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Optics Communications 258 (2006) 67–71
OPTICS COMMUNICATIONS
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Compact efficient 1.5 W continuous wave $Nd:YVO_4/LBO$ blue laser at 457 nm

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Received 23 March 2005; received in revised form 21 June 2005; accepted 25 July 2005

Abstract

A compact folded three-mirror cavity with length of 100 mm is optimized to obtain high efficient 457 nm laser. When the incident pump power into $Nd:YVO_4$ is 16.3 W, as high as 1.52 W continuous wave 457 nm blue laser is achieved by LBO intracavity frequency doubled. The optical-to-optical conversion efficiency is greater than 9.3%.

Keywords: Blue light; $Nd:YVO_4$; Intracavity doubling; Solid-state laser

1. Introduction

Several applications such as laser display, spectroscopy and underwater communication require multiwatt power level in the blue region of the visible spectrum. Blue laser diode (LD) has been developed, but its output power is limited to tens of milliwatts level. As a natural replacement for relatively inefficient 488 nm Ar ion high power laser, LD pumped all solid-state blue lasers are flourishing.

After Fan and Byer [1] first introduced LD pumped quasi-three-level 946 nm Nd:YAG laser at room temperature in 1987, the 473 nm blue light produced by intracavity second harmonic generation was extensively studied [2–9]. To our best knowledge, the highest cw output power achieved from such a laser so far has been 2.8 W at 473 nm by intracavity frequency doubled Nd:YAG/BIBO laser [2]. A Z-cavity as long as near 1 m is used in this system. In order to obtain the deeper blue spectrum region such as below 460 nm, two kinds of promising candidates $Nd:YVO_4$ and $Nd:GdVO_4$ are chosen. Using the same resonator structure as 2.8 W blue laser at 473 nm, the Nd:YAG and BIBO are replaced by $Nd:GdVO_4$ and LBO, respectively,

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2005.07.061

840 mW output power at 456 nm is obtained [3]. Cw output power of 3 W at 914 nm is reported by LD pumped N:YVO_4 [4]. The corresponding 457 nm blue laser produced by intracavity doubled frequency is available commercially for 400 mW of output power [10]. However, there are few papers about high power all solid-state blue laser at 457 nm based on Nd:YVO_4.

In this work, a compact folded three-mirror resonator is carefully designed. The length of the cavity is about 100 mm. Compact efficient cw 457 nm blue laser is achieved based on LD pumped N:YVO_4 and intracavity doubled frequency by LBO. With an incident pump power of 16.3 W, the laser produces up to 1.52 W blue laser at 457 nm. The optical–optical conversion efficiency is greater than 9.3%.

2. Experimental setup

The layout of the compact intracavity doubled Nd:YVO_4/LBO blue laser at 457 nm is shown in Fig. 1. The pump source is a 20 W 808 nm fiber-coupled laser diode array (LDA) with a core diameter of 400 μm and a number aperture of 0.22 for cw pumping. Its emission center wavelength is 808.2 nm at 25 °C and can be tuned by changing the temperature of the heat sink to meet the best absorption of the laser crystal. Coupling optics consists of two identical plano-convex lenses with focal length of 10 mm to re-image the pump beam into the laser crystal with ratio of 1:1. The coupling efficiency is 98%. For the reason of pump intensity being big enough in the pump spot regions, the first lens must be adjusted well to collimate the pump beam because it will affect the focus spot seriously. However, the distance between the two lenses can be adjusted according to the experiments freely. For the aberration, the average pump spot radius ω_p is around 220 μm. The laser crystal is an a-cut 0.1 at.%-doped Nd:$^{3+}$, 5 mm long Nd:YVO_4 with antireflection coating at 808 nm ($R < 2\%$) and high-reflection coating at 914 nm ($R > 99.9\%$) on the left side acting as one mirror (M_1) of the cavity. Low doped and long laser crystal is favorable to reduce thermal lens and the re-absorption of quasi-three-level, while guaranteeing to absorb enough pump energy. When the pump wavelength is tuned to mach the absorption peak of the Nd:YVO_4, pump power of 53% is absorbed. The crystal is wrapped with indium foil, mounted in a copper holder and cooled through the resonator base plate, which is kept at a constant temperature of 15 °C by a thermo-electric cooler favorable to yield a small thermal population of the terminal laser level and the stability of the output power. Lower temperature is essential to obtain efficient operation of spectrum line of Nd:YVO_4 914 nm. When the coating requirements on the left side of Nd:YVO_4 are satisfied, measurement curve of the coating film indicates that reflections at 1064 and 1342 nm are 87% and 30%, respectively. The right side of the laser crystal is antireflection coated at 914, 1064 and 1342 nm to reduce loss of the resonating 914 nm light and suppress the strong 1064 and 1342 nm lines which can oscillate parasitically with the left side. The remaining reflection is less than 0.2%.

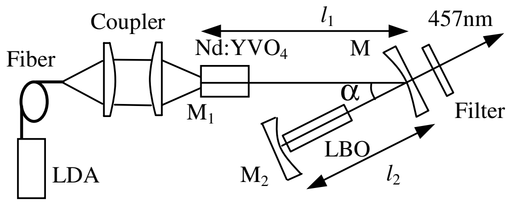

Fig. 1. Compact folded three-mirror cavity setup for the intracavity frequency doubled Nd:YVO_4/LBO blue laser at 457 nm.

Type I critical phase-matching 10 mm long LBO non-linear crystal ($\theta = 90°$, $\phi = 21.7°$ at 300 K) is used to double frequency 914 nm in the resonator. A folded plano-concave mirror (M) with small curvature of radius ($R = 50$ mm) is adopted to reduce the length of the system. The concave surface is high reflection coated at 914 nm ($R > 99.9\%$) and high transmission coated at 457 nm ($T > 96\%$), 1064 nm ($T > 90\%$) and 1342 nm ($T > 85\%$). The requirements of coating film for plane surface are the same as the right side of Nd:YVO_4, except high transmission at 457 nm. The end mirror (M_2) with the curvature of radius 300 mm is high reflection coated at 914 ($R > 99.9\%$) and 457 nm ($R > 99\%$), which double reflection the second harmonic wave.

Two arms constitute the folded three-mirror resonator. One is collimating arm ($l_1 = 69$ mm) which has a larger beam radius (ω_1) in the middle of Nd:YVO$_4$ and the other is focusing arm ($l_2 = 35$ mm) which has a smaller beam waist radius (ω_{02}) in LBO. The physical lengths of the two arms are $L_1 = l_1 - (l_{Nd} - l_{Nd}/n_e) \approx 66$ mm and $L_2 = l_2 - (l_{LBO} - l_{LBO}/n_o) \approx 31$ mm, respectively. Where l_{Nd} and l_{LBO} are the geometric lengths of Nd:YVO$_4$ and LBO. $n_e = 2.175$ and $n_o = 1.608$ are refractive indexes of extraordinary ray in Nd:YVO$_4$ and ordinary ray in LBO. When the mechanical structures are satisfied, the beam incident angle (α/2) upon the folded mirror is set as small as possible ($\approx$5°) to reduce the astigmatism without additional optical stigmatism compensating elements.

For a fiber-coupled laser diode array, the thermal-lens power is given by Chen et al. [11]. When the pump power is 16.3 W, the thermal-lens focal length is estimated 400 mm equivalent to a curvature mirror (R_1) with same numerical value on the end of the cavity [12]. Note that geometrical length of the cavity must be replaced by physical length for the lengths of the crystals can be compared to the compact cavity length. The beam radius (ω_1) on this mirror (M_1) is corresponding to that in the middle of Nd:YVO$_4$ assuming the thermal-lens is a thin lens. Because beam quality factor M^2 of real laser is usually greater than 1, ABCD matrix formalism including M^2 [13] (assuming 2) is introduced to study the dynamic operation of the compact folded three-mirror resonator.

As shown in Fig. 2, beam radii in the middle of Nd:YVO$_4$ and LBO are nearly constant in a broad region of thermal-lens focus length from infinity down to 100 mm (1000 mm to infinity is not drawn). So it is not necessary to realign the cavity while increasing the pump power from 0 to 16 W or even higher. As the α is very small, the differences between tangential and sagittal beam radii in Nd:YVO$_4$ and LBO are only 2 and 0.5 μm, respectively. The tolerances of the compact cavity are simulated in the same way. The results are shown in Fig. 3. One can conclude that the length of the first arm has little effect on the parameters of cavity mode; however, they are very sensitive to the length of the second arm, especially effect on ω_1. ±1 mm Changing of the second arm will decrease or increase 10 μm of in radius. Therefore,

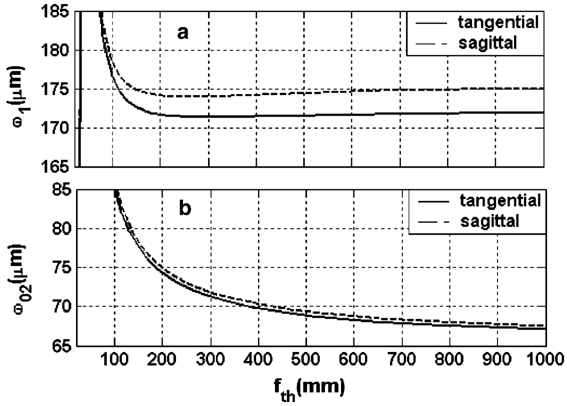

Fig. 2. Tangential and sagittal beam radii in Nd:YVO$_4$ and LBO as a function of thermal-lens focal length (assuming $M^2 = 2$).

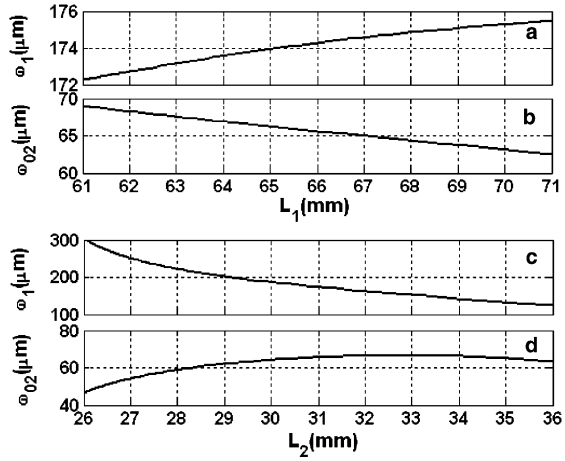

Fig. 3. Average beam radii in Nd:YVO$_4$ and LBO as a function of the physical length of two arms (assuming $M^2 = 2$ and ignoring astigmatism).

attention must pay to adjust the second arm in the experiments.

3. Results and discussion

Fig. 4 shows the output results of 457 nm obtained with a 20 W fiber-coupled laser diode array. There are two main characteristics about the output power as a function of input pump power. The first is high lasing threshold (10.4 W) and the second is that there is a turning point

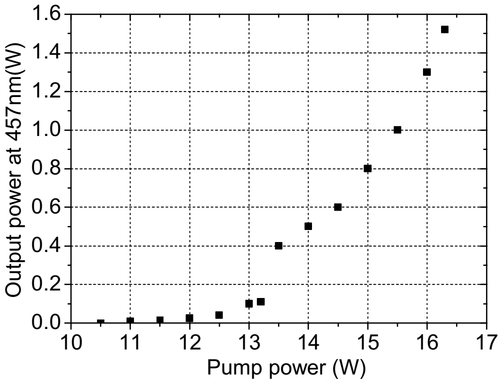

Fig. 4. The output power at 457 nm as a function of the pump power at 808 nm.

(13.5 W) where the 457 nm output power rises rapidly from tens of milliwatts to hundreds of milliwatts. The reasons for these characteristics are all attribute to the saturation of re-absorption loss of the quasi-three-level for fundamental wave 914 nm. At lower pump power, lower circulating intensity exists in the cavity and the corresponding high re-absorption loss leads to high threshold. As the pump power increasing, the circulating intensity becomes so high that it bleaches the re-absorption loss and the output power increases suddenly at this point. The laser will operate like four-level system after this turning point for the re-absorption loss is approaching zero [4]. When the pump power incident into Nd:YVO_4 is 16.3 W, the output power is measured by filtering infrared 808 and 914 nm light, as high as 1.52 W blue laser is achieved. The optical-to-optical conversion efficiency is greater than 9.3%.

Stability of better than 3% for an hour is measured by FieldMaster-GS power meter as shown in Fig. 5.

However, as shown in Fig. 6, the noise of the 457 nm blue laser is observed with a Si fast photodiode by filtered fundamental wave and pump light and attenuated by neutral filter. This is due to cross saturation in the laser crystal and sum-frequency in the doubling frequency crystal [14]. In our experiments, because no ways (such as changing the polarization state of 914 nm or forcing operation of single frequency) are adopted to overcome this problem, the noise is always observed

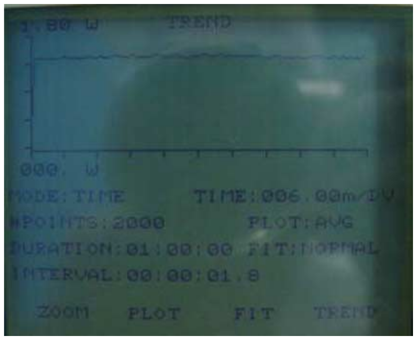

Fig. 5. Stability of blue laser for an hour. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

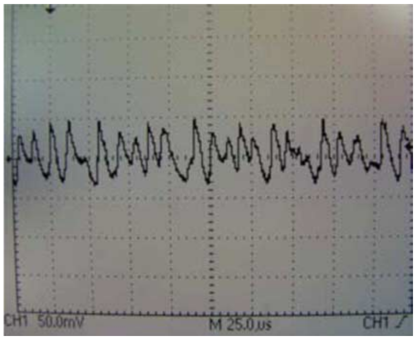

Fig. 6. Fluctuations of 457 nm blue laser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

except very short time stability on the starting of the laser for longitudinal mode competing.

The system emits nearly TEM_{00} mode with beam quality factor $M^2 \approx 2.2$ measured by the

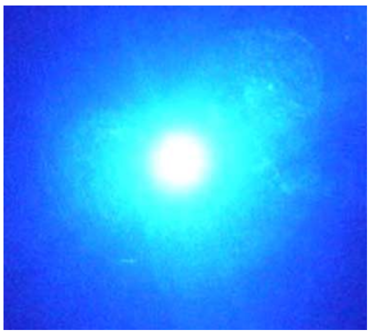

Fig. 7. The beam shape of 457 nm blue laser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

knife-edge technique [15], which is consistent with the analysis of the resonator. Fig. 7 shows the shape of 457 nm blue laser beam at pump power of 16.3 W.

4. Conclusion

In summary, a compact efficient continuous wave end pumped Nd:YVO_4/LBO blue laser at 457 nm is demonstrated successfully. A folded three-mirror cavity with about length of 100 mm is optimized to obtain high efficient blue laser. When the incident power into Nd:YVO_4 is 16.3 W, as high as 1.52 W continuous wave 457 nm blue laser is achieved. The optical-to-optical conversion efficiency is greater than 9.3%.

Acknowledgement

This work is supported by Hi-Tech 863 plan of the PR China.

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