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RESEARCH

2.53 W of 261 nm continuous wave generation in a pr: YLF laser pumped by blue laser diode at 444.2 nm

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1 Introduction

Many trivalent rare-earth ions (RE^{3+}) exhibit visible radiative transitions that potentially enable visibly emitting all solid state lasers [1, 2]. So far, various visible lasers based on RE^{3+}-doped crystalline media have been demonstrated. Among them, trivalent praseodymium ion (Pr^{3+}) is recognized as one of the most useful active ions for achieving efficient visible lasers because the visible transitions of Pr^{3+} perform as a four energy level system, and their emission cross sections are larger than that of other RE^{3+}. Praseodymium trivalent ion (Pr^{3+}) doped materials have been used to realized laser operation in the visible region, such as Pr: YLF at green, orange and red wavelengths.

An important and successful application of Pr: YLF crystal is the generation of continuous wave ultraviolet laser with second harmonic method, which has high conversion efficiency and high output power, especially deep ultraviolet below 280 nm. 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. Most researches on ultraviolet radiation concentrate more on pulse laser. There is few research on continuous-wave ultraviolet radiation.

Hitherto, continuous-wave laser operation in green range of 522 nm and 546 nm has been reported in Pr: YLF. In 2014, P. W. Metz et al. demonstrated the performance of 2ω-OPSL(optically pumped semiconductor laser) pumped Pr: YLF laser with the output power of 2.9 W at 522 nm and 2 W at 546 nm respectively [3]. High efficiency is achieved by using 2ω-OPSL as a pump source since the matched absorption peak and its perfect beam quality. However, OPSLs operating at blue wavelengths are much more expensive than InGaN-based diode lasers. In 2016, S.Y.Luo et al. reported a blue-InGaN pumped Pr: YLF laser at wavelength of 522 nm, and its maximum output power was 1.6 W [4]. Although laser outputs above the watt-level in the green region at 522 nm and 546 nm have been achieved, the research has focused only on fundamental laser emission at $^3P_1 \rightarrow {}^3H_5$ (522 nm) and $^3P_0 \rightarrow {}^3H_5$ (546 nm) in the pi-polarized direction [3–8]. Without the OPSL laser, a novel LD is adopted in our research which has the lower cost but higher pump-to-laser conversion efficiency. In 2023 and 2024, the watt-level 261 nm laser is reported by K.Feng, D.Wang et al. and S.Y. Zhang, S.X. Wang et al. with low beam quality which is not sufficient for commercial usage [9, 10].

In this paper, we demonstrate the generation of a compact deep UV laser at 261 nm by efficient frequency doubling of a CW laser diode-pumped Pr: YLF laser at 522 nm. With an incident pump power of 19.8 W, a TEM_{00} mode deep UV laser radiation at 261 nm with an output power of 2.53 W was achieved. The highest efficiency generated deep UV laser emission at 261 nm could be utilized in the study of optical storage, spectral analysis, and industrial applications.

We demonstrate the generation of a watt-level continuous wave deep ultraviolet laser at 261 nm by efficient frequency doubling of a blue-diode-pumped Pr: YLF laser at 522 nm for the first time. With a novel method of coating and LD collimating, a TEM_{00} mode deep UV laser radiation at 261 nm with an output power of 2.53 W was obtained. To the best of our knowledge, this is the first report on a watt-level Pr: YLF laser operating at 261 nm with perfect beam quality.

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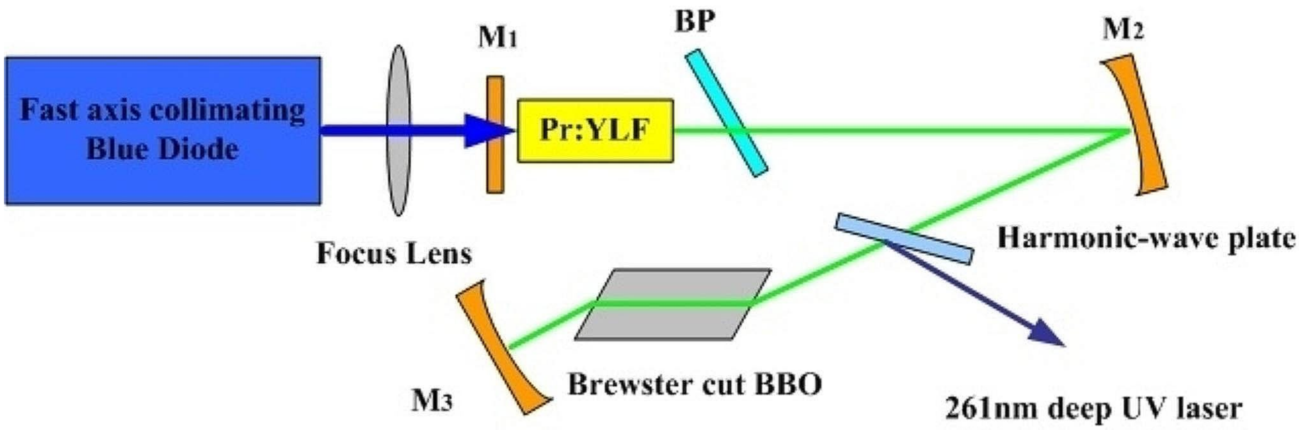


Fig. 1 the schematic of the 261 nm laser

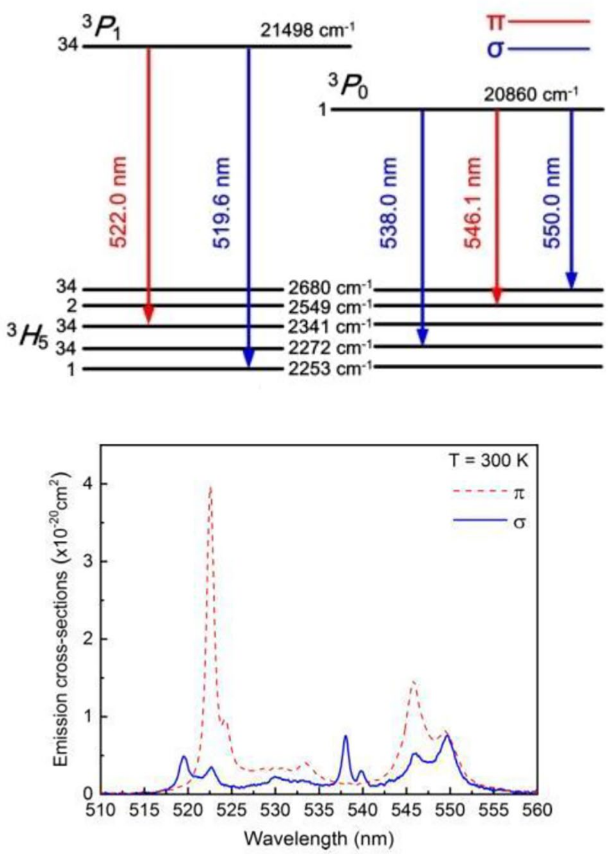


Fig. 2 the energy level and room temperature polarization-dependent emission cross-sections of Pr: YLF

1.1 Experimental setup

The experimental setup of a frequency doubling of laser-diode pumped Pr: YLF green laser is shown in Fig. 1.

The laser gain medium was an a-cut Pr: YLF crystal with the dopant concentration of 0.1at.% and the dimensions of 3 mm×3 mm×18 mm. Both end faces of the crystal were polished and coated at 400 nm-700nmm AR. The crystal was wrapped with indium foil and held in a water-cooled copper block to remove the heat. Figure 2 is the energy level schematics and room temperature polarization-dependent emission cross-sections of Pr: YLF in green spectral region.

The fluorescence testing spectrum from 500 m to 570 nm is shown in Fig. 3 and four main laser lines are marked in the figure. A spatially-combined InGaN laser diode module with 19.8 W maximum output power was used as the pump source. The pump source emitted light at a peak wavelength of approximately 444.2 nm with a spectral width (full width at half maximum, FWHM) of about 1.8 nm. The M^2 factors of pump source were $M^2{}_x = 46.81$, $M^2{}_y = 13.53$ in the horizontal and vertical directions corresponding to slow axis and fast axis. This bad beam quality influence the pump mode matching and the beam quality of the output laser. Normal method to reshape the pump beam is sticking a 200 µm fiber or spheric lens near the LD to compress the divergence angle of fast axis, and then focus by a lens. The disadvantage of this method is that the divergence angles of two direction have large difference after collimating fiber or spheric lens. So the focus spot has large ellipicity and bad beam quality which could not satisfy the mode matching condition of DPSSL. In our research, an aspheric lens is fixed between the blue LD and focusing lens, and the distance between the LD and aspheric lens is adjustable. The purpose of adopting aspheric lens is to decrease the divergence angle of fast axis LD laser and no influence on slow axis. A proper location for the fast axis collimation lens could be found that made the diameter of the beam at two directions with same dimension. Under this condition, a perfect pump beam spot is obtained, as shown in Fig. 4 which is benefit for mode matching and generation laser beam with good beam quality.

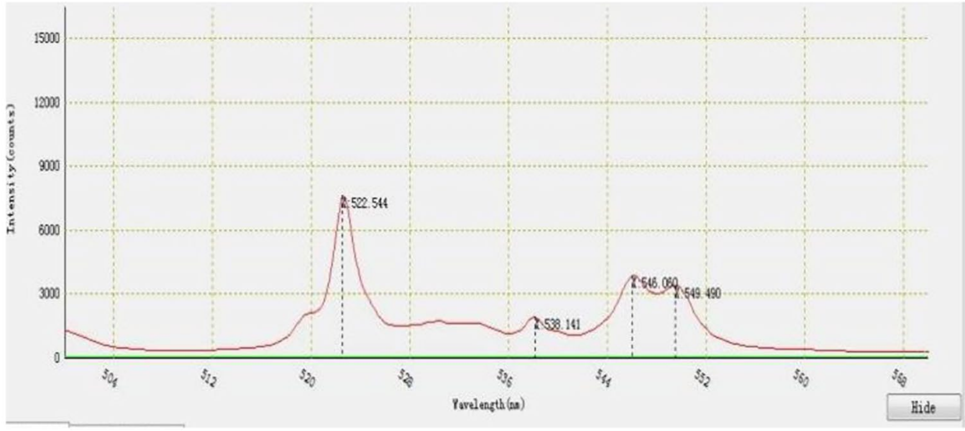


Fig. 3 fluorescence testing spectrum from 500 m to 570 nm of Pr: YLF

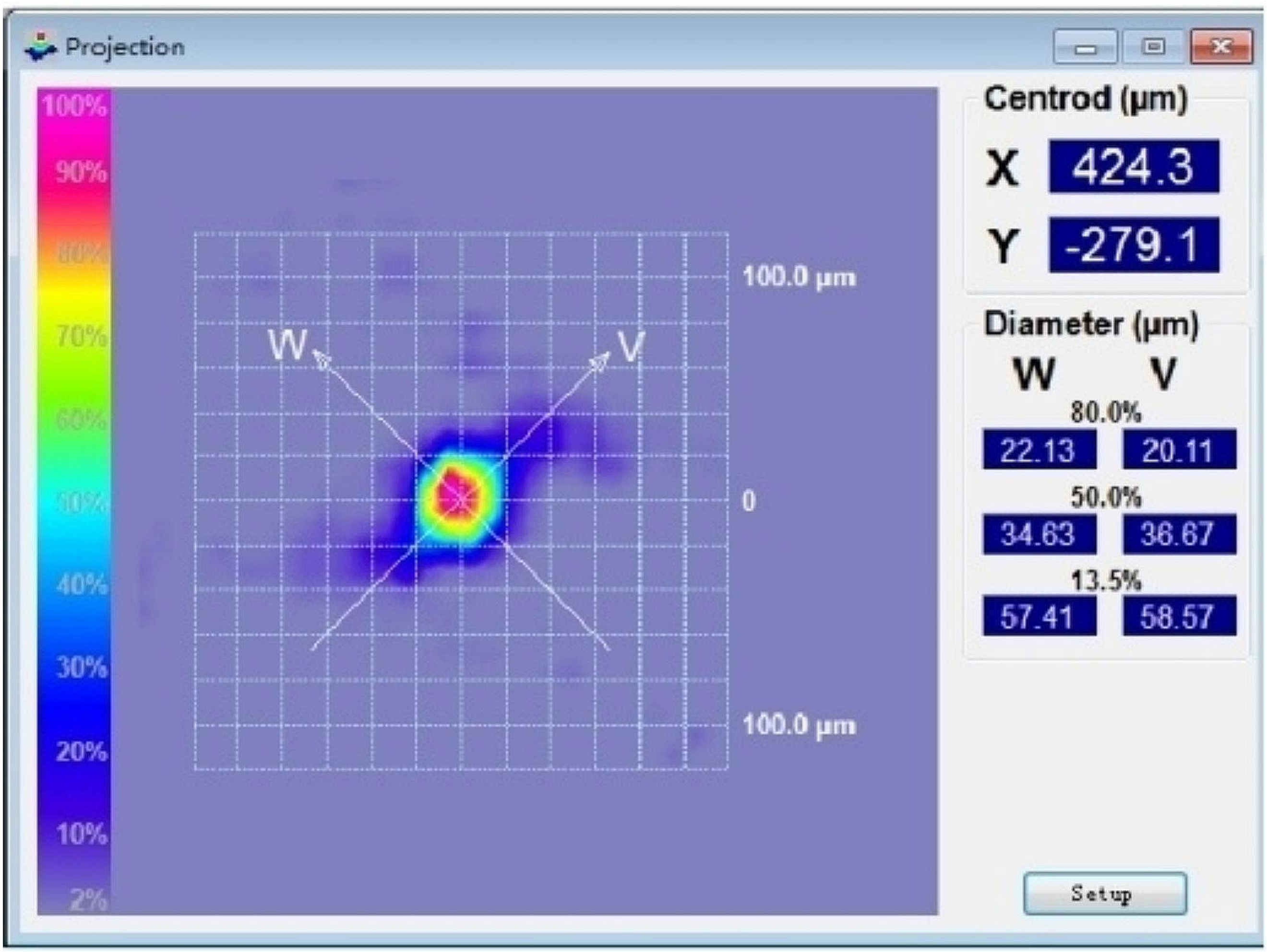


Fig. 4 focusing shape and size of pump beam spot with fast-axis collimating blue diode

The pump beam was focused into the middle of laser crystal using a single plane-convex focusing lens with ~95% transmission rate and 25 mm focal length. The absorption efficiency of Pr: YLF crystal for pump has been measured to be about 80%. The folded V-type cavity consisted of one plane input mirror M_1 and two curved mirrors M_2 and M_3 with radii of curvature of 100 mm. The beam sizes in the cavity is calculated by the reZonator software, and the fundamental mode size in the Pr: YLF is near 65 μm with satisfy the mode matching condition. The beam radius in BBO is about

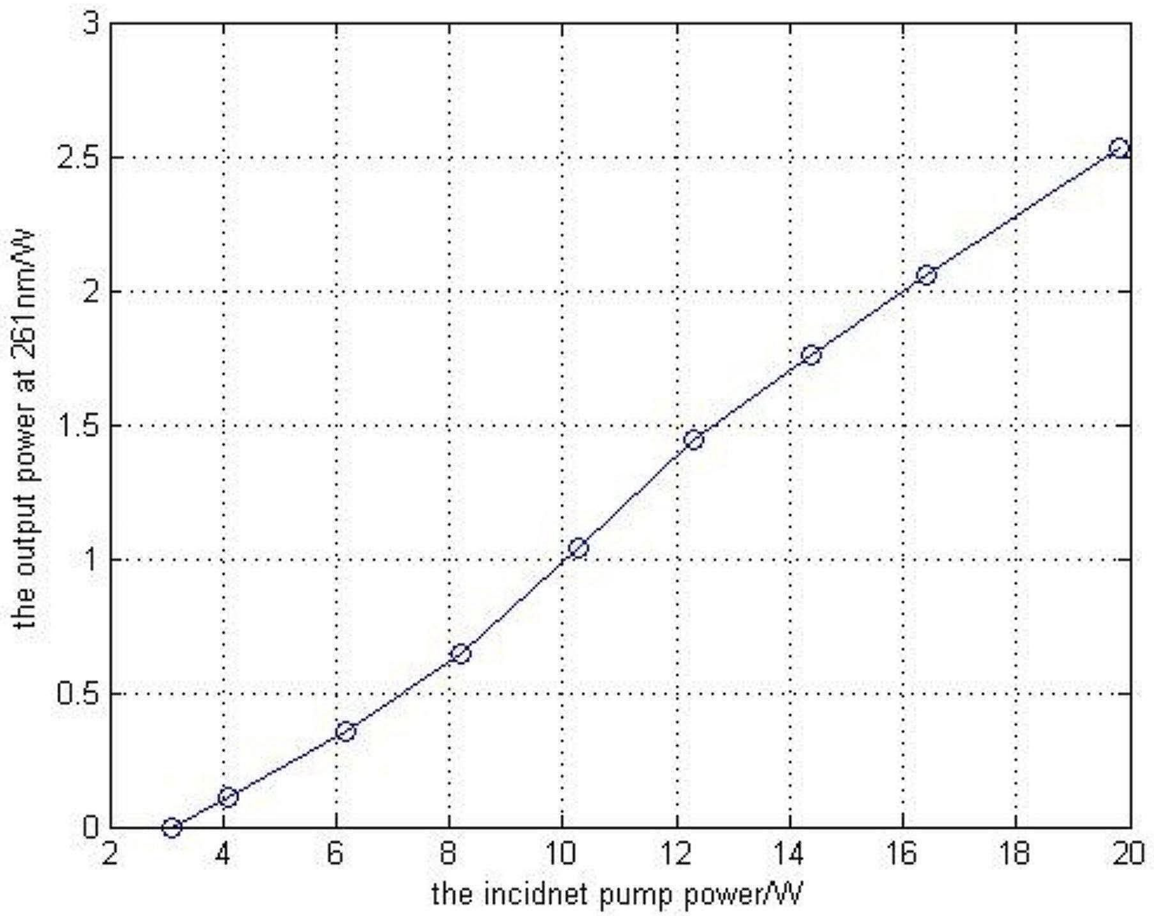
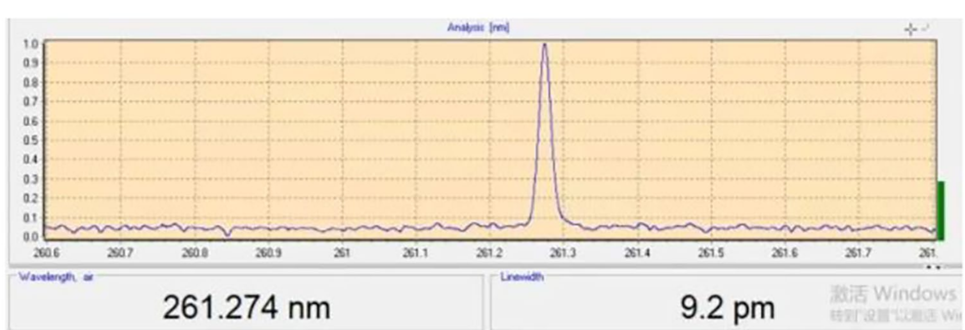


Fig. 5 the output power of 261 nm versus the incident pump power

100 μm and it could provide the high frequency doubling efficiency as well as the long life time. The input coupler M_1 is anti-reflection (AR) coated for 444.2 nm and high-reflection(HR) coated for the fundamental laser wavelength from 500 nm to 750 nm including 550 nm. The input mirror could be used for the research on all the wavelengths of Pr: YLF. For Pr: YLF crystal, 522 nm and 546 nm could establish the laser oscillation in pi-direction and 538 nm, 519 nm and 550 nm in sigma-direction. A Brewster plate(BP) is also inserted into the cavity at sigma-direction with 56degree incident angle to suppress the 519 nm, 538 nm and 550 nm at sigma-direction. Due to the strong laser line at 639 nm and 607 nm, M_2 is coated at 522 nm HR as well as 639 nm and 607 nm AR to get the single fundamental laserline. M_3 is coated at 522 nm and 261 nm HR which plays as a highly reflection mirror at the second harmonic laser of 261 nm.

The output CW 261 nm laser does not transmit through the M_2 mirror. The UV laser has strong damage effect for the

Fig. 6 the spectrum of 261 nm laser



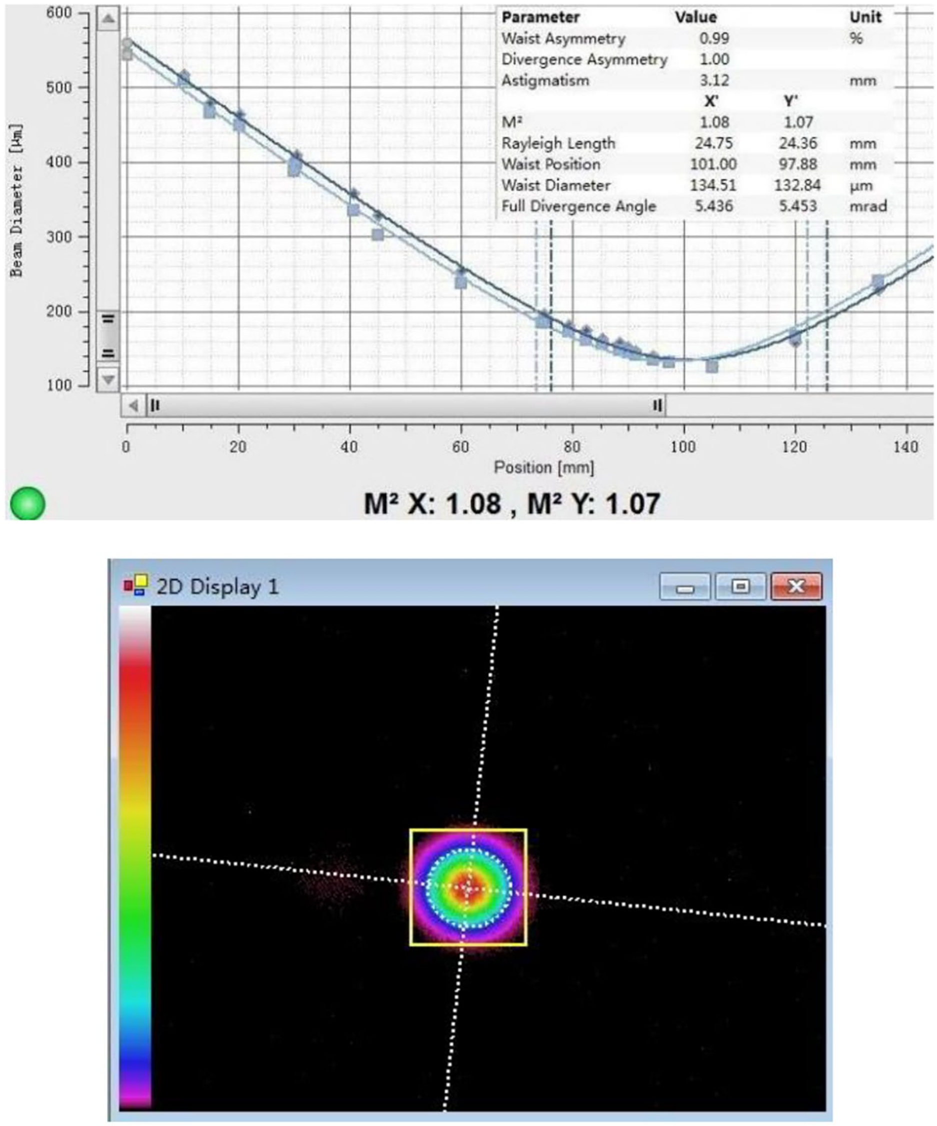


Fig. 7 the beam spot and M-square of 261 nm laser

coating material. It is known that UV AR coatings have very limited lifetime, can be easily damaged, have strong absorption in the UV range and they tend to change the reflectivity over time. To couple out the UV radiation we used a 2 mm thick Brewster plate. The plate was made from fused silica, with one side uncoated and the other side HR coated for 261 nm and AR coated for 522 nm. This type of Brewster plate was proven to be a reliable UV output coupler with long lifetime and small insertion losses for 522 nm. For intracavity frequency doubling of 522 nm, a 10 mm long Brewster/Brewster BBO crystal, with uncoated facets was used. The nonlinear crystal, cut for type I frequency conversion, was mounted on TEC for temperature control. BBO is known to be highly hygroscopic, and uncoated facets are a significant risk factor. The BBO crystal, which was designed for critical type I phase matching ($\theta = 49.0°$, $\Phi = 0°$) in the beam waist located at the surface of M_3.

2 Results and discussion

The output characteristic of the CW intracavity frequency doubling Pr: YLF laser at deep UV spectral region at 261 nm is shown in Fig. 5.

The laser oscillation threshold is about 3.2 W of the incident pump power. The maximum output power is 2.53 W at 19.8 W of incident pump power, resulting in 15.2% absolute efficiency. The optical to optical slope efficiency is about 12.8%. The deep UV laser output power grows monotonically with the increasing of incident pump power and no sign of saturation is observed, which suggests that there is a potential to obtain higher deep UV power by means of increasing the power of the incident laser. Stable laser oscillation is always important for various applications. The laser spectrum of single lasing wavelength at 261 nm was registered in Fig. 6 with a wavelength meter (High Finesse model LSA).

The central wavelength of deep UV laser is 261.274 nm. To characterize the beam quality of the 261 nm deep UV laser beam, the beam profile and M square factor were measured in the x and y directions under maximum output power were shown in Fig. 7. The stability of the 261 nm laser was deduced to be about 0.8% (RMS, root-mean-square). The stability demonstrates that there is no wavelength competition in the resonator and this novel LD collimating method could be adopted on the oscillation of other laser line.

The beam profile testing result shows that the 261 nm laser operates in TEM_{00} mode with a Gaussian far-field intensity distribution. The cavity design and novel pump mode could compensate the walk-off effect that occurred in the BBO crystal and the thermal lens effect of Pr: YLF, as well as the astigmatism of the V-resonator.

3 Conclusion

In this paper, we demonstrate the generation of a watt-level compact deep UV laser at 261 nm by efficient frequency doubling of a CW laser diode-pumped Pr: YLF laser at 522 nm. With an incident pump power of 19.8 W, a TEM_{00} mode deep UV laser radiation at 261 nm with an output power of 2.53 W was obtained. The novel generated deep UV laser emission at 261 nm has the highest conversion efficiency and highest output power.

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Author contributions Yao Yi proposed research topics, designed experimental schemes and implemented experiments, consulted literature, collected and analyzed data, wrote and revised papers.Chen xi, Wang Jinyan, Xiaohuidong assisted with experiments and text review.Wang Yan, Wangyuning collected data and prepared figures. Liuhuizhen and Tiandonghe prepared figures.Quan Zheng mainly responsible for the final review of papers and provided guidance support.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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