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LASERS
AND THEIR APPLICATIONS

All-Solid-State Continuous-Wave Frequency Doubling $Nd:LuVO_4$/LBO Laser with 2.17 W Output Power at 543 nm[1]

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Abstract—Efficient and compact green–yellow laser output at 543 nm is generated by intracavity frequency doubling of a CW diode-pumped $Nd:LuVO_4$ laser at 1086 nm under the condition of suppressing the higher gain transition near 1064 nm. With 16 W of diode pump power and the frequency-doubling crystal LBO, as high as 2.17 W of CW output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 13.6% and the output power stability over 8 hours is better than 2.86%. 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 $Nd:LuVO_4$ laser at 1086 nm.

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INTRODUCTION

Diode-pumped all-solid-state lasers have facilitated considerable advances in various fields of science and technology. $Nd:LuVO_4$ 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 $Nd:LuVO_4$ crystals were focused mostly at 1064, 1344, and 914 nm. 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 $Nd:LuVO_4$ crystal. 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 [1–3].

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 [4], the output power was enhanced up to 105 mW in 2009 by using type I LiB_3O_5 (LBO) as the frequency doubling crystal by Q. Zheng and co-workers [5]. The output power at 543 nm has been enhanced to 2.35 W with $Nd:YVO_4$ crystal [6].

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 $Nd:LuVO_4$/LBO is demonstrated. With an incident pump power of 16 W, low-doped bulk $Nd:LuVO_4$, a long type I phase matching LBO crystal, and a compact, three-mirror fold cavity, up to 2.17 W of green–yellow laser emission at 543 nm is achieved. The optical-to-optical conversion efficiency is greater than 13.6%, and the stability of the output power is better than 2.86% for 8 h.

THEORETICAL ANALYSIS

Considering the performance of the main laser lines of $Nd:LuVO_4$ crystal as a laser gain medium, since the stimulated emission cross section for the 1086 nm transition is approximately five times smaller than that for the 1064 nm line and about three times smaller than that for the 1344 nm line, operation of the $Nd:LuVO_4$ laser at 1086 nm requires suppression of the competing transitions at 1064 and 1344 nm. In our experiment, the stronger transitions near 1064 and 1344 nm are suppressed by use of specifically coated mirrors, especially the end mirror M2, 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 1344 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 1344 nm, which can suppress the oscillation at 1064 nm, but some loss at the 1086 nm line also exists. Figure 1 shows the coating curves

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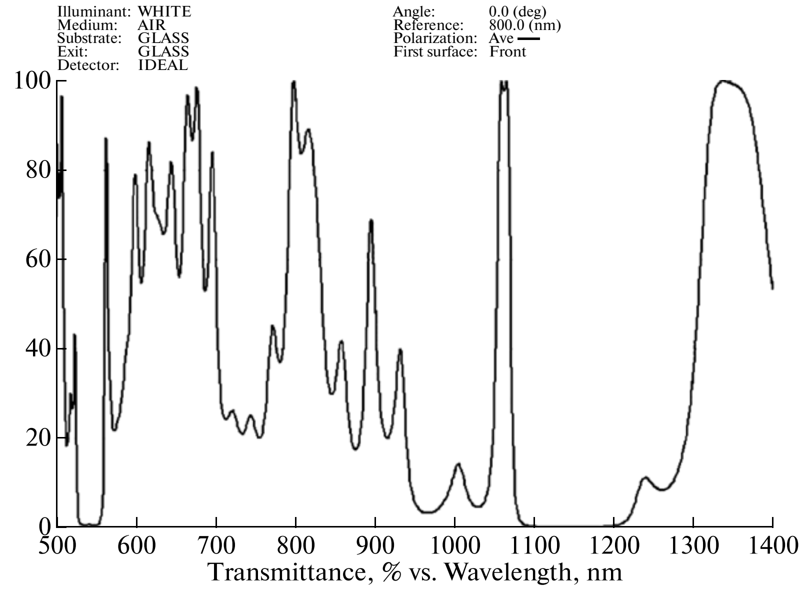

Fig. 1. Transmissivity of the end mirror M2 of the 543 nm laser.

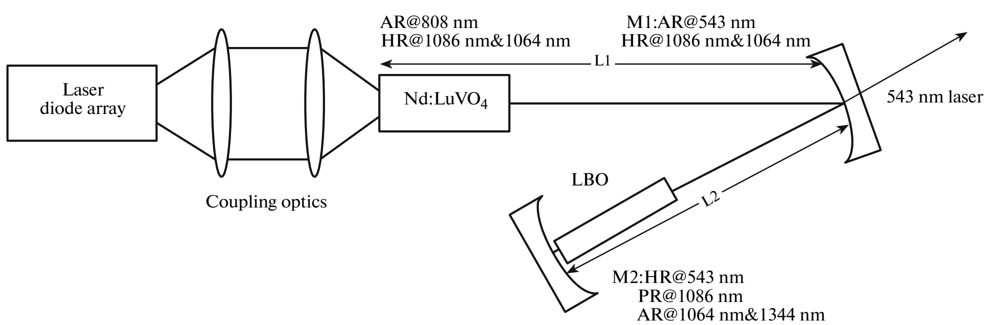

Fig. 2. Schematic for the intracavity frequency-doubled 543 nm Nd:$LuVO_4$/LBO laser.

of the concave surface of the end mirror M2. The left side of the Nd:$LuVO_4$ is coated at 808 nm AR and at 1064 and 1086 nm HR. The other facet of the Nd:$LuVO_4$ is AR coated at 1064, 1086 nm. The concave facet of M1 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 M1 is AR coated at 543 nm. The end mirror M2 is HR coated at 543 nm, AR coated at 1064 and 1344 nm, and PR coated at 1086 nm.

The LBO is a $2 \times 2 \times 15$ mm^3 nonlinear crystal ($\theta = 90°$, $\varphi = 9.9°$). 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. LBO is selected as the frequency-doubling material 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.

EXPERIMENTAL SETUP

The experimental setup of the intracavity doubling 543 nm Nd:$LuVO_4$/LBO green–yellow laser is shown in Fig. 2. The pump source is a 16 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 808.2 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

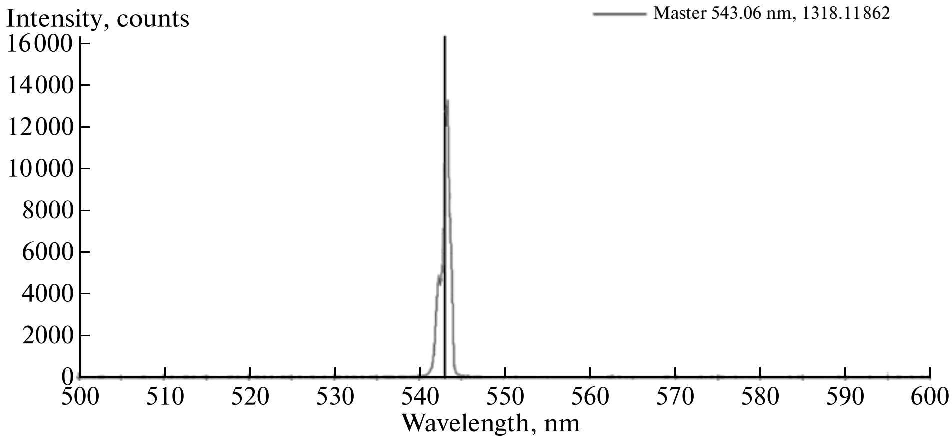

Fig. 3. Spectrum of the 543 nm green-yellow laser.

about 1.5 nm. The coupling optics consists of two identical plano-convex lenses with focal lengths of 20 mm used to reimage the pump beam into the laser crystal at a ratio of 1:1. The coupling efficiency is 97%. 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 70 and 260 mm for M1 and M2, respectively. L1 and L2 are the lengths of the arms in the cavity. L1 and L2 are about 70 and 45 mm, respectively. The beam's incident angle on the folded mirror is set to be as small 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 ±0.1°C.

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 M2. 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 16 W, corresponding to an output power of 2.17 W at 543 nm. The M square factors are about 1.65 and 1.82 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 M2 factor in two directions is result from the walk off between the fundamental wave and the second in direction of LBO. Some stability testing is carried out by monitoring the green laser with FieldMaster-GS powermeter at 20 Hz. The fluctuation of the output power is about 2.86% in 8 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 20 kHz and the % rms noise value is 2.63%. 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

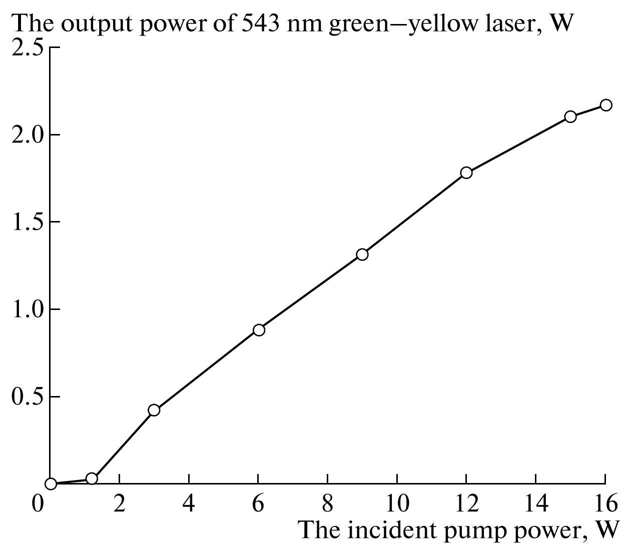

Fig. 4. The output power at 543 nm versus the incident pump power.

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:$LuVO_4$ 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:$LuVO_4$ 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 [7], 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.

CONCLUSIONS

In summary, an efficient and compact green–yellow laser output at 543 nm is generated by intracavity frequency doubling of a CW diode-pumped Nd:$LuVO_4$ laser at 1086 nm under the condition of suppressing the higher gain transition near 1064 nm. With 16 W of diode pump power and the frequency-doubling crystal LBO, as high as 2.17 W of CW output power at 543 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 13.6%; the output power stability over 8 hours is better than 2.86%.

ACKNOWLEDGMENTS

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REFERENCES

1. R. Zhou, B. G. Zhang, and X. Ding, Opt. Express **13**, 5818 (2005).
2. Y. F. Chen, M. L. Ku, and K. W. Su, Opt. Lett. **30**, 2107 (2005).
3. F. Q. Jia, Q. H. Xue, and Q. Zheng, Chin. J. Lasers **32**, 1017 (2005).
4. Z. Zhang, H. M. Tan, and L. L. Gao, Opt. Commun. **267** (2), 487 (2006).
5. Y. Yao, D. P. Qu, and Q. Zheng, Chin. J. Lasers **36**, 1740 (2009).
6. Y. Yao, Q. Zheng, D. P. Qu, X. Y. Gong, K. Zhou, Y. Liu, and L. Zhao, Opt. Lett. **34** (23), 3758 (2009).
7. D. Li, C. Zhu, V. Gabler, B. Liu, H. J. Eichler, Z. Zhang, Y. Wang, Z. Li, and J. Qiu, Opt. Commun. **189**, 357 (2001).