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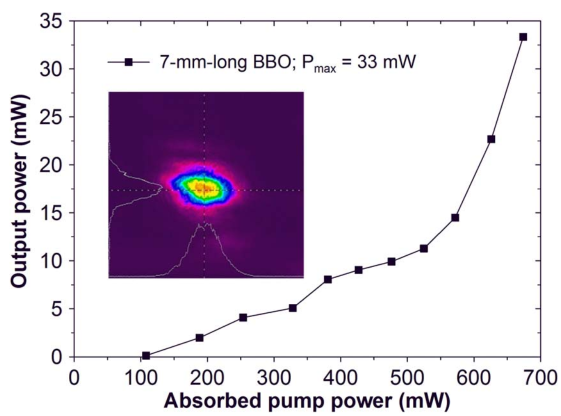

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Continuous-Wave Ultraviolet Generation at 349 nm by Intracavity Frequency Doubling of a Diode-Pumped Pr:LiYF$_4$ Laser

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Abstract: We report a continuous-wave ultraviolet laser at 349 nm obtained by intracavity frequency doubling of a diode-pumped Pr^{3+}-doped LiYF$_4$ laser. Power scaling of lasers at 698-nm fundamental wavelength was realized using an InGaN laser diode with a maximum output power of 850 mW and a 5-mm-long 0.5 a.t. % laser crystal. The maximum output power at 698 nm was 215 mW. With beta barium borate crystal employed as the nonlinear medium, 33 mW of output power at 349 nm has been achieved.

Index Terms: Pr-doped lasers, intracavity frequency doubling, ultraviolet lasers.

1. Introduction

Continuous-wave ultraviolet (UV) solid-state lasers are in high demand for various scientific and industrial applications, such as spectroscopy, biophotonic techniques, semiconductor manufacturing, photolithography and material processing. Typically, these sources rely on a two-stage nonlinear frequency conversion process. The visible radiation is first obtained by second harmonic generation (SHG), and then a second SHG stage [1] or sum frequency generation (SFG) [2] is used to achieve the UV radiation. External cavities are often employed to enhance the conversion efficiency.

Praseodymium (Pr^{3+}) ion-doped materials are of great interest because they can offer various laser transitions in the blue, green, orange, red, and deep red spectral regions. Moreover, UV radiation can be obtained by a single intracavity frequency doubling of Pr-doped lasers. Compared with UV lasers using the two-stage nonlinear process, UV lasers based on the Pr^{3+}-doped materials are more compact and more suitable to get a high average power. In recent years, compact and efficient Pr-doped visible lasers have become widely known [3]–[9]. So far, continuous-wave operation at 261.3 nm and 319.8 nm has been obtained by intracavity frequency doubling of Pr:LiYF$_4$ (Pr:YLF) lasers pumped by frequency doubled optically pumped semiconductor lasers (OPSLs) [5], [10] or InGaN laser diodes [11], [12]. Continuous-wave operation at 373.5 nm has also been obtained with Pr:YAP pumped by an InGaN laser diode [13]. Typical devices of the OPSL-pumped frequency-doubled Pr-lasers were described in a patent [14].

In a recent publication on the diode-pumped Pr-doped lasers [15], we demonstrated efficient Pr:YLF laser working on the $^3P_0 \rightarrow {}^3F_3$ transition at 698 nm. In this paper, we report UV generation at

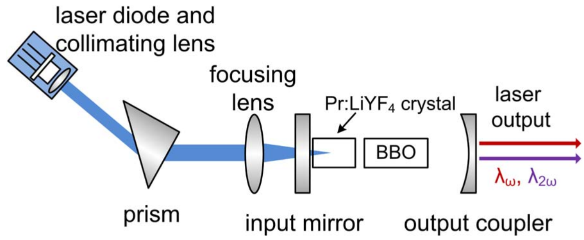

Fig. 1. Schematic layout of the laser setup. The fundamental wave experiments were carried out without the BBO crystal.

349 nm by intracavity frequency doubling of a diode-pumped Pr:YLF laser at 698 nm. Power-scaled Pr:YLF laser operation at 698 nm was first realized, with a maximum output power of 215 mW. Employing a beta barium borate (BBO) crystal as the nonlinear material, 33 mW of output power at 349 nm has been achieved. To the best of our knowledge, this is the first Pr:YLF laser emitting at 349 nm.

2. Experimental setup

For the experiments we used a Pr:YLF crystal with an atomic doping level of 0.5% and a length of 5 mm, which was cut with the crystallographic *c* axis orthogonal to the optical resonator axis. It was grown by the Czochralski method. The facets have been polished in laser quality and had no special coatings. The spectroscopic properties of Pr:YLF have been investigated in other works [11], [16]. The nonlinear crystal was a 7-mm-long type I phase-matched 33.8°-cut BBO, anti-reflection coated for 698 nm and 349 nm at normal incidence. An InGaN laser diode delivering output power of up to 850 mW was employed as the pumping source. At the maximum driven current the emission wavelength of this diode was centered at 444 nm, corresponding to the maximum absorption of the $^3H_4 \rightarrow {}^3P_2$ transition. The beam quality was determined to be $M_x^2 = 2.3$ and $M_y^2 = 9.2$ with a 1.2 nm linewidth (FWHM). The pump power was varied by a variable attenuator.

A schematic of the laser setup is illustrated in Fig. 1. The pump beam was collimated using a spherical lens with a focal length of 5.5 mm. A right-angle prism was used to reshape the pumping beam. The incident angle on the first surface of the prism was 68°, corresponding to a magnification of ~2. The prism was anti-reflection coated for the blue wavelength. After being reshaped, the pump beam was focused into the laser crystal using a spherical lens with a focal length of 50 mm. A simple plano-concave resonator was used. The input mirror had a high transmission $(T > 97\%)$ at 444 nm and a high reflection $(R > 99.7\%)$ at 698 nm. For the 698 nm fundamental wavelength output, power characteristics were measured with various output couplers with transmissions of 0.5%, 0.9%, and 2.1%. The radius of curvature of the output couplers was 50 mm. Approximately 13% of the pumping light was lost on the coupling optics placed between the laser diode and the laser crystal, and the amount of the absorbed power in a single pass was 91%. The laser was operated near the edge of the cavity stability.

For the second harmonic generation, a BBO crystal was inserted into the plano-concave cavity behind the Pr:YLF. The output coupler with a radius of curvature of 100 mm was used to extract the 349 nm emission. The transmission of this mirror at 349 and 698 nm was 81% and 0.5%, respectively. According to the different stimulated emission cross sections [8], the laser mirrors were specially designed to suppress oscillation of the $^3P_0 \rightarrow {}^3F_2$ (640 nm) and $^3P_0 \rightarrow {}^3F_4$ transition (721 nm) of Pr^{3+} [15].

3. Results

Before obtaining the UV light, the characteristics of the fundamental wave at 698 nm were investigated. Fig. 2 presents the output power at 698 nm versus the absorbed pump power. Using the output couplers with transmissions of 0.5% and 0.9%, no lasing at 640 nm or 721 nm was observed in the experiments. Laser oscillation occurred in the $^3P_0 \rightarrow {}^3F_3$ transition at 697.6 nm in

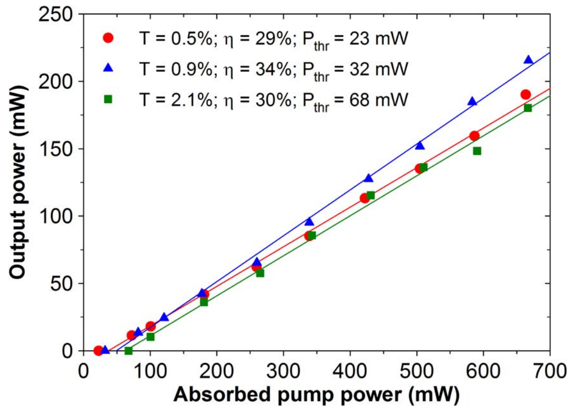

Fig. 2. Laser output power at 698 nm versus absorbed pump power for different output couplers.

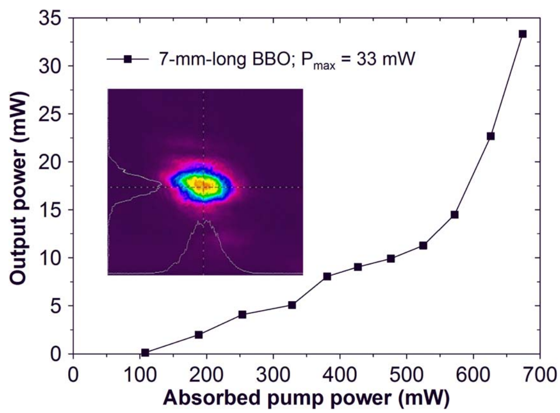

Fig. 3. UV laser output power versus absorbed pump power. The inset shows the beam profile of the UV laser.

π polarization. However, for the output coupler with a transmission of 2.1%, single wavelength lasing on the 698 nm line was observed only when the absorbed power was below 325 mW. Higher pump power led to a simultaneous lasing on 698 nm and 721 nm, which was due to a low transmission (1.7%) of this output coupler at 721 nm. A maximum laser power of 215 mW with an absorbed power of 667 mW was obtained using the 0.9% output coupler. This corresponds to an optical-to-optical conversion efficiency of 32.2%. Compared to the previous reports on the $^3P_0 \rightarrow {}^3F_3$ laser transition of Pr:YLF [15], [17], we have obtained a higher output power of Pr-laser at 698 nm. The beam quality of the 698 nm laser at the maximum output power is close to diffraction limited.

The Findlay-Clay analysis [18] indicated an intracavity round-trip loss value of $\sim$0.3%. The coefficient K_c [19] that describes the single-trip small-signal gain as a function of absorbed power was determined to be 0.17 W^{-1}, which is 16% of this value obtained in a Pr:YLF laser using a similar setup but working on the strongest $^3P_0 \rightarrow {}^3F_2$ transition [4].

After insertion of the BBO crystal, continuous-wave UV generation at 349 nm was obtained through intracavity frequency doubling. The polarization of the output beams at 349 nm and 698 nm were examined and found to be orthogonal to each other. Fig. 3 shows the 349 nm output power as a function of the absorbed pump power. A UV laser output power of 33 mW was obtained at the maximum absorbed power, yielding an optical-to-optical efficiency of 5% with respect to the

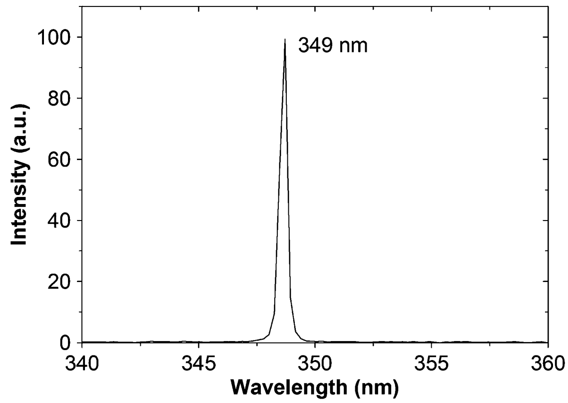

Fig. 4. Spectral line shape of the UV laser at 349 nm measured by a fiber spectrometer (HR2000+, Ocean Optics, Inc.). The resolution is 0.24 nm.

absorbed pump power. The beam profile shows a slightly elliptical shape (see the inset in Fig. 3), which is probably due to the high walk-off angle in BBO. The spectral line shape of the UV laser is shown in Fig. 4.

It should be noted that the output mirror for the UV laser still had a transmission of 0.5% at the fundamental wavelength. When the maximum UV laser power was obtained, laser output power at the fundamental wavelength was measured to be 116 mW. All the laser coatings in the experiments were fabricated in our lab using a direct-current (DC) sputtering process. We fabricated output mirrors which have higher reflections at 698 nm, too. However, these mirrors could not give better results because the losses at 349 nm were too high due to the usage of more oxide layers. Better UV laser results can be obtained using an output mirror which both has a higher reflection at 698 nm and a higher transmission at 349 nm. Moreover, the linear cavity used in this experiment is very compact but only suitable for low operating power. UV Lasers with higher pump power need to employ more complex resonators with several mirrors to improve the effective nonlinearity of the nonlinear crystal.

4. Conclusion

In conclusion, UV continuous-wave radiation at 349 nm obtained by intracavity frequency doubling of a diode-pumped Pr:YLF laser has been demonstrated. Using an 850 mW InGaN-laser-diode pumping and a plano-concave cavity, power-scaled continuous-wave laser at 698 nm with an output power of 215 mW was obtained. The corresponding optical-to-optical efficiency was 32.2%. Then, a UV output power up to 33 mW was obtained using a BBO nonlinear crystal with a length of 7 mm. For the UV beam, the optical-to-optical efficiency with respect to the absorbed pump power was 5%. Moreover, the UV laser results are supposed to be improvable by employing output mirrors with maximal possible reflection at 698 nm and a folded laser cavity, which is our next experimental goal.

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