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LASERS
AND THEIR APPLICATIONS

All-Solid-State Dual End Pumped YVO_4:Nd/LBO Blue Laser with 21.8 W Output Power at 457 nm[1]

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Abstract—It is reported 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 YVO_4:Nd laser on the ${}^4F_{3/2} \to {}^4I_{9/2}$ 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. With dual end pump configurations at total incident pump power of 60 W, as high as 21.8 W of CW output power at 457 nm is achieved with 20-mm-long LBO. The optical-to-optical conversion efficiency is up to 36.3%, and the power stability in 8 h is better than 2.36%.

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INTRODUCTION

Diode-pumped solid-state lasers in the visible spectral range have applications in the fields of measurement technique, printing and display technology, etc. [1–8]. Especially in the fields of under water communications, high-density optical storage, medical diagnostics, and color display technologies, there has been great interest in multiwatt level blue laser emission. 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 YAG:Nd laser that operates on the ${}^4F_{3/2} \to {}^4I_{9/2}$ transition, and they founded the corresponding theoretical model [9]. 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 [10]. When this point is reached, the laser will either come into a benign operational state and higher optical conversion efficiency will be expected, or the laser will come into the opposite state. Overcoming these problems, a 2.8 W 473 nm YAG:Nd/BIBO laser and an 840 mW 456 nm $GdVO_4$:Nd/LBO laser were demonstrated with a Z cavity as long as almost 1 m. A 13.2 W, 457 nm doubling-frequency YVO_4:Nd/LBO, which is available commercially, has been reported [11].

[1] The article is published in the original.

In this paper, a high-power, compact, and efficient fiber-coupled laser-diode (LD) pumped YVO_4:Nd, intracavity frequency doubling LBO CW 457 nm blue laser is demonstrated. With dual end pump configurations at total incident pump power of 60 W, YVO_4:Nd with low doped concentration, a long type I critical phase matching LBO crystal, and a compact three-mirror folded cavity, up to 21.8 W of deep blue laser emission at 457 nm is achieved. The optical-to-optical conversion efficiency is greater than 36.3%, and the power stability in 8 h is better than 2.36%.

EXPERIMENTAL SETUP

A schematic of the intracavity deep blue laser is shown in Fig.1. The pump sources are two laser diode arrays which used at both end of the laser crystal. And one of the pump sources is a 30 W 808 nm fiber-coupled LDA 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 tempera-

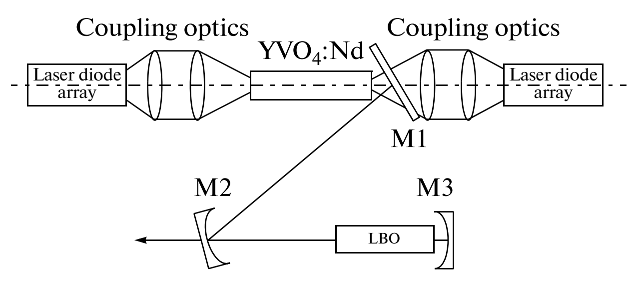

Fig. 1. The schematic for the intracavity frequency-doubled 457 nm YVO_4:Nd/LBO deep blue laser.

ture and can be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The coupling optics consists of two identical plano-convex lenses with focal lengths of 15 mm used to reimage 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 × 3 × 15 mm, 0.2% Nd^{3+} doped YVO_4:Nd. It is wrapped with indium foil and mounted in the copper heat sink. The left side of the laser crystal is coated with antireflection films at the pump wavelength and 1064 nm ($R < 2\%$), and with high reflection films 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 YVO_4:Nd, about 60% of pump power is absorbed. The temperature of the laser crystal is kept at a constant of 15°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 YVO_4:Nd spectral line of 914 nm. The right side of the laser crystal is antireflection coated at 808 nm, 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. The left side of the plane mirror M1 is AR coated at 808 nm, 1064 nm, and 1342 nm and HR coated at 914 nm. The other side of M1 is AR coated at 808 nm. The concave facet of the M3 is HR coated at 914 nm and 457 nm. The plano-concave mirror M2 is the output mirror and the concave face is HR coated at 914 nm and AR coated at 457 nm. The plane facet of M2 is AR coated at 457 nm. When the coating requirements on the both sides of the YVO_4:Nd and the mirrors are satisfied, the 914 nm spectral line could oscillate independently. 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 × 2 × 20 mm^3 nonlinear crystal ($\theta = 90°$, $\varphi = 21.7°$). Although $KNbO_3$ and BIBO have high nonlinearity, LBO is selected as the frequency doubling material in our experiment for its small walk-off angle and large spectral and angular acceptance bandwidth. 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.

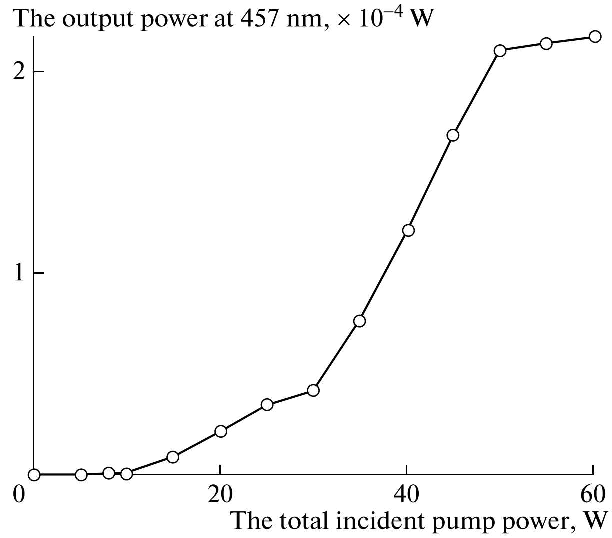

Fig. 2. The output power at 457 nm versus the total incident pump power.

RESULTS

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 SHG experiment, a 20 mm LBO is inserted into the cavity close to the end mirror M3. The deep blue laser output power versus the incident pump power is shown in Fig. 2. The threshold of the blue laser is about 8 W, with the total incident pump power of 60 W, corresponding to an output power of 21.8 W at 457 nm.

The reason for the step response in Fig. 2 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 2.23 and 2.65 in X and Y directions respectively measured by knife-edge technique. The asymmetry of the M^2 factor in two directions is result from the walk-off between the fundamental wave and the second in direction of LBO. Figure 3 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. 3 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 2.36% in 8 h. The chaotic blue-noise state is also stable when the environment is 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 YVO_4:Nd crystal and the function of

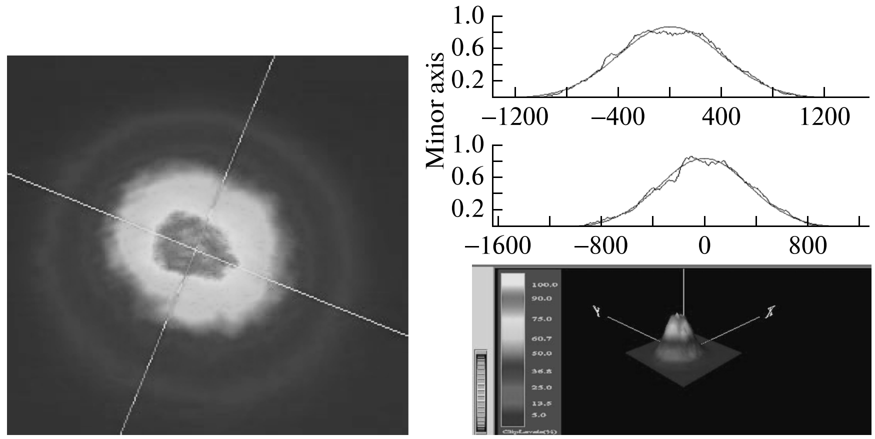

Fig. 3. The beam profile distribution of 457 nm blue laser.

LBO as a polarizer influence the noise state of the 457 nm blue laser. YVO_4:Nd 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 [8], 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 YAG:Nd crystal, the larger thermal conductivity of YVO_4:Nd 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. The YVO_4:Nd crystal has a broad gain line width, 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.

CONCLUSIONS

An efficient, compact LD-pumped deep blue laser has been demonstrated by using YVO_4:Nd 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 dual end pump configurations at total incident pump power of 60 W, as high as 21.8 W of CW output power at 457 nm is achieved with 20-mm-long LBO. The optical-to-optical conversion efficiency is up to 36.3%, and the power stability in 8 h is better than 2.36%.

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