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The Three-wavelength PR^{3+}:YLF Laser at 604 nm 607 nm and 640 nm with Fabry-Perot Etalon

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A three-wavelength Pr^{3+}:YLF laser at 604 nm, 607 nm and 640 nm simultaneously output by Fabry-Perot (F-P) etalon has been obtained. A 444 nm blue laser diode is used for pumping the Pr^{3+}:YLF crystal, and a 0.1 mm F-P etalon is inserted in the resonator to select wavelength. The theoretical model of three-wavelength Pr^{3+}:YLF laser is established, by adjusting the tilt angle of the etalon, the transmittances of the different wavelengths can be controlled, and the threshold values can be made to equalize by controlling the loss among different wavelengths. In the experiment, when the tilt angle of etalon is 9° and the optimized length of resonator is 48 mm, the total output power of 25 mW at the three-wavelength is achieved at incident pump power of 7.5 W.

Keywords : Three-wavelength, Pr^{3+}:YLF, Fabry-Perot etalon
OCIS codes : (140.3430) Laser theory; (140.3480) Lasers, diode-pumped

I. INTRODUCTION

The all-solid-state multi-wavelength laser is particularly useful in many fields, such as the area of scientific applications, including spectroscopy, quantum optics, and bio-photonics [1, 2]. The requirement of continuous wave (CW) yellow-orange light sources is growing steadily, and scientists look forward a novel laser which can emit the yellow-orange spectrum [3, 4]. At present, most multi-wavelength lasers operate at the invisible spectral laser region while the visible spectral laser region is infrequent [5]. There is still a lack of effective methods to directly obtain the orange spectral region around 600 nm. Trivalent praseodymium (Pr^{3+}) doped laser materials have attracted many scientists' attention for which having abundant spectra in the visible light band [6-9], so the Pr^{3+} laser can emit multiple spectral lines simultaneously, and the most striking is the dual-wavelength Pr^{3+} laser. For example, Yongjie Cheng first reported dual-wavelength diode-pumped Pr^{3+}:YLF lasers at 604 nm and 607 nm by inserting a Febry-Perot to select wavelength, among which are the π-polarized laser at 604 nm with maximum output power and slope efficiency of 115 mW and 17.3% and the σ-polarized laser at 607 nm with maximum output power and slope efficiency of 287 mW and 39.7% [10]. With the same method, Bin Xu *et al*. obtained InGaN-LD-pumped Pr^{3+}:YLF continuous-wave deep red lasers at 697.6 and 695.8 nm by using a simple and compact Brewster-angle orientated intracavity etalon, the maximum output power of the π-polarized laser emission at 697.6 nm was up to 348 mW with slope efficiency of about 32.7% and the maximum output power of the σ-polarized laser emission at 695.8 nm was 116 mW with slope efficiency of about 18.5% [11]. However, up to now, the three-wavelength Pr^{3+} laser has been rarely studied. In this paper, the π-polarized Pr^{3+}:YLF laser at 604 nm, 607 nm and 640 nm is researched by using a 0.1 mm uncoated F-P etalon, and the maximum output power is 25 mW when the pump power is 7.5 W.

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II. THEORETICAL ANALYSIS

F-P etalon is an interferometer with high resolution and the principle of the etalon is multi-beam interference. It should be possible to obtain single-frequency operation or multi-wavelength output by using a suitable wavelength selecting etalon [12].

The transmittance of different wavelengths can be controlled artificially by adjusting the parameters of the F-P etalon. The transmittance function of a single etalon is shown [13]:

$$T(v) = \frac{1}{1+F\sin^2(\delta/2)} = \frac{1}{1+F\sin^2(2\pi v n h\cos\theta/c)} \quad (1)$$

where F is the finesse of the etalon, defined as $F=4R/(1-R)^2$, R is the reflectivity of mirror, δ is the phase difference of the adjacent two beams in the F-P cavity, $\delta=4\pi nh\cos\theta/\lambda$, n is the refractive of the etalon medium; h is the thickness of the etalon, and θ is the refraction angle of the transmitted light in the F-P cavity, corresponding to the incident angle θ_1 as $\sin\theta_1 = n\sin\theta$, c is the speed of light; T is the transmittance of the etalon. The transmittance can be controlled by altering the etalon's thickness and the refraction angle of F-P etalon.

The mechanism of the F-P etalon is that the loss among different modes can be regulated by altering the tilt angle. According to the energy levels diagram of Pr^{3+}ions in $LiYF_4$, except that the blue light wavelength (479 nm, $^3P_0 \rightarrow ^3H_4$) is a quasi-three level, all other wavelengths belong to the four-level [14]. So the threshold pumping power expression of the Pr^{3+}:YLF laser can be given [15]:

$$P_{th} = \frac{\gamma}{\eta_p}\left(\frac{hv_{mp}}{\tau_f}\right)\left(\frac{A}{\sigma}\right) \quad (2)$$

where γ is the loss of the cavity, defined as $\gamma=[\gamma_1+(1-T)]$, γ_1 is the round-trip loss of the cavity, η_p is the pumping efficiency, h is the Plank constant, v_{mp} is the frequency difference between the upper laser level and the ground level and $v_{mp}=c/\lambda$, λ is the wavelength of the laser, τ_f is the upper level lifetime, A is the area of the active medium and $A=\pi r^2$, r is the spot radius of the laser, σ is the stimulated emission cross-section [16]. Eq. (2) can be used to discuss the relationship between the refraction angle and the Pr^{3+}:YLF laser threshold power. A summary of the parameters of the characterized lasers are given in Table 1. The calculated threshold values of the 604 nm 607 nm and 640 nm laser are shown in Fig. 1.

As shown in Fig. 1, the intersection of curves can be controlled by adjusting refraction angle of the etalon, these points represent that the 604 nm, 607 nm and 640 nm lasers have the same threshold, and the wavelengths of 604 nm, 607 nm, 640 nm can oscillate simultaneously when the power reaches or exceeds the threshold power and the three-wavelength laser can be simultaneously outputed at these angles of the etalon. It can be seen that there are several suitable angles for which the threshold of the three wavelengths of the laser are equal. We assume that the threshold powers of 604 nm, 607 nm and 640 nm lasers are approximately equal if the threshold power difference among them are less than 50 mW, the points which meet the above conditions are shown in Table 2.

From Table 2, several tilt angles of the etalon which satisfied the three-wavelength laser output can be found. The three-wavelength laser will be generated in these angle regions when the crystal absorbed power reaches the specific threshold.

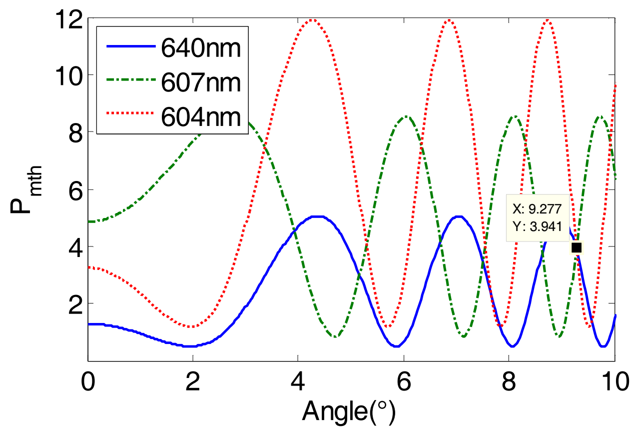

FIG. 1. The threshold pumping powers of the 604 nm 607 nm and 640 nm laser.

TABLE 2. The equal threshold points versus refraction angle

Angle (°)	Threshold value
9	3.9
24	2.8
56	1.1

TABLE 1. Parameters of the characterized lasers

σ (nm)	$\sigma(10^{-23}m^2)$	R (%)	n	h (mm)	γ_1 (%)	$\tau_f(10^{-6}s)$	r (μm)
604	0.98	5	1.45	0.01	2	35.7	200
607	1.36						
640	2.18						

III. EXPERIMENTAL SETUP

Figure 2 shows the schematic of the three-wavelength operation. The pump source is a 200 μm core diameter, with the maximum output power of about 7.5 W, emitting at 442~444 nm which shows good agreement with absorption of the Pr^{3+}:YLF crystal. A lens coupling system is employed in order to re-image the pump beam into the laser crystal. The spot radius after re-imaging is 250 μm.

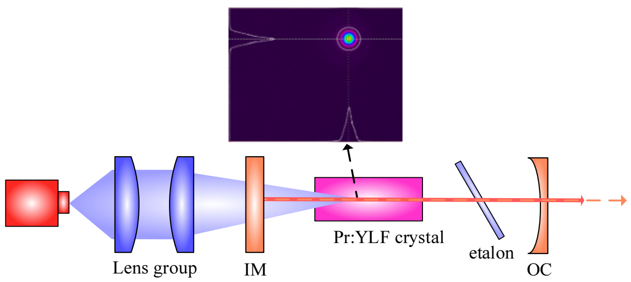

FIG. 2. Schematic of the three-wavelength Pr:YLF laser with F-P etalon.

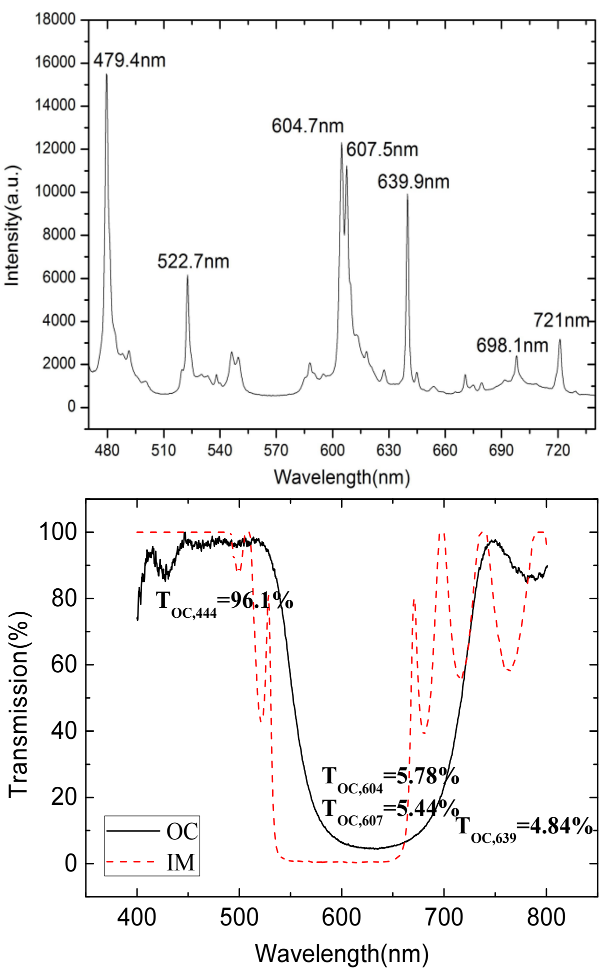

FIG. 3. The stimulate emission spectrum of the Pr:YLF laser crystal and The coatings curve of the IM and OC.

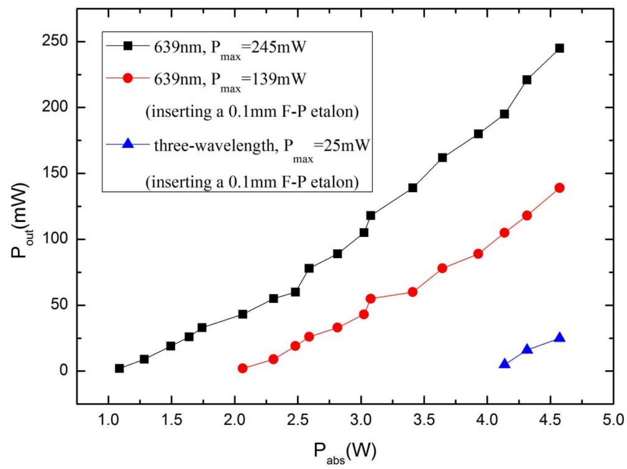

FIG. 4. The output power characteristic of 640 nm and three-wavelength lasers.

The beam profile of the laser was captured by recording its intensity profile using a CCD camera, which is shown in Fig. 2. The three-wavelength resonator cavity is composed of a highly reflective mirror IM, a Pr^{3+}:YLF crystal as a gain medium, a F-P etalon, and a output coupling OC. The gain medium is an uncoated a-cut 0.5at.% Pr^{3+}:YLF crystal with the length of 5 mm and transverse aperture of 3 mm × 3 mm, the stimulated emission spectrum of the laser crystal is shown in Fig. 3. Moreover, we adopted water-cooling and controlled the temperature of the crystal at about 12°C. The wavelength of the pump source increased at high drive current, and the absorption efficiency is increased from 46.3% to 60% due to the shift of the pump wavelength. The coatings of the plane-plane mirror IM and the plane-concave mirror OC (R = 50 mm) are shown in Fig. 4. A glass plates with thickness of 0.1 mm acting as an F-P etalon is inserted into the cavity to adjust the loss between different wavelengths. Through repeated experiments, the optimized length of the resonator of about 48 mm is chosen.

IV. RESULTS AND DISCUSSIONS

A free-running operation is firstly demonstrated without inserting the F-P etalon. The red laser at 640 nm is obtained with maximum output power of 245 mW (see in Fig. 5), the pump threshold is about 1.05 W. Then, by suitably adjusting the glass etalon to an optimized orientation and location, the pump threshold is increased to 2.05 W , and the 640 nm laser emission is realized with maximum output power of 139 mW. Due to the etalon the loss of cavity is increased , the threshold value is increased to 4.10 W and the maximum output power is lower than previously. Finally, the three-wavelength laser is achieved with maximum output power of 25 mW, When the laser diode with the maximum output power of 7.5 W

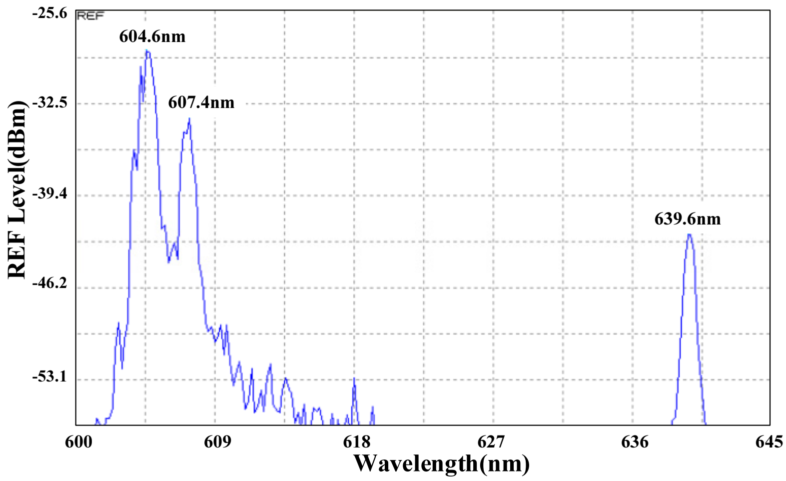

FIG. 5. Laser spectra of three-wavelength at 604 nm and 607 nm and 640 nm lasers.

(crystal absorbed power is 4.57 W) and tilt angle of the etalon is 9°.

The laser cavity cannot operate the 604 nm or 607 nm laser automatically, which should be explained as the stimulated emission cross-section of 640 nm is larger than 607 nm and the threshold value of 607 nm is lower than 604 nm at room temperature. The 640 nm laser play an important role in gain competition. Hence, a frequency selector must be employed to control the loss of the high-gain 640 nm laser. The three-wavelength laser emission is realized by inserting a 0.1 mm uncoated glass plate which acts as F-P etalon for intra-cavity loss adjustment. The tilt angle and location of the etalon would influence the loss of the resonator.

The reason for low output power is that the spot radius of laser diode after re-imaging is large. Accordingly the threshold value was increased in the experiment, and the cavity loss would further increase when inserting an F-P etalon. Figure 5 shows the spectra of the three-wavelength lasers at 604 nm 607 nm and 640 nm, which were detected by using a high resolution spectrometer analyzer (AQ6373, Yokogawa, Japan).

V. CONCLUSION

In this paper, the three-wavelength Pr^{3+}:YLF laser at 604 nm 607 nm and 640 nm by Fabry-Perot (F-P) etalon are obtained by using the a-cut Pr^{3+}:YLF laser crystal. The plane-concave resonator cavity is adopted and the cavity length is 48 mm, the transmission of the couple output mirror is about 5% at 600~650 nm. And only 640 nm laser is emitted before the 0.1 mm F-P etalon is inserted, the maximum output power is 245 mW at an incident pump power of 7.5 W. However, the output power of 640 nm laser is decreased after the F-P etalon is inserted, and the 604 nm, 607 nm and 640 nm three wavelength lasers were emitted when the inclination angle of F-P etalon is adjusted to 9°, and the maximum output power is 25 mW which limited by the pumping condition.

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