Regenerative Amplifier for the OMEGA Laser System

The 60-beam OMEGA Nd:glass laser is a direct-drive inertial confinement fusion (ICF) laser facility capable of achieving 30-kJ UV energy with an arbitrary temporal pulse shape predetermined by the target design. The initial low-energy, temporally shaped pulse is generated by the pulse-shaping system[1] (similar to a design developed at the Lawrence Livermore National Laboratory[2]), followed by multistage amplification with splitting, resulting in 60 laser beams with 1-kJ IR energy per beam. At the first amplification stage a negative-feedback-controlled, Nd:YLF regenerative amplifier (regen) is used. In this regen, the shaped pulse is amplified up to nine orders of magnitude to the submillijoule level.

In this article we present the requirements, design, and experimental results for the regens currently in use on OMEGA. These externally synchronizable regens boost the energy of the temporally shaped pulses to the submillijoule level with long-term energy variations of ~0.2% and with the output parameters of the amplified pulse insensitive to the injected pulse energy. The temporal distortions of the amplified pulse caused by the negative feedback are immeasurable. Four regenerative amplifiers equipped with this negative feedback system have operated flawlessly on OMEGA for the past two years.

Regenerative Amplifier Requirements for the OMEGA Laser System

The pulse-shaping system on OMEGA must meet a number of specifications[3] with a large safety margin to allow stable and reliable OMEGA operation. The low-energy pulses generated by this system must be amplified to an ~400-μJ energy with better-than-2% stability; the output pulses must be externally synchronizable; and the amplification process should introduce minimum and predictable temporal-pulse-shape distortions.

Multipass regens have been shown to provide high gains.[4,5] Flash-lamp-pumped regens, however, have typical output energy fluctuations[5,6] in the range of 5% to 10% for externally synchronized laser pulses. These fluctuations are caused primarily by an intrinsic flash-lamp instability. The relative variation in the flash-lamp output $\delta E_{\rm pump}/E_{\rm pump}$ leads to a variation of the amplified pulse energy $\delta E_{\rm out}/E_{\rm out}$ as[7]

$$\delta E_{\rm out}/E_{\rm out} \approx \ln\left(G_{\rm tot}\right)\delta E_{\rm pump}/E_{\rm pump}, \qquad (1)$$

where $G_{\rm tot}$ is the total small-signal gain. For a standard regen, $G_{\rm tot} \approx 10^7$ to 10^9; therefore, for $\delta E_{\rm out}/E_{\rm out} \approx 2\%$, the pump energy variation must be $\delta E_{\rm pump}/E_{\rm pump} \le 0.1\%$. For a standard flash-lamp–pumped regen, this is difficult, if not impossible, to achieve.[6,7] In addition, fluctuations in the pulse energy injected into the regen can also affect the regen output stability. For an externally synchronizable pulse, 2% regen output stability requires approximately the same stability for the injected pulse. This is difficult to achieve since the efficiency of injecting an optical pulse into the regen is affected by many factors that are difficult to control. A negative feedback can enhance the stability and external synchronizability of the regen,[8] but the time-dependent losses introduced by that negative feedback can cause undesirable temporal-pulse-shape distortions of the injected pulse during amplification. These distortions are difficult to model accurately, which seriously hampers the generation of a desired pulse shape at the regen output.

We developed a flash-lamp–pumped Nd:YLF regen with a redesigned negative-feedback system that completely satisfies OMEGA requirements. This feedback system introduces no temporal-pulse distortions, apart from pulse distortion due to gain saturation, that can be accurately modeled and compensated for. In the following sections we will discuss practical aspects of this regen design and present results of our numerical modeling and experimental measurements.

Negative-Feedback System for the Regenerative Amplification of Temporally Shaped Pulses

A negative feedback renders the regen output insensitive to input variations as well as to gain and loss fluctuations inside the regen cavity. The feedback signal is derived from the intracavity pulse energy and controls the intracavity losses. A block diagram of this regen is shown in Fig. 76.11. The instantaneous intracavity pulse energy is sensed by a photodiode whose signal is amplified by feedback electronics and applied to the Pockels cell electrode; thus, the losses increase as the circulating pulse energy increases, resulting in a steady-state round-trip gain near unity. After the feedback (pre-lase) phase, all cavity losses are eliminated, and the pulse is amplified as in a standard *Q*-switched oscillator.

The pre-lase phase is crucial for stabilizing the output pulse energy. Pulses injected into the regen above the average energy reach the steady-state phase early in time, while injected pulses with less energy reach the steady-state phase later. In the steady-state phase, the circulating intracavity pulse energy is constant and independent of the injected pulse energy (Fig. 76.12); thus, the regen with negative feedback is very insensitive to input fluctuations, in contrast to a regen without feedback.

The steady-state phase also compensates for gain fluctuations caused by flash-lamp fluctuations. During the steady-state phase the circulating-pulse energy remains approximately constant while the gain continuously decreases due to the energy dissipated by the feedback losses. The rate at which gain is reduced after each round-trip depends on the ratio of the intracavity pulse fluence to the saturation fluence. The exact value of the intracavity pulse energy in the pre-lase phase can be controlled externally to minimize the regen output fluctuations due to gain or loss variations (Fig. 76.12).

Successful implementation of this distortionless negative-feedback system places stringent requirements on the feedback electronics. Our intracavity Pockels cells are KD*P crystals that require the feedback electronics to deliver high-voltage electrical signals in the 2- to 3-kV range in order to introduce noticeable intracavity losses. Past experience has

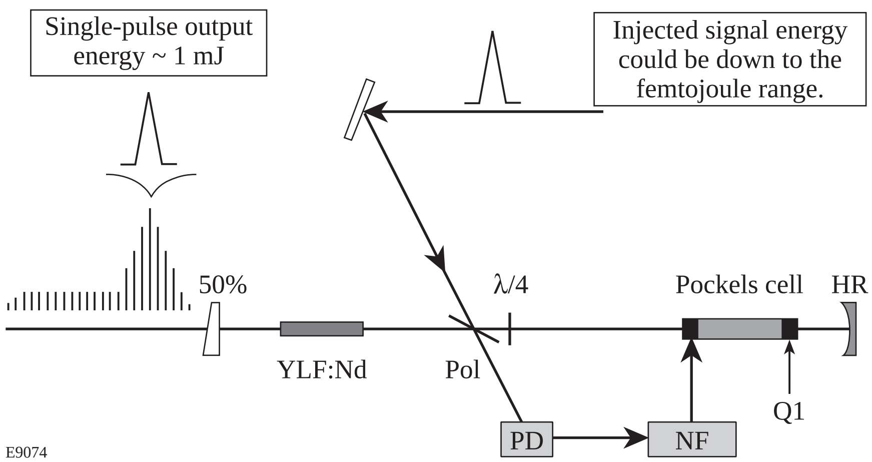

Figure 76.11
Block diagram of the regen with negative feedback.

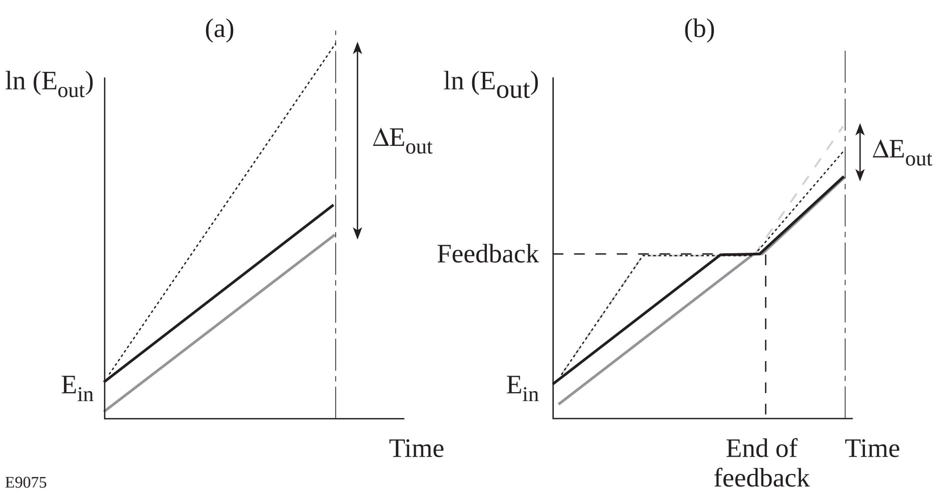

Figure 76.12
Semilog schematic plot of the energy evolution in the regen (a) without feedback and (b) with negative feedback. Negative feedback mitigates effects of shot-to-shot gain and loss fluctuations and injected-pulse energy variation. The solid curve represents the average injected energy and the average regen gain. The dotted curves represent the average injected energy and a regen gain higher than the average gain. The shaded curve represents a case where the injected energy is less than average and the regen gain is average.

shown[9] that the negative-feedback electronics must have a delay time shorter than 2 to 3 regen cavity round-trips. To stabilize the intracavity pulse energy, the feedback electronics must respond faster than the relaxation-oscillation frequency[10]

$$\omega_0 = \sqrt{(r-1)\gamma_c \gamma_{\mathrm{YLF}}}\,, \tag{2}$$

where γ_c is the inverse photon lifetime in the regen cavity, γ_{YLF} is the inverse relaxation time of the upper laser level of Nd:YLF, and r is the pumping rate. These feedback requirements are difficult, if not impossible, to fulfill with standard electronics.

Typical fast, high-voltage feedback electronics strongly distort the output pulse shape because of small feedback-induced intracavity loss variations during the time the circulating pulse propagates through the Pockels cell. Although the single-pass distortions are small, their effect is cumulative, and after many round-trips the distortions become severe. To eliminate these distortions the negative-feedback signal applied to the Pockels cell must be constant while the shaped pulse propagates through the Pockels cell. This requires that the negative-feedback signal have no fast-frequency components, which contradicts Eq. (2).

This problem can be circumvented with a two-component, negative-feedback signal. The first component is a high dc voltage that introduces a time-independent constant loss and brings the regen very close to the steady-state phase. In this phase the relaxation-oscillation frequency of the regen is very small [see Eq. (2) with $r \approx 1$]; thus, the circulating pulse energy can be held constant with a second low-voltage, low-frequency electrical-feedback signal. Due to the low voltage and slow temporal variation of the second feedback component, the temporal shape of the amplified pulse is not distorted.

Regen Modeling

The regen dynamics were modeled in a manner similar to that published in Ref. 11. Using an ideal four-level amplifying medium, neglecting fluorescence depumping, and assuming that the pulse fluence J is much smaller than the saturation fluence J_s of the gain medium ($J_{s,\mathrm{Nd:YLF}} \approx 0.8$ J/cm^2 at 1053 nm), one obtains a pair of simplified recurrent rate equations:[4]

$$J_{k+1} = T_k \exp\left(g_k\right) J_k\,, \tag{3}$$

$$g_{k+1} = g_k - \left[\exp\left(g_k\right) - 1\right] J_k / J_s\,. \tag{4}$$

Here k is the index for the resonator round-trip; T_k, g_k, and J_k are the resonator transmission, gain coefficient, and pulse fluence during the k^{th} round-trip, respectively; and $g_k = \ln(G^{ss}{}_k)$, where $G^{ss}{}_k$ is the small-signal gain of the k^{th} round-trip. We have also assumed that the $G^{ss} J_k / J_s << 1$. The gain coefficient at the time of injection, g_0, is proportional to the pump energy E_{pump}. The calculated intracavity fluence of the regen is shown in Fig. 76.13(a) for an initial net round-trip gain $G_0 = 2.1$, which is typical for OMEGA regens. The dependence of the output pulse train (pulse energy and build-

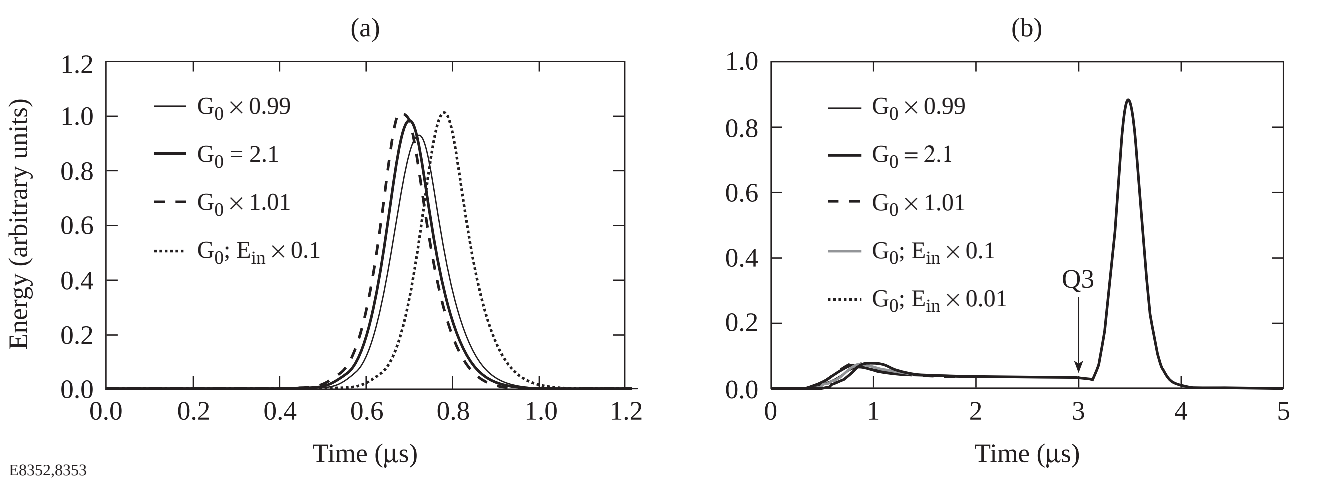

Figure 76.13
Numerical simulations clearly demonstrate the stabilizing effect of the negative feedback on the output energy of the regen: (a) thick solid line—standard regen output; dashed/thin solid lines—pumping energy varied by ±1%; dotted line—10× less injected pulse fluence; (b) same as (a) but with negative feedback.

up time) on variations in net round-trip gain G_0 and injected pulse energy E_{in} are also shown in this figure.

The two-component negative feedback is modeled by multiplying the right side of Eq. (3) by the transmission functions T_{dc} and T_{ac}. The former models the time-independent loss while the latter accounts for the modulated feedback losses required to maintain constant circulating pulse energy. The actual value of T_{dc} is adjusted in such a way that the regen operates just slightly above threshold. In the steady-state phase, T_{ac} is inversely proportional to the difference between the intracavity pulse fluence and the threshold fluence J_{th} of the pulse at the time when the dc feedback losses were introduced. In Fig. 76.13(b), modeling results for the regen with the feedback are presented for the same initial conditions as in Fig. 76.13(a). The negative-feedback stabilization of the regen output is clearly apparent by the insignificant variations in maximum amplitude of the train envelope as well as by the constant build-up time beyond the externally triggered Q-switch [Q3 in Fig. 76.13(b)].

Experimental Results

The block diagram for the regen with negative feedback is shown in Fig. 76.14. A temporally shaped optical pulse is injected into the regen through a polarization-maintaining, single-mode fiber and a Faraday isolator. At the time of injection, a step-like quarter-wave voltage (~4.1 kV) is applied to the Pockels cell, and the injected pulse experiences small losses and relatively high round-trip gain. When the energy of the amplified pulse reaches a predetermined level (~10 μJ), a second step of ~2 kV applied to the second Pockels cell electrode changes the differential voltage applied across the Pockels cell, adding a time-independent constant intracavity loss. As a result, the net round-trip gain is reduced to just slightly above threshold, preventing further rapid buildup of the laser pulse. At this time, a small feedback voltage applied to the Pockels cell is sufficient to control and maintain a constant steady-state pulse energy over periods of a few microseconds. Furthermore, since the regen operates close to the threshold, the response time of the regen (equal to the inverse of the relaxation-oscillation frequency) is very long compared to the regen round-trip time of 26 ns. This completely eliminates pulse distortions caused by the negative feedback. At a predetermined time [Q3 in Fig. 76.13(b)], a third Q-switch voltage step is applied to the Pockels cell, which compensates the losses caused by the previous loss-producing voltages. This process produces a train of highly stable pulses under a Q-switched envelope as shown in Fig. 76.15. Single shaped pulses of ~1 mJ and exceptional energy stability (~0.2% rms) have been generated over periods exceeding 4 h of continuous 5-Hz operation [$\sim 7.7 \times 10^4$ shots (see Fig. 76.16)]. A 0.5% rms energy stability was observed over a 9-h period ($>1.6 \times 10^5$ shots). In addition to its excellent energy stability, the regen output is also very insensitive to the injected energy (see Fig. 76.17).

Injection of a square pulse confirms that the only measurable distortions of the temporal pulse shape are due to gain saturation. These distortions can be modeled precisely by simple rate equations[11] and can be effectively precompensated (see Fig. 76.18). With the present system we have experimentally demonstrated the generation of kilojoule-level laser pulses from the OMEGA laser system with prescribed temporal pulse shapes (see Fig. 76.19).

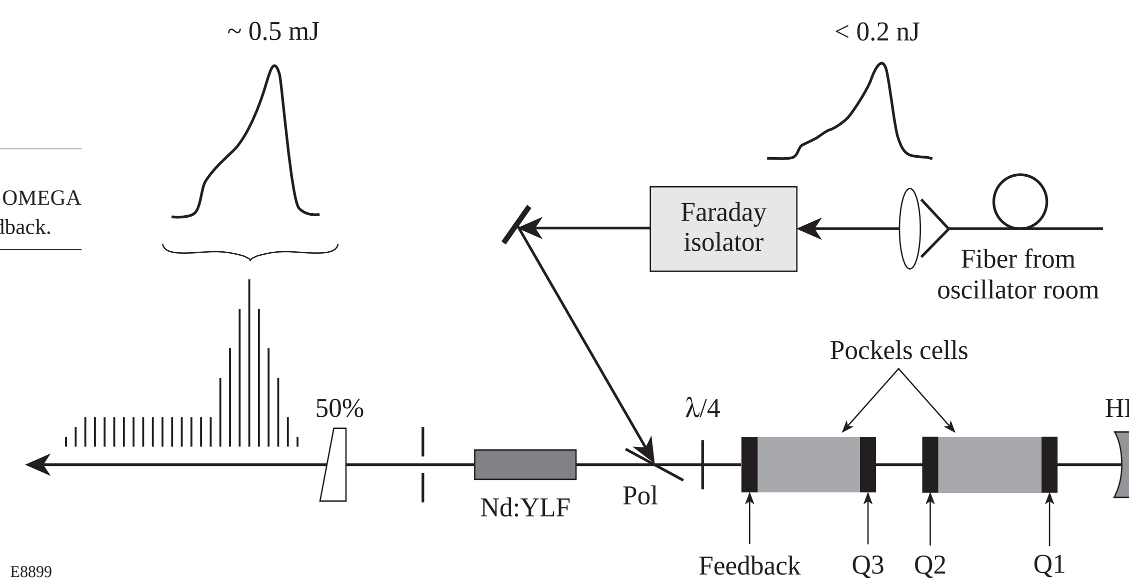

Figure 76.14
Block diagram of the OMEGA regen with negative feedback.

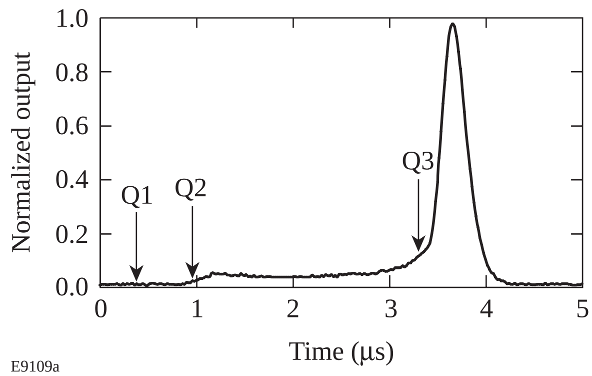

Figure 76.15
Measured envelope of the output pulse train from the regen with negative feedback.

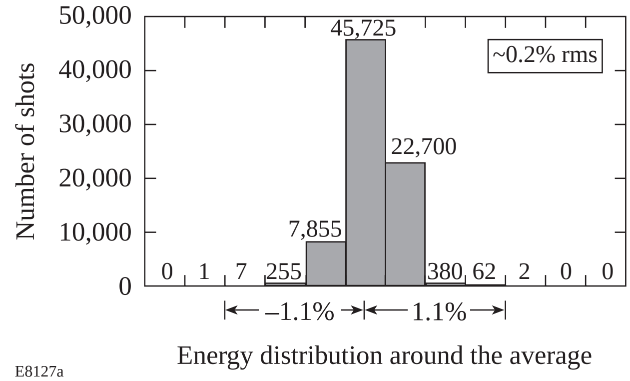

Figure 76.16
Stability histogram for the single-pulse energy distribution at the regen output. Data were collected over 4 h of continuous operation at a 5-Hz repetition rate.

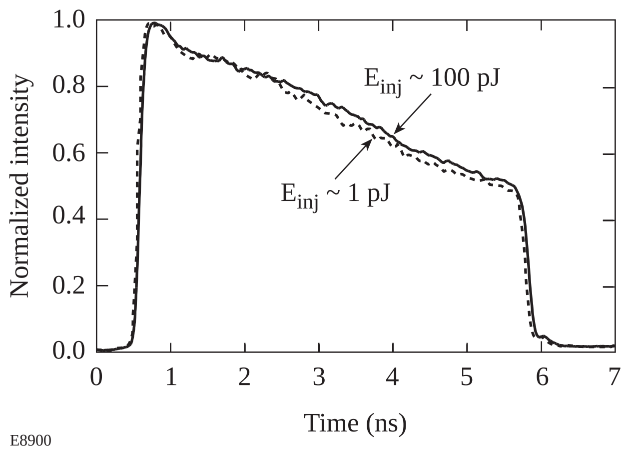

Figure 76.17
IR streak camera measurements of the regen output. Solid line—the injected pulse at nominal energy; dashed line—the injected pulse energy attenuated by a factor of 100.

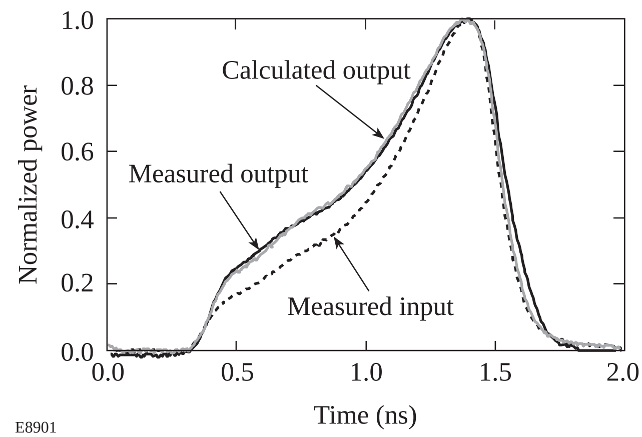

Figure 76.18
Measured and simulated regen output pulse shapes.

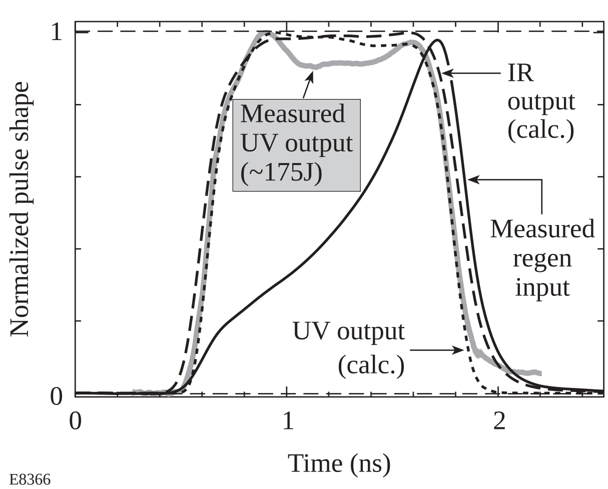

Figure 76.19
Measured and simulated UV output pulse shapes for a 10-kJ UV OMEGA laser shot. The simulated UV pulse shape uses the measured regen input pulse shape. The calculated IR pulse shape at the input to the frequency triplers is also shown.

Conclusion

In conclusion, we have developed a negative-feedback–controlled and externally synchronizable Nd:YLF regenerative amplifier capable of amplifying shaped optical pulses to the millijoule level. Long-term, shot-to-shot energy fluctuations of ~0.2% rms represent, to our knowledge, the best energy stability ever demonstrated for a millijoule-level laser system, either flash lamp pumped or diode pumped. In addition to superior stability and reproducibility, the current OMEGA regen output is very insensitive to the injected energy, and the temporal distortions due to the negative feedback are immeasurable. Four regens equipped with this negative-feedback system have operated flawlessly on OMEGA for over two years.

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