

The Output Signal-to-Noise Ratio of a Nd:YLF Regenerative Amplifier

A regenerative amplifier (regen) is a common element in a variety of laser systems because of its compactness and ability to significantly boost the energy of an optical pulse with minimal temporal distortion and added noise.^{1,2} Net gains of the order of 10^8 are easily obtainable. Noise is the unwanted portion of the optical signal that can originate from stochastic or deterministic processes within the system. For some applications, even small amounts of noise are an important concern. One such application is laser fusion, where an optical pulse with less than 1 nJ of energy is amplified with an overall net gain of approximately 10^{14} to the 60-kJ level, frequency tripled to a 351-nm wavelength, and focused onto fusion targets. In such a system, even a relatively small amount of prepulse signal can be detrimental to target performance; therefore, to minimize the prepulse noise signal it is very important to control and maximize the signal-to-noise ratio (SNR) at every step of the amplification process.

In this article we present measurements of the output SNR (defined as the ratio of the peak power of the amplified signal to the average power of the prepulse noise) of a regen used as the first amplification stage in the OMEGA laser system. We compare our measurements to a simple theoretical model that we developed. We find that the prepulse noise signal in the output of our regen has two main contributions: one is due to the intrinsic noise generated within the regen during the amplification process, as studied previously,² and the other is due to the prepulse signal on the optical pulse injected into the regen. Our model of the regen output SNR includes both contributions. We experimentally demonstrate that the regen output SNR can be very high for an injected pulse with low noise. We also demonstrate that, in general, the regen output SNR equals the SNR of the pulse injected into the regen in the limit of strong signal injection. Our measurements are in excellent agreement with our theoretical model.

Theory

The total optical power circulating in the regen evolves according to the equation³

$$\frac{dP}{dt} = \gamma P(t) + \gamma N_{se}, \quad (1)$$

where γ is the exponential net gain coefficient, P is the optical power circulating in the regen, and N_{se} is phenomenologically included as the noise power in the regen due to spontaneous emission. Equation (1) can be integrated to give

$$P(t) = G P_0 + G N_{inj} + N_{se}(G - 1), \quad (2)$$

where $G = \exp(\gamma t)$ is the net gain of the regen, P_0 is the signal power injected into the regen, and

$$N_{inj} = \frac{P_0}{\text{SNR}_{in}} \quad (3)$$

is the noise on the signal injected into the regen with SNR_{in} the signal-to-noise ratio of the signal injected into the regen.

It is instructive to describe each term on the right-hand side of Eq. (2). The first term simply represents amplification of the injected signal into the regen and is the regen output signal in the absence of noise. The second and third terms are noise terms. The second term is the amplified injected noise power that describes the amplification of the noise injected into the regen with the optical pulse. The third term is due to the amplification of the spontaneous emission noise generated by the regen itself. The output SNR of the regen is then given by

$$\text{SNR}_{out} = \frac{P_0}{N_{se}(1 - 1/G) + N_{inj}}. \quad (4)$$

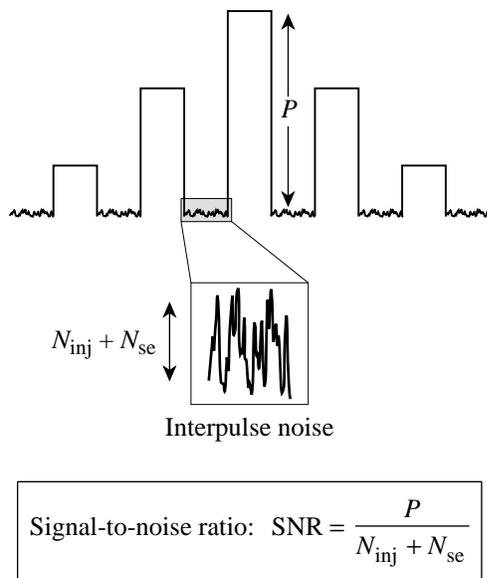
For most cases of practical interest the total net gain is much greater than unity ($G \gg 1$). If the injected noise power is much less than the spontaneous emission noise power ($N_{inj} \ll N_{se}$), the second term in the denominator can be neglected and the output SNR of the regen is proportional to the power injected into the regen. For the case where the injected noise power is

much greater than the spontaneous emission noise power ($N_{inj} \gg N_{se}$), the first term in the denominator can be dropped. In this case the output SNR_{out} of the regen equals the injected SNR_{in} and is independent of the amount of injected signal power. This model of the regen output SNR is verified by the experiments described below.

Experimental Results

Experiments have been performed to verify the above theory. The details of the regen operation are given elsewhere.^{4,5} A pulse is injected into the regen and allowed to evolve until the circulating pulse energy reaches a threshold value. Losses are then introduced in the cavity to maintain the round-trip gain at unity. Later, the cavity losses are removed, and a Q-switched train of amplified pulses separated by the regen cavity round-trip time of 26 ns evolves. In our experiment we define the regen output SNR as the ratio of the peak power of a pulse in the pulse train to the power measured between this pulse and an adjacent pulse (i.e., the interpulse noise). This definition is illustrated schematically in Fig. 80.16.

To measure the output SNR of our regen, a high-contrast (>1000:1) Pockels cell with a 10-ns square transmission func-



E10034

Figure 80.16 Signal-to-noise ratio (SNR) measurement setup. The regen output SNR is defined as the ratio of the power of the injected pulse averaged over a cavity round-trip time to the noise power measured between two regen output pulses.

tion is used to select the output power of the regen at various times in the output-pulse train. The timing of the Pockels cell transmission window is first adjusted to pass a single optical pulse from the regen output. The pulse is attenuated and sent to a photodetector, and the peak voltage of the detector is measured and recorded as the regen signal. The Pockels cell transmission window is then moved in time by 13 ns, which is half the regen round-trip time, in order to measure the interpulse noise power between this pulse and the previous pulse in the regen output-pulse train. The calibrated attenuation is removed from the detector, and the average voltage of the photodetector over a portion (~2 ns) of the 10-ns Pockels cell transmission window is measured and recorded as the regen noise power. The overall bandwidth of our measurement system is approximately 1 GHz. These measurements are made as the power of the injected signal is varied. In this way the regen output SNR is recorded versus the power of the injected signal.

The pulse injected into the regen is generated with two integrated electro-optic modulators.⁶ We apply a square electrical pulse to each modulator synchronous with the transmission through the modulator of an optical pulse from a single-longitudinal-mode (SLM) laser. The transmission function of a dual-channel modulator in this case is given by

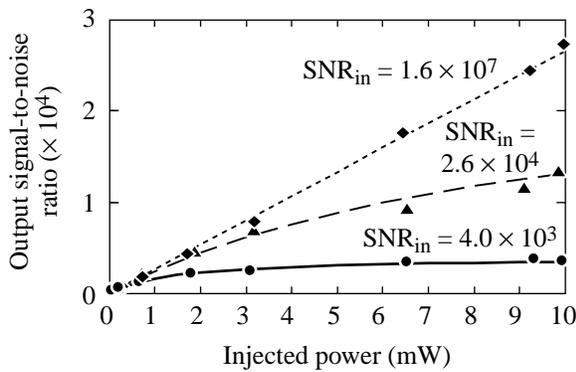
$$I_{out}(t) = I_{in}(t) \sin^4 \left\{ \frac{\pi}{2} \left[\frac{V(t) + V_{dc}}{V_{\pi}} \right] + \phi \right\}, \quad (5)$$

where $I_{in}(t)$ is the intensity profile at the modulator input, $V(t)$ is the modulation voltage applied to each channel of the modulator, V_{π} is the half-wave voltage of the modulator (~10 V), ϕ is a constant phase shift, and V_{dc} is a dc voltage that can be applied to cancel the constant phase shift. Square electrical pulses of 3-ns duration with amplitude V_{π} are synchronously applied to both channels of the modulator during the peak of the 200-ns Gaussian pulse sent into the modulator from the SLM laser. For this reason, the input-intensity profile to the modulator, $I_{in}(t)$, is assumed to be a constant independent of time. The resulting 3-ns square optical pulse from the modulator is injected into the regen.

A dc bias voltage (V_{dc}) is applied to the modulators to compensate the constant phase term in Eq. (5). When optimally compensated in this way, the modulators provide “zero” transmission for zero applied modulation voltage. This results in a high-contrast pulse (that is, very low prepulse signal) from the modulator. For our experiments, we alter SNR_{in} of the pulse

injected into the regen by changing the dc bias voltage (V_{dc}). As the dc bias voltage is varied away from the high-contrast value, light from the SLM laser leaks through the modulator prior to and after the 3-ns optical pulse. The ratio of the peak power in the 3-ns optical pulse from the modulator to the prepulse (postpulse) power from the modulator is our definition of the SNR_{in} of the pulse injected into the regen. With this definition, the SNR_{in} depends only on the dc-applied voltage to the modulators and is calculated from Eq. (5). This prepulse and postpulse power injected into the regen is the nature of the regen interpulse noise given by the second term in the denominator in Eq. (4). Varying the dc-applied voltage to the modulators varies the SNR of the injected pulse into the regen. The injected power into the regen is varied by attenuating the optical pulse at the input to the modulator.

Measurements of the output SNR of a regen versus the injected power into the regen are shown in Fig. 80.17. For the three curves, the injected SNR was varied as indicated. Using Eq. (4), plots of the regen output SNR are overplotted with the data. To obtain best fits to the data we used 375 nW for N_{se} in all plots, and to determine SNR_{in} we used our measured dc voltages applied to the modulators in Eq. (4). As seen in Fig. 80.17, our measurements are in excellent agreement with theory.



E10036

Figure 80.17
Signal-to-noise ratio measurements at the output of a regen versus the injected power into the regen for three values of the SNR of the injected power into the regen.

Separate measurements were made to estimate the amount of equivalent spontaneous-emission noise power, N_{se} , in the regen. A pulse was injected into the regen and the buildup time for the pulse to reach a power level of ~ 100 W in the regen was measured for different power levels of the injected signal. In

Fig. 80.18 the average power of the injected pulse is plotted on a semi-log scale versus the buildup time in the regen. From Eq. (2) and $G \gg 1$ the time t_1 for the regen output power to reach a fixed predetermined power level P_1 is given by

$$t_1 = \frac{\ln P_1 - \ln(P_0 + N_{inj} + N_{se})}{\gamma} \tag{6}$$

When the injected signal power into the regen is much greater than the spontaneous-emission noise power ($P_0 \gg N_{se}$), the buildup time t_1 exhibits an exponential dependence on the injected power P_0 . The logarithmic fit to the experimental data points in Fig. 80.18 reveals good agreement with this theory. From this logarithmic fit we can estimate N_{se} by using the measured buildup time of 789 ns for the case with no signal injected into the regen. From this we estimate N_{se} to be approximately 80 nW, which is within a factor of 5 of the 375-nW value that was used to obtain the best fit to our data in Fig. 80.17.

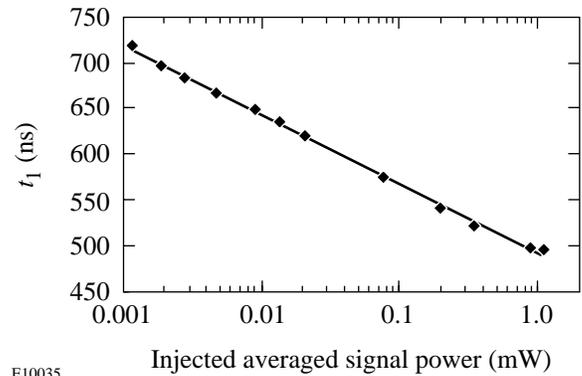


Figure 80.18
Measured time t_1 required for the regen output to reach a preset power level versus averaged power of the pulse injected into the regen. The power of the injected pulse was averaged over one regen round-trip.

Conclusions

We measured the output SNR of a regen and compare our measurements to a simple model that we developed. We show that the noise in the output of a regen has two contributions: one is due to amplified spontaneous emission; the other is due to noise (in our case in the form of a prepulse) injected into the regen. We simulate noise on the input pulse to the regen and conclude from our measurements that the regen output SNR saturates to the SNR of the pulse injected into the regen. We measured an output SNR from the regen as high as 2.7×10^4 .

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

REFERENCES

1. W. H. Lowdermilk and J. E. Murray, *J. Appl. Phys.* **51**, 2436 (1980); **51**, 3548 (1980).
2. W. Koechner, *Solid-State Laser Engineering*, 3rd rev. ed., Optical Sciences Series, Vol. 1 (Springer-Verlag, New York, 1992).
3. A. Yariv, *Optical Electronics*, 4th ed. (Saunders College Publishing, Philadelphia, 1995).
4. A. Babushkin, W. Bittle, S. A. Letzring, M. D. Skeldon, and W. Seka, in *Third International Conference on Solid State Lasers for Application to Inertial Confinement Fusion*, edited by W. H. Lowdermilk (SPIE, Bellingham, WA, 1999), Vol. 3492, pp. 124–130.
5. M. D. Skeldon, A. Babushkin, W. Bittle, A. V. Okishev, and W. Seka, *IEEE J. Quantum Electron.* **34**, 286 (1998).
6. Modulator technical data at <http://www.crisel-instruments.it/alemia/html/index01.htm>.