A Stable 22-W Low-Noise Continuous-Wave Single-Frequency Nd:YVO_4 Laser at 1.06 μm Directly Pumped by a Laser Diode *

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We report a low-noise continous-wave single-frequency Nd:YVO_4 laser at 1.06 μm directly pumped by an 880-nm laser diode. A maximum output power of 22 W is achieved with an optical-to-optical conversion efficiency of 46.3%. The stability of the output is better than ±0.7% in the given four hours. The output beam is almost diffraction-limited with a measured beam quality of $M_x^2 = 1.05$ and $M_y^2 = 1.02$. The intensity noise and the phase noise of the laser reach the shot-noise limit at an analysis frequency of 5 MHz.

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All solid-state continous-wave (cw) single-frequency Nd:YVO_4 lasers with high output power have attracted great interest for their important applications. such as the pumping of single resonant optical parametric oscillators to expand the wavelength of a laser,[1,2] capturing cold atoms,[3] scientific research in quantum optics and quantum information experiments,[4,5] and interferometric gravitational wave detectors.[6] The development of cw single-frequency lasers is currently concentrated on how to improve the beam quality, the long-term power stability and the intensity and phase noise while increasing the output power. Direct pumping is an efficient method, because the heat load of the laser medium induced by the quantum-defect ratio decreases more than the pumping at 808 nm. In 1999, Lavi *et al.*[7] compared Nd:YVO_4 lasers pumped by 880 nm and 808 nm; the slope efficiency increased by 5% and the threshold decreased by 11%. The laser slope efficiency of 75% near the quantum defect in the 1.06 μm Nd:YVO_4 laser was achieved under direct pumping at 880 nm.[8] Zhu *et al.*[9] generated a maximum 1.06 μm output of 165 W in an Nd:YVO_4 stable–unstable hybrid slab oscillator pumped at 880 nm with $M^2 = 1.7$. However, these lasers were operated in a single-transverse mode. A cw single-frequency monolithic nonplanar ring oscillator (NPRO)[10,11] was frequently used in high-precision experiments, but only several Watts can be obtained by NPRO. To obtain high-power cw single-frequency lasers, the master oscillator power amplifier (MOPA) system was used. As high as hectowatt cw single-frequency lasers were obtained by MOPAs,[12,13] but the optical emission spectrum and beam quality were degraded due to the amplification process, which was undesirable in quantum optics and high-precision experiments.

In this Letter, in order to obtain a high-power good beam-quality low-noise cw single-frequency laser, a ring resonator was designed and a Nd:YVO_4 crystal was directly pumped by an 880 nm laser diode (LD). A polarized and dual-end pumping scheme was used to improve the pump absorption efficiency to achieve homogeneous absorption along the length of the crystal, and to reduce the thermal effects. A stable cw single-frequency 1.06 μm laser was obtained. The laser characteristics such as power stability, beam quality, and the noise–power spectrum were investigated in detail.

The experimental setup of the cw single-frequency Nd:YVO_4 laser is shown in Fig. 1. The pump source was a fiber-coupled LD with a central wavelength of 880 nm and a fiber-core diameter of 400 μm. A polarizing beam splitter (PBS) was used to split the beam from the fiber which was collimated by the lens L1 into two orthogonally polarized beams. One beam was focused through lens L2 with a spot-size diameter of 1 mm into one end of the Nd:YVO_4 crystal. To obtain the high-pump absorption efficiency, the pump polarization was along the *c* axis of the crystal. The polarization of another beam was rotated 90° by a half-wave plate (HWP) so that it was also along the *c* axis. The beam was focused through lens L3 into another end of the crystal, also with a spot size of 1 mm. This kind of dual-end pumping scheme can realize homogeneous absorption along the length of the laser crystal, so that defects such as serious thermal aberration, bulging of the entrance faces, and stress fracture risks, which are encountered in the one-end pumping configuration, are reduced. The polarized pump scheme could also solve the problem of different absorption coefficients of orthogonal polarizations in the Nd:YVO_4 crystal.

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The Nd:YVO_4 was a composite crystal consisting of a 15 mm long 0.2at.% Nd-doped part in the middle with two 2.5 mm long undoped end caps. Both end faces of the Nd:YVO_4 were anti-reflection coated at 1.06 µm and 880 nm ($R_{1.06\,\mu m, 880\,nm} < 0.25\%$). The Nd:$YVO_4$ rod was tightly wrapped with indium foil and mounted in a copper block which was temperature-controlled at 20℃ by a home-made temperature controller with an accuracy of ±0.01℃ (YG-4S, YuGuang Co., Ltd). The pump absorption efficiency of 95% was measured.

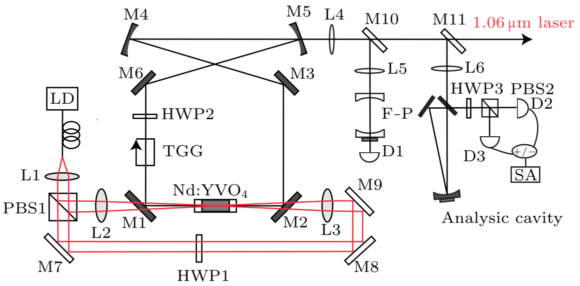

Fig. 1. Experimental setup of the cw single-frequency Nd:YVO_4 laser at 1.06 µm. LD: laser diode; L1-L6: lenses; PBS: polarizing beam splitter; HWP: half-wave plate; F-P: Fabry-Perot interferometer; D1-D3: photodiode detectors; SA: spectrum analyzer.

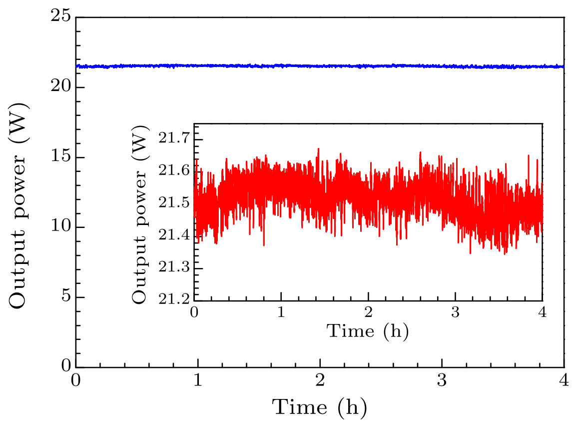

Fig. 2. Measured power stability of the 1.06-µm laser at average power of 21.5 W.

A ring resonator was designed, formed by four plane mirrors (M1, M2, M3, and M6) and two plano-concave mirrors (M4, M5) with a radius of 100 mm. M1 and M2 were high-reflection (HR) coated at 1.06 µm ($R_{1.06\,\mu m} > 99.7\%$) and high transmission coated at 880 nm ($T_{880\,nm} > 95\%$). M3, M4 and M6 were HR coated at 1.06 µm ($R_{1.06\,\mu m} > 99.7\%$). M5 was the output coupler with the transmission of 20% at 1.06 µm. The cavity length was designed by the ABCD matrix analysis, taking into account the thermal lensing effect of the crystal. The measured thermal focal length was about 400 mm at the pump power of 50 W. The optimal cavity length was 95 mm (between M4 and M5) plus 520 mm (residual path length). The cavity configuration ensured that the resonator was stable and was insensitive to the thermal lensing effect at high pump power around 50 W. According to the calculation, the waist radius in the center of the crystal was about 530 µm, and good mode-matching between the pump and oscillation beams was achieved. Using an optical diode formed by an HWP and a terbium gallium garnet (TGG) crystal in the resonator,[14] a cw Nd:YVO_4 laser of single-frequency operation was achieved.

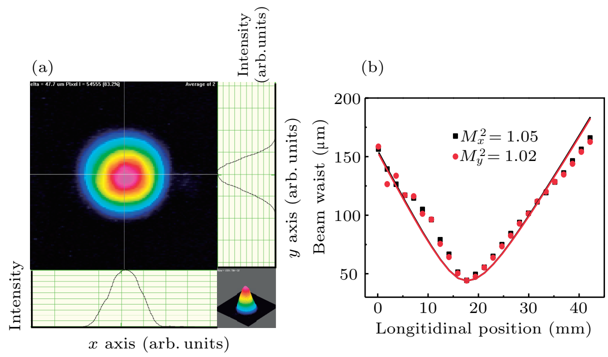

Fig. 3. Beam characters of the 1.06-µm laser: (a) energy distribution and intensity profile in two orthogonal axes, (b) the measured beam quality.

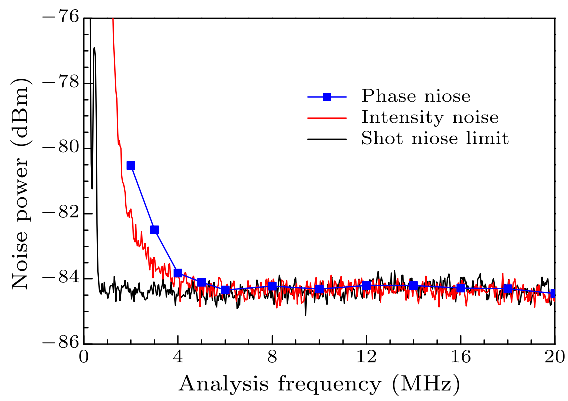

Fig. 4. Measured intensity and phase noise of the Nd:YVO_4 laser from 0 to 20 MHz. The parameters of the spectrum analyzer: resolution bandwidth 100 kHz, video bandwidth 100 Hz, and sweep time 1.5 s.

The laser could oscillate when the pump power was above 28 W. The reason for such a high threshold is that the ring resonator was designed for high pump power and the resonator was outside the stable region at pump power of below 28 W. The measured maximum power was 22 W at pump power of 50 W. The optical-to-optical conversion efficiency was 46.3% taking into account the pump absorption efficiency. The long-term power stability was measured by a power meter (LabMax-TOP, Coherent) and recorded by a computer at an average output of about 21.5 W. As shown in Fig. 2, the power stability was better than ±0.7% (peak-to-peak) over a period of four hours. The longitudinal mode of the 1.06 µm laser was monitored by a scanning confocal Fabry–Perot (F–P) interferometer with free spectral ranges of 750 MHz and a fineness of 400. The transmitted intensity of the F-P interferometer was recorded by a digital storage oscilloscope (Tektronix DPO 4054). The laser was single-frequency operation and the frequency drift was better than 8 MHz in 1 min when the laser was free-running.

The beam quality was measured by a laser beam analyzer (DataRay, WinCamD+M2DU M2 system) at an output power of 22 W. Figure 3(a) shows the recorded energy distribution of the laser beam. The intensity along two orthogonal axes exhibits a perfect Gaussian intensity profile. The measured beam quality is $M_x^2 = 1.05$ and $M_y^2 = 1.02$, and the output beam is almost diffraction limited.

A low noise level of the laser that reaches the shot noise limit (SNL) is required for many applications, including high-resolution spectroscopy, precision measurement, and quantum optics. The intensity noise power of the laser was measured using a balanced homodyne detection system,[15,16] formed by HWP3, PBS2 and a pair of low-noise, broadband photodetectors (D2 and D3). The detected signals were recorded by a spectrum analyzer (N9010A, Agilent) with resolution bandwidth of 100 kHz, video bandwidth of 100 Hz, and sweep time of 1.5 s. The intensity noise power spectrum is shown in Fig. 4; the sum signal gives the intensity noise power of the laser (red line) and the difference signal gives the SNL (black line). The SNL was calibrated by a thermal white light source. It can be seen that the intensity noise reaches the SNL at analysis frequency of 5 MHz. The electronic noise level of the balanced homodyne detector is 10 dB below the SNL (not shown in Fig. 4). To investigate the phase noise, an empty off-resonance ring cavity (the analysis cavity in Fig. 1) is used as a phase-to-amplitude converter.[17] The analysis cavity is constructed by an input coupler with transmission of about 2.8% and two high-reflectivity mirrors with the measured finesse of 220 and bandwidth of 0.7 MHz. The phase-noise power was measured at each analysis frequency by scanning the analysis cavity with a triangular wave of 2 Hz. The measured phase-noise power spectrum is shown in Fig. 4 (blue line), and the phase noise reaches the SNL at analysis frequency of 5 MHz.

In summary, a stable low-noise cw single-frequency $Nd:YVO_4$ laser at 1.06 µm directly pumping at 880 nm has been created. With the help of a polarized and dual-end pumping scheme and a proper ring-resonator design, the laser could be operated with high output power, good beam quality and long-term stability. The measured maximum output is 22 W with the optical-to-optical conversion efficiency of 46.3%. The long-term power stability is better than ±0.7% over a period of four hours. The beam quality of $M_x^2 = 1.05$ and $M_y^2 = 1.02$ has been measured. The noise characteristics of the laser are also investigated. The measured intensity and phase noise reach the SNL at an analysis frequency of 5 MHz. This kind of high-quality $Nd:YVO_4$ laser can be used as a pump source for optical parametric oscillators to expand the wavelength of the laser and for generating nonclassical light in quantum optics.

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