第 48 卷 第 13 期/2021 年 7 月/中国激光 快 报

中国激光

高效率单通倍频实现 610 W 连续波单模绿光输出

苏梦琪[1,2]，尤阳[1,2]，全昭[1*]，沈辉[1]，李秋瑞[1]，陈汝风[1]，漆云凤[1,2**]

[1] 中国科学院上海光学精密机械研究所上海市全固态激光器与应用技术重点实验室，上海 201800；

[2] 中国科学院大学材料与光电研究中心，北京 100049

摘要 基于窄线宽线偏振光纤激光单通倍频方案获得了 610 W 单模绿光输出，倍频效率达到 56.27%，光束质量 M^2 为 1.05。这是目前报道的基于单通倍频方案获得数百瓦级连续波绿光激光输出的最高效率，可进一步通过两路绿光偏振合束实现千瓦级高亮度绿光激光输出。

关键词 激光光学；倍频；相位匹配；绿光激光；光纤激光

中图分类号 TN248 **文献标志码** A **doi**：10.3788/CJL202148.1315002

高功率蓝绿激光光源在高反射材料(铜及其合金)的焊接[1]、泵浦钛宝石激光器[2-3]、深紫外激光产生[4-5]、半导体加工[6]以及水下光通信和探测[7]等领域有着广泛应用。目前获得高功率蓝绿激光的主要技术方案有蓝光半导体激光器、薄片激光器倍频和窄线宽光纤激光器倍频等。2019 年，Nuburu 公司[8]报道了通过蓝光半导体激光器合束获得的 1.5 kW 的蓝光激光器，其光束质量因子 M^2 为 76.8，M^2 系数较大是由半导体激光器的结构决定的。2020 年，Pricking 等[9]报道了一种基于薄片激光器倍频的绿光激光系统，其最大功率为 2 kW，M^2 为 36.6，薄片激光器 M^2 因子随热效应的增强而减小。光纤激光器具有全光纤结构、高效率、易散热和柔性化等优点，近 10 年来取得迅猛发展。1 μm 波段 kW 量级近衍射极限窄线宽全保偏光纤激光器[10]是实现高效率倍频、获得高功率高光束质量绿光的理想基频光源。LBO 晶体具有极高的损伤阈值和可实现非临界相位匹配等优点[11]，是通常被用作高功率倍频的非线性晶体。相对于蝶形腔谐振倍频结构[12]，单通倍频方案具有结构简单紧凑、鲁棒性好、成本低等优点，无需单频基频光源，功率拓展性强。2014 年，Gapontsev 等[13]基于 1 kW 连续保偏光纤激光器结合单通倍频实现 356 W 绿光输出，倍频效率为 35%。2020 年，Ahmadi 等[14]基于非保偏光纤激光器结合主动偏振控制技术获得 1.8 kW 线偏振基频光源，采用单通倍频实现 1 kW 绿光输出，倍频效率为 54%，这也是目前基于该方案报道的最高效率。

本文的实验装置原理示意图如图 1 所示，基频光源为课题组自主研制的 kW 级窄线宽保偏全光纤激光器，单频种子光的中心波长为 1064.7 nm，经相位调制展宽，再采用典型的主振荡功率放大(MOPA)结构进行全光纤三级放大，实现输出功率约为 1.1 kW、线宽约为 20 GHz(～0.077 nm)、偏振消光比(PER)高于 15 dB、光束质量 M^2 优于 1.1 的基频光源。选用一类非临界相位匹配的 LBO 晶体作为倍频晶体，为克服走离效应并尽可能利用晶体长度，晶体切割角度 $\theta=90°$，$\varphi=0°$。基频光源输出的光束通过准直器的准直后，依次通过半波片(HWP)和透镜聚焦到LBO晶体内，通过调节半波

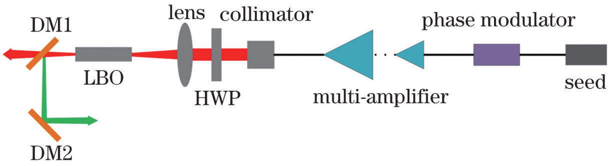


图 1 实验装置原理示意图

Fig. 1 Schematic diagram of experimental setup

收稿日期：2021-03-16；**修回日期**：2021-04-04；**录用日期**：2021-04-13

基金项目：国家自然科学基金(61705243)、广东省重点领域研发计划(2018B090904001)

通信作者：*quanzhao0205@163.com；**dreamer_7@siom.ac.cn

片改变进入 LBO 晶体的基频光偏振方向，并优化聚焦透镜焦距以获得最高的倍频效率，采用双色镜 DM1 和 DM2(均对 532 nm 高反，对 1064 nm 高透)滤除基频光后，进行绿光激光特性测量。

仿真分析了 LBO 晶体对基频光的接受线宽和匹配温度，如图 2(a)所示，接受线宽和晶体长度成反比，40 mm 晶体倍频效率的波长接受半峰全宽为 0.96 nm，60 mm 晶体倍频效率的波长接受半峰全宽为 0.64 nm，实验采用的基频光源线宽(~0.077 nm)远小于晶体接受线宽；根据 LBO 晶体的塞米尔方程计算得到在 1064.7 nm 处匹配温度为 148.3 ℃。通过优化设计聚焦透镜焦距和晶体控制温度，选取焦距为 400 mm 的聚焦透镜，晶体工作温度在 150 ℃左右，实验的最佳温度和理论的差异主要和基频光的入射角度有关[15]。在基频光最大输出功率为 1084 W 时，实现了 610 W 连续波绿光激光输出，倍频转换效率为 56.27%，倍频功率与效率曲线如图 2(b)所示。在最高绿光输出功率下的光束质量测量结果如图 3 所示，其光束质量因子 M^2 为 1.05，输出远场光斑具有基横模形态。这是公开报道的基于单通倍频技术路线实现高功率单模连续波绿光输出的最高倍频效率。

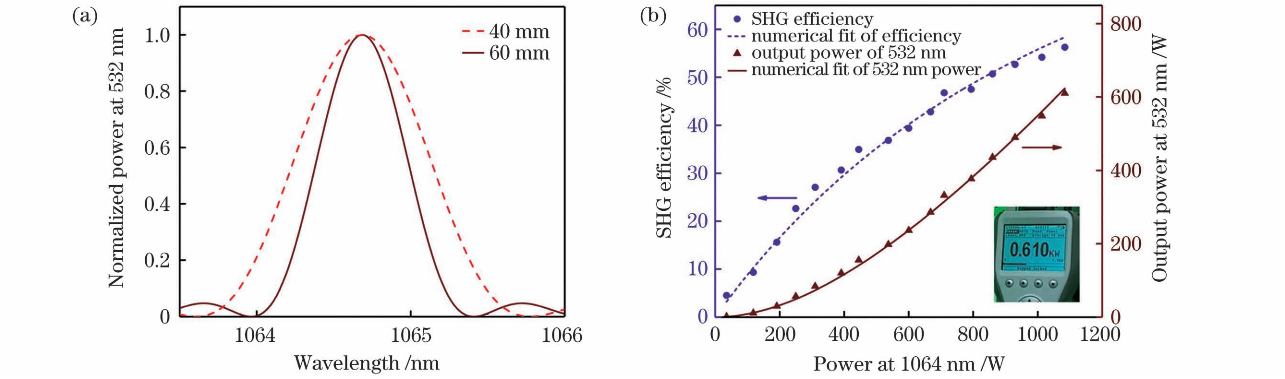
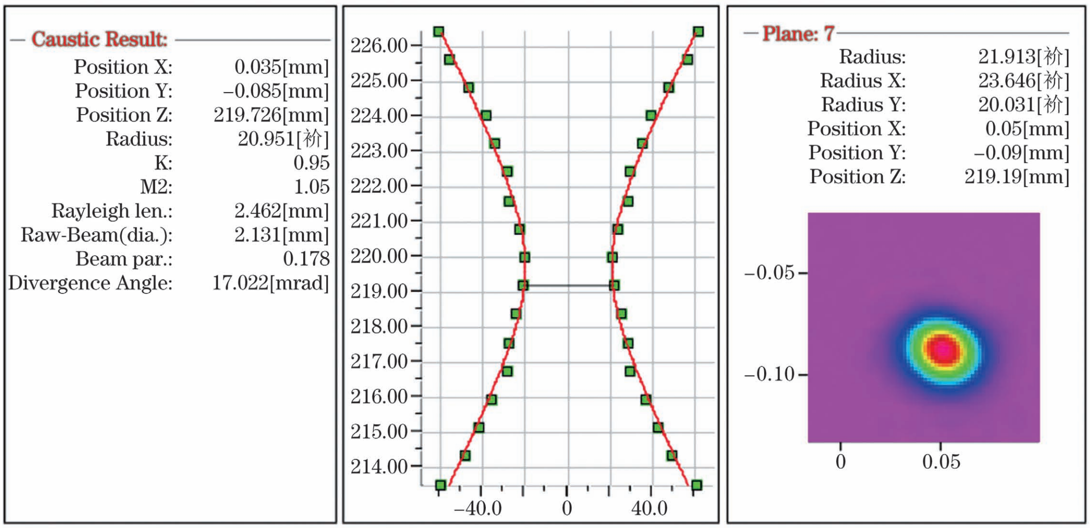


图 2 不同晶体长度下的计算和实验结果。(a)不同晶体长度的倍频效率随波长的变化；(b)倍频效率和绿光功率随基频光功率的变化曲线(插图为绿光在 610 W 时功率计表头图片)

Fig. 2 Calculated and experimental results for different crystal lengths. (a) Frequency doubling efficiency at different crystal lengths varies with wavelength; (b) curves of frequency doubling efficiency and green light power as functions of fundamental frequency light power (inset is a picture of power meter head at 610 W under green light)


Caustic Result:

Position X:	0.035[mm]
Position Y:	−0.085[mm]
Position Z:	219.726[mm]
Radius:	20.951[祄]
K:	0.95
M2:	1.05
Rayleigh len.:	2.462[mm]
Raw-Beam(dia.):	2.131[mm]
Beam par.:	0.178
Divergence Angle:	17.022[mrad]

Plane: 7

Radius:	21.913[祄]
Radius X:	23.646[祄]
Radius Y:	20.031[祄]
Position X:	0.05[mm]
Position Y:	−0.09[mm]
Position Z:	219.19[mm]

图 3 绿光在 610 W 时的光束质量

Fig. 3 Beam quality of green laser at 610 W

基于窄线宽光纤的激光单通倍频技术可获得高功率、高效率单模绿光输出，还可以通过两路绿光偏振合束实现千瓦级高亮度绿光激光输出，在贵金属增材制造、电动汽车制造、消费电子产品制造、高功率深紫外频率转换和水下光通信和探测等领域具有广泛的应用前景。

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610-W Continuous-Wave Single-Mode Green Laser Output Based on Highly Efficient Single-Pass Frequency Doubling

Su Mengqi[1,2], You Yang[1,2], Quan Zhao[1*], Shen Hui[1], Li Qiurui[1], Chen Rufeng[1],
Qi Yunfeng[1,2**]

[1] *Shanghai Key Laboratory of All Solid-State Laser and Applied Techniques, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*;

[2] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing* 100049, *China*

Abstract

Objective High-power blue-green laser light sources are widely applied in the welding of highly reflective materials (e. g., copper and its alloys), pumping Ti: sapphire lasers, deep ultraviolet laser generation, semiconductor processing, and underwater optical communication and detection. High-power blue-green lasers are mainly derived from blue semiconductor lasers, disk laser frequency doubling, and narrow-linewidth fiber laser frequency doubling. Compared to blue LDs and disc lasers, a fiber laser has the advantages of all-fiber structure, high efficiency, easy heat dissipation, and flexibility. A fiber laser with a 1-μm band kW-level near-diffraction-limit narrow linewidth and full polarization maintenance is an ideal fundamental-frequency light source for high-efficiency frequency doubling and high output power. This paper introduces a high-efficiency green laser based on single-pass frequency doubling of a polarization-maintaining fiber laser.

Methods Figure 1 shows experimental principle. Based on the master oscillator power amplifier cascaded amplification technology, we achieved a fundamental light source with an approximate output power of 1.1 kW and a beam quality at the near-diffraction-limit. The linewidth was ~20 GHz (~0.077 nm) and the polarization extinction ratio was better than 15 dB. We selected a non-critical phase-matched lithium triborate (LBO) crystal as the frequency doubling crystal cut at angles of $\theta = 90^\circ$ and $\varphi = 0^\circ$. The acceptance linewidth and matching temperature of the non-critical phase matching LBO crystal for the fundamental-frequency light were theoretically calculated. High-efficiency frequency multiplication can be obtained by optimizing the focal length of the focusing lens and the crystal control temperature.

Results and Discussions The calculated acceptance linewidths of the 40-mm and 60-mm LBO crystals were inversely proportional to crystal length. The focal length of the focusing lens and the crystal working temperature were selected as 400 mm and ~150 ℃, respectively. The difference between the experimental and theoretical optimal temperatures can mainly be explained by the incident angle of the fundamental-frequency light. When the maximum output power of the fundamental-frequency light was 1084 W, the laser output continuous green light at 610 W, and the efficiency of second-harmonic generation was 56.27% (Fig. 2). The beam-quality factor M^2 of the green light was 1.05, and the output far-field spot presented a fundamental transverse-mode shape (Fig. 3).

Conclusions Based on the narrow-linewidth linear polarization fiber laser and the single-pass frequency doubling scheme, a 610 W single-mode green laser output was obtained. The efficiency of frequency doubling reached 56.27%, and the beam quality M^2 was 1.05. To the best of our knowledge, we present the most efficient generation of hundreds of watts of continuous-wave green laser using the single-pass frequency doubling scheme. Furthermore, two green-light polarization beams can be combined to realize a kilowatt-level high-brightness green laser output.

Key words laser optics; frequency doubling; phase matching; green laser; fiber laser

OCIS codes 140.3515; 190.5040; 140.7300