CHINESE OPTICS LETTERS

Vol. 21, No. 9 | September 2023

High efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm generation by an intracavity frequency-doubled optical parametric oscillator

Xiangxiang Li (李翔翔)[1,2,†], Yuntao Bai (白云涛)[1,2,†], Xin Ding (丁 欣)[1,2,*], Guoxin Jiang (蒋国鑫)[1,2], Peng Lei (雷 鹏)[1,2], Xingrui Zhang (张兴瑞)[1,2], Yang Sun (孙 杨)[1,2], Jiangeng Du (杜建耕)[1,2], Fangying Wei (危芳莹)[1,2], Ruofan Zhang (张若凡)[1,2], Liang Wu (吴 亮)[1,2], Guizhong Zhang (张贵忠)[1,2], and Jianquan Yao (姚建铨)[1,2]

[1] Institute of Laser and Opto-electronics, School of Precision Instrument and Opto-electronics Engineering, Tianjin University, Tianjin 300072, China

[2] Key Laboratory of Opto-electronics Information Technology, Ministry of Education, Tianjin University, Tianjin 300072, China

*Corresponding author: dingxin@tju.edu.cn

Received April 15, 2023 | Accepted June 2, 2023 | Posted Online August 21, 2023

A high efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm was demonstrated. A high-efficiency KTP optical parametric oscillator was achieved by double-pass pumping with a high-maturity 5 kHz 532 nm laser. Thanks to the efficient intracavity frequency doubling of the circulating signal wave by a BIBO crystal, the threshold pump power of the 486.1 nm output was 0.9 W, and the maximum output power of 1.6 W was achieved under the pump power of 7.5 W. The optical–optical conversion efficiency was 21.3%, with the pulse duration of 45.2 ns, linewidth of ∼0.12 nm, and beam quality factor M^2 of 2.83.

Keywords: 486.1 nm H-β Fraunhofer line; intracavity frequency-doubled optical parametric oscillator; high efficiency; low threshold; high repetition rate.

DOI: 10.3788/COL202321.091403

1. Introduction

The coherent blue-green sources with output wavelength in the region of 450–550 nm are important in applications such as ocean lidar, underwater target detection, and underwater communication due to low-loss underwater transmission[1–7]. In this region, it is worth noting the wavelength matched the Fraunhofer lines, at which the solar irradiance is reduced with respect to the adjacent peak. The signal-to-noise ratio of lidar during daytime detection can be increased due to the reduced background. There are several Fraunhofer lines in the region of 450–550 nm, including the H-β line at 486.13 nm with a linewidth of 0.14 nm, the Mg line at 516.73, 517.27, and 518.36 nm, with the broadest linewidth of 0.2 nm[8–10]. However, the H-β line at 486.13 nm is more of interest due to its lower attenuation coefficient in deep ocean applications.

At present, it is difficult to directly obtain the H-β Fraunhofer line at 486.13 nm due to the lack of corresponding laser gain media. Therefore, the method of nonlinear frequency conversion is proposed to realize a frequency shift of the laser. The H-β Fraunhofer line at 486.13 nm can mainly be obtained by means of a laser diode (LD) combined with second-harmonic generation (SHG)[11], tunable near-infrared lasers represented by Ti:sapphire combined with SHG and sum-frequency generation (SFG)[12–14], and an optical parametric oscillator (OPO)[15-21]. However, an LD has no obvious advantages in terms of the high peak power and high beam quality output; the output power and beam quality of the tunable near-infrared lasers are also limited by the severe thermal effect of crystal. In contrast, OPO is currently the optimal method for generating the H-β Fraunhofer line at 486.13 nm due to the simple structure, wide wavelength-tuning range, and less heat production. In recent years, high-energy 486.1 nm OPO pumped by 355 nm pulse laser has been reported. In 2018, Ma *et al.* achieved a BBO-OPO operating at a pulse repetition frequency (PRF) of 20 Hz. When the 355 nm pump energy was 190 mJ, the maximum output energy at 486.1 nm was 62 mJ, with the conversion efficiency of 32.6%[22]. In 2020, they also reported a BBO-OPO pumped by a 355 nm laser with a PRF of 100 Hz, and obtained 9.6 mJ of 486.1 nm output under the maximum pump energy of 43.5 mJ[7]. In 2021, Zhang *et al.* reported a BBO-OPO pumped by 355 nm laser with a PRF of 10 Hz. The maximum output energy at 486.1 nm was 162 mJ, with the conversion efficiency of 39.4%[23]. The high-energy 486.1 nm blue sources reported above have important value in ocean lidar and underwater detection applications.

In addition, high-power 486.1 nm blue sources operating at high PRF also show important research value owing to their high data transmission rate, high confidentiality, and strong anti-interference ability. However, there are few reports of high-power and high repetition rate 486.1 nm OPO. This is because high repetition rate OPO has a higher threshold and lower efficiency due to the lower pump single-pulse energy. In this case, the conversion efficiency of the OPO is more dependent on the performance of the pump source. In 2018, Rao *et al.* reported a BBO-OPO pumped by a 355 nm laser with a PRF of 5 kHz and a pulse duration of 10 ns. The threshold energy of pump pulse was reduced to ≤ 1 mJ by cylindrically focusing the pump beam. The average output power at 492 nm was 2.6 W, with the conversion efficiency of 26%[24]. Compared with 355 nm lasers, the 532 nm lasers are more suitable as pump sources for OPO due to their higher maturity, lower cost, and less damage to the device. In 2003, Bi *et al.* reported an LBO-OPO double-pass pumped by a high-quality 532 nm laser with a PRF of 10 kHz and M^2 of 3. A 50-mm-long LiB_3O_5 (LBO) crystal was adopted to minimize the OPO threshold and improve the efficiency. The maximum conversion efficiency of 940 nm signal wave was 54% under the pump power of 17 W, and the efficiency of extracavity frequency-doubling by three BiB_3O_6 (BIBO) crystals at 470 nm was 21%[25]. The above results show that a high-power and high repetition rate OPO needs to solve the problems of high threshold, low conversion efficiency, and device damage.

In this paper, we demonstrated a high-efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm generation by an intracavity frequency-doubled singly resonant OPO (SR-OPO). A high-maturity 5 kHz 532 nm laser was adopted to double-pass pump a $KTiOPO_4$ (KTP) crystal with large effective nonlinear coefficient (d_{eff}) to reduce the threshold and improve the conversion efficiency of the OPO. Moreover, a BIBO crystal with large d_{eff} was used to efficiently intracavity frequency-double the circulating signal wave, in order to achieve a high-power 486.1 nm output.

2. Experimental Setup

The schematic of high-efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm generation by an intracavity frequency-doubled SR-OPO is shown in Fig. 1. The 532 nm pump source was a multimode frequency-doubled Nd:YAG laser, with a PRF of 5 kHz. The pulse duration was 88 ns, and the beam quality factor M^2 was 17 under a maximum output power of 7.5 W. An optical isolator was inserted between the 532 nm laser and the double-pass pumped OPO in order to avoid the retroreflection of the pump beam. After adjusting the polarization by rotating the half-wave plate, the pump light was focused onto a KTP crystal with a radius of ~235 μm by a focusing lens f ($f = 300$ mm) and a flat mirror, M_1. In this case, the pump light was focused directly onto the KTP crystal without passing through the resonator mirrors, which reduced the risk of mirror damage. The 5 mm × 5 mm × 25 mm KTP crystal ($d_{eff} = 3.74$ pm/V) was cut at $\theta = 74.8°$, $\varphi = 0°$ for type-II phase matching, with both surfaces coated to be antireflective (AR) at 532 nm and 950–1200 nm.

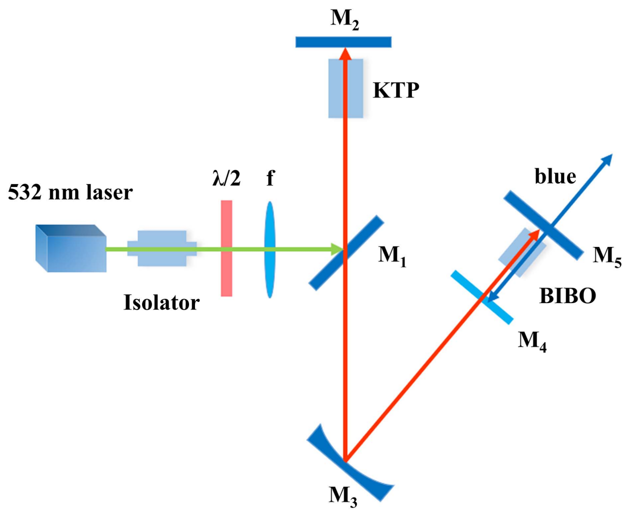

Fig. 1. Schematic of high-efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm generation by an intracavity frequency-doubled SR-OPO.

A V-shaped SR-OPO cavity consisted of M_2, M_3, and M_5 mirrors. By elaborately designing the cavity, a good mode matching between the pump and oscillating beam in the OPO crystal can always be achieved with the increase of the incident pump power. Moreover, benefiting from the folding mirror, a smaller radius of the oscillating beam can be achieved in the SHG crystal. Therefore, a higher intensity of the oscillating beam can be obtained in the SHG crystal to ensure a high-efficiency frequency-doubling. In order to further improve the conversion efficiency of SR-OPO, the flat mirror M_2 was coated for high reflection (HR) at 532 nm to return the remaining pump light back to the KTP crystal for secondary pumping. The M_3 mirror was a concave folding mirror with a radius of curvature of 100 mm and the half-folding angle of ~20°. A 4 mm × 4 mm × 10 mm BIBO crystal was cut at $\theta = 163.2°$, $\varphi = 90°$ for type-I phase matching, which was used to intracavity frequency-double the circulating signal wave owing to its high d_{eff} of 3.27 pm/V. The crystal was coated to be AR at 900–1000 nm and 450–500 nm. Both crystals were wrapped in indium foil and placed in water-cooled aluminum holders at 17°C. A flat dichroic mirror M_4 was placed between the BIBO crystal and the M_3 mirror to collect the backpropagation 486.1 nm blue light. All the coatings of mirrors are listed in Table 1.

The total cavity length of the SR-OPO was 133 mm. Figure 2 shows the fundamental-mode beam size of the signal wave in the cavity calculated according to the ABCD transmission matrix. The tangential and sagittal beam radii in KTP were ~169 and ~211 μm, respectively. Therefore, a good mode matching between the pump and oscillating signal beam was satisfied with such a cavity arrangement. In our experiment, the optical power was measured using a Molectron EPM1000 laser power meter, and the pulse shapes were recorded using a fast photodiode (Thorlabs DET10A) and an oscilloscope (Tektronix

Table 1. Coatings of Mirrors.

Mirrors	Coatings
M_1	45° HR@532 nm, HT@972.2 nm
M_2	HR@532 nm and 972.2 nm, HT@1174.9 nm
M_3	HR@972.2 nm, HT@1174.9 nm
M_4	HT@972.2 nm, HR@486.1 nm
M_5	HR@972.2 nm, HT@486.1 nm

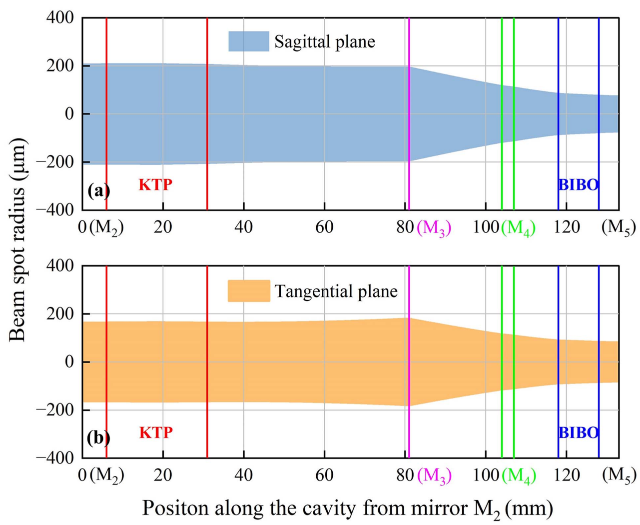

Fig. 2. Fundamental-mode beam size of the signal wave in (a) sagittal plane and (b) tangential plane.

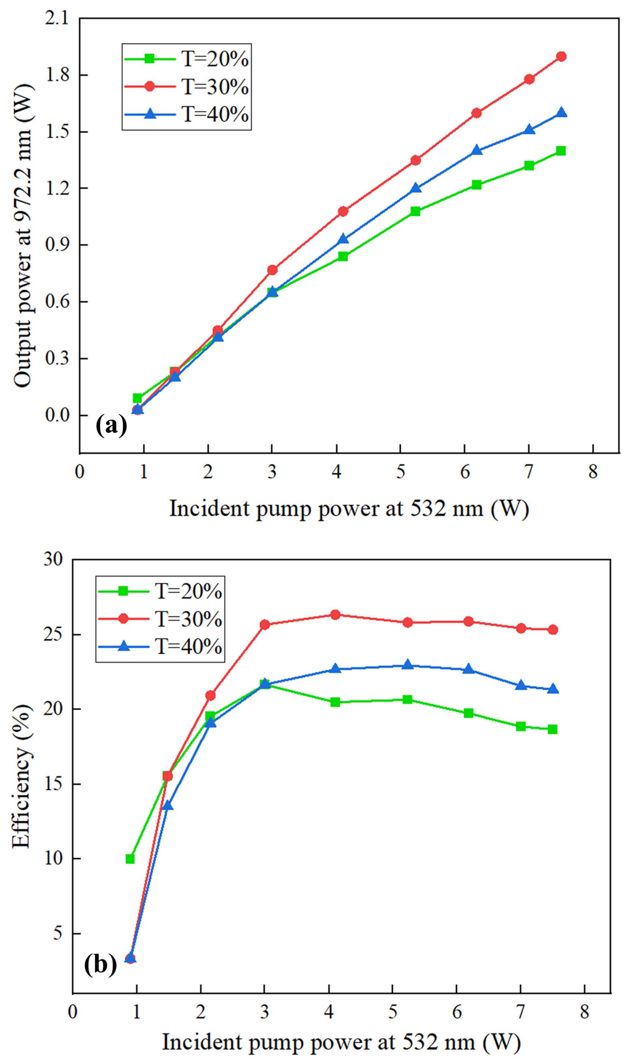

Fig. 3. (a) Power transfer and (b) conversion efficiency of the signal output in SR-OPO at different transmittances (T = 20%, 30%, 40%).

MDO3024). The central wavelength and spectral linewidth were measured by optical spectrum analyzers (Yokogawa AQ6370D and Ocean Optics USB4000-FL). The beam profile of the output wave was recorded using a pyroelectric array camera (Ophir Pyrocam III).

3. Results and Discussion

In the experiment, the output performance of fundamental signal wave of 972.2 nm was first investigated without the BIBO crystal and the M_4 mirror. By replacing the M_5 mirror by a signal output coupler (OC) with different transmittance ($T = 20\%$, 30%, 40%), the power transfer and conversion efficiency of the signal output in SR-OPO with double-pass pump were measured; this is shown in Fig. 3. The thresholds of 972.2 nm were less than 1 W with the transmittance of 20%, 30%, and 40% due to the double-pass pump scheme and good mode matching between the pump and oscillating signal beam. In addition, a maximum signal output power of 1.4, 1.9, and 1.6 W was achieved at the pump power of 7.5 W, with the corresponding conversion efficiency of 18.7%, 25.3%, and 21.3%, respectively. Noticeably, with the increase of transmittance, the threshold pump power was higher, and the saturation of conversion efficiency occurred at a higher pump power, due to a higher loss. There was an optimal transmittance of $T = 30\%$ to achieve the highest output power and conversion efficiency at a 972.2 nm signal wave. Moreover, the output power would be further increased with a higher output power pump source.

When the transmittance of the OC was 30%, the central wavelength and linewidth of the signal wave were measured by an optical spectrum analyzer (Yokogawa AQ6370D) at the maximum power of 1.9 W, as shown in Fig. 4(a). The central wavelength of the signal wave was 972.2 nm, with a linewidth of 0.12 nm. The measured pulse train of 972.2 nm at the maximum power of 1.9 W is shown in Fig. 4(b). The PRF was 5 kHz, and the pulse duration was 47 ns.

Based on the above experiments, the BIBO crystal and dichroic mirror M_4 were inserted into the cavity, and the OC

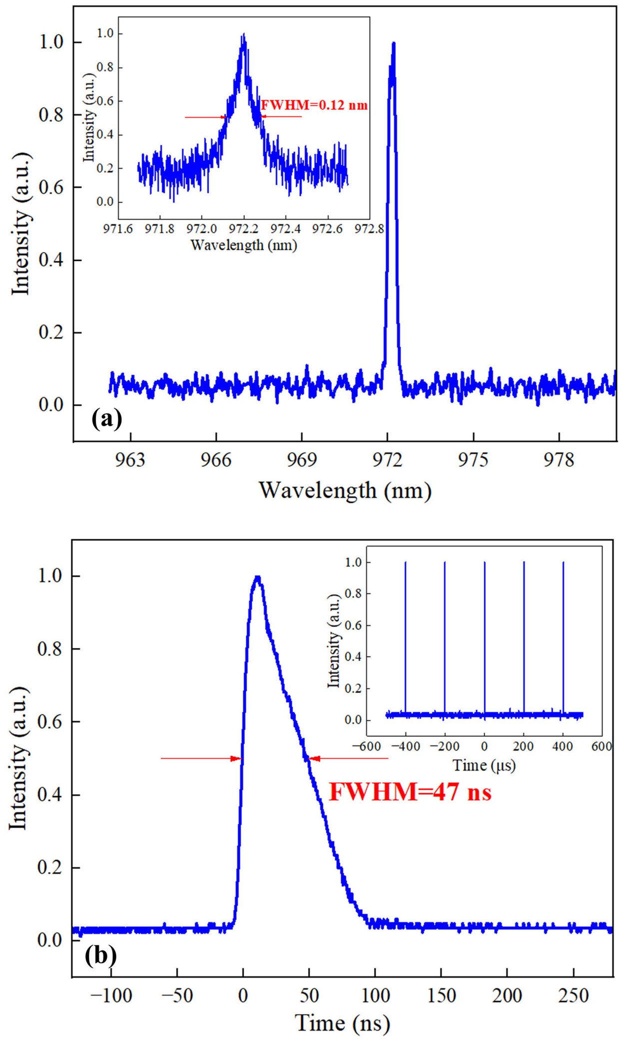

Fig. 4. (a) Spectrum of 972.2 nm at the maximum power of 1.9 W (FWHM); (b) oscilloscope trace of 972.2 nm at 1.9 W; inset, pulse train of 972.2 nm.

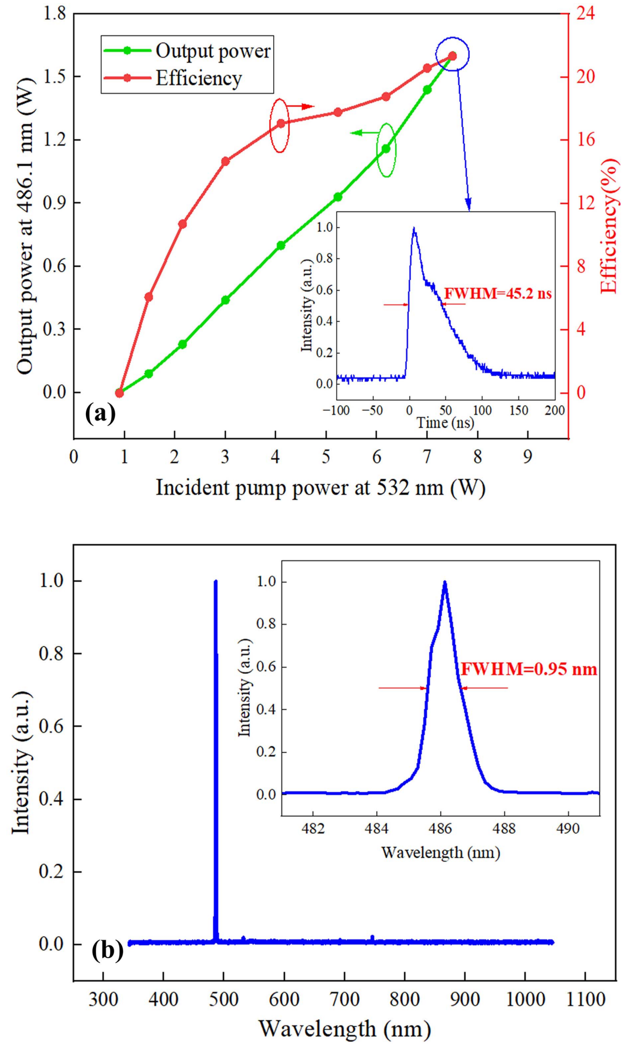

Fig. 5. (a) Power transfer at 486.1 nm; inset, oscilloscope trace of 486.1 nm at the maximum power of 1.6 W; (b) spectrum of 486.1 nm at 1.6 W.

M_5 was replaced by HR at 972.2 nm and HT at 486.1 nm. With this arrangement, the power transfer and conversion efficiency of the 486.1 nm output are shown in Fig. 5(a). The threshold pump power of the 486.1 nm output was 0.9 W. A maximum output power of 1.6 W at 486.1 nm was obtained under the pump power of 7.5 W, with the corresponding conversion efficiency of 21.3%. It was observed that the conversion efficiency gradually began to saturate. The pulse duration of 486.1 nm at the maximum power of 1.6 W was measured to be 45.2 ns, as shown in Fig. 5(a). Noticeably, a slight distortion of the pulse shape was observed, which indicated that a slight inverse conversion process occurred in the OPO. This was because the rapid accumulation of the intensity of the oscillating signal wave in the cavity resulting in a secondary SFG, which occurred between the back edge of the signal and the idler pulses. Therefore, a partial absence was observed along the back edge of the blue pulse due to the loss of SFG. The distortion of the blue pulse could be eliminated by improving the efficiency of intracavity frequency doubling by increasing the length of the BIBO crystal. In fact, a similar distortion of the pulse shape of the signal wave in Fig. 4(b) was observed, which seemed to be smaller. This indicated that the inverse conversion effect could be suppressed effectively by reducing the intensity of the oscillating signal wave in the cavity.

The spectrum of the blue output at the maximum power of 1.6 W was measured by an optical spectrum analyzer (Ocean Optics USB4000-FL). The central wavelength was measured to be 486.13 nm, with a linewidth of 0.95 nm, as shown in Fig. 5(b). It should be noted that due to the low resolution of the spectrometer (10 nm), the measured linewidth of the 486.1 nm output was inaccurate. The actual value of the linewidth should be ∼0.12 nm, which was close to the fundamental signal wave of 972.2 nm. The beam quality factor M^2 of the 486.1 nm output at the maximum power of 1.6 W was measured to be 2.83 by knife-edge scanning. The fitting curve and far-field spatial beam profile are shown in Fig. 6(a). Figure 6(b) shows the power stability of the 486.1 nm output measured over 2 h, which exhibited a root-mean-square (RMS) fluctuation of 1.05%.

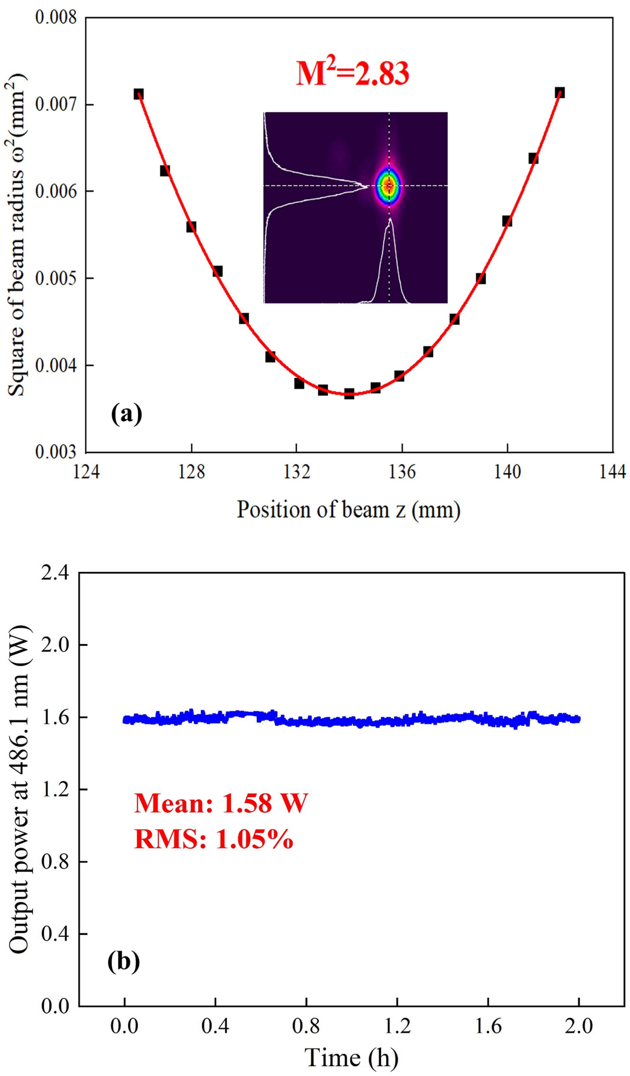

Fig. 6. (a) Beam quality measurement of the 486.1 nm output at the maximum power of 1.6 W; inset, beam profile collected; (b) power stability of the 486.1 nm output at the maximum power over 2 h.

4. Conclusion

In summary, we have demonstrated a high-efficiency, low threshold, high repetition rate H-β Fraunhofer line light at 486.1 nm generation by an intracavity frequency-doubled KTP-OPO double-pass pumped by a 532 nm laser PRF of 5 kHz. Using a BIBO crystal to intracavity frequency-double the circulating signal wave, the threshold power of the 486.1 nm output was only 0.9 W. The maximum output power of 1.6 W at 486.1 nm was achieved under the pump power of 7.5 W. The corresponding conversion efficiency was 21.3%, with the pulse duration of 45.2 ns, linewidth of ~0.12 nm, M^2 of 2.83, and RMS fluctuation of 1.05% over 2 h. The experimental results showed that the 486.1 nm H-β Fraunhofer line light can be obtained by the above simple and compact intracavity frequency-doubled SR-OPO scheme, which has important application value in the field of ocean studies. In addition, a narrower linewidth, better beam quality, and higher optical-to-optical conversion efficiency of 486.1 nm H-β Fraunhofer line light can be achieved by injecting a single longitudinal mode seed light from M_2 or M_3.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 62175181).

†These authors contributed equally to this work.

References

1. X. W. Cai, Z. J. Yuan, and L. Wang, "Development of compact 2 kHz mJ-level 532 nm laser as laser source of lidar," Chin. J. Lasers **41**, 0602005 (2014).
2. H. Liu, P. Chen, Z. H. Mao, D. L. Pan, and Y. He, "Subsurface plankton layers observed from airborne lidar in Sanya Bay, South China Sea," Opt. Express **26**, 29134 (2018).
3. J. Baghdady, K. Miller, S. Osler, K. Morgan, W. Z. Li, E. Johnson, and B. Cochenour, "Blue-light digital communication in underwater environments utilizing orbital angular momentum," Proc. SPIE **9827**, 98270G (2016).
4. L. K. Rumbaugh, K. J. Dunn, E. M. Bollt, B. Cochenour, and W. D. Jemison, "An underwater chaotic lidar sensor based on synchronized blue laser diodes," Proc. SPIE **9827**, 98270I (2016).
5. T. C. Wu, Y. C. Chi, H. Y. Wang, C. T. Tsai, and G. R. Lin, "Blue laser diode enables underwater communication at 12.4 Gbps," Sci. Rep. **7**, 40480 (2017).
6. P. L. Wang, C. Li, and Z. Y. Xu, "A cost-efficient real-time 25 Mb/s system for LED-UOWC: design, channel coding, FPGA implementation, and characterization," J. Light. Technol. **36**, 2627 (2018).
7. J. Ma, T. T. Lu, Y. He, Z. Y. Jiang, C. H. Hou, K. P. Li, F. H. Liu, X. L. Zhu, and W. B. Chen, "Compact dual-wavelength blue-green laser for airborne ocean detection lidar," Appl. Opt. **59**, C87 (2020).
8. M. G. Lovern, M. W. Roberts, S. A. Miller, and G. T. Kaye, "Oceanic *in-situ* Fraunhofer-line characterizations," Proc. SPIE **1750**, 149 (1992).
9. S. H. Wu, X. Q. Song, and B. Y. Liu, "Fraunhofer lidar prototype in the green spectral region for atmospheric boundary layer observations," Remote Sens. **5**, 6079 (2013).
10. G. Giuliano, L. Laycock, D. Rowe, and A. E. Kelly, "Solar rejection in laser based underwater communication systems," Opt. Express **25**, 33066 (2017).
11. Z. Burkley, C. Rasor, S. F. Cooper, A. D. Brandt, and D. C. Yost, "Yb fiber amplifier at 972.5 nm with frequency quadrupling to 243.1 nm," Appl. Phys. B **123**, 5 (2017).
12. F. Q. Li, H. J. Li, and H. D. Lu, "Realization of a tunable 455.5-nm laser with low intensity noise by intracavity frequency-doubled Ti:sapphire laser," IEEE J. Quantum Electron. **52**, 1700106 (2016).
13. M. Zhu, X. Ding, Y. Z. Yu, W. Lv, P. Wang, and J. Q. Yao, "Study on the method of expanding the Ti:sapphire laser spectrum to short wavelength by using sum-frequency mixing technology in KTP crystal," J. Tianjin Univ. **35**, 58 (2002).
14. U. Demirbas and I. Baali, "Power and efficiency scaling of diode pumped Cr: LiSAF lasers: 770–1110 nm tuning range and frequency doubling to 387–463 nm," Opt. Lett. **40**, 4615 (2015).
15. Y. Liu, Z. Qiu, Q. G. Li, X. L. Zhu, X. C. Yang, and B. C. Zhu, "Visible optical parametric oscillator with BBO crystal," Chin. J. Lasers **18**, 517 (1991).
16. L. Peng, G. Ren, B. Zhang, W. Huang, and B. W. Cai, "Study of 410–2200 nm angle-tuned BBO optical parametric oscillator," Acta Photon. Sin. **31**, 249 (2001).
17. X. C. Lin, H. B. Zhang, H. Q. Li, Y. P. Kong, Y. Bi, Z. P. Sun, and Z. Y. Xu, "Continuous tuning high power blue light by frequency doubling in BiB_3O_6 crystals," Proc. SPIE **6028**, 60280C (2005).
18. G. K. Samanta and M. Ebrahim-Zadeh, "Continuous-wave, single-frequency, solid-state blue source for the 425–489 nm spectral range," Opt. Lett. **33**, 1228 (2008).

19. B. Ruffing, A. Nebel, and R. Wallenstein, "High-power picosecond LiB_3O_5 optical parametric oscillators tunable in the blue spectral range," Appl. Phys. B **72**, 137 (2001).
20. R. C. Bapna, C. S. Rao, and K. Dasgupta, "Low-threshold operation of a 355 nm pumped nanosecond β-BaB_2O_4 optical parametric oscillator," Opt. Laser Technol. **40**, 832 (2008).
21. M. Wang, J. Ma, T. T. Lu, S. J. Hu, X. L. Zhu, and W. B. Chen, "Development of single-resonant optical parametric oscillator with tunable output from 410 nm to 630 nm," Chin. Opt. Lett. **20**, 021403 (2022).
22. J. Ma, T. T. Lu, X. L. Zhu, X. H. Ma, S. G. Li, T. H. Zhou, and W. B. Chen, "Highly efficient H-β Fraunhofer line optical parametric oscillator pumped by a single-frequency 355 nm laser," Chin. Opt. Lett. **16**, 081901 (2018).
23. J. L. Zhang, J. Ma, T. T. Lu, J. L. Wang, X. L. Zhu, and W. B. Chen, "16.9 MW, efficient 486.1 nm blue optical parametric oscillator using single BBO crystal," Laser Phys. Lett. **18**, 025001 (2021).
24. C. S. Rao, S. Kundu, and A. K. Ray, "High repetition rate nanosecond optical parametric oscillator pumped by the third harmonic of a DPSSL," Appl. Phys. B **124**, 163 (2018).
25. Y. Bi, H. B. Zhang, Z. P. Sun, R. Zhao, H. Q. Li, Y. P. Kong, X. C. Lin, G. L. Wang, J. Zhang, W. Hou, R. N. Li, D. F. Cui, Z. Y. Xu, L. W. Song, P. Zhang, J. F. Cui, and Z. W. Fan, "High-power blue light generation by external frequency doubling of an optical parametric oscillator," Chin. Phys. Lett. **20**, 1957 (2003).