Diode-end-pumped Nd:YVO₄/LBO lasers with 4.2W continuous-wave output at 457 nm

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A continuous-wave (CW) 457 nm blue laser operating at the power of 4.2 W is demonstrated by using a fiber coupled laser diode module pumped Nd: YVO₄ and using LBO as the intra-cavity SHG crystal. With the optimization of laser cavity and crystal parameters, the laser operates at a very high efficiency. When the pumping power is about 31 W, the output at 457 nm reaches 4.2 W, and the optical to optical conversion efficiency is about 13.5% accordingly. The stability of the output power is better than 1.2% for 8 h continuously working.

High power all-solid-state blue laser has been used in various fields, such as biology, entertainment, communications, scientific research, medical treatment, data-storage, military affairs, etc.. A preferred way to get CW blue laser is frequency-doubled of Nd:YAG 946 nm to generate 473 nm radiation in an intra-cavity[1-10]. However, owing to the intrinsic property of Nd:YAG crystal, it is very difficult to get the output at 473 nm higher than 3W. On the other hand, the color of the 473 nm radiation is a bit too weak to well satisfy the matching requirements for laser display. Recently, research interests in this domain have been switched to the diode-end-pumped Nd:YVO₄ laser to generate 914 nm radiation, and then its frequency is doubled to obtain 457 nm blue laser [11-14].

In this letter, we have successfully accomplished a high power, 457 nm blue laser by optimizing the length and dopant-concentration of the active medium and the coatings of the optical components. Finally, a 4.2 W CW 457 nm blue lase output is achieved by using Nd:YVO₄/LBO scheme.

Fig.1 is the schematic configuration of the energy levels of Nd:YVO₄ crystal. Due to the present of the lattice field, the upper level $^4F_{3/2}$ of the Nd^{3+} ion splits into two adjacent sub-levels (R_2 and R_1) whose population distribution follows the Boltzmann distribution law. The populations on R_2 and R_1 levels are calculated to be 45% and 55% of the total number, respectively [15]. Moreover, the sub-levels of Z_1-Z_5, which come from the Stark splitting of the lower level $^4I_{9/2}$,

also follow the Boltzmann distribution law. Hence, the 914 nm laser line can be obtained from the transition between the sub-levels of R_1 and Z_5. According to the Boltzmann distribution law, the population on Z_5 occupies 5% (f_1=5%) of the total population on $^4I_{9/2}$, which is larger than that (f_1=0.74%) in Nd:YAG crystal. Since Z_5 is very close to the ground state, the population of the lower level in Nd:YVO₄ is quite large. It essentially leads to the high oscillation threshold of the 914 nm line. Therefore, compared with Nd:YAG, it is much more difficult to achieve efficient quasi-three level operation of Nd:YVO₄ crystal[11].

However, due to the natural birefringent property of Nd:YVO₄ crystal, the quasi-three level operation of 914 nm radiation is linearly polarized. Hence, it can exhibit much higher conversion efficiency of frequency-doubled in Nd:YVO₄ than that in Nd:YAG which is intrinsically isotropic.

Therefore, by optimizing such parameters as crystal length, dopant concentration, etc., we expect even higher out-
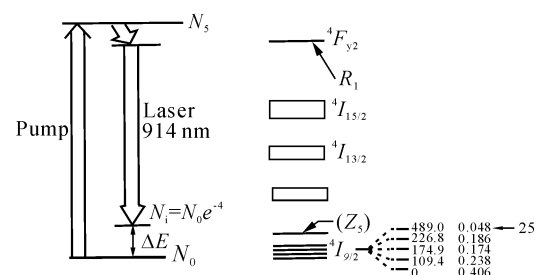

Fig.1 Structure of energy level for Nd: YVO₄ at 914 nm

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put at 457 nm than that at 473 nm, which has been testified by the following experiment.

The threshold formula for the quasi-three level laser system is defined by

$$P_{th} = \frac{\pi h \nu_p \left(\omega_p^2 + \omega_l^2\right)\left(\delta + 2f_1 N^0 \sigma l\right)}{4\sigma\tau(1-e^{-\alpha_{p}l})\eta_p\left(f_1 + f_2\right)} \quad , \qquad (1)$$

where $h\nu_p$ is the photon energy of the pump wave, δ is the intracavity loss, ω_p is the pump spot radius, ω_l is the fundamental beam waist, f_1 and f_2 correspond to the ratios of the population of the upper and lower levels with respect to the total number, respectively. N^0 is the dopant-concentration-dependent total population intensity, σ and τ is the emitting cross section and the upper level fluorescence life time of the active medium, respectively, η_p is the quantum efficiency, and l is the crystal length. According to Eq. (1), we can conclude that,

- The laser threshold is proportional to $(\omega_p^2+\omega_l^2)$, namely, the smaller the pump beam and fundamental beam spots are, the lower the oscillation threshold is.

- The existence of the population on the lower level will enhance the intracavity loss and increase the laser threshold. It is obviously different from the common four-level laser system.

- l exists both the numerator and denominator of Eq. (1), which hints that the value of l can be optimized to obtain the lowest oscillation threshold.

The optimized value of l should satisfy the condition of $\partial P_{th}/\partial l = 0$, and that for l_0 can be written as

$$\alpha \exp(-\alpha l_0)\left(\frac{2\sigma N_1^0}{\alpha} + \delta + 2\sigma N_1^0 l_0\right) - 2\sigma N_1^0 = 0 , \qquad (2)$$

where N_1^0 is the population on the lower level. In practice, the dopant concentration can also influence the absorption coefficient and upper level life-time of the active medium. Therefore, the parameters mentioned above should also be taken into account when optimizing the oscillation threshold.

The schematic configuration of the intracavity frequency-doubled CW blue laser is shown in Fig.2. A fiber-coupled 808 nm CW diode array (LIMO Co., Germany) with a maximum output power of 32 W and NA=0.22, is used as the pump source of the fundamental laser. The pump beam is re-imaged into the laser crystal through a collimating and focusing lens-pair with a coupling efficiency of 95%, resulting in a pump spot radius of about 200 μm.In order to reduce the influence of the thermal lens effect, a 0.1% doped, 3 mm× 3 mm× 6 mm Nd:YVO$_4$ crystal is used as the active medium

which is anti-reflection (AR) coated at 808 nm, 914 nm, 1064 nm and 1342 nm. The crystal is wrapped in the indium foil and mounted in a water-cooled copper to keep its temperature at 15 ℃. As the input mirror, M1 is a plane-parallel mirror which is AR coated at 808 nm on one side, and high-reflection (HR) coated at 914 nm and AR coated at 808 nm, 1064 nm and 1342 nm on the other side. M2 is a plane-concave mirror with a radius of curvature of 50 mm. The concave side of M2 is HR coated at 914 nm and AR coated at 457 nm (simultaneously AR coated at 1064 and 1342 nm), and the other side is AR at 457 nm. The plane-concave mirror M3, with a radius of curvature of 75 mm, is HR at 457 and 914 nm on the concave side. The plane-parallel mirror M4 which is HR at 457 nm is used to switch the laser transmitting direction. M5 is a filter which is HR at 914 nm and AR at 457 nm. For the aim of collimating and suppressing the divergence angle of the blue laser at 457 nm, the plane-convex lens M6 (AR at 457 nm) is employed with a focal length of 75 mm. A 3 mm×3 mm×18 mm, type-I critically phase-matched (θ =90º, φ =21.7º) LBO crystal is used for frequency doubling.
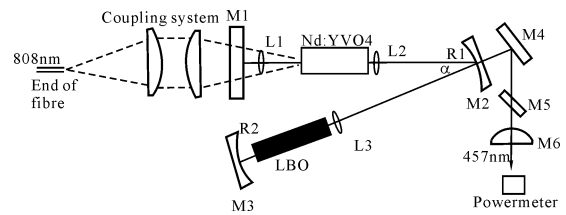

Fig.2 Configuration of the high power 457 nm blue laser

The basic principle to design a quasi-three level frequency-doubled blue laser is to make the fundamental reflectivity as high as possible. When the condition is satisfied, we then have to strive for the perfect transmission at 457, 1064 and 1342 nm to increase the net gain for the 914 nm line. However, it is very difficult to simultaneously achieve HR at 914 nm and AR at 1064 and 1342 nm on the same coating, since these wavelengths are very close to each other. In our experiment, in order to obtain the efficient oscillation of the 914 nm line, we set R_{914}= 99.9%, T_{808}= 98%, $T_{1064,1342}$> 80%.

Before inserting the LBO crystal, the fundamental output and beam quality at 914 nm should be optimized, which is very important for the efficient frequency doubling. It is necessary to mention that we do not take the refractive index of the LBO crystal into account in the previous theoretical analysis. So, when we placed the LBO into the cavity, the cavity length should be appropriately adjusted with an offset: $\Delta=L_{LBO}[1-(1/n_{LBO})]$, and it can be calculated to be 6.75 mm

by using n_{LBO}=1.6 and L_{LBO}=18 mm. After elaborating optimization of various parameters that affect the 457 nm output, we eventually obtained 4.2 W CW output power at 457 nm with an incident diode pump power of 31 W. The corresponding optical-to-optical conversion efficiency is up to 13.5%.

Fig.3 depicts the output power and conversion efficiency of the frequency-doubled blue laser with respect to the incident diode pump power. It is seen that there is a critical pump power of 20 W. When the pump level is lower than this point, the slope efficiency of the 457 nm output is very low, whereas, when the pump power is higher than 20 W, it increases dramatically. This phenomenon has been theoretically analyzed by Zeller et al[15]., and they attributed it to the re-absorbing loss of the quasi-three level system. At the lower pump level, the population inversion and fundamental gain are very small, and the re-absorbing loss will lead to a relatively low slop efficiency. As the pump power increased, the fundamental gain is large enough to offset the impact of re-absorbing which can be neglected at this stage.
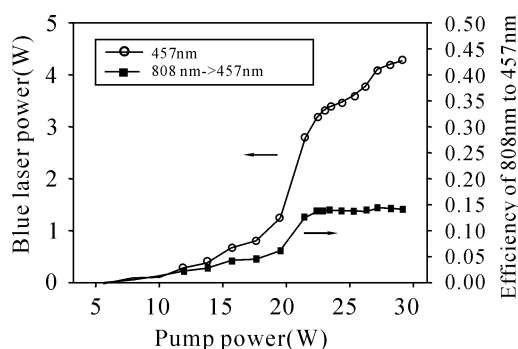

Fig.3 The 457 nm blue laser power and O-O efficiency versus pump power

The far field beam spot of the frequency-doubled laser is illustrated in Fig.4. As it shows, the beam spot has an elliptical profile which is prolonged along the vertical direction. It could be explained as the following: the LBO crystal used here is type-I phase-matched, and there is a walk-off of 12.48 mrad along the polarization direction (vertical) of the e-ray. Together with the large crystal length of 18 mm, these result in the non-ideal beam profile.

In order to evaluate beam quality accurately, we employed a laser beam diagnostics device (Spiricon M^2-200) to measure the beam profile at the highest output level. Fig.5 illustrates the corresponding experimental results. Although we have ensured the optimized mode-matching in the previous cavity design, the output beam profile is still very poor. It can be interpreted as that the pump beam waist used in the theoretical calculations is smaller than the average radius of the pump beam travelling in the active medium, which destroyed the mode-matching condition and eventually results in the bad beam quality, and the walk-off of SHG process also deteriorated the beam quality. We also detected the eight hours' power stability of the 457 nm radiation at the maximum output power of 4.2 W continuously, and the root mean square (RMS) stability is within1.2%. It indicates that the output is very stable.
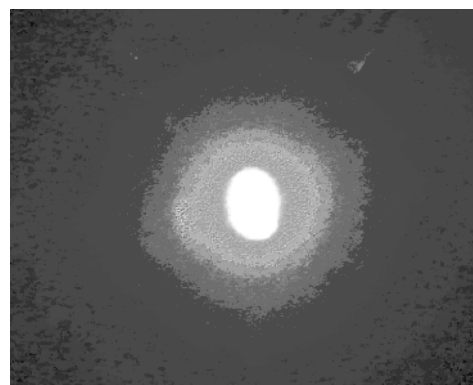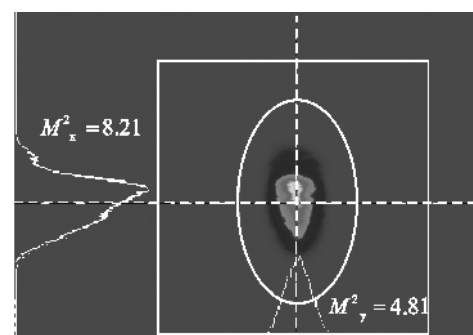

Fig.4 The beam profile of far field

Fig.5 Test result of blue laser beam quality

In summary, we have analyzed the characteristics of the quasi-three level operation at 914 nm of Nd:YVO$_4$ crystal, and have obtained the optimized crystal length. The efficient fundamental operation at 914 nm has been achieved by optimizing the cavity design and the parameters of the materials, and then a high power blue laser at 457 nm has also been obtained through intracavity frequency-doubling with LBO. With 31W incident pump power, the output power at 457 nm is 4.2 W, corresponding to an optical-to-optical conversion efficiency of 13.5%. In addition, the continuous power stability is better than 1.2% after eight hours continuous working.

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