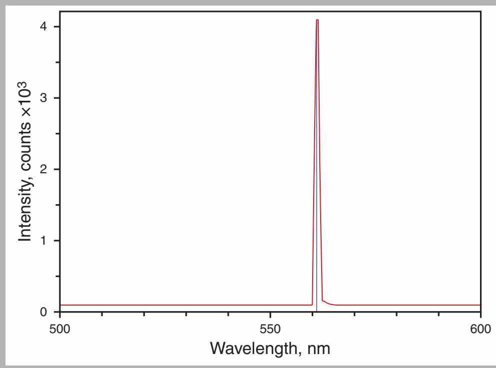
Abstract: We demonstrate for the first time the generation of yellow-green laser at 561 nm in critically type-I phase matching LBO with intracavity frequency doubling of a diode-pumped Nd:YAG laser operated at 1123 nm under room temperature in a compact three-fold cavity. As high as 1.2 W of continuous wave output at 561 nm is achieved with an incident pump power of 10 W. The total optical to optical conversion efficiency is up to 13.3% and the stability of output power is better than 3% in 3 h. To the best of our knowledge, this is the first Watt-level 561 nm yellow laser generation by frequency doubling of Nd:YAG laser.



The spectrum of 561 nm yellow laser

All-solid-state continuous-wave frequency-doubled Nd:YAG/LBO laser with 1.2 W output power at 561 nm

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1. Introduction

Nd:YAG is a very superior material for diode-pumped high-power lasers due to its excellent thermal properties and output characteristics. Generally, Nd:YAG laser operates at the most commonly used wavelengths of 1064 nm [1], 1319 nm [2], and 946 nm [3]. However, the 1123 nm spectral line is an important laser line of Nd:YAG and the second harmonic generation(SHG) of this line is 561 nm, which has potential application in the region of display, illumination, molecular biology and chemistry. The 1123 nm and 1064 nm line of Nd:YAG are both the transition from $^4F_{3/2} - ^4I_{13/2}$ but with different stark energy levels. Particularly, 1064 nm laser transition comes from $R_2 - Y_3$ and 1123 nm from $R_1 - Y_6$. The 1123 nm line must compete with 1064 nm line, which has higher gain because the emission cross section for 1123 nm is 1/16 of that for the 1064 nm line [4]. Consequently, efficient operation at 1123 nm requires the suppression of parasitic oscillation at 1064 nm, high pump intensity, and optimal resonator with low-loss.

After N. Moore et al. had demonstrated a diode-pumped continuous wave (CW) Nd:YAG laser at 1123 nm with 1.7 W output power [5], Y.F. Chen et al. and X.P. Guo et al. had reported the average output power of passively and actively acoustic-optical Q-switched diode-pumped 1123 nm Nd:YAG lasers is 150 mW and 3 W respectively [6–8]. The CW output of 1123 nm laser has been enhanced to 10.8 W by S.S. Zhang et al. using a simple plano-concave resonator and ceramic Nd:YAG [9]. The 556 nm laser was firstly demonstrated by Q. Zheng et al.

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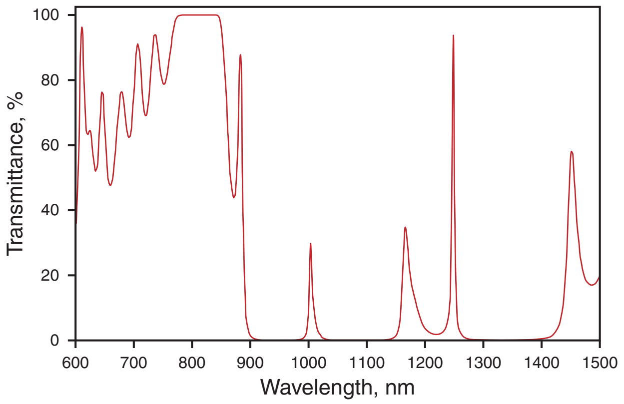

Figure 1 (online color at www.lphys.org) Transmissivity of the left side of Nd:YAG crystal

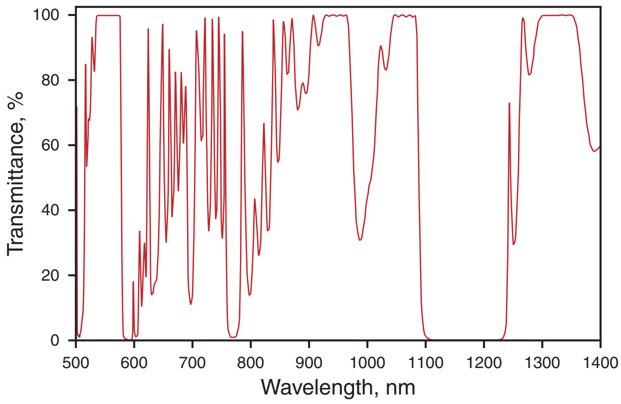

Figure 2 (online color at www.lphys.org) Transmissivity of output coupler of 561 nm laser

that 102 mW output powers was obtained and it was enhanced to 3.2 W in 2009 using a type-I LBO as the frequency doubling crystal [10], but no report about 561 nm laser watt-level output is demonstrated.

In this letter, the generation of watt-level yellow-green laser at 561 nm is demonstrated for the first time in critically type-I phase matching LBO with intracavity frequency doubling of a diode-pumped Nd:YAG laser operated at 1123 nm under room temperature in a compact three-fold cavity. As high as 1.2 W of continuous wave output at 561 nm is achieved with an incident pump power of 10 W. The total optical to optical conversion efficiency is up to 13.3% and the stability of output power is better than 3% in 3 h. To the best of our knowledge, this is the first Watt-level 561 nm yellow laser generation by frequency doubling of Nd:YAG laser.

2. Theory analysis

Comparing the performance of main laser transition lines in Nd:YAG, in order to obtain the laser oscillation at 1123 nm, which has a lower gain cross-section than the other main laser lines, not only 1064 nm oscillation, but also the 1319 nm and the 946 nm must be suppressed at the same time. Generally, the left side of Nd:YAG is coated at 946 nm and 1319 nm antireflection to suppress the oscillation of the two laser lines, and the output coupler is coated at 1064 nm antireflection to restrain the oscillation at 1064 nm. This method brings inconvenience to the coating progress and is not advantage to the commercial utility although the 1123 nm laser could be obtained. In our experiment the output coupler is coated at 1064, 946, and 1319 nm antireflection and the suppression of the three chief laser lines is accomplished by one cavity mirror. The left side of Nd:YAG is coated at 808 nm AR and 946, 1064, 1319, and 1123 nm HR and the output coupler is antireflection to the main laser lines at 1064, 946, and 1319 nm, as well as the SHG laser at 561 nm, and highly reflection at 1123 nm. Fig. 1 and Fig. 2 are the coating curves of the left side of Nd:YAG crystal and the concave surface of the output coupler. However, the second harmonic discrimination of 1123 nm and 1112 nm is difficult to be accomplished by traditional film designing. A thick etalon could be inserted into the 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 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 3.69 pm/V, which is much larger than that of LBO at 0.83 pm/V, the walk-off angle of LBO is as small as 4.62 mrad than 25.53 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 for a long time. So LBO is selected to be the frequency doubling crystal.

3. Experimental setup

The experimental setup is shown in Fig. 3. The pump source is a 10 W LD with emission wavelength at 808 nm. Its emission central wavelength at room temperature could be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The optics coupled system is antireflection coated at 808 nm. The pump beam is imagined into the crystal at ratio of 1:1. The laser crystal is a 1.0 at.% Nd^{3+} doped, $3\times3\times5$ mm^3 Nd:YAG crystal, which is wrapped with indium foil and mounted at a thermal electronic cooled (TEC) cooper block, and the temperature is maintained at $20\,^\circ$C. The relative performance of 1123 nm line is half of 1064 nm

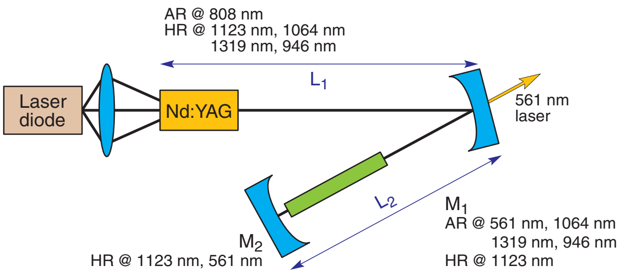

Figure 3 (online color at www.lphys.org) The schematic of the intracavity frequency doubling of Nd:YAG/LBO at 561 nm

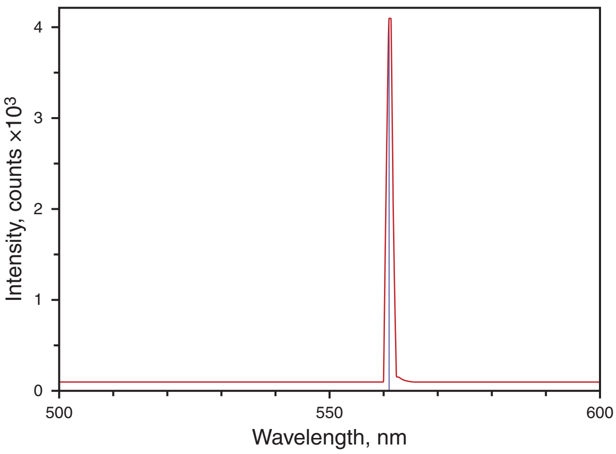

Figure 4 (online color at www.lphys.org) The spectrum of 561 nm yellow laser

line and its emission cross section is much smaller than the main spectral lines of Nd:YAG. In order to obtain the oscillation of 1123 nm, coating loss should be added to the 1064, 1319, and 946 nm line.

The left facet of Nd:YAG is the input coupler with antireflection coatings at 808 nm and high reflection coatings at 946, 1064, 1123, and 1319 nm. The other facet of Nd:YAG is antireflection coated at 946, 1064, 1123, and 1319 nm. M_1 is a 50 mm radius-of-curvature plano-concave output mirror. The concave facet is antireflection coated at 1064, 1319, 946, and 561 nm and high reflection coated at 1123 nm. The plano facet of M_1 is antireflection coated at 561 nm. The end mirror M_2 is a 200 mm radius-of-curvature concave mirror with high reflection coated at 1123 nm and 561 nm. LBO is a frequency doubler of $2{\times}2{\times}10$ mm^3, cut for critical type-I phase matching ($\theta = 90°$, $\phi = 7.7°$) and antireflection coated at 1123 nm and 561 nm to reduce the intracavity loss of fundamental laser and yellow laser.

The resonator is a three-mirror-folded cavity with two separate waists, one is near the left side of Nd:YAG to satisfy the mode matching condition, the other is near surface

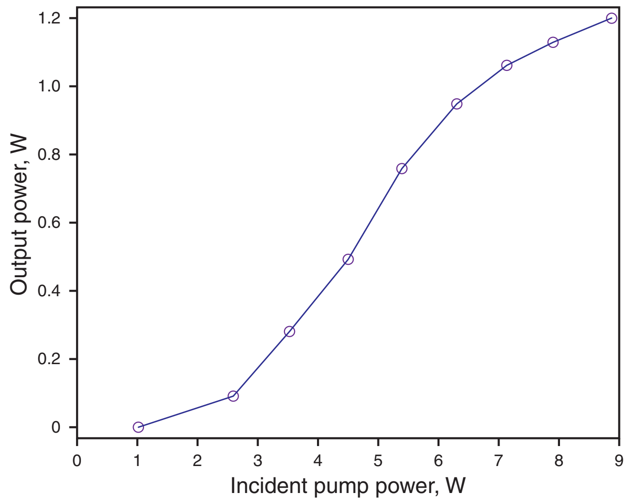

Figure 5 (online color at www.lphys.org) The output power at 561 nm versus the incident pump power

of M_2, which could enhance the efficiency of SHG. Considering the thermal effect of Nd:YVO_4 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 75 mm and 45 mm respectively under the numerical simulation by MATLAB software. After numerical calculating, one beam waist of 150 μm is in the crystal, which could satisfy the mode matching design requirement, and the other beam waist of 60 μm is just near the end mirror M_2, which could enhance the efficiency of frequency doubling.

4. Results and discussions

When tuning the temperature control of the pump source and aligning each component to good state, the color of the fluorescence in Nd:YAG is blue due to the excited state absorption (ESA) of the upper laser level. Although the Nd:YAG is isotropy, the frequency doubling crystal LBO and LD with high polarization ratio make the fundamental wave with high polarization characteristic, and it is not necessary to insert a polarizer such as Brewster plate into the cavity. While 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 1.2 W at 561 nm is achieved.

Using the LABRAM-UV 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 561 nm yellow laser is about 1.1 W and the dependence of the output power at 561 nm on the incident pump power is shown in Fig. 5. With the incident pump power of 10 W, corresponding to an output power of 1.2 W at 561 nm.

The output power fluctuation is due to the spectral line competition between 1123 nm line and 1112 nm line.

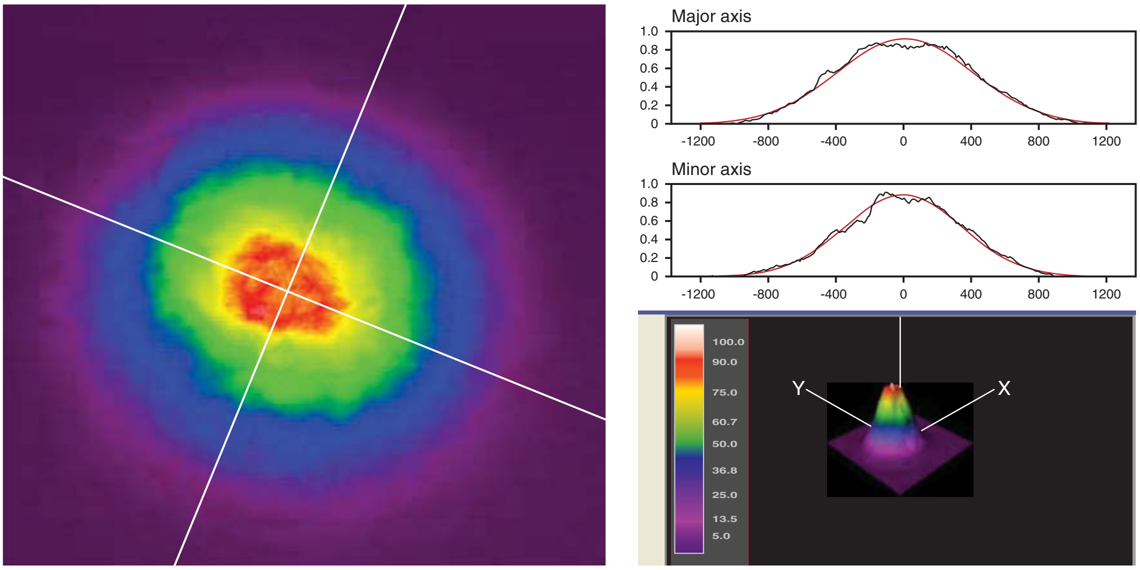

Figure 6 (online color at www.lphys.org) The beam profile of 561 nm yellow laser

While inserting an LBO cut for 1123 nm SHG into the cavity, the output at 561 nm could be considered as the loss of 1123 nm fundamental wave. The loss of 1123 nm line makes the net gain of 1112 nm line increase that leads to the intracavity power at 1112 nm becomes higher. This competition progress decreases the loss of 1123 nm line and that equals to the net gain at 1123 nm increases. So the power of second harmonic wave arises. The output power fluctuation is due to this process. Fig. 6 is the beam quality testing result, which show that the 561 nm laser is operating at near TEM_{00} mode and far-field intensity distribution is near Gaussian distribution. The M^2 factor is about 1.67 measured by knife-edge method with Spiricon Beam star FX.

5. Conclusions

In summary, the generation of yellow-green laser at 561 nm is obtained in critically type-I phase matching LBO with intracavity frequency doubling of a diode-pumped Nd:YAG laser operated at 1123 nm under room temperature in a compact three-fold cavity. As high as 1.2 W of continuous wave output at 561 nm is achieved with an incident pump power of 10 W. The optical to optical conversion efficiency is up to 13.3% and the stability of output power is better than 3% in 3 h.

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