GENERATION OF GIGAWATT SUBNANOSECOND 1.06 μm PULSES BY REGENERATIVE AMPLIFICATION IN Nd:GLASS.

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A 0.1 μJ, 40 ps pulse, selected from a TEM₀₀ Nd:YAG master oscillator has been regeneratively amplified in a single 0.9 cm diameter gain module to the 100 mJ level while preserving both its temporal and spatial characteristics. Scaling of regenerative amplifiers to larger aperture 1.06 μm lasers is discussed.

At present Nd:glass lasers are capable of producing single subnanosecond pulses of higher power than any other type of laser [1]. Systems typically consist of a small oscillator, a pulse selection system and a number of stages of amplification. The amplifier stages increase in aperture as the power in the beam increases while high spatial frequency structure is removed between stages by image relaying spatial filters. Due to the large gain inherent in such system, isolation is required between some or all stages of amplification.

A second, and potentially simpler, option for achieving high power 1.06 μm radiation has been suggested [2,3]. In this scheme a pulse from a master oscillator is switched into a slave cavity where it is regeneratively amplified to the desired energy and is then switched out (fig. 1). Thus short regenerative amplifiers (or injection mode-locked oscillators as they are frequently called) would repetitively use the same gain medium, spatial filter and isolator and, in principle, could consist of only the largest amplifier stage.

Single ns pulse systems similar to the above have been demonstrated using CO₂ lasers [4–6]. At 10.6 μm the mode-locking problems were largely solved some time ago [7–9] and recent research has concentrated on improved high power optical switches for selecting single pulses from large aperture slave cavities

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Fig. 1. Experimental configuration used to investigate regenerative amplification.

[10]. At 1.06 μm, on the other hand, large aperture (~10 cm) Pockels' cells are commercially available, yet with but one exception [11] only small aperture (TEM₀₀ mode) injection mode-locked oscillators (in Nd:YAG) have been investigated [12–14]. (Long pulse regenerative amplifiers, often called injection locked oscillators [15] have been used on 1.06 μm

* Ref. [11] has only recently come to our attention. It appears to be the first published work on short pulse regenerative amplification. A number of technical difficulties were apparently experienced and the work was largely forgotten.
lasers fitted with unstable resonators. However, they
cannot provide a reliable guide for short pulse systems
due to nonlinear index of retraction (n2) effects.)
Clearly, large aperture mode-locking techniques must
be more fully investigated before regenerative ampli-
fiers can be used in high power, short pulse, Nd:glass
lasers.

The experiment described in this paper demonstra-
tes:
(i) high power short pulse regenerative amplifica-
tion in 1.06 μm lasers using a technique that is aper-
ture scalable,
(ii) control of the spatial structure of the output
from a slave glass cavity with injected radiation,
(iii) regenerative amplification of ~ 40 ps, ~10^3 W
pulses to a power of <10^9 W while maintaining an
A.S.E. level of <1 watt.

The experiment (fig. 1) was carried out using a pas-
sively mode-locked Nd:YAG master oscillator operat-
ed with a stable resonator formed by a 5 m radius of
curvature concave mirror and a plane output coupler
with 30% reflectivity. Mode-locking was achieved with
the aid of a 1 mm thick dye cell containing Kodak
9860 dye dissolved in dichloroethane in contact with
the output mirror. A typical TEM00 output from the
master oscillator consisted of a train of pulses (fig. 2a)
with a total energy of ~2 mJ. The duration of the in-
dividual mode-locked pulses varied from shot to shot
between ~25 ps and ~60 ps. A streak record of an
~25 ps pulse is shown in fig. 2c after up-conversion to
0.53 μm.

The slave cavity consisted of a 0.9 cm diameter
X 25 cm long ED2 glass amplifier and a KD*P Pockels’
cell between crossed polarizers. Filtering of the high
frequency spatial noise (about 18 cm^-1) was automati-
cally provided by the 0.9 cm aperture of the gain
module. A 100% and a 95% reflectivity mirror com-
pleted the slave cavity.

In operation ~20% of the output from the master
oscillator was used to trigger a laser-triggered spark gap
which, in turn, generated a rectangular voltage pulse
to open the electro-optic switch in the slave cavity.
This switch served simultaneously three functions:
1) Pulse selection. Before the Pockels’ cell was ac-
tivated all pulses entering the cavity double passed the
second polarizer and exited along the same path they
entered. After the Pockels’ cell was activated all pulses
were automatically dumped at the second polarizer.

Fig. 2. a) Oscilloscope trace of the output train of the master
oscillator. b) Oscilloscope trace of a single pulse dumped from
the slave oscillator. c) Streak record of a single pulse selected
from the master oscillator (or at the output of the slave). The
markers (○) are separated by ~25 ps.
Only those pulses that were in transit between the Pockels' cell and the 95\% mirror passed through the electro-optic switch and were subsequently regeneratively amplified. By placing the Pockels' cell a distance \( L_1 \approx T_m c/2 \) (1) from the 95\% mirror, it was possible to ensure that on most shots (depending on the rise time of the voltage pulses) only one pulse was selected. In eq. (1) \( T_m \) is the round trip cavity transit time of the master oscillator. The use of this configuration for pulse selection required some method of decoupling the master and slave oscillators [16]. This was achieved with an attenuator having 1\% transmission. When diffraction and other losses are included an estimated isolation of \( 10^5 \) was achieved between the two cavities. (Configurations where two or more Pockels' cells are used would not require this attenuator.)

2) \textit{Q-switching}. For regenerative amplification to be useful the injected pulse must be much more energetic than the (amplified) spontaneous emission already present in the cavity. For Nd:glass lasers this requires that the contrast of the Q-switch when closed, significantly exceeds the gain of the amplifier rod.

3) \textit{Cavity dumping}. As with the standard amplifier design, damage will occur due to self-focussing if the 1.06\,\mu m intensity becomes too high. In an amplifier chain this is controlled by minimizing the total gain path length of each stage for a given output. In addition to the above, a regenerative amplifier must be Q-spoiled to avoid runaway intensity build-up. In the present experiment the pulse was dumped with 100\% certainty at the second polarizer after \( n \) round trips through the gain medium. To insure this, \( L_2 \), the optical path length between the Pockels' cell and the 100\% reflectivity mirror, was adjusted such that

\[
L_2 \approx \frac{1}{2}(T_m + T_f)c
\]

(2)

(\( T_f \) is the fall time of the voltage pulse on the Pockels' cell) and the voltage pulse was applied to the Pockels' cell for a time \( t \) given by

\[
t = 2(n-1)(L_1 + L_2)/c + T_m.
\]

(3)

With \( 10^3 \) W injected into the slave cavity three round trip cavity transits were required to amplify the signal to the \( \sim 10^9 \) W power level. The natural beam divergence of the injected beam, coupled with whole beam self-focussing during the last two passes through the rod, were sufficient to fill the 0.9 cm aperture of the rod. In this configuration single pulses that were switched from the slave resonator contained \( \sim 100 \) mJ (fig. 2b) in 40 \pm 15 ps.

In order to estimate the underlying spontaneous emission the voltage pulse on the Pockels' cell was extended to allow 7 round trip cavity transits. With no injected signal, 10 mJ of amplified spontaneous emission (a Q-switched output) was observed. Using the measured net round trip gain of our system (\( \sim 100 \)) this implies that the energy contained in spontaneous emission at the time of injection is \( \sim 10^{-9} \) times the injected pulse energy. Such a figure corresponds to a spontaneous emission level of \( 10^{-6} \) W. Such a low level of spontaneous emission could permit the use of c.w. mode-locked oscillators as drivers for large aperture regenerative amplifiers.

The maximum energy that can be extracted from a short pulse regenerative amplifier is ultimately limited by the same constraints that apply to amplifier chains. This limitation is expressed by the so-called break-up integral \( B \) which is a measure of both the phase distortion which contributes to the whole beam collapse and also the logarithmic gain experienced by the most unstable spatial frequency [17]. For an ED2 glass rod of length \( L \), the \( B \) integral is given by

\[
B = 2.4 \times 10^{-13} \int_0^L I(Z) \, dZ \text{ radians} \quad (4)
\]

where \( I(Z) \) is the beam intensity at \( Z \).

In the small signal gain regime, neglecting any gain recovery considerations, the \( B \) integral may be expressed as

\[
B = 2.4 \times 10^{-13} \left( \frac{1}{f^2} \right) \frac{1}{\tau} \frac{1}{\alpha} E(L) \left( 1 - G^{-1} \right) \text{ radians}. \quad (5)
\]

Here, \( f \) and \( \phi \) the spatial and temporal fill factors respectively, \( A \) the area of the rod, \( \tau \) the fwhm pulse duration, \( E \) is the output energy, and \( G = \exp(\alpha L) \), the gain of the rod. In applications where it is necessary to focus the laser output onto a small target, it is imperative that most of the energy should be contained in a diffraction-limited focus. It is found that the maximum value of \( B \) at which the output energy can be effectively coupled to small targets is \( 4.5 \) [18]; however, temporal distortion of the laser pulse begins to occur at \( B > 2.5 \). In the regenerative amplifier, assum-
ing a single pass gain of 10 and an output energy of 100 mJ in a 45 ps pulse having spatial distribution of the form ~ exp\(- (r/r_0)^2\), the B integral contribution of the last pass through the gain medium is 2.7. Thus the output of the regenerative amplifier cannot be safely increased beyond the present levels without intracavity spatial filtering. It should be noted, however, that because of the small aperture of the gain medium and the relatively long slave cavity length, diffraction served to filter out spatial frequencies \(\nu_{\text{cutoff}}\) above

\[
\nu_{\text{cutoff}} \sim \frac{D}{2.44 L \lambda} \gtrsim 18 \text{ cm}^{-1},
\]

where \(D\) is the diameter of the smallest aperture in the slave cavity length \(L\) and \(\lambda\) is the wavelength of the radiation. According to linearised theory [17] the most unstable spatial frequency (i.e. the one which has the most gain) is given by

\[
\nu_{\text{max}} = (2k^2 \gamma I(Z))^{1/2},
\]

where \(k\) is the wavenumber and \(\gamma I(Z)\) is the fractional refractive index change \(\delta n/n\). For an energy output of 100 mJ in a 45 ps pulse, \(\nu_{\text{max}} = 115 \text{ cm}^{-1}\). Thus the most unstable frequency is effectively filtered by diffraction. The cut-off frequency \(\nu_{\text{cutoff}}\), however, does have \(\sim 20\%\) of the ripple gain of the most unstable frequency \(\nu_{\text{max}}\).

No attempt was made to measure either the temporal steepening or broadening of the frequency spectrum of the output pulse due to self-phase modulation. The streak camera record of the output pulse showed the same qualitative features as the injected pulse; however, the limited time resolution and up-conversion to second harmonic made quantitative measurements difficult. As in the case of an amplifier chain, regenerative amplifier parameters which minimise \(B\) also minimise the “built-in” self-phase modulation. An estimate shows that the temporal distortion of the injected pulse should not be too severe for our conditions.

It should be emphasized that, in our view, short pulse regenerate amplifiers can be applied even now to moderate (\(\sim 5 \text{ cm aperture}\)) Nd:glass systems. Two problems, however, remain to be resolved before larger aperture regenerative amplifiers can be operated with maximum efficiency.

1) Neither vacuum spatial filtering, nor image relaying were used in our experiment. Clearly image relay-