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Diode-pumped 593.5 nm cw yellow laser by type-I CPM LBO intracavity sum-frequency-mixing

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Abstract

A design of LD-pumped Nd:YVO_4 laser that generates simultaneous laser action at wavelengths 1064 and 1342 nm by optimizing film design is presented. An optimized continuous-wave (cw) yellow laser at 593.5 nm in room temperature is obtained for the first time. Using type-I critical phase-matching (CPM)LBO crystal, a yellow laser at 593.5 nm is obtained by 1064 and 1342 nm intracavity sum-frequency mixing. The maximum laser output power of 85 mW is obtained when an incident pump laser of 1.8 W is used. The optical-to-optical conversion is up to 4.7%, and the power stability in 24 h is better than $\pm 2.8\%$.

Keywords: Dual-wavelength operation; Intracavity sum-frequency mixing; Yellow laser

1. Introduction

In recent years, coherent continuous-wave (cw) yellow laser sources have recieved interest because of their potential technical applications in medicine, testing, color display and other areas. In particular, diode-pumped solid-state lasers have been established as efficient and compact light sources for these applications. Unfortunately, because of the absence of efficient fundamental lasers, the yellow radiation from 550 to 650 nm cannot be obtained by frequency doubling as the blue, green and red radiation. But other ways of generating the yellow laser have been found. Typically, one approach is based on sum-frequency mixing, in which coherent frequencies of v_1 and v_2 are mixed, generating radiation of frequency $v_3 = v_1 + v_2$. In the past, radiations of pulse sum-frequency-mixing by dual-wavelength Nd:YAG, Nd:YLF, and Nd:YVO_4 pulsed lasers had been reported [1–3] in KDP, KDP* and BBO crystals, respectively. Shen Lei et al. used type-I CPM MgO:$LiNbO_3$ in Nd:YAP to achieve a yellow laser at 598.1 nm cw operation [4]. Recently, the cw yellow laser by single-pass sum-frequency mixing of a diode-pumped Nd:YVO_4 dual-wavelength laser was also achieved [5]. The dual-wavelength laser was implemented with a three-mirror cavity; the cw yellow laser was obtained using the of single-pass sum-frequency mixing from the dual-wavelength laser with a periodically poled lithium niobate (PPLN) crystal. When the incident pumped power was 15 W, the yellow output power was only 78 mW. Because this approach used a three-mirror cavity and mainly extracavity-sum-frequency mixing, with low efficiency and a complexical structure, it is not suitable for commercial production.

In this paper, a diode-end-pumped Nd:YVO_4 laser with a single gain mediuml, collinear cavity was proposed for the generation of stable simultaneous cw emission at wavelengths 1064 and 1342 nm. In cavity design, we used a single collinear cavity that could provide a rugged, compact solid-state device, design simply, align easily, with a shorter cavity length and exploit higher intracavity intensities. By using type-I CPM LBO crystal intracavity sum-frequency mixing, the yellow laser at 593.5 nm was obtained. The

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maximum sum-frequengy output power was up to 85 mW with 1.8 W pump power by optimizing the output mirror transmittance for 1064 and 1342 nm.

2. Theory analysis

Simultaneous dual-wavelength lasing is a kind of useful source for nonlinear frequency conversion. Shen et al. [6] analyzed the possibility of simultaneous dual-wavelength lasers in Nd:YAG, Nd:YLF, and Nd:YAP crystals at transitions from $^4F_{3/2}$–$^4I_{11/2}$ to $^4F_{3/2}$–$^4I_{13/2}$. and realized that dual-wavelength operation of Nd-host crystal is more easier to accomplish with pulse operation and difficult to obtain with cw operation. Their analysis showed that the ratio of stimulated-emission-cross (SEC) section between $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{13/2}$ transitions cannot be too large for obtaining a cw dual-wavelength operation. There are two main radiating transitions in Nd:YVO$_4$ crystal. It was well known that Nd^{3+} doped in YVO$_4$ can also emit 1342 nm in addition to 1064 nm. Furthermore, Nd^{3+} can have a high-doped concentration and emit polarized light in YVO$_4$. So Nd:YVO$_4$ is highly suitable to generate diode-pumped lasers. In Nd:YVO$_4$ crystal, the SEC sections at 1064 nm ($^4F_{3/2}$–$^4I_{11/2}$) and 1342 nm ($^4F_{3/2}$–$^4I_{13/2}$) are, respectively, $12\times10^{-19}\,cm^2$ and $6\times10^{-19}\,cm^2$ [7]; therefore, the ratio of SEC section in the Nd:YVO$_4$ crystal is approximately 2, i.e., the Nd:YVO$_4$ crystal is more suitable than the other crystals such as Nd:YAG, for dual-wavelength cw operation at the $^4F_{3/2}$–$^4I_{11/2}$ and $^4F_{3/2}$–$^4I_{13/2}$ transitions. Fig. 1 presents the Nd:YVO$_4$ energy level, which we use here.

The standard expression for sum-frequency power in the small signal limit is of the form

$$P_3 = (\text{const})P_1P_2, \tag{1}$$

where P_3 is the power at the sum frequency obtained by mixing radiation of the two original frequencies of powers P_1 and P_2. To achieve high sum-frequency output power it would be best to maximize product of powers for P_1 and P_2 according to the above equation. Firstly, in cavity design, a single collinear cavity is built and the intracavity sum-frequency is used to guarantee the higher intracavity power for P_1 and P_2; the nonlinear crystal is positioned at the beam waist. When the two fundamental lasers assure high intracavity power, high sum-frequency power P_3 can be achieved.

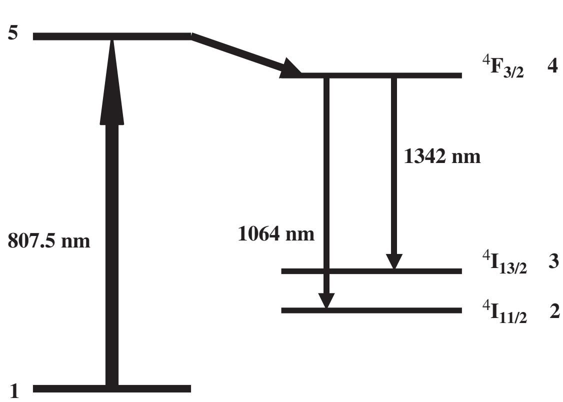

Fig. 1. The energy level of Nd: YVO$_4$ crystal under study.

Simultaneously, on the basis of the sum-frequency-mixing optimization theory, to obtain high efficiency of sum-frequency mixing, not only high power density for fundamental laser lines, but also approximately equal photon numbers of the two fundamental wavelengths 1064 nm and 1342 nm in the cavity are required, i.e., $N_{1064} = N_{1342}$, for $P_{1064} \propto h\nu_{1064}N_{1064}$, $P_{1342} \propto h\nu_{1342}N_{1342}$, where ν_{1064} and ν_{1342} are the frequency of the fundamental wavelengths 1064 nm and 1342 nm. So when N_{1064} is equal to $N_{1342,}$ we can see $P_{1064}/P_{1342} = \nu_{1064}/\nu_{1342} = \lambda_{1342}/\lambda_{1064} = 1342/1064 = 1.26$. Therefore, first of all, assuring high fundamental laser power, and when the ratio of intracavity power for 1064 and 1342 nm would be approximately satisfied with the value 1.26, we can achieve higher efficiency of sum-frequency mixing. By the experiment, the approach is proved feasible.

Based on the above analysis, because of the substantial gain difference between two lasing wavelengths, to optimize high efficiency sum-frequency mixing, the loss values of each respective wavelength at the output coupler should be set to approximately balance the gain matching. Here, we mainly depend on increasing transmission loss of 1064 nm in the cavity to optimize the gain matching by designing and coating the highly excellent optical thin film. To reduce the design difficulty, the left facet of Nd:YVO$_4$ was coated with 1064/1342 nm high reflection (HR) coatings as were all reflective mirrors: The concave surface of the output mirror was coated with 1342 nm HR, and 1064 nm partly transmission. Practically, it is very difficult to achieve the exact transmission values of the output mirrors for wavelength 1064 nm because of experiment errors. After several experiments, eventually, using the output mirror with the optimum transmission value of 1% for 1064 nm, the maximum yellow laser at 593.5 nm output power was achieved. The final experiment result is given below.

3. Experimental setup

Fig. 2 shows the experimental setup of the sum-frequency-mixing cw yellow laser. There are three parts in the setup: couple optics system, resonator system and temperature adjusting system. The pumping source is a laser diode with maximum output 1.8 W, a central emitting wavelength of 807.5 nm at 23 °C and a

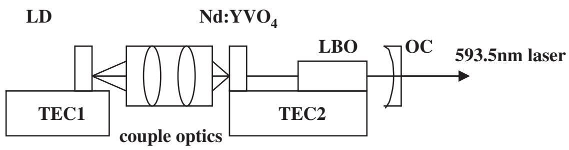

Fig. 2. The setup of LD-pumped yellow laser.

divergent angle of $8.2 \times 34.5^{\circ}$. After going through the coupling optics system, the light emitted from LD was reshaped to high-quality pumping light (with an ellipticity of 0.91, beam waist's radius is about $95\,\mu m$) and was injected into the $Nd:YVO_4$ crystal ($3 \times 3 \times 2\,mm^3$). The Nd^{3+} concentration of the crystal was 1.0 at%, a-cut off. The left facet of the crystal was directly coated with dielectric reflective film as the resonator's end facet; the output mirror was a 50 mm radus-of-curvature concave mirror, was the resonator's other facet. By optimizing computing, the resonator's length is about 18 mm. Nonlinear crystal LBO ($2 \times 2 \times 10\,mm^3$), used type-I critical phase-matching. On the basis of the dual-wavelength operation theory, when the two fundamental lasers simultaneously operated, using different nonlinear parameter LBO, sum-frequency generation of the two radiation wavelengths (1064 and 1342 nm) to produce yellow light (593.5 nm) and second-harmonic generation of each fundamental radiation wavelength to produce red (671 nm) or green (532 nm) light can be achieved conveniently.

Data listed in Table 1 showed the different LBO crystal nonlinear parameters. Laser diode, $Nd:YVO_4$ and LBO were strictly temperature controlled by TEC1 and TEC2, respectively. The current of TEC1 was adjusted to make the central wavelength emitted from the LD coincide with the absorption peak of Nd^{3+} in order to utilize the pumping light very well. Nd: YVO_4 and LBO were cooled by the same cooler TEC2 to reduce thermal effect of Nd: YVO_4 and keep the phase-matching condition of LBO from changing with the environment. To generate simultaneous laser action at the wavelengths 1064 and 1342 nm, obtain the optimum power about sum-frequency mixing, it is necessary to reasonably distribute the system optics component's transmittance and reflectance characterictic for 808, 1064, 1342 and 593.5 nm. First of all, arranging the transmission power ratio for the fundamental lasers 1064 and 1342 nm reasonably to obtain excellent gain matching and approximate equal number of intracavity photons is very important.

Here, the left facet of $Nd:YVO_4$ was coated with 808 nm antireflection (AR), $T > 95\%$ and 1064/1342 nm HR coatings as all reflective mirrors; the right facet was coated with 1064/1342 nm(AR), $T > 98\%$; the concave surface of the output mirror was coated with 1319 nm HR, $R > 99.9\%$, 593.5 nm AR, $T > 95\%$ and 1064 nm partly transmission. After many experiments, when the output mirror with the transmission value of 1% for 1064 nm, the maximum yellow laser at 593.5 nm output power was achieved. Two facets of LBO ($2 \times 2 \times 10\,m^3$) both with 1342/1064/593.5 nm AR coatings. Figs. 3 and 4 show the film design curve in $Nd:YVO_4$ and output mirror.

Table 1
Comparision of three different CPM crystals for nonlinear frequency conversion

LBO crystal (nm)	Phase-matching angle θ_m (°)	Orientation angle φ (°)	Effective nonlinear coefficient d_{eff} (pm/V)
532	90	11.3	0.832
671	86.1	0	0.817
593.5	90	2.5	0.837

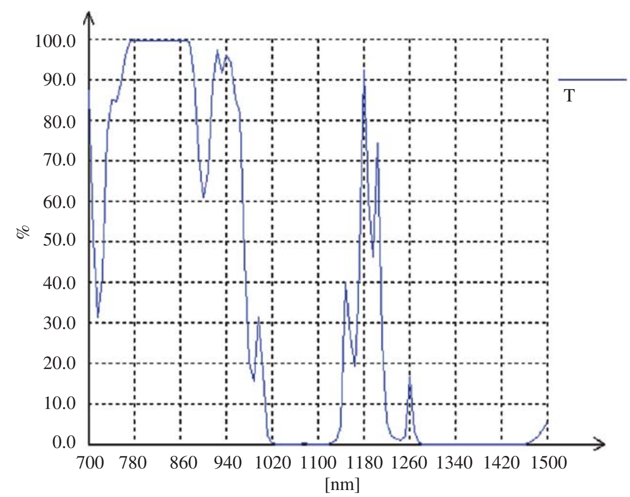

Fig. 3. Transmission curve of incident face on $Nd:YVO_4$.

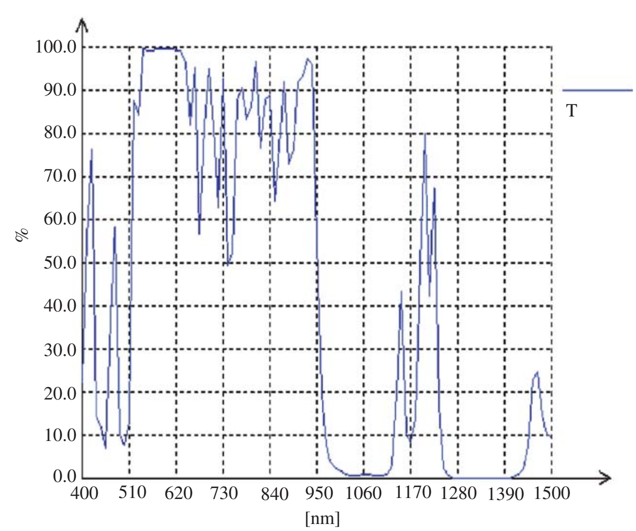

Fig. 4. Transmission curve of left face on output mirror.

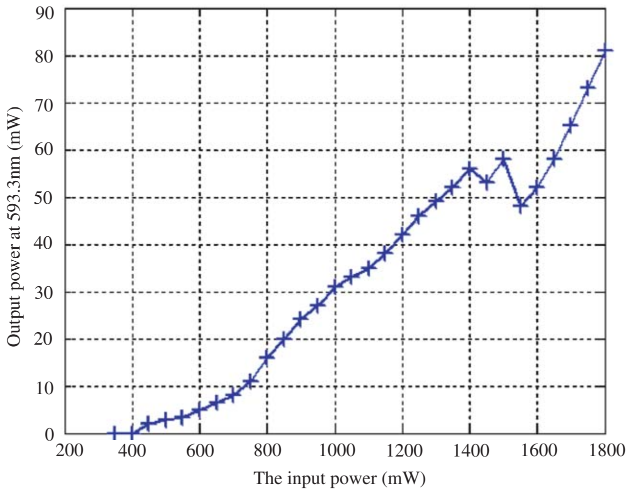

Fig. 5. The output power o at 593.5 nm laser as a function of pump power.

4. Experimental results and discussions

In room temperature, by adjusting the current of LD, when the incident pump power is 350 mW, the IR laser output is observed without the LBO crystal. Then the LBO is placed in the resonator, and by careful adjustment, the yellow-laser at 593.5 nm is obtained when the current of LD is 400 mA. With the current of TEC1 and TEC2 increasing, the maximum sum-frequency-mixing output power of 593.5 nm is obtained by type-I critical phase-matching LBO when the pumping power is 1.8 W. After 808, 1064 and 1342 nm lasers were filtered, the yellow laser at 593.5 nm output power was up to 85 mW. Fig. 5 shows the yellow laser output power as a function of the incident pump power. Based on the curve, it can be found that as the pump power increased, the output power at 593.5 nm rose correspondingly, whereas in the rising process, the output power produced two little fluctuations. The output power decreased, but later the power became stable little by little. We believe the gain competition between 1064 and 1342 nm laser results in the instability of the output power. When the other LBO crystal was used for intracavity frequency doubling, the green laser at 532 nm output power was 108 mW and the red laser at 671 nm is up to 87 mW. On the basis of sum-frequency-mixing and frequency doubling output characteristic, it can be concluded that 1064 and 1342 nm fundamental lasers have good spatial, temporal overlap and gain matching. The optical-to-optical conversion is up to 4.7%. The power stability in 24 h is better than $\pm 2.8\%$.

5. Conclusion

By using reasonable film optimum designing and reasonator designing, we have achieved a good balance for the numbers of intracavity photons and gain matching between 1064 and 1342 nm lasers. Diode-end-pumped Nd:YVO_4 laser that generates simultaneous cw laser action at wavelengths 1064 and 1342 nm is demonstrated. Using type-I critical phase-matching LBO crystal intracavity sum-frequency-mixing yellow laser at 593.5 nm cw output is obtained.

Acknowledgements

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