

单纵模 261 nm 紫外激光器的研制

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摘要 设计了一种使用两个不同波长的蓝光激光二极管合束抽运的 261 nm 单纵模紫外激光器。激光器腔型结构为 V 型。单纵模的选取使用法布里-珀罗(F-P)标准具。将波长分别为 444 nm 和 469 nm、最大抽运功率分别为 1.4 W 和 1.5 W 的蓝光激光二极管各一支作为抽运源。将尺寸为 3 mm×3 mm×5 mm、掺杂浓度(质量分数)为 0.5% 的掺镨氟化钪晶体作为增益介质。将 I 类相位匹配的偏硼酸钡(BBO)晶体用作倍频晶体。优化谐振腔参数并调整两个法布里-珀罗标准具的参数,当注入功率为 2500 mW 时,获得了最大连续功率为 110 mW 的单纵模 261 nm 紫外激光输出。

关键词 激光器; 单纵模; 紫外激光器; 偏硼酸钡晶体; 法布里-珀罗标准具

中图分类号 TN248.1

文献标识码 A

DOI: 10.3788/CJL202249.0901002

1 引言

单纵模激光器具有输出线宽窄、频率稳定等优点,被广泛应用于高分辨率激光光谱学、相干通信、引力波探测、量子光学、相干探测等科学研究领域中^[1-3]。其中紫外激光器受到了国内外研究人员的广泛关注,能应用于紫外光刻、拉曼光谱、半导体晶片微处理等领域^[4]。根据结构的不同,激光器分为半导体、气体和固体激光器。其中,利用激光二极管(LD)泵浦的全固态激光器性能良好,具有效率高、输出稳定等优点,得到广泛研究^[5-7]。

全固态激光器输出 261 nm 紫外激光有两种方式,一种方式是使用 Nd:YLF 晶体先输出 1047 nm 基频红外激光,再经过两次频率转换最终实现 261 nm 紫外激光输出;另一种方式是使用 Pr:YLF 晶体先输出 522 nm 基频激光,再经过一次频率转换输出 261 nm 紫外激光。第一种方法需要进行两次频率转换,转换效率低,因此第二种方法是实现 261 nm 激光输出较为合适的方式。Pr³⁺ 能够直接输出可见光,备受科研人员的关注^[8-14]。

2007 年, Ostroumov 等^[15] 利用输出功率为

5.3 W 的 479 nm 光泵半导体激光器(Optically Pumped Semiconductor Lasers, OPLS)泵浦 Pr:YLF 晶体,成功输出了功率为 2.5 W 的 522 nm 激光和功率为 620 mW 的 261 nm 的连续紫外激光。2008 年, Ostroumov 等^[16] 基于两台 479 nm 光泵半导体激光器,采用双端泵浦技术提高了泵浦功率,对 Pr:YLF 晶体进行抽运并采用腔内倍频技术,实现了 1 W 输出功率的 261 nm 波长的激光。2014 年, Kojou 等^[17] 成功实现了 261 nm 脉冲激光器,最大峰值功率为 61.8 W。单纵模激光器具有线宽窄、噪声低的特点,可应用于远距离传感系统等多个领域,具有高灵敏度、高精度的优点。目前,国内外还没有报道过单纵模 261 nm 紫外激光器。本文将两支波长不同的蓝光二极管发出的光进行合束并将其作为抽运源,将偏硼酸钡(BBO)晶体作为倍频晶体,将法布里-珀罗(F-P)标准具用于单纵模选取,最后得到了最高功率为 110 mW 的 261 nm 单纵模紫外激光。

2 实验设计

2.1 蓝光二极管抽运 Pr:YLF 晶体

522 nm 激光是 Pr³⁺ 在可见光波段辐射跃迁产

收稿日期: 2021-09-13; 修回日期: 2021-09-29; 录用日期: 2021-10-15

基金项目: 吉林省科技攻关计划(20170203013GX)

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生的,对其进行频率转换即可输出 261 nm 紫外激光。 Pr^{3+} 在蓝光波段存在三个吸收带,对应峰值波长分别为 444, 469, 479 nm, 且 Pr^{3+} 具有偏振吸收特性,对 π 偏振方向的抽运光吸收最多。由于单管蓝光激光二极管的输出功率低,因此本文将两支蓝光二极管发出的光进行空间合束并利用其抽运 $\text{Pr}:\text{YLF}$ 晶体。同时,在固定蓝光激光二极管时,使其发出的光沿 π 偏振方向注入到 $\text{Pr}:\text{YLF}$ 晶体中,提高 $\text{Pr}:\text{YLF}$ 晶体对抽运光的吸收效率。

2.2 实验装置

本实验装置的抽运源为德国 OSRAM 公司生产的 1 支 469 nm 蓝光激光二极管和 1 支 444 nm 蓝光激光二极管,最大输出功率分别为 1.5 W 和 1.4 W。以焦距为 4.2 mm 的非球面透镜作为准直镜,对两支自由空间输出的蓝光激光二极管进行准直,利用 45° 合光片(镀有高透射膜和高反射膜,前者透射率 $T > 99.5\% @ 444 \text{ nm}$,后者反射率

$R > 99\% @ 469 \text{ nm}$)将两支蓝光激光二极管的抽运光合束,合束光经过一个焦距为 12 mm 的球面聚焦透镜后注入 $\text{Pr}:\text{YLF}$ 晶体中,实验装置图如图 1 所示。

激光工作物质采用 $\text{Pr}:\text{YLF}$ 晶体,其尺寸为 $3 \text{ mm} \times 3 \text{ mm} \times 5 \text{ mm}$, Pr^{3+} 掺杂浓度(质量分数)为 0.5%。将靠近抽运源一端的 $\text{Pr}:\text{YLF}$ 晶体端面作为腔镜(M1),并镀有 444 nm、469 nm 增透介质膜以及 261 nm、522 nm 高反介质膜。 $\text{Pr}:\text{YLF}$ 晶体的另一个端面镀有 261, 444, 469, 522 nm 增透介质膜,该介质膜对 261 nm 激光的透过率约为 95%。倍频晶体为 I 类相位匹配切割的 BBO 晶体,其长度为 3 mm,切割角度为 49° ,并且晶体表面未镀膜。若镀膜,BBO 晶体表面的介质膜会被 261 nm 紫外激光损坏,最终影响激光器的寿命。将蓝光激光二极管、 $\text{Pr}:\text{YLF}$ 晶体以及 BBO 晶体固定在铜质热沉上进行散热,并使用热电冷却器(TEC)进行精确控温。

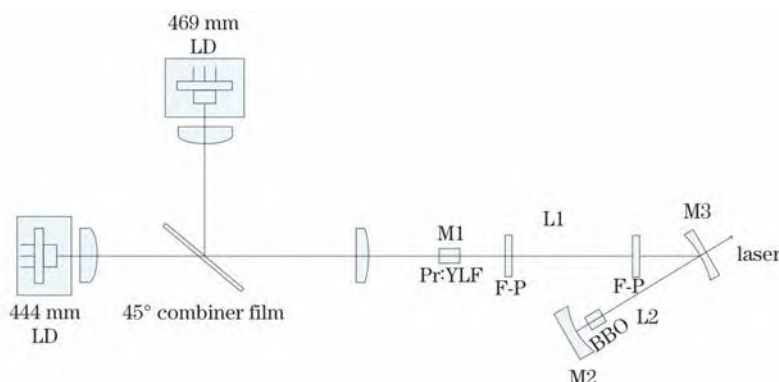


图 1 实验装置图

Fig. 1 Schematic of experimental device

激光器谐振腔采用 V 型腔,输出镜(M3)为曲率半径为 50 mm 的凹面镜,镀有 522 nm 高反射介质膜、261 nm 高透射介质膜,该介质膜对 261 nm 激光的透过率约为 96%。全反镜(M2)为曲率半径为 200 mm 的凹面镜,镀有 261 nm、522 nm 高反射介质膜。谐振腔长臂(L1)长度为 45 mm,短臂(L2)长度为 32 mm。如图 2 所示,由于 $\text{Pr}:\text{YLF}$ 晶体是负折射率晶体,因此激光晶体热透镜焦距取负值,当激光晶体热透镜的焦距取 -300 mm 时,利用 ABCD 传输矩阵,计算可得腔内 $\text{Pr}:\text{YLF}$ 晶体处的光腰半径约为 $92 \mu\text{m}$,BBO 晶体处的光腰半径约为 $41 \mu\text{m}$ 。

2.3 选模分析

当激光器运转时,光学谐振腔的尺寸远大于光波波长,因此在增益曲线内同时存在大量的纵模振荡。当谐振腔内只有一个纵模振荡,其他纵模被抑

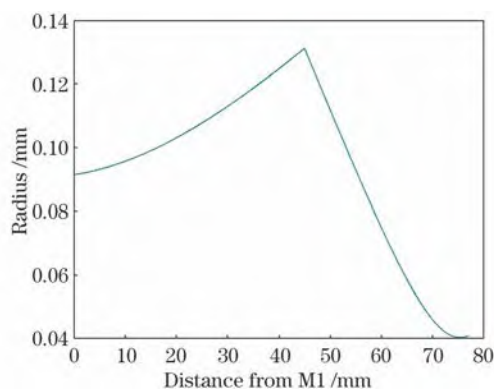


图 2 谐振腔内各位置的光斑半径

Fig. 2 Spot radius at each position within resonator cavity

制而无法振荡时,激光器输出的激光为单纵模激光。目前,激光器实现单纵模运转的方法有短腔法、F-P 标准具法、耦合腔法、扭转模法等^[18]。

本实验采用双 F-P 标准具法实现单纵模运转, 两个 F-P 标准具的间距为 20 mm。由于存在多光束干涉, F-P 标准具只允许若干个具有很窄频率带宽的光通过, 其可用于增大飞秒脉冲激光频率梳的梳齿间距^[19]。本实验装置使用的 F-P 标准具双面镀膜, 反射率为 60%, 厚度为 1 mm, 自由光谱范围 (FSR) 为 24.75 GHz。当 F-P 标准具与光轴夹角为 0.78° 时, 透过率曲线如图 3 所示, 在一定的光谱范围内, 透过率存在周期性变化。只有 F-P 标准具处的透过率足够高, 并且达到起振的阈值, 才可输出激光。

当 F-P 标准具与腔内光轴之间的夹角发生改变时, 透过率曲线的变化如图 4 所示。

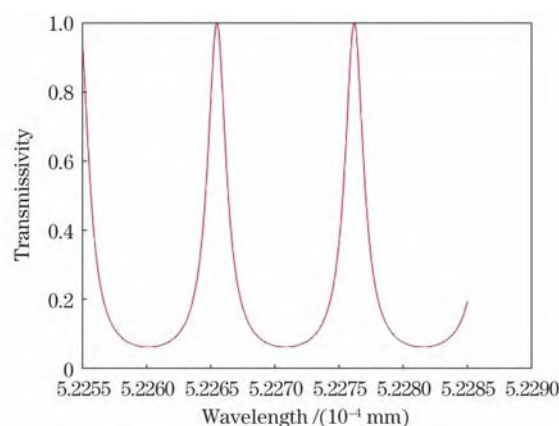
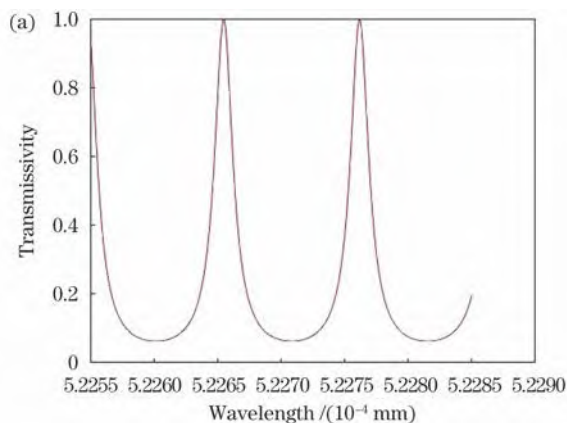


图 3 F-P 标准具的透过率曲线

Fig. 3 Transmittance curve of F-P etalon

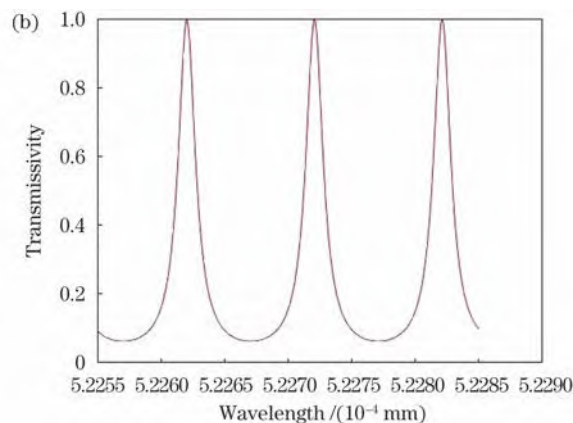


图 4 F-P 标准具的角度调节。(a) 0.78° 夹角; (b) 0.5° 夹角

Fig. 4 Angle adjustment of F-P etalon. (a) 0.78° angle; (b) 0.5° angle

当使用两个 F-P 标准具 (F-P-1 和 F-P-2) 进行选模时, 组合 F-P 标准具的透过率曲线如图 5 所示, 其中圆点位置为组合 F-P 标准具的最高透过率点。单个标准具的透过率曲线线宽较宽, 当两个标准具同时使用时, 透过率曲线的线宽变窄, 此时更容易实现单纵模的选取。

本实验使用锆钛酸铅压电陶瓷 (PZT) 来调节

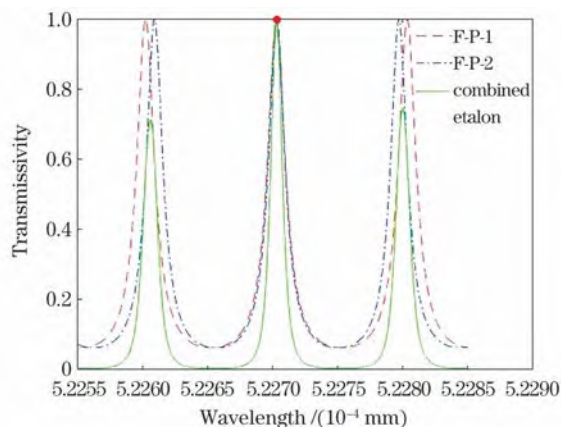


图 5 组合标准具的透过率曲线

Fig. 5 Transmittance curves of combined etalon

F-P 标准具与光轴之间的夹角, 进而实现激光器的单纵模运转。F-P 标准具的角度调谐装置如图 6 所示, F-P 标准具被固定在玻璃卡具上, 通过精确调节 PZT 的电压, 可改变标准具与光轴之间的夹角, 达到精确选模的目的。

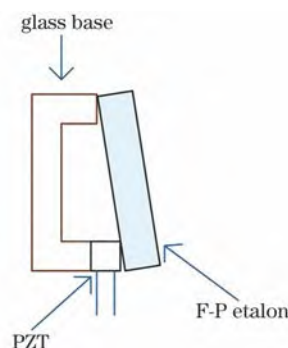


图 6 F-P 标准具的角度调节装置

Fig. 6 Angle adjusting device of F-P etalon

3 实验结果与分析

按照设计的腔型搭建实验光路, 调节 LD 准直

透镜和聚焦镜的位置,使泵浦光更好地匹配腔内光,同时精确调节 F-P 标准具的角度调谐装置。

使用 High Finesse 公司的 WS7-60 型号波长计

测试输出激光的波长,测试结果为 261.35238 nm,且沿频谱横向方向无其他频率的纵模存在,说明为单纵模,如图 7 所示。

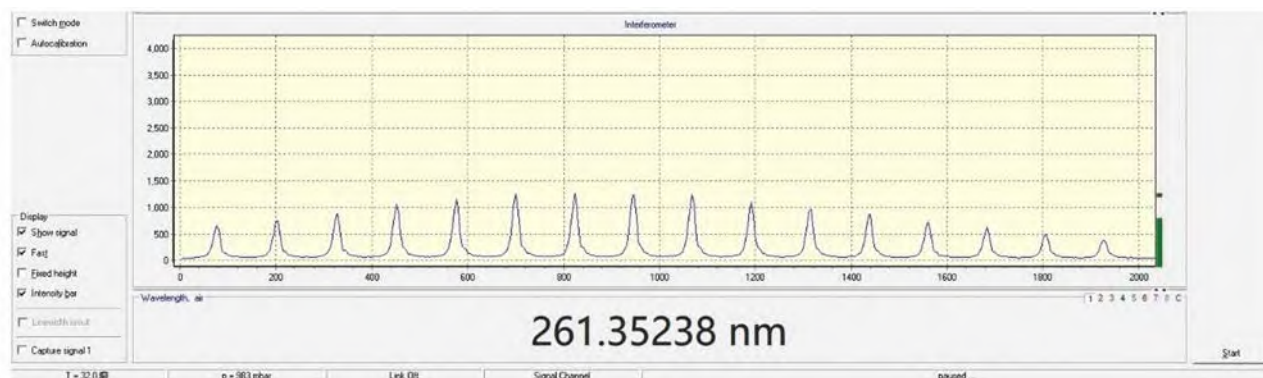


图 7 纵模测试图

Fig. 7 Test diagram of longitudinal mode

使用 Spiricon 轮廓分析仪及 Thorlabs 光束质量测试设备测试 261 nm 激光的光束质量(M^2),如

图 8 所示,测试结果显示,横向光束质量(M_x^2)为 2.29,纵向光束质量(M_y^2)为 2.21。

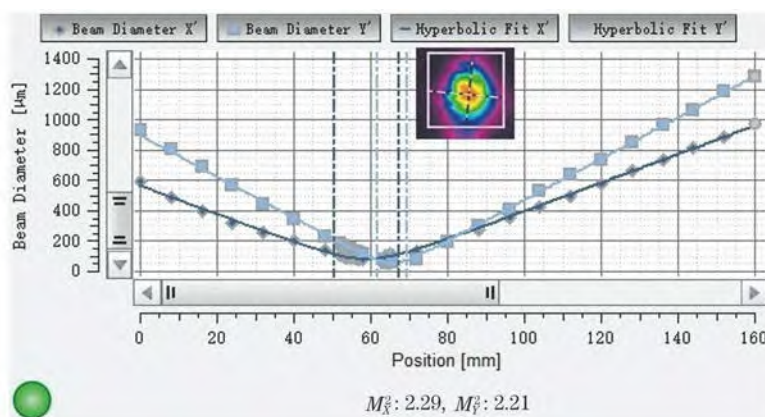


图 8 261 nm 激光的光斑及光束质量

Fig. 8 Laser spot and beam quality at 261 nm

使用功率计测试 261 nm 紫外激光的功率随注入泵浦功率的变化,结果如图 9 所示。连续测试 2 h, 261 nm 紫外激光的功率稳定性如图 10 所示,

可以看出,261 nm 紫外激光的功率稳定性为 1.40%,最大功率为 110 mW。

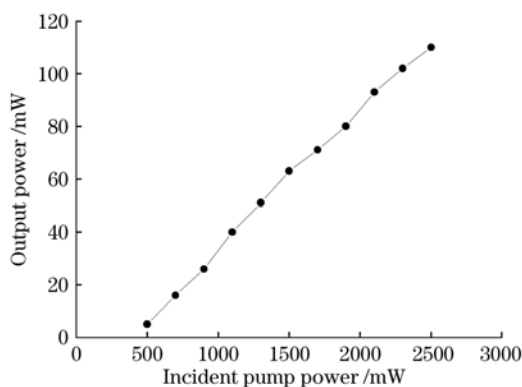


图 9 261 nm 激光的输出功率随注入泵浦功率的变化

Fig. 9 Output power of 261 nm laser versus incident pump power

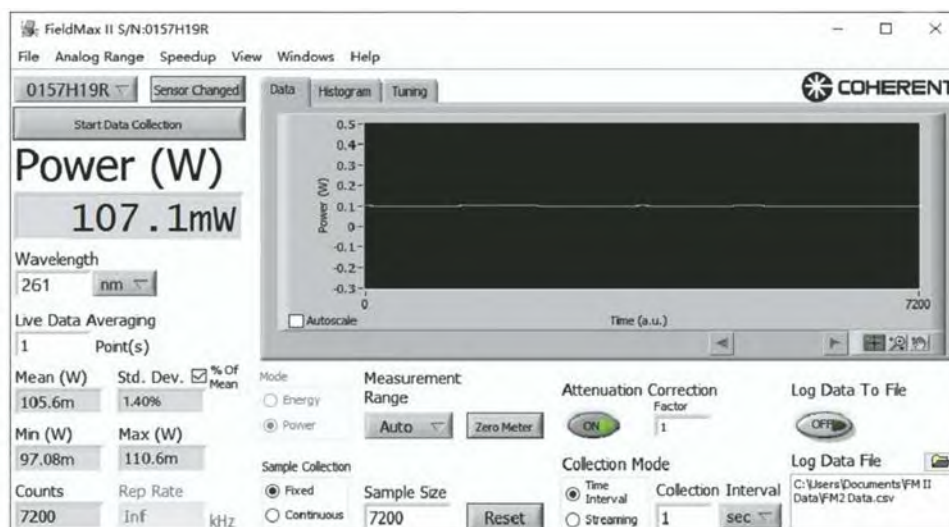


图 10 261 nm 紫外激光的功率稳定性

Fig. 10 Power stability of 261 nm UV laser

4 结 论

利用 V 型腔结构,选择波长为 444 nm 和 469 nm 的蓝光激光二极管,将其输出的光进行合束并作为抽运光,同时在固定蓝光激光二极管时,使其发出的光沿 π 偏振方向注入到激光工作物质中,以提高激光工作物质对抽运光的吸收效率。利用 F-P 标准具的特性,通过改变 F-P 标准具与腔内光之间的角度来选取单纵模。当注入功率为 2500 mW 时,获得了最大连续功率为 110 mW 的 261 nm 单纵模紫外激光。连续测试 2 h,261 nm 单纵模紫外连续激光的功率稳定性优于 1.40%。目前,该项成果已实现产业化。

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Development of 261 nm Single-Longitudinal Mode Ultraviolet Laser

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Abstract

Objective The single longitudinal mode laser has the advantages of narrow linewidth and stable frequency. It is widely used in the scientific research fields such as high-resolution laser spectroscopy, coherent communications, gravitational detection, quantum optics, and coherent detection. The ultraviolet (UV) laser can be used in UV lithography, Raman spectroscopy, semiconductor wafer micro-processing, and other fields, which has received extensive attention from researchers at home and abroad. All-solid-state lasers pumped by laser diodes have the advantages of high efficiency and stable output. At present, as far as we know, the 261 nm single longitudinal mode UV laser has not been reported at home and abroad. The 261 nm single longitudinal mode UV laser can provide a new light source for the above research fields.

Methods The laser experimental apparatus uses two blue laser diodes as the pump source. A 444 nm blue laser diode has the maximum pump power of 1.4 W. And a 469 nm blue laser diode has the maximum power of 1.6 W. An aspherical lens with a focal length of 4 mm is used to collimate the blue laser diode. A 45° combiner is used to combine the pump light of the two blue laser diodes. The transmittance at 444 nm is more than 99.5% and the reflectivity at 469 nm is more than 99%. Finally, a spherical focusing lens with a focal length of 12 mm is used to

inject the pump light into the Pr:YLF crystal. The Pr:YLF crystal with the size of $3\text{ mm} \times 3\text{ mm} \times 5\text{ mm}$ and doping concentration (mass fraction) of 0.5% is used as the gain medium. The end face of the Pr:YLF crystal near one end of the pump source is plated with 444 nm and 469 nm antireflective dielectric films. The other end face of the Pr:YLF crystal is plated with 261, 444, 469, and 522 nm antireflective dielectric films. The two blue laser diodes are fixed in the π polarization direction. The purpose is to improve the absorption efficiency of the Pr:YLF crystal. A type-I phase-matched BBO crystal with the size of $3\text{ mm} \times 3\text{ mm} \times 3\text{ mm}$ is used as the frequency-doubling crystal. The surface of the BBO crystal is not coated to avoid UV laser damages to the crystal. The laser experimental apparatus is V-shaped. The purpose is to improve the conversion efficiency of the frequency doubling crystal. Two Fabry-Perot etalons are used to select the single longitudinal mode. The thermoelectric cooler is used to control the temperatures of the Pr:YLF crystal and the frequency doubling crystal to improve efficiency. The lead zirconate titanate piezoelectric ceramics is used to control the position of the Fabry-Perot etalon in the laser resonator. By carefully adjusting the length of the cavity, the position of the Fabry-Perot etalon, and the temperature of the thermoelectric cooler (TEC), a good 261 nm single longitudinal mode UV laser is realized.

Results and Discussions The laser experimental apparatus (corresponding to the scheme mentioned above) achieves good experimental results with single longitudinal mode (Fig. 7). The laser experimental apparatus uses two Fabry-Perot etalons. The purpose is to select a stable single longitudinal mode. The lead zirconate titanate piezoelectric ceramics is used to control the position of the Fabry-Perot etalon in the laser resonator (Fig. 6). The maximum output power of the 261 nm single longitudinal mode laser is 110 mW when the incident pump power is 2500 mW (Fig. 9). A CCD laser beam analyzer is used to measure the beam quality of the 261 nm single longitudinal UV laser with an output power of 110 mW. A laser beam quality analyzer is used to measure the beam quality factor of the 261 nm single longitudinal mode UV laser with an output power of 110 mW (Fig. 8). A laser power detector is used to measure the power stability of the 261 nm single longitudinal mode UV laser for 2 h (Fig. 10).

Conclusions A 444 nm blue laser diode and a 469 nm blue laser diode, whose maximum pump powers are 1.4 W and 1.5 W, respectively, are used as the pumping source. The two blue laser diodes are fixed in the π polarization direction. A 45° combiner is used to combine the pump light of the two blue laser diodes. An aspherical lens with a focal length of 4 mm is used as a collimator to collimate the pump light emitted by the blue laser diode. A spherical lens with a focal length of 12 mm is used as a focusing lens to focus the pump light emitted by the blue laser diode. The cavity structure of the laser is V-shaped. The Fabry-Perot etalon is used to select a single-longitudinal mode. The Pr:YLF crystal with a size of $3\text{ mm} \times 3\text{ mm} \times 5\text{ mm}$ and doping concentration (mass fraction) of 0.5% is used as the gain medium. The type-I phase-matched BBO crystal with a size of $3\text{ mm} \times 3\text{ mm} \times 3\text{ mm}$ is used as the frequency-doubling crystal. By optimizing the resonator parameters and the parameters of two Fabry-Perot etalons, the maximum output power of 261 nm single-longitudinal ultraviolet laser is 110 mW when the incident pump power is 2500 mW.

Key words lasers; single longitudinal mode; ultraviolet laser; BBO crystal; Fabry-Perot etalon