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All-Solid-State 543-nm Green Laser Generated by Frequency Doubling of a Diode-Pumped Nd:YVO_4 Laser at 1086 nm[1]

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Abstract—An efficient and compact green laser at 543 nm is generated by intracavity frequency doubling of a continuous wave (CW) laser operation of a diode pumped Nd:YVO_4 laser at 1086 nm under the condition of suppression the higher gain transition near 1064 nm. With 10 W diode pump power and a frequency doubling crystal LBO, as high as 2.13 W of CW output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 21.3% and the output power stability in 3 h is better than 2.27%.

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1. INTRODUCTION

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 of the research involving Nd:YVO_4 crystals were mostly focused at 1064 [1–3], 1342 [4], and 914 nm [5, 6]. 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 [7]. The room temperature fluorescence spectrum shows that one of the Stark components has a central emission wavelength at 1086 nm. Diode end pumped configuration can provide much stronger pump power density than transversely pump structure. Therefore it is possible for CW operation to be achieved at some weak transitions such as 1086 nm by diode end pumped configuration [8–10].

After Zhang et al. had firstly demonstrated an efficient intracavity second harmonic generation at 1084 nm in a nonlinear optical crystal of BIBO where 19 mW laser at 542 nm is obtained [11], the output power is enhanced up to 105 mW in 2009 using a type-I LBO as the frequency doubling crystal by Zheng [12].

In this letter, a high power, compact, efficient CW 543 nm green laser based on fiber-coupled LD pumped intracavity frequency doubling Nd:YVO_4/LBO is demonstrated. With an incident pump power of 10 W, high doped bulk Nd:YVO_4, a long type I phase-matching LBO crystal, and a compact, three-mirror-fold cavity, up to 2.13 W of green laser emission at 543 nm is achieved. The optical to optical conversion efficiency is greater than 21.3%, and the stability of the output power is better than 2.27% for three hours.

2. EXPERIMENTAL SETUP

The experimental setup of the intracavity doubling 543 nm Nd:YVO_4/LBO green laser is shown in Fig. 1. The pump source is a 10 W 808 nm LD for CW pumping. Its emission central wavelength is 808.7 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 pump source is about 1.5 nm. The pump beam is reimaged into the laser crystal at a ratio of 1 : 1. The laser crystal is a 0.3 at % Nd^{3+} doped, $3 \times 3 \times 5$ mm^3 Nd:YVO_4 crystal which is wrapped with indium foil and mounted at a thermal electronic cooled (TEC) cooper block to keep the temperature at 20°C.

The cavity configuration we used is three mirrors folded cavity which had two separate beam waists, one could satisfied the mode matching condition, the other could enhance the frequency doubling efficiency. The radiuses of the concave face 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 incident angle upon the folded mirror is set to be as small as possible to reduce the astigmatism without additional optical astigmatism compensating elements. The LD, the laser crystal, and the nonlinear frequency doubling crystal are cooled by TEC for an active temperature control at 20°C with stability of ±0.1°C.

Considering the performance of main laser lines of Nd:YVO_4 crystal as a laser gain medium, since the

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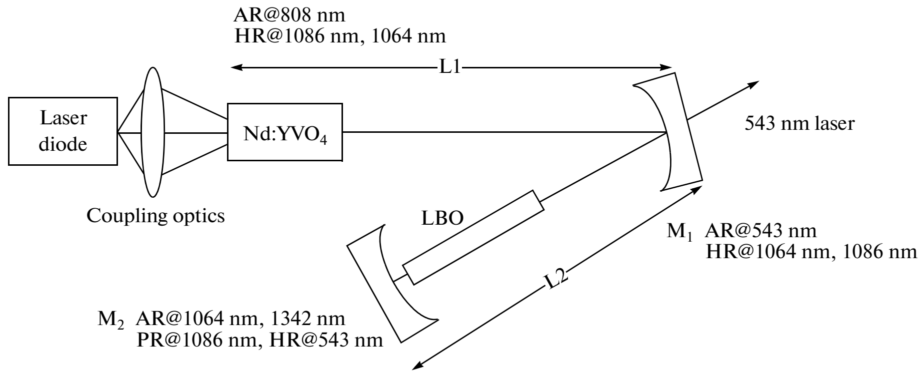

Fig. 1. Schematic for the intracavity frequency-doubled 543 nm $Nd:YVO_4$/LBO green laser.

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 transition at 1064 nm and 1342 nm. In our experiment, the stronger transition near 1064 and 1342 nm are suppressed by use of specifically coated mirror especially on the end mirror M_2 which is convenience for coating progress and commercial utility. Although the ideal coating condition is HR(R > 99.9%) coated at 1086 nm and AR(R < 0.1%) coated at 1064 and 1342 nm, the two chief laser lines at 1064 and 1086 nm are so near that the ideal condition is impossible to achieve. Therefore, the end mirror is PR(R = 90%) coated at 1086 nm and AR(R = 15%) coated at 1064 nm and 1342 nm which could suppress the oscillation at 1064 nm but some loss at 1086 nm line also exists. Figure 2 is the coating curves of the concave surface of the end mirror M_2. The left side of $Nd:YVO_4$ is coated at 808 nm AR(R < 0.1%) and

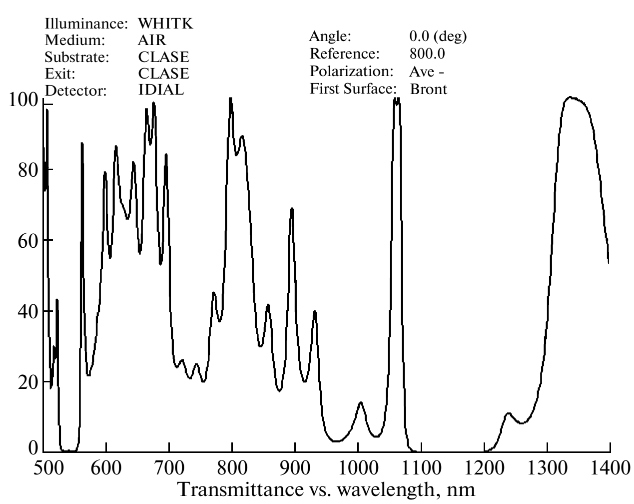

Fig. 2. The transmissivity of the end mirror M_2 of 543 nm laser.

1064 nm, 1086 nm HR(R > 99.9%). The other facet of $Nd:YVO_4$ is antireflection coated at 1064 and 1086 nm. The concave facet of M_1 is AR(R < 0.1%) coated at 543 nm and HR(R > 99.9%) coated at 1064 nm and 1086 nm which has the same coating as normal green laser output coupler. The plano facet of M_1 is antireflection coated at 543 nm.

LBO is a $2 \times 2 \times 10$ mm^3 nonlinear crystal ($\theta = 90°$, $\varphi = 9.9°$). Though BIBO has a high nonlinearity of 2.26 pm/V in frequency doubling of 1086 nm laser, the large walk-off angle of 84.35 mrad, which gets the beam spot with low beam quality, makes BIBO not suitable for this application. 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 LBO could be extended to compensate the relatively smaller value of nonlinear coefficient. Both facets of the LBO crystal are coated for antireflection at 543 and 1086 nm to reduce the reflection losses in the cavity. It is mounted in a copper block, which is also fixed on a TEC for an active temperature control.

3. RESULTS AND DISCUSSION

The laser output at 1086 nm is linearly polarized, so it is not necessary to insert a Brewster plate for the frequency doubling. For the SHG experiment, a 10 mm LBO is inserted into the cavity close to the end mirror M_2. Using the LABRAM-UV spectrum analyzer to scan SHG laser and dealing with the data by software, the spectrum of the SHG laser is shown in Fig. 3. The dependence of the green laser output power on the incident pump power is shown in Fig. 4. The threshold of the 543 nm laser is about 1.2 W, with the incident pump power of 10 W, corresponding to an output power of 2.13 W at 543 nm.

The M square factors are about 1.57 and 1.72 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 from the walk-

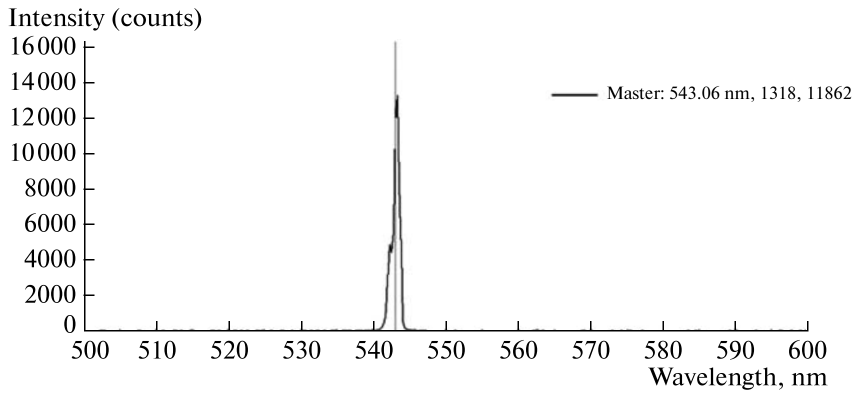

Fig. 3. The spectral of 543 nm green laser.

off between the fundamental wave and the second in direction of LBO.

Some stability testing is carried out by monitoring the green laser with Field-Master-GS power-meter at 10 Hz. The fluctuation of the output power is about 2.27% in 3 h. The chaotic green-noise state is also stable when the environments without large fluctuations. The short term power stability is measured by Lab-Master Ultima whose operates at 50 kHz and the % 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 progress between the two laser lines will make the output of 543 nm laser fluctuation after a frequency doubling crystal LBO inserted into the cavity. The output at 543 nm could be considered as the loss of 1086 nm fundamental wave. The loss of 1086 nm line makes the net gain of 1084 nm line increase that leads to the intracavity power at 1084 nm becomes higher. This competition decreases the loss of 1086 nm line and that equals to the net gain at 1086 nm increases. So the output power of SHG laser fluctuates. And the polarization characteristic also influences the selection of fundamental wave. Nd:YVO_4 crystal has a high absorption coefficient of pump beam with π polarization and it emits fundamental wave in π direction with high efficiency. Among the chief fluorescence spectrum of Nd:YVO_4 between 1050 to 1100 nm, the 1086 nm line is polarized oscillation in π direction and the 1084 nm in σ direction. The characters of absorption and emission of 1084 nm are much weaker than that of 1086 nm which could suppress the 1084 nm line in some extent. Based on the theoretical model [13], LBO plays as a polarizer except for 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 543 nm green laser fluctuated but with relatively tow noise state.

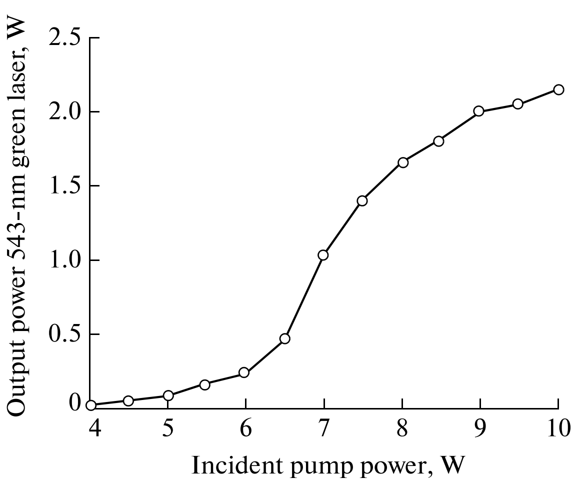

Fig. 4. The dependence of the output power at 543 nm on incident pump power.

In summary, an efficient and compact green laser at 543 nm generated by intracavity frequency doubling of a continuous wave laser operation of a diode pumped Nd:YVO_4 laser at 1086 nm under the condition of suppression the higher gain transition near 1064 nm. With 10 W diode pump power and a frequency doubling crystal LBO, as high as 2.13 W of CW output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 21.3% and the output power stability in 3 h is better than 2.27%.

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