All-Solid-State 543-nm Green Laser Generated by Frequency Doubling of a Diode-Pumped Nd:YVO₄ Laser at 1086 nm

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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:YVO₄ 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:YVO₄) 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:YVO₄ 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_{15/2} transition of an Nd:YVO₄ 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:YVO₄/LBO is demonstrated. With an incident pump power of 10 W, high doped bulk Nd:YVO₄, 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:YVO₄/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 % Nd³⁺ doped, 3 × 3 × 5 mm³ Nd:YVO₄ 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 M₁ and M₂ respectively. L₁ and L₂ are the lengths of the arms in the cavity. L₁ and L₂ 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:YVO₄ 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:YVO₄ 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 M₂ 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 M₂. The left side of Nd:YVO₄ is coated at 808 nm AR(\(R < 0.1\%\)) and 1064 nm, 1086 nm HR(\(R > 99.9\%\)). The other facet of Nd:YVO₄ is antireflection coated at 1064 and 1086 nm. The concave facet of M₁ 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 M₁ is antireflection coated at 543 nm.

LBO is a 2 × 2 × 10 mm³ nonlinear crystal (\(\theta = 90°, \phi = 9.9°\)). 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 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 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 TEM₀₀ mode. The asymmetry of the M² factor in two directions is result from the walk-