Development of High Power All-Solid-State Red, Green and Blue Lasers

Dafu CUI, Jialin XU, Yong BO, Qianjin CUI, Qinjun PENG, and Zuyan XU

*Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences,
Beijing 100080, China*

(Received January 1, 2008)

The high power all-solid-state red, green and blue lasers have been developed by means of Q-switched diode side-pumped Nd:YAG laser modules and the intracavity nonlinear frequency conversion in the LBO nonlinear crystals. The red laser generates based on the frequency doubled 1.3 μm Nd:YAG transition, and corresponding maximum output power is 64 W. The green output power of 218 W from frequency doubled 1064 nm Nd:YAG transition have been obtained. The blue laser based on the frequency tripled 1.3 μm Nd:YAG transition delivers the output power of 7.6 W. To best of our knowledge, this is the maximum blue output power for the intracavity frequency tripled 1319 nm Nd:YAG laser.

Key Words: All-solid-state laser, High power laser, Red, Green, Blue.

1. Introduction

The high power compact all-solid-state red laser can be used as a source for laser therapy and pumping source for frequency conversion.¹⁻³⁾ The green lasers with high power and high beam quality have in demand for precise material processing, bi-medicine and scientific application as pumping source for parametric oscillations or for fourth harmonic generation of solid-state lasers.⁴⁻⁶⁾ For all-solid-state blue laser sources, there exist numerous applications such as in high-density optical data storage, biological and medical diagnostics, underwater communication or underwater imaging.⁷⁾ Also, the compact high power all-state-solid red-green-blue (RGB) laser system is suitable for large image laser projection systems.⁸⁾

Here we report the high power quasi-continuous wave all-solid-state red, green and blue lasers. The red and green lights are generated by means of intracavity frequency doubled diode side-pumped 1064 nm and 1.3 μm Nd:YAG lasers with a LBO nonlinear crystal, respectively. The blue laser is generated based on the diode side-pumped intracavity frequency tripled 1.3 μm Nd:YAG laser with two LBO nonlinear crystals. Here, one LBO is for the second harmonic generation and other LBO crystal is for third harmonic generation. The maximum output power of the red laser is 64 W at 808 nm LD pump power of 650 W. The green laser reaches up to the output power of 218 W at pump power of 930 W and the blue laser with the output power of 7.6 W have been obtained at the pump power of 480 W.

2. Experiment and results

The high power all-solid-state quasi-continuous wave red, green and green lasers are generated by means of the acousto-optic Q-switched diode side-pumped Nd:YAG laser modules and intracavity nonlinear frequency conversion in the LBO nonlinear crystals. The acousto-optic Q-switch has an active aperture of 5 mm, and their RF power is up to 100 W. Pulsed operation is necessary for efficient of the intracavity frequency conversion. The high efficiency laser module

consists of a Nd:YAG rod with Nd³⁺ doping concentration of 0.6 at.% and five-fold symmetry diode arrays. Each array contains six 20 W continuous-wave diode bars. The diffusive reflector made of gold-filled copper is used for the homogeneous pumping. Figure 1 exhibits the schematic cross section of a diode-side-pumped laser module.

Figure 2 shows a typical fluorescence intensity distribution of a laser module measured with a CCD camera. Obviously, the fluorescence intensity distribution is uniform for our laser module. Effective and uniform pumping of the laser module is important for high average power and high beam quality laser generation. All of nonlinear crystals for second harmonic generation and third harmonic generation are the LBO because of its high optical damage threshold, low absorption at whole fundamental, second harmonic and third harmonic wavelength region, moderate nonlinear coefficients and sufficient birefringence to provide phase matching needed in our experiment. The LBO nonlinear crystal is placed in an oven, whose temperature is maintained by a precise temperature controller to a precision of ± 0.1 K. The beam quality factor M^2 is measured by a laser beam analyzer (Model M²-200, Spiricon, Inc.).

Fig.1 The schematic cross section of a diode-side-pumped Nd:YAG laser module.

Fig.2 Typical fluorescence intensity distribution of the Nd:YAG laser module.

2.1 Red laser

The all-solid-state red laser is generated by using the intracavity frequency doubled 1.3 μm Nd:YAG laser. A L-shaped cavity laser resonator is composed of an acousto-optic Q-switch, two side-pumped Nd:YAG laser module, a quartz 90° polarization rotator and a 4 x 4 x 40 mm³ LBO nonlinear crystal with type-II noncritical phase matching ($\theta = 0^\circ$, $\phi = 0^\circ$) at a temperature of 315.3 K. The LBO crystal was coated dual-wavelength antireflection around 1.3 μm and 660 nm simultaneously. The quartz 90° polarization rotator is placed between two Nd:YAG rods of the laser modules for polarization dependent birefringence compensation.

The red output power as function of the 808 nm LD pump power is shown in Fig.3. The maximum average output power of the red laser is 64 W for the pump power of 650 W at repetition rate of 5 kHz and pulse width of 161 ns. We observe a roll over effect, i.e. output power up to the maximum and then falls with increasing pump power because of the Nd:YAG rods thermal effect.

As well known, 1.3 μm Nd:YAG laser radiation contains two fundamental wavelengths. One is the $R_2 \rightarrow X_1$ transition at the wavelength of 1.319 μm and the other is the $R_2 \rightarrow X_3$ transition at the wavelength of 1.338 μm . Their effective

Fig.3 The red output power as function of the 808 nm LD pump power.

Fig.4 The single red spectrum at 659.5 nm is obtained at pump power of 500 W.

stimulated emission cross section is nearly same, which is one third of the $R_2 \rightarrow Y_3$ transition for the wavelength of 1.064 μm . Therefore, the red light obtained by using the frequency doubled 1.3 μm Nd:YAG laser includes both 659.5 nm and 669 nm wavelengths while without wavelength selection element is employed.

Also, we have demonstrated the single wavelength 659.5 nm red light by using one side-pumped Nd:YAG laser module, and a etalon is inserted in the cavity in order to suppress the Nd:YAG laser 1.338 nm oscillation. The etalon was made of polished thin YAG without coating. YAG material, not silica, is selected because of its high refractive-index and perfect laser performance. It can improve the transmission difference between 1.319 μm and 1.338 μm from 12% to 28% than silica etalon. The insertion loss for the etalon at 1.319 μm has been calculated to be less than 0.1%.

We have measured the spectrum distribution of the red light by using Avantes mini fiber spectrum meter AvaSpec2048 with resolution power of 0.5 nm. Under pump power of 500 W, only single red spectrum at 659.5 nm can be seen as shown in Fig 4. The average output power of 28 W at 659.5 nm with beam quality factor of $M^2=22$ is obtained for the pump power of 500W at repetition rate of 5 kHz and pulse width of 250 ns.⁹⁾

2.2 Green laser

High power green laser can be achieved by external frequency doubling or intracavity frequency doubling a Q-switched Nd:YAG laser. In general, the former has better beam quality but its laser system is complicated. The later is simple and has higher conversion efficiency. In recent years, many more than 100-W intracavity-frequency-doubled green lasers have been developed. Also, more than 200-W intracavity- frequency-doubled green laser obtained; however, the green beam exported out of two directions and the beam quality was not reported.

Here, a 218 W all-solid-state 532 nm green laser is obtained with Q-switched intracavity frequency doubled 1064 nm Nd:YAG laser based on a LBO nonlinear crystal. A thermally near-unstable resonator with two Nd:YAG rods in a L-shaped flat-flat cavity with a total length of 1050 mm is designed for the high output power and high beam quality. As same as the red laser system, a quartz 90° polarization rotator is placed between two Nd:YAG rods of the laser modules for

Fig.5 Calculated fundamental mode radius ω_0 at the center of rods as the functions of the pump power.

polarization dependent birefringence compensation. Two orthogonal acousto-optic Q-switches are used to sustain fully holding off the laser gain in order to keep the pulse operation under high pump power. A type II phase-matched $5 \times 5 \times 20$ mm³ LBO ($\theta = 27.20^\circ$, $\phi = 90^\circ$) a temperature of 373 K is employed for the second harmonic generation. The LBO crystal was coated dual-wavelength antireflection at 1064 nm and 532 nm, simultaneously.

To achieve high power and high beam quality green laser, a thermally near-unstable resonator is used. In a thermally near-unstable resonator, the laser operates near the unstable region at the border of the thermally stable zones. The flat-flat cavity used in our experimental acts as a unstable resonator, which leads to more diffraction loss for high order transverse modes and the fundamental mode size at the gain medium is large. Then, both high beam quality and high average output power can be expected.¹⁰⁾

Figure 5 illustrates the dependence of the fundamental mode radius ω_0 at the center of the rods on the pump power. The fundamental mode radius is calculated by using the standard ABCD ray propagation matrix as the function of the thermal lens focal length for the diode-pumped Nd:YAG rod. The dependence of the thermal lens focal length of the rod on the pump power is experimentally confirmed with the unstable-resonator method.

Figure 6 shows the dependence of 532nm green output power versus the 808 nm diode pump power. The maximum average output power of the green laser reaches 218 W with pulse width of 86 ns and repetition rate of 12.5 kHz under pump power of 930 W, which operates just at the border of the thermally stable zones as seen in Fig.5. The measured green beam quality factor is $M^2 = 6.2$ at output power of 120 W¹¹⁾ and $M^2=20.2$ at output power of 218 W, respectively. To our knowledge, those beam quality is best results for hundred W level all-state-solid 532 nm green lasers with intracavity frequency doubling.

2.3. Blue laser

Power levels up to 2.8 W have previously been achieved for blue lasers based on frequency doubling of a neodymium laser, but are limited to lower power levels due to considerable reabsorption and thermal losses. Power levels up to 10.1 W have been reported by frequency doubling of tunable lasers in

Fig.6 The 532 nm green output power as function of the LD pump power.

the near-IR region or by blue lasers produced directly through optical parametric oscillators (OPOs); however, these lasers are expensive and often too complicated for routine operation. Here, a simpler blue laser has been developed, that is based on frequency tripling of a compact Nd:YAG 1319 nm diode-pumped solid-state laser.

The all-solid-state blue laser is performed by using Q-switched intracavity frequency tripled 1319 nm Nd:YAG laser. Figure 7 depicts the typical experiment configuration for the blue generation.

The laser resonator is composed of four mirrors, a acousto-optic Q-switch, two side-pumped Nd:YAG laser modules, a quartz 90° rotator, a thin YAG etalon, a Brewster plane and two LBO nonlinear crystals. Here, one LBO crystal is for the second harmonic generation, which was cut into a $4 \times 4 \times 20$ mm³ with type I phase matching ($\theta = 84^\circ$, $\phi = 0^\circ$) at a temperature of 330 K. Other LBO crystal is for third harmonic generation, which was cut into a $4 \times 4 \times 40$ mm³ with type-II noncritical phase matching ($\theta = 0^\circ$, $\phi = 0^\circ$) at a temperature of 433.1 K. Both LBO crystals were coated three-wavelength antireflection around 1.3 μ m, 660 nm and 440 nm, respectively.

In order to reach optimum second harmonic generation and

Fig.7 The schematic drawing of the experiment arrangement for the blue laser : M1 is the plane cavity mirror; M2,M3,M4, the concave mirrors; AO-QS, the acousto-optic Q-switch; Rotator, the quartz 90° polarization rotator; P, the Brewster plane; SHG-LBO, the nonlinear crystal for second harmonic generation; THG-LBO, the nonlinear crystal for third harmonic generation.

Fig.8. The 439.7 nm blue output power as function of the LD pump power.

third harmonic generation simultaneously, a special Z-type resonator, which has two focuses, was designed. Because Nd:YAG is an isotropic laser medium and emits unpolarized radiation, it is necessary to polarize the laser beam with a Brewster plane in order to meet the phase matching for maximize frequency conversion efficiency.

The LBO crystals are set close to those focuses, respectively. In the first LBO crystal (named as SHG-LBO in Fig. 7), some fraction of the fundamental radiation at 1319 nm is converted to the second harmonic radiation at 659.5 nm. In another LBO crystal (named as THG-LBO in Fig.7), unconverted fundamental radiation is mixed with second harmonic to produce the third harmonic blue light at 439.7 nm. The conversion efficiency and the stability of the blue laser output power are both improved through the suppression of 1338 nm Nd:YAG laser operation by means of the YAG etalon.

Experimentally, we measured the 439.7 nm blue output power by a laser meter (Ophir F300A). Figure 8 shows the blue output power as function of the 808 nm LD pump power. The blue output started at a pumping power around 170 W. The blue laser delivers output power of 7.6 W at diode pump power of 480 W with the repetition rate of 5 kHz and pulse width of 170 ns. The slope efficiency is about 2.1%. To best of our knowledge, this is the maximum blue output power for the intracavity frequency tripled 1319 nm Nd:YAG laser.

We have measured the spectrum distribution of the blue light by using Avantes mini fiber spectrum meter AvaSpec2048 with resolution power of 0.5 nm. Under pump power of 480 W, the spectrum only shows a single blue line at 439.7 nm.

The far field intensity distribution of the 439.7 nm blue beam is exhibited in Fig.9, and the corresponding beam quality factor is measured to be $M^2 = 12$ for both horizontal and vertical directions. At a lower output, the beam quality becomes better. For example, under an output power of 3 W, the value of M^2 is reduced to about 8. The long-term power fluctuation is less than 1% at output power of 6 W.^[2]

3. Conclusions

The high power all-solid-state red and green lasers are developed by means of intracavity frequency doubled 1064nm Nd:YAG laser and 1.3μm Nd:YAG laser in the LBO nonlinear

Fig.9 The far field intensity distribution of 439.7 nm blue beam.

crystals with type-II phase matching and type-II noncritical phase matching, respectively. The high power all-solid-state blue light is generated based on the intracavity frequency tripled 1.3 μm Nd:YAG laser with two LBO nonlinear crystals, one LBO is for the second harmonic generation with type I phase matching and other LBO crystal is for third harmonic generation with type-II noncritical phase matching. The maximum average output power of the red laser reach 64W at 808 nm diode pump power of 650 W. The green laser output power is up to 218 W at pump power of 930 W. The blue laser delivers the power of 7.6W at pump power of 480 W. To best of our knowledge, this is the maximum blue output power for the intracavity frequency tripled 1319 nm Nd:YAG laser.

Acknowledgment

This work was supported by the State Key Program for Basic Research of China, the National High Technology Research and Development Program of China, the National Natural Science Foundation of China, and the Knowledge Innovation program of Chinese Academy of Sciences.

References

- 1) Z. Sun, R. Li, Y. Bi, X. Yang, Y. Bo, Y. Zhang, G. Wang, W. Zhao, H. Zhang, W. Hou, D. Cui, and Z. Xu; Opt. Commun. **241** (2004) 167.
- 2) A. Yao, W. Hou, X. Lin, Y. Bi, R. Li, D. Cui and Z. Xu; Opt. Commun. **231** (2004) 413.
- 3) C. Du, S. Ruan, Y. Yu and F. Zeng, Opt. Express **13** (2005) 2013.
- 4) J. Golden: Laser Focus world **28** (1992) 75.
- 5) S. Konno, H.J. Moon and J. Lee: Opt. Lett. **25** (2000) 105.
- 6) H. Li, H. Zhang, Z. Bao, J. Zhang, Z. Sun, Y. Kong, Y. Bi, X. Lin, A. Y. Yao, G. Wang, W. Hou, R. Li, D. Cui and Z. Xu: Opt. Commun. **232** (2004) 411.
- 7) S. Bjurshagen, D. Evekull and R. Koch: Appl. Phys. B **76** (2003) 135.
- 8) Z. Xu and Y. Bi: Proc. SPIE. **5632** (2005) 115.
- 9) H. Peng, W. Hou, Y. Chen, D. Cui, Z. Xue, C. Chen, F. Fan and Y. Zhou: Opt. Express **14** (2006) 3961.
- 10) Y. Feng, Y. Bi, Z. Xu, and G. Zhang: Proc. SPIE **4969** (2003) 227.
- 11) Y. Bo, A. Geng, Y. Bi, Z. Sun, X. Yang, Q. Peng, H. Li, R. Li, D. Cui and Z. Xu: Appl. Opt. **45** (2006) 2499.
- 12) H. Peng, W. Hou, Y. Chen, D. Cui, Z. Xu, C. Chen, F. Fan and Y. Zhou: Opt. Express **14** (2006) 6543.