pump laser and target laser.



**Figure 4.** Variation of the absorbed pump power with the injection pump power.

After the cavity mirrors were adjusted, the CW lasers of the Yb:LaF<sub>3</sub> crystal were obtained in D1. The relationship between the average output power and the absorbed pump power for different transmittance values is illustrated in Figure 5. When the transmittance of M2 was 1% and the absorbed pump power was 1.54 W, the Yb:LaF<sub>3</sub> laser was obtained. When the absorbed pump power was increased to 4.91 W, a maximum average output power of 904 mW was achieved, corresponding to a slope efficiency of 28.2%. With the highest transmittance of 5%, a maximum output power of 656 mW with a slope efficiency of 32.2% was obtained. The optimal average output power was 1.19 W, when the transmittance of output coupler was 2%. The highest slope efficiency was 37.1%.



**Figure 5.** The average output power as a function of the absorbed pump power.

The spectra of the Yb:LaF<sub>3</sub> lasers were recorded using a spectrometer (USB2000, Ocean Optics, Largo, Florida, FL, United States). For different transmittance values of M2, the experimental results are shown in Figure 6 at the maximum average output power. When M2 had transmittance values of 1% and 5%, the output spectra both exhibited a single peak. The central wavelengths were 1029 nm

and 1018 nm, respectively. At a transmittance value of 2%, double peaks appeared with wavelengths of 1028 nm and 1033 nm. Because the sampling resolution of the spectrometer was 0.7 nm, the fine spectral components were not tested. However, our experimental results could reflect the information of the output spectra to a certain extent.

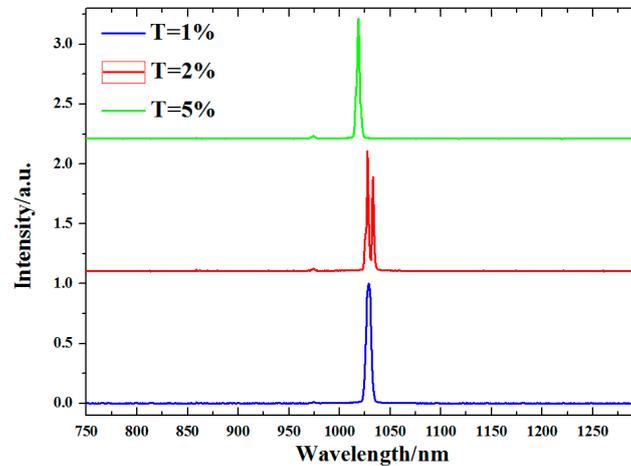


Figure 6. Spectra of three different output parameters.

After the position of the cavity mirrors was carefully adjusted, Tm,Ho:LaF<sub>3</sub> lasers were acquired in D2. The experimental results of the relationship between the absorbed pump power and the average output power are explained in Figure 7. For different output mirrors, it is obvious that the absorbed pump power and average output power were almost linear functions. At the absorbed pump power of 3.53 W, the maximum average output power was 574 mW and the slope efficiency was 18.5% under 2% transmittance by M2. When a higher transmittance of M2 of 5% was adopted, the maximum average output power and the slope efficiency were decreased to 416 mW and 14.2%, respectively. The power was tested using a power meter (30(150)A-BB-18, Ophir, Jerusalem, Israel).

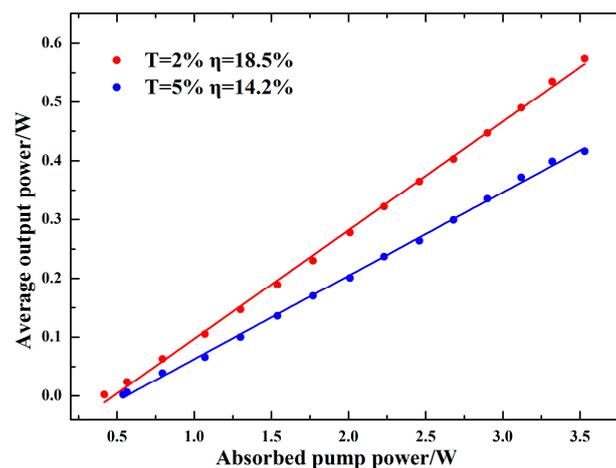


Figure 7. Average output power as a function of the absorbed pump power.

The spectra of the Tm,Ho:LaF<sub>3</sub> lasers, shown in Figure 8, were measured using a spectrometer (NIRQuest-512, Ocean Optics, Largo, Florida, FL, United States). The laser spectra exhibited two peaks with both of the two output mirrors used in the laser test. When the transmittance was 2% and the average output power was 574 mW, the spectra showed two peaks at 2043 nm and 2048 nm. At a transmittance of 5% and output power of 416 mW, the peaks were 2039 nm and 2041 nm.

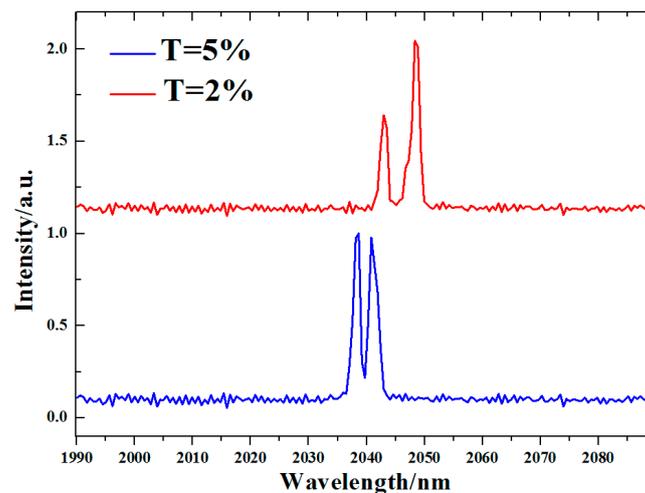


Figure 8. Spectra for Tm,Ho:LaF<sub>3</sub> lasers at the maximum average output power.

According to the research, both Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> lasers were successfully obtained. However, the laser stability and the size of the fundamental TEM<sub>00</sub> mode were not measured. The Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals were uncoated and vertically incident with LDs, which increased the loss of the laser cavity. Supposing that the crystal was doped to a higher concentration, coated with antireflection film, and placed at the Brewster angle, the experimental data are expected to reach a higher slope efficiency and average output power. Moreover, the orientation of the crystal, the polarization in the spectra, and the polarization of the laser radiation need to be researched in detail.

#### 4. Conclusions

Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> lasers were successfully employed for CW operation, for the first time to our knowledge. Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals with high optical quality were grown by the Bridgman method. They both had a suitable absorption spectrum, and their emission spectra were broad. Using a commercial LD as the pump source, the Yb:LaF<sub>3</sub> laser obtained a maximum average output power of 1.19 W with a slope efficiency of 37.1%. For the Tm,Ho:LaF<sub>3</sub> laser, the maximum average output power and corresponding slope efficiency were 574 mW and 18.5%, respectively. The laser wavelengths were 2043 nm and 2048 nm. In brief, our experiments proved that Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> crystals are effective laser gain materials, increasing the laser gain material selectivity.

**Author Contributions:** Y.X.L. supervised and supported the experiments. C.L. designed and executed the experiments. S.M.L. and Y.H. provided the Yb:LaF<sub>3</sub> and Tm,Ho:LaF<sub>3</sub> materials and tested their spectra.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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