Received: 4 February 2021
DOI: 10.1002/mop.32891

WILEY

RESEARCH ARTICLE

Low noise continuous-wave single-frequency dual wavelength lasers at 671 and 1342 nm

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Funding information
National Key R&D Program of China, Grant/Award Number: 2016YFA0301401

Abstract

A kind of all-solid-state continuous-wave single frequency dual-wavelength lasers delivering high power low-noise radiations at 671 and 1342 nm was designed and fabricated. To lower the laser noise and obtain dual-wavelength laser outputs, the resonator length was optimized and an LBO crystal was adopted for intracavity second harmonic generation. Under 47 W pumping, 3.17 W laser at 671 nm and 2.15 W laser at 1342 nm were obtained simultaneously. The power and frequency fluctuations of the 671 nm laser in a given 4 h were better than ±0.55% and ±50 MHz, respectively. The power and frequency fluctuations of the 1342 nm laser in a given 4 h were better than ±0.60% and ±25 MHz, respectively. The intensity noises and the phase noises of both the 671 and 1342 nm lasers reached the shot noise limit beyond the analysis frequency of 2 MHz.

KEYWORDS

astigmatism compensation, continuous-wave single frequency laser, dual-wavelength, low noise, power scaling

1 | INTRODUCTION

Over the past decades, continuous-wave (CW) single frequency all-solid-state lasers (ASSLs) have been exploited as an indispensable light source in some fields like precise metrology, quantum optics, and cold atom physics.[1,2] Because the noise of the CW single frequency ASSL reach the shot noise limit (SNL) in a wide analysis frequency range, and the spatial mode quality is nearly diffraction limited, this kind of laser was frequently used in the generation of nonclassical light fields.[3–5] In particular, when it comes to the realm of practical quantum information network,[6,7] compact high-power CW single frequency ASSLs at 1342 and 671 nm dual-wavelength are highly required to provide multiple local fields and pump sources of the large scale multipartite continuous variable entanglement field, for the reason that the 1342 nm laser experiences zero dispersion and low-transmission loss when it is passing through a silica fiber.[8]

In general, challenges to get the high-power CW single frequency Nd:YVO_4 laser at 1342 and 671 nm are the poor effective gain stem from the little stimulated emission cross-section of the Nd:YVO_4 at 1342 nm and the significant excited state absorption (ESA),[9] as well as the serious thermal lens effect originated from the large quantum defect and the nonradiative processes involved in the energy transfer upconversion (ETU) and ESA.[10,11] In 2012, Zheng et al. optimized the cavity design by taking into account the influence of the ESA on the thermal lens of the laser crystal, the maximal output powers of 2.8 W at 671 nm and 850 mW at 1342 nm were achieved simultaneously.[12] In 2013, Eismann et al. lowered the quantum defect by employing 888 nm laser diode (LD) pumping, 2.1 W 671 nm laser in CW single frequency operation was obtained using a periodically poled $KTiOPO_4$ (PPKTP) based intracavity second harmonic generation (ICSHG) device.[13] In 2018, we demonstrated a mode-hop-free laser with 11.3 W output at 1342 nm and 0.3 W output at 671 nm by controlling the nonlinear loss induced by ICSHG.[14,15] To the best of our knowledge, there was no report on generating CW single frequency lasers at 1342 and 671 nm with powers exceeding 2 W simultaneously using a single oscillator.

In this article, a CW single frequency ASSL with 1342 and 671 nm dual-wavelength outputs was fabricated. The laser resonator was especially designed to compensate the astigmatism, improve the fundamental laser mode volume, as well as lower the noise of both the 1342 and 671 nm lasers.

2 | EXPERIMENTAL SETUP

The experimental setup of a LD-pumped CW single frequency dual-wavelength lasers operating at 1342 and 671 nm is shown in Figure 1. 880 nm LD dual-end pump scheme was adopted to reduce the heat deposition in the gain medium and consequently diminish the ETU and ESA. The gain medium was an *a*-cut YVO_4-Nd:YVO_4-YVO_4 composite crystal with a length of 5 + 27 + 5 mm. The doping concentration of the Nd^{3+} was 0.27 at.%. Both end-faces of the composite crystal were anti-reflection (AR) coated at 880 and 1342 nm. To suppress the oscillation of the σ-polarization mode and eliminate the etalon effect, a wedge shape of 1.5 degree is cut on one of the end-faces of the crystal with respect to the *c*-axis of the crystal. For longitudinal mode selection, unidirectional traveling wave ring cavity with a TGG crystal and a half-wave plate (HWP2) acting as optical diode was employed. To generate 671 nm laser via intracavity ICSHG, a 18 mm-long LBO crystal was used. Both end-faces of the LBO crystal were AR coated at 1342 and 671 nm. The LBO crystal was also used to introduce an additional nonlinear losses related to the sum frequency and second harmonic processes, since the nonlinear loss of non-resonating mode is twice as large as that of the resonating mode, the possible multi-longitudinal mode oscillation and mode hop can be suppressed.

In order to enlarge the mode volume of the fundamental laser inside the gain medium, as well as minimize the astigmatism effect, an 8-mirror ring resonator containing two convex mirrors was designed. The two plane mirrors (M1, M8) high-reflection (HR) coated at 1342 nm and high-transmission (HT) coated at 880 nm were used to satisfy the dual-end-pump scheme. The concave mirrors M3, M4 and M6 were HR coated at 1342 nm, M5 was partially transmission coated at 1342 nm ($T_{1342nm} = 1\%$) and HT coated at 671 nm. Owing to the use of the four concave mirrors, the fundamental laser radius inside the LBO crystal was optimized to raise up the ICSHG efficiency, and the cavity length was lengthened to 967 mm in comparison with that the lengths of the typical dual-wavelength lasers were either 534 mm[12] or 490 mm.[14] Since the contributions of the noise sources to the laser intensity noise are all positively correlated to the stimulated emission rate, the intensity noise can be lowered among the whole frequency region when stimulated emission rate is reduced by lengthening the resonator length.[16] The convex mirrors M2 and M7 were HR coated at 1342 nm and HT coated at 1064 nm. Figure 2 shows the simulated fundamental mode radii on the meridian and sagittal planes as functions of the thermal focal length of the Nd:YVO_4 crystal when the radius of curvature (ROC) of the concave mirrors were all 100 mm. The solid curves indicate the case that M2 and M7 were

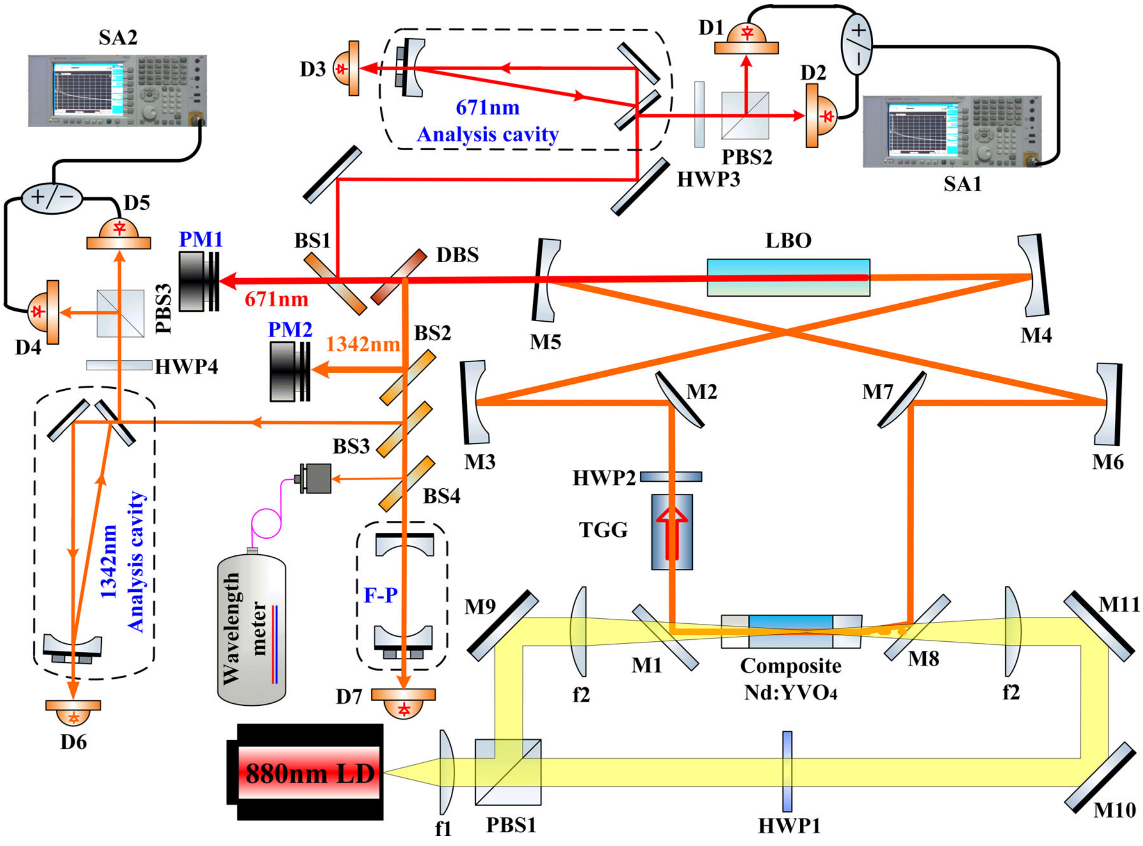

FIGURE 1 Experimental setup of the LD-pumped CW single frequency dual-wavelength Nd:YVO_4 laser. DBS, dichroic beam splitter; D1–D7, photo detectors; HWP, half-wave plate; OI, optical isolator; PBS, polarizing beam splitter; PM, power meter; SA, spectrum analyzer [Color figure can be viewed at wileyonlinelibrary.com]

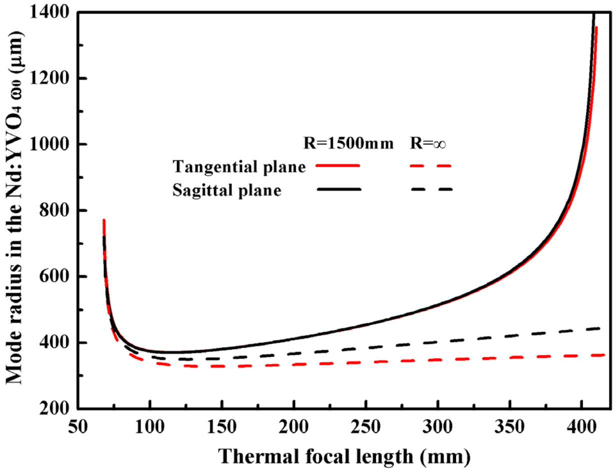

FIGURE 2 Fundamental mode radii on the meridian and sagittal planes as functions of the thermal focal length of the Nd:YVO_4 crystal [Color figure can be viewed at wileyonlinelibrary.com]

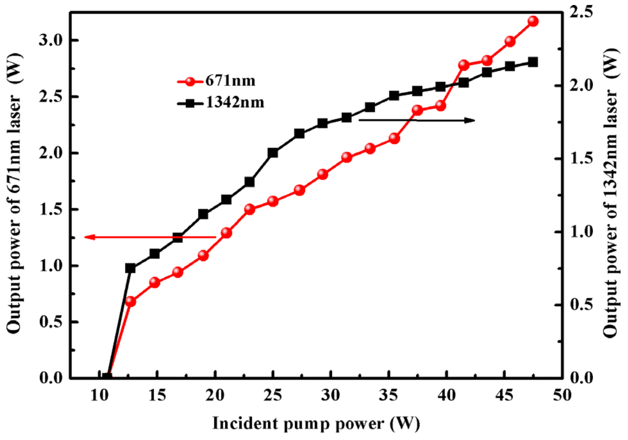

FIGURE 3 Powers of the 1342 and 671 nm lasers as functions of the incident pump power [Color figure can be viewed at wileyonlinelibrary.com]

convex mirrors with ROC of 1500 mm, the dashed curves indicate the case that M2 and M7 were plane mirrors. It can be seen, although the laser stable region in the previous case is narrower leading to a higher pump threshold, the astigmatism can be significantly compensated in the range of the thermal focal length from 75 to 400 mm. Since the average pump radius inside the gain medium was 440 μm, and the measured thermal focal length of the gain medium under 47 W dual-end pumping was 115 mm[15] leading to a laser mode radius of 370 μm, mode matching between the pump and intracavity laser beams can be realized.

3 | EXPERIMENTAL RESULTS AND DISCUSSION

The output characteristics of the dual-wavelength lasers were measured, as shown in Figure 3. When the total pump power was 47 W, CW 671 nm laser with 3.17 W and 1342 nm laser with 2.15 W were obtained simultaneously. The longitudinal-mode spectrum of the 1342 nm laser was monitored using a scanning Fabry-Perot (F-P) interferometer (free spectral range: 750 MHz; finesse: 370). As shown in the inset in Figure 3, the laser is confirmed in single frequency operation. Since the slopes of the two curves in Figure 3 is not reduced at the pump power of 47 W, dual-wavelength lasers with higher power can be expected when the incident pump power is further raised up.

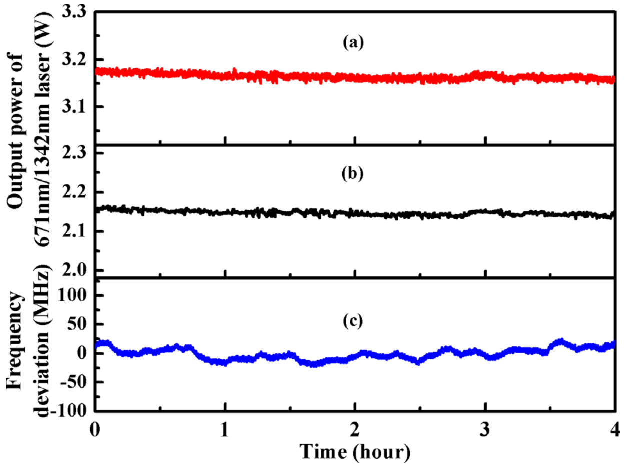

FIGURE 4 Long-term power fluctuations of the 1342 and 671 nm laser and the frequency fluctuation of the 1342 nm laser [Color figure can be viewed at wileyonlinelibrary.com]

The power fluctuations of the lasers were measured using two power meters (PM1 and PM2, Model: LabMax-Top, Coherent) with a resolution of 0.001 mW. When the dual-wavelength lasers were operated at the maximum power, power fluctuations of the 671 and 1342 nm lasers in a given 4 h were better than ±0.55% and ± 0.60% respectively, as shown in Figure 4(A),(B). The frequency fluctuations of the lasers were measured using a wavelength meter with a resolution of 0.1 pm (Model: WS6-771, HighFinesse). Figure 4(C) indicated the frequency fluctuation of the 1342 nm laser in a given 4 h was less than ±25 MHz, and that of the 671 nm laser was calculated to be less than ±50 MHz. The laser beam quality of the 671 nm laser was measure using a laser beam analyzer (Model: M2SETIR, Thorlabs), as shown in Figure 5. The measured M^2 factors were $M^2_x = 1.04$ and $M^2_y = 1.05$.

To measure the intensity noises of the dual-wavelength lasers, the lasers were directly injected into two balanced self-homodyne-detection systems (D1&D2, D4&D5, self-made detectors with common mode rejection ratio of 50, the exhibited shot noise level at 10 mW illumination was 23 dB higher than the electronic noise in the detection band) shown in Figure 1. Since the phase noises of the lasers cannot be measured directly, two 1.61 m-long analysis cavities were used to transfer the laser phase noise to intensity noise.[17] The analysis cavity for 671 nm laser has a finesse of 440 and a linewidth of 0.42 MHz, hence the phase noise beyond 0.6 MHz can be transferred to intensity noise completely. The analysis cavity for 1342 nm laser has a finesse of 460 and a linewidth of 0.4 MHz allowing for a complete conversion of the phase noise to intensity noise for frequencies above 0.58 MHz. To allow precise noise measurement in the low-frequency region, the resolution bandwidth and the video bandwidth of the spectrum analyzer (SA, Model: N9030A, Keysight) were respectively set as 1 kHz and 100 Hz during the experiments. Figure 6(A),(B) show respectively the noise behaviors of the 1342 nm laser and 671 nm laser when the resonator length is 490 mm. It can be seen; the intensity noises and the phase noises of the two lasers reach SNL beyond 4.5 MHz. When the resonator length is extended to 967 mm, as shown in Figure 6(C),(D), the intensity noises and the phase noises of the two lasers are all lowered that reach SNL beyond 2 MHz.

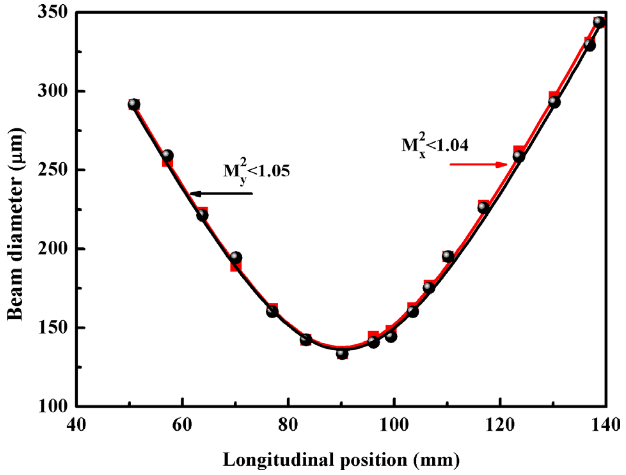

FIGURE 5 Measured beam quality of the 671 nm laser [Color figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSION

A low-noise CW single frequency ASSL with 1342 and 671 nm dual-wavelength outputs both exceeding 2 W was demonstrated. By designing and optimizing an eight-mirror ring resonator, the mode volume of the fundamental laser inside the gain medium was enlarged, and the astigmatism was significantly compensated. When the pump power was 47 W, 3.17 W laser operating at 671 nm and 2.15 W laser operating at 1342 nm with excellent power and frequency stabilities were emitted simultaneously. The beam quality of the 671 nm laser was nearly diffraction limited. Owing to the smaller stimulated emission rate stem from longer resonator length, the intensity noises and the phase noises of both the 671 and 1342 nm lasers reached SNL beyond the analysis frequency of 2 MHz. This kind of high power low-

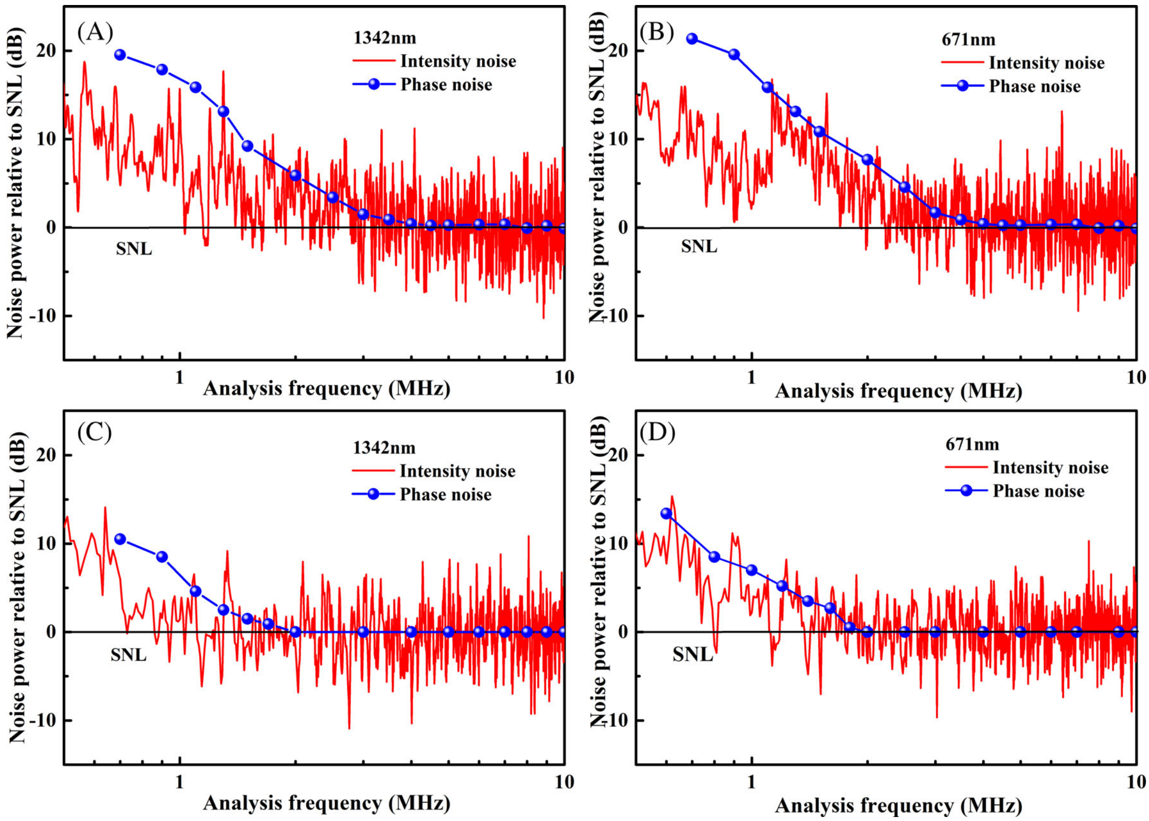

FIGURE 6 (A) and (C): Intensity noise and phase noise of the 1342 nm laser relative to SNL when the resonator length were 490 and 967 mm; (B) and (D): intensity noise and phase noise of the 671 nm laser relative to SNL when the resonator length were 490 and 967 mm. SNL, shot noise limit [Color figure can be viewed at wileyonlinelibrary.com]

noise dual-wavelength lasers can be used in the generation of 1.3 μm entanglement source and the investigations of the fine spectra of the lithium atoms.

ACKNOWLEDGMENTS

This research was supported by National Key R&D Program of China (NO. 2016YFA0301401).

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How to cite this article: Yan L, Li Y, Feng J, Zhang K. Low noise continuous-wave single-frequency dual wavelength lasers at 671 and 1342 nm. *Microw Opt Technol Lett*. 2021;63:2085–2089. https://doi.org/10.1002/mop.32891