High power high beam quality diode-pumped 1319-nm Nd:YAG oscillator-amplifier laser system*

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This paper demonstrated a high power and high beam quality diode-pumped 1319-nm Nd:YAG master oscillator-power amplifier laser system. A thermally near-unstable resonator with four-rod birefringence compensation flat–flat cavity was adopted as the master oscillator. A solid etalon was inserted in the unidirectional ring resonator to compress the laser linewidth. Under a repetition rate of 500 Hz and pulse width of 160 μs, the master oscillator delivers an average output power of 16.8 W at 1319 nm with linear polarisation, beam quality factor $M^2 = 1.16$ and linewidth of 3.2 GHz. A double-pass power amplifier with two amplifier stages was employed for higher power scaling and the output power was amplified to be 25.9 W with $M^2 = 1.43$.

Keywords: master oscillator-power amplifier system, Nd:YAG ring laser

PACC: 4260, 4260B

1. Introduction

High power diode-pumped solid-state lasers with high beam quality operating at 1319 nm are very useful for specific applications. For example, they can be employed to pump fibre optical parameter amplifiers and Raman amplifiers.[1] They are important in fibre transmission since silica-based optical fibre exhibits low attenuation and minimum dispersion at the wavelength approximately equal to 1300 nm.[2] They can also be used to generate red light at 660 nm by second harmonic generation,[3] which has extensive applications in high brightness display and photon dynamic therapy, etc.

However, there have been few reports on high power, high beam quality and narrow linewidth 1319-nm laser sources. Hall *et al.* obtained 0.65-W TEM_{00}, single-frequency 1319-nm output with out-of-plane Nd:YAG ring configuration.[4] Saito *et al.* reported a 4.99-W 1319-nm actively mode-locked Nd:YAG laser with $M^2 \approx 1.1$.[5] Denman *et al.* achieved 60-W single-longitudinal mode output at 1319 nm from an injection-locked Nd:YAG laser with $M^2 < 1.1$.[6] Unfortunately, their laser system is very complex and expensive.

In this paper, we presented a relatively simple and practical master oscillator-power amplifier (MOPA) scheme for producing a quasi-continuous-wave (QCW) 1319-nm laser with high power, high beam quality and narrow linewidth. Based on a thermally near-unstable resonator, an Nd:YAG three-mirror unidirectional ring cavity with four diode-pumped laser rods and effective birefringence compensation was employed as the master oscillator. To achieve unidirectional output from the ring laser, an optical isolator was formed by a Faraday rotator, a half-wave plate, and a polarizer. A solid Fabry–Perot (F–P) etalon was inserted in the cavity to compress laser linewidth. As a result, 16.8-W linearly polarized 1319-nm laser with linewidth of 3.2 GHz and beam quality factor of 1.16 was obtained. In order to achieve higher power, a double-pass power amplifier with two amplifier stages was adopted and output power of 25.9 W with $M^2 = 1.43$ was ultimately achieved.

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2. Experimental setup

The experimental setup is shown in Fig. 1. The master oscillator contains two flat mirrors M1 and M2, four identical laser heads LH1, LH2, LH3 and LH4, a 90° quartz rotator QR1, a Faraday rotator FR, a half-wave plate HW, a thin film polarizer P1, an F-P etalon FP and a temperature controller TC. The three cavity mirrors are made up of M1, M2 and P1. The M2 is coated with high reflection (HR) film at 1319 nm and M1 ($T = 10\%$) is an output coupler. The QR1 coated with antireflection (AR) film at 1319 nm was placed between the four LHs so as to compensate the thermally induced birefringence.[7−10] The polarizer was set at the Brewster angle to select the polarization state of the oscillating laser. The combination of the FR, the HW plate and the P1 made the ring laser unidirectional operation. The solid F-P etalon which was used to compress laser linewidth was fixed at an angle and its temperature was accurately controlled by TC.

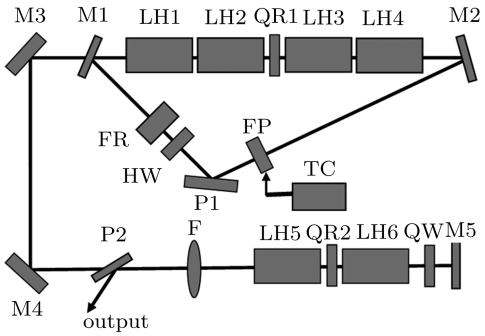


Fig. 1. Overall optical layout of the MOPA system.

The oscillating output laser incidents into the power amplifier after being reflected by M3 and M4 which were both 45° HR-coated at 1319 nm. The power amplifier contains P2, a lens F, two laser heads LH5 and LH6, QR2, a quarter-wave plate QW and a flat mirror M5. The P2 and QR2 performed the same functions as that of P1 and QR1 in the master oscillator. The lens F AR-coated at 1319 nm was used to reach the aperture matching between incident laser and laser rods in the amplifier. The QW was used to change the polarization state of laser. The M5 is HR-coated at 1319 nm.

Each LH in the MOPA system is pumped by 12 QCW 808-nm laser diodes with a maximum available pump power of 60 W at a repetition rate of 500 Hz. The laser rod is symmetrically surrounded by three laser diode arrays which are respectively formed by combining 4 1-cm long bars. The four Nd:YAG rods in the master oscillator are doped with 0.6% of Nd^{3+} with the dimension of Φ 3 mm × 80 mm. The use of low doping concentration which results in a uniform gain distribution in Nd:YAG rod can conduce a better beam quality. The two Nd:YAG rods in the power amplifier are doped with 1.1% of Nd^{3+} with the dimension of Φ 2 mm × 80 mm. The use of high doping concentration which is preferred for a high energy storage density in Nd:YAG rod can conduce a higher energy extraction efficiency. Both facets of the Nd:YAG rods are flat and AR-coated at 1319 nm for reducing losses.

3. Experiment and results

3.1. Master oscillator

In order to achieve high power and high beam quality 1319-nm oscillating output, a thermally near-unstable resonator with four-rod birefringence compensation in a three-mirror ring cavity is designed. Under the thermally near-unstable condition, a laser operates at the border of the stable region near the unstable region, where the fundamental mode size of the gain medium is larger and the diffraction loss of the high-order transverse modes is higher, so high output power and good beam quality can be expected. To design the resonator accurately, the thermal focal lengths of the Nd:YAG rods in our experiment are carefully measured by using the method suggested by Lancaster *et al.*[11] The thermal focal length of a rod versus the laser diode pump power is shown in Fig. 2. It is very evident that the thermal focal length decreases with the increase of the pump power. Based on the measurement, the cavity length of 1319-nm ring laser is designed by using the standard ABCD ray propagation matrix to make the resonator operate at the border of the stable region near the unstable region.

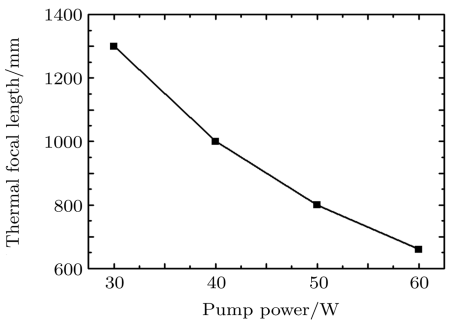


Fig. 2. Relationship between the thermal focal length and pump power.

As is well known, an internal element set at Brewster's angle introduces astigmatic distortions that deteriorate the beam quality. A method to compensate the astigmatic distortions is realized for a specific relation between element thickness and folding angle.[12] In our experiment, the polarizer is set as the cavity mirror to determine the direction of polarization so that the astigmatic distortions induced by inserting polarizer at Brewster's angle are avoided successfully.

For the homogeneously broadened linewidth of the Nd:YAG laser transition at 1319 nm, the narrow linewidth laser can be obtained by using the ring travelling-wave cavity configuration to avoid spatial hole burning. The unidirectional operation of the ring laser is realized by a combination of an FR, an HW, and a polarizer. To eliminate the mode-hopping and compress the linewidth of the 1319-nm laser, a solid F-P etalon is inserted in the cavity. It is known that the output powers are distinct for the different gain coefficients at different operating wavelengths, so we need to tune the laser wavelength in order to obtain maximum output power. In our master oscillator, the wavelength of the laser can be adjusted accurately by controlling temperature and angle of the etalon. Since the change of the etalon angle is too sensitive, its accurate reproducibility is difficult. We adopted the temperature controlled etalon for remote operation of our laser as a result of its accurate reproducibility. In the experiment, the solid etalon was fixed at an angle and its temperature was controlled by a TC which changes in steps of 0.1 °C corresponding to an adjustable accuracy of ∼0.85 pm for 1319 nm.

The cavity length of the master oscillator was designed to be 1140 mm. Figure 3 showed 1319-nm output power of master oscillator as a function of the diode pump power under a repetition rate of 500 Hz and pulse width of 160 μs. The maximal output power of 16.8 W was obtained at the diode pump power of 154 W. In the experiment, the inserting loss of the etalon was also measured. Under the condition without the etalon, the QCW 1319-nm output power was up to the maximal value of 16.9 W for the diode pump power of 151 W. Obviously the output power only decreased 0.1 W at maximum value after inserting the etalon, so the inserting loss was very low, which could be negligible in our experiment.

At the maximum output power of 16.8 W, the two-dimensional profile of the laser beam was measured by a beam quality analyser (M^2-200, Spiricon Inc.), as shown in Fig. 4. The beam quality factor M^2 values of the horizontal axis and the vertical axis are $M_x^2 = 1.10$ and $M_y^2 = 1.22$, respectively. Accordingly, the M^2, which is usually shown as the average value of M_x^2 and M_y^2, is about 1.16. An F-P interferometer with 15-GHz free spectral range and 200-MHz resolution at 1319 nm was used to monitor 1319-nm output. The laser spectrum was recorded by an IR-sensitive CCD camera as shown in Fig. 5 and the linewidth of 1319-nm laser was calculated to be ∼3.2 GHz.

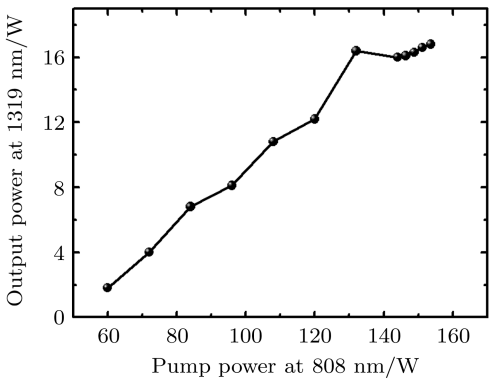


Fig. 3. The 1319-nm output power of master oscillator as a function of the diode pump power at 808 nm.

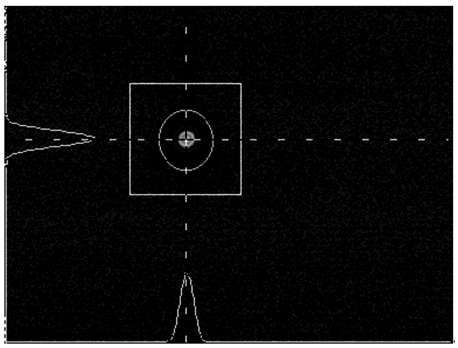


Fig. 4. Two-dimensional profile of laser beam at master oscillator maximum output power.

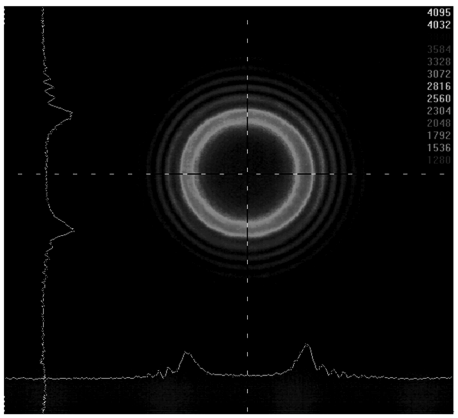


Fig. 5. Output spectra of master oscillator with etalon resolved by the F-P interferometer.

3.2. Power amplifier

A double-pass amplifier consisting of two LHs was adopted for higher output power. The distance between the lens and LH5 was selected precisely and the beam radius in the laser rods of the amplifier was chosen as a compromise of maximum extraction of the stored energy and minimal beam quality degradation through diffraction at the apertures of the rods. To prevent the amplification of weak back reflexes from the AR-coated rod endfaces, the rods were tilted slightly with regard to the optical axes. The QW was used to change the polarization state of light so as to make sure the laser output vertically (s-) polarized from the polarizer P2 after passing the power amplifier twice. The output power was amplified to be 22 W and 25.9 W for single-pass and double-pass amplifier, corresponding to the energy extraction efficiency of 4.8% and 8.4%, respectively. In order to display the stability of the output power, we read the output power value from the power meter with a step of 5 s for 5 min, as shown in Fig. 6, the fluctuation of the output power was less than 2.7%. The two-dimensional profile of the laser beam at the maximum output power was shown in Fig. 7 and the M^2 was measured to be 1.43 ($M_x^2 = 1.34$ and $M_y^2 = 1.52$).

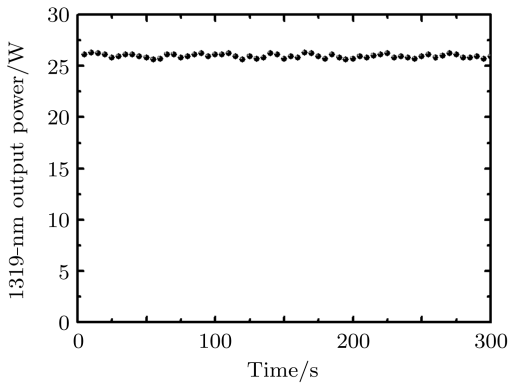


Fig. 6. Stability measurement of 1319 nm for 25.9-W output.

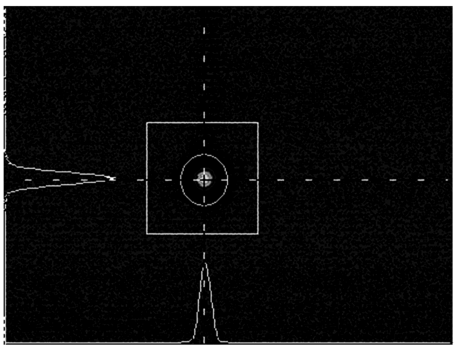


Fig. 7. Two-dimensional profile of laser beam at MOPA system maximum output power.

4. Conclusions

In summary, a simple MOPA system for producing high power QCW 1319-nm laser with high beam quality was demonstrated. Based on a thermally near-unstable resonator, a unidirectional three-mirror ring cavity with four-rod birefringence compensation was employed as the master oscillator. An etalon was inserted to compress the linewidth. The polarizer was set as the cavity mirror to avoid the astigmatic distortions induced by inserting a polarizer at Brewster's angle. The 16.8-W 1319-nm output with linewidth of 3.2 GHz and beam quality factor M^2 of 1.16 at a repetition rate of 500 Hz and pulse width of 160 μs was achieved in the master oscillator. A double-pass power amplifier with two amplifier stages was adopted and the output power of MOPA system was up to 25.9 W with a beam quality factor M^2 of 1.43. The high power and high beam quality 1319-nm laser can be used to generate 589-nm yellow laser by sum-frequency mixing with the 1064-nm Nd:YAG laser[13] and further work is on the way.

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