Multiple-Wavelength Up-Conversion Laser in Tm^{3+}-Doped ZBLAN Glass Fiber

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***Abstract*—In this letter, we report on a multiple-wavelength up-conversion laser in Tm^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF glass fiber pumped by an 1120-nm fiber laser. Single-wavelength, two-wavelength, and three-wavelength up-conversion lasers can be obtained by adjusting the distance between the coupler mirror and the fiber end, which is attributed to the frequency-filter effect in the etalon composed of the coupler mirror and the fiber end. The effects of the pump power on the performance of dual-wavelength laser were also discussed.**

***Index Terms*—Etalon, multiple-wavelength laser, Tm^{3+}, up-conversion, ZrF_4–BaF_2–LaF_3–AlF_3–NaF (ZBLAN) glass fiber.**

I. Introduction

MULTIPLE wavelength fiber lasers are useful sources in wavelength-division-multiplexed fiber communication systems, differential absorption lidar systems, high-purity terahertz generation, fiber sensors, and optical instrument testing. Various techniques have been proposed to realize multiple wavelength oscillations by utilizing cascaded fiber Bragg grating (FBG) cavities [1], polarization-dependent loss element [2], an FBG written in a birefringent fiber [3], a sampled FBG, and a polarization-dependent multiple-quantum-well waveguide [4]. Recently, Li *et al.* [5] reported on multiple wavelength fiber lasers by an etalon. In this letter, we report on a multiple-wavelength up-conversion laser in Tm^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF (ZBLAN) glass fiber pumped by an 1120-nm fiber laser. To the best of our knowledge, this is the first report on multiple-wavelength up-conversion fiber lasers. Single-wavelength (~784 nm), two-wavelength ($785 + 805$ nm or $788 + 793$ nm), and three-wavelength ($787 + 794 + 802$ nm) up-conversion lasers can be obtained by adjusting the distance between the coupler mirror and the fiber end, which is attributed to the frequency-filter effect in the etalon composed of the coupler mirror and the fiber end. The effects of the pump power on the performance of dual-wavelength laser were also discussed.

II. Experimental Setup

In our experimental setup, the pump laser is a Raman fiber laser operating at 1120 nm, pumped by a 1064-nm Yb^{3+}-doped fiber laser, which is similar with our previous report on an 1178-nm Raman fiber laser [6]. The commercial Tm-doped ZBLAN fluoride fiber (KDD Fiberlabs, Japan) we used had a thulium concentration of 1000 ppm (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 m was used in all experiments. Both fiber ends were cut by a FK-11 fiber cleaver with the tension of 50–60 grams and the measurement results by a microscope showed that the cleaved surfaces were very flat. A 1120-nm pump light was launched into the fiber core by a couple of aspheric lens. Tests with a short fluoride fiber (10 cm) showed the launched efficiency, defined as launched power divided by power incident on the lens, was about 43%, and the maximum launched pump power is 1.640 W. For the mirrors forming cavity, one is high reflectivity (HR) at 780 nm, high transmission at 1120 nm, and the other 92% reflectivity at 780 nm, high transmission at 1120 nm. Both mirrors were butt directly with the fiber end. The output spectrum of the fiber end and the launched or output power were measured using an AQ-6315A optical spectrum analyzer (ANDO, Japan) and a LABMASTER optical power meter (Coherent, USA). All the experiments were made at room temperature.

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III. Results and Discussions

Fig. 1(a) presents the up-conversion mechanism of Tm^{3+} in ZBLAN glass fiber. First, by excitation with an 1120-nm fiber, 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 $^3H_4$ level, and the state $^1G_4$. Without the mirrors forming the cavity, as the pump power was relatively low (~200 mW), we measured the up-conversion emission spectrum of the fiber end, as shown in Fig. 1(b). Emissions in the visible and near-infrared range come from the following transitions: $^1G_4 \rightarrow {}^3H_6$ (~474 nm), $^1G_4 \rightarrow {}^3F_4$ (~647 nm), $^1G_4 \rightarrow {}^3H_5$ (~784 nm), and $^3H_4 \rightarrow {}^3H_6$ (~810 nm). With increasing the pump power, both 784- and 810-nm amplified spontaneous emissions (ASEs) could be observed (data not shown) [7]. Then both mirrors were butt directly with the fiber end. When the pump power is larger than 500 mW, the threshold of the laser, we obtained a stable simultaneous two-wavelength (784 + 808 nm, which come from the states $^1G_4$ and $^3H_4$, respectively [7]) up-conversion laser, as shown in Fig. 1(c). In Tm^{3+}-doped ZBLAN glass fiber, 480-, 810-, and 1474-nm fiber lasers have been widely investigated, but to our knowledge, a simultaneous two-wavelength (784 + 808 nm) up-conversion laser was not reported. Why can the two-wavelength up-conversion laser be obtained in our Tm^{3+}-doped ZBLAN glass fiber?

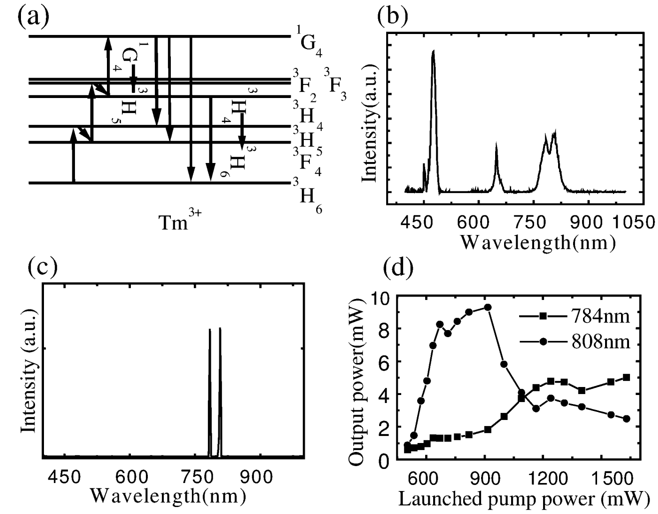

Fig. 1. (a) Frequency up-conversion mechanism of Tm^{3+}-doped ZBLAN glass fiber pumped by an 1120-nm fiber laser. (b) The up-conversion emission spectrum of Tm^{3+} in ZBLAN glass fiber pumped by an 1120-nm fiber laser. (c) Simultaneous two-wavelength $(784 + 808$ nm) up-conversion laser emission spectrum. (d) Measured output power of dual-wavelength up-conversion laser at different pump power.

From [8], we can obtain that the stimulated emission cross sections of Tm^{3+} : $^1G_4 \rightarrow {}^3H_5$ and $^3H_4 \rightarrow {}^3H_6$ transitions are 3.05×10^{-25} and 4.75×10^{-25} m^2, respectively. From the loss spectrum of the ZBLAN glass fiber (data not shown), the internal loss at 784 nm is nearly the same as that at 808 nm. In addition, for 784-nm laser, the population of the upper laser state $^1G_4$ mainly comes from the upper laser state $^3H_4$ of 808-nm laser [7]. The above-mentioned conditions make 808-nm lasing easier than 784-nm lasing. On the other hand, 784-nm ($^1G_4 \rightarrow {}^3H_5$ transition) lasing is a four-level laser and 808-nm ($^3H_4 \rightarrow {}^3H_6$ transition) lasing a three-level laser, which makes 784-nm lasing easier than 808-nm lasing. So there exists a competition among these conditions. It is very difficult to analyze these conditions quantitatively for simultaneous two-wavelength lasing. In order to clarify these conditions in part, we performed lasing experiments without the coupler mirror (the laser cavity is formed by 4% Fresnel reflections at the end face of Tm^{3+}-doped ZBLAN fiber); two-wavelength $(784 + 808$ nm) up-conversion laser could not be obtained in this cavity at the largest pump power (1.640 W, the power up-limit of our pump laser), only 784-nm up-conversion laser was observed. This result shows that 784-nm laser is obtained more easily than 808-nm laser. In other words, for this system, despite larger stimulated emission cross section and priority population of the $^3H_4 \rightarrow {}^3H_6$ transition, the properties of four-level lasing make 784-nm ($^1G_4 \rightarrow {}^3H_5$ transition) lasing obtained more easily than 808-nm laser. For high loss cavity (without the coupler mirror), the threshold of 784-nm laser is lower than that of 808-nm laser, the threshold of 808-nm laser should be larger than 1.640 W. However, for low loss cavity (with HR coupler mirror), the difference between the threshold of the four-level lasing and that of three-level lasing will be reduced. For the cavity with an HR coupler mirror, the threshold of 808-nm laser may be equal to that of 784-nm laser, so simultaneous two-wavelength up-conversion laser can be obtained in this cavity, as shown in Fig. 1(c). We believe that our two-wavelength lasing depends on our proper selection of the coupler mirror. That is to say, an HR coupler mirror (the reflectivity at 784 nm is about 92%, and 808 nm 85%) can guarantee that the loss of the cavity is low for these two transitions, which can make the lasing for these two transitions easy. So stable two-wavelength $(784 + 808$ nm) up-conversion laser can be observed in our experiments.

The output power of this two-wavelength laser was measured, as shown in Fig. 1(d). As we can see from Fig. 1(d), at the initial stage, with increasing the pump power, both the output power of 784-nm laser and that of 808-nm laser increase. When the launched power is larger than 915 mW, the output power of 808-nm laser decreases and that of 784-nm laser still increases. It is easily understood, for 784-nm laser, the population of the upper laser state $^1G_4$ comes from the upper laser state $^3H_4$ of 808-nm laser. At the initial stage, with increasing the pump power, more launched power is converted to 808-nm laser, until its saturation. As the launched power is larger than 915 mW, more electrons are excited to the upper laser state $^1G_4$ of 784 nm from the $^3H_4$ level, which destroys the net gain of 808-nm laser and makes it weaker. For the certain launched power, such competition may keep the balance of simultaneous two-wavelength $(784 + 808$ nm) up-conversion laser and make it stable [9]. In addition, from Fig. 1(d) we can find that the total output power of the laser decreases with increasing the pump power (when the launched power is larger than 915 mW). Why does it occur? Considering the up-conversion mechanism of Tm^{3+} in ZBLAN glass fiber [8], with increasing the pump power of 1120-nm laser, more electrons are promoted to the states $^1D_2$ and $^3P_0$ [not shown in Fig. 1(a)] up-conversion process, respectively. These processes not only depopulate the $^3H_4$ level (the upper state of 808-nm laser, as discussed above) but also reduce the net gain of 784-nm laser. So we consider that decreasing of the total output power of the laser is due to the efficiency of these processes at high pump power.

For our simultaneous two-wavelength $(784 + 808$ nm) up-conversion laser, there exists no separation between the mirror and the fiber end, which confirms that optimal cavity can be formed. It is well known that etalon can be used as a comb filter to produce multiwavelength oscillations, and the spacing of the lasing lines is determined by the free spectral range (FSR) of it. Recently, Li *et al.* [5] reported multiple wavelength fiber lasers by an etalon composed of the fiber end face and the mirror. Following Li's work, we fixed the distance between the HR mirror and the front fiber end (no separation) and increased the distance between the coupler mirror ($\sim$92% reflectivity) and the back fiber end. Stable two-wavelength $(785 + 805$ nm), three-wavelength $(787 + 794$ nm $+ 802$ nm), two-wavelength $(788 + 793$ nm), and single-wavelength ($\sim$784 nm) up-conversion lasers can be obtained, as shown in Fig. 2(a). In our present experimental conditions, the exact value of the distance between the coupler mirror and the back fiber end cannot be obtained. But repeated measurements showed that they were stable and reproductive. For the larger distance (up to 1 mm), the laser is inhibited due to low reflectivity of the fiber end ($\sim$4%), only modulated 784-nm ASE signals can be observed [as shown in Fig. 2(b)], which is attributed to the frequency-filter

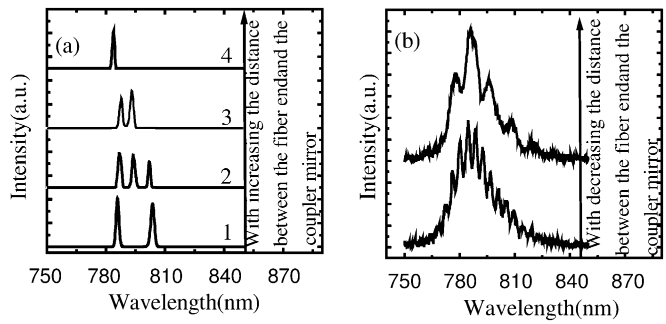

Fig. 2. (a) Stable single-wavelength (~784 nm), two-wavelength ($785+805$ nm or $788+793$ nm), and three-wavelength ($787+794+802$ nm) up-conversion laser emission spectra. (b) The 784-nm ASE spectra modulated by the frequency-filter effect in the etalon composed of the coupler mirror and the fiber end.

effect in the etalon composed of the back fiber end and the coupler mirror [5]. From Fig. 2(b), with decreasing the distance between the back fiber end and the coupler, FSR of the etalon increases, which agrees with Li's calculation [5]. This result confirms that our multiple-wavelength up-conversion lasers are attributed to the frequency-filter effect in the etalon composed of the coupler mirror and the fiber end. From our and Li's experimental results, this special etalon can present a simple way to obtain multiple wavelength fiber lasers.

In addition, as in the above-mentioned results, with the increase of the cavity length of the etalon, the FSR decreases, and thus the spacing of the lasing lines also decrease. Considering that the gain bandwidth does not change, why is the number of lasing lines decreased while the cavity length of the etalon is increased? As we can see from Fig. 2(a), from Curves 1 to 2, the number of lasing lines is increased from two to three, which agrees with the properties of the etalon. However, from Curves 2 to 4, the number of lasing lines is decreased from three to one. In order to understand this phenomenon, another effect should be considered, i.e., the additional cavity loss induced by this special etalon. As described by Li [5], the increase of the separation between the fiber end and the coupler mirror not only make FSR of this special etalon decreased but also introduce the additional cavity loss to the system. The additional cavity loss will enhance the threshold of 808-nm ($^3H_4 \rightarrow {}^3H_6$ transition, a three-level laser) laser and further inhibit 808-nm lasing. However, the lasers shown in Curves 3 and 4 of Fig. 2(a) are attributed to lasing of the $^1G_4 \rightarrow {}^3H_5$ transition, which is a four-level laser. Since the threshold of this four-level laser is lower than that of 808-nm laser (a three-level laser) despite the additional cavity loss induced by the etalon, 784-nm lasing still can work when 808-nm lasing is inhibited by the additional cavity loss at a certain pump power. So we think that this additional cavity loss inhibits 808-nm lasing and makes the number of lasing lines decrease with increasing the cavity length of the etalon.

IV. Conclusion

We have reported a multiple-wavelength up-conversion laser in Tm^{3+}-doped ZBLAN glass fiber pumped by an 1120-nm fiber laser. Single-wavelength (~784 nm), two-wavelength ($785 + 805$ nm or $788 + 793$ nm), and three-wavelength ($787 + 794 + 802$ nm) up-conversion lasers can be obtained by adjusting the distance between the coupler mirror and the fiber end, which is attributed to the frequency-filter effect in the etalon composed of the coupler mirror and the fiber end. It presents a simple way to obtain multiple wavelength fiber lasers.

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