Modeling Pulse Shape Distortions in the OMEGA Laser

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Summer High School Research Program 2000

We present a study of two potential sources of pulse shape distortion: Stimulated Brillouin Scattering (SBS) in optical fibers and a gain grating in the active medium of the regenerative amplifier. SBS, the major contributor to nonlinearities in optical fibers, is shown to be insignificant in OMEGA. Scattering from the gain grating formed in the laser crystal was included into a model of regenerative amplification. The developed model demonstrates good agreement with experiment. The model is not yet complete, but may have the potential to identify and explain other pulse shape distortions in the OMEGA front end.

The mission of the OMEGA laser is threefold: to conduct implosion experiments and basic physics experiments in support of the National Inertial Confinement Fusion (ICF) program, to develop new laser and materials technologies, and to conduct research and development in advanced technology related to high-energy-density phenomena. The laser begins with a monomode laser, which emits a 200-nanosecond Gaussian optical pulse. A 20 ns square pulse is cut from its peak and is focused into a fiber, where it reaches high intensities. The pulse enters a pulse shaping system, which shapes the pulse according to its settings. The pulse is then sent to the pulse generation room (PGR) where it is injected into a regenerative amplifier (regen). In the regen, the pulse is amplified. A pulse is sliced out of the regen pulse train, and sent through various OMEGA amplifiers, frequency tripled, and sent into the target chamber. The two nonlinear processes that I concentrated on were stimulated Brillouin scattering (SBS) in optical fibers, which occurs when high laser intensities enter the optical fiber, and pulse shape distortions which occur in the regen if the pulse overlaps with itself in the gain medium.

I. SBS in Optical Fibers

When the laser beam first enters an optical fiber, directly after the monomode laser, it reaches high intensities which can cause various nonlinear effects, one of which is stimulated Brillouin scattering (SBS). The SBS process begins when a high intensity pulse propagates in a medium, such as the optical fiber. The wave may scatter in the backward direction off density fluctuations. The backward-scattered wave will then form a "beat" with the original waveform, and drive an acoustic wave through the process of electrostriction. More incident light will then scatter off the acoustic wave with the result that the scattered wave experiences exponential gain. The scattered wave has a frequency of $\nu-\Omega$, where the incident light has a frequency of ν and the acoustic wave has a frequency of Ω. There are several reasons for SBS to be of concern to OMEGA. One of them, the most obvious, is that the backward scattered light causes a reduction and temporal distortion of the input pulse energy. The SBS light may damage the monomode laser, but a Faraday isolator is used to prevent such. Also, the distortion of the original pulse by even a few percent is significant at the intensities seen in the OMEGA laser, and lower original

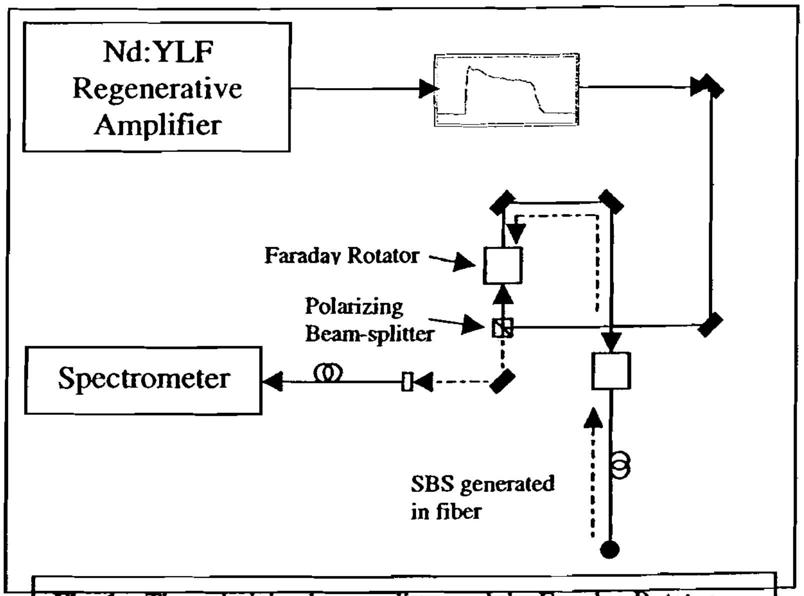


Fig. 1 – The polarizing beam splitter and the Faraday Rotator work to allow nearly 100% of the SBS energy to return to our detector

pulse energy means less overall amplification. Finally, the pulse shape is distorted by the SBS, leading to a faster rise time which may, depending on the project, distort the results.

The intensity of the backward-scattered SBS depends on many factors, and is given by[1]

$$I_s(z,t) = I_s(l,t)\exp\left\{2\sqrt{\frac{g_B^e(\max)E_L ct}{nA\tau_B}} - \frac{t}{\tau_B}\right\} \tag{1}$$

where $I_s(z, t)$ is the intensity of the output SBS signal, $I_s(l, t)$ is the intensity of the noise or Stokes signal, g_B is the gain coefficient particular to SBS in a given medium, E_L is the energy of the input laser, c is the speed of light in a vacuum, t is the interaction time, *n* is the refractive index of the medium, A is the cross-sectional area of the interaction region, and τ_B is the phonon lifetime. Typical values given for τ_B and g_B in the literature[2] are τ_B = 10-100 ns, and $g_B = 5 \times 10^{-9}$ cm/W. Our goal was to verify these values and to determine whether SBS would be a threat to future projects on the OMEGA laser and, if so, to what degree.

Our setup was designed to be able to produce high intensities into the fiber, as well as to

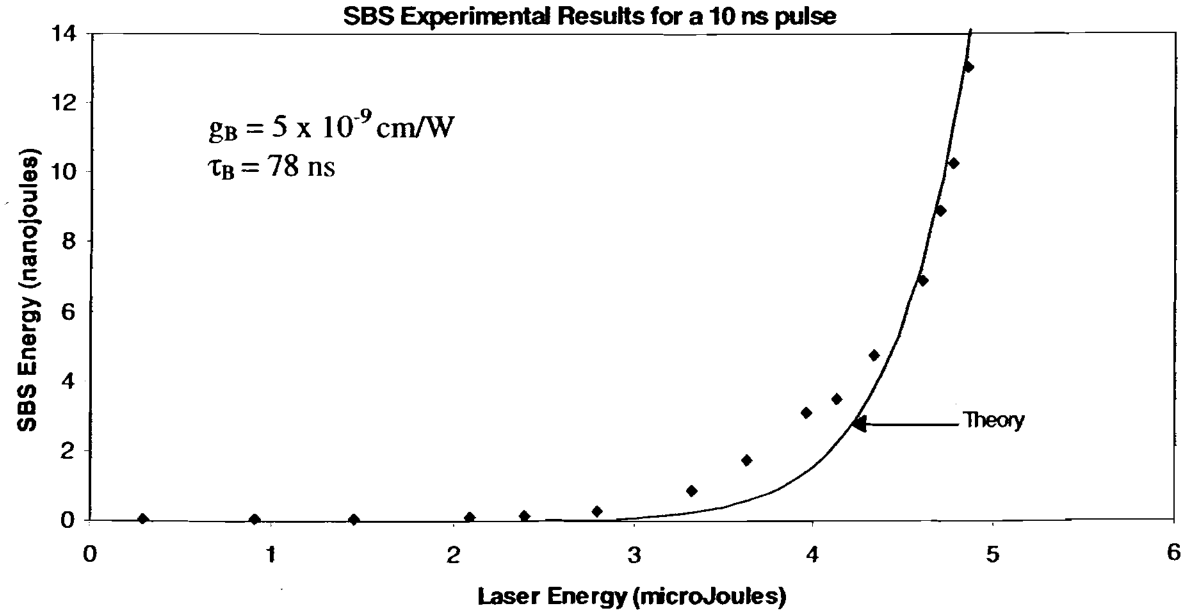


Fig. 2 – The theory shows good agreement with experimental results.

be able to analyze the SBS coming back out. This was achieved by using polarizers, a polarizing beam splitter, and a 45° Faraday Rotator as shown in Fig. 1. The polarizing beam-splitter directed the input pulse through the Faraday Rotator and into the fiber. The SBS was linearly polarized coming back so that it would not be reflected, but would instead pass through the beam splitter into the spectrometer, where it could be analyzed to ensure that it was at the correct frequency for SBS. The fiber under test was a single mode polarization-maintaining fiber from 3M (FS-PM-5121), with a mode field diameter of 7.2 μm.

We took a series of measurements, and fitted Eq. 1 to the experimental results by choosing an appropriate phonon lifetime. The results are shown in Fig. 2. The variables g_B and τ_B that gave the best fit could then be plugged back into Eq. 1 for varying pulse widths. These results are shown in Fig. 3.

Our results stayed well within the bounds of previous experiments, and showed that SBS

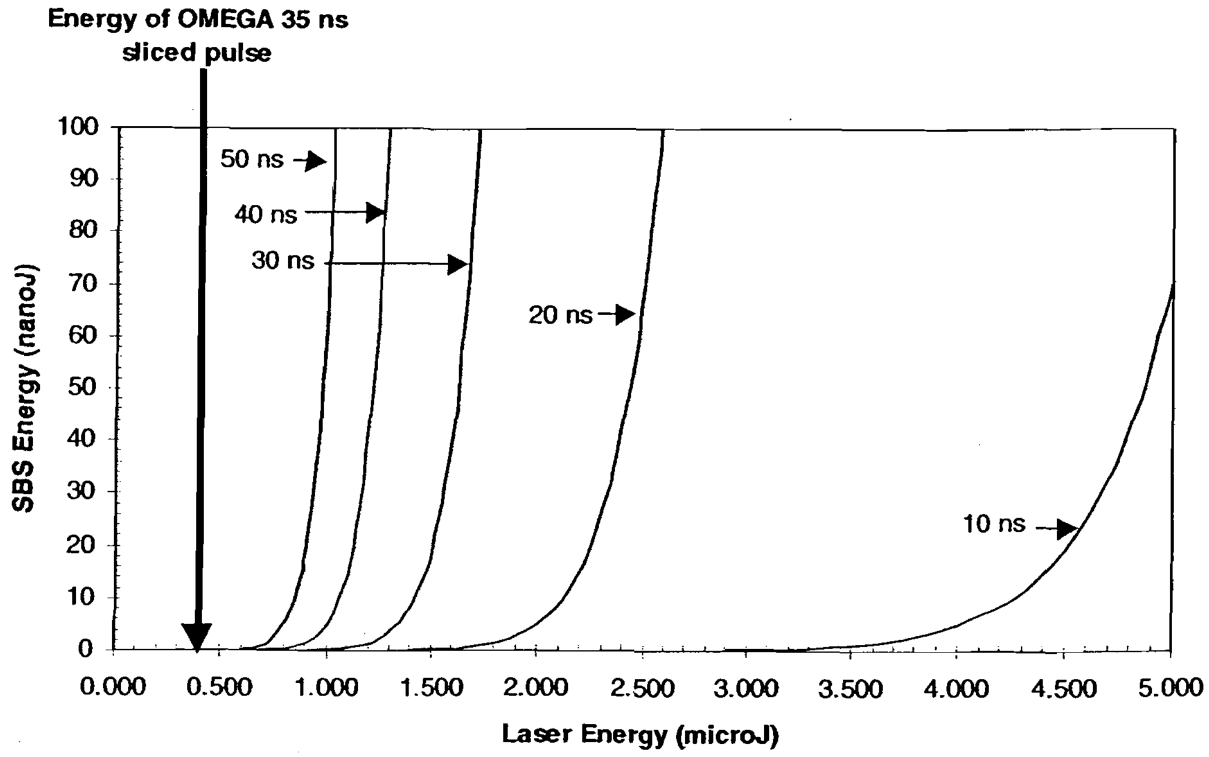
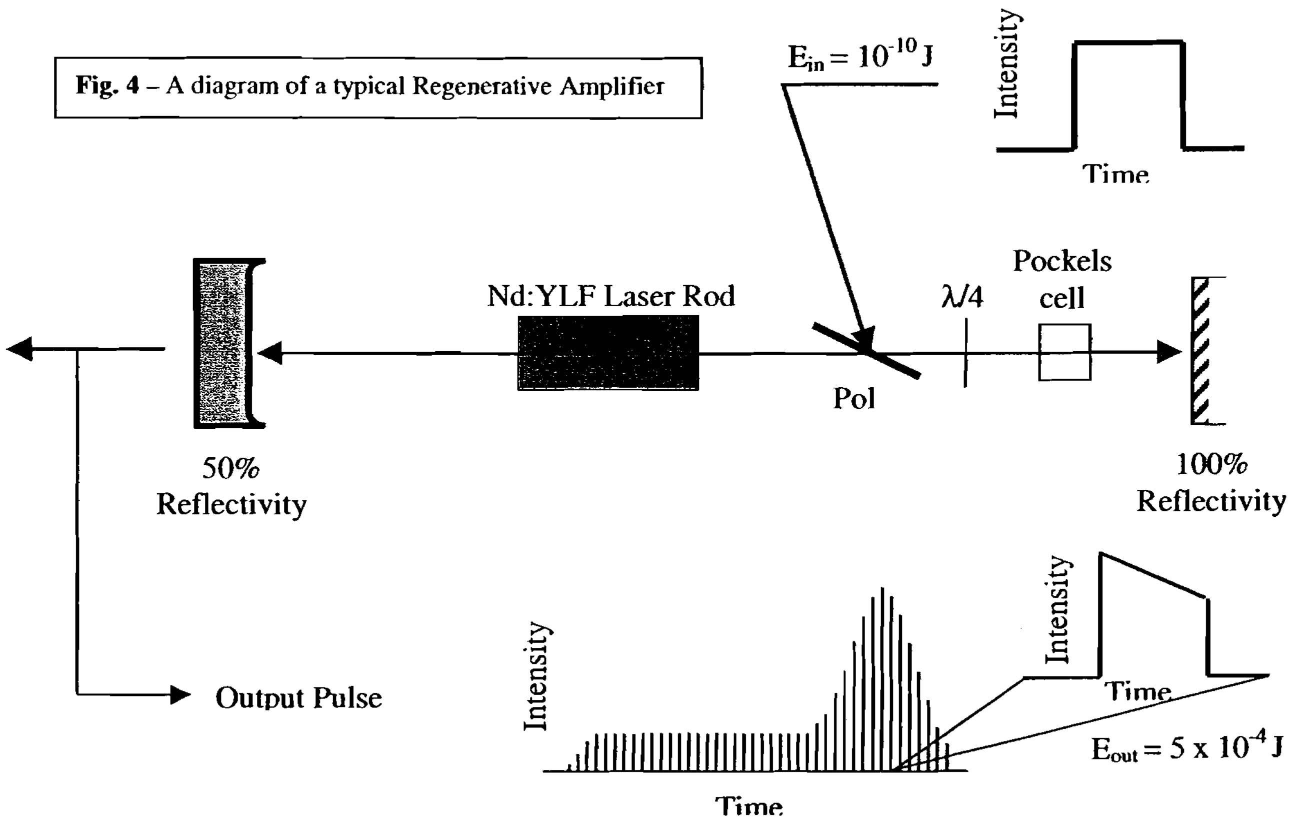


Fig. 3 – With current OMEGA energies, no pulse widths approach the SBS threshold.

was unlikely to become a problem with the short pulses (1-4 ns) generally used in the OMEGA system. Also, the current monomode laser energy (400 nJ) at which OMEGA is operating does not show significant amounts of SBS for greater pulse widths, such as the 40 or 50 ns pulse widths shown in Fig. 3.

II. Gain Gratings in a Regenerative Amplifier

Fig. 4 – A diagram of a typical Regenerative Amplifier



A regenerative amplifier begins with the injection of a shaped pulse, with energy approximately 0.1 nJ. That pulse travels through the cavity, receiving gain each time it goes through the laser rod. Also, each time it hits the output coupler (50% reflectivity mirror), a pulse is released from the amplifier. The other 50% of the pulse is reflected and receives more gain from the laser rod. The Pockels cell is used for feedback purposes and produces the shape of the output pulse train seen in Fig. 4. After many round trips through the cavity, the pulse reaches its peak, and is "switched out" of the pulse train to be used in the experiment. The output pulse is expected to have some square pulse distortion due to gain saturation, and experiences a gain of approximately five million. When the pulse width is longer than the round-trip-time between the end of the gain medium and the end mirror (6 ns), there are some unusual effects that are observed which have not been analyzed before. This pulse shape distortion can be seen in Fig. 5.

A theory is developed whereby gain gratings are set up in the gain medium for pulse widths greater than 6 ns, the beginning and the end of the pulse interfere with each other in the gain medium to form a standing wave. The standing wave forms a gain grating through the process of spatial hole burning, from which the light may then scatter. The greater the width of the pulse, the more time the standing wave is formed, and consequentially the stronger the effect. When the pulse reflects from the gain grating, it undergoes a π-phase shift[3], and so is subtracted from the electric field of the original pulse. Therefore, we see two reflections that are π phase shifted, displaced from the original pulse on either side by the round trip time from the gain medium to the nearest end mirror (which, in our case, is six nanoseconds).

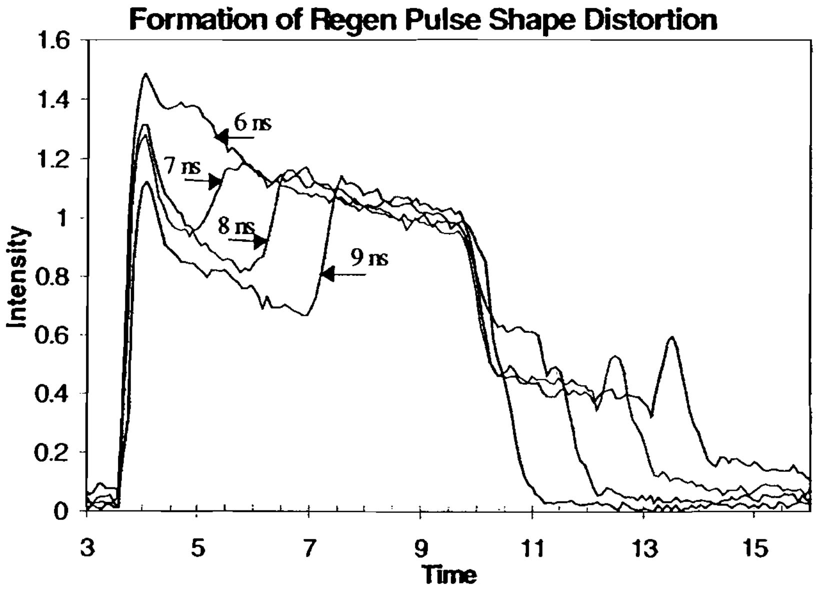


Fig. 5 – As the pulse shape grows longer than 6 ns, the regen pulse shape distortion becomes prominent

Let us consider the total electric field in the medium. The process is modeled as four waves in the classical four wave mixing setup shown in Fig. 6. The total electric field is the sum of the electric fields of all of the interacting waves as follows:

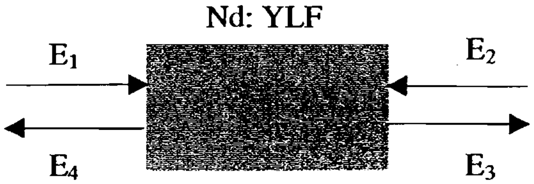


Fig. 6 – The gain grating resembles the traditional four-wave mixing effect.

$$E^T = E_1 + E_2 + E_3 + E_4\,. \tag{2}$$

We can write the wave equation for the total electric field in the gain medium as:

$$\frac{\partial^2 E^T}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E^T}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P}{\partial t^2} \tag{3}$$

where c is the speed of light, and P is the polarization of the material which is dependent on the susceptibility, χ, and the total electric field as follows:

$$P = \chi E^T \tag{4}$$

$$\chi = \frac{i2g}{k}\,. \tag{5}$$

In Eq. 5, i is $\sqrt{-1}$, k is the wave number, and g is the gain coefficient. Both k and g are defined as:

$$k = \frac{2\pi}{\lambda} \tag{6}$$

$$g = g_O \exp\left[-\frac{U^T}{U_S}\right] \tag{7}$$

where U^S is the saturation fluence, 0.7 J/cm^2 for the Nd:YLF laser rod we are using, λ is the wavelength of the laser (1053 nm), and U^T is defined as:

$$U^T = \int_0^t I'(z,t')\partial t'. \tag{8}$$

These equations cannot be solved analytically. They have been solved numerically[3], however we developed a model that simply takes into account the π phase shifted reflections of the gain gratings. This model is far from complete, but has been shown to model the experimental data to a high degree of accuracy.

This simplified program was designed which would reflect a certain percentage of the pulse off the gain grating for every round trip in the regen. There is also a transient effect as the very beginning of the pulse travels through the gain material. There is a transient reflection time on the very front of the pulse, for a period approximately equal to the time it takes light to pass through the gain material. This is due to scattering from a distributed gain grating as opposed to reflecting from a plane surface.

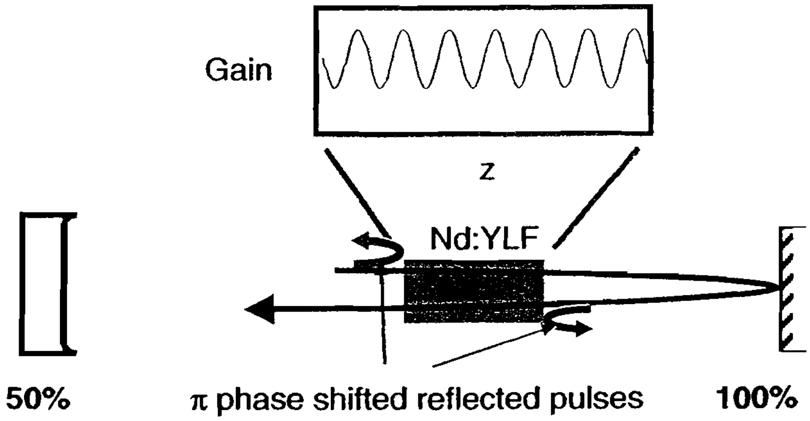


Fig. 7 – The front and back of the pulse both interfere in the gain medium to form a gain grating

In order to detect this phenomenon, we used the same regen design as is found in OMEGA, but we use longer pulses. The laser rod is about one meter from the end 100% reflecting mirror. The pulse exits through the 50% reflecting end mirror, and is cut out of a train of pulses. It then enters an optical fiber coupled detector (New Focus 1414) where it can be read by the Tektronix SCD 5000 oscilloscope.

Theory was calculated by using the process described earlier. A square pulse was created with a specified width. The square pulse (Fig. 8A) was then decreased by the reflectivity of the grating (taking into account a transient response time), amplified, combined with a later reflection (the later reflection is π out of phase, and therefore its electric field is subtracted from the electric field of the pulse). It is then reflected off of the mirror (some calculations involved a 50% rather than 100% reflecting mirror), reflected off of the gain grating (again with transient effects – this reflection has already been recombined with the pulse), amplified, and combined with the original reflection (which is, again, π-phase shifted). The three pulses produced can be seen relative to each other in Fig. 8B, and the output after one round trip can be seen in Fig. 8C. This process is repeated many times, as the pulse goes through many round trips in the regen. The pulse is then modeled as a function of intensity (i.e. E^2), rather than one of electric field, since the intensity is what is actually measured. Square pulse distortion is simulated by dividing the pulse into temporal sections and amplifying each section by a decreasing amount of gain. Finally, the pulse is convolved with a Gaussian in order to simulate limited bandwidth.

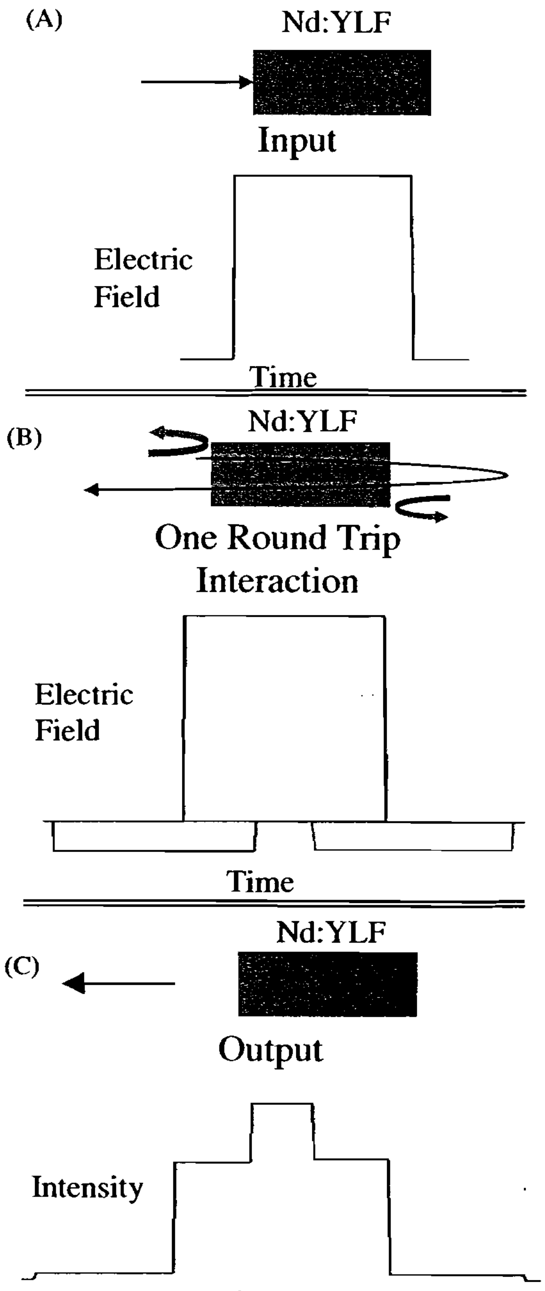


Fig. 8 – (A) is the pulse that is input into the regen; (B) shows the input pulse superimposed on the two reflected pulses; (C) shows the output intensity.

The theory calculated by the process above seems to match the experimental results well. For example, using a nine-nanosecond pulse and a grating reflectivity of only 0.03% and 20 round trips, Fig. 9 was produced. The experimental data matches up very

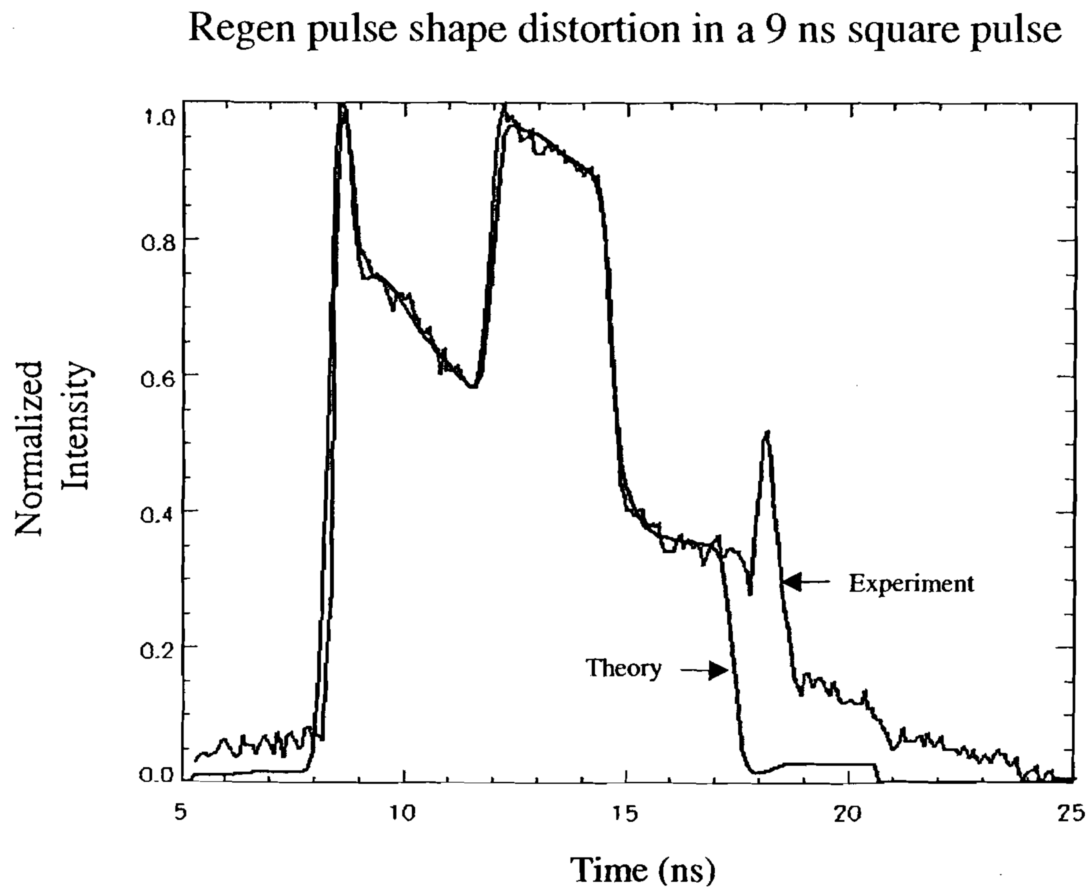


Fig. 9 – Theory based on the formation of a gain grating accurately models the regen pulse distortion, except for the peak on the trailing edge of the pulse

well with the theoretical curve, as you can see, with the exception of the nose seen at the end of the pulse. Seeing that this model is sufficient to describe the experimental data, we can put in some other data to determine the output under different conditions.

There are also many other effects that may be observed using this model, such as a dip or a stair step, simply by modifying some basic parameters, as you can see in Fig. 10. These models match other sorts of distortions which have been noted in the regenerative amplifier, and show that this model may have potential to explain them. However, since the model is still fairly inaccurate (there is a long list of properties which have not been taken into account), there are still some things which are not well understood, as well as some events which can not be accurately modeled.

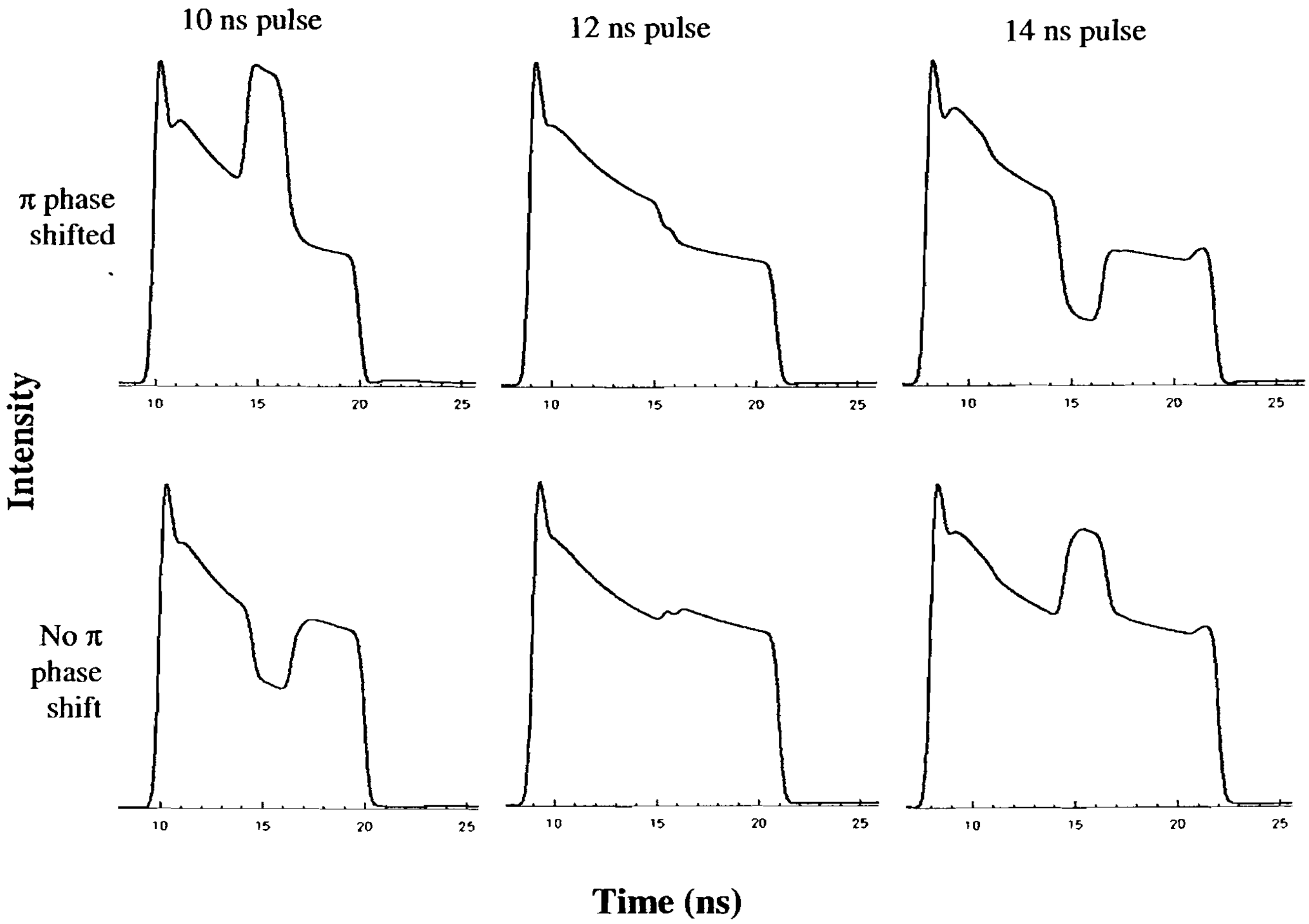


Fig. 10 – Different features are evident in each of these simulations of the regen pulse shape distortion. The round trip time of the simulated cavity is 6 ns

Clearly, the improved modeling of the OMEGA front end has led to identification and evaluation of the potential sources for pulse shape distortions. SBS is shown to be insignificant in OMEGA. More importantly, an accurate model for the pulse shape distortion in the regenerative amplifier based on a gain grating has been developed. This model may have the potential to explain other, more essential, sources of pulse shape distortion in the regenerative amplifier if improved on.

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