Generation of 4.3-W coherent blue light by frequency-tripling of a side-pumped Nd:YAG laser in LBO crystals

Zhipei Sun, Ruining Li, Yong Bi, Xiaodong Yang, Yong Bo, Wei Hou, Xuechun Lin, Hongbo Zhang, Dafu Cui, Zuyan Xu

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

Zhipei Sun, Yong Bi, Xiaodong Yang, Xuechun Lin
Graduate School of the Chinese Academy of Sciences, Beijing 100080, China

Abstract: High average power nanosecond pulsed light is obtained using a compact all solid state Nd:YAG laser. The laser is operated in Q-switched mode at the 1.3 micron fundamental and internally frequency tripled using two LiB₃O₅ (LBO) crystals. 4.3 W average power at 440 nm was demonstrated at 3.5 kHz and a pulse width of 150±10 ns (FWHM). The beam quality of M² value is 5±1 in both dimensions. The short-term average power stability of the light source is better than 5.6%. Spectral selecting is proposed to increase production efficiency at 440 nm.

©2004 Optical Society of America

OCIS codes: (140.3480) Lasers diode-pumped; (140.3580) Lasers, solid-state; (140.7300) Visible lasers; (190.2620) Frequency conversion.

References and links

1. Introduction

High power blue light is urgently desired for many applications, such as optical data storage, communications, spectroscopy, large image projection and medical applications. For such applications, the high power blue light source must be compact, have a high electrical to optical efficiency and have a long and reliable operational life. A diode pumped solid state blue laser is a promising path to such a blue light source.

The technologies to obtain low-power solid-state blue laser (power of 200 mW and below) are discussed in Ref. [1]. Presently, there are several ways to get high power diode-pumped solid-state laser system in the blue spectral region (power of 1 W and above): 1. Frequency-doubling of the diode-pumped quasi-three-level Nd³⁺ Laser operated on the 4F3/2→4I9/2 transition [2-5]; 2. Tunable output produced directly by optical parametric oscillators (OPOs) or by frequency-doubling of all-solid-state tunable laser system in the near-infrared spectral region, such as OPOs pumped by the all-solid-state laser [6-9]. The first way is the efficient one to get watt level blue laser output currently, however the output of laser oscillated on the 4F3/2→4I 9/2 transition is limited because of the considerable reabsorption loss due to thermal population at the lower level caused by the quasi-three-level operation. Hitherto, the highest output power reported of a blue light was merely 2.8 W by method 1 [5]. The second method potentially represents the most tunable and flexible solution, but it is often too complicated for routine operation. Picosecond blue light at 462 nm with output power up to 5 W has been generated by a LBO OPO synchronously pumped by the third harmonic of a continuous wave diode-pumped mode-locked Nd:YVO₄ oscillator-amplifier system [6].

Frequency-tripling of diode-pumped solid-state laser operated at 1.3-µm is a possible way to obtain high power blue radiation. Ref. [11] and Ref.12 show that the blue light can be obtained by the way efficiently with their experiments using picosecond lasers at 1.3-µm and the periodically poled nonlinear crystals [10-11]. However the highest output power published in the blue by this way so far was limited to 1 watt.

In this paper, we demonstrated a significant improvement in the generation of the high power blue light by frequency tripling inside a compact and simple diode-pumped solid-state Nd:YAG laser operated at 1.3-µm, yielding 4.3-W blue light at 440 nm with high beam quality (M²=5±1). It was the first demonstration to experimentally demonstrate high power nanosecond blue light obtained by frequency-tripling of 1.3-µm laser. To the best of our knowledge, the blue laser reported in this paper has the highest output power among the all-solid-state nanosecond blue lasers reported.

2. Experimental setup

The experimental arrangement of the system is illustrated in Fig. 1. The laser system in our experimental study contains two identical diode-pumped Nd:YAG laser modules in a folded-mirror resonator designed to oscillate at 1.3 µm. The resonator depicted in the figure is a three-mirror design, in which the reflection losses can be kept much smaller [12]. This cavity provides a tight intracavity focus. It is valuable for frequency conversion. The flat mirror 1 (M1) was coated for high reflection at 1319 nm and 659.4 nm. The 300-mm radius of curvature concave mirror 2 (M2) is an output coupler for 440 nm, with high transmission at 440 nm (T₄₄₀nm≈75%) and high reflection for 1319 nm and 659.4 nm (T₁₃₁₉nm≈0.1%, T₆₅₉nm≈0.3%). The 300-mm radius of curvature concave mirror 3 (M3) was coated for high reflection at 1319 nm, 659.4 nm and 440 nm (T₁₃₁₉nm=0.01%, T₆₅₉nm=0.2%, T₄₄₀nm= 0.01%). The coatings of the three mirrors and the Nd:YAG have the transmissions greater than 60% at 1064 nm. The high transmission at 1064 nm for the components is necessary since the gain of the oscillation line at 1064 nm is much higher than that at 1319 nm. The highly wavelength-selective dielectric coatings suppress the laser oscillation at the strongest transition at 1064 nm and provide optimum conditions at 1319 nm. Each face of the elements in the cavity was coated for high transmission at 1319 nm, 659.4 nm and 440 nm to minimize insertion losses.

In order to compensate the thermal birefringence thus to improve the output power and beam quality, a quartz 90° polarization rotator at 1319 nm was inserted between the two
identical laser modules [13]. With this technique, the radial and tangential components of the polarizations are exchanged between two identical laser rods to achieve equal phase retardation in the cross-section along the entire Nd:YAG rods. An acousto-optic modulator with high diffraction loss at 1319 nm was used for Q switching to generate the repetition rate of 3.5 kHz. Pulsed operation was necessary for efficient operation of the intracavity nonlinear crystals. Because Nd:YAG is an isotropic laser medium and emits unpolarized radiation, it was also necessary to polarize the cavity with a Brewster plate in order to maximize frequency conversion in our experiment.

![Diagram](image)

Fig. 1. The schematic drawings of the experimental arrangement: M1, plane cavity mirror; M2, M3, 300-mm radius of curvature concave mirrors; AO-Q switch, acousto-optic Q switch; Quartz rotator, quartz 90° polarization rotator; P, Brewster plate; SHG-LBO, LBO for second harmonic generation; THG-LBO, LBO for third harmonic generation.

The Nd:YAG rod is surrounded by a flow tube and a circular reflector. Pump light from the diodes is coupled into the Nd:YAG rod directly. From the design standpoint, this is a simple and compact approach to couple the radiation emitted from the laser diodes to the Nd:YAG rod without any other auxiliary beam shaping techniques and imaging optics. But it is not a very high effective way with about 15% pump light lost. The Nd:YAG rod in each module has a diameter of 3 mm and 80 mm in length. It is doped with 1% of Nd$^{3+}$. The YAG host is hard, of good optical quality and has a high thermal conductivity. In addition, Nd:YAG has a relative strong transition at 1.3 µm. To reach the maximal overlap of the pump energy volume with the volume occupied by a low-order resonator mode, the pump energy distribution within the gain medium has been optimized through the geometric parameters of our pump configuration according to the design of our folded 3-mirror cavity. The pump energy distribution matched maximally with the oscillation beam profile helps to increase the gain extraction in the medium and the beam quality of the output laser [14].

Two LBO crystals are used as the nonlinear crystals for intracavity frequency conversion in the experiment. One is for the SHG, which was cut into 3×4×20 mm$^3$ with type-I phase matching SHG ($\theta=84^\circ \phi=0^\circ$); the other is cut into 4×4×40 mm$^3$ for type-$\Pi$ noncritical phase matching THG ($\theta=0^\circ \phi=0^\circ$). The LBO was chosen for its high optical damage threshold, low absorption at both the fundamental, second harmonic and third harmonic outputs, moderate nonlinear coefficients and sufficient birefringence to provide phase matching needed in our experiment. LBO was cut for type-$\Pi$ noncritical phase matching THG in the experiment, which is very valuable to generate high power triple-frequency harmonics. The crystals are placed in their respective ovens, whose temperatures were all maintained by temperature controllers to a precision of ±0.1 K. The LBO crystals are set close to each other near the middle of the folded arm of the resonator, where the beam waist is located based on the design of the cavity, to take the advantage of the strongest power density of the beam in the cavity. In the first LBO crystal (named as SHG-LBO in Fig. 1), some fraction fundamental radiation at 1319 nm is converted to the second harmonic radiation at 659.4 nm. In the other LBO crystal
(named as THG-LBO in Fig. 1), unconverted fundamental radiation is mixed with the second harmonic to produce the third harmonic radiation at 440 nm.

3. Results and discussion

Experimentally, we measured the output power of the blue light as a function of the total pump power of the diodes. Figure 2 shows the THG output power versus the pump power at 808 nm under the repetition rate of 3.5 kHz. The laser started to oscillate at pumping power of approximately 340 W. The slope efficiency is about 2.6%. The maximum average output power of blue light obtained is 4.3 W with the pump power at 480 W. To the best of our knowledge, this experimental result is the highest power reported for an all-solid-state nanosecond blue laser. When we replace the M2 to the same curvature concave mirror coated for high reflection at 1319 nm and high transmission at 660 nm ($T_{1319nm}=0.1\%$, $T_{660nm}=94.4\%$) and tune the temperature of the THG-LBO out of the phase-match value, the maximum power of red light obtained is about 9.35 W.

![Fig. 2. The output power of blue light at 440 nm versus pump diode power](image)

The maximum optical-to-optical efficiency is about 1.1%. Main cause of low efficiency is that two wavelengths can be obtained around 1.3-µm at the same time in the output of a Nd:YAG laser. Besides the R$_2$ to X$_1$ transition (1319 nm) there is probable competition form the R$_2$ to X$_3$ transition (1338 nm) [13]. The coexistence of the two wavelengths is a problem for the generation of high efficiency frequency conversion to get efficient output of blue light. First, the existence of 1338 nm radiation, consuming the energy stored in the Nd:YAG material, reduces the peak power density of 1319 nm radiation in the cavity accordingly, which is disadvantageous for high efficiency frequency doubling of the stronger transition at 1319 nm and high efficiency sum-frequency conversion between the 1319 nm radiation and its second harmonic; Second, the coexistence of the two transitions closely around 1.3-µm generate multi-wavelength red radiation from frequency doubling and sum-frequency between 1319 nm and 1338 nm [15]. The coexistence of multi-wavelength red radiation holds back the efficient frequency tripling. A detailed investigation about the effect of the coexistence of two wavelengths around 1.3-µm in the all-solid laser system on the intracavity frequency-conversion has been published elsewhere [16].

From discussed above, to improve efficiency we need to eliminate the other frequency component of fundamental wave in the cavity. This can be done by inserting a mode-selector such as etalons or dispersive prisms in the cavity [15]. In order to improve the optical efficiency, further investigations are under the way. A higher output is expected.

Other characteristics of the blue light laser were also experimentally studied. The temporal profile of the output blue beam is shown in Fig. 3. The pulse width is about 150±10 ns at the maximum output power. The time trace of the average output power around the 3 W operating
point is shown in Fig. 4. At the average output power level of 3 W, the fluctuation of the blue beam output power was better than 1.0% in the given 20 minutes. While at maximum average output of 4.3 W it was about 5.6% in the same duration. This is consistent with higher mode competition under harder pumping [15-16].

Beam intensity distribution and beam propagation characteristics are very important for many high-precision laser-based applications. At maximum average output of 4.3 W, the $M^2$ value measured by Spiricon beam analyzer is 5±1 in both transverse directions. Far-field intensity distribution of the beam is displayed in the Fig. 5. This good beam quality suggests that we have good matching of the gain region to the low-order resonator modes.
4. Conclusion

In conclusion, a diode-pumped compact and simple Nd:YAG laser system operated at 1.3 μm has been demonstrated with the maximum average output up to 4.3 W in the blue by utilizing two side-pumped laser modules and intracavity frequency-tripling in LBO crystals. Average power fluctuation of less than 5.6% was obtained. At maximum output, the beam quality of $M^2$ value was about 5±1 in both transverse directions.

Acknowledgments

Authors thank the fruitful discussions with Prof. Zhang Jingyuan and acknowledge the referees for their comments. This work was supported by the Knowledge Innovation Programme of the Chinese Academy of Sciences, the National High Technology Research and Development Programme of China under Grant No 2002AA311120, the National Key Basic Research and Development Programme of China under Grant No G1998061413, and the council for Science and Technology of Beijing under Grant No H02042006060110.