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Output Characteristics of Narrow No-Gain Competition Linewidth Dual-Wavelength Laser at 912 nm and 1064 nm

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Abstract

The output characteristics of a narrow linewidth, no-gain competition, dual-wavelength solid-state laser using an intra-cavity pumped method are reported. This system consists of an intra-cavity pumped $Nd:YVO_4$ laser emitting at 1064 nm, using a 912 nm $Nd:GdVO_4$ laser. A Fabry-Perot etalon is used to compress the linewidth that located at the common cavity of 912 nm and 1064 nm laser. Theoretical analysis and experimental verification were carried out. When the pump power is 32.8 W, the output of 912 nm and 1064 nm theoretical value is 0.036 W and 0.046 W, and the experimental value is 0.017 W and 0.016 W, respectively. The change trend of the theoretical simulated output power value was the same as the actual measured value in the experiment. In addition to this, the experimental measurement shows when the etalon with an angle of 15˚, corresponding minimum linewidths were 0.284 nm and 0.627 nm, respectively.

Keywords

Dual-Wavelength, Narrow Linewidth, Intra-Cavity Pumped

1. Introduction

The improvement of simultaneous emission at dual-wavelengths is of interest for practical applications, such as optical communication, laser lidar, low light detection and single photon detection technology [1] [2]. In recent years, the intra-cavity pumping has been widely used in the development of multi-wavelength lasers, and it is worth noting that the narrow linewidth dual-wavelength lasers are active areas of interest in this regard. The operation of solid-state dual-wavelength lasers primarily based on four-level laser systems has been widely demonstrated by various research groups [3] [4]. In 2016, an intra-cavity pumping method was used to pump a Nd:YAG crystal which emits at 946 nm, and a Nd:YVO_4 crystal which emits at 1064 nm. The incident pump power of 17 W was found to 1.1 W and 2.9 W, respectively [5]. However, narrow linewidth dual-wavelength lasers are primarily based on the erbium-doped fiber laser. In 2010, a polarization-maintaining fiber Bragg grating and a F-P fiber filter were used to facilitate a dual-wavelength output with a power separately −2.259 dBm and 0.568 dBm, with a 3 dB bandwidth separately 0.102 nm and 0.1402 nm and the central wavelength separately 1547.778 nm and 1548.222 nm [6]. In 2018, the narrow linewidth dual-wavelength lasers were obtained, by using a F-P etalon with an angle of refraction of 15˚, the linewidths were reduced from 1.52 nm to 0.28 nm and 1.16 nm to 0.63 nm at 912 nm and 1064 nm, respectively, with the the output power of 17 mW at 912 nm and 16 mW at 1064 nm [7], however the output characteristics of narrow linewidth dual-wavelength solid-state laser were not studied.

In this report, the output characteristics of a narrow linewidth dual-wavelength solid-state laser using an intra-cavity pumped method is reported. An F-P etalon was introduced in the common cavity of the laser, and it was used to simultaneously narrowed the linewidth of both wavelengths. The setup is schematically shown in **Figure 1**. Theoretical analysis and experimental verification were carried out and when the etalon with an angle of refraction of 15˚ was introduced into the cavity and the pumping power was 32.48 W, the narrow linewidth dual-wavelength laser was obtained, the corresponding minimum linewidths were 0.284 nm and 0.627 nm, respectively. The output power of theoretical value is 0.036 W and 0.046 W, and the experimental value is 0.017 W and 0.016 W, respectively.

2. Theoretical Analysis

In the intravaity pumped dual-wavelength narrow linewidth solid-state laser system, an F-P etalon was introduced in the common cavity of the laser. And the F-P etalon is a high resolution interferometer, which is based on multi-beam interference and has different transmittance to incident laser.

The transmittance of a single F-P etalon can be expressed as follows:

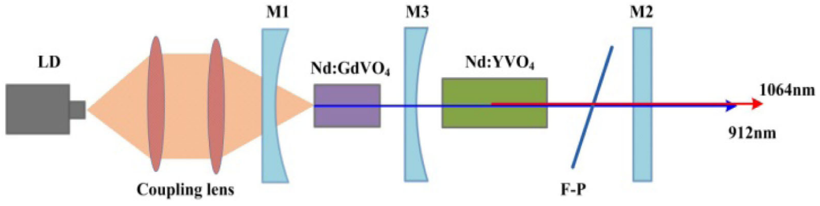

Figure 1. Experimental setup of a narrow linewidth, dual-wavelength laser based on intra-cavity pumping using a F-P etalon.

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

$$\delta(\lambda)=\frac{4\pi nd\cos\theta}{\lambda} \quad (2)$$

where F is the fineness of the etalon that indicated as $F=\frac{4R}{(1-R)^2}$, T_2 is the reflectivity of the etalon, $\delta(\lambda)$ is the phase difference between adjacent two wavelength lasers with multi-beam interference in the etalon, n is the refractive index of the etalon, h is the thickness of the etalon, θ is the refraction angle of the etalon, and c is the speed of light.

We assume that the Nd:$GdVO_4$ and Nd:YVO_4 crystals lengths are l_I and l_{II}, the laser waist radii are ω_{0I} and ω_{0II}, respectively. The pump power is P_p and the pump light waist radius is ω_{0p}. $R_p=\frac{P_p}{hv_p}\frac{2\left[1-\exp\left(-\sigma_1 l_1\right)\right]}{\pi l_1\left(\omega_{0I}^2+\omega_{0p}^2\right)}$ and $R_{pII}=\frac{\eta P_{in}}{hv_I}\frac{2\left[1-\exp\left(-\sigma_2 l_2\right)\right]}{\pi l_2\left(\omega_{0I}^2+\omega_{0II}^2\right)}$ are the pumping rates, σ_{eI} and σ_{aI} are the effective emission and absorption cross-sections of the quasi-three-level laser, respectively, and $f=\frac{\sigma_{aI}}{\sigma_{eI}}$. $\tau_{cI}=\frac{L_{eI}}{\gamma_I C}$ represents the intra-cavity photon lifetime of the quasi-three-level laser. υ_1 and υ_2 represents the 912 nm and 1064 nm. σ_1 represents the absorption coefficient of Nd:$GdVO_4$ 912 nm to pump source 808nm laser and σ_2 represents the absorption coefficient of Nd:YVO_4 1064 nm to 912 nm laser, h is Planck constant.

$$\gamma_I=\gamma_0+\frac{\gamma_{1I}+\gamma_{2I}}{2}+\alpha_I+S+T_{lossI}+T_{fp-912} \quad (3)$$

Equation (3) is the one-way total loss of the quasi-three-level laser, $\gamma_{1I}=\ln\left(1-T_{1I}\right)$ and $\gamma_{2I}=-\ln\left(1-T_{2I}\right)$ are the losses of the total-reflection and output mirrors, respectively. T_{1I} and T_{2I} represents the transmittance of M1 mirror at 912 nm and 1064 nm, N_t represents total number of reversed particles, L_{eI} and L_{eII} represents optical length of the quasi-three-level and four-level laser cavity. And $T_{lossI}=-\log(1-T_I)$ and $T_{lossII}=-\log(1-T_{II})$ is the transmittance loss caused by 912 nm and 1064 nm laser by full reflection mirror, T_1 and T_2 is the transmittance of 912 nm and 1064 nm laser by four-level laser full reflection mirror, respectively. And $\alpha_I=1-\exp\left[-\left(\sigma_2 l_{II}\right)\right]$ is the absorption loss of the quasi-three-level laser by the four-level laser gain medium. $S=2N_I^0\sigma_{eI}l$ is the ratio of reabsorption loss to the quasi-three-level laser cavity loss, and N_I^0 is the neodymium-ion concentration in the Nd:$GdVO_4$ crystal (0.1 at. %) [8]. $\tau_{cII}=\frac{L_{eII}}{\gamma_{II}c}$ represents the intra-cavity photon lifetime of the four-level laser. $B=\frac{2\sigma_{eII}c}{\pi\omega_{0II}L_{eII}}$ is a constant describing the spot size and gain medium of the four-level laser.

$$\gamma_{II} = \gamma_{0II} + \frac{\gamma_{2I}}{2} + T_{lossII} + T_{fp-1064} \tag{4}$$

Equation (4) is the one-way total loss of the four-level laser. V_I is the mode volume of the quasi-three-level laser, V_{aI} and V_{aII} are constants related to the mode volume. With a stable output of a dual-wavelength laser, the intra-cavity and output powers of a quasi-three-level laser were respectively obtained as:

$$P_{in} = \left(\frac{c}{2L_{eI}}\right)(h\nu_I)\frac{\left[R_p(1+f)-fN_t\right]V_{aI}\sigma_{eI}\tau_{cI}c - V_I}{(\sigma_{aI}+\sigma_{eI})\tau c} \tag{5a}$$

$$P_{1out} = \left(\frac{T_{2I}c}{2L_{eI}}\right)(h\nu_I)\frac{\left[R_P(1+f)-fN_t\right]V_{aI}\sigma_{eI}\tau_{cI}c - V_I}{(\sigma_{aI}+\sigma_{eI})\tau c} \tag{5b}$$

Furthermore, Equation (5a) is regarded as a pumping source of a four-level laser.

$$P_{2out} = \left(\frac{T_{2II}c}{2L_{eII}}\right)(h\nu_{II})\frac{R_{p2}BV_{a2}\tau\tau_{cII} - 1}{B\tau} \tag{6}$$

Based on Equations (5a), (5b), and (6), the output characteristics of a simultaneous dual-wavelength laser with reabsorption loss and F-P etalon transmittance loss are obtained.

3. Experimental

The pumping source for the 912 nm laser was an LD operated at 808 nm to match the $^4I_{9/2}$-$^4F_{3/2}$ transition in the Nd^{3+} ion. The resonant cavity length is 65 mm. The Nd: $GdVO_4$ crystal was c-cut and doped with Nd^{3+} at a concentration of 0.1 at. % and the crystal was 3 × 3 × 6 mm^3 in size. A low-doped laser crystal assists in reducing thermal lensing and losses from reabsorption of the quasi-three-level system. Both sides of the Nd: $GdVO_4$ crystal were polished to laser quality and coated for high transmission (HT) at 912 nm and the pump wavelength of 808 nm (T > 99%). They were also coated with an antireflection coating (AR) for 1064 nm (R < 2%), which suppressed the more efficient four-level transitions. The Nd: YVO_4 crystal was doped with Nd^{3+} at a concentration of 0.5 at. %, and a 3 × 3 × 5 mm^3 crystal was selected. Both sides of the Nd: YVO_4 was coated for HT at 912 nm (T > 99%) and 1064 nm (R < 1.0%). The radius of curvature for M1, M2, and M3 were 200 mm and +∞, with ϕ20 × 3 mm, respectively. The total reflector mirror M1 which is plano-concave, was AR-coated for 808 and 1064 nm (R < 5%) on both sides and HR-coated for 912 nm (R > 99.8%) on the concave side. The M3 is the total reflector for the four-level laser. The output mirror M2, a plano-plano, was coated for T = 2% at 912 nm and T = 5% at 1064 nm, while the outer surface was AR-coated for 912 and 1064 nm. The distance between the two crystals was set to 20 mm. The mounted in a newly designed micro-channel copper heat sink which was kept at 12.9˚C by water cooling. The F-P etalon had a thickness of 0.3 mm.

4. Results and Discussion

The transmittance at 912 nm and 1064 nm when the rotation angle of F-P etalon changed from 0˚ to 20˚ is shown in **Figure 2** and **Figure 3**. It can be seen that the F-P etalon with different angles (0˚ to 20˚) in the intra-cavity pumped dual-wavelength laser cavity cause different changes in the transmittance of the two wavelengths.

Detected using the high-resolution visible wavelength optical spectrum analyzer AQ6373 (Yokogawa Electric Corp., Tokyo, Japan) the resolution ration is 0.02 nm. When the pumping power is 32.48 W, the experiment output power and linewidth at 912 nm and 1064 nm with different angles of the F-P etalon is listed in **Table 1**. It was shown that the dual-wavelength laser without the F-P etalon linewidths with FWHM values of 1.52 nm and 1.16 nm at 912 nm and 1064 nm when the pump power was 32.48 W. and when the etalon with an angle was 15˚, corresponding minimum linewidths were 0.384 nm and 0.627 nm, respectively. The conversion efficiency was 0.1% with the output power of 17 mW at 912 nm and 16 mW at 1064 nm. After the etalon was introduced, the compression value of the linewidth for the quasi-three-level laser was higher than that of the four-level laser.

When the pumping power is 32.48 W, the theoretical and experiment value output power with the different angles of the F-P etalon is shown in **Table 2**. The theoretical calculation results show that when the rotation angle of F-P etalon is 15˚, the transmittance loss introduced corresponds to 0.27 and 0.11 for

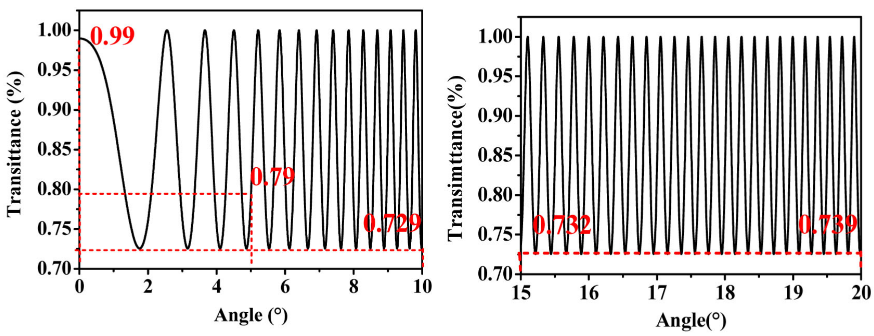

Figure 2. The transmittance at 912 nm when the angles of F-P etalon changed from 0˚ to 20˚.

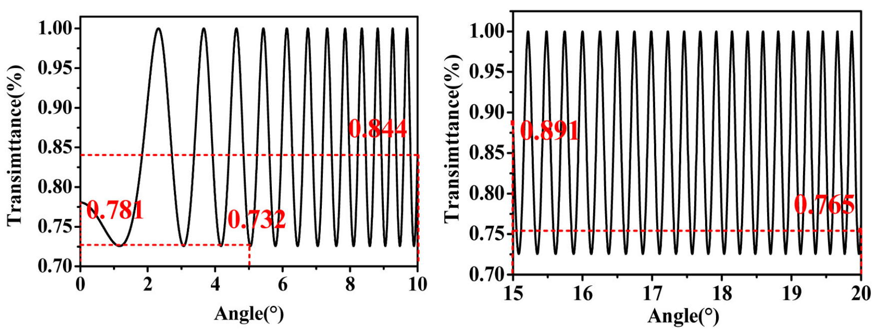

Figure 3. The transmittance at 1064 nm when the angles of F-P etalon changed from 0˚ to 20˚.

Table 1. The output power and linewidth with the different angles of the F-P etalon.

α (˚)	Output power (W)		Linewidth (nm)	
	912 nm	1064 nm	912 nm	1064 nm
Without F-P	0.166	0.33	1.156	1.160
0	0.070	0.041	0.484	0.752
5	0.032	0.085	0.396	0.705
10	0.107	0.035	0.501	0.905
15	0.017	0.016	0.384	0.627
20	0.011	0.015	0.141	0.684

Table 2. The theoretical and experiment value output power with the different angles of the F-P etalon.

α (˚)	Theoretical value (W)		Experiment value(W)	
	912 nm	1064 nm	912 nm	1064 nm
0	0.041	0.029	0.07	0.041
5	0.06	0.033	0.02	0.085
10	0.037	0.019	0.107	0.035
15	0.036	0.046	0.017	0.016
20	0.036	0.021	0.015	0.015

912 nm and 1064 nm lasers, respectively. **Table 2** shows that the output power of 912 nm laser is 0.036 W and that of 1064 nm laser is 0.046 W.

The output power of F-P etalon with different angles in dual-wavelength narrow linewidth laser is shown in **Figure 4**, and when the angle of F-P etalon was 15˚, the output power of 912 nm and 1064 nm laser is shown in **Figure 5**. Because the introduction of transmittance loss of F-P etalon, the number of particles in the cavity bagan to accumulate before the threshold of 912 nm, and no photons were generated in the cavity. With the increase of pump power, the quasi-three level begin to oscillate in the cavity, the density of the reversed particles began to increase and a small number of phonots were produced. When the pump power is 12 W, the four-level laser bagan to oscillate and the density of the reversed particles bagan to increas with the photos are produced, then the stability of the intracavity pumped daul-wavelength narrow linewidth laser output.

The basic parameters of the theoretical simulation are as follows: the foundation loss in the cavity is 2%, the transmittance loss caused by the F-P etalon and the four-level full refraction mirror is more than 4%, and the total loss in the cavity is more than 6%. Therefore the output power of the dual-wavelength laser is lower than without F-P etalon.

Corresponding to the experimental measurement results, the output power of the two laser shows a trend of "from high to low" and "from low to high" when the pump power is 32.48 W. **Figure 6** shows the change trend of the theoretical simulated output power value was the same as the actual measured value in the experiment.

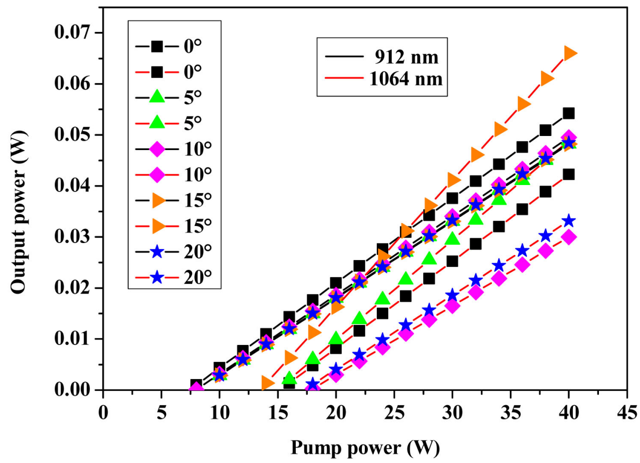

Figure 4. The output power of F-P etalon with different angles in dual-wavelength narrow linewidth laser.

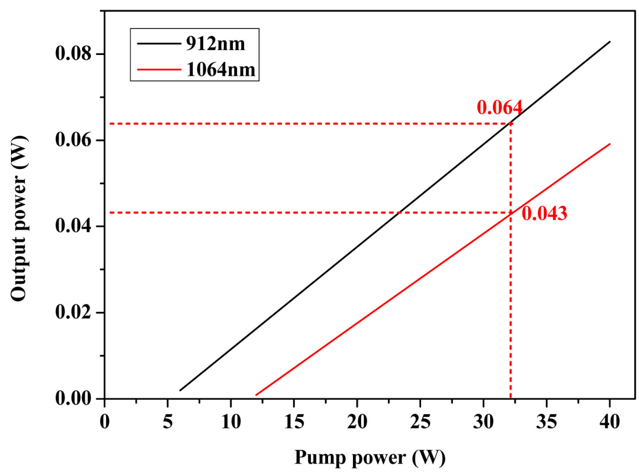

Figure 5. When the angle of F-P etalon was 15˚, the output power of 912 nm and 1064 nm laser.

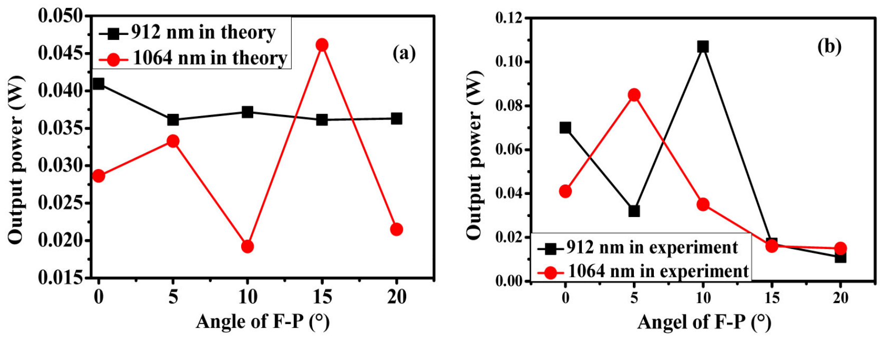

Figure 6. The theoretical (a) and experiment (b) value output power with the different angles of the F-P etalon.

It can be found from the comparative analysis, the theoretical calculation results show that the output power of the quasi-three-level laser has a relatively gentle change trend with no sharp, while the output power of the four-level laser has a relatively obvious change trend with a sharp compared with the quasi-three-level laser. Moreover, when the angle of F-P etalon is 15˚, the output power of the four-level laser increases significantly, which is more than twice of the actual measured value.

5. Conclusion

In summary, the output characteristics of a narrow linewidth dual-wavelength laser with F-P etalon was reported. When the pumping power was 32.48 W, the dual-wavelength laser (without F-P etalon) had linewidths with FWHMs of 1.52 nm and 1.16 nm at 912 nm and 1064 nm, respectively. By using a F-P etalon with an angle of 15˚, the linewidths were reduced to 0.28 nm and 0.63 nm at 912 nm and 1064 nm, respectively, corresponding the conversion efficiency was 0.1%. Theoretical analysis and experimental verification were carried out, the theoretical value is 0.036 W and 0.046 W, and the experimental value is 0.017 W and 0.016 W, respectivly. And the change trend of the theoretical simulated output power value was the same as the actual measured value in the experiment. Compared with a conventional dual-wavelength laser, 912 and 1064 nm narrow linewidth outputs were simultaneously laser is more conducive to application in detection system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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