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RESEARCH

Generation of continuous wave deep UV radiation at 273 nm based on frequency doubling of a diode pumped PR:YLF laser

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Abstract
This report is about a continuous wave (CW) deep ultraviolet laser operation at 273 nm by intracavity frequency doubling of laser diode pumped Pr^{3+} doped $LiYF_4$ lasers. We use two 3 W InGaN laser diodes, one 3 mm long Pr^{3+}:$LiYF_4$ (Pr:YLF) crystal and one 5 mm long beta-barium-borate (BBO) crystal, coherent radiation with an output power of 128 mW at 273 nm was obtained with a 2.9% optical to optical conversion efficiency. To the best of our knowledge, this is the first report detailing a Pr:YLF laser that emits light at 273 nm.

1 Introduction

Deep ultraviolet (UV) lasers with wavelengths shorter than 280 nm have found many promising applications in sterilization, communication, optical storage, spectral analysis, and biochemical detection [1–3]. Most studies on ultraviolet radiation concentrate more on pulse laser [4]. There are few experiment based studies on continuous-wave ultraviolet radiation. All solid-state UV lasers have more advantages in terms of long lifetime, high-efficiency, high reliability, and compactness in comparison with traditional UV gas lasers [5]. Fourth-harmonic generation of a 1064 nm laser line of Nd:YAG is one of the most common methods and has been commercialized for years. Unfortunately, the nonlinear optics conversion is inefficient. Until now, more attention has been focused on 355 nm and 266 nm UV sources based on frequency tripling and frequency quadrupling of 1.06 µm Nd-doped lasers [6–11]. As we know there have been no studies on 273 nm deep UV laser yet.

The laser crystal is one of the most important components in a solid-state ultraviolet laser. Pr3+ ion based visible solid-state lasers have attracted a lot of attention in the past two decades. That's because of in comparison with other rare-earth ions supporting visible laser radiation generation, the Pr3+ ion energy level structure offers several laser transitions that cover practically the whole visible spectral range [12–14]. To obtain these visible lasers, the Pr3+ ions need to be pumped from the 3H4 ground level to 3P0 (around 480 nm), 3P1 + 1I6 (around 469 nm), or 3P2 (around 444 nm) excited energy level. As a result, three pump sources have been developed to realize the pumping of various Pr3+ doped materials effectively. For example, an OPSL (optically pumped and frequency-doubled semiconductor laser) at ~ 480 nm, a diode-pumped and frequency doubled Nd:YAG laser at ~ 469 nm, and an InGaN laser diode at ~ 444 nm. The InGaN laser diodes are the most common ones, in general because of they are compact, commercially available, and inexpensive. The InGaN laser diode is capable of outputting a blue laser from 441 to 445 nm with a maximum power of 3 W, and the laser also has polarization emission characteristics to meet the polarization absorption characteristics of Pr:YLF crystals.[15–18]. Efficient laser emission of Pr:YLF at room temperature has been demonstrated in the green (523 nm:3P1 + 1I6 → 3H5), orange (607 nm: 3P0 → 3H6), red (640 nm:3P0 → 3F2), and deep red (698 nm:3P0 → 3F3 and 721 nm:3P0 → 3F4) spectral region [19–21]. The main energy levels and laser transitions of Pr:YLF are shown in Fig. 1. Even more important, visible high-power lasers could enable UV or even deep UV generation by frequency doubling with the aid of nonlinear crystals, and the nonlinear optical conversion is efficient. The Pr:YLF based ultraviolet wavelengths were reported as being less than visible wavelengths, only at 261 nm [22], 303 nm [23], 320 nm [24], 349 nm [25], and 360 nm [26]. Besides, previous studies on the spectral properties [27]

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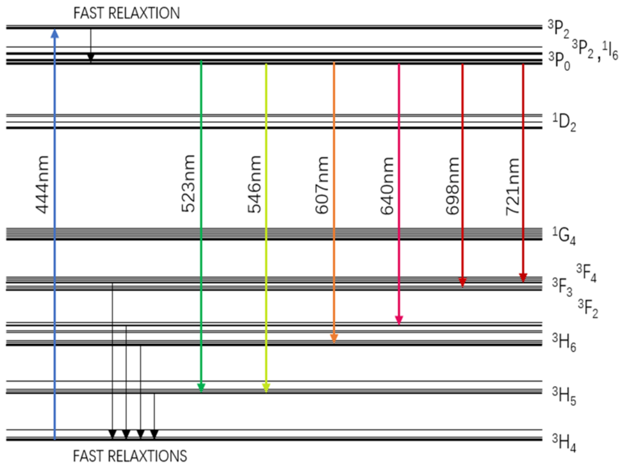

Fig. 1 Energy level scheme of a Pr:YLF crystal

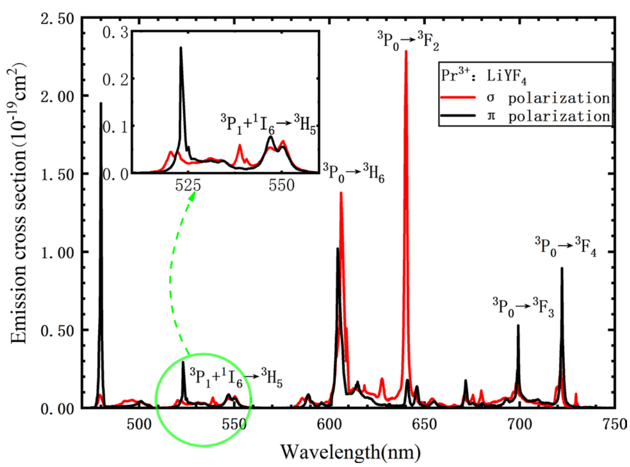

Fig. 2 Polarization-dependent emission cross-sections of a Pr:YLF crystal. (The inset shows the details of the investigated emission spectrum.)

discovered that in the transition from the upper 3P1 level to the lower 3H5 manifold, the Pr3+ ions in the YLF crystal can emit radiation at 546 nm (Fig. 2.). To the best of our knowledge, the corresponding frequency doubled Pr:YLF ultraviolet lasers have not been reported.

In this paper, we demonstrate the generation of a compact deep UV laser at 273 nm by efficient frequency doubling of a CW laser diode-pumped Pr:YLF laser at 546 nm. With an absorbed total pump power of 4.48 W, a near TEM00 mode deep UV laser radiation at 273 nm with an output power of 128 mW was obtained. The newly generated deep UV laser emission at 273 nm could be utilized in the study of the decomposition of sertraline (SRT) under hydrolytic stress conditions (acid, neutral, alkaline, and oxidative) [28]. We expect the 273 nm emission in a Pr:YLF crystal to be a new and promising UV laser.

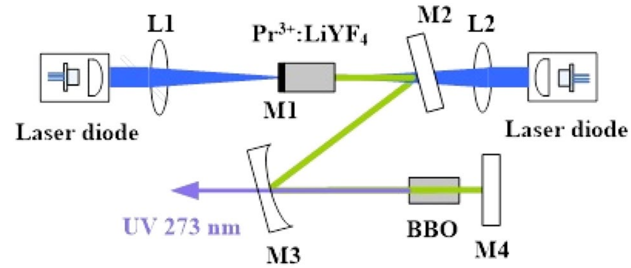

Fig. 3 Schematic for the intracavity frequency-doubled 273 nm Pr3+:YLiF4/BBO UV laser

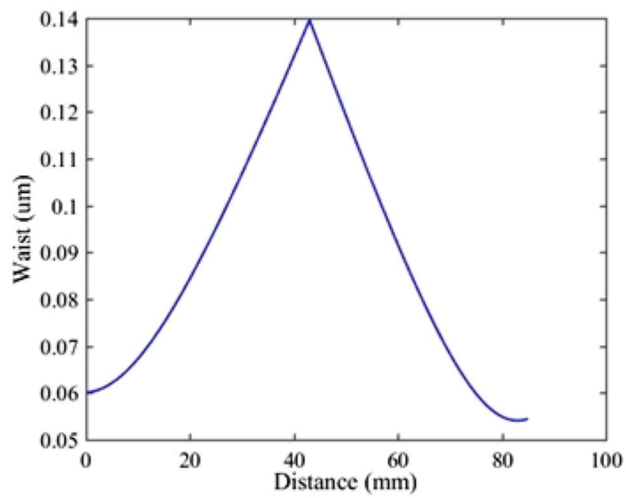

Fig. 4 Beam waist radii at different positions within the resonator cavity

2 Experimental setup

Figure 3. shows the laser setup used for the intracavity SHG experiments. A folded Z-type cavity was used in order to pump the Pr:YLF laser crystal from two sides and to provide optimal beam waists both in the laser crystal and in the nonlinear BBO crystal. In addition, no deep UV light passes through the laser crystal which avoid deep UV induced degradation in this setup. The spot size of each position in the resonator was simulated by MATLAB software (Fig. 4.). When the thermal focal length of the crystal is − 300 mm, the beam waist radii inside the 3 mm long laser crystal and the 5 mm long BBO crystal were approximately 62 μm and 54 μm, respectively. The Pr:YLF laser crystal with a dopant concentration of 0.5 at.% Pr3+ was pumped by two laser diodes emitting at 443.9 nm with a maximum output power of approximately 3 W each. The 3 W laser diode itself was integrated with an aspheric lens

(focal length $f = 4.2$ mm) for collimating the pump beam. Lenses L1 and L2 of 31 mm focal length were used to focus the pump beams into the laser crystal. The Pr:YLF crystal was oriented such that the crystallographic c axis was parallel to the electric field of the pump laser. The laser diodes and Pr:YLF were mounted on a copper heat sink, and the temperature was controlled strictly by a thermal electric cooler to achieve stable operation of the laser.

The folded Z-type cavity consisted of three plane mirrors (M1, M2, M4) and a curved mirror M3 with a radius of curvature of 50 mm. The two input couplers M1 and M2 were anti-reflection (AR) coated for 443.9 nm and high-reflection (HR) coated for the fundamental laser wavelength at 546 nm. The end mirror M4 was HR coated for 546 nm, and the second harmonic wavelength at 273 nm. The BBO crystal, which was designed for critical type I phase matching ($\theta = 45.9°$, $\Phi = 0°$) and AR coated for 546 nm, was placed in the beam waist located at the surface of M4. The main part of the generated deep UV radiation was coupled out at the folding mirror M3, which has transmission coefficients of 0.2% (546 nm) and 85% (273 nm). In our experiments, the stronger transitions near 522 nm, 607 nm and 639 nm were suppressed by the mirror M3. The coating is shown in Fig. 5. All mirrors were highly reflective ($R > 99.8\%$) at the fundamental laser wavelength of 546 nm. The physical length of the cavity was 85 mm (M1–M2: 15 mm, M2–M3: 28 mm, M3–M4: 42 mm).

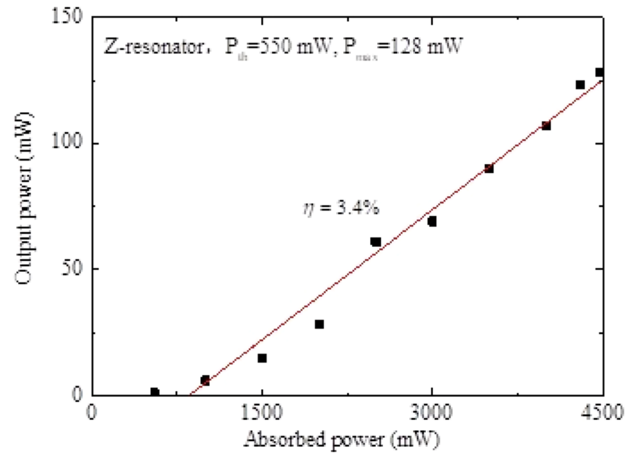

Fig. 6 Output power characteristics of a 273 nm laser

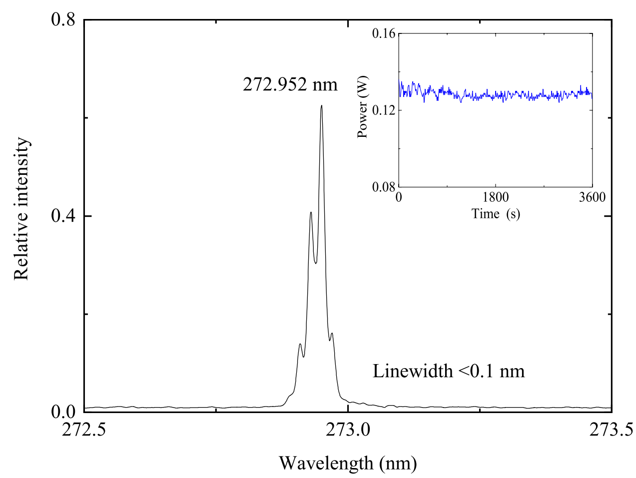

Fig. 7 Spectra of 273 nm deep UV laser; *Inset* power stability of a deep UV laser at a maximum output power of 128 mW about 1 h

3 Results and discussion

A free-running operation was first demonstrated without inserting any mode selector inside the laser cavity. Although the emission at about 522 nm has a 3.2 times higher emission cross-section than that of 546 nm, no lasing at 522 nm was observed in this experiment thanks to the relatively high total transmission. The output characteristic of the CW intracavity frequency-doubled Pr:YLF laser emitting radiation in the deep UV spectral region at 273 nm is shown in Fig. 6. The laser oscillation threshold is about 550 mW of the pump power absorbed. The maximum output power is 128 mW at 4.48 W of absorbed incident pump power, resulting in 2.9% absolute efficiency. The slope efficiency is about 3.4%. The deep UV laser output power grows monotonically with the increasing input power and shows no sign of saturation, which suggests that there is a potential to obtain higher deep UV power by means of increasing the power of the input laser.

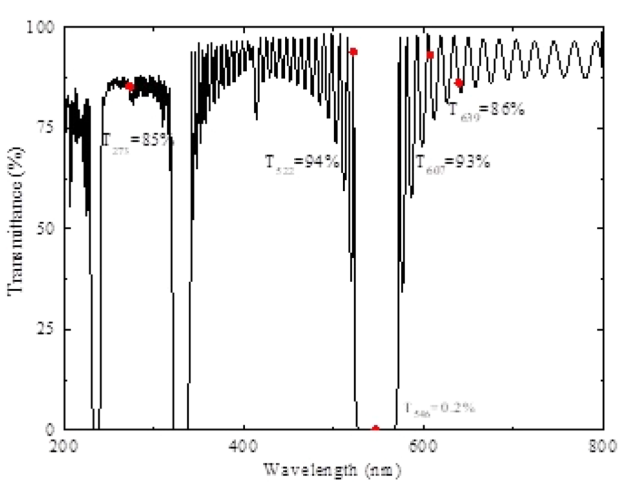

Fig. 5 Transmittance of 273 nm laser output coupler M3

Stable laser output is always desirable for various applications. The output power stability of the 273 nm laser can be easily estimated by registering the instantaneous

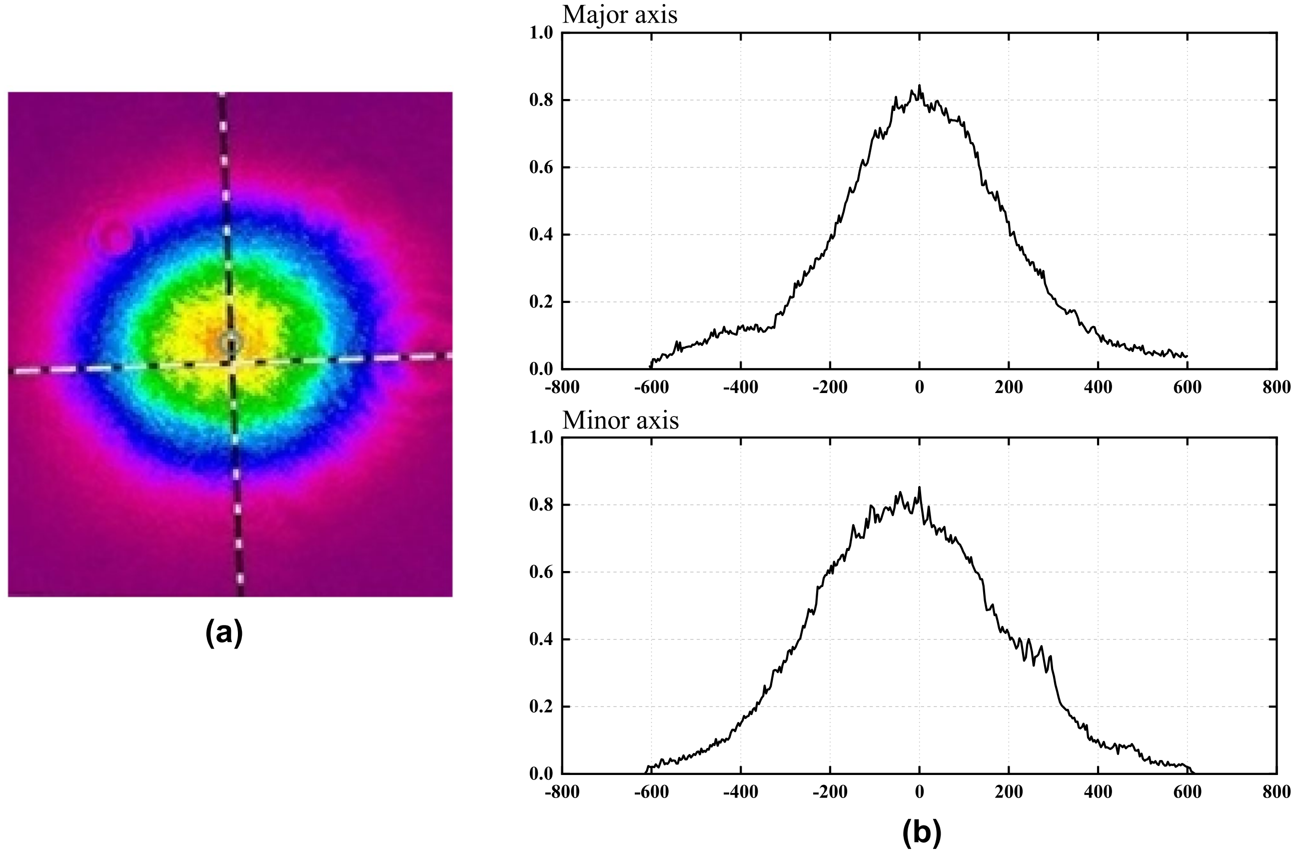

Fig. 8 Beam profile of the 273 nm output

values of the output powers with time. Thus, the stability of the maximum output power for the 273 nm laser was deduced to be about 1.72% (RMS, root-mean-square). The laser spectrum of single lasing wavelength at 273 nm was registered separately in Fig. 7. by using a wavelength meter (High Finesse model LSA). The central wavelength of deep UV laser is 272.952 nm.

To characterize the beam quality of the 273 nm deep UV laser beam, its beam profile was measured in the x and y directions at maximum output power (see Fig. 8.). The beam profile testing result shows that the 273 nm laser operates in near TEM00 mode with a near Gaussian far-field intensity distribution. The beam spot became a slight ellipse, which may be caused by the walk-off effect that occurred in the BBO crystal.

4 Conclusions

This article studies an all-solid-state continuous deep UV laser produced by the intracavity frequency doubling of a Pr:YLF crystal double-end pumped by two blue diodes. Adopting the Z cavity structure, optimizing the film system design of the cavity mirror, and using the weak spectrum (546 nm) generated by nonlinear crystal BBO frequency-doubled Pr:YLF, the continuous deep UV laser was finally successfully obtained for the first time. The centre wavelength of the deep UV continuous spectrum measured by the spectrometer is 272.952 nm, and the maximum output power is 128 mW. The acquisition of this wavelength for the first time lays the foundation for the further study of the weak line produced by the frequency doubling of the Pr:YLF crystal.

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Author contributions Wei Dou proposed research topics, designed experimental schemes and implemented experiments, consulted literature ,collected and analyzed data, wrote and revised papers.Shuangshuang Pu,Dapeng Qu assisted with experiments and text review.Zhiyuan Zheng collected data and prepared figures.Ke Wang prepared figures. Quan Zheng mainly responsible for the final review of papers and provided guidance support.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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