Stable-Relaxation-Oscillation Nd Lasers for Long-Pulse Generation

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***Abstract*—A simple method to produce high-energy neodymium (Nd) laser pulses with durations on the order of 1 μs is described here. Solid-state lasers can be pumped by relatively short flashlamp pulses to produce well-behaved relaxation oscillations in a diffraction-limited beam. Under the right conditions, each output laser pulse consists of a series of discrete subpulses that are ideally suited to efficient, high-energy amplification. Experimental results for a Nd:$LiYF_4$ oscillator/amplifier system are presented along with numerical simulations. These demonstrate that the system operation is predictable and well behaved. Data are also included for a Nd:glass tunable oscillator based on this concept.**

I. Introduction

THE pulse duration of a conventional Q-switched solid-state laser is typically in the 10–100 ns range. However, for many applications of high-energy solid-state lasers systems, pulsewidths on the order of 1 μs are desirable. These include cases where the transform-limited spectral width of the Q-switched laser is too large, such as in LIDAR measurements of wind velocity, as well as cases where peak power presents a materials breakdown problem. The latter situation can occur in gas diagnostics, delivery of energy via optical fibers, and optical pumping of other lasers. In particular, longitudinal pumping of the Ti:Al_2O_3 laser [1] by a frequency-doubled neodymium (Nd) laser source may be limited by optical damage at the surface of the Ti:Al_2O_3 crystal. The threshold fluence for the onset of damage is believed to increase with the square root of the pulse duration [2] so that, given the upper state lifetime of 3.2 μs at room temperature, the ideal Ti:Al_2O_3 pump is envisioned as a green source capable of delivering the required energy in a 1–2 μs pulse. High-energy pulsed systems typically involve one or more stages of amplification, and efficient energy extraction requires at least the final stage to be strongly saturated. In this case, the temporal profile of the input pulse may be severely distorted. In the worst case, rapid intensity variations on the leading edge of the pulse may lead to extreme pulse shortening. Therefore, it is important to consider both the duration and the shape of the oscillator pulse when evaluating sources for high-energy systems.

Here we report on the development of a Nd stable-relaxation-oscillation laser (SROL) that is a candidate "long-pulse" source. The SROL oscillator provides a diffraction-limited beam with a characteristic smooth temporal profile that is ideal for saturated amplification without pulse shortening. Experimental demonstrations include a Nd:$LiYF_4$ (YLF) oscillator/amplifier system and a Nd:glass tunable oscillator. (YLF was selected as the fixed wavelength host material primarily because much higher single-rod gain can be sustained in YLF than in other crystals [3], thereby simplifying the construction of Joule-level systems.) The SROL design is simple and allows the user to vary the pulsewidth over a wide range by controlling the operating point of the oscillator. Rate-equation simulations, together with the experimental results, demonstrate that the SROL system output is predictable and well behaved.

Various techniques have been employed for long-pulse generation with solid-state lasers. The simplest may be to use an optical modulator to gate the output of a CW laser [4]. This method is inefficient and, given typical CW laser outputs, requires considerable amplification to generate Joule-level energies (e.g., a 1 kW CW laser would be required to generate 1 mJ, 1 μs pulses). A better approach is to gate the output of a conventional normal-mode laser, particularly one in which relaxation oscillations have been suppressed [5], although residual fluctuations in the output may present a problem for pulsewidths on the order of 1 μs. Pulse durations of up to 300 ns can be achieved with conventional Q-switching of Nd lasers in very long, high-Q cavities. Considerably longer pulses can be generated through careful electronic control of the loss of a continuously variable Q switch [6]–[8]. By programming the Q-switch driver without feedback, Schmid demonstrated 0.65-μs rectangular pulses from a Nd:YAG laser [8]. However, the required control sensitivity and bandwidth are difficult to achieve, even in a laboratory environment. Variable-Q-switch systems are subject to problems with oscillations during the pulse and poor pulse-to-pulse stability. Any temporal structure on the pulse can lead to significant temporal pulse distortion in the output of subsequent amplifier stages. Saturable absorbers have also been employed as variable-loss elements in Q-switched cavities with limited success [9].

Another option for generating the required long pulse is to operate a normal-mode laser in a single transverse mode in order to produce well-defined relaxation oscillations. Under the right conditions, the initial portion of

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each output pulse consists of a train of distinct, gain-switched, temporally smooth subpulses, a phenomenon often referred to as "spiking." An acoustooptic modulator (AOM) outside the cavity can be used as a shutter to isolate a single one of these subpulses for amplification. The characteristic subpulse temporal profile is ideal for saturated amplification without pulse shortening. Given the relatively long cavity lifetimes that can be achieved with low-transmission output couplers, it is possible to generate subpulses that are hundreds of nanoseconds in duration with energies on the order of 1 mJ. Relatively high-Q cavities can be employed because the intracavity peak powers are greatly reduced from the Q-switched case. This is the concept behind the SROL system.

The following sections describe SROL operation in detail beginning with a discussion of the oscillator design concept. Numerical models of the Nd:YLF SROL are presented along with experimental results. Pulse amplification is considered in Section III. Over 100 mJ of diffraction-limited output has been obtained from a Nd:YLF system consisting of an oscillator followed by a 64-mm-long amplifier. Numerical results indicate that scaling such a system to the 1–2 J level by incorporating additional gain stages results in desirable pulse broadening. The characteristics of a tunable Nd:glass SROL developed for atmospheric spectroscopy are included in Section IV and simulations of a diode-laser-pumped Nd:YLF SROL are the subject of Section V.

II. The SROL Oscillator

The merit of the SROL depends largely on the ability to produce very strongly modulated relaxation oscillations, one of which can be isolated with an optical gate. Relaxation oscillations in lasers are generally modeled as the response of a harmonic oscillator. The single-transverse-mode, pulsed Nd laser behaves like a damped, nondriven harmonic oscillator so that each output pulse consists of a series of subpulses with decreasing amplitude and increasing duration. In lasers where the oscillations represent small fluctuations in the output, the time T between subpulses is nearly constant. In this case, the subpulse durations are proportional to T which may be approximated by the relation [10]

$$T = 2\pi\left[t_c\tau_s/(r-1)\right]^{1/2} \tag{1}$$

where t_c is the cavity lifetime, τ_s is the spontaneous lifetime of the laser transition, and r is the pump rate normalized to the threshold value. Assuming reasonable values for the Nd:YLF laser in (1) ($t_c = 45$ ns, $\tau_s = 480$ μs [11], $r = 10$), $T = 9.7$ μs so that the FWHM duration of the initial subpulse is expected to be several microseconds. In fact (1) does not hold for the SROL because it involves very strong modulation of the output intensity in the leading subpulses. However, it provides a design guide that can be augmented with numerical solutions of the laser rate equations [12] for accurate modeling. Qualitatively, (1) illustrates the concept that to produce broad subpulses, it is desirable to have a long cavity lifetime and to pump near threshold. Furthermore, selecting the SROL operating point involves a tradeoff between the energy of the selected subpulse and its duration.

Relaxation oscillations with nearly 100 percent intensity modulation in the initial subpulses can be generated by pumping the oscillator in one of two ways: either 1) for a short time at well above the threshold rate, or 2) for a much longer time just above threshold. In experiments with flashlamp pumping, the best pulse-to-pulse repeatability was achieved at high pump rates where the fractional flashlamp intensity fluctuations were small.

Fig. 1 is a schematic of the Nd:YLF SROL system demonstrated here. The 100-cm oscillator cavity included a concave high-reflectivity (HR) mirror with a 10-m radius of curvature, an aperture that limited oscillation to the lowest order transverse mode, and a flat, partially transmitting output coupler. Besides having excellent amplifier material properties (relatively high energy-storage capacity and parasitic-gain limit), YLF has the practical advantage that thermal lensing is negligible. Unlike Nd:YAG, Nd:YLF is naturally birefringent and the $^4F_{3/2}$–$^4I_{11/2}$ laser transition is split into two transitions peaked at 1047 nm (π) and 1053 nm (σ) where π and σ refer to the two crystal axes perpendicular to the longitudinal axis of the rod [13]. The larger cross section corresponds to π-polarized light so that the oscillator output was linearly polarized at 1047 nm. The Nd:YLF oscillator rod was 5 mm in diameter and 7.1 cm long. It was antireflection coated on both ends with opposing 30′ wedged surfaces. The data included here were obtained with a 450 torr, xenon flashlamp pumped by a single-mesh discharge circuit ($C = 17$ μF, $L = 10$ μH) pulsed at 5 Hz.

A shear-wave AOM followed the oscillator. The device was gated to deflect only the selected subpulse into the first diffraction order at a separation of 10.6 mrad from the unshifted beam. A 3-mm-diameter aperture was placed 30 cm from the AOM to stop all but the first-order beam.

The Nd:YLF SROL operating point was chosen to meet a specific design goal so that the subpulse duration was sacrificed in order to obtain 100 mJ from a single-pass amplifier with a gain length of 64 mm. A rate-equation analysis of the Nd:YLF SROL was performed given the following input data: 1) a piecewise-linear approximation of the 29-μs, full-width-at-half-maximum (FWHM) flashlamp pulse at 8.8× threshold, 2) the 2.8-percent-per-pass internal cavity loss determined from slope-efficiency measurements with various output couplers ($t_c = 43.5$ ns), and 3) the upper state lifetime given above. Fig. 2 shows the corresponding analytical and experimental waveforms. Both sets of results for the first three subpulses are listed in Table I. The temporal jitter observed in these subpulses was about equal to their duration and much less than their separation, so that reliable gating was easily achieved. At the operating point of Fig. 2, the flashlamp input energy was 11.4 J and the energy in the initial subpulse transmitted by the AOM was 0.84 mJ. The relative energy in subsequent subpulses can be approximated from

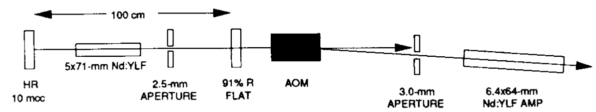


Fig. 1. Schmatic of the Nd : YLF SROL system.

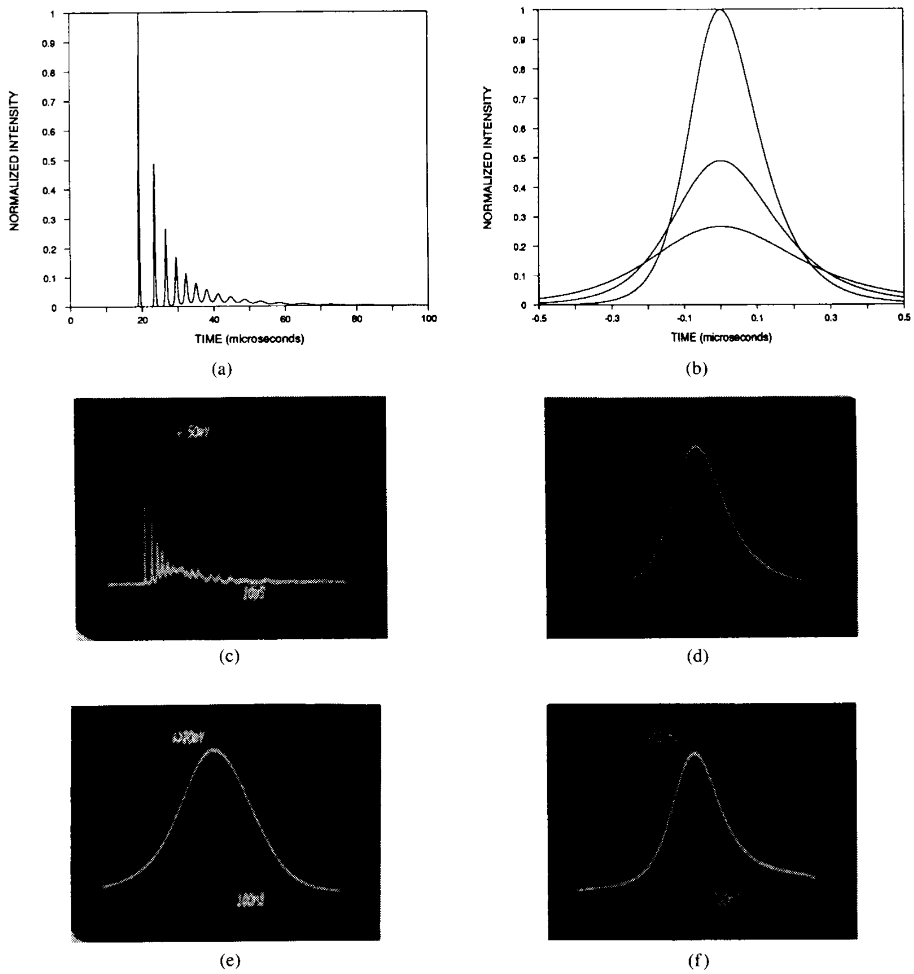


Fig. 2. Nd : YLF oscillator output pulse at 8.8 × threshold: (a) rate-equation simulation, (b) first three calculated subpulses overlaid on an expanded time scale, (c) experimental result (10 μs/div), (d) experimental first subpulse on an expanded time scale (100 ns/div), (e) experimental second subpulse (100 ns/div), and (f) experimental third subpulse (200 ns/div).

TABLE I
Nd:YLF SROL SUBPULSE CHARACTERISTICS AT 8.8 × THRESHOLD

Subpulse Position	Calculated Value	Experimental Result
FWHM Duration (ns):		
First	225	270
Second	330	360
Third	475	490
Normal Peak Intensity:		
First	1.0	1.0
Second	.49	.42
Third	.27	.28

the product of peak intensity and FWHM duration. This product, a useful figure of merit for the SROL, is largest for the initial subpulse.

III. SROL PULSE AMPLIFICATION

The issue of temporal distortion due to high-gain amplification highlights the utility of the SROL system. While this effect was negligible in the single-stage experiments presented here (in agreement with numerical simulations), it becomes very important when higher energy systems are considered.

In order to meet the design goal for the Nd : YLF SROL system, the initial subpulse was selected at the operating point described in the previous section. The beam diameter (e^{-2}) was expanded to 2.9 mm for input to a 6.4 × 64 mm Nd : YLF amplifier, with the beam polarized along the π axis. The rod was antireflection coated with wedged endfaces and pumped by a xenon flashlamp. Small-signal gain measurements were made at 1047 nm with two different amplifier pump cavities: 1) a diffuse reflector with a samarium-doped glass filter surrounding the Nd : YLF rod, and 2) a close-coupled, silver-plated brass cavity. The results are shown in Fig. 3, where it is evident that much higher gains were achieved in the diffuse-reflection cavity. Also included in Fig. 3 are data for the σ-polarized small-signal gain measured in the close-coupled cavity. The measured ratio of the Nd : YLF small-signal exponential gain coefficients (cm^{-1}) at 1047 nm was $g_{0\pi}/g_{0\sigma} = 2.3$. These data are useful for evaluating more complicated amplifier configurations.

With the insertion loss of the beam expander, the amplifier input energy was 0.76 mJ. Operating the diffuse-reflection cavity with a small-signal gain of 630 (163 J flashlamp input energy), the input subpulse was amplified from 0.76 to 116 mJ. As noted above, the amplified pulse exhibited negligible temporal distortion. The corresponding result calculated using the Frantz–Nodvik amplifier equation [14]–[15], and accounting for the Gaussian spatial profile of the beam, was 127 mJ. The numerical analysis was performed by dividing the input pulse into 2 ns segments. The amplified segments were calculated sequentially, updating the amplifier gain each time to account for the energy extracted by the previous segment. In order to model the Nd : YLF SROL system, the input pulse was derived from the rate-equation calculations (taking the initial subpulse at the experimental operating point).

The only variable involved in the Frantz–Nodvik calculation that was not measured directly was the saturation fluence E_s given by

$$E_s = (h\nu)/(\beta\sigma) \tag{2}$$

where $h\nu$ is the photon energy at 1047 nm, $\beta = 0.5$ is the occupation factor for the upper state of the laser transition, and σ is the gain cross section. E_s, for π-polarized light at 1047 nm, was determined indirectly from published data as the product of 1) the saturation fluence for σ-polarized light at 1053 nm [16] and, 2) the ratio of the peak gain cross section at 1053 nm (σ) to that at 1047 nm (π) [17]. The amplifier calculations are sensitive to the saturation fluence so that the consistent agreement between experimental and numerical results has confirmed the accuracy of the value $E_s = 0.56$ J/cm^2.

Using the time-dependent Frantz–Nodvik calculation to model multistage amplifiers, the pulse-distortion issue is graphically illustrated. Fig. 4(a) shows the numerical result for the system as demonstrated. The broken line is the initial profile of the subpulse before amplification and the solid line is the amplified subpulse. It is evident that while the peak moves toward the leading edge, the shape is not appreciably altered. Desirable distortion occurs when identical gain stages (i.e., 6.4 × 64 mm rods pumped to a small-signal gain of 630) are added to the system. Fig. 4(b) and (c) show the results for two-stage and three-stage amplifiers, respectively. According to the calculations, the two-stage system would increase the input energy from 0.76 mJ to 0.89 J, while the three-stage system would boost the energy to 2.0 J. In both cases, the subpulse duration increases. In contrast, Fig. 4(d)–(f) show parallel results calculated for a 500 ns, 0.76 mJ rectangular input pulse. It is apparent that the amplifier energy is extracted primarily by the leading edge in such a way that the pulse duration is radically reduced. These calculations indicate the important role that the leading edge of the input pulse plays. The leading edge of the SROL subpulse rises slowly enough to allow the amplifiers' stored energy to be extracted in a gradual fashion. Furthermore, the SROL output is characteristically free of intensity fluctuations that might otherwise lead to rapid extraction and pulse shortening.

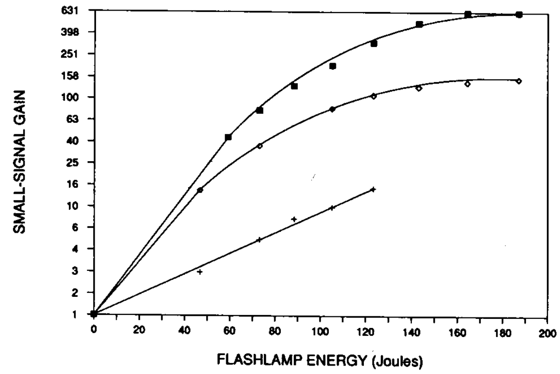


Fig. 3. Small-signal gain at 1047 nm in the 6.4 × 64 mm Nd : YLF amplifier: π-polarized diffuse reflector ("solid square"), π-polarized close-coupled cavity ("open diamond"), and σ-polarized close-coupled cavity ("plus").

IV. Nd : Glass SROL

Substantially higher SROL figures of merit can be achieved with host materials characterized by higher saturation fluences than YLF. This has been demonstrated with an Nd-doped phosphate-glass [18] SROL (Fig. 5) designed for use with a four-stage, 1 mJ to 10 J glass amplifier. The oscillator was tunable over the range 1050–1070 nm (Fig. 6). Dispersion was provided by a BK-7 equilateral prism pair. A 0.1-mm-thick etalon was included to maintain the spectral width below 0.05 nm. The 6.4 × 100 mm rod was pumped by a 60 μs FWHM flashlamp pulse at 1.3× threshold. At this operating point, the energy in the first subpulse was 1.75 mJ with an FWHM duration of 600 ns near the gain peak at 1053 nm (Fig. 7). The actual energy–duration product varied somewhat with wavelength. For example, the same energy was achieved at 1058 nm in a 750 ns subpulse.

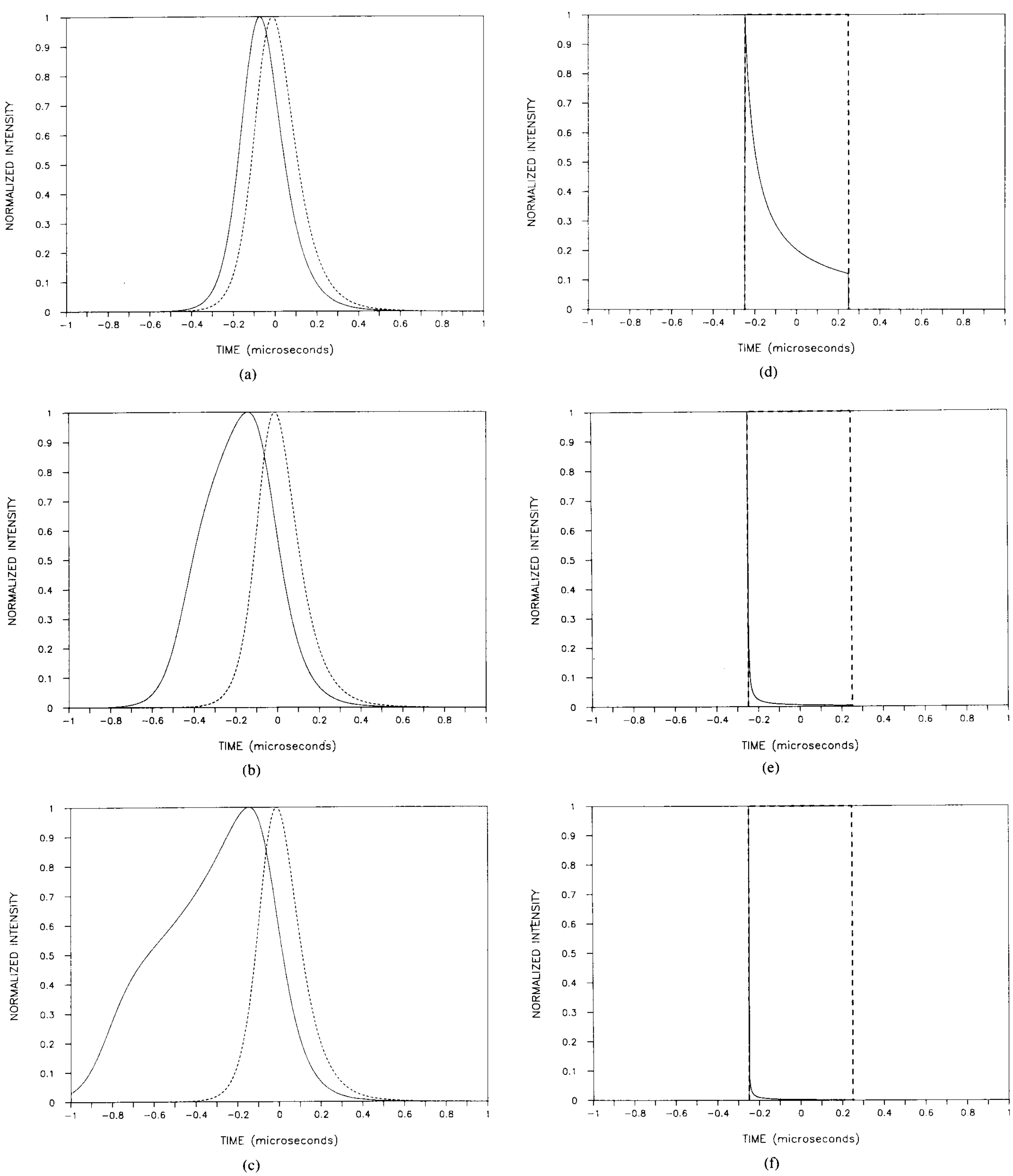


Fig. 4. Time-dependent Frantz–Nodvik simulations (solid lines) of multistage 6.4 × 64 mm Nd:YLF amplifiers (small-signal gain equal to 630 per stage). Initial SROL subpulse (broken line) input: (a) one stage, (b) two stages, and (c) three stages. 500 ns rectangular input pulse (broken line): (d) one stage, (e) two stages, and (f) three stages. The input energy is 0.76 mJ in all cases and the output energy is 127 mJ (one stage), 0.89 J (two stages), and 2.0 J (three stages).

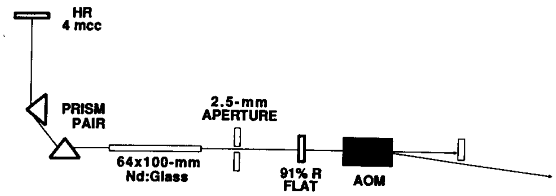


Fig. 5. Schematic of the Nd:glass SROL.

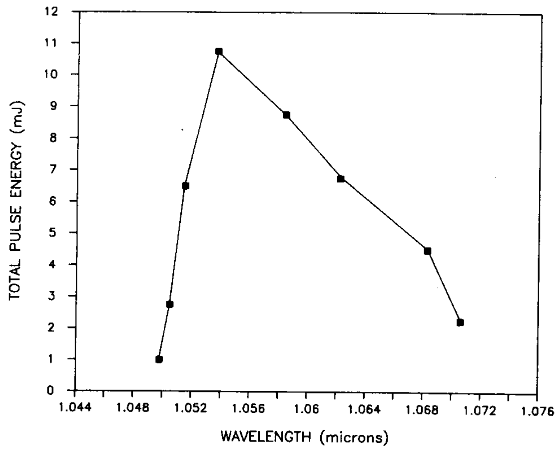
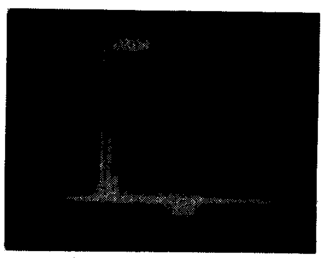
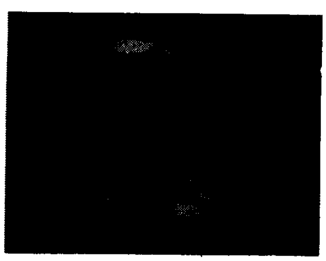


Fig. 6. Nd:glass SROL tuning curve obtained with 15 J input flashlamp energy. Total pulse energy refers to the subpulse energy sum.



(a)



(b)

Fig. 7. Experimental Nd:glass SROL output at 1.3× threshold and 1053 nm: (a) entire pulse (50 μs/div), and (b) first subpulse on an expanded time scale (500 ns/div).

V. Diode-Laser Pumping

Initial analyses indicate that SROL operation may be enhanced by replacing the flashlamp pump source with GaAlAs-diode-laser arrays. Aside from the inherent system advantages related to their environmental tolerance, pumping with diode lasers allows for optimum control of subpulse amplitudes and pulse-to-pulse stability and operation at repetition rates up to 100 Hz.

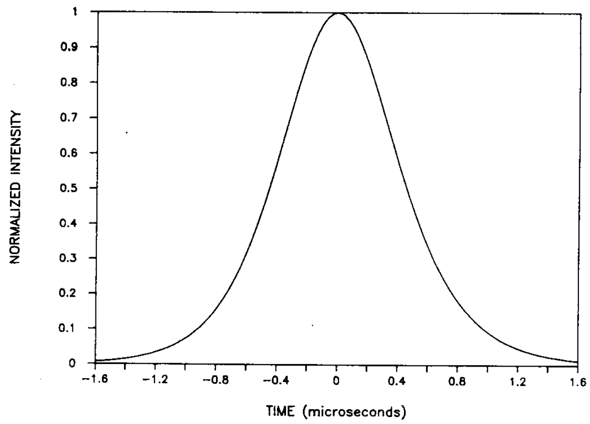


Fig. 8. Rate-equation simulation of diode-laser-pumped Nd:YLF SROL at 2.3× threshold.

A diode-pumped SROL was simulated with rate-equation calculations. Two 1-cm-long, 5 mJ arrays (similar to devices that are commercially available at present) were assumed to transversely pump a 2.5 cm Nd:YLF rod with 200 μs pulses. According to the calculations, employing a resonator identical to that described in Section II and pumping at 2× threshold would result in an initial subpulse with an FWHM duration of 946 ns (Fig. 8). The subpulse would occur about 100 μs after the pump turn-on. The model pump pulse was flat with a 10 μs turn-on ramp. In practice, the pump would be turned off before the development of any subsequent subpulses so that if the initial subpulse were utilized, the system could be operated without the AOM. The calculations indicate that 27 percent of the stored energy would be extracted in the initial subpulse.

It is possible to estimate the mode volume required to operate the oscillator at twice threshold with a 10 mJ source as described above given the gain cross section (2) and the roundtrip cavity loss. Using values appropriate for the oscillator of Section II, the required mode volume is calculated to be 0.08 cm^3 so that a 2-cm-long cylindrical pump volume would have a radius of 0.11 cm, a dimension similar to that of the Nd:YLF flashlamp-pumped SROL. If the overall pumping efficiency (including the quantum defect) were 20 percent, the output energy in the initial subpulse would be 0.14 mJ.

VI. Conclusions

The potential of the SROL system for high-energy, "long-pulse" generation has been investigated with encouraging results. Numerical simulations indicate that the characteristic smooth temporal profile undergoes desirable broadening in saturated amplifiers. A Nd:YLF oscillator/amplifier system has been demonstrated along with a tunable Nd:glass oscillator. In both cases, system operation was reliable and in agreement with the calculations. Future work in this area includes demonstration of Joule-level systems, experiments with diode-laser-pumped oscillators, and the extension of the SROL concept to other materials.

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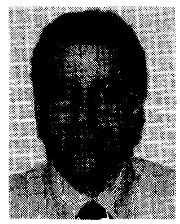

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Dr. Harrison is a member of the Optical Society of America and Sigma Xi.

Glen A. Rines, for a photograph and biography, see this issue, p. 973.

Peter F. Moulton (M'69-S'74-SM'84), for a photograph and biography, see this issue, p. 973.