13.2 W laser-diode-pumped $Nd:YVO_4$/LBO blue laser at 457 nm

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We report the efficient compact deep-blue laser at 457 nm generation by intracavity frequency doubling of a continuous wave (cw) laser operation of a diode-pumped $Nd:YVO_4$ laser on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 914 nm. An LBO crystal, cut for critical type I phase matching at room temperature is used for second-harmonic generation (SHG) of the laser. At an incident pump power of 38 W, as high as 13.2 W of cw output power at 457 nm is achieved with 15-mm-long LBO. The optical-to-optical conversion efficiency is up to 34.7%, and the power stability in 2 h is better than ±2.68%. © 2009 Optical Society of America

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1. INTRODUCTION

Diode-pumped solid-state lasers in the visible spectral range have applications in the fields of measurement techniques, printing, and display technology, etc. [1–7]. Especially in the fields of underwater communications, high-density optical storage, medical diagnostics, and color display technology, there has been great interest in multiwatt-level blue laser emission. Use of a laser diode-(LD-) pumped solid-state quasi-three-level Nd^{3+} laser has been proved to be an efficient way to achieve this goal.

Fan and Byer first successfully demonstrated the operation of an LD-pumped quasi-three-level Nd:YAG laser that operates on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition, and they founded the corresponding theoretical model [8]. Thereafter, Risk established a similar model to describe this kind of laser. An important conclusion can be drawn from these theoretical models: that is, the quasi-three-level system can be regarded as a four-level structure once the intracavity fundamental-wave circulating intensity is high enough that the reabsorption loss is bleached [9]. When this point is reached, the laser will come into a stable operational state and higher optical conversion efficiency will be expected. Overcoming these problems, a 2.8 W, 473 nm Nd:YAG/BiBO laser and an 840 mW, 456 nm $Nd:GdVO_4$/LBO laser were demonstrated with a Z cavity as long as almost 1 m. A 4.6 W, 457 nm doubling-frequency $Nd:YVO_4$/LBO, which is available commercially, has been reported [10].

In this paper, a high-power, compact, and efficient fiber-coupled LD-pumped $Nd:YVO_4$, intracavity-frequency-doubling LBO cw 457 nm blue laser is demonstrated. With an incident pump power of 38 W, $Nd:YVO_4$ with low-doped concentration, a long type I critical phase-matching LBO crystal, and a compact three-mirror folded cavity, up to 13.2 W of deep blue laser emission at 457 nm, is achieved. The optical-to-optical conversion efficiency is greater than 34.7%, and the stability of the output power is better than 2.68% for 2 h measured by FieldMaster-GS power meter whose analog bandwidth is 10 Hz.

2. THEORETICAL ANALYSIS

A. Laser Crystal Length Optimization

The threshold equation of quasi-three-level laser system is

$$P_{\mathrm{th3}} = \frac{\pi h \nu_p (\omega_L^2 + \omega_p^2)(L + T_3 + 2N_1^0 \sigma_3 l)}{4\sigma_3 \tau \eta_{p3} \eta_a (f_1 + f_2)}, \qquad (1)$$

where $h\nu_{\mathrm{p}}$ is the pump photon energy, ω_{L} and ω_{p} are the radius of laser beam and pump beam, L is the round-trip loss expect for transmission loss, T_3 is transmission of fundamental wave, s_3 is the stimulated emission cross section of 914 nm laser, l is the length of $Nd:YVO_4$, N_1^0 is the population density of lower laser level without pumping, t is the fluorescence lifetime, η_{p3} is the pump quantum efficiency, $\eta_\alpha = 1 - \exp(-\alpha l)$, α is the absorption coefficient, f_1 and f_2 are the fraction population of the lower and upper laser level. The equation indicates that there is an optimal length of $Nd:YVO_4$ to make the laser operating under the condition of lowest threshold.

As shown in Fig. 1, when ω_{L} and ω_{P} are 200 μm, L is 0.01 and $Nd:YVO_4$ is 0.1% Nd^{3+} doped, taking the lowest threshold condition into account: the length of $Nd:YVO_4$ is chosen as 3 mm–4 mm. With the commercial use of high-power laser diode array (LDA) and the development of a coating technique, not the lowest threshold but the maximal output power is the ultimate purpose for diode-pumped solid-state laser (DPSSL) design. Set the numerical calculation parameters as below: $Nd:YVO_4$ is 0.1% at.% doped whose stimulated cross section is about 25 $\times 10^{-2}$ cm^2, ω_{L} and ω_{P} are both 150 μm, the round-trip loss is 2%, and transmission of fundamental wave is 20%.

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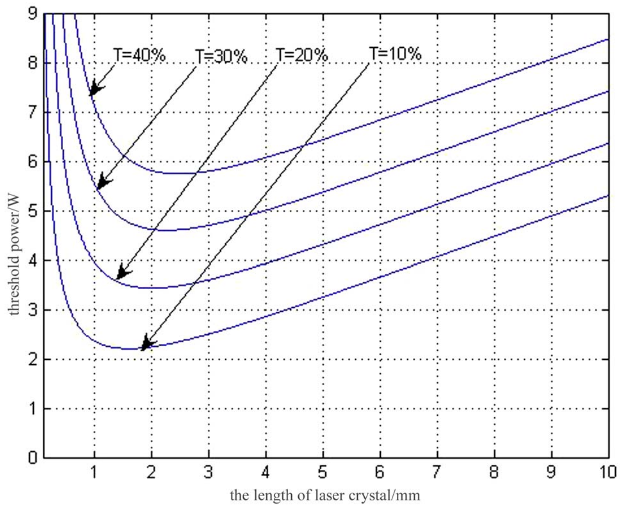

Fig. 1. (Color online) Length of laser crystal versus the threshold power with different transmission loss

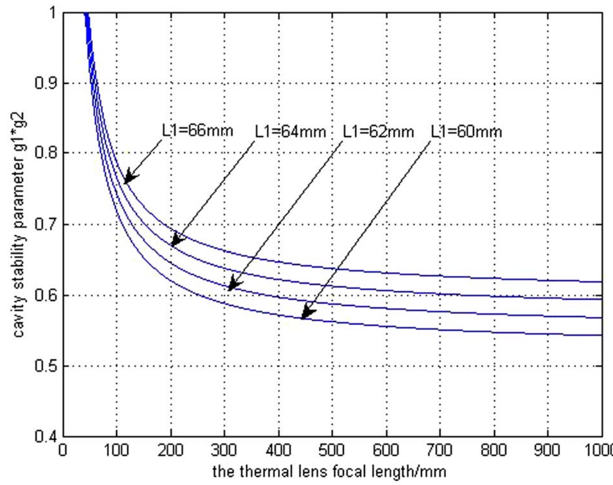

Fig. 3. (Color online) Influence of the length of arm L_1 on the stability of the cavity.

Deriving from the stable-state rate equation of the quasi-three-level system, the relation between length of the laser crystal and the output power is obtained. Figure 2 demonstrates that with high incident pump power, the optimal length adds 4 mm−5 mm under the principle of "output power maximization" with the same doped density laser crystal. A difference between the optimal lengths of laser crystal is apparently of 1 mm while considering the maximal output power prior to the lowest threshold. So the Nd:YVO_4 with optimal length and lower doped concentration is advantageous for achieving higher output and reducing the thermal effect of the laser crystal.

B. Cavity Parameter Optimization

In this experiment, a three-mirror folded cavity is introduced to reduce the whole length of the cavity and to produce two separate beam waists. One is aimed at mode matching, has relatively low threshold, and makes use of the pump power with high efficiency; the other is for high-efficiency frequency doubling in LBO. Based on the ABCD law and design principle of thermal insensitive cavity, Fig. 3 and Fig. 4 show the influence of the lengths of arm L_1 and L_2 on the stability of the cavity. It is obvious that different thermal lens focal lengths do not affect the stable region of the cavity. There are about 10 mm that can be adjusted for arm L_1 with the same length of arm L_2. So the stability of the cavity is insensitive to the length of arm L_1. However, we should notice that a ±1 mm change of the second arm L_2 will decrease or increase the cavity stability parameter by 0.2. Therefore the length of L_2 must be adjusted carefully in the experiment. When the incident pump power is increased, in order to maintain the same parameters of the cavity in the laser and the nonlinear crystal as that for lower pump power, one has to lengthen L_2 slightly, although the cavity is still a stable one. Based on the theoretical analysis above and the dimension of the device, L_1 and L_2 are about 60 mm and 30 mm, respectively. Figure 5 shows the beam waists in both arms, which are thermally stable.

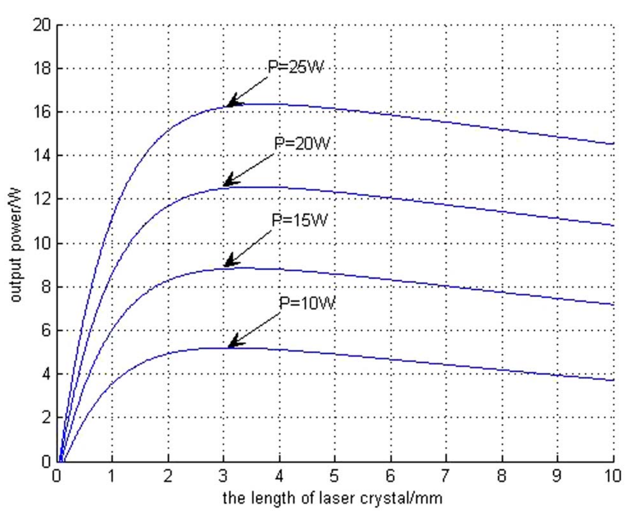

Fig. 2. (Color online) Length of crystal versus the output power of 914 nm with $T_3=20\%$.

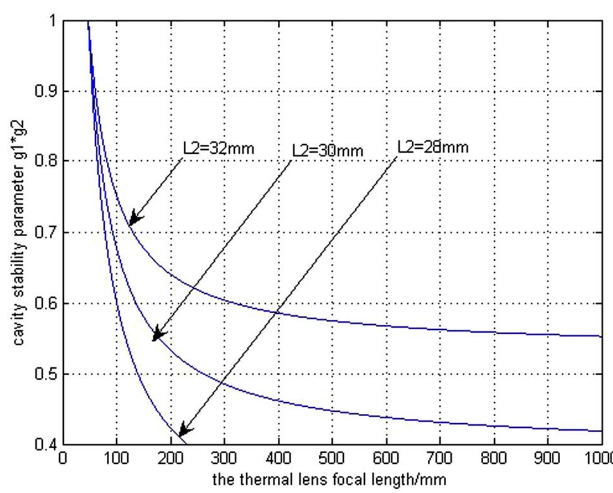

Fig. 4. (Color online) Influence of the length of arm L_2 on the stability of the cavity.

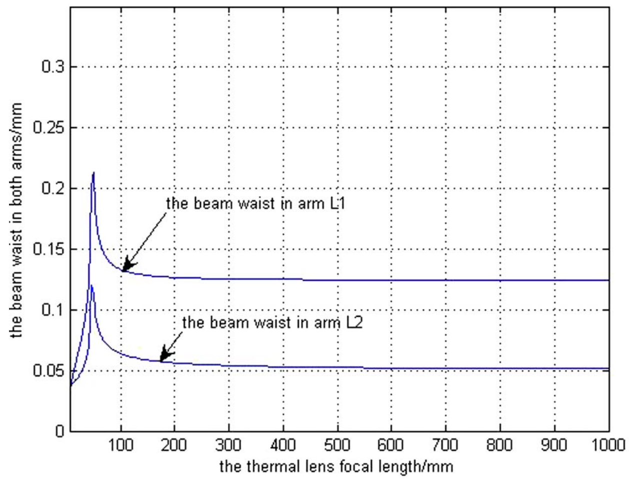

Fig. 5. (Color online) Beam waists in both arms of L_1 and L_2.

3. EXPERIMENTAL SETUP

A schematic of the intracavity deep-blue laser is shown in Fig. 6. The pump source is a 40 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 806.4 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 1.8 nm, and its temperature is kept at 28°C in the experiment to match the absorption peak of Nd:YVO_4 crystal. The coupling optics consist of two identical plano–convex lenses with focal lengths of 15 mm used to re-image 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 220 μm.

The laser crystal is a $3\times3\times5$ mm^3, 0.1% Nd^{3+}-doped Nd:YVO_4. It is wrapped with indium foil and mounted in the copper heat sink. The left side of the laser crystal is coated with antireflection film at the pump wavelength and 1064 nm ($R<2\%$) and with high-reflection film at 914 nm ($R>99.9\%$), acting as one mirror of the cavity. A long laser crystal with low-doped concentration is used to reduce thermal lensing and the reabsorption of quasi-three-level emission while guaranteeing that enough pump energy will be absorbed. When the pump wavelength is tuned to match the absorption peak of the Nd:YVO_4, about 60% of pump power is absorbed. The temperature of the laser crystal is kept at a constant of 23°C by a thermoelectric cooler (TEC), which helps to yield a small thermal population of the terminal laser level and stable output power. The lower temperature is essential to yield efficient operation at Nd:YVO_4 spectral line of 914 nm. The right-hand side of the laser crystal is antireflection coated at 914 nm, 1064 nm, and 1342 nm to reduce loss of the resonating 914 nm oscillation and suppress the strong lines of 1064 nm and 1342 nm. When the coating requirements on both sides of the Nd:YVO_4 are satisfied, the 914 nm spectral line could oscillate independently.

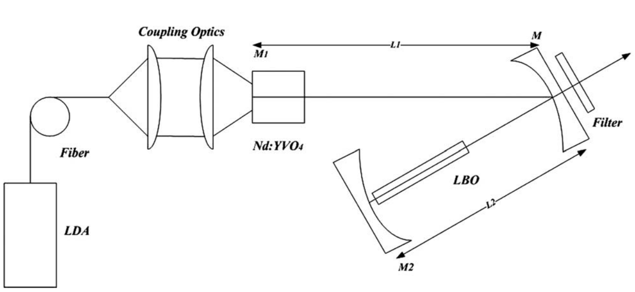

Fig. 6. Schematic for the intracavity frequency-doubled 457 nm Nd:YVO_4/LBO deep-blue laser.

The radii of the concave face are 50 mm and 200 mm for M and M_2 respectively. The concave face of M is highly reflective at 914 nm and highly transmitive at 1064 nm, 1342 nm, and 457 nm. The coating films for the plane surface is the same as for the right-hand side of laser crystal except with high transmission at 457 nm. The end mirror M_2 is coated at 914 nm and 457 nm high-reflection. L_1 and L_2 are the lengths of the arms in the cavity. L_1 and L_2 are about 60 mm and 30 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 LDA, the whole cavity, and the crystal are cooled by TEC for an active temperature control with stability of ±0.1°C. LBO is a $2\times2\times15$ mm^3 nonlinear crystal ($\theta=90°$, $f=21.7°$). Though BiBO has a high nonlinearity of 3.43 pm/V in frequency doubling of 914 nm laser, the large walk-off angle of 44.73 mrad, which gets the beam spot with low beam quality, makes BiBO unsuitable for this application. LBO is selected as the frequency-doubling material in our experiment for its small walk-off angle of 12.48 mrad. Although the nonlinear coefficient of LBO is 0.8 pm/V, the length of LBO could be extended to compensate the relatively smaller value of the nonlinear coefficient. Both facets of the LBO crystal are coated for antireflection at 457 nm and 914 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.

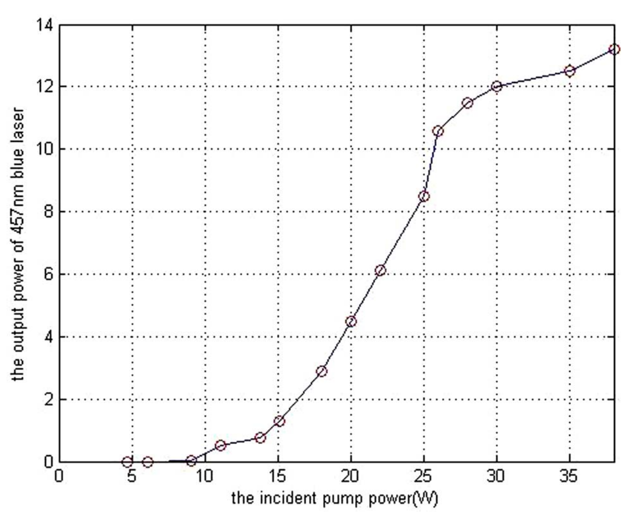

Fig. 7. (Color online) Dependence of the output power at 457 nm on incident pump power.

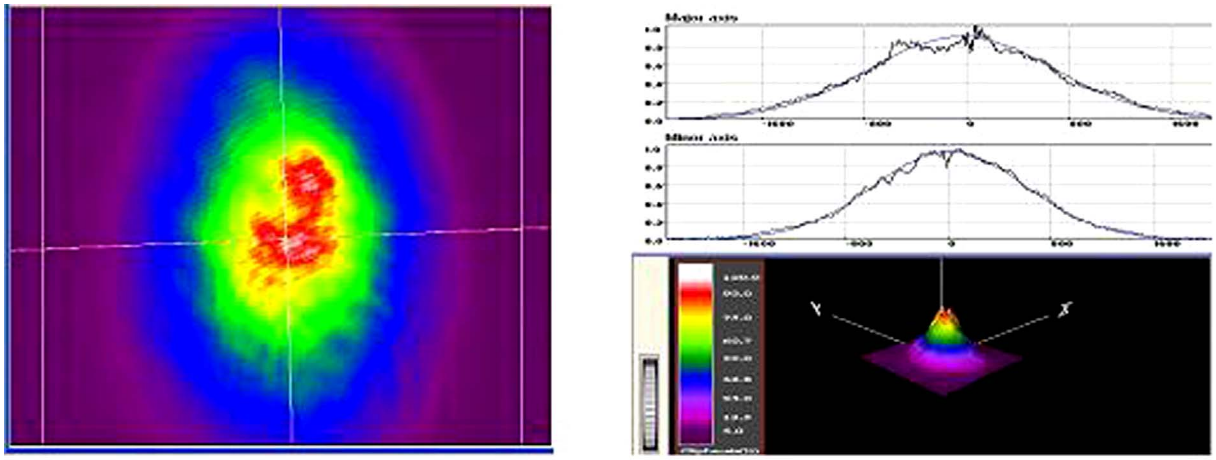

Fig. 8. (Color online) Beam profile distribution of 457 nm blue laser.

4. RESULTS AND DISCUSSION

The laser output at 914 nm is linearly polarized, so it is not necessary to insert a Brewster plate for the frequency doubling. For the second-harmonic (SHG) experiment, a 15 mm LBO is inserted into the cavity close to the end mirror M_2. The dependence of the deep-blue laser output power on the incident pump power is shown in Fig. 7. The threshold of the blue laser is about 9 W, with the incident pump power of 38 W, corresponding to an output power of 13.2 W at 457 nm.

The reason for the step response in Fig. 7 is due to the saturation of the reabsorption loss of the quasi-three-level laser for the fundamental wave of 914 nm. The M^2 factors are about 2.13 and 2.53 in X and Y directions, respectively, measured by knife-edge technique. The asymmetry of the M^2 factor in two directions is a result from the walk-off between the fundamental wave and the second in direction of LBO. Figure 8 is the beam-quality testing result, which shows that the laser output at 457 nm is operating at near TEM_{00} mode, and far-field intensity distribution of the beam is also displayed in Fig. 8 that is near Gaussian distribution.

Some stability testing is carried out by monitoring the deep-blue laser with a FieldMaster-GS power meter at 10 Hz. The fluctuation of the output power is about 2.68% in 2 h. The chaotic blue-noise state is also stable when the environments without large fluctuations and the short-term power stability is measured by LabMaster Ultima, which operates at 50 kHz. The %rms noise value is 2.83%. The chaotic noise of the 457 nm output in this experiment is due to longitudinal mode cross saturation in the laser crystal and sum-frequency mixing in the double-frequency crystal. The polarization character of $Nd{:}YVO_4$ crystal and the function of LBO as a polarizer influence the noise state of the 457 nm blue laser. $Nd{:}YVO_4$ crystal has a high absorption coefficient of pump beam with p polarization, and it emits fundamental wave in p direction with high efficiency. Based on the theoretical model [11], LBO plays as a polarizer except for a frequency-doubling crystal, which limits the oscillation of a fundamental wave that is vertical to the p direction. Since the coupling of the longitudinal modes that are vertical to each other is the source of noise, the high polarization ratio of 914 nm fundamental wave relieves coupling of orthogonal modes and eliminates the influence of sum-frequency generation on frequency-doubling progress. In comparison with the 473 nm blue laser generated by Nd:YAG crystal, the larger thermal conductivity of $Nd{:}YVO_4$ crystal is also attributed to the little effect that temperature fluctuation in the laser crystal has on the population of the lower level in the quasi-three-level laser system, and it enhances the laser efficiency as well as suppresses the noise. In the experiment the length of the cavity is about 105 mm, and the number of longitudinal modes oscillating in the resonator is about 527. The $Nd{:}YVO_4$ crystal has a broad gain linewidth, which ensures that there is not a longitudinal mode, and it gets enough peak gain that leads to the nonlinear loss of other modes. All the physical phenomena demonstrated above causes the noise of the 457 nm blue laser to be suppressed relatively lower without an additional element.

5. CONCLUSIONS

An efficient, compact LD-pumped deep-blue laser has been demonstrated by using $Nd{:}YVO_4$ and LBO crystals as a gain medium and a nonlinear crystal for intracavity frequency doubling. A three-mirror folded cavity is employed to enhance the conversion efficiency. With an incident pump power of 38 W, the maximum output power at 457 nm can amount to 13.2 W. The optical-to-optical conversion efficiency is 34.7%, and the stability of the output power is better than 2.68% for 2 h.

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