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RESEARCH

# 679/339.5 nm radiation generation of pr: YLF laser pumped by fiber coupled blue laser diode module

**Wei Dou[1] · Shanshan Hou[1] · Xinyue Wang[1] · Fang Ma[1] · Huiwen Ji[1] · Quan Zheng[1,2]**

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**Abstract**

We demonstrate the high-power continuous-wave (CW) operation of a Pr: YLF laser at 679 nm by suppressing the higher gain transitions near 640 nm, 670 nm and 698 nm. For 679 nm, the maximum output power is 3.5 W. The absorbed pumping power is 22 W in σ polarization. The optical-to-optical conversion efficiency is quite high, reaching 15.9%, and the output power stability in 2 h is better than 0.5%. Moreover, intracavity second harmonic generation had been achieved output power of 620 mW at 339.5 nm by using a LBO nonlinear crystal. To the best of our knowledge, laser diode-pumped laser action at 679/339.5 nm was demonstrated for what is believed to be the first time.

## 1 Introduction

Laser diode pumped all-solid-state ultraviolet (UV) laser emitting in 320–340 nm spectral region has many applications in many fields such as mold fabrication, photobiology, and photomedicine, especially in various manifestations of fluorescence detection and imaging. At present, the available coherent sources in this wavelength region are mostly gas lasers such as 325 nm heliumcadmium (He-Cd) laser and 337 nm nitrogen ($N_2$) laser [1, 2]. Compared to conventional UV gas lasers, all-solid-state UV lasers have many advantages. And the prominent of which is long life, high efficiency, high reliability and compactness. In the past few decades, most all-solid-state UV lasers are based on frequency conversion from a corresponding infrared laser in nonlinear optical crystals [3–8]. More attention was focused only on 355 and 266 nm UV sources based on frequency tripling and frequency quadrupling of 1.06 μm Nd-doped lasers. Only Ogilvy et al. achieved output of 20 mW at 336 nm wavelength using a frequency quadrupled, diode-pumped Nd: $YVO_4$ laser, in which a LBO crystal was used to generate the second harmonic (SHG) in the cavity and a BBO crystal for fourth harmonic generation (FHG) using a double-pass geometry [9]. However, the efficiency of nonlinear optics conversion was low.

In recent years, praseodymium-doped crystals are one of the most significant and alternative laser crystals developed [10–12]; praseodymium-doped yttrium lithium fluoride (Pr: YLF), in particular, has been proven as an excellent candidate for laser emissions in the whole visible region [13–16]. The typical operating wavelengths of the visible Pr: YLF lasers are 523 nm (in π polarization, $3P^1 + 1I^6 \rightarrow 3H^5$), 546 nm (in π polarization, $3P^0 \rightarrow 3H^5$), 607 nm (in σ polarization, $3P^0 \rightarrow 3H^6$), 640 nm (in σ polarization, $3P^0 \rightarrow 3F^2$), 670 nm (in π polarization, $3P^1 \rightarrow 3F^3$), 698 nm (in π polarization, $3P^0 \rightarrow 3F^3$), and 721 nm (in π polarization, $3P^0 \rightarrow 3F^4$) [17–19]. In addition, there are a few reports about the weak spectral lines of Pr: YLF crystals, such as 546 nm [20], 604 nm [21], 670 nm [22] and 910 nm [23]. What's more, in comparison to other solid-state lasers, $Pr^{3+}$ lasers need only a single nonlinear step for generation of several wavelengths in the UV [24–28], and the nonlinear optical conversion efficiency is high. In 2007, Vasily Ostoumov et al. adopted the V-tpye structure, and the output power reached 2.5 W at 522 nm. After frequency doubling, the 261 nm UV output of 620 mW was obtained, and the overall optical conversion efficiency was about 12.4% [29]. In 2008, Vasily Ostoumov et al. adopted a Z-cavity structure and used two 5.3 W OPS to pump Pr: YLF crystal, successfully achieving a maximum output power of 1 W at 261 nm [30], which is also the highest index that Pr: YLF crystals can achieve at 261 nm so far. The reports on the continuous ultraviolet light of Pr: YLF

✉ Quan Zheng
douniweixiao@163.com

1 Changchun New Industries Optoelectronics Technology Co., Ltd, Changchun 130012, China

2 Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

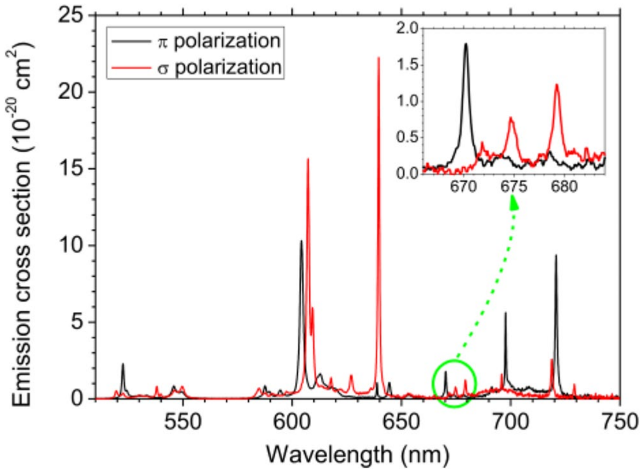



Fig. 1 Polarization-dependent emission cross sections of a Pr: YLF crystal. The inset shows the details of the investigated emission spectrum

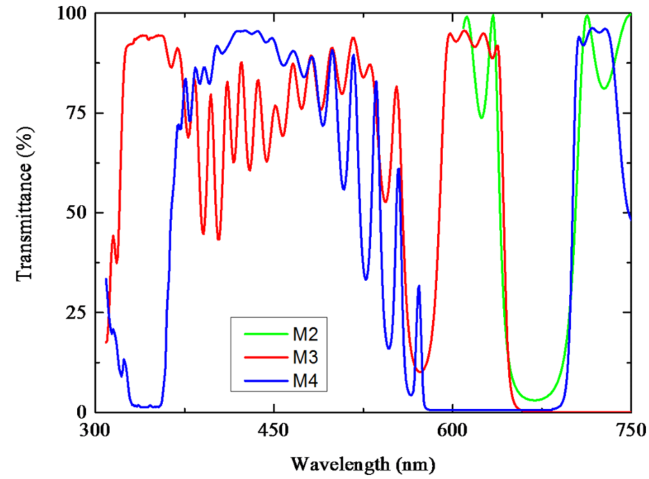



Fig. 4 Coating of mirrors, M2 and M3 are output mirrors; M4 is reflective mirror

intracavity frequency doubling mainly focus on 261 nm, and the research is relatively mature, while the reports on 320–340 nm laser are very few [31]. However, with the continuous improvement of pump power and conversion efficiency, other weak spectral lines of Pr: YLF crystal are also expected to be successfully obtained. Recently, we have demonstrated the generation of a compact deep UV laser at 273 nm with a maximum output power of up to 128 mW at 546 nm by effective frequency doubling amplification of a CW laser diode-pumped Pr: YLF laser [32]. In addition, previous studies on the spectral properties discovered that $Pr^{3+}$ ions in the YLF crystal can emit radiation at 679 nm in σ polarization (Fig. 1). As far as we know, the weak spectral line of Pr: YLF at 679 nm and the corresponding frequency doubled at 339.5 nm UV laser have not been reported.

Fig. 2 Schematic diagrams of 679 nm laser setup. The distance of M1–M2 was 38 mm

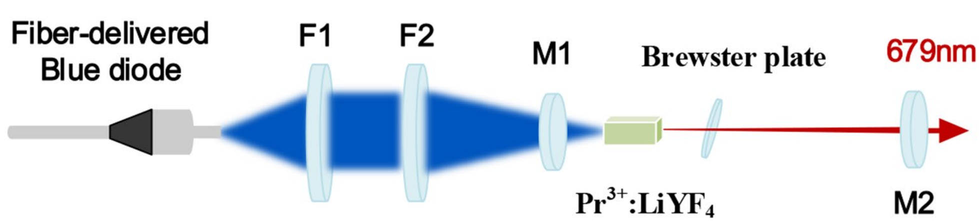
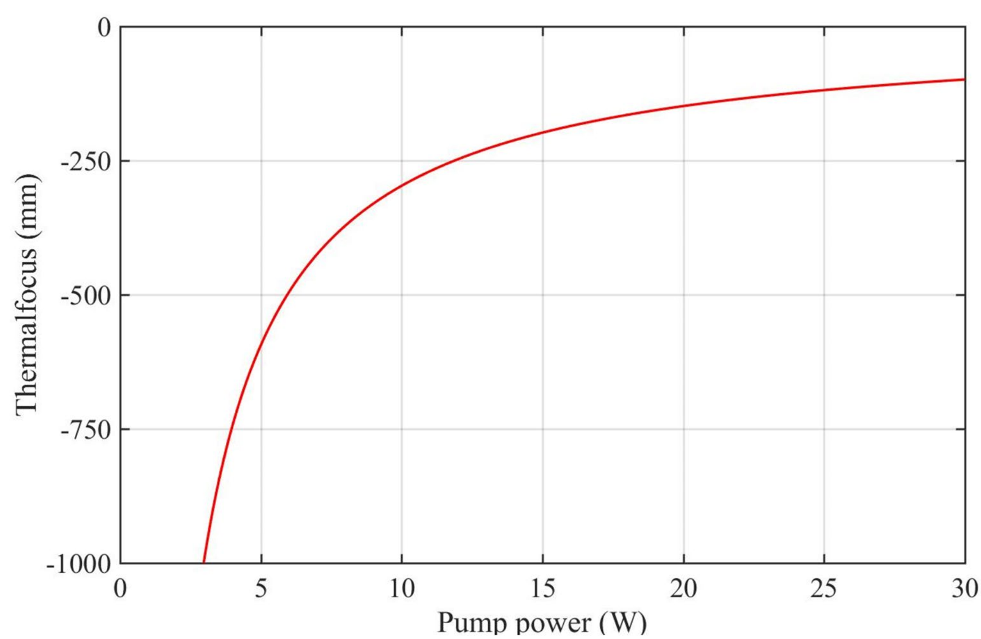



Fig. 3 The thermal focal length as the function of the pump power



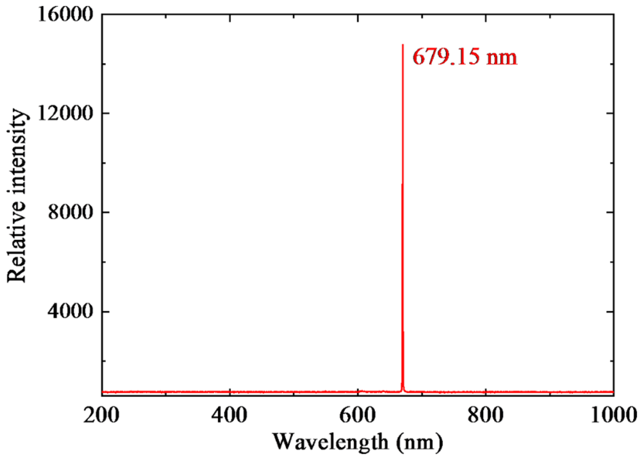



**Fig. 5** Spectra of 679 nm laser

The above-mentioned 679 nm and 339.5 nm wavelength is crucial for certain laser spectrosc, organic molecules and biophotonic applications. For example, 679 nm laser has been used to excite photoluminescence to study the effect on the cooling and trapping of strontium atoms. Using 340 nm laser as excite photoluminescence to study the structural and luminescent properties of nanophosphors synthesized [33]; Modulated 339 nm laser has been used as the light source for formaldehyde detection [34]. In this paper, we report for the first time a 3.5 W output power at 679 nm for the Pr: YLF laser end pumped by 32 W fiber-coupled at 444 nm, and on 620 mW of cw UV radiation at 339.5 nm, which has been obtained by intracavity frequency doubling of the Pr: YLF laser with a LBO crystal.

## 2 Fiber-coupled blue-diode-pumped pr: YLF laser at 679 nm

From the polarization-dependent emission cross section (see Fig. 1) [23], we can see the σ-polarized 679 nm deep red emission has a stimulated emission cross section of about $1.25\times10^{-20}$ cm$^2$, which is lower than the π-polarized 670 nm lasing ($1.8\times10^{-20}$ cm$^2$), π-polarized 698 nm lasing ($5.63\times10^{-20}$ cm$^2$) and σ-polarized 640 nm lasing ($22.3\times10^{-20}$ cm$^2$). Therefore, operation of the Pr: YLF laser at 679 nm requires suppression of these competing transitions.

Figure 2 shows the experimental setup of the Pr: YLF laser. The laser active medium was a 12 mm long YLF crystal doped with 0.3 at% Pr-ions. The fiber-coupled LD module is the pump source, which emits at 444 nm and outputs approximately 32 W from a multimode fiber. The fiber output was imaged to the laser crystal through the two convex spherical lenses with a focal length of 1.2 times, resulting in a pump spot diameter of ~240 µm. At the highest incident pump power of 28 W, the remaining pump power was 6 W corresponding to the absorption efficiency of 78.5%. 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 installed on a heat sink made of cooper, and temperature needed to be controlled strictly by a water-cooled cooper and kept at around 22 °C constantly.The quasi-basic frequency 679 nm laser uses a planar input reflector (M1) and a plane-concave output coupler (M2) to construct a simple end-pumped concave cavity, as shown in Fig. 2. The physical cavity length is preferably 38 mm.

In a high-power Pr: YLF solid-state laser, the thermal effect of the gain medium is particularly important. The focal length of the thermal lens of Pr: YLF crystal can be expressed as [35]:

$$f = \frac{\pi K_c \omega_p^2}{\xi \eta_\alpha P_{abs}\left[\frac{dn}{dT} + n(1+\mu)\alpha_T\right]} \quad (1)$$

where $K_c$ is the thermal conductivity, $\omega_p$ is the pump beam waist radius, $\xi$ is the heat transfer coefficient, $\eta_\alpha$ is fractional thermal load, $P_{abs}$ is absorption pump power, $n$ is the refractive index of the crystal, $\mu$ is the Poisson's ratio, and $\alpha_T$ is the thermal expansion coefficient of laser gain medium Pr: YLF. The curve of the thermal lens focal length of Pr: YLF crystal as a function of pump power is simulated as shown in Fig. 3. The thermal lens focal length of the Pr: YLF crystal increases logarithmically with the increase of pump power.

In our experiments, the stronger transitions near 640, 670 and 698 nm were suppressed by the use of output couplers. Coating of mirrors is shown as Fig. 4, The M1 was coated on the crystal as an input coupler to realize AR for the pump wavelength at 444 nm and HR for the fundamental wavelength at 679 nm. Straight-cavity output coupler' radius of curvature (M2) is 100 mm, which transmits 2.9% at 679 nm and T > 22% at 640, 670 and 698 nm. The laser transitions at 670, 679, and 698 nm are close to each other, so it is not easy to suppress the 670 and 698 nm lines only by optical coatings. However, the polarizations of the 679 nm line and that of the 670 and 698 nm lines are orthogonal, so that the 679 nm (σ polarization) can be selected by selecting a specific polarization. A simple way to select a specific polarization is to insert a birefringence element into the cavity. Thus, a 1 mm thick Brewster plate was used as the birefringence element.

With a good match between the specially coated cavity mirrors and the phase delay plate, only a single wavelength of 679 nm can oscillate in the resonant cavity. For 679 nm laser, the spectrum was recorded separately in Fig. 5 by using a spectrometer (Ocean Optics model HR4000). It can

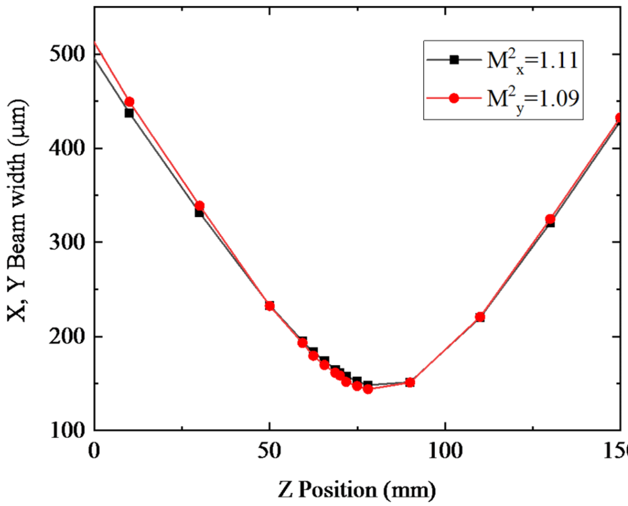



**Fig. 6** *X* and *Y* diameters of the output laser beam at 679 nm as a function of their *Z*-axis location

be seen that there are no other impurity peaks except for the desired wavelength, indicating that the spectral purity is very good. Its central wavelength is 679.15 nm. A Thorlabs beam profiler (BP209-VIS/M) was used to measure the beam quality. As shown in Fig. 6, the 679 nm laser radiation has good beam quality, the values of $M^2$ in the *x* and *y* directions are measured to be 1.11 and 1.09, respectively. Through Fig. 7, we can clearly see the laser characteristics. If the absorption pump power is 22 W, the maximum output power can reach 3.5 W. For the optical-optical conversion efficiency, 15.9% can be achieved, and the slope efficiency is about 19.8%. The slope efficiency is lower when the absorber pump power is less than 6 W. When the absorbed pump power increases, the slope efficiency tends to increase. Stable laser output is always desirable for various applications. The output power stability of the 679 nm laser can be easily estimated by recording the instantaneous values of the output powers with time. Thus, the stability of the maximum output powers for the 679 nm laser were deduced to be about 0.27% (RMS, root mean square).

However, the total output power of the pump source has not been fully utilized. When the pump power exceeded a

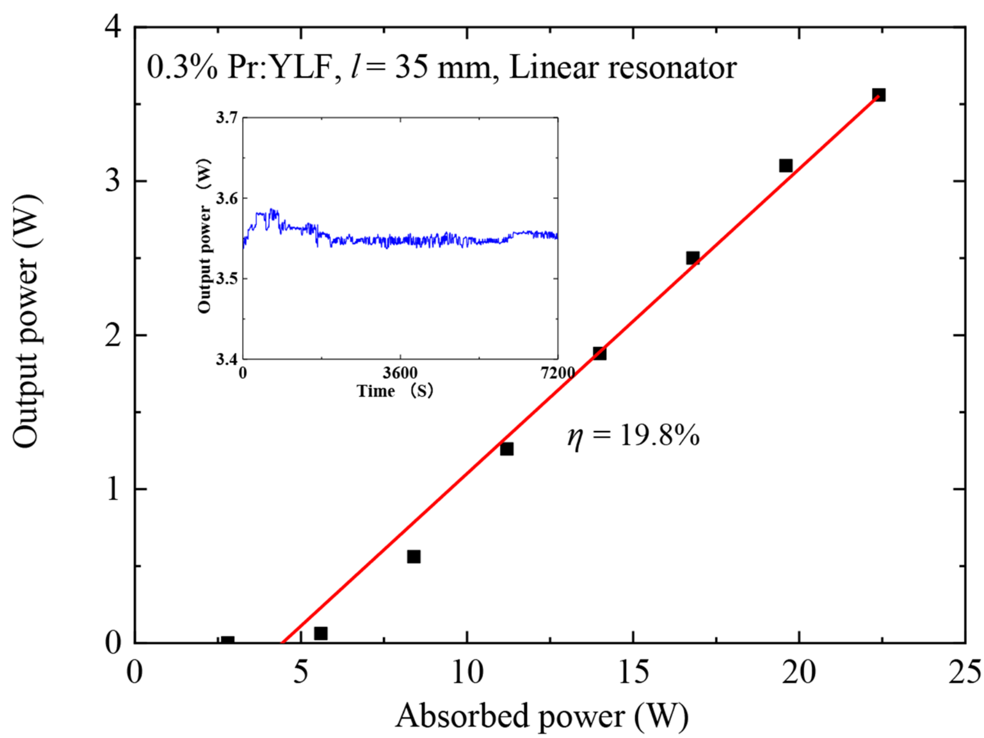



**Fig. 7** Output power characteristics of 679 nm laser; Inset: power stability at a maximum output power of 3.5 W

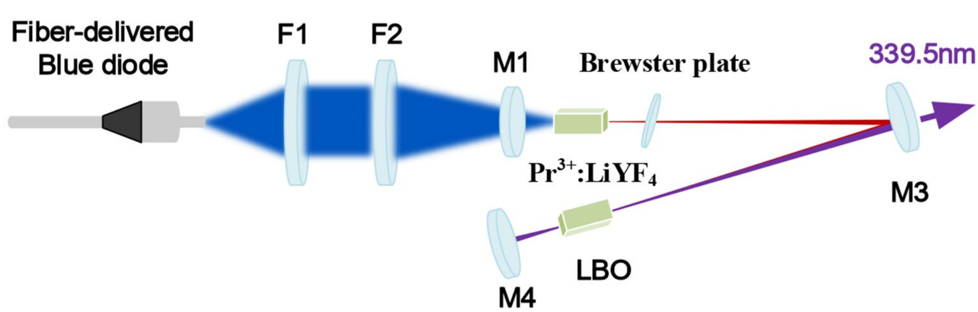



**Fig. 8** Schematic diagrams of the frequency doubled UV laser setup. The distances of M1–M3 and M3–M4 were 75 and 97 mm, respectively

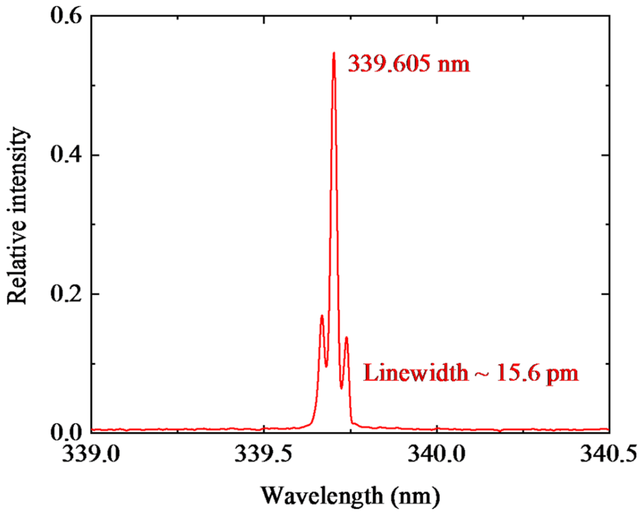



**Fig. 9** Spectra of 339.5 nm laser

certain value, the power of 679 nm laser did not increase, even has a downward trend. The possible reason is that the pump source is comprised of several LDs, not all the LDs can emit at the relatively low current level. Hence, the pump beam patterns at the high and the low output power levels are different. In our opinion, the essential reason might be the reduction of absorption efficiency caused by the thermal lensing effects and the laser mode variation.

## 3 Continuous-wave ultraviolet generation at 339.5 nm

Figure 8 displays the schematic of intracavity frequency doubling of 679 nm, an 8 mm LBO type I crystal (θ = 90°, φ = 46.5°) was used. It was mounted on TEC and temperature controlled. Double sides of LBO crystal are AR coated for 679/335.5 nm to reduce the reflection losses in the cavity. A Folded V-resonator was used in laser experiment; the whole second harmonic generation (SHG) in one direction was realized by reflecting it back from the end mirror. No UV laser passes through gain material, preventing it from the additional risks of optical degradation. The folded V-resonator consisted of M1, M3 and M4. The physical length of the cavity was 172 mm (M1-M3: 75 mm, M3-M4: 97 mm). The concave HR mirror's incident angle was set to ~10° to minimize cavity astigmatism. The stronger transitions near 640, 670 and 698 nm were also suppressed by the use of output couplers. The curvature radius of the folded cavity output coupler (M3) is 100 mm, the high reflectivity $R > 99.5\%$ around 679 nm, the high transmittance T > 92% around 339.5 nm and the transmittance T > 89% around 640 nm. The folded cavity reflector (M4) is a plane mirror, the reflectivity $R > 99.3\%$ around 679 and 339.5 nm, and the transmittance T > 93% around 698 and 721 nm (Fig. 4). Similarly, a 1 mm thick Brewster plate was used in the experiment.

The laser spectrum of single lasing wavelength at 339.5 nm was registered separately in Fig. 9 by using a wavelength meter (High Finesse model LSA). The UV laser's central wavelength is 339.605 nm and the linewidth is 15.6 pm. A folded resonator can provide optimal beam waists both in nonlinear crystals and gain crystals. When the thermal focal length of Pr: YLF crystal is -100 mm, the simulated optical waist radius at the gain crystal is approximately 92 µm, and the optical waist radius at the LBO is about 93 µm. As the pumping power increases, the thermal effect of the crystal increases, the inner waist size of LBO decreases obviously, the SHG efficiency increases, and the slope efficiency of the laser output power tends to increase. For the intracavity frequency doubled 339.5 nm laser performance was presented in Fig. 10. With an absorbed pump power of 22 W, a continuous wave SHG total output power of 620 mW at 339.5 nm UV band was obtained, and the stability of the maximum output power was about 0.51%. The optical-to-optical conversion efficiency was 2.8%. In the future, the optical-to-optical conversion efficiency at 339.5 nm can be improved by increasing the reflectivity of the cavity mirrors at 679 nm and 339.5 nm, optimizing the cavity design for better phase matching, and appropriately reducing the beam waist size at LBO.

To characterize the beam quality of the 339.5 nm UV laser beam, its diameter was measured in the x and y directions at maximum output power (see Fig. 11). The fits of these data then lead to the $x$ and $y$ $M^2$ factors $M^2{}_x = 1.18$ and $M^2{}_y = 1.13$, which clearly shows a good beam quality.

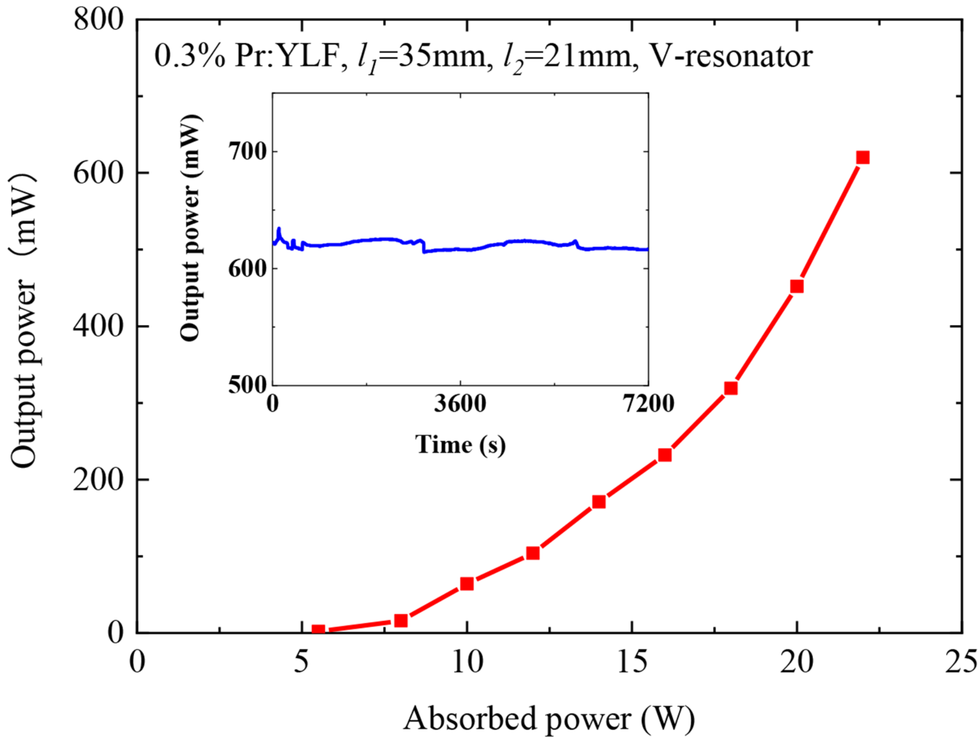



**Fig. 10** Output power characteristics of UV laser; Inset: power stability at a maximum output power of 620 mW

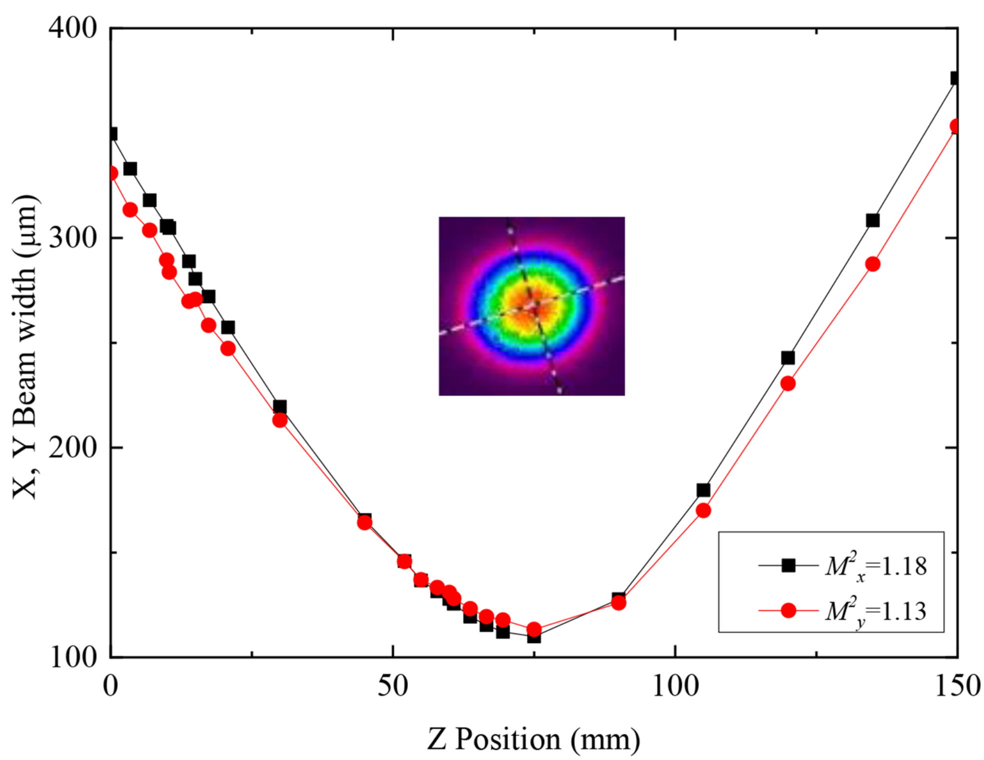



**Fig. 11** *X* and *Y* diameters of the output laser beam at 339.5 nm as a function of their *Z*-axis location

## 4 Conclusions

In conclusion, we succeeded in the realization of what we believe to be the first a fiber-coupled LD module pumped Pr: YLF-LBO laser at 679/339.5 nm. When the wavelength is 679 nm, the output power of continuous wave is 3.5 W, and the conversion efficiency is 15.9%. After SHG, the maximum power at wavelength 339.5 nm is 620 mW, and the optical-optical conversion efficiency is 2.8%. The propagation coefficients $M^2_x$ and $M^2_y$ in the *x* and *y* directions are 1.18 and 1.13, respectively. It opens up a new way for the realization of ultraviolet laser. In the future, we expect to develop more emission lines of $Pr^{3+}$ crystals.

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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. Shanshan Hou assisted with experiments and text review. Xinyue Wang, Fang Ma collected data and prepared figures. HuiWen Ji 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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