All-solid-state continuous-wave frequency-doubling Nd:YVO_4/LBO laser with 2.35 W output power at 543 nm

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Efficient and compact green–yellow laser output at 543 nm is generated by intracavity frequency doubling of a cw diode-pumped Nd:YVO_4 laser at 1086 nm under the condition of suppressing the higher gain transition near 1064 nm. With 14.5 W of diode pump power and the frequency-doubling crystal LiB_3O_5, as high as 2.35 W of cw output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 15.7%; the output power stability over 5 h is better than 2.56%. To the best of our knowledge, this is the highest watt-level laser at 543 nm generated by intracavity frequency doubling of a diode pumped Nd:YVO_4 laser at 1086 nm.

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Diode-pumped all-solid-state lasers have facilitated considerable advances in various fields of science and technology. Neodymium-doped yttrium vanadate (Nd:YVO_4) has proved to be an excellent gain medium because of its high pump absorption coefficient and high gain character. The output wavelengths in research involving Nd:YVO_4 crystals were focused mostly at 1064 [1], 1342 [2], and 914 nm [3,4]. However, a spectroscopic study with crystal-field analysis has demonstrated that there are five or six emission bands with the $^4F_{3/2}$–$^4I_{11/2}$ transition of an Nd:YVO_4 crystal [5]. The room temperature fluorescence spectrum shows that one of the Stark components has a central emission wavelength at 1086 nm. The diode end-pumped configuration can provide much stronger pump power density than the transverse pump structure. Therefore it is possible for cw operation to be achieved at some weak transitions such as 1086 nm in the diode end-pumped configuration [6–8].

After Zhang *et al.* demonstrated an efficient intracavity second-harmonic generation (SHG) at 1084 nm in a nonlinear optical crystal of BiB_3O_6 (BIBO) where 19 mW laser output at 542 nm is obtained [9], the output power was enhanced up to 105 mW in 2009 by using type I LiB_3O_5 LiB_3O_5 (LBO) as the frequency doubling crystal by Q. Zheng and co-workers [10]. In this Letter, a high-power, compact, efficient cw 543 nm green–yellow laser based on fiber-coupled laser-diode (LD) -pumped intracavity frequency-doubling Nd:YVO_4/LBO is demonstrated. With an incident pump power of 14.5 W, low-doped bulk Nd:YVO_4, a long type I phase-matching LBO crystal, and a compact, three-mirror-fold cavity, up to 2.35 W of green–yellow laser emission at 543 nm is achieved. The optical-to-optical conversion efficiency is greater than 15.7%, and the stability of the output power is better than 2.56% for 5 h.

The experimental setup of the intracavity doubling 543 nm Nd:YVO_4/LBO green–yellow laser is shown in Fig. 1. The pump source is a 15 W 808 nm fiber-coupled LD with a core diameter of 400 μm and a numerical aperture of 0.22 for cw pumping. Its emission central wavelength is 810.2 nm at room temperature and can be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The spectral width (FWHM) of the pump source is about 1.5 nm. The coupling optics consists of two identical plano-convex lenses with focal lengths of 15 mm used to reimage the pump beam into the laser crystal at a ratio of 1:1. The coupling efficiency is 95%. Because the pump intensity is high enough in the pump spot regions, the first lens must be well adjusted to collimate the pump beam, since it will strongly affect the focal spot. However, the distance between the two lenses can be freely adjusted by experiment. For the aberration, the average pump spot radius is about 220 μm.

The cavity configuration we used is a three-mirror folded cavity, which had two separate beam waists; one waist could satisfy the mode-matching condition, and the other could enhance the frequency-doubling efficiency. The radii of the concave faces are 50 and 200 mm for M_1 and M_2, respectively. L_1 and L_2 are the lengths of the arms in the cavity. L_1 and L_2 are about 75 and 43 mm, respectively. The beam's incident angle on the folded mirror is set to be as small

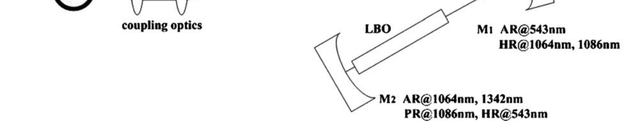

Fig. 1. Schematic for the intracavity frequency-doubled 543 nm Nd:YVO_4/LBO green–yellow laser.

as possible to reduce the astigmatism without additional optical astigmatism-compensating elements. The LD, the whole cavity, and the crystal are cooled by a thermoelectric controller for active temperature control with a stability of $\pm 0.1°C$.

Considering the performance of the main laser lines of $Nd:YVO_4$ crystal as a laser gain medium, since the stimulated emission cross section for the 1086 nm transition is approximately six times smaller than that for the 1064 nm line and about three times smaller than that for the 1342 nm line, operation of the $Nd:YVO_4$ laser at 1086 nm requires suppression of the competing transitions at 1064 and 1342 nm. In our experiment, the stronger transitions near 1064 and 1342 nm are suppressed by use of specifically coated mirrors, especially the end mirror M_2, which is convenient for the coating process and commercial utility. Although the ideal coating condition is highly reflective (HR) coated at 1086 nm and antireflective (AR) coated at 1064 and 1342 nm, the two chief laser lines at 1064 and 1086 nm are so close that the ideal condition is impossible to achieve. Therefore, the end mirror is partially reflective (PR) coated at 1086 nm and AR coated at 1064 and 1342 nm, which can suppress the oscillation at 1064 nm, but some loss at the 1086 nm line also exists.

Figure 2 shows the coating curves of the concave surface of the end mirror M_2. The left side of the $Nd:YVO_4$ is coated at 808 nm AR and at 1064 and 1086 nm HR. The other facet of the $Nd:YVO_4$ is AR coated at 1064, 1086 nm. The concave facet of M_1 is AR coated at 543 nm and HR coated at 1064 and 1086 nm, which has the same coating as for normal green laser output coupler. The plano facet of M_1 is AR coated at 543 nm. The end mirror M_2 is HR coated at 543 nm, AR coated at 1064 and 1342 nm, and PR coated at 1086 nm.

The LBO is a $2mm \times 2mm \times 10$ mm nonlinear crystal ($\theta = 90°$, $\phi = 9.9°$). Though BIBO has a high nonlinearity of 2.26 pm/V in frequency doubling of the 1086 nm laser, the large walk-off angle of 84.35 mrad, which yields a beam spot with low beam quality, makes BIBO not suitable for this application.

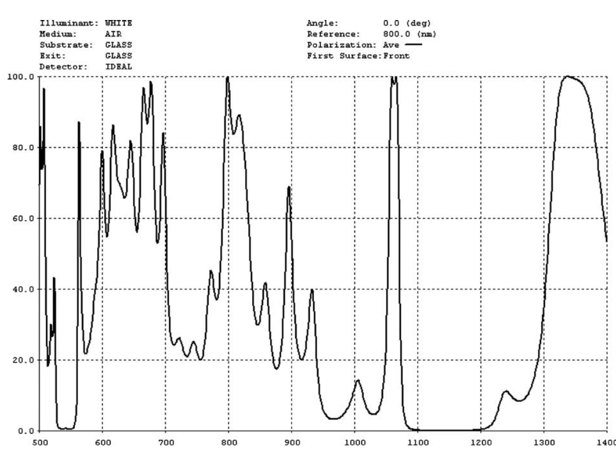

Fig. 2. Transmissivity of the end mirror M_2 of the 543 nm laser.

LBO is selected as the frequency-doubling material in our experiment for its small walk-off angle of 6.05 mrad. Although the nonlinear coefficient of LBO is 0.834 pm/V, the length of the LBO could be extended to compensate for the relatively smaller nonlinear coefficient. Both facets of the LBO crystal are AR coated at 543 and 1086 nm to reduce the reflection losses in the cavity. The LBO is mounted in a copper block, which is also fixed on a thermoelectric controller for active temperature control. The laser output at 1086 nm is linearly polarized, so it is not necessary to insert a Brewster plate for frequency doubling. For the SHG experiment, a 10 mm LBO crystal is inserted into the cavity close to end mirror M_2. Using the LABRAM-UV spectrum analyzer to scan the SHG laser and dealing with the data with software, the spectrum of the SHG laser is shown in Fig. 3. The dependence of the green–yellow laser output power on the incident pump power is shown in Fig. 4. The threshold of the 543 nm laser is about 2.3 W, with an incident pump power of 14.5 W, corresponding to an output power of 2.35 W at 543 nm.

The M^2 factors are about 1.57 and 2.18 in X and Y directions respectively measured by knife-edge technique which shows that the laser output at 543 nm is operating at near TEM_{00} mode. The asymmetry of the M^2 factor in two directions is result of the walk-off between the fundamental wave and the second in the direction of the LBO.

Some stability testing is carried out by monitoring the green–yellow laser with a Field-Master-GS powermeter at 10 Hz. The fluctuation of the output power is about 2.56% in 5 h. The chaotic green-noise state is also stable when the environment is without large fluctuations. The short-term power stability is measured by a LabMaster Ultima that operates at 50 kHz, and the percent rms noise value is 2.83%. The chaotic noise of the 543 nm output in this experiment is due to the competition between the two laser lines at 1086 and 1084 nm. The stimulated emission cross section for the 1086 nm transition is only two times larger than that for the 1084 nm line. Therefore the gain competition process between the two laser lines will make the output of 543 nm laser fluctuate after the frequency-doubling crystal LBO is inserted into the cavity. The output at 543 nm could be considered the loss of the 1086 nm fundamental wave. The loss of the 1086 nm line makes the net gain of the 1084 nm line increase, which leads to the intracavity power at 1084 nm becoming higher. This competition decreases the loss of the 1086 nm line, and thus the net gain at 1086 nm increases. So the output power of the SHG laser fluctuates. The polarization characteristic also influences the selection of the fundamental wave. $Nd:YVO_4$ crystal has a high pump-beam absorption coefficient with π polarization, and it emits the fundamental wave in the π direction with high efficiency. Within the chief fluorescence spectrum of $Nd:YVO_4$ between 1050 and 1100 nm, the 1086 nm line exhibits polarized oscillation in the π direction, and the 1084 nm in the σ direction. The characters of absorption and emission of

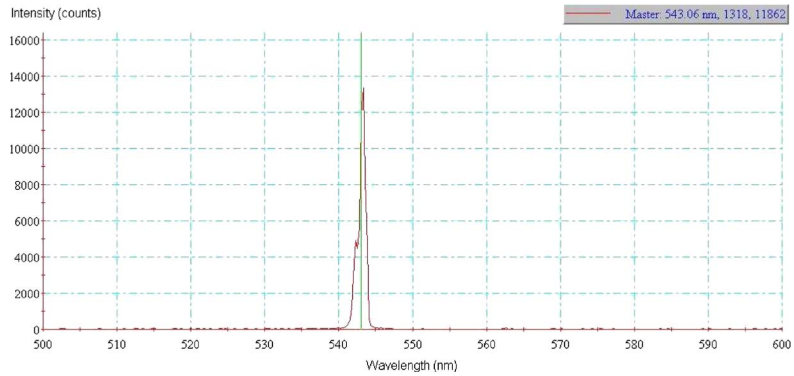

Fig. 3. (Color online) Spectrum of the 543 nm green–yellow laser.

1084 nm are much weaker than that of 1086 nm, which could suppress the 1084 nm line to some extent. Based on the theoretical model [11], LBO functions as a polarizer except as a frequency-doubling crystal, which limits the oscillation of fundamental wave that is vertical to the π direction. All the physical progress mentioned above makes the output power of the 543 nm green–yellow laser fluctuate but with a relatively low-noise state.

In summary, an efficient, compact green–yellow laser at 543 nm generated by intracavity frequency doubling of the cw laser output of a diode-pumped Nd:YVO_4 laser at 1086 nm under the condition of higher gain transition suppression near 1064 nm.

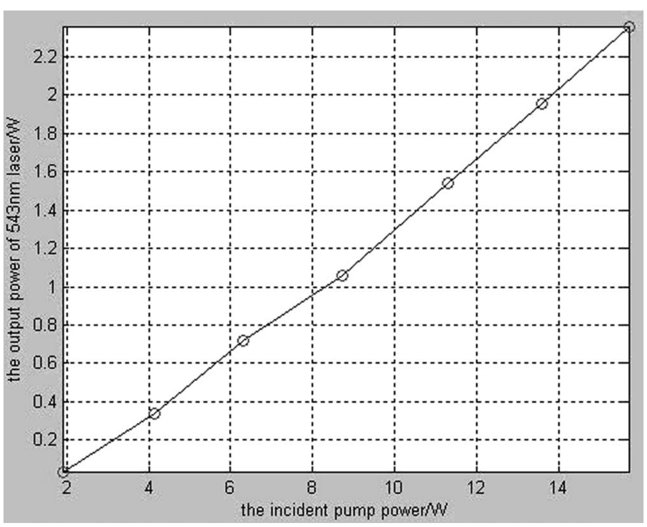

Fig. 4. Dependence of the output power at 543 nm on incident pump power.

With a 14.5 W diode pump power and the frequency-doubling crystal LBO, as high as 2.35 W of cw output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 15.7%, and the output power stability over 5 h is better than 2.56%.

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