A diode-pumped injection-seeded Nd:YAG laser system with an average output power of 38 W is described. The laser operates at 300 Hz with pulse energies up to 130 mJ. The temporal pulse shape is nominally flat in time and the pulse width is user selectable from 350 to 600 ps. In addition, the spatial profile of the beam is near top hat with contrast <10%. © 2007 Optical Society of America

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1. Introduction

High-peak power (>10 MW), high-average power (>10 W) laser operation with Nd:YAG is typically achieved by power oscillator [1,2,3,4,5] operation or by MOPA (master-oscillator power amplifier) [6,7,8,9,10,11] operation. In the case of q-switched power oscillators, pulse widths typically range from 7–100 ns. The minimum pulse widths for q-switched power oscillators are limited by the required build-up times and the achievable gain-to-loss ratio [12,13,14]. Mode-locking, either as a power oscillator or as a MOPA, is another option and this technique can generate pulses from 2–100 ps [15,16,17,18]. In this case, the minimum pulse width depends upon the reciprocal of the gain linewidth. To obtain HPP (high-peak power), HAP (high-average power) laser operation with pulse widths in the 300 ps to 1 ns regime using Nd:YAG generally requires a MOPA [19].

HPP-HAP laser operation using MOPAs has been demonstrated in Nd:YAG with pulse widths ranging from 7–100 ns. These lasers typically employ a q-switched or mode-locked laser as the master oscillator whose temporal characteristics ultimately determine the pulse width. Work by Schiemann et al. [20] showed that HPP-HAP laser pulses can be obtained by pulse compression but the pulse-to-pulse energy and temporal stability were less than ideal due to the stochastic nature of the compression process. The primary focus in most HPP-HAP lasers is peak power, average power, beam quality, energy efficiency or some combination of the above. The actual temporal pulse shape is rarely of concern. The effects of gain saturation in the amplifier modify the oscillator temporal pulse shape by steepening the leading edge and sometimes reducing the overall pulse width.

In fusion-class lasers [21,22], the temporal pulse shape can be very important as it drives the dynamics of the target interaction [23]. Fusion-class lasers are currently large beams (>1000 cm²) with very high peak power but very low repetition rate. Optics damage due to these very high peak power lasers is always of concern [24]. Studies [25–28] for developing scaling laws relating laser fluence, pulse width, and pulse shape to damage probability exist but are difficult to test since most lasers do not have well-defined temporal and spatial pulse shapes. A HHP-HAP laser that has a FIT (flat in time) pulse shape with user-selectable pulse width as well as a spatially flat beam profile can be an excellent tool to raster scan optics and acquire large amounts of statistical data to test the scaling laws.
2. Experimental System

The MOPA laser system described in this paper consists of three major components, an oscillator, a regenerative amplifier, and a power amplifier.

A. Oscillator

The oscillator for this laser system is modeled after the NIF (National Ignition Facility) [21] and OMEGA [29] oscillators. It is an all-fiber-based system with components as shown in Fig. 1. A 10-mW cw single-frequency fiber oscillator [30] is injected into an AO (acousto-optic) modulator that carves out a 30-ns pulse. This 30-ns pulse is injected into a fiber amplifier [31] and amplified to $\frac{1}{100}$ nJ. The 10-nJ pulse is injected into a two-channel amplitude modulator as described in Ref. [29]. One channel of the modulator is driven by a PSPL (Picosecond Pulse Laboratory) pulse generator that creates a 0 to 10 V square pulse with user-selectable pulse width. The other channel is driven by an ACSL (aperture-coupled strip line) [29], that generates a 3 V to 6 V linear ramp voltage over 600 ps. The resultant light pulse exiting the modulator is a shaped pulse of $\frac{1}{100}$ 300 pJ as shown in Fig. 2. The pulse shape can be varied by adjusting the relative timing between the PSPL pulse generator and the ASCL.

B. Regenerative Amplifier

The regen (regenerative amplifier) for this laser is a simple modified-V-shaped oscillator cavity shown schematically in Fig. 3. The regenerative cavity is relatively long (1.5 m) and allows for easy injection and extraction of pulses with widths up to 3 ns. The gain is provided by a JMAR-designed [32] end-pumped Nd:YAG rod. The rod is 3 mm in dia., has a gain length of 20 mm and an atomic doping of 1%. In addition, the rod has a piece of un-doped YAG [33], (3-mm dia., 5-mm long) diffusion-bonded [34] to the diode-pump end. This un-doped piece serves two purposes: 1) it helps to homogenize the pump light; 2) it takes some of the thermal load away from the dichroic coating on the rod end, minimizing wavefront aberrations. The pump light is provided by a 4-bar Spectra Physics diode array and is focused into the rod with a simple, spherical plano-convex lens.

The narrow V-shaped cavity allows the use of 0° angle-of-incidence mirrors and reduces the overall footprint to fit on a single 30.5-cm by 122-cm breadboard. The 5-m radius of curvature end mirror makes the cavity passively stable and, in conjunction with the thermal lensing of the end-doped rod, places the beam waist near the quarter wave-plate.

The 300-pJ signal oscillator pulse exits the single-mode fiber and is mode-matched to the regenerative amplifier cavity using a single commercial aspheric lens (focal length 8 mm). This expanded and nearly collimated oscillator beam passes through a tandem Faraday isolator to provide more than 70 db isolation. The injected oscillator pulse is trapped in the regenerative amplifier cavity using a FastPulse 5046E pulse slicer. After approximately 30 round trips, the 2.3-mJ amplified oscillator pulse is switched out. A photograph of the oscillator fiber launch, tandem isolator, and regenerative amplifier on the breadboard is shown in Fig. 4.

C. Power Amplifier

The power amplifier for this laser is a modified JMAR BrightLight four-pass amplifier, shown schematically in Fig. 5.

The amplifier heads are diode-pumped Nd:YAG rods, 8-mm diameter, 72-mm long. The atomic doping concentration is 0.8%. Each head is pumped by five 14-bar diode arrays arranged in pentagonal symmetry. A 90° quartz rotator and the clocking of the two identical amplifier heads at 36° with respect to each other assist in birefringence compensation. With a gain of $\frac{1}{100}$ per head, birefringence compensation is crucial to prevent the amplifier from spontaneously lasing.

The vacuum telescope has a single f = 408 mm plano-convex lens on each end. In combination with the thermal lensing of each amplifier head (f = $\sim$1600 mm), one obtains $\sim$1500 mm between relay planes. This layout is similar to [35] except in this case the relay planes are not in the rods but at the end mirror. This arrangement allows us to maintain relay for four passes instead of two. Each of the vacuum telescope lenses is mounted on a bellows to permit fine-tuning of the relay. A 2-mm aperture at the focus of the vacuum telescope eliminates parasitic oscillation and helps to reduce diffraction effects.
The beam from the regenerative amplifier is expanded and collimated using a pair of plano-convex lenses. A custom-made chrome-on-glass serrated aperture (140 teeth, 1.25-mm tooth length, 4.5-mm-dia. clear aperture) creates a beam with a rounded tophat spatial profile. The serrated aperture plane becomes the reference plane for the relay imaging. The reference plane is relay-imaged onto M2, back to M4, back again to M2, and finally onto a plane 15 cm to the right of input polarizing beam splitter, PB. The quarter wave plate (QWP) near M2 allows the user to select two-pass or four-pass amplification. We only discuss four-pass operation in this paper. The entire assembly fits on a single 30-cm by 140-cm breadboard. A photograph of the power amplifier is shown in Fig. 6.

3. Results

The laser system normally runs at 300 Hz. The pump diodes (for the regenerative amplifier and for the power amplifier) are pulsed for 200 μs. Near-field beam images (at the output relay plane) and pulse shape measurements are monitored continuously. The pulse shape measurements are obtained using a New Focus 1011 45-GHz detector into a Tektronix 8200 sampling oscilloscope. The amplifier pulse shapes for 350, 400, 500, and 600 ps are shown in Fig. 7 below. The FWHM (full width half maximum) is
used to define pulse width. The relatively long tails of the pulse shapes are artifacts of the detector and the long cable length to the oscilloscope. In each case, the output energy of the amplifier is 128 mJ which, at 300 Hz, corresponds to an average output power of >38 W. At each pulse width, the pulse-to-pulse energy stability is <3%. Because of gain saturation in the amplifier, the required pulse shapes from the oscillator and the regenerative amplifier are not FIT. Each successive amplification stage tends to sharpen the leading edge of the pulse. The pulse shapes from the oscillator and the regenerative amplifier that result in FIT amplifier pulses are shown in Figs. 8 and 9. The output energy of the oscillator is 400 pJ with pulse-to-pulse energy stability of <1%. The output energy of the regenerative amplifier is 2.3 mJ with pulse-to-pulse energy stability of <2%.

The amplifier output beam image is continuously monitored using a Cohu 4800 camera and Coherent Beamview software. The camera is located at an equivalent output relay plane and a beam image can be recorded on any shot. Output beam images for four different FIT pulse widths are shown in Fig. 10. The method for determining the statistics for a given beam image is discussed in Section 4.

4. Discussion

One of the goals of this laser system is to generate both a FIT and a tophat spatial profile pulse. A mathematical way of representing a FIT or tophat spatial profile pulse is with a super-Gaussian shape, given by an equation of the form

\[ f(t) = Ae^{-\left(\frac{(t-t_0)^2}{\sigma^2}\right)^n} \]  

(1)

where \( A \) is an arbitrary constant, \( \sigma \) is the Gaussian half width, \( t_0 \) is the center location of the super-Gaussian, and \( n \) is the order of the super-Gaussian. The 500-ps pulse shape and a second-order super-Gaussian fit with \( \text{FWHM} = 500 \text{ ps} \) is shown in Fig. 11. All four of the FIT pulses described in this paper are well approximated by a second-order super-Gaussian.

As we see in Fig. 8, the oscillator pulse shapes required for a FIT amplifier becomes less linear and more exponential as the desired pulse width increases. This temporal curvature is obtained simply by changing the relative timing between the PSPL pulse generator and the ASCL, as described above. No other adjustments are necessary.

The spatial profiles can be fitted by a 5th-order super-Gaussian. Horizontal (x) and vertical (y) line-
out profiles taken through the 500-ps beam centroid and the corresponding super-Gaussian fits are shown in Fig. 12.

The beam statistics shown in Fig. 10 are calculated as follows. First, the captured beam image is fit to a two-dimensional super-Gaussian of the form

$$f(x, y) = A e^{-\frac{1}{2} \left[ \left( \frac{x-x_0}{a} \right)^2 + \left( \frac{y-y_0}{b} \right)^2 \right]^{n}}$$

(2)

where $A$ is an arbitrary constant; $a, b$ are the Gaussian half widths in $x$ and $y$, respectively; $x_0, y_0$ represent the center location of the super-Gaussian in $x$ and $y$, respectively; and $n$ is the order of the super-Gaussian.

The binary beam image file has a one-to-one correspondence between relative fluence per pixel and pixel value. The 90%-amplitude ellipse of this super-Gaussian is defined as the ROI (region of interest). The normalized mean beam fluence is calculated by determining the average pixel value of all pixels within the ROI. At the same time, a histogram of all the pixels within this ROI is generated. The beam contrast is then defined as (the standard deviation of all the pixels within the ROI) $\div$ (the mean pixel value). The 10% energy fraction is defined as (the number of pixels whose pixel value falls within $\pm 5\%$ of the mean pixel value) $\div$ (the number of pixels within the ROI). Similarly, the 20% energy fraction is defined as (the number of pixels whose pixel value falls within $\pm 10\%$ of the mean pixel value) $\div$ (the number of pixels within the ROI). Finally, the peak-to-mean value is defined as (the maximum pixel value anywhere in the image) $\div$ (the mean pixel value within the ROI).

We see that as the FIT pulse width becomes shorter, the beam contrast and peak-to-mean ratios increase. While the beam contrast remains below 10%, the beam images and beam statistics clearly show that the beam is degrading with decreasing pulse width. Using our energy and pulse width numbers in a plane-wave Frantz-Nodvik model [36] indicates that the B-integral ranges from 1.5 (600-ps pulse width) to 2.7 (350-ps pulse width). The 350-ps pulse width is probably the lower limit for this laser because of B-integral concerns. In all likelihood, we are already beginning to see self-focusing effects.

Beam quality $M^2$ measurements were not performed. Since we relay image the near field spatial profile onto the sample plane, the near-field beam quality is of primary interest. We plan to perform beam quality experiments and report on them in the future.
5. Summary

We have demonstrated the operation of a Nd:YAG-based MOPA generating 127-mJ pulses at 300 Hz with an average power of >38 W. The MOPA integrates a 400-pJ fiber-based oscillator with a 2.4-mJ regenerative amplifier and a relay-imaged 4-pass diode-pumped Nd:YAG amplifier to generate a 300-Hz train of output pulses with <3% pulse-to-pulse energy stability. This laser generates both FIT pulses as well as a tophat spatial beam. The FWHM temporal pulse width is continuously user adjustable from 350 ps to 600 ps by two simple electronic adjustments. Longer and different pulse shapes could easily be generated by designing a different ASCL. We have begun frequency conversion experiments using this laser and we plan to report on these results in the near future.

We dedicate this work to our friend and colleague, Jerry Auerbach. This research was performed under the auspices of the U.S. Departments of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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