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A diode-pumped Nd:YAlO$_3$ dual-wavelength yellow light source

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Abstract
We present what is, to the best of our knowledge, the first diode-pumped Nd:YAlO$_3$ (Nd:YAP) continuous-wave (cw) dual-wavelength yellow laser at 593 nm and 598 nm, based on sum-frequency generation between 1064 and 1339 nm in *a*-axis polarization using LBO crystal and between 1079 and 1341 nm in *c*-axis polarization using PPKTP crystal, respectively. At an incident pump power of 17.3 W, the maximum output power obtained at 593 nm and 598 nm is 0.18 W and 1.86 W, respectively. The laser experiment shows that Nd:YAP crystal can be used for an efficient diode-pumped dual-wavelength yellow laser system.

(Some figures may appear in colour only in the online journal)

1. Introduction

Lasers emitting simultaneously at multiple wavelengths can find wide applications in many fields such as environmental monitoring, laser radar, spectral analysis and THz research, etc. The yellow laser was obtained using the sum-frequency mixing (SFM) from the dual-wavelength laser [1–3]. The yellow laser has been required by many applications, such as medicine [4], Bose–Einstein condensation [5], LiDAR measurement in the atmosphere region 15–100 km [6], and as a source for creating guide stars. As we know, there exist three transitions: $^4F_{3/2}$–$^4I_{13/2}$, $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{9/2}$ in Nd^{3+} ion, leading to potential laser radiations around 1.3, 1.0 and 0.9 μm, respectively. The first report about the multiple-wavelength laser was presented by Bethea in 1973 by using Nd:YAG as the gain medium [7]. After that, dual-wavelength lasers based on Nd:YAG [8–10], Nd:YLF [11], Nd:YVO$_4$ [12–15], and Nd:YAP [16, 17] were reported. Among the various neodymium-doped crystals, Nd:YAP crystal is an important candidate for the dual-wavelength laser. This is because Nd:YAP crystal not only possesses high thermal conductivity and an excellent optomechanical coefficient but also has a large stimulated emission cross section [18]. Moreover, the large natural birefringence of Nd:YAP may overcome the limitations on fundamental mode operation and depolarization losses caused by thermally induced stress birefringence and bifocals at high average powers [19]. A diagram of the energy levels of Nd^{3+} in Nd:YAP crystal is shown in figure 1. The wavelength of the strongest line comes from the $^4F_{3/2}$–$^4I_{11/2}$ transition. The wavelengths of the main lines are 1064 nm (*a*-axis polarization) and 1079 nm (*c*-axis polarization) generated by R1 → Y1 and R2 → Y3 transitions, respectively.

The $^4F_{3/2}$–$^4I_{13/2}$ transition has two intense overlapped stark transitions: R1 → X1 at 1339 nm and R2 → X3 at 1341 nm. The stimulated emission cross sections vary with polarization in the anisotropic Nd:YAP crystal [20]. For $^4F_{3/2}$–$^4I_{11/2}$ (or $^4F_{3/2}$–$^4I_{13/2}$) transition of *b*-axis laser rod, the gain is greatest for 1079 nm (or 1341 nm) with polarization in the *c*-axis direction and greatest for 1064 nm (or 1339 nm) with polarization in the *a*-axis direction. To the best of our knowledge, no research work of four-wavelength operation in Nd:YAP lasers, with emission on two wavelengths orthogonally polarized to emission on

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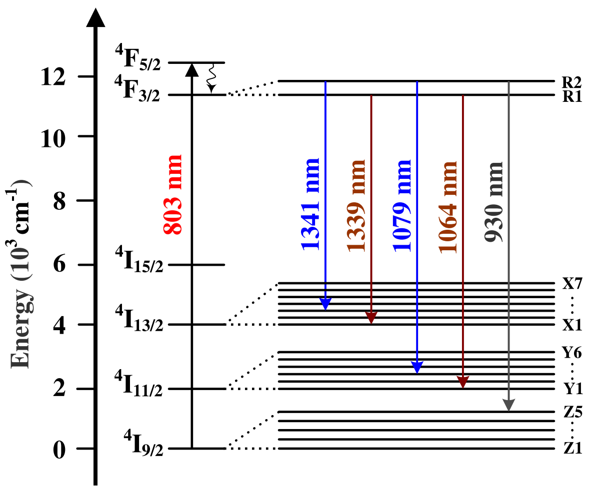

Figure 1. Energy structure of a Nd:YAP crystal.

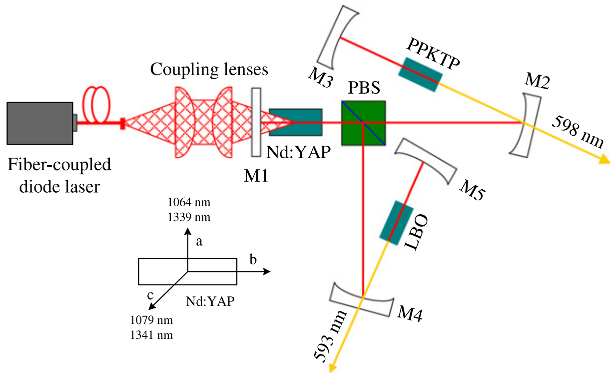

Figure 2. Experimental configuration for the diode-pumped Nd:YAP dual-wavelength yellow laser.

two other wavelengths, has been reported. In this work, simultaneous cw emission of four wavelengths (1064 and 1339 nm in *a*-axis polarization and 1079 and 1341 nm in *c*-axis polarization) from a diode-pumped Nd:YAP laser was investigated. The cw dual-wavelength yellow laser is realized by intracavity SFM using emission at two wavelengths polarized along the *a*-axis and at the other two polarized along the *c*-axis.

2. Experimental setup

The experimental setup is presented in figure 2. The optical pumping was realized by using fiber-coupled (diameter of 400 μm and numerical aperture NA = 0.22) diode lasers from Coherent Co., USA. The 803 nm emitting diode delivered 20 W of pump power with an emission bandwidth of 2.5 nm (FWHM).

The coupling optics consisted of two identical plano-convex lenses with focal lengths of 15 mm used to re-image the pump beam into the laser crystal at a ratio of 1:1. The coupling efficiency was 95%. A *b*-axis 1.0 at.% Nd^{3+}-doped Nd:YAP crystal with a dimension of 8 mm in length and 3 mm in diameter was used as the laser rod. It was wrapped with indium foil and mounted in a TEC (thermal electronic cooled) copper block, and the temperature was maintained at 20 °C. The whole cavity was also cooled by TEC. Both sides of the laser crystal were coated for high transmission (HT) at 1.0 and 1.34 μm. The input mirror, M1, was HT coated at the pump wavelength and highly reflective (HR) at 1.0 and 1.34 μm. The concave mirror, M2, with a 50 mm radius of curvature, was used as the output coupler for the *c*-axis polarized beam, which was coated to be partially transmitting (PT) at 1079 nm ($T = 27.6\%$), PT at 1341 nm ($T = 12.5\%$) and HT at 598 nm. The concave mirror, M3, with a 200 mm radius of curvature was HR coated at 1079, 1341 and 598 nm. The concave mirror, M4, with a 50 mm radius of curvature, was used as the output coupler for the *a*-axis polarized beam, and was coated to be PT at 1064 nm ($T = 8.8\%$), HR at 1339 nm and HT at 593 nm. The concave mirror, M5, with a 200 mm radius of curvature was HR coated at 1064, 1339 and 593 nm.

The distances of M1–M2 and M3–M4 were 65 mm and 28 mm, respectively. The distances of M1–M4 and M4–M5 were 69 mm and 27 mm, respectively.

A polarization beam splitter (PBS) was placed in the cavity to split the beams polarizing in two orthogonal directions. LBO crystal cut for type-I critical phase matching ($\theta = 90°, \varphi = 2.7°$ with $d_{\mathrm{eff}} = 0.83$ pm V^{-1}) was chosen as the nonlinear crystal. The size of the LBO crystal was $2 \times 2 \times 10$ mm^3 and both end facets of the LBO crystal were HT coated at 1064, 1339 and 593 nm to reduce the reflection losses in the cavity. An intracavity PPKTP crystal was employed to obtain an SFM 598 nm output. The PPKTP crystal was 5 mm long, 1 mm thick, and 2 mm high, and had a 12.8 μm grating period with antireflection coatings at 1079 and 1341 nm on both faces. The PPKTP was mounted in a copper housing with its temperature fixed by a thermoelectric device, a negative temperature coefficient thermistor and a controller. With this controller, the PPKTP temperature was stabilized with an accuracy of 0.25 °C.

3. Results and discussion

Considering the SFM process in the PPKTP, the quasi-phase matched (QPM) condition in a collinear interaction is $(n_3/\lambda_3) - (n_2/\lambda_2) - (n_1/\lambda_1) = (1/\Lambda)$, where λ_3 is the wavelength of the sum-frequency beam, n_3 is the refractive index of the wave at λ_i for $i = 1$–3, and Λ is the domain grating period of the PPKTP. Substituting the published Sellmeier equation [21, 22], into the QPM condition for SFM, we calculated the phase-matching temperature as a function of the grating period of the PPKTP and plotted the result in figure 3. In our experiment, the PPKTP sample was fabricated to have a 12.8 μm grating period. The optimum QPM temperature was found to be 52 °C. Figure 4 shows the experimental result for the dependence of the relative output powers at 598 and 593 nm on the temperature of the PPKTP crystal at a pump power of 17.3 W.

The output powers at two wavelengths of 598 and 593 nm versus the temperature of the PPKTP crystal at a pump power of 17.3 W are given in figure 4. The power of the yellow emission at 598 nm varies as a sin c^2-function, and the optimum temperature is found to be 52 °C. On the other hand,

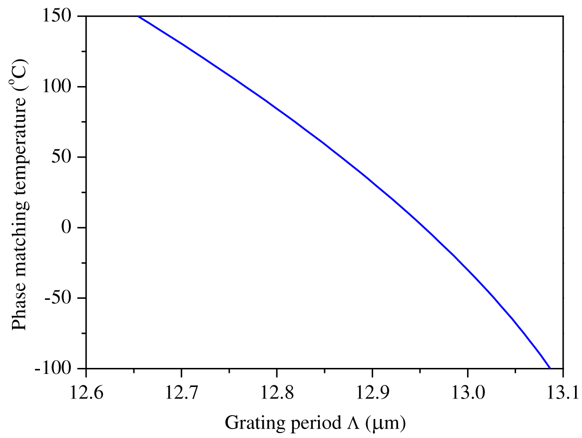

Figure 3. The calculated result for the phase-matching temperature as a function of the grating period of the PPKTP for SFM process at 1079 and 1341 nm.

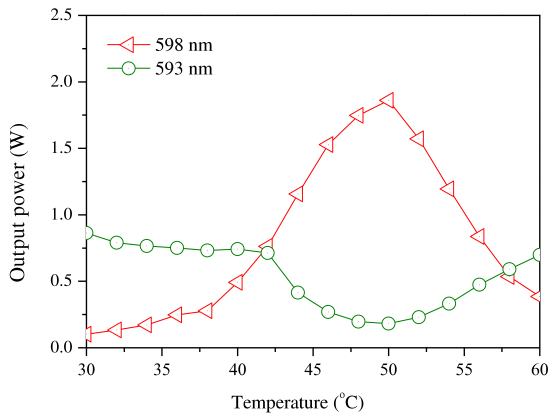

Figure 4. The output power at two wavelengths of 598 and 593 nm as a function of the temperature of the PPKTP crystal at a pump power of 17.3 W.

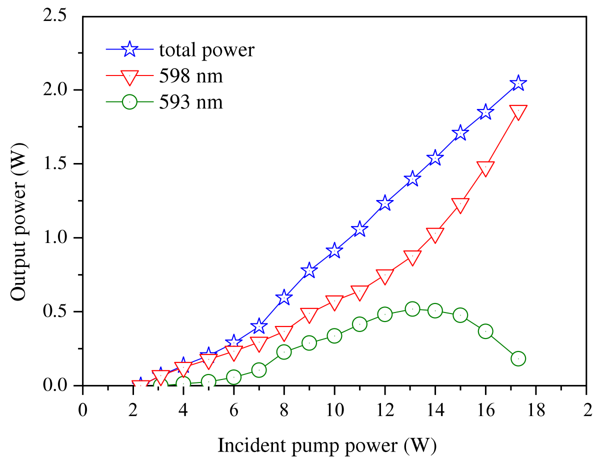

Figure 5. Dependence of the output powers at 598 and 593 nm on the incident pump power.

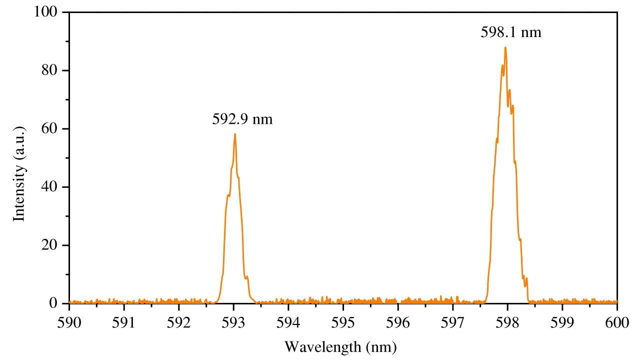

Figure 6. Optical spectrum of dual-wavelength operation at a pump power of 13.1 W.

the output power of 593 nm first descends monotonically with the temperature of the PPKTP crystal, reaches its minimum power of 0.18 W at 52 °C, and then increases monotonically. We believe that four-wavelength operation with the same laser medium demonstrates strong gain competition between the transition $^4F_{3/2}$–$^4I_{11/2}$ around 1.0 μm and the transition $^4F_{3/2}$–$^4I_{13/2}$ around 1.3 μm. Figure 5 shows the output power at each lasing wavelength with respect to the incident pump power. Because the gain of the *c*-axis polarized beam is much greater than that of the *a*-axis polarized beam, the *c*-axis polarized beam is obtained first. The threshold pump power is 2.3 W for 598 nm, and 3.1 W for 593 nm. The output power of the 598 nm line increases monotonically as the pump power increases. On the other hand, the output power of the 593 nm line increases at first linearly with the pump power, reaches its maximum power of 0.52 W at the pump power of 13.1 W, and then decreases monotonically. We believe that the gain competition between the dual-wavelength emission with *a*-axis polarization and the dual-wavelength emission with *c*-axis polarization results in the output power decrease of 593 nm light above 13.1 W of pump power. The laser beams were observed at different pump powers. The M^2 factor of 593 nm emission is estimated to be approximately 1.16 near threshold, and then increases to 2.53 at pump power greater than 17.3 W. On the other hand, the 598 nm emission maintains a beam quality factor M^2 of less than 1.15 over the full range of pump powers. Figure 6 shows the measured optical spectrum for the simultaneous dual-wavelength laser at the pump power of 13.1 W. The central wavelengths are 598.1 nm and 592.9 nm, with the spectral linewidths of 0.40 nm and 0.35 nm, respectively.

4. Conclusion

We succeeded in obtaining a diode-pumped Nd:YAP cw dual-wavelength yellow laser at 593 nm and 598 nm based on sum-frequency generation between 1064 and 1339 nm in *a*-axis polarization using LBO crystal and between 1079 and 1341 nm in *c*-axis polarization using PPKTP crystal, respectively. A doubly folded cavity in two perpendicular directions was built, and the maximum output powers of the yellow emission 0.52 and 1.86 W were obtained. Furthermore, nonlinear crystal for SFM PPKTP was investigated. The optimum phase-matching temperature is in good agreement with the result calculated from the reported values of temperature-dependent refractive index for the PPKTP crystal. The temperature acceptance bandwidth was found to be ∼20 °C for a 5 mm length PPKTP crystal.

Acknowledgment

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