Compact, Single-Frequency, High-Power ND: Glass Laser

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***Abstract*— A compact, single-frequency high-power Nd:glass laser was developed. Single longitudinal mode operation of the oscillator was provided by injection-seeding it with CW laser radiation. A four-pass amplifier with a spatial filter provided an output energy of 2.7 J with more than 30% extraction efficiency. The output beam divergency was twice the diffraction limit.**

I. INTRODUCTION

HIGH-power Nd:glass lasers are commonly used for a variety of scientific applications. For many years inertial confinement fusion has been a primary impetus behind the development of these lasers, forcing strict requirements on high peak power, pulse-shape control, beam uniformity, and focusing ability [1]. These features are now also required in other applications of high-power lasers. Laser-plasma sources, particularly laser-plasma x-ray sources for x-ray lithography [2] and microscopy [3], require reproducible, uniform focal spot distribution, which place limits on laser beam amplitude and phase uniformity. Nonlinear optics applications such as coherent anti-Stokes Raman scattering, high harmonic generation, and studies of multiphoton ionization, need narrow-bandwidth, high-power lasers with well characterized, stable output beam parameters. The requirements of these applications extend beyond those of available commercial systems. In a general sense, however, they can be met with a suitable choice of existing laser and electrooptics technologies.

In this paper we describe a Nd:YAG oscillator/Nd:glass amplifier system having pulsed output conditions that meet the requirement for laser plasma X-ray source studies for lithography and microscopy. This laser system employs two new techniques: the use of single-mode injection seeding, and the use of a novel multipass amplifier architecture. The incorporation of these techniques in this system provides an output performance superior to that of comparable lasers in its class.

The basic design for high power laser systems is the so called master oscillator power amplifier (MOPA) design, used extensively in all inertially confined fusion laser systems. The master oscillator produces a laser pulse of specified shape and duration that is amplified by several subsequent stages of power amplifiers in series. For the nanosecond range of pulsewidths single-mode Q-switched oscillators are used as master oscillators for two reasons: First, they provide a narrow bandwidth, and second, the oscillator output energy is very stable because of the lack of mode beating. The most convenient and reliable method of achieving single-mode operation is through injection seeding [4]. In this technique light from a low-power single-frequency CW oscillator is injected into a Q-switched laser cavity (slave oscillator). The slave oscillator lases on a single longitudinal mode, if the injected signal has sufficient power in this mode to saturate the gain before other modes develop. A reliable source of single-mode CW laser light, the monolithic diode pumped laser, was developed by Kane and Byer [5].

An efficient approach to amplifying millijoule energy laser pulses from a master oscillator to the saturation fluence of Nd:glass, capable of providing several joules per square centimeter in a cost effective manner is through the use of a multipass amplifier. An effective and simple four-pass amplifier has been demonstrated by Andreev *et al.* [6]. An analogous design, suggested by Hunt [7], included a spatial filter inside the four-pass amplifier design. The use of the spatial filter in the multipass amplifier would have two advantages, 1) in improving the laser beam quality and 2) in preventing the amplifier from self-lasing [7]. We demonstrate here a third benefit from the spatial filter, that of compensating for the thermal lensing in the amplifier medium.

In this paper we report the development of a single-frequency compact high-power Nd:glass laser incorporating for the first time both injection seeding and four-pass amplifier design, including a spatial filter. This laser provides reliable, stable quasi-Gaussian-shaped (10 ns FWHM) pulses of energy up to 2.7 J with smooth spatial beam distribution and 2 times diffraction limit divergency. The principal use of this laser will be for the study of X-ray generation in laser-produced plasmas. However, its characteristics should be attractive for several other applications where a low divergence output beam or a uniform predictable focal spot distribution are required from a high-power laboratory-size laser.

II. DESIGN

The principal laser design is shown in Fig. 1. A single-frequency CW monolithic Nd:YAG laser [5] is used as a master oscillator. The unidirectional ring resonator of this laser [8] is formed by the YAG laser crystal facets. The nonplanarity of this resonator permits the incorporation, within a monolithic structure, of an effective half waveplate polarization rotator, a Faraday rotator, and a polarizer. The combined effect of these elements provides lower loses in one direction. Thus, this travelling wave laser possesses no spatial hole burning and consequentially there is no discrimination against modes that would exist in a standing wave resonator. The crystal is diode pumped and temperature controlled. The output of the master oscillator is decoupled from the slave oscillator by a separate Faraday insulator (not shown in Fig. 1). The slave oscillator

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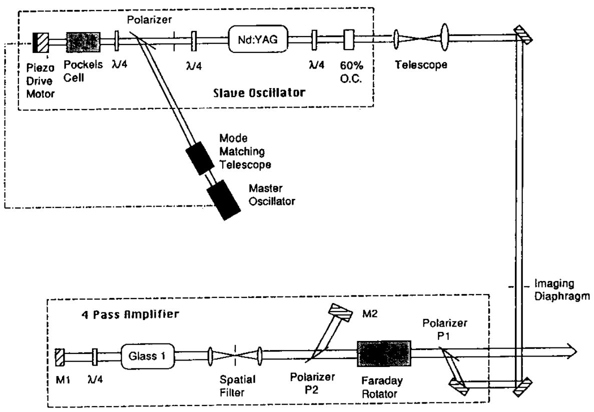

Fig. 1. Compact injection-seeded neodymium laser system.

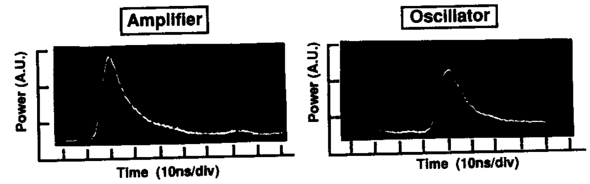

Fig. 2. Pulseshape. (a) At the four-pass amplifier output. (b) At the slave oscillator output (10 pulses superimposed).

comprises a Nd:YAG laser rod (4 mm diameter, 65 mm long), in a linear resonator formed by a planar partially reflecting (60%) output coupler, and a fully reflecting concave (5 m radius of curvature) mirror, mounted on a piezoelectrically controlled translator. The laser is Q-switched with a quarter-wave Pockels cell, and two quarter-wave plates ensure circular polarization of the two counter-propagating waves inside the rod, suppressing spatial hole burning effects. The spectrum of the injected signal selects the axial mode of the slave oscillator that will dominate in the buildup process, and thus helps to ensure single mode operation of the slave oscillator. The piezoelectrically controlled high-reflection mirror is driven by an error signal derived from a closed-loop feedback circuit that optimizes the cavity length of the slave oscillator for maximum gain and thus minimum Q-switched buildup time of its output. Minimum Q-switch buildup time provides for the best match of the slave oscillator cavity length to the master oscillator wavelength.

The output beam of the slave oscillator is expanded 15 times by a telescope. The central portion of the beam, isolated by the imaging diaphragm (1 cm in diameter), is then amplified by the four-pass amplifier. The four-pass amplifier consists of a silicate Nd:glass (ED-2) laser rod (16 mm in diameter, 460 mm long), a permanent magnet Faraday rotator, an evacuated spatial filter (unity magnification, f/26, f = 1.3 m), thin-film polarizers, mirrors, and a quarter-wave plate. The oscillator beam transmitted by the imaging diaphragm, which is horizontally polarized, is reflected by a polarizer P1, is rotated by a quarter of a wave by passage through the Faraday rotator, and passes unhindered through the second polarizer, P2, which is rotated 45° out of the amplifier plane. It then passes through the spatial filter and the amplifier rod and through the quarter-wave plate. After retro-reflection by the mirror M1, it passes a second time through the amplifier rod and the spatial filter and is then reflected by the polarizer P2 because its polarization direction has been changed by 90 degrees after two passes through the quarter-wave plate. After retroreflection by the second high-reflecting mirror, M2 the beam passes two more times through the laser rod and is then transmitted through both polarizers and the Faraday rotator to the output, as its polarization direction has been changed by a further 90 degrees after two passes through the quarter-wave plate. The spatial filter relays the image of the diaphragm through the four sequential passes of the amplifier to the output, preserving the beam quality. At each pass the beam travels at a slightly different angle (about 1 arc min) and passes the spatial filter through four separate diaphragms of 1.5 mm in diameter. This avoids the problem of plasma closure of the diaphragm and helps to prevent amplifier self-oscillation as well. The diaphragm diameter is 10 times [9] larger than the diffraction-limited beam size at the focal plane of the spatial filter lens and does not degrade significantly the quality of the imaging. In addition to filtering, imaging and self-lasing insulation, the spatial filter in our design has one more function, that of thermal lens compensation. By increasing the lens separation by a small amount (several percent) greater $2f$ compensation can be made for the thermal lensing in the laser rod caused by optical pumping.

III. PERFORMANCE

The slave oscillator runs at a repetition rate of 6 Hz. A repetition rate of more than 4 Hz is necessary for the successful operation of the closed-loop feedback circuitry matching the slave oscillator cavity length to the master oscillator wavelength. The glass laser amplifier head can operate only on a single shot basis. An electronic circuit synchronizes the glass laser pump pulse with one of the oscillator discharges. The operation cycle of the system, as a whole, is 3 min and is determined by the amplifier thermal lens "fade out" time. The slave oscillator produces a smooth output pulse [Fig. 2(b)] with shot-to-shot amplitude variations of $\pm 1\%$. The pulse energy and pulse duration depend on the pumping. For the highest possible pumping level the oscillator delivers to the amplifier through the imaging aperture an energy of ~ 7 mJ in a ~ 10 ns pulse. The overall oscillator output energy reaches 15 mJ. The beam divergence of the system at the amplifier output was found to be diffraction limited when the amplifier was unpumped. It was twice the diffraction-limited value after passing through the pumped amplifier (amplifier thermal lens was optimally compensated for a given pump level). The output beam had a cross-sectional area of 1 cm^2.

The amplifier output energy dependence on the input energy is shown in Fig. 3. The input energy was changed with neutral density filters inserted between the oscillator and the amplifier. Fig. 3 shows that the amplifier is heavily saturated at the maximum input energy implying good extraction efficiency. The extraction efficiency can be estimated from the saturation

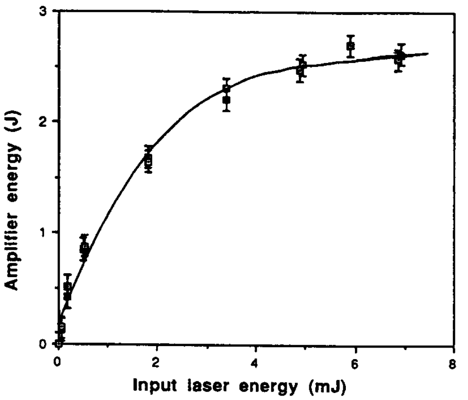

Fig. 3. Dependence of the four-pass amplifier output energy on the input energy. The solid curve is the best fit to the experimental data.

curve of Fig. 3. The derivative to the curve at the coordinates' origin provides an estimate of the overall small-signal gain G in the four-pass amplifier. The slope of the curve for the highest output energy provides an estimate of the saturated gain S. Taking into consideration the measured transmission of the unpumped four-pass amplifier ($T = 36\%$), we can estimate from Fig. 3 values for G and for S of 5560 and 140, respectively. The stored energy density of an amplifier equals $F\mathrm{x}\ln G_0$, where F is the saturation flux [10], and G_0 is the single-pass small-signal gain. We can write an energy balance equation for the output flux E (for the present system the maximum output flux $E_m = 2.7\,\mathrm{J/cm^2}$)

$$F\frac{(\ln G - \ln S)}{4} = \frac{E}{T^{1/4}}$$

from which the saturation flux value F can be determined as

$$F = \frac{4E}{T^{1/4}(\ln G - \ln S)}.$$

Inserting the above values for T, G, and S, we obtain a value of $F = 3.8\,\mathrm{J/cm^2}$ for $E = E_m$. This value for F falls midway between the experimental values quoted for ED-2 in [10], ranging from 3.4 to 4.4 $\$J/\mathrm{cm}^2$.

Finally, the extraction efficiency ε equals

$$\varepsilon = \frac{4E}{F\ln G} = T^{1/4}\left(1 - \frac{\ln S}{\ln G}\right) - 0.33$$

Substituting the values of T, S, and G gives a value for the extraction efficiency of 33%.

The near- and far-field distributions of the output of this laser were analyzed photographically. The far-field distribution was measured using a long focal length ($f = 5$ m) lens and a wedged optical plate coated on both sides with $R = 75\%$ dielectric coatings. This provided an single shot array of images of the far-field distribution having a known decrease (factor of 2) in intensity.

In conclusion, we have developed a compact single-frequency high-power Nd:glass laser, based on an injection-seeded oscillator and a four-pass amplifier. The output energy reaches 2.7 J with more than 30% extraction efficiency for a 10 ns pulsewidth. The output beam divergency is 2 times greater than the diffraction limit.

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REFERENCES

[1] J. F. Holzrichter, "High power solid state lasers," *Nature*, vol. 316, pp. 309–313, 1985.

[2] A. M. Rogoyski, P. Charalambous, C. Hills, and A. G. Michette, "Characterization and optimization of a laser generated plasma source of soft X rays for biological imaging and soft X-ray lithography," *Proc. SPIE*, vol. 831, *X Rays from Laser Plasmas*, pp. 84–90, 1987.

[3] A. G. Michette, "Laser-generated plasmas: Source requirements for X-ray microscopy," *J. X-Ray Sci. and Tech.*, vol. 2, no. 1, pp. 1–16, 1990.

[4] Y. K. Park, G. Giuliani, and R. L. Byer, "Stable single-axial-mode operation of an unstable-resonator Nd-YAG oscillator by injection locking," *Opt. Lett.*, vol. 5, pp. 96–98, 1980.

[5] T. J. Kane and R. L. Byer, "Monolithic, unidirectional single-mode Nd-YAG ring laser," *Opt. Lett.*, vol. 10, pp. 65–67, 1985.

[6] N. F. Andreev, G. A. Pasmanimk, P. P. Pashinin, S. N. Sergeev, R. V. Serov, S. I. Shklowsky, and V. P. Yanovsky, "Multipass amplifier with the full use of the active rod aperture," *Sov. J. Quantum Electro.*, vol. 13, pp. 641–643, 1983.

[7] J. T. Hunt, "High peak power Nd : glass laser facilities for end users," *Proc. SPIE*, vol. 1410, *Solids State Lasers II*, pp. 2–14, 1991.

[8] Lightwave Electronics, Mountain View, CA, Model S-100.

[9] J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, "Suppression of self-focusing through low-pass spatial filtering and relay imaging," *Appl. Opt.*, vol. 17, pp. 2053–2057, 1978.

[10] W. Koechner, *Solid State Laser Engineering*. Berlin: Springer-Verlag, 1988.