Long-pulse generation with a stable-relaxation-oscillation Nd:YLF laser

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A simple technique for long-pulse (0.2–2 μsec) generation with neodymium lasers has been demonstrated. Under the proper conditions, a normal-mode oscillator, operated in a single transverse mode, produces well-defined relaxation oscillations from which a single subpulse can be isolated for amplification. The characteristic subpulse temporal profile is ideal for saturated amplification without pulse shortening. Data are presented for a Nd:YLF system consisting of an oscillator followed by a 64-mm-long amplifier. Pulse energies in excess of 100 mJ were achieved with a small-signal gain of 630.

There are a number of applications for solid-state lasers in which improved performance could be achieved given energetic pulses somewhat longer than those typically produced (10–100 nsec) by conventional Q-switched systems. These include cases in which 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 in which peak power presents a material 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 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 μsec at room temperature, the ideal Ti:Al_2O_3 pump is envisaged as a green source capable of delivering the required energy in a 1–2-μsec pulse.

Here we report on the development of a Nd:YLF stable-relaxation-oscillation laser (SROL) that provides the basis for a long-pulse source and on the demonstration of greater than 100 mJ of diffraction-limited output from a system consisting of an oscillator followed by a 64-mm-long amplifier. The characteristic oscillator pulse shape is well suited to amplification without pulse shortening, a severe limitation of systems that generate rectangular pulses. YLF was selected as the 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.

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 requires considerable amplification to generate joule-level energies, given typical cw laser outputs. A better approach is to use a modulator with 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 pulse widths of the order of 1 μsec. Pulse durations as long as 300 nsec 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 obtained 0.65-μsec 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 to poor pulse-to-pulse stability. Any temporal structure on the pulse can lead to significant pulse-shape distortions in the output of subsequent amplifier stages. Saturable absorbers have also been employed as variable-loss elements in Q-switched cavities but 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 proper conditions, the initial portion of each output pulse consists of a train of distinct, gain-switched, temporally smooth subpulses, a phenomenon often referred to as spiking. A modulator outside the cavity can be used as a shutter to isolate a single one of these subpulses for amplification. 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 of the order of 1 mJ. This is the concept behind the system described here.

The Nd:YLF SROL system was operated in the π polarization at 1047 nm and is shown schematically in Fig. 1. Selecting the SROL operating point involves a trade-off between the output energy of the subpulse and its duration. In this case, the duration was sacrificed in order to obtain 100 mJ of energy from a single-pass amplifier (AMP) with a gain length of 64 mm.

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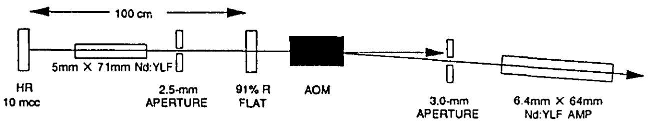

Fig. 1. Schematic of the Nd:YLF SROL system. 10 mcc, concave mirror with 10-m radius of curvature.

Relaxation oscillations with nearly 100% 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 flash-lamp pumping, the best pulse-to-pulse repeatability was achieved at high pump rates where the fractional flash-lamp intensity fluctuations were small. Note that in some applications, flash-lamp lifetime considerations may dictate the selection of the second pump method. The data included here were obtained with a 450-Torr xenon flash lamp pumped by a single-mesh discharge circuit ($C = 17\ \mu$F, $L = 10\ \mu$H).

The temporal form of the SROL was simulated by using a standard rate-equation analysis including the following input date: (1) a piecewise linear approximation of the 29-μsec full width at half-maximum (FWHM) flash-lamp pulse at 8.8× threshold, (2) the measured cavity loss, and (3) the upper-state lifetime of Nd:YLF [480 μsec (Ref. 10)]. Figure 2 shows the corresponding analytical and experimental results. The SROL behavior was in excellent agreement with the results of the rate-equation calculations.

The oscillator output was gated by an acousto-optic modulator (AOM) to spatially separate the desired pulse. The typical pulse-to-pulse temporal jitter observed in the initial pulses was about equal to the pulse duration and much less than the pulse separation, so that reliable gating was easily achieved. At the operating point of Fig. 2, the energy in the first pulse gated by the AOM was 0.84 mJ, and the corresponding FWHM durations of the first three subpulses were $\tau_1 = 270$ nsec, $\tau_2 = 360$ nsec, and $\tau_3 = 490$ nsec, respectively.

A possible figure of merit for the SROL is the energy–duration product of the subpulse selected from the oscillator output. Significantly higher products can be achieved with host materials characterized by higher saturation fluences (i.e., lower stimulated-emission cross sections) than YLF. For example, with a tunable (1049–1075-nm) Nd-doped phosphate glass SROL operated near 1.25× threshold, the pulse energy measured at the AOM output was 1.75 mJ with a FWHM duration of 600 nsec near the gain peak at 1053 nm (750 nsec at 1058 nm). As with the Nd:YLF device, the results were consistent with numerical simulations. Details of the tunable SROL will be published elsewhere.

By operating the 6.4 mm × 90 mm Nd:YLF amplifier rod in a 6.4 mm × 64 mm diffuse reflection cavity, a small-signal gain of 630 was achieved with a flash-lamp input energy of 163 J. At this operating point, with the oscillator beam diameter ($1/e^2$) increased to 2.9 mm, the input subpulse was amplified from 0.76 to

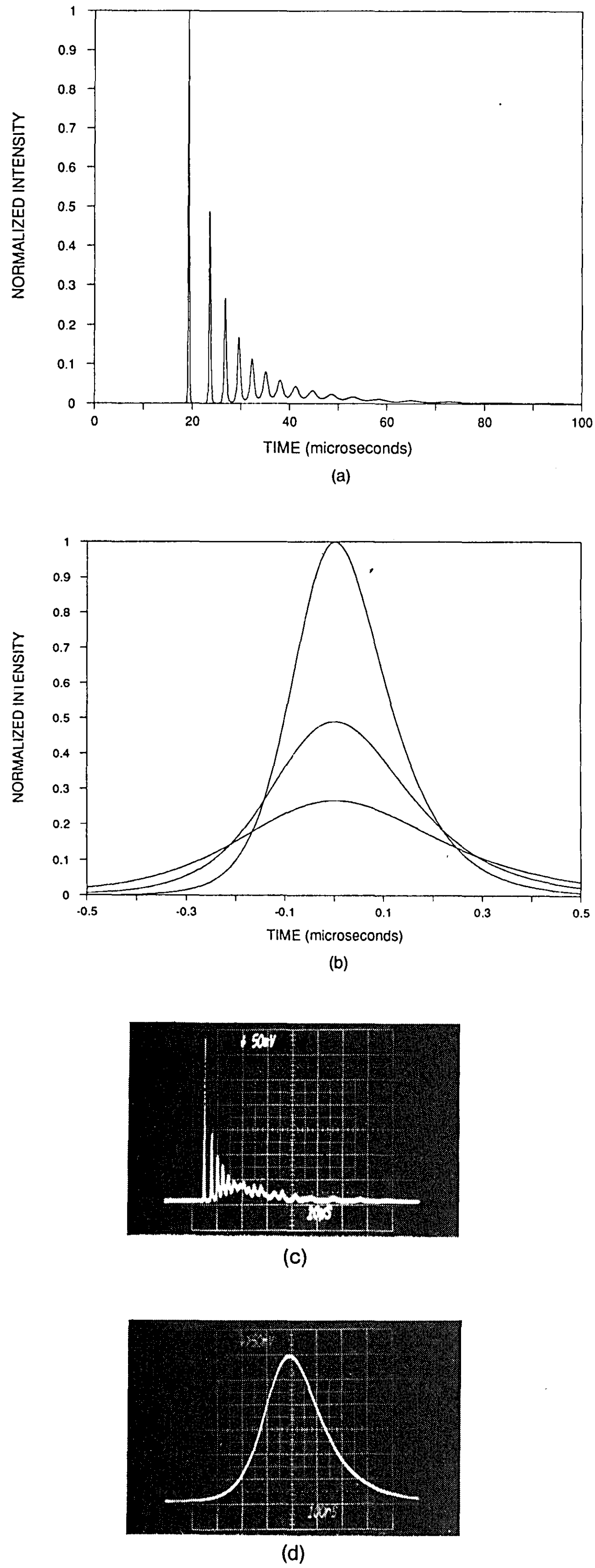

Fig. 2. Oscillator output pulse at 8.8× threshold: (a) rate-equation simulation, (b) first three calculated subpulses overlaid on an expanded time scale, (c) experimental result (10 μsec/division), and (d) experimental first subpulse on an expanded time scale (100 nsec/division).

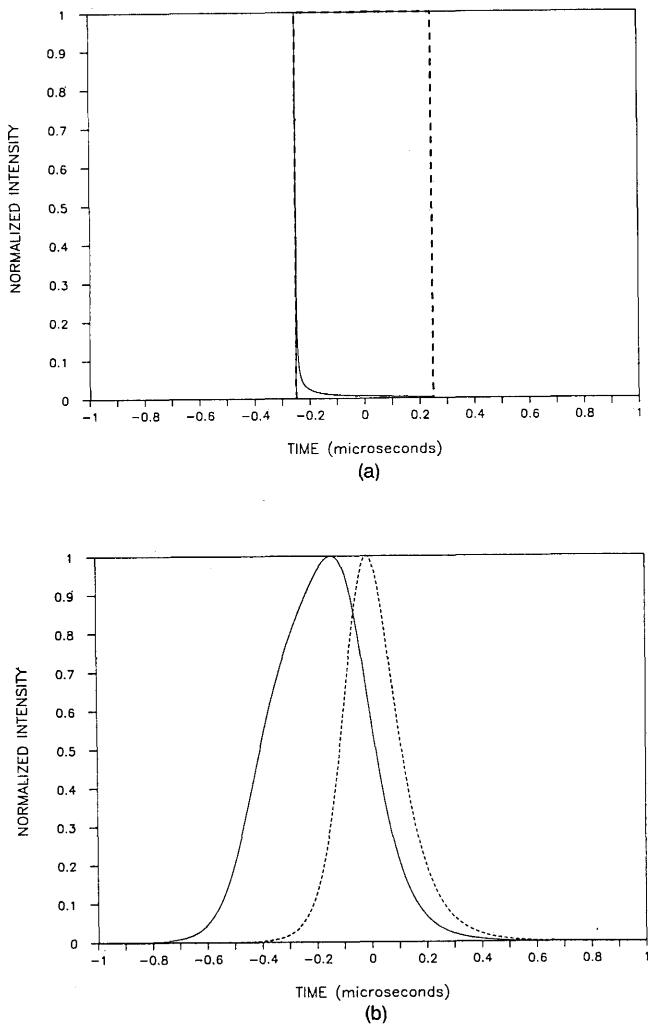

Fig. 3. Time-dependent Frantz–Nodvik simulations (solid lines) of a symmetric two-stage amplifier. (a) 500-nsec rectangular input pulse (dashed line), (b) SROL first subpulse (dashed line) input [Figs. 2(a) and 2(b)]. The amplifier pair increases the energy from 0.76 to 0.89 J.

116 mJ. The result, calculated using the Frantz–Nodvik equation[11] and accounting for the Gaussian spatial profile of the input beam, was 127 mJ. The calculation employed the measured small-signal gain and assumed a saturation fluence (π) of 0.56 J/cm^2.[12,13]

At the fluences described above, the temporal distortion of the amplified subpulse was minimal. This observation was in agreement with a time-resolved Frantz–Nodvik analysis. However, pulse distortion is a critical issue in the evaluation of multistage amplifiers required to achieve output energies of the order of 1 J. This is illustrated in Fig. 3, which shows the calculated output pulse shapes (solid lines) for two different input pulse shapes (dashed lines) assuming a 2.9-mm beam diameter and a two-stage amplifier consisting of two 6.4 mm × 64 mm rods, each uniformly pumped to an unsaturated gain level of 630. In both cases, the input energy was 0.76 mJ and the output energy was 0.89 J. Figure 3(a) shows the result given a 500-nsec rectangular input pulse, while Fig. 3(b) shows the result given an input pulse identical to the first subpulse calculated in the operating point rate-equation simulation of the SROL [Fig. 2(a)]. It is evident that, in contrast to the severe pulse shortening suffered by the rectangular pulse, the FWHM of the SROL subpulse is approximately doubled by the amplifier.

In summary, a relatively simple, inexpensive technique for long-pulse generation has been demonstrated with a Nd:YLF system. Numerical simulations indicate that the characteristic SROL pulse can be used to extract energy from strongly saturated gain media without pulse shortening. This technique should be especially useful in high-energy systems involving multistage amplifiers in which the final stages determine system efficiency. Ongoing experiments include the extension of this technique to other host materials and the analysis and construction of joule-level amplifier systems.

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