High-power, kHz-repetition-rate, long-pulse-duration, narrow-linewidth 1319 nm Nd:YAG solid-state laser for a guide star laser system

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Abstract

We propose and demonstrate a new approach to scale the average output power with narrow linewidth and good beam quality simultaneously for a 1319 nm laser. A polarization and sequence pulsed beam combining technology is developed to add two lasers. Each laser is based on a quasi-continuous-wave diode-pumped Nd:YAG master-oscillator power-amplifier system. One provides output power of 81 W with s-polarization, $M^2 = 1.49$, and a repetition rate of 500 Hz. Another also operates at 500 Hz, but delivers power of 78 W with $M^2 = 1.47$ and p-polarization. After combination, a maximum average power of 156 W with beam quality of $M^2 = 1.5$ is achieved, corresponding to a combining efficiency of 98.1%. The combined beam has a 1 kHz repetition rate with 120 μs pulse duration and ~0.3 GHz linewidth. To the best of our knowledge, this is a record-high output power for the solid-state 1.3 μm lasers. All results indicate the technique of polarization beam in conjunction with sequence pulsed beam combining not only allows the scaling of the laser power while maintaining narrow linewidth and good beam quality, but also is an effective approach for increasing the pulse repetition rate.

1. Introduction

High-power solid-state lasers operating at 1.3 μm have attracted considerable attention in recent years for their important requirements in optical communications, materials processing, laser medicine, and nonlinear frequency conversion [1–6]. Especially, high-power narrow linewidth pulsed 1319 nm laser is extremely important for 589 nm sodium laser using Sum-Frequency Generation (SFG) technique with 1064 nm laser [7–12] to efficiently generate sodium Laser Guide Star (LGS) for ground-based telescopes’ Adaptive Optics (AO) system [13–16]. The pulsed output format of the laser is also an easier solution for solving LGS’s Rayleigh back-scattering and fratricide problems [17–19]. As single LGS has a finite corrected field with only few tens of arc-seconds, it could not meet the need of next-generation large telescopes. Therefore, multi-laser guide stars (MLGS) is proposed and developed to increase the field of view of AO-corrected images [20–22]. Obviously, a high power laser beam with good beam quality and narrow linewidth is desirable and required especially for such a system, where the beam could be split into several beamlet lasers to produce those MLGS. In order to achieve a high power high beam quality pulsed 589 nm laser, it is very essential and urgent to develop high power pulsed 1064 and 1319 nm fundamental laser sources with narrow linewidth and good beam quality.

The 1319 nm emission line come from the $^4_{13/2} - ^4_{11/2}$ transition of Nd$^{3+}$ ion, and it is well known that Nd:YAG crystal is the most widely used as solid-state laser gain medium for its excellent thermal properties and output characteristics so far [23]. Compared to 1064 nm operation, however, it is more difficult to scale the laser...
power with narrow linewidth and excellent beam quality for operation at 1319 nm due to the small stimulated-emission cross section and the large quantum defect [24]. Clearly, the key objective to achieve the high power 589 nm lasers is how to scale the power of the 1319 nm lasers. Therefore, we focus our attention on to develop the high power 1319 nm lasers. A common way to scale power is based on master–oscillator–power-amplifier (MOPA) technology [25–29]. For instance, a system with 85 W mode-locked ps output at 1319 nm from three waveguide amplifiers was reported, where a 58 W 589 nm laser had been generated [10]. However, high peak power of the ultra-short pulse laser would easily induce absorption saturation of sodium atoms, thereby decreasing the photon return. For the pulse format of 100 μs level, a 100 W quasi-continuous-wave (QCW) μs pulse 1319 nm Nd:YAG laser was obtained by employing three stages amplifiers with relative poor beam quality $M^2$ of ~3.0 and a repetition rate of 250 Hz, providing an 81 W average-power 589 nm output [11]. Unfortunately, the low repetition rate is not fast enough to correct the atmosphere turbulence for LGS-AO system. More recently, using a double-stage double-pass Nd:YAG amplifier chain, we successfully achieved a 105 W QCW μs output power with beam quality of $M^2 = 1.85$ for 1319 nm, and a 65 W SFG at 589 nm was realized at 500 Hz [12]. A prototype of the laser system had been installed on an astronomical telescope at Xinglong Observatory of China, and the highest return flux of Na LGS (1820 photons/cm$^2$/s) was achieved for the field test. However, further scaling power at 1319 nm into the range of 150 W level while maintaining a good beam quality remains challenging due to the amplified spontaneous emission (ASE) resulting in lower extraction efficiency and the serious thermal effect leading to the beam quality degradation.

In this paper, a novel highly efficient polarization and sequence pulse beam combining technology was developed and employed for the first time, to combine two independent QCW diode-pumped 1319 nm Nd:YAG MOPA laser beamlets. For each pulsed Nd:YAG master oscillator, a twisted-mode cavity was employed as the seed source to realize the narrow-linewidth laser output. In order to avoid the degradation of beam quality, moreover, only single-stage amplifier architecture was adopted to achieve higher power output. Under the repetition rate of 500 Hz, a 81-W s-polarized 1319 nm MOPA1 and a 78-W p-polarized 1319 nm MOPA2 were achieved with beam quality of $M^2 = 1.49$ and $M^2 = 1.47$, respectively. As a result, we successfully scale the output power of a 1319 nm QCW laser to 156 W with beam quality factor $M^2 = 1.5$, which represents the highest average-power for 1.3 μm lasers. This corresponds to a combining efficiency of 98.1%, and the repetition rate of combined beam was 1 kHz with a pulse width of 120 μs and a line width of ~0.3 GHz. An electro-optic modulator was used to adjust final polarization state of the combined laser beam to the same direction. Based on such high power 1319 nm laser system, more than 100 W 589 nm laser could be expected.

2. Experimental setup

The experimental setup of the polarization and sequence pulsed beam combining was shown in figure 1. Because the two MOPA systems shared the same configuration, only MOPA1 was presented in detail. The master oscillator employed a symmetrical twisted-mode cavity, which was well known technique to eliminate the troublesome spatial hole-burning for high-power narrow-linewidth operation. Here, two Nd:YAG laser modules LH1 and LH2 were adopted for power scalability. The Nd:YAG rods (Φ 5 mm × 82 mm) were doped with 0.6% of Nd$^{3+}$ and coated with Anti-Reflection (AR) coating at 1319 nm on both ends. Each rod was threefold symmetrically side-pumped by three QCW pulsed 808 nm diode arrays with a total maximum pump power of 240 W, 120 μs pulse duration at a repetition rate of 500 Hz. A 90° quartz rotator Q1 was placed between the two Nd:YAG rods to compensate the thermally induced birefringence which could improve overall beam quality. The thin-film polarizer TFP1 was coated with High-Reflective (HR) coating at laser lines in vertical direction and High–Transmittance (HT) coating in parallel direction at an incidence angle of 45°. A pair of zero-order quarter-wave plates QW1 and QW2 were put on both sides of the Nd:YAG crystals to form a twisted mode cavity in order to suppress spatial hole-burning. The resonator adopted two convex mirrors M1 and M2 with an equal curvature radius of 1000 mm as rear mirror and output coupler, respectively. In order to suppress parasitic oscillation of the 1064 nm line, M1 was coated with HR at 1319 nm and AR at 1064 nm. M2 had a transmission of 20% at 1319 nm. A suprasil Fabry–Perot (FP) etalon was specially designed, with the free spectral range (FSR) of 17 GHz and the finesse of 6, to get the tunable output wavelength with narrow linewidth. A type–II noncritical phase-matching LBO crystal with an aperture of $4 \times 4$ mm$^2$ was employed as an intracavity frequency doubler, so as to suppress the inherent spiking behavior due to relaxation oscillations in pulse-pumped solid-state lasers. More details of spiking suppression could be found in [30]. Temperatures of the etalon and LBO as mentioned above were maintained with a precision of ±0.05 °C by the temperature controller. Furthermore, the basic design of the oscillator was based on thermally near-unstable resonator, where the fundamental mode size in the gain medium was larger and the diffraction loss of the high order transverse modes was higher, so that both of high output power and good beam quality could be expected simultaneously. To optimize the resonator architecture, the cavity length of the twisted-mode laser was designed by using the ABCD propagation matrix.
based on the measurement of the thermal focal length of Nd:YAG rod. The relevant work and research result had been published as our previous paper [31].

The 1319 nm seed output was reflected by two high reflective flat mirrors M3 and M4, then coupled into the amplifier with a pair of mode-matching lenses F1 and F2. In order to remain a good beam quality, only single-stage double-pass amplifier chain was employed to amplify the pulse train up to the power required. The amplifier comprised two identical laser modules LH3 and LH4, similar to LH1 and LH2, and a quartz rotator QR2. To achieve high extraction efficiency and good beam quality simultaneously, and the optimum performance of the amplifier modules was obtained by arranging for the signal beam diameter in each amplifier to be approximately 0.8 times the diameter of laser rod. Behind laser module LH4, a spatial filter, constructed of two lenses F3, F4, and an aperture AP, was utilized to clean the laser beam spatial profile. After first-pass amplification, the beam was reflected back by the mirror M5. A quarter-wave plate QW3 was used to adjust the polarization of the laser beam to make sure the laser output was vertically s-polarized from the thin-film polarizer TFP2 after passing the power amplifier twice.

In our experimental study, two pulsed 1319 nm MOPA lasers were operated with orthogonal polarization state, as so to implement the polarized beam combining. The two output beamlets after amplification were expanded and collimated with the same size as perfectly as possible by sets of F5, F6 and F7, F8, respectively, then synthesized to be one beam by means of the thin-film polarizer TFP3.

The sequence controlling of pulsed beamlets was accomplished based on the synchronizing and delay technique of pulses. Here, we used a digital pulse generator with double output channels to trigger the two 1319 nm beamlet lasers. The combined pulse temporal sequence was monitored by an oscilloscope, which was used as a reference signal to optimize the delay between the two channels. For the case, the schematic of pulse train of polarization and sequence pulse beam combining was illustrated in figure 2. Figures 2(a) and (b) show s- and p-polarized pulse trains for beamlet1 and beamlet2, as well as the relative time delay, respectively, under the same duty cycle of ~6%. Figure 2(c) depicts the combined pulsed train. Reasonably, a doubled power and repetition rate laser could be achieved after combining, but the two adjoining pulses were independent with alternate s- and p-polarization. A Pockels cell was utilized as the high repetition rate voltage-increased electro-optical phase modulator (EOM) to make all the pulses polarized to the same direction. When Pockels cell was biased to its half-wave voltage, the polarization direction of p-polarized beamlet2 would be changed by 90° after passing through the Pockels cell, but polarization of s-polarized beamlet1 keeps unchanged. Then, a combined s-polarized laser beam was produced ultimately, as shown in figure 2(d).

Figure 1. Schematic diagram of experimental setup of two pulsed MOPA beams combining. BS: beam splitter; HR: high reflective mirror; EOM: electro-optical modulator; PM: power meter; CCD: charge coupled device.
3. Results and discussion

For MOPA1, the seed provides an output power of 37.8 W at 500 Hz with beam quality of $M^2 = 1.18$; after amplification, the s-polarized output as beamlet1 was up to 81 W with the beam quality of $M^2 = 1.49$. For MOPA2, using a 37.3 W, 500 Hz and $M^2 = 1.17$ seed source, the amplified p-polarized output, referred to beamlet2, reached 78 W with $M^2 = 1.47$. By the polarized pulse beam combining approach mentioned above, the two 1319 nm beamlets have been added sequentially. The total average power of the combined beam was measured to be as high as 156 W with a combining efficiency of $\sim 98.1\%$, which is, to our knowledge, the highest output power ever reported for an all-solid-state 1.3 $\mu$m laser. After modulated by the EOM, the linear s-polarization ratio of the combined beam is better than 100:1. The measured power fluctuation at the maximum output power is within $\pm 2\%$ over 12 h, as seen in figure 3. The unstable laser power is attributed to the variation of laser-diode pump power as well as the thermally induced distortions in the laser rod and the associated lensing and birefringence, which also strongly influences the beam quality and pointing stability, especially for the high power regimes. The stabilities of laser operation can be improved by apply highly stable QCW laser-diode pumping. Moreover, the thermal effect in laser crystal can be mitigated by using direct pumping technique.

At the maximum output power, the spectral purity of the combined beam was checked by an optical spectrometer (NIRQuest256-2.5 Ocean optics Inc.). As illustrated in figure 4, no other laser lines but 1319 nm are observed in combined beam. Meanwhile, the beam quality of the combined beam was measured with a beam quality analyzer ($M^2$-200, Spiricon Inc.). The combined beam quality factor was measured to be $M^2 = 1.50$, which was very close to the $M^2$ value of beamlet1 ($M^2 = 1.49$) and beamlet2 ($M^2 = 1.47$). Figures 5(a)–(c) shows the two- dimensional (2D) spatial intensity profiles of beamlet1, beamlet2, and the combined beam, respectively, which indicates that the combined laser is operating in good Gaussian mode. As the above result

\[ \text{Figure 2. Combining process schematic of polarized pulse train (a) s-polarized beamlet 1;} \]
\[ \text{(b) p-polarized beamlet 2; (c) combined pulse train without EOM, indicating alternate s- and p-polarization; (d) combined pulse train with EOM, indicating identical s-polarization.} \]

\[ \text{Figure 3. Power-stability test of combined beam at the highest output over 12 h.} \]
shows, compared with coherent beam combining that a precise control of wavelengths and relative phase stabilization between the individual lasers are required [32], the approach of polarization and sequence pulsed beam incoherent combining is one of the high effective and simple combined techniques, without introducing further complexity and without any specific restriction on phase and frequency spectrum, which can improve laser output power with excellent beam quality. Furthermore, a refraction displacement pulse combining technique could be employed, which provides the potential for scaling to a much higher power level with good beam quality by combining a large number of laser beams. More details could be found in other publication [33].

The temporal profile of 1319 nm pulsed laser was monitored by an InGaAs high-speed photo detector (ALPHALAS GMBH, UVIR-P, rise time < 40 ps) connected to a 1 GHz bandwidth digital phosphor oscilloscope (Agilent, DPO 4014B-L). As shown in figures 6(a) and (b), both beamlet laser1 and laser2 operate at pulse repetition rate of 500 Hz, respectively. For the time sequence, the pulse of beamlet2 is delayed by 1 ms with respect to the beamlet1. The pulse sequential relationship of the combined beam is exhibited in figure 6(c), and the repetition rate is doubled up to 1 kHz. Figure 6(d) expresses the expanded single pulse temporal profile with a pulse width of 120 μs. With inserting a frequency doubling crystal into each oscillator, it is noticeable that a smooth single pulse profile is observed without much pulse packages, except for the initial overshoot. The physical mechanism of pulse package trains and spike suppression is described in detail in our previous work [30]. This results in high 589 nm sum-frequency efficiency when mixed with a smooth 1064 nm laser pulse [12].

Moreover, the linewidth of the combined laser was measured by a scanning confocal FP interferometer (ThorLabs SA200- 12B, FSR of 1.5 GHz, frequency resolution of 7.5 MHz). In figure 7, the upper line represents the scanning voltage signal of PZT and the lower line plots the corresponding transmission intensity. It can be clearly seen form figure 7 that the laser spectrum contains only three modes, and the frequency spacing of two adjacent modes is the longitudinal mode spacing of the cavity. The laser linewidth can be estimated to be less than 0.3 GHz full width at half maximum of the envelope of the modes. For many applications, we greatly concern about the long-term pointing stability of the combined laser. The pointing jittering was monitored by a charge coupled device (CCD, BASLER, ACA2000-50gm, NIR) and a lens F9 with the focus length of 150 mm. Figure 8 shows the location of all the beam spots measured for 12 h, suggesting that the tilting angles root-mean-squared (RMS) are 28.8 μrad and 29.5 μrad in x and y directions, respectively.
In conclusion, we have demonstrated an 150 W-level high beam quality narrow linewidth QCW microsecond-pulse all-solid-state 1.3 μm laser based on a novel technique of polarization and sequence pulse beam combining. Two 80 W-level 500 Hz pulsed beamlets were added together. The average power of the combined beam as high as 156 W was achieved at 1319 nm with a beam quality of $M^2 = 1.5$ and a line width of $\sim 0.3$ GHz. The combined beam has a repetition rate of 1 kHz and pulse duration of 120 μs. The power fluctuation was measured over 12 h to be within ±2%, and the tilting angles RMS of the combined beam are both less than 30 μrad in x and y directions, respectively. All results indicate the technique of polarization beam in conjunction
with sequence pulsed beam combining not only allows the scaling of the laser power while maintaining narrow linewidth and good beam quality, but also is an effective approach for increasing the pulse repetition rate. Further power scaling of 1319 nm laser could be expected by combining multiple beamlets. Similarly, a higher power of 1064 nm laser is also available. Moreover, this opens up a way to further scale the power to 100 W level for a QCW pulse 589 nm laser. Then, one can be split into five beamlets of 20 W to produce five Na beacons for MLGS application.

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