

All-Solid-State Continuous-Wave Frequency Doubling Nd:YLF/LBO Laser with 2.15 W Output Power at 526 nm¹

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Abstract—An efficient and compact green laser at 526 nm generated by intracavity frequency doubling of a continuous wave (CW) laser operation of a diode pumped Nd:YLF laser at 1053 nm under the condition of suppression the high gain transition at 1047 nm. With 19.5 W diode pump power and a frequency doubling crystal LBO, as high as 2.15 W of CW output power at 526 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 11.2% and the output power stability in 8 h is better than 2.87%. To the best of our knowledge, this is the highest watt-level laser at 526 nm generated by intracavity frequency doubling of a diode pumped Nd:YLF laser at 1053 nm.

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1. INTRODUCTION

The neodymium lasers are widely spread in various fields of industry, scientific research and entertainment [1–5]. Nd:YLF is a very superior material for diode-pumped high-power lasers due to its excellent thermal properties and naturally birefringence which reducing the thermal effects in the crystal and making the resonators with wider stable range [6].

Nd:YLF is a uniaxial crystal with two characteristic wavelengths polarized parallel and perpendicular to the optical axis which are the 1047 nm in π direction and 1053 nm in σ direction respectively. With normal a-cut crystal, the stimulated emission cross section at the 1047 nm line is higher than that at 1053 nm by a factor of 1.5. Therefore, the 1047 nm should be suppressed if the 1053 nm laser operation is desired. Considering the polarization feature of the fundamental laser of Nd:YLF, the crystal should be cut with its optical axis parallel to the resonator axis which is c-cut, the mainly emitted 1047 nm photons will propagate in the direction perpendicular to the cavity axis and could not stably oscillate in the resonator. Although the 1047 nm line could also operate in σ direction, it could not obtain enough gain to compete with the 1053 nm line and only 1053 nm single laser line is achieved.

After Frei and Balmer had demonstrated a diode-pumped continuous wave (CW) Nd:YLF laser at 1053 nm with 1.9 W output power [7], Clarkson et al. had reported the output power of continuous wave and actively acoustic-optical Q-switched diode-pumped 1053 nm Nd:YLF lasers is 11.1 W and 8.4 W, respectively [6]. The 523 nm laser was firstly demonstrated by

Fan et al. [8] that 145 μ W output powers was obtained and it was enhanced to 1.2 W in 1994 using a type-II KTP as the frequency doubling crystal, but no report about 526 nm laser watt-level output for commercially use is demonstrated.

In this letter, the generation of watt-level green laser at 526 nm is demonstrated for the first time in critically type I phase matching LBO with intracavity frequency doubling of a diode-pumped Nd:YLF laser operated at 1053 nm under room temperature in a compact three-fold cavity. As high as 2.15 W of continuous wave output at 526 nm is achieved with an incident pump power of 19.5 W. The total optical to optical conversion efficiency is up to 11.2% and the stability of output power is better than 2.87% in 8 h. To the best of our knowledge, this is the highest watt-level laser at 526 nm generated by intracavity frequency doubling of a diode pumped Nd:YLF laser at 1053 nm.

2. THEORETICAL ANALYSIS

Comparing the performance of main laser transition lines in Nd:YLF, in order to obtain the laser oscillation at 1053 nm which has nearly the same stimulated emission cross section with the other main laser line, the 1047 nm oscillation must be suppressed [10]. Generally, we select the line by the method of coating film to add internal loss to one spectral line. However, the two main laser lines are so near that the second harmonic discrimination of 1053 nm and 1047 nm is difficult to be accomplished by traditional film designing. Also, this method brings inconvenience to the coating progress and is not advantage to the commercial utility although the 1053 nm laser could be obtained. A thick etalon could be inserted into the

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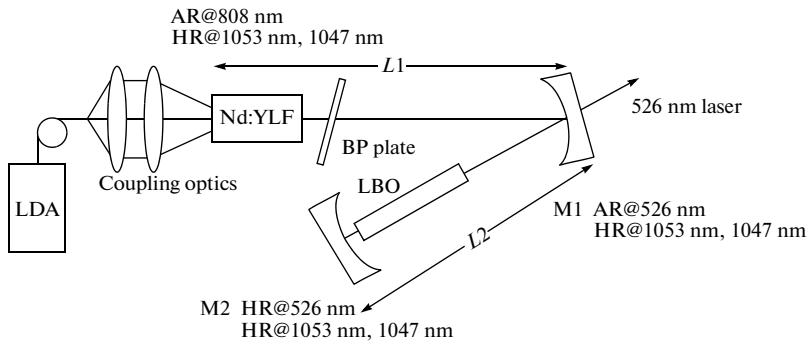


Fig. 1. Schematic for the intracavity frequency-doubled 526 nm Nd:YLF/LBO green laser.

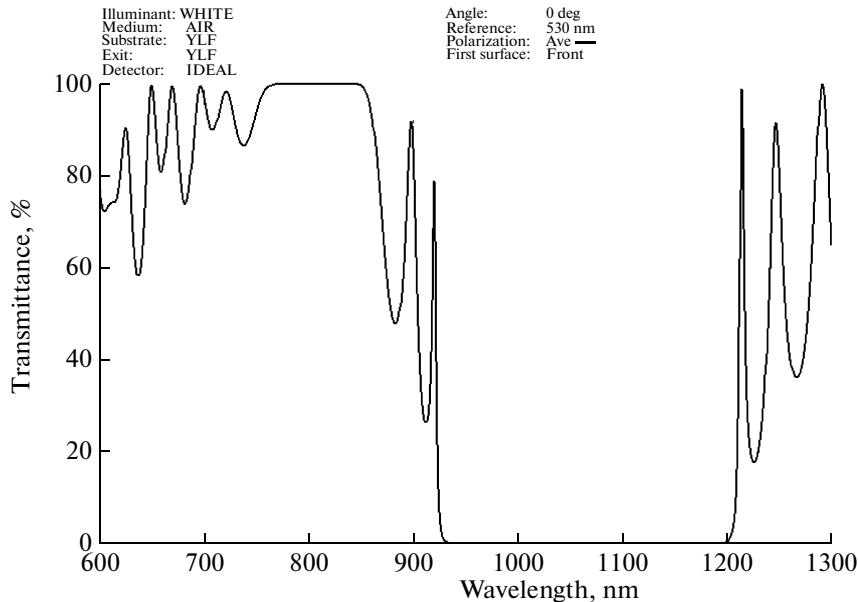


Fig. 2. Transmissivity of the left side of Nd:YLF crystal.

cavity to suppress the oscillation of one fundamental wavelength. Although the etalon plays as a line selector, large inserting loss is disadvantage for the increase of output power. The special polarization characteristic of the 1047 nm and 1053 nm gives us an opportunity to select the single transition line. According to the natural character of the Nd:YLF, especially in the σ direction, the gain character of the 1053 nm line is twice larger than that of 1047 nm line. With the c-cut Nd:YLF crystal and LD end pumping schematic, the polarization direction of the fundamental lasers at 1053 nm and 1047 nm are always perpendicular to the c axis of the laser crystal which is the σ direction. Using the Brewster plate, the polarization character of the fundamental laser in the cavity could be restricted into the σ direction strictly. And the 1053 nm line could obtain more gain during the period of oscillation establishing and achieve the stable oscillation state.

The nonlinear frequency doubling crystal also help to select the spectral lines because the crystal is cut for the second harmonic generation at 1053 nm and coating for 1053 nm, which equals to the internal loss to the 1047 nm line. Considering the factors above, only the 1053 nm fundamental could be selected.

The nonlinear crystal such as KTP and LBO is always used in the second harmonic generation field. Comparing the characteristic of the two crystal, although the effective nonlinear optical coefficient of KTP is 1.83 pm/V which is larger than that of LBO at 0.83 pm/V, the walk-off angle of LBO is as small as 7.39 mrad than 28.80 mrad of KTP. An LBO crystal with longer length could be used to obtain higher SHG efficiency. Due to the characteristic of KTP, high intracavity power will incur gray trace which makes the output of harmonic wave unstable and become lower

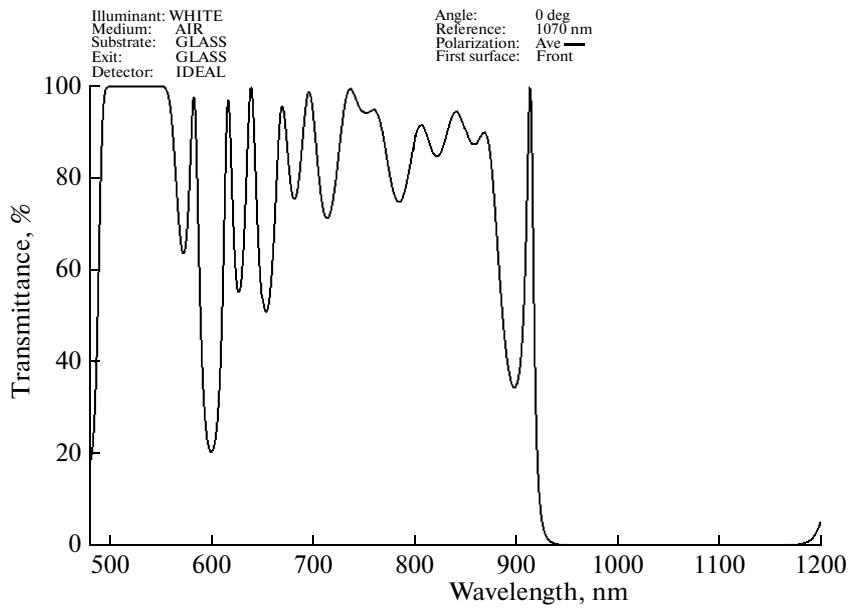


Fig. 3. Transmissivity of output coupler of 526 nm laser.

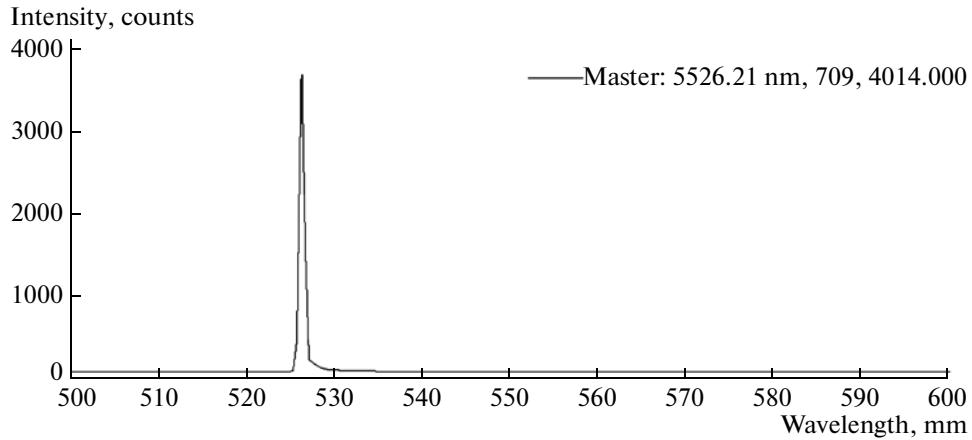


Fig. 4. The spectrum of 526 nm green laser.

for a long time. So LBO crystal is selected to be the frequency doubling crystal.

3. EXPERIMENTAL SETUP

The experimental setup of the intracavity doubling 526 nm Nd:YLF/LBO green laser is shown in Fig. 1. The pump source is a 20 W 808 nm fiber-coupled LD array with a core diameter of 400 μm and a numerical aperture of 0.22 for CW pumping. Its emission central wavelength is 807.6 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 coupling optics consists of two identical plano-convex lenses with focal lengths of 10 mm used to reimaging 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 230 μm .

The laser crystal is a c-cut, 1.0% at % Nd³⁺ doped, 3 \times 3 \times 5 mm³ Nd:YLF crystal which is wrapped with

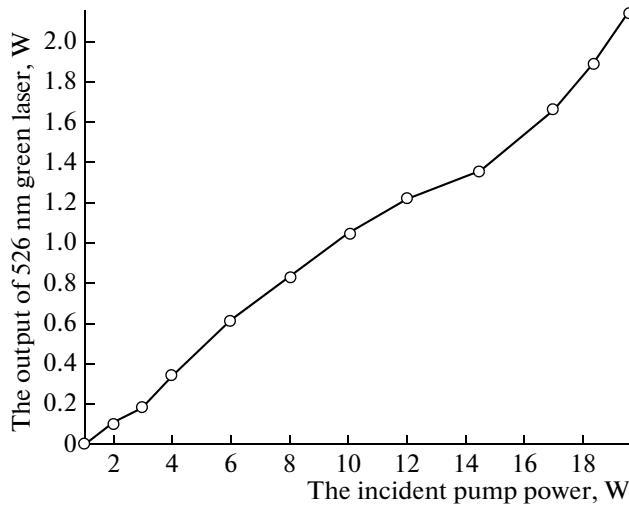


Fig. 5. The output power at 526 nm versus the incident pump power.

indium foil and mounted at a thermal electronic cooled (TEC) cooper block to keep the temperature at 20°C.

Although the gain coefficient of 1053 nm is twice higher than that of 1047 nm in the σ direction of c-cut Nd:YLF, wavelength selection method and internal loss of 1047 nm should be added in order to achieve the stable oscillation at 1053 nm. The left facet of Nd:YLF is the input coupler with high reflection coatings at 1047 nm, 1053 nm and antireflection coatings at 808 nm. The other facet of Nd:YLF is antireflection coated at 1047 nm, 1053 nm. M_1 is a 50 mm radius-of-curvature plano-concave output mirror. The concave facet is antireflection coated at 526 nm and high reflection coated at 1047 nm and 1053 nm. The piano facet of M_1 is antireflection coated at 526 nm. The end mirror M_2 is a 200 mm radius-of-curvature concave

mirror with high reflection coated at 1053 nm, 1047 nm, and 526 nm. Figures 2 and 3 are the coating curves of the left side of Nd:YLF crystal and the concave surface of the output coupler. As shown in the two figures, no loss is added to the two fundamental wavelengths and both of them have the condition to operate in the cavity.

A Brewster plate is inserted into the cavity to restrict the fundamental laser at 1053 nm oscillated in the σ direction and to suppress the parasitic oscillation at 1047 nm. LBO is a frequency doubler of $2 \times 2 \times 10 \text{ mm}^3$, cut for critical type I phase matching ($\theta = 90^\circ$, $\phi = 12.2^\circ$) and antireflection coated at 1053 nm and 526 nm to reduce the intracavity loss of fundamental laser and green laser.

The resonator is a three-mirror-folded cavity with two separate waists, one is near the left side of Nd:YLF to satisfy the mode matching condition, the other is near surface of M_2 which could enhance the efficiency of SHG. Considering the thermal effect of Nd:YLF crystal, the thermal stable three-mirror-fold resonator is designed with the ABCD laws of laser optics. The length of cavity arms L_1 and L_2 are about 72 mm and 44 mm respectively under the numerical simulation by MATLAB software. After numerical calculating, one beam waist of 165 μm is in the crystal which could satisfy the mode matching design requirement, and the other beam waist of 57 μm is just near the end mirror M_2 which could enhance the efficiency of frequency doubling.

4. RESULTS AND DISCUSSION

When tuning the temperature control of the pump source and aligning each component to good state and inserting the LBO into the cavity close to the end mirror M_2 , and tuning the aligning angle of LBO, the maximal output power of 2.15 W at 526 nm is achieved with the incident pump power of 19.5 W. Using the

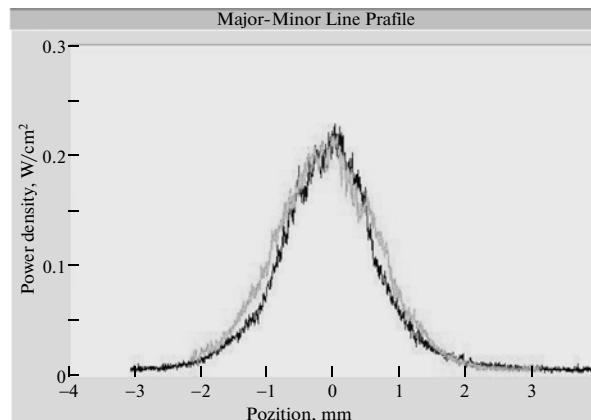
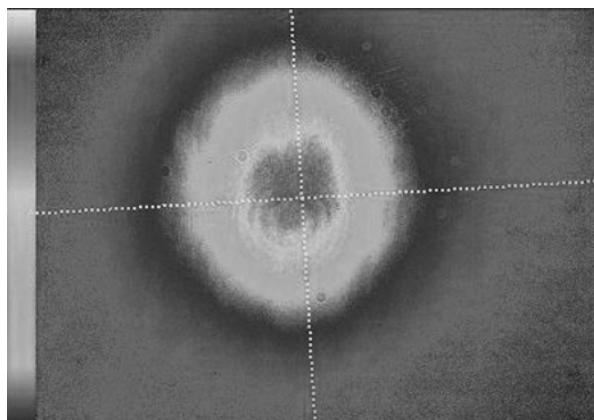


Fig. 6. The beam profile of 526 nm green laser.

Ocean Optics HR4000 spectrum analyzer to scan SHG and dealing with the data by software, the spectrum of the SHG laser is shown in Fig. 4. The threshold of 526 nm green laser is about 1.3 W and the dependence of the output power at 526 nm on the incident pump power is shown in Fig. 5.

The output power fluctuation is due to the spectral line competition between 1047 nm line and 1053 nm line. While inserting an LBO cut for 1053 nm SHG into the cavity, the output at 526 nm could be considered as the loss of 1053 nm fundamental wave. The loss of 1053 nm line makes the net gain of 1047 nm line increase that leads to the intracavity power at 1047 nm becomes higher. This competition progress decreases the loss of 1053 nm line and that equals to the net gain at 1053 nm increases. So the power of second harmonic wave arises. The output power fluctuation is due to this process. Figure 6 is the beam quality testing result which show that the 526 nm laser is operating at TEM₀₀ mode and far-field intensity distribution is near Gaussian distribution. The M-square factor is about 1.46 measured by the slit scanning method with M2SET-VIS/M from Thorlabs.

5. CONCLUSION

In summary, an efficient and compact green laser at 526 nm generated by intracavity frequency doubling of a continuous wave laser operation of a diode pumped Nd:YLF laser at 1053 nm under the condition of suppression the high gain transition near 1047 nm. With 19.5 W diode pump power and a frequency doubling

crystal LBO, as high as 2.15 W of CW output power at 526 nm is achieved, corresponding to an optical-to-optical conversion efficiency of 11.2% and the output power stability in 8 h is better than 2.87%.

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