Generation of UV radiation at 335.5 nm based on frequency-quadrupling of a diode-pumped Nd:YVO_4 laser

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The generation of ultraviolet (UV) light at 335.5 nm based on frequency quadrupling of a diode-end-pumped Q-switched Nd:YVO_4 laser at 1342 nm was demonstrated. KTP crystal was used for generation of wavelength of 671 nm by intracavity doubling and LBO (BBO) crystal was exploited for the subsequent external fourth harmonic generation (FHG). With 6.3-W absorbed pump power and 10-kHz frequency repetition rate, the UV output power of 35 and 63 mW were obtained by using LBO and BBO as frequency quadrupling nonlinear crystals, respectively. The experimental results show that the conversion efficiency (red-UV) of 6.4% for BBO crystal is higher than that of 3.5% for LBO crystal, but the UV beam quality obtained by LBO crystal is better than by BBO crystal.

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Laser diode pumped all-solid-state ultraviolet (UV) laser emitting in $320-340$ nm spectral region have many applications in many fields such as mold fabrication, photobiology and photomedicine, particularly in various manifestations of fluorescence detection and imaging[1,2]. At present the available coherent sources in this wavelength region are mostly gas lasers such as 325-nm helium-cadmium (He-Cd) laser and 337-nm nitrogen (N_2) laser. However the application of N_2 laser is seriously limited due to the inherently low repetition rate (< 100 Hz), and the available continuous-wave (CW) He-Cd lasers are also impractical for many purposes. Compared with traditional UV gas lasers, all solid-state UV lasers have obvious advantages including long lifetime, high efficiency, high reliability and compactness. Moreover, the operation with high pulse repetition rates (multi-kHz) can be obtained from all-solid-state UV laser. With greater than 50 mW of solid-state UV output, average power is high enough to replace older He-Cd laser technology in photopolymerization applications with a laser that is one-third of the size. However, up to now, in the field of all-solid-state UV laser, more attention focus only on the 355- and 266-nm UV sources based on frequency tripling and frequency quadrupling of 1.06-μm Nd-doped lasers[3−5], few report on 335.5-nm laser has been found. Only Ogilvy *et al.* achieved output of 20 mW at 335.5-nm wavelength using a frequency quadrupled, diode-pumped Nd:YVO_4 laser, in which a LBO crystal was used for intra-cavity second harmonic generation (SHG) and a BBO crystal for fourth harmonic generation (FHG) using a double-pass geometry[6].

In this paper, an efficient all-solid-state UV laser at 335.5 nm is reported. Firstly, the output at 671 nm was obtained by intra-cavity SHG with a KTP crystal in an acousto-optical Q-switched, laser diode pumped Nd:YVO_4 laser. At the absorbed pump power of 6.3 W and the pulse repetition rates of 10 kHz, the average output power was 989 mW and the pulse width was 26 ns. Then a LBO crystal and a BBO crystal were used for the extra-cavity FHG to produce UV output at 335.5 nm. The output powers of 35 mW for LBO crystal and 63 mW for BBO crystal were obtained, respectively. The optical-to-optical conversion efficiencies (red-UV) were 3.5% for LBO crystal and 6.4% for BBO crystal, respectively. Though the average output power for LBO crystal was lower than for BBO crystal, the beam quality was better.

The Nd:YVO_4 crystal has been identified as one of the promising materials for diode-pumped solid-state lasers because of its high absorption over a wide pumping wavelength bandwidth, large stimulated-emission cross section and polarized output[7]. What's more, its emission cross section at 1342 nm is roughly equal to that of the 1064 nm transition in Nd:YAG[8]. These are beneficial to the efficient generation of 1.3-μm emission and its frequency doubling red light at 671 nm. There is a large quantum defect between pump and laser wavelength for 1342-nm generation, the thermal effect in the laser crystal have serious effect on the resonator stability, optimum resonator mode size and the frequency conversion efficiency. For low doping, the reduced absorption coefficient at the pump wavelength permits the deposited heat to be spread along the axis of the laser-crystal, which result in reducing heat load, and consequent thermal lensing[9,10]. So a Nd:YVO_4 crystal with 0.27 at.-% Nd^{3+} concentration as the active medium was chosen to be used.

In our experiment, a cavity setup was presented schematically in Fig. 1. The pump source was a fiber-coupled laser diode with a core diameter of 400 μm and a

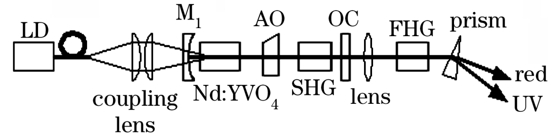

Fig. 1. Experimental setup for 335.5-nm UV generation. LD: laser diode; AO: acousto-optical Q-switch; OC: output coupler; FHG: fourth harmonic generation; SHG: second harmonic generation; M_1: input mirror.

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Table 1. NLO Properties for 335.5 nm Generation (25 °C)

Crystal	PM Type	PM Angle θ, φ (deg.)	d_{eff} (pm/V)	Max Acceptance Angle (mard·cm)	Max Acceptance Bandwidth (cm^{-1}·cm)	Acceptance Temperature Range (K·cm)	Walk off Angle (mard)
LBO	I	90.0 47.8	0.607	2.19 2.19	17.14 17.14	23.73	18.94
BBO	I	$\theta = 35.4$	1.95	0.52 0.52	10.89 10.89	11.91	77.09
	II	$\theta = 52.2$	0.746	6.78 0.53	8.18 24.38	13.52	75.45

numerical aperture of 0.22. The fiber output was focused into the crystal and the pump radius was around 200 μm. The Nd:YVO_4 crystal, with dimension of $4 \times 4 \times 8$ (mm), was mounted in a copper block to keep water-cooling. In order to reduce the cavity loss, both sides of the gain crystal were coated for anti-reflection (AR) at 1342 nm and pumping light at 808 nm($R < 0.2\%$). For efficient frequency conversion process, high peak power and narrow pulse width were necessary. A two-mirror resonator was used to get maximal 671-nm output by using intracavity SHG of the 1342-nm fundamental wave, followed by extra-cavity SHG of the 671 nm to 335.5 nm. The input mirror M_1 was a 500-mm radius-of-curvature concave mirror with AR at the pump wavelength on the entrance face, and with high-reflection coating (HR) at 1342 nm and at 671 nm ($R > 99.8\%$), high-transmission coating (HT) at the pump wavelength ($T > 95\%$) and HT ($T > 80\%$) at 1064 nm on the second surface in order to suppress lasing at 1064-nm transition. The output coupler (OC) was a flat mirror with HR at 1342 nm, HT at 671 nm on the inside surface and with AR at 671 nm on the outside surface. LBO crystal has been identified as one of the excellent nonlinear materials[11−14], but the refractive index of LBO is sensitive to temperature. So an oven was needed for accurate temperature control, it was disadvantageous for shortening the geometrical length of the resonator. A II-type phase matched (PM) KTP crystal ($\theta = 59°$, $\varphi = 0°$) with dimension of $4 \times 4 \times 8$ (mm) was used for 671-nm generation and both sides were coated for AR at 1342 nm and 671 nm. An acousto-optical Q-switch (NEOS) with AR-coated at 1342 nm was inserted into the cavity, the RF power was 50 W and the repetition rate was variable from 1 to 50 kHz. The length of the resonator was 88 mm. In order to enhance the FHG conversion efficiency, the 671-nm light wave was focused into the FHG nonlinear crystal by a lens with the focus length of 50 mm. The major nonlinear optical (NLO) properties of LBO and BBO crystals for FHG at 1342 nm are listed in Table 1. Compared with LBO crystal, BBO for I-type PM exhibits high effective NLO coefficient (d_{eff}), but the walk off angle is several times larger than that of LBO. A comparative study of LBO and BBO crystal for FHG has been conducted in our experiment.

Figure 2 illustrates the average output power of 671 nm at a repetition rate of 10 kHz as a function of absorbed pump power. The maximal average output power of 989 mW was achieved at the absorbed pump power of 6.3 W. The optical-to-optical conversion efficiency with respect to the absorbed pump power was 15.7% and the 671 nm peak power reached 3.53 kW.

Basing on the Table 1, a BBO crystal ($\theta = 35.4°$) with dimension of $4 \times 4 \times 8$ (mm) and a LBO crystal ($\theta = 90°$, $\varphi = 47.8°$) with dimension of $3 \times 3 \times 10$ (mm) were cut for the I-type PM condition. Both crystals were optically polished and both sides of the BBO crystal were coated for AR at 671 nm and 335.5 nm, but the LBO crystal was uncoated. The FHG output powers of BBO and LBO crystals versus 671-nm input power are given in Fig. 3. The maximal average output power at 335.5 nm of 35 mW is obtained with LBO crystal, while the value for BBO crystal is 63 mW.

Figure 4 shows the oscilloscope traces of red and UV pulses at a pulse repetition rate of 10 kHz, in which the red light pulses of 26 ns and UV pulses obtained by BBO and LBO crystal as short as 12 ns can be seen. The

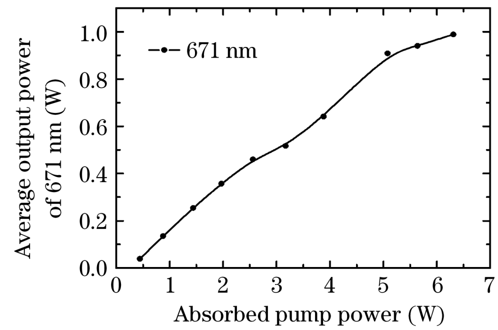

Fig. 2. Average output power of 671 nm as a function of the absorbed pump power at pulse repetition rate of 10 kHz.

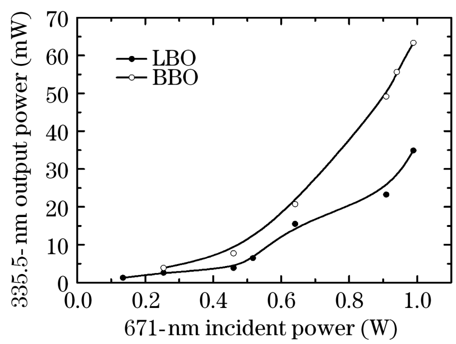

Fig. 3. Dependence of the relative output powers at 335.5 nm on the 671-nm incident power for BBO and LBO crystals.

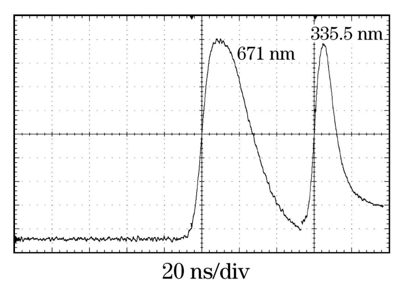

Fig. 4. Pulse profiles of red and UV laser.

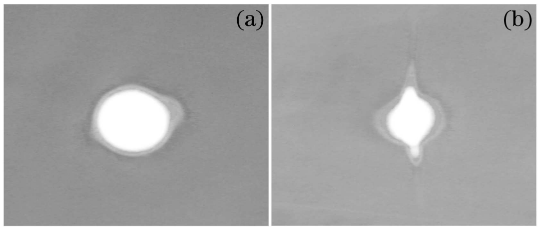

Fig. 5. Far-field shapes of beam spots of the 335.5-nm laser. (a) With LBO; (b) with BBO.

conversion efficiency from red incident power to UV output power is 3.5% for LBO crystal and 6.4% for BBO crystal, respectively. Taking into account the Fresnel reflections from the front and rear faces of the LBO crystal and the focusing lens, the maximal average output power is about 37 mW and the internal conversion efficiency is about 4.3%. The far-field shape of beam spot at the range of 125 cm behind OC is shown in Fig. 5. It is clearly that the beam spot of LBO is better than that of BBO. Because of the smaller d_{eff} (0.607 pm/V), higher acceptance angle (2.19 mrad·cm) and smaller walk off angle (18.94 mrad) of LBO crystal are obtained than those of BBO crystal (1.95 pm/V, 0.52 mrad·cm, 77.09 mrad). The UV output power obtained by LBO crystal is lower than by BBO crystal, but the beam quality obtained by LBO crystal is better than by BBO crystal.

In conclusion, an efficient, all-solid-state 335.5-nm source based on a frequency quadrupled, Q-switched, diode-pumped Nd:YVO_4 1342-nm laser was demonstrated. A comparative performance of LBO and BBO crystal for frequency-quadrupling was conducted. A 63-mW average output power at 335.5 nm is obtained with a BBO crystal at the absorbed pumping power of 6.3 W and the pulse repetition rates of 10 kHz. The single pass frequency conversion efficiency (red-UV) is 6.4%. With a LBO crystal, the values are 35 mW and 3.5%, and the good beam quality is achieved.

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