Using a Newport refractive beam shaper to generate high-quality flat-top spatial profiles from a flashlamp-pumped commercial Nd:YAG laser

Darrell J. Armstrong and Arlee V. Smith

Dept. 1118, Sandia National Laboratories, Albuquerque, NM 87185-1423, USA

ABSTRACT

We've generated high-quality flat-top spatial profiles from a modified Continuum Powerlite 9010 Nd:YAG laser using the Gaussian-to-flat-top refractive beam shaper available from Newport Corporation. The Powerlite is a flashlamp-pumped, Q-switched, injection-seeded Nd:YAG laser manufactured in 1993 that delivers ∼ 1.6 J at 10 Hz using an oscillator and two 9 mm diameter amplifier rods. While its pulse energy is impressive, its beam quality is typically poor, an all too common characteristic of research-grade Nd:YAG lasers manufactured in the late 1980's and early 1990's. Structure in its near-field spatial fluence profile is reminiscent of round-aperture diffraction that is superposed with additional "hot spots." These characteristics are largely due to poor beam quality from the oscillator coupled with over-filled amplifier rods, and reflect a design philosophy from the era of organic dye lasers. When these older laser systems are used for tasks like pumping optical parametric oscillators (OPO's), or for other applications demanding good beam quality, their designs are simply inadequate.

To improve the 9010's beam quality we spatially filter the oscillator beam and remove the resulting Airy rings with an iris, then collimate and magnify the remaining central disk so its diameter is appropriate for input to the refractive shaper. The output of the beam shaper is then double-pass amplified through two amplifier rods with thermally induced focusing compensated by a negative lens before the first pass and by a convex mirror before the second pass. Using this approach we've obtained single-pass energy exceeding 250 mJ with little degradation of the flat-top profile and ∼ 950 mJ after double pass amplification. After double-passing the two amplifier rods the beam suffers some degradation in symmetry and uniformity, but is still much improved compared to the beam obtained using the 9010's original factory configuration. We find the modified 9010's flat-top profile improves conversion efficiency when used for our applications in crystal nonlinear optics.

Keywords: Beam shaping, refractive beam shaper, flat-top spatial profile, Gaussian to flat-top converter, Nd:YAG laser, nonlinear optics

1. INTRODUCTION

A long-standing and largely unresolved problem in laser technology is the near complete absence of nanosecond solid-state lasers with 1–5 J pulse energies that have good beam quality. This problem afflicts almost all high-energy laser systems and it can be argued that it has hampered development of important technologies. For example, throughout its entire 40 year-plus history, poor quality "pump" lasers have plagued the field of crystal nonlinear optics (NLO). This problem is particularly acute in the realm of nanosecond NLO devices where the standard for pump lasers is the venerable Q-switched Nd:YAG. While commercial Nd:YAG lasers are reliable and readily available with pulse energies of 1–5 J, for the most part their beam quality remains relatively poor. Furthermore, there are almost no lasers on the market that produce a true high-quality flat-top spatial profile that is required for obtaining the highest conversion efficiency in applications like nonlinear mixing.

Over the years there have been attempts to obtain high-quality flat-top beams from commercial research-grade Nd:YAG lasers. In particular the unique but now defunct Coherent Infinity with its phase-conjugated amplifier chain was the first and perhaps only widely available research-grade laser with a true flat-top profile.

Further author information: Send correspondence to D. J. Armstrong
E-mail: darmstr@sandia.gov, Telephone: 505 844 4757

Laser Beam Shaping V, edited by Fred M. Dickey, David L. Shealy, Proc. of SPIE Vol. 5525
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.557848

While the Infinity delivered a high-quality flat-top beam, its phase-conjugate mirror shortened the pulse length to 2–3 ns, too short for many NLO applications, and the pulse energy was only 400–500 mJ. For various reasons the Infinity succumbed to market forces and was taken out of production and no manufacturer has offered a suitable replacement. Users with applications requiring high-pulse-energy high-quality flat-top beams are left to accept a compromise from conventional laser systems or resort to expensive custom designed lasers. With today's reduced research budgets, purchase of conventional lasers costing ∼ $100k is difficult, and custom systems are financially out of reach.

As end users of commercial Nd:YAG lasers with demanding applications in crystal nonlinear optics we fully appreciate the beam quality problem.[1, 2] Yet like many other researchers, our budgets rarely permit the purchase of newer laser systems. For these reasons we've pursued a more cost-effective solution and have devised a method for beam clean-up based on refractive beam shaping. In this paper we describe a recipe for clean-up and flat-top generation that can be applied to most older commercial Nd:YAG lasers. Our modifications have improved nonlinear conversion efficiency and reduced the likelihood of optical damage in our applications of crystal nonlinear optics.

As we have now demonstrated, for researchers on limited budgets who own older Nd:YAG lasers there is a way to improve their laser's performance using beam shaping.[3] If one can tolerate a reduction in pulse energy an older Nd:YAG laser design can be modified to generate a surprisingly good flat-top beam for a total cost of ∼ $10k. All that's required is spatial filtering, Newport's recently introduced Gaussian-to-flat-top refractive shaper,[4, 5] a sufficiently large optical table, and a few long days in the lab.

2. A BRIEF HISTORY OF OUR BEAM CLEAN-UP EFFORTS

Our motivation for obtaining a high-quality flat-top spatial fluence profile from an Nd:YAG laser with 1064 nm energy of order 1 J is for pumping OPO's and for high-efficiency sum-frequency generation. Complete details of these applications are described in Refs. 1 and 2. From a historical perspective, there is nothing new about obtaining high-quality high-energy flat-top profiles as it's been done for years in the inertial confinement fusion programs at Lawrence Livermore National Laboratory and elsewhere. These laser systems use specially designed tapered pinholes and serrated edge apodizers in multiple stages of amplification and high f/# vacuum spatial filtering, and the results are impressive.[6–9] However for the confined space of an optical table this approach is probably impractical, and furthermore, these systems are based on Nd:glass and designed to reach pulse energies of 10 kJ or more.

On a more modest scale there are several approaches for improving beam quality in typical research-grade Nd:YAG lasers that possess an oscillator and one or more amplifiers. For relatively low pulse energies of 40–50 mJ one can "loosely" spatially filter the oscillator beam for throughput $\gtrsim 50\%$ using a ∼ 2 m focal length lens and diamond wire die with diameter of 500–1000 μm. The approximate Gaussian spatial profile of the central disk provides a very useful beam for low-energy moderate-conversion-efficiency applications in crystal NLO. For example, if the beam diameter remains small relative to the length of an OPO cavity the low cavity Fresnel number and Gaussian-like profile can yield very high beam quality for the OPO signal beam. While this method works well and we have used it in carefully characterized laboratory measurements,[10–12] energy is limited by optical breakdown in air, or by destruction of the wire die in vacuum, so its use is limited to low pulse energy applications.

To obtain higher pulse energies we first experimented with loosely spatially filtering the oscillator beam in air or vacuum, followed by single- or double-pass amplification. We hoped that gain saturation during amplification would sufficiently flatten the Gaussian-like profile to produce a useful flat-top beam. However this was not the case as the resulting spatially smooth profiles were closer to 2nd-order super-Gaussian than flat-top. While this profile is useful for some applications, Gaussian-like spatial profiles deplete at beam center first with overall inefficient amplification, and we obtained only 400–600 mJ. Furthermore beam diameters must be small compared to the diameter of the amplifier rod to accommodate the Gaussian wings or else diffraction effects immediately destroy beam quality. These methods and their results are described in more detail in Refs. 1, 2 and 13.

While these first attempts at flat-top generation were unsatisfactory we were fortunate that the refractive beam shaper designed by Hoffnagle et al. at IBM became commercially available from Newport.[4,5] We now use the shaper to prepare a flat-top profile prior to amplification and in large part have achieved the beam characteristics we require. The shaper is relatively easy to incorporate into a laser system, and because it uses no hard apertures for shaping but instead relies purely on redirection of rays, the resulting rounded-edge Fermi-Dirac flat-top beam propagates distances ≥ 1 m without significant degradation. Although the shaper is essentially a low f/# Keplerian telescope, its midpoint focus is evidently enlarged due to its aspheric lenses, so 8–10 ns pulses containing ≥ 10 mJ have not caused any optical breakdown of air inside the shaper.

3. A RECIPE FOR BEAM CLEAN-UP BASED ON SPATIAL FILTERING AND REFRACTIVE BEAM SHAPING

Figure 1 shows the layout of our system for obtaining a high-quality flat-top spatial fluence profile from the Continuum Powerlite 9010. We begin by directing at least half the oscillator's output to a beam stop and then carefully control the remaining energy for "tight" spatial filtering to generate a Gaussian-like beam profile. Wavefront distortion for this particular oscillator consists of very weak astigmatism but for many Nd:YAG oscillators astigmatic aberration is strong and requires compensation with a cylindrical lens to extend the life of the wire-die spatial-filter. Because diamond wire dies are dielectric and slightly tapered, the resulting profile for the transmitted central disk is neither Airy nor Gaussian, but the profile is sufficiently Gaussian for input to the shaper. A simple fit to a transverse slice through the peak of the fluence profile indicates it is typically 96% lowest-order Gaussian.

In our spatial filter we focus the oscillator beam with a 2236 mm focal length lens and place a 550 μm wire die at the beam waist to obtain a "tightly" filtered beam. While "tight" is a qualitative description, for filtering nanosecond pulses with mJ energies we are implying energy throughput $\lesssim 50\%$ with high-contrast Airy-rings surrounding the central disk. After filtering the Airy rings are easily removed with an iris after the central-disk diameter is allowed to expand to several mm. Following clipping of the rings, the remaining Gaussian-like beam is collimated and imaged with magnification onto the input of the shaper using a high f/# Keplerian telescope. Newport's refractive shaper, model GBS-AR18, requires an input beam diameter of 4.73 mm $1/e^2$ for ideal output beam characteristics, but some deviation from this value still produces an acceptable flat-top profile.* In our system the energy reaching the shaper never exceeds 15 mJ.

Proper adjustment of the beam shaper is critical for generating a uniform flat-top profile with tip-tilt and axial alignment being equally important. For this reason we mounted the shaper on a Newport Model 36 tip-tilt platform with the center of rotation located near the center of its entrance lens, and then mounted this assembly on a Newport 460P Series *xy*-translation stage to control vertical and horizontal offset. The shaper is equipped with C-mount threads at its entrance end to facilitate mounting. We found it very convenient to center an iris on the axis of the shaper for determining axial alignment. This was done using a Thorlabs SM1R mounting ring, SM1A10 C-mount adapter, and SM1D12 threaded iris which screws into into the SMR1 mounting ring.

As shown in Fig. 1, the output beam from the shaper passes through an optical isolator, but the exit of the shaper is otherwise placed as close as practical to the entrance of the amplifiers. Close proximity is important because if located distances ≥ 1 m it may be tempting to image the shaper's output onto the amplifiers. Unfortunately the Guoy phase shifts among higher-order modes of the flat-top profile will alter beam characteristics after the long propagation path required for double-pass amplification, and beam quality will suffer. Higher-order Guoy phase shifts are easily ignored because experimenters naturally think about imaging and propagation in terms of low-order Gaussian beams. While the $\text{TEM}_{0,0}$ Gaussian can be imaged and subsequently propagated without penalty, this is not true for the high-order modes contained in the flat-top

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*Newport suggests using a continuously-variable Galilean expander/collimator from Sill Optics GmbH to control input beam diameter. Sill's Galilean expanders are very well engineered, but they can only be used with nanosecond pulses having energies less than a few mJ or damage to optical surfaces is likely. Damage from pulsed light will occur in most commercially available adjustable Galilean expanders.

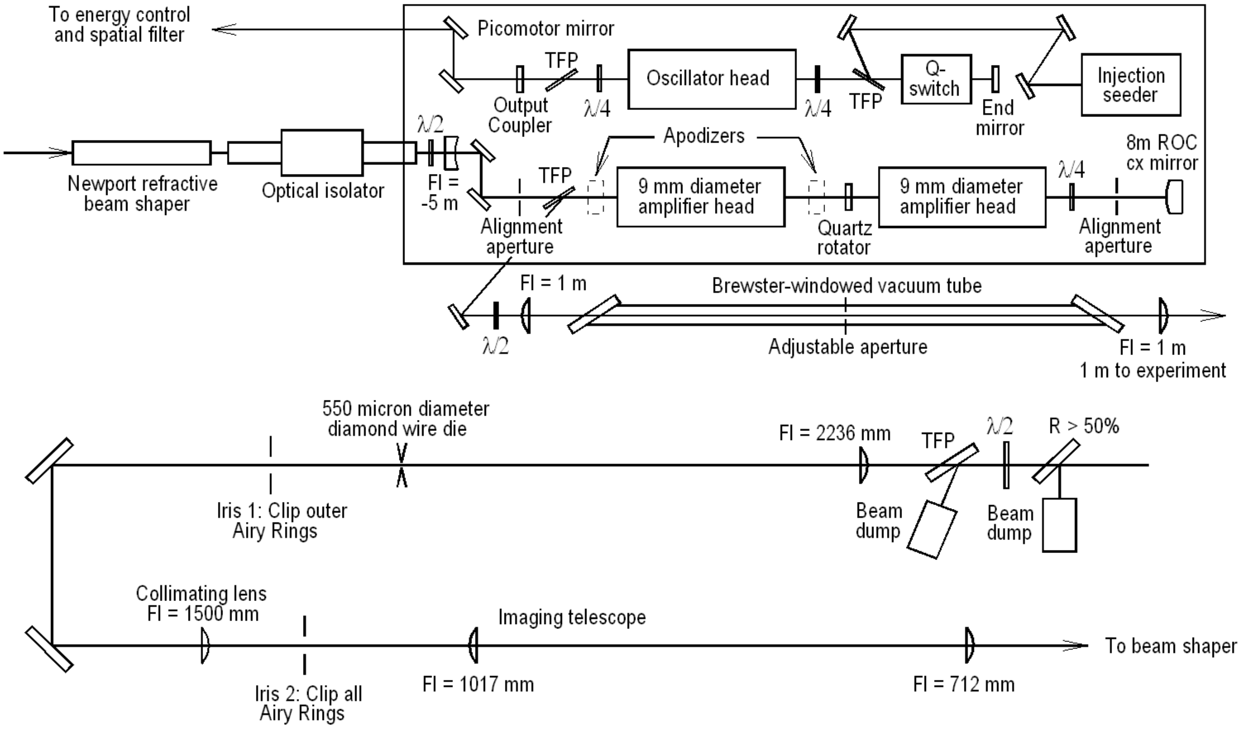

Figure 1. Layout of the modified Continuum Powerlite 9010 Nd:YAG laser and associated optical components for generating a beam with a flat-top spatial fluence profile. In factory configuration the beam from the oscillator enters the amplifiers after passing through a Galilean beam expander (not shown). Because the diameter of the flat-top profile beam generated by the Newport refractive shaper is less than that of the amplifer rods, the factory-configuration frosted-glass apodizers shown by dashed lines are unnecessary. TFP denotes thin film polarizer; ROC radius of curvature; Fl focal length; $\lambda/2$, $\lambda/4$ half- or quarter-wave retarders. The New Focus Picomotor mirror allows precise control of beam pointing for spatial filtering the oscillator beam. The position of the wire die is fixed on a 1.5 inch diameter solid stainless steel post to provide a point-like reference position for the beam path through the refractive shaper and amplifier chain. See text in Secs. 3 and 4 for complete details.

profile.[14] A good image will be obtained at a conjugate plane, but beyond that point the fluence profile can evolve rapidly, with the rate of evolution dependent on the f/# of the imaging system.

Between the isolator and amplifiers we insert a $\lambda/2$ plate to rotate the polarization 45° to horizontal and place a negative 5 m lens prior to the amplifier rods to compensate for thermally induced focussing. The beam then enters the amplifier chain by passing through a thin-film polarizer (TFP). After traversing both amplifiers the light is reflected from an 8 m radius of curvature convex mirror to compensate a second time for thermal focussing, and it double-passes a $\lambda/4$ plate to rotate the polarization by 90° to reflect from from the TFP. The negative lens and convex mirror together produce well collimated output and their values were determined largely by trial and error.

When the vertically-polarized beam leaves the laser after reflection from the thin film polarizer it is reflected from a 34° angle of incidence mirror and directed through a Keplerian telescoped formed by two 1 m focal length lenses. Because the high energy pulse causes optical breakdown when focussed, the beam passes through a Brewster-windowed vacuum tube before reaching the second lens of the telescope.

During amplification from 5–10 mJ up to $\sim$ 950 mJ the flat profile becomes somewhat asymmetric and acquires unwanted structure due to various agents, one culprit likely being ASE. Evidence for contamination from ASE is observed while adjusting the isolator because reflections from the exit lens of the shaper and from the convex mirror can lead to long-pulse oscillation in the amplifier chain. However even complete isolation does not eliminate contributions from ASE. Using a CCD camera we observe that the fluence acquires high-order structure that can only be removed by "scraping" with a large diameter aperture placed at the focus of the vacuum-imaging telescope. Because the pulse of interest has duration of 8–10 ns and ASE persists on μs time scales it's possible the structure in the fluence profile is irrelevant during the ns duration of the pulse, and is only observable due to the long integration time of the CCD array. Nonetheless, it is relatively simple to remove and has no effect on energy throughput. The aperture diameter is approximately 3 mm which is much greater than the beam diameter at focus where $\lambda\,$f/#$\sim$ 200 μm.

4. PRACTICAL CONSIDERATIONS FOR IMPROVING BEAM QUALITY IN ND:YAG LASERS USING REFRACTIVE BEAM SHAPING

There are a few practical considerations we've encountered that are worth passing along. As usual many are common sense but some were learned by time consuming trial and error. For example, when the beam from the oscillator is focussed with an $\sim$ 2 m focal length lens, net wavefront tilt acquired from refractive turbulence causes the focal point to wander, resulting in shot-to-shot fluctuations in energy transmitted through the wire die. Turbulence is reduced by covering beam paths with tubes such as inexpensive solid electrical conduit. While it is good practice to cover any long beam path, care must be taken if the beam is covered on the exit side of the wire die. The rings of the Airy pattern will scatter from the inside walls of the tubes and impose high-frequency interference structure onto the central disk. For this reason it is usually necessary to remove the outer rings a short distance past the wire die. The beam can then propagate without interference inside the tube for $\sim$ 1 m until the remaining rings are removed and the central disk collimated. We have tested applying special light-absorbing coatings to the inside of the tubes and found little reduction in interference.

Also useful for spatial filtering and the subsequent critical alignment of all downstream optics and amplifiers, including the refractive shaper, is the ability to permanently fix the position of the wire die and tilt the incident beam as necessary. While not a true point source due to its finite dimensions the wire die nonetheless plays the role of a point-like source in the optical system. Fixing its position on a stable large diameter stainless steel post is advantageous for maintaining alignment. This arrangement is aided by providing fine tilt control in the turning mirror labelled "Picomotor mirror" in Fig. 1. Placing this mirror inside the laser's enclosure shortens the beam path susceptible to refractive turbulence, and by using New Focus Picomotors allows control of beam tilt of order 1μrad or smaller.

Maintaining alignment over propagation distances $>$ 1 m is difficult, but spatial filtering of energetic ns pulses requires long focal lengths and large waist diameters. We've found the newer 1 inch diameter solid stainless steel posts and clamping forks are superior to the older but more commonplace post holder and 0.5 inch diameter post designs. We strongly recommend their use. As for aligning the beam shaper itself, it is relatively simple as long as tip and tilt occur about the center of its entrance lens as described in Sec. 3. Once the beam propagates parallel to the shaper's axis, small vertical and horizontal translations are usually sufficient to maintain a uniform flat-top profile on a day-to-day basis. If the optical path is covered with tubes as described previously, and all mirrors mounted on 1 inch posts, we find alignment is maintained for a month or longer. However, we note that initial alignment of the shaper is impossible without a beam-profiling CCD camera. In addition, the experiment should be configured so alignment can be continuously monitored. The diameter of the shaper's output beam exceeds the dimensions of common 2/3 inch format CCD's, but spatial uniformity of the beam's central region is easily determined, and its perimeter can be seen by tilting the beam or translating the camera.

For aligning the flat-top beam to the amplifier chain we find alignment irises are very useful. When mounted on translation stages they can be accurately aligned with the bore of the amplifiers by brightly illuminating a white card placed behind the iris and viewing the position of the iris through the amplifier rod using a mirror. The position of the alignment irises is shown in Fig. 1. Aligning the beam is then simple as long as the laser electronics provide control over the flashlamp delay for the amplifiers so there is little or no amplification during initial alignment. Many Nd:YAG lasers of the Continuum Powerlite's vintage provide this control. Note that the small amount of leakage viewed on the iris placed before the TFP provides a very good guide for aligning the second pass through the amplifiers. To view this leakage and carry out most other alignment tasks requires a near IR viewer. An adjustable iris mounted on the front of the viewer for attenuation reduces saturation effects and helps protect the fragile tube in the viewer from damage due to bright laser light.

Finally, in any experiment using flat-top beams imaging is required unless the laser is placed very close to the point of interest, e.g., the input coupler of an optical parametric oscillator. However, because the shaper's slightly rounded-edge Fermi-Dirac spatial profile propagates well for distances of order 1 m, placement of the first lens of the the imaging telescope is not critical. However, as discussed in Sec. 3, the resulting Guoy phase shifts dictate that placement of the experiment relative to the image plane may be critical.

5. RESULTS AND DISCUSSION: EXAMPLE BEAM PROFILES

We begin our discussion with an unmodified laser which produces a spatial fluence profile typical of Nd:YAG laser systems with over-filled amplifier rods. Figure 2(a) shows the near-field image of the exit aperture a Continuum NY82-10 Nd:YAG laser in factory configuration. Note the clearly visible circular-aperture diffraction pattern and slowly-varying non-uniform fluence in the horizontal direction, indicating off-axis propagation through the amplifiers. For this laser we always observe slow horizontal drift in the pointing of the oscillator's beam during a very long warm-up time, making perfect alignment in factory configuration difficult to achieve. As discussed in Sec. 4 and shown in Fig. 1 the fixed position of the diamond wire-die spatial filter largely eliminates this problem by providing a point-like reference position for the subsequent beam path. With this fixed reference position and the ability to adjust beam tilt using the Picomotor controlled mirror-mount shown in Fig. 1, these alignment problems largely vanish.[†]

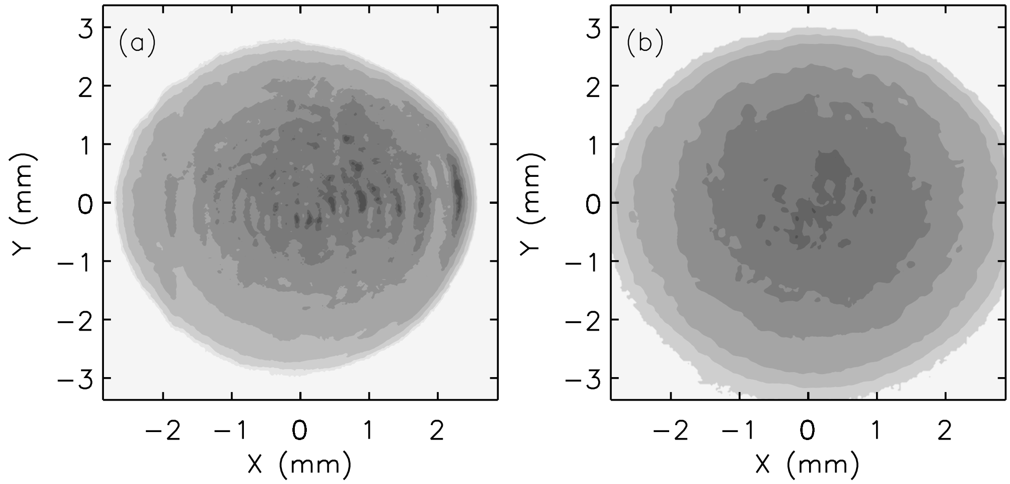

Figure 2. (a) Contour plot of typical near-field spatial fluence profile obtained from a commercial Nd:YAG laser with over-filled amplifier rods. After propagating distances ≥ 1 m, the nonuniform but otherwise characteristic round-aperture diffraction ring pattern can lead to severe hot spots that damage optical coatings and crystals. (b) Contour plot of the approximate 2nd-order super-Gaussian fluence profile obtained by "loose" spatial filtering of the beam, followed by single-pass amplification in the Continuum Powerlite 9010's twin 9 mm diameter amplifier rods.

The profile in Fig. 2(b) shows the result of "loose" spatial filtering of the Continuum Powerlite 9010's oscillator followed by single-pass amplification in its two 9 mm diameter amplifier rods. As described in Sec. 2,

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[†] Our intention is not to criticize Continuum's laser products but to describe ways to improve the performance of older Nd:YAG laser systems. The author has three early 1990's Continuum Nd:YAG laser systems in his lab and they are reliable and generally well engineered. Unfortunately they were not designed to generate high-quality flat-top beams.

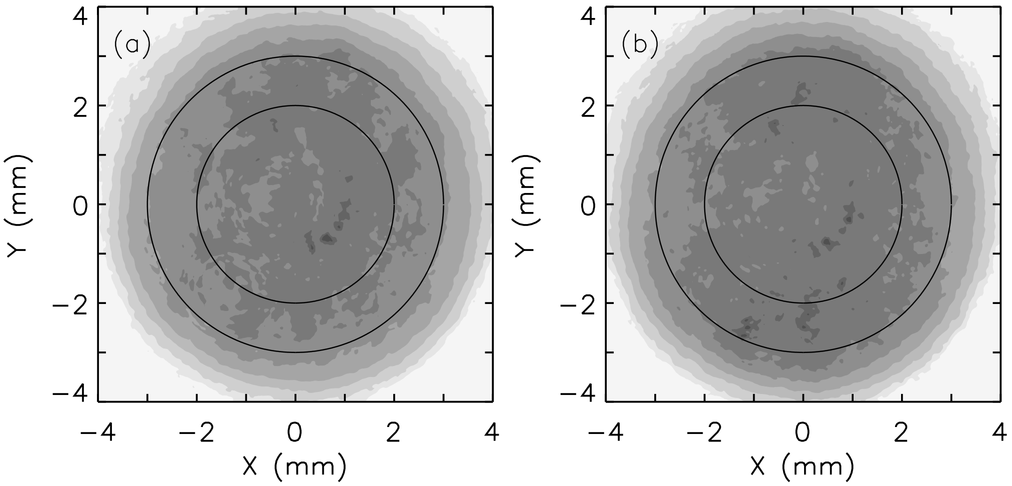

Figure 3. (a) The flat-top spatial fluence profile generated by the Newport refractive beam shaper after a single-pass through the Continuum Powerlite 9010's amplifiers without amplification. The propagation distance from the end of the shaper is $\sim$ 950 mm. (b) Same as (a) but with amplification. The faint ring patterns in both profiles are due to diffraction from dust particles. The circles denote regions used to calculate the standard deviation of the normalized fluence as a figure of merit for comparing the different flat-top profiles. See text for additional details.

we hoped gain saturation would result in a more flattened spatial profile using this technique but the measured profile is closer to 2nd-order super-Gaussian. Nonetheless this profile is an improvement over that shown in Fig. 2(a), being devoid of diffraction effects and severe hot spots. The pulse energy after spatial filtering was $\sim$ 40 mJ and the maximum energy after amplification was $\sim$ 450 mJ. Because the spatial profile is not lowest-order Gaussian imaging is required to retain its spatial properties if propagated distances $\gtrsim$ 1 m.

Figure 3(a) shows the first successful use of the Newport refractive shaper where the flat-top profile is observed at the exit of the second amplifier in the Continuum Powerlite 9010 after a single-pass through the amplifiers, but without amplification. This was done by delaying the firing time of the amplifier's flashlamps so there was little or no gain, but thermal effects are still present. The spatial fluence is definitely more uniform than for either profile in Figs. 2(a) or 2(b). While there may not be an agreed upon figure of merit for flat-tops we can compare our results by calculating $\sigma_{\rm flu} \equiv$ standard deviation of the normalized fluence within the circular regions in Figs. 3 and 4. Using this figure of merit we find $\sigma_{\rm flu} = 0.057$ within the 4 mm diameter region and $\sigma_{\rm flu} = 0.072$ within the 6 mm diameter region for the unamplified profile in Fig. 3(a), which has a FWHM diameter > 6 mm. For comparison, $\sigma_{\rm flu} \approx 0.17$ and 0.24, respectively, for a 6 mm $1/e^2$ diameter lowest-order Gaussian profile sampled within the same circular regions. In these calculations the data are sampled at the $14 \times 14\ \mu\text{m}^2$ pixel resolution of a Dalsa 4M15 full-frame transfer CCD camera. We note that the propagation distance from the end of the beam shaper to the end of the second amplifier rod is a rather long $\sim$ 950 mm. At the exit of the shaper we expect $\sigma_{\rm flu}$ to be lower than reported here, but we neglected to make these measurements.

The measured profile in Fig. 3(b) was recorded at the same position as that shown in Fig. 3(a), but with amplification. Again the spatial fluence is fairly uniform with $\sigma_{\rm flu} = 0.053$ within the 4 mm diameter region and $\sigma_{\rm flu} = 0.068$ within the 6 mm diameter region. Evidently single-pass amplification reduced the amplitude fluctuations and made the profile slightly flatter because this beam has a better figure of merit than the unamplified beam in Fig. 3(a). We made no attempt to determine if gain saturation was responsible for these improvements. For these profiles the pulse energy leaving the shaper is 10–15 mJ, and the maximum energy after amplification is ≤ 250 mJ.

Finally, Fig. 4 shows the double-pass amplified and frequency-doubled 532 nm beam that we currently

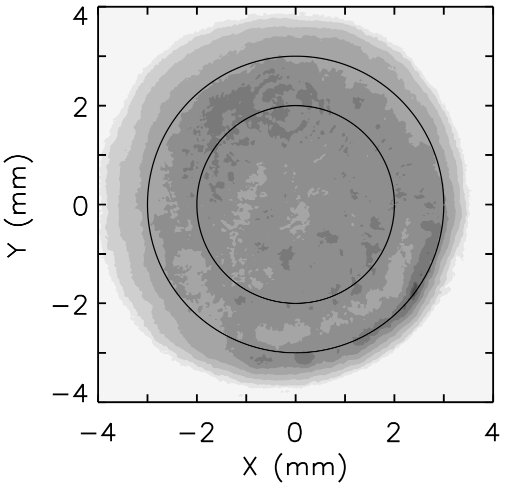

Figure 4. Double-pass amplified frequency-doubled flat-top spatial fluence profile generated by the Newport refractive shaper after propagation through the vacuum imaging tube shown in Fig. 1. An iris adjusted to ~ 3 mm diameter placed at the focus in the vacuum tube removes high-spatial frequency light that may be due to amplified spontaneous emission. The faint ring patterns are due to diffraction from dust particles. The circles denote regions used to calculate the standard deviation of the normalized fluence as a figure of merit for comparing the different flat-top profiles. See text for additional details.

use to pump an optical parametric oscillator. This profile is obtained after imaging through the vacuum telescope shown in Fig. 1 with the ~ 3 mm aperture centered about the focus in the telescope to remove the high-order structure as described in Sec. 3. The spatial fluence profile is slightly asymmetric and continues to exhibit amplitude fluctuations, so it appears the second amplification pass did not improve flatness or uniformity. Again we made no attempt to determine the degree of gain saturation, but starting with ~ 10 mJ and amplifying to ~ 950 mJ, the gain is likely saturated at some points in the beam. We find the figure of merit is slightly worse than before with $\sigma_{\text{flu}} = 0.076$ within the 4 mm diameter region and $\sigma_{\text{flu}} = 0.086$ within the 6 mm diameter region. The beam diameter is slightly smaller than in Figs. 3(a) and 3(b) as it was reduced using a Galilean de-expander for pumping the OPO. We did not adjust the diameter of the circular regions to compensate for this change when calculating σ_{flu}. We note that the origin of the slightly asymmetric shape has not been determined but it may arise from imperfect alignment in the amplifiers or perhaps from nonuniform pumping of the laser rods.

6. CONCLUSIONS

We have generated a flat-top beam containing ~ 950 mJ per pulse from a flashlamp-pumped Continuum Powerlite 9010 Nd:YAG laser manufactured in 1993. Lasers of this era were designed primarily for pumping organic dye lasers and typically have poor beam quality due to overfilled amplifier rods. While these lasers can produce pulse energies exceeding 1 J, their near-field spatial fluence profiles are usually dominated by a diffraction ring structure superposed with "hot spots" that lead to optical damage. To eliminate these effects but still obtain high pulse energy, we spatially filtered the oscillator beam to generate an approximate Gaussian spatial profile, followed by Gaussian to flat-top beam shaping prior to amplification. Beam shaping was accomplished using Newport Corporation's recently introduced refractive shaper. Using standard deviation σ_{flu} of the normalized fluence as a figure of merit we obtained $\sigma_{\text{flu}} = 0.076$ within a 4 mm diameter region and $\sigma_{\text{flu}} = 0.086$ within a 6 mm diameter region for a beam with FWHM diameter $\gtrsim 6$ mm. For comparison, $\sigma_{\text{flu}} \approx 0.17$ and 0.24, respectively, for a 6 mm $1/e^2$ diameter lowest-order Gaussian profile sampled within the same circular regions.

Our method of flat-top generation is relatively simple to incorporate into most older Nd:YAG laser designs that have an oscillator followed by one or more amplifier stages, and the total cost is around $10k. We plan to modify additional Nd:YAG lasers and also plan to improve on our method. While our initial results are promising we suspect the less-than-perfect quality of our double-pass amplified beam profile may be due to thermal effects, nonuniform pumping, or perhaps amplified spontaneous emission. To mitigate these effects and obtain more uniform spatial fluence we may investigate additional "loose" filtering/scraping stages in our current setup on the Continuum Powerlite 9010 laser. These can be added after the first pass through both amplifiers, and perhaps even between the two amplifiers. Additional filtering may alter the fluence and result in a profile with a softer, more round-edged perimeter. However, if the essentially flat central region of the profile remains, the beam will still be very useful for applications such as high-efficiency nonlinear mixing. As we refine our method and apply it to more Nd:YAG lasers, we'll report our results in subsequent publications.

ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. We thank Ron Allman of Department 1118 at Sandia National Labs for technical assistance, and acknowledge additional financial support from NASA Langley Research Center, Hampton, VA, USA.

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