中国激光

532 nm激光泵浦单谐振光参量振荡器倍频蓝光技术

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摘要 利用腔内倍频532 nm激光器抽运单谐振光学参量振荡器(SRO)，设计了一种可输出972 nm激光的脉冲激光器，通过腔外倍频成功获得486 nm蓝光。在重复频率为1 kHz的条件下，当532 nm激光脉冲能量为3.87 mJ时，972 nm SRO信号光单脉冲能量可达0.96 mJ，此时获得最大转换效率24.8%，与理论计算值22.3%相近。倍频后获得最大能量为49 μJ的486 nm蓝光脉冲，脉冲宽度约为6.9 ns，最大倍频效率为5.3%。

关键词 激光光学；蓝光激光；光参量振荡；腔外倍频；三硼酸锂晶体；全固态激光

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1 引 言

海水的透光窗口在420～580 nm蓝绿光波段，因此海洋探测激光雷达常用蓝绿波段激光作为发射光源[1-6]。研究发现，近岸海水的最佳透光波长为520～580 nm，而在清澈大洋水中激光探测的最佳波长为420～510 nm[6]。目前，海洋激光雷达常用波段为532 nm。从探测深度和信噪比两个方面分析星载海洋激光雷达的最佳波长，488 nm的蓝光在全球海洋探测深度上具有明显的优势。从激光的回波信噪比和雷达系统的有效工作时长角度来说，当系统以靠近488 nm波段的486.1 nm为工作波长[7-8]时，可以利用太阳光谱的夫琅禾费暗线的优势，降低背景噪声、提高信噪比，同时延长白天工作时间[9]。

目前，获得480～490 nm波段蓝光的技术手段主要有以下两种[7-8,10-11]：一是基于掺铥光纤激光器产生1.8～2.0 μm激光再进行四倍频，获得480～490 nm波段蓝光输出。代表性的工作有Honea等[10]采用输出功率为700 mW、重复频率为10 kHz的1940 nm调Q激光器作为主振荡器，利用790 nm激光二极管泵浦的掺铥大模场(LMA)光纤对脉冲激光进行放大，再通过周期性极化铌酸锂(PPLN)晶体倍频输出970 nm激光，最后通过三硼酸锂(LBO)晶体倍频获得485 nm蓝光激光脉冲输出，蓝光平均功率为1.2 W，脉宽为65 ns，单脉冲能量约为120 μJ。另一种获得480～490 nm波段激光输出的技术手段是基于1064 nm掺钕离子固体激光器的非线性谐波转换技术，利用其三倍频输出的355 nm紫外激光脉冲泵浦光参量振荡器(OPO)，进而获得480～490 nm波段的蓝光激光输出。2021年，Zhang等[8]采用355 nm紫外脉冲激光泵浦偏硼酸钡(BBO)晶体OPO，获得了最高单脉冲能量为162 mJ、峰值功率为16.9 MW的486 nm蓝光激光输出，该研究结果解决了486 nm蓝光单脉冲能量低的难题，但其重复频率只有10 Hz，难以满足高分辨率海洋激光探测需求。采用532 nm激光脉冲泵浦OPO可获得黄光到近红外光的输出[12-15]，但进而通过倍频获得蓝光输出的报道相对较少。2009年，Hu等[16]采用输出功率为400 mW、重复频率为4 kHz的532 nm激光泵浦的周期性极化钽酸锂(PPLT)晶体OPO，在晶体的中心温度为140 ℃的条件下，通过腔内自倍频获得了60 mW的440 nm蓝光输出。

本文以重复频率为1 kHz的腔内倍频532 nm电光调Q Nd:YAG激光器作为单谐振光学参量振荡器(SRO)泵浦光源，采用两块串联的三硼酸锂(LBO)晶体作为参量晶体，在20 ℃温控条件下，当532 nm泵浦激光脉冲能量为3.87 mJ时，获得了OPO 972 nm信号光脉冲最大0.96 mJ的能量输出，脉冲宽度约为7.5 ns，光-光转换效率约为24.8%。进一步在OPO输出腔镜后插入一块I类相位匹配切割的LBO倍频晶体，成功获得了49 μJ的486 nm蓝光激光脉冲输出，倍频效率约为5.3%，激光脉冲宽度约为6.9 ns，水平方向和竖直方向的光束质量M_x^2和M_y^2分别为1.26和1.15。相较于传统480～490 nm波段蓝光的主要技术手段，本实验装置结构简单紧凑，且完全避

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免了紫外激光脉冲对腔镜膜的损伤风险，可有效提高激光器的寿命，有利于研制更加稳定可靠的海洋激光探测系统。

2 实验装置及原理

传统的光学参量振荡器根据谐振波数量可分为SRO和双谐振光学参量振荡器（DRO），如图1所示。DRO中谐振腔信号光与空闲光同时在腔内往返振荡获得增益放大并最终实现输出，而SRO中谐振腔只对信号光或空闲光中的一个光波频率共振响应，另一个频率的光波完全透射出腔外，使得只有一个参量光在腔内振荡并耦合输出。研究表明，当OPO谐振腔腔镜受到机械扰动或环境温度变化影响时，DRO结构的谐振频率变化量大于SRO结构，因此，本文实验采用光谱和功率稳定性相对较好的SRO结构设计[17]。

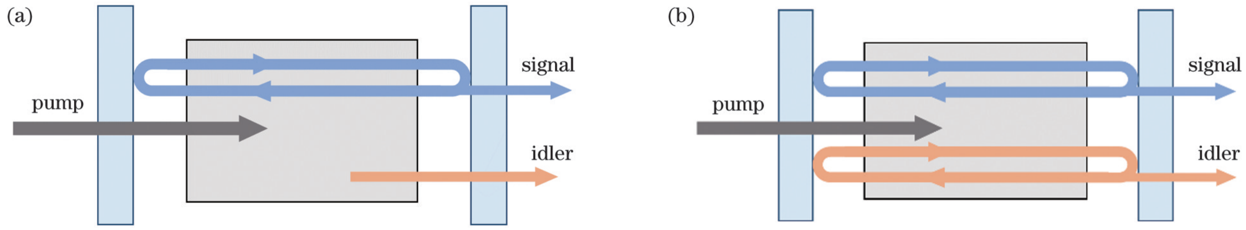


图1　不同结构的OPO工作原理示意图。(a)SRO；(b)DRO

Fig. 1　Working principle diagrams of OPOs with different structures. (a) SRO; (b) DRO

图2为激光器系统的光路，激光器主要由三个部分组成，即腔内倍频532 nm激光器、单谐振LBO晶体OPO和LBO晶体倍频单元。其中，532 nm激光器是实验室自主搭建的重复频率为1 kHz的电光调Q Nd:YAG腔内倍频激光器，在该激光器谐振腔内插入I类相位匹配的LBO晶体，可获得532 nm激光脉冲输出，LBO晶体的切割角为$\theta=90°$和$\varphi=11°$，几何尺寸为4 mm×4 mm×12 mm。

在532 nm激光器后续光路中插入半波片，用于调整改变532 nm激光脉冲的偏振状态。焦距比为5:2的光束变化系统用于压缩532 nm激光束的直径，以提高进入OPO晶体的泵浦光的功率密度。平面腔镜M1镀有532 nm高透膜和972 nm高反膜，与曲率半径为2000 mm且镀有532 nm高透膜和972 nm部分反射膜（反射率$R=65\%$）的耦合输出平凹镜M2构成平凹腔，两腔镜同时对1175 nm空闲光波长高透，保证OPO 972 nm信号光单谐振输出。OPO腔的几何长度为33 mm，将腔内两块I类相位匹配的LBO晶体放置在合适位置，使其在走离方向上彼此补偿，晶体尺寸为4 mm×4 mm×12 mm，切割角为$\theta=90°$和$\varphi=11.4°$，有效非线性系数为0.83 pm/V。

分束镜BS1镀有532 nm高反膜和972 nm增透膜。972 nm信号光脉冲由OPO输出镜M2输出，经BS1入射到LBO倍频晶体（LBO3）上，获得486 nm蓝光激光脉冲输出。用于倍频的LBO晶体的尺寸为4 mm×4 mm×12 mm，切割角为$\theta=90°$和$\varphi=17.6°$，有效非线性系数为0.82 pm/V，走离角为10.4 mrad。

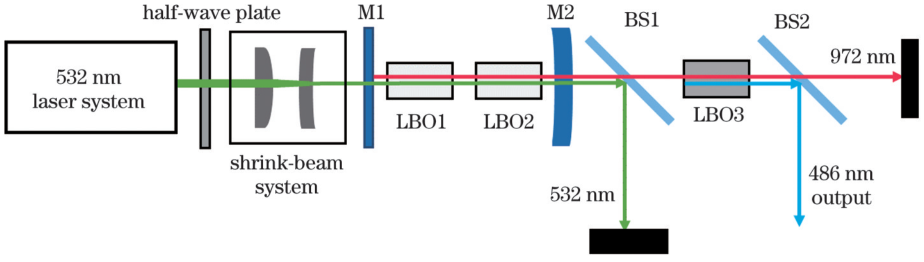


图2　532 nm泵浦OPO腔外倍频蓝光输出实验装置图

Fig. 2　Experimental setup for extracavity frequency-doubling blue laser output based on OPO pumped by 532 nm

3 分析与讨论

实验中，532 nm激光脉冲的最大输出能量为3.87 mJ，线宽为0.05 nm，脉冲宽度约为9.2 ns，水平方向和竖直方向的光束质量M_x^2和M_y^2分别为1.33和1.21。泵浦光经过缩束耦合系统后入射到OPO腔内LBO晶体表面时的光斑直径约为0.63 mm，发散角小于4.0 mrad，泵浦脉冲的峰值功率密度达到148 MW/cm^2，脉冲能量变化曲线和脉冲序列分别如图3、4所示，计算得到脉冲能量的不稳定性优于1.12%。

微调OPO腔内LBO晶体角度，使得OPO输出信号光的中心波长处于972 nm。实验测得的OPO信号光脉冲能量随泵浦脉冲能量的变化曲线如图5所示，

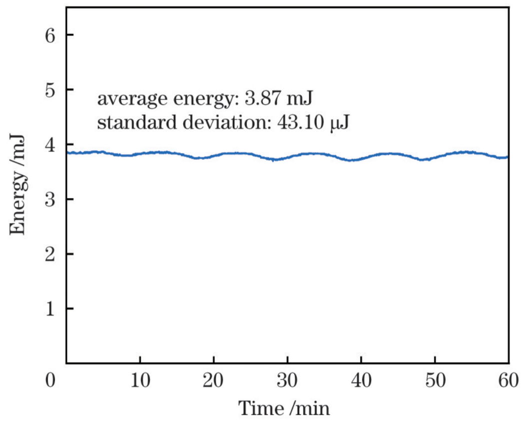
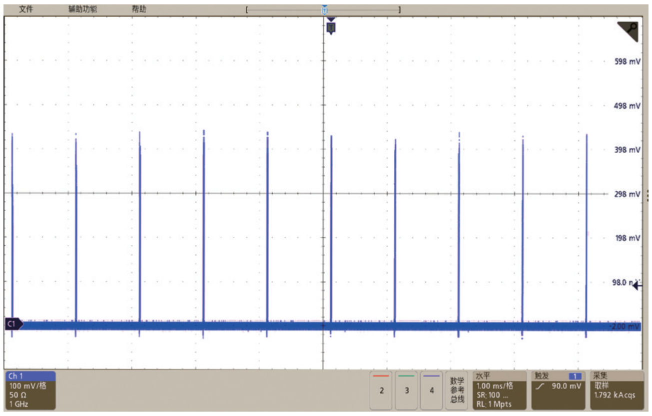


图 3　泵浦光输出能量的稳定性测量

Fig. 3　Stability measurement of pump laser output energy



Ch 1
100 mV/格
50 Ω
1 GHz

水平
1.00 ms/格
SR: 100 ...
RL: 1 Mpts

触发 1
90.0 mV

采集
取样
1.792 kAcqs

图 4　泵浦光脉冲序列的稳定性测量

Fig. 4　Stability measurement of pump laser pulse sequence

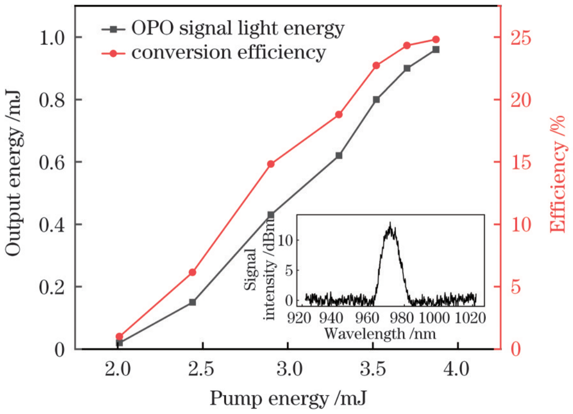


图 5　OPO 信号光能量和转换效率随泵浦光能量的变化，插图为 972 nm 光谱图

Fig. 5　OPO signal light energy and conversion efficiency versus pump light energy with 972 nm spectrum shown in inset

OPO 的阈值泵浦能量约为 1.8 mJ，信号光脉冲的最大输出能量为 0.96 mJ，泵浦光到信号光的光-光转换效率达到 24.8%。

对于实验采用的 OPO 设计，理论上其转换效率可以表示为

$$\eta_{\mathrm{Gaus}} = 0.9 \times \frac{1-R}{1-R(1-\delta)} \times \frac{(\ln N)^{2.33}}{N}, \qquad (1)$$

式中：R 为 OPO 输出镜的反射率；δ 为腔内损耗；N 为实际泵浦脉冲能量与 OPO 阈值泵浦能量的比值[18]。将具体实验参数代入式(1)，可以得到 OPO 的转换效率理论值约为 22.3%，与实验结果基本吻合。

图 5 的插图部分为 OPO 输出信号光脉冲的光谱分布，972 nm 激光的光谱线宽约为 11 nm。光谱线宽较大的原因如下：当 532 nm 光泵浦 LBO OPO 时，在输出 972 nm 信号光波段附近，信号光波长随相位匹配角变化的曲线的斜率较大。利用 SNLO 软件计算可得，斜率约为 13 nm/mrad。考虑到 LBO 晶体的相位匹配接收角约为 2 mrad，理论上信号光最大线宽可达 26 nm。实验中将两块 LBO 晶体放置在合适位置，使其在走离方向上彼此补偿，选择合适的晶体间距以压窄光谱线宽。图 6 给出了 OPO 输出信号光脉冲能量在 60 min 内的变化情况，测得输出脉冲能量抖动的标准差为 15.79 μJ，能量不稳定性为 1.64%。

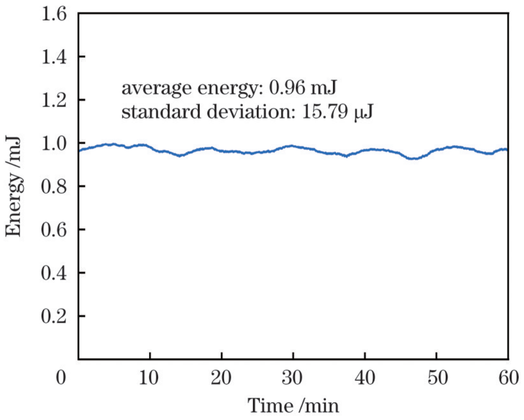


图 6　972 nm 输出能量的稳定性测量

Fig. 6　Stability measurement of 972 nm output energy

在 OPO 输出光的重复频率为 1 kHz 的条件下，对 972 nm 信号光脉冲的时间波形进行探测，获得了图 7 所示的脉冲波形，激光脉冲宽度约为 7.5 ns。使用电荷耦合器件(CCD)测得 972 nm 信号光的近场光斑强度分布，如图 7 插图所示，光斑呈椭圆状，水平和竖直方向上的光斑直径分别为 1.86 mm 和 1.59 mm，水平和竖直方向上的远场发散角为 θ_x=3.0 mrad 和 θ_y=2.9 mrad，对应水平方向和竖直方向上的光束质量分别为 M_x^2=1.30 和 M_y^2=1.22，如图 8 所示。

为了获得 486 nm 蓝光激光输出，对 OPO 输出 972 nm 信号光脉冲进行倍频转换，图 9 给出了实测的倍频后的蓝光脉冲能量随信号光脉冲能量的变化曲线，在 OPO 输出最大信号光脉冲时，获得的最大蓝光脉冲能量为 49 μJ，倍频效率约为 5.3%。倍频效率较低主要是由基频光 972 nm 脉冲的峰值功率密度较低造成的，仅为 6.4 MW/cm^2。此外，972 nm 信号光较大的光谱线宽也制约了倍频效率的提高。图 9 的插图

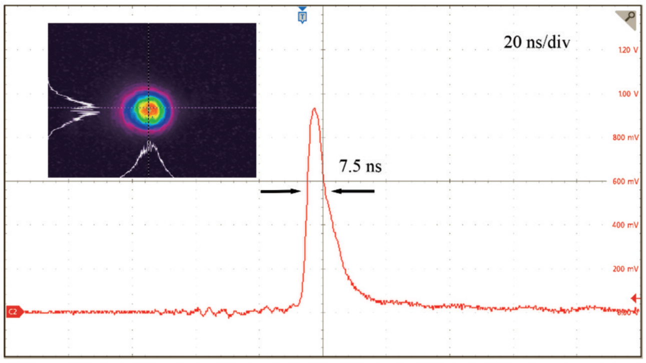


图 7　972 nm 脉冲波形，插图为 972 nm 近场光斑

Fig. 7　972 nm pulse waveform with 972 nm near-field spot shown in inset

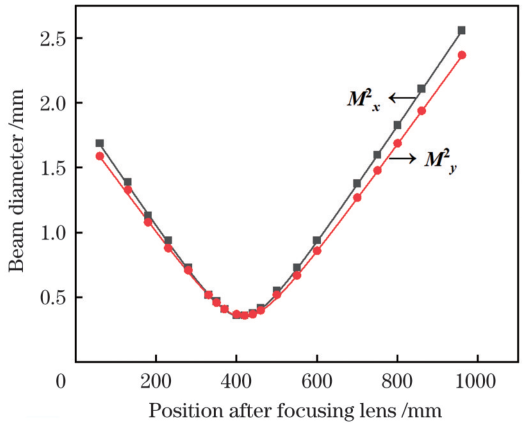


图 8　972 nm 光束质量测量结果

Fig. 8　Measurement results of beam quality at 972 nm

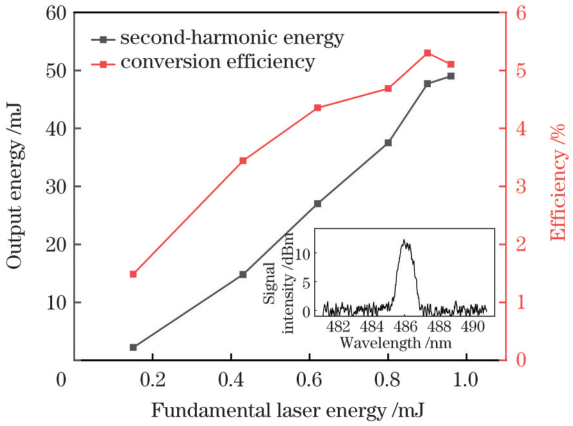


图 9　倍频光能量和转换效率随基频光能量的变化，插图为 486 nm 光谱图

Fig. 9　Second-harmonic energy and conversion efficiency versus fundamental energy with 486 nm spectrum shown in inset

给出了倍频蓝光光谱，蓝光的中心波长为 486 nm，线宽约为 1 nm。

实验测得蓝光激光脉冲宽度约为 6.9 ns，比 972 nm 脉冲宽度略窄，如图 10 所示。蓝光光束的近场光斑维持椭圆形状(图 10 插图)，光斑在水平和竖直方向上的尺寸分别为 1.54 mm 和 1.42 mm，光束发散角分别为 θ_x=3.1 mrad 和 θ_y=2.9 mrad，对应水平方向和竖直方向的光束质量 M_x^2 和 M_y^2 分别为 1.26 和 1.15，如图 11 所示。蓝光在竖直方向上的发散角比水平方向小，蓝光与基频光和泵浦光的光束特性相似。

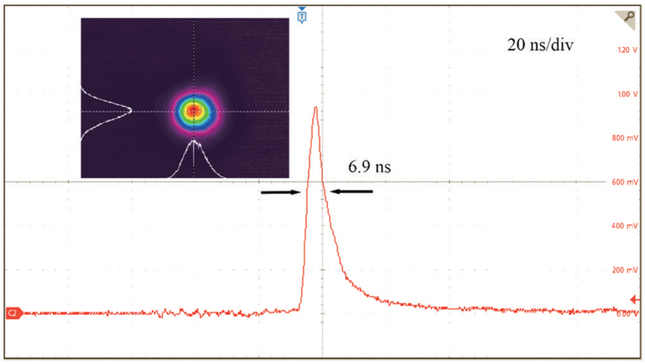


图 10　486 nm 脉冲波形，插图为近场光斑

Fig. 10　486 nm pulse waveform with near-field spot shown in inset

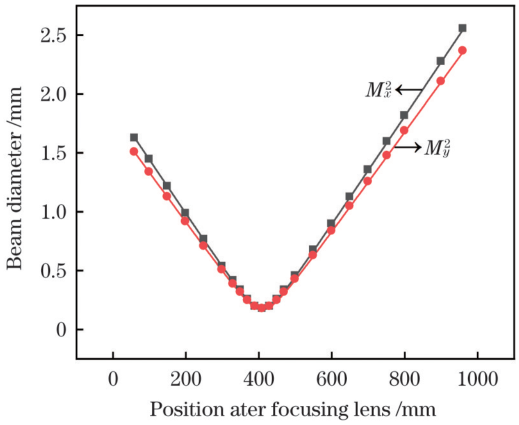


图 11　486 nm 光束质量测量结果

Fig. 11　Measurement results of beam quality at 486 nm

4　结　论

采用重复频率为 1 kHz 的腔内倍频 532 nm Nd:YAG 激光器抽运单谐振 LBO OPO，成功获得了 972 nm 波长激光脉冲输出。当泵浦能量提升到 3.87 mJ 时，获得的 972 nm 激光的单脉冲能量为 0.96 mJ，OPO 光-光转换效率为 24.8%。进一步用 LBO 晶体进行倍频，获得最大脉冲能量为 49 μJ 的 486 nm 蓝光输出，平均功率为 49 mW，脉冲峰值功率达到 7 kW。在实验上证明了通过采用高重复频率的 532 nm 激光脉冲泵浦 OPO 获得高重复频率蓝光激光脉冲输出的可行性，有效避免了紫外 355 nm 激光脉冲作为蓝光 OPO 泵浦源时容易出现的光损伤现象。所提方案有望为海洋激光雷达提供更为可靠的激光光源。

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Frequency-Doubling Blue Laser Technology with Singly-Resonant Optical Parametric Oscillator Pumped by 532 nm Laser

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Abstract

Objective Blue-green lasers have been widely used in ocean lidar systems owing to the optical transmission window of seawater. Researchers have found that green lasers in the 520–580 nm region penetrate deeper into coastal seawater, whereas blue lasers in the 420–510 nm region are more suitable for deep clean seawater. Comprehensively considering the lidar detection range and signal-to-noise ratio, a blue laser at approximately 488 nm has significant advantages for global ocean exploration. If the working wavelength of a laser detection system is located at 486.1 nm, which is also at the Fraunhofer dark line of the solar spectrum, the signal-to-noise ratio can be further improved, and the working hours can be extended. Generally, there are two methods to obtain a blue laser with a wavelength of more than 480 nm: one is based on a frequency-quadrupling Tm-doped fiber laser, and the other is based on an optical parametric oscillator pumped using a 355 nm laser. This study presents a novel method for obtaining a 486 nm blue laser using an optical parametric oscillator based on frequency-doubling technology. The optical parametric oscillator is pumped using a homemade 532 nm laser to avoid damage caused by an ultraviolet laser. We hope that this novel method will provide a reliable laser source for ocean laser detection systems.

Methods The laser system consists of three components: a homemade 532 nm pump laser, a 972 nm singly resonant optical parametric oscillator, and a frequency-doubling unit from 972 nm to 486 nm.

A homemade 532 nm pulse laser with 1 kHz repetition rate and 9.2 ns pulse duration, which is provided by an intra-cavity frequency-doubling electro-optical *Q*-switched Nd∶YAG laser, is used as the pump source for the optical parametric oscillator. To improve the peak power density of the 532 nm pump laser, a shrink-beam system is placed before the optical parametric oscillator cavity. Then, the 532 nm laser is used as the pump source of the singly resonant optical parametric oscillator. The optical parametric oscillator cavity is a 33 mm-long linear plane-concave resonator consisting of a plane mirror and a concave output coupler with a transmission of 35% at a signal wavelength of 972 nm.

The plane mirror has an antireflection coating at 532 nm and 1175 nm, and a high-reflection coating at 972 nm. A concave output coupler with a curvature radius of 2000 mm has an anti-reflection coating at 532 nm and 1175 nm and a local reflection coating at 972 nm. Thus, the optical parametric oscillator is singly resonant at 972 nm. Two type-Ⅰ LiB_3O_5 (LBO) crystals with a size of 4 mm× 4 mm×12 mm and phase matching cut angles of $\theta=90°$ and $\varphi=11.4°$ are used as the parametric crystals. The frequency-doubling unit is placed behind the optical parametric oscillator. A type-Ⅰ LBO crystal with a size of 4 mm×4 mm×12 mm and phase matching cut angles of $\theta=90°$ and $\varphi=17.6°$ is used for the second harmonic generation from the 972 nm fundamental laser of the singly resonant optical parametric oscillator to the 486 nm blue laser.

Results and Discussions Under a repetition of 1 kHz, when the pump energy is 3.87 mJ, a 972 nm output laser with a single pulse energy of 0.96 mJ is obtained in the optical parametric oscillator (Fig. 5), and the optical to optical conversion efficiency of the optical parametric oscillator is 24.8%, which is close to the theoretical calculation value of 22.3%. The 972 nm pulse energy instability within 60 min is approximately 1.64% (Fig. 6), and the pulse width is 7.5 ns with a smooth pulse temporal profile (Fig. 7). The laser beam is slightly elliptical, approximately 1.7 mm in diameter, with beam quality factors of $M_x^2=1.30$ and $M_y^2=1.22$ in two directions (Fig. 8). The 486 nm laser with single pulse energy of 49 μJ is obtained by frequency-doubling the 972 nm output laser with a corresponding frequency-doubling efficiency of 5.3%. The pulse duration of the blue laser is 6.9 ns, which is slightly narrower than that of the fundamental laser (Fig. 10). The beam quality factors of the blue laser in the two directions are $M_x^2=1.26$ and $M_y^2=1.15$ (Fig. 11).

Conclusions A 486 nm blue laser frequency doubled by a 972 nm singly resonant optical parametric oscillator pumped using a 532 nm laser is demonstrated. At a repetition rate of 1 kHz, the 972 nm signal laser energy of the singly resonant optical parametric oscillator reaches 0.96 mJ when the 532 nm pump laser energy is 3.87 mJ, with a corresponding conversion efficiency of 24.8%. The maximum energy of the frequency-doubled 486 nm laser is 49 μJ with a pulse width of 6.9 ns, and the corresponding frequency-doubling efficiency is 5.3%. The results show that high-repetition-rate blue laser pulses can be obtained using an optical parametric oscillator pumped by a 532 nm pulsed laser, which can avoid ultraviolet damage caused by the 355 nm laser. It can be used as a laser source for ocean laser LiDAR systems to achieve stable detection.

Key words laser optics; blue laser; optical parametric oscillator; extracavity frequency-doubling; LiB_3O_5 crystal; all-solid-state lasers