Regenerative amplification of picosecond pulses in Nd:YAG at repetition rates in the 100-kHz range

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An all-acousto-optically switched picosecond Nd:YAG regenerative amplifier has been developed for operation at pulse repetition rates in the 20–100-kHz range. The amplifier produces stable 50-ps pulses at 1064 nm in a TEM00 transverse mode with pulse energies of the order of 20–100 μJ. Generation of the second harmonic at 532 nm in KTP crystal results in conversion efficiencies greater than 40%. Using the frequency-doubled TEM00 output of the regenerative amplifier to pump a two-pass dye amplifier, we have amplified the 50-fs output pulses from an antiresonant ring dye laser to the 200-nJ level and have successfully produced a stable white-light continuum at a 100-kHz repetition rate. This preliminary demonstration of synchronous dye-laser amplification and continuum generation attests to the overall quality of the regenerative amplifier output and the general utility of this approach for high-repetition-rate amplification. Limitations of the current regenerative amplifier design and scaling to higher pulse energies are briefly discussed.

INTRODUCTION

Regenerative amplification is a well-established means of generating stable, high-power, synchronized optical pulses.1–12 Used in conjunction with chirped pulse amplification and pulse compression techniques,4–8 regenerative amplifiers are capable of generating ultrashort pulses with extremely high peak powers. In addition, they have proved particularly effective as pump sources for the synchronous amplification of ultrashort dye-laser pulses.13,14 An attractive feature of these devices is their potential for operation at high pulse repetition rates. The regenerative amplification process involves injection seeding a Q-switched resonator with a pulse from a master oscillator and subsequent cavity dumping of the amplified pulse at saturation. Gain and loss characteristics of the amplifier determine the pulse amplitude, but considerations regarding the buildup time for stable pulse formation are unnecessary since the output pulse is formed in the master oscillator. If the regenerative amplifier is continuously pumped, the maximum achievable pulse repetition frequency will be determined solely by the switching speed of the active elements in the cavity. Of course, for a particular resonator the relative pulse energy and average power at a given repetition rate will depend on the intrinsic properties of the gain medium. At pulse repetition frequencies less than the inverse storage time of the gain medium, the pulse energy will remain constant, and the average power will be inversely proportional to the repetition rate. On the other hand, when the pulse repetition rate exceeds the inverse storage time of the gain medium, the pulse energy will be proportional to the repetition rate, and the average power will remain constant. At these high repetition rates, the available pulse energy will be limited by the pumping rate of the gain medium and will simply scale with the maximum cw output power of the amplifier. Although the roll-off in gain for most commonly used solid-state materials (Nd:YAG, Nd:YLF) occurs for pulse repetition frequencies of the order of 2–5 kHz, the energy storage capabilities of these materials can still be exploited to provide reasonable gain well into the 100-kHz regime. Moderate pulse energies (at the 100-μJ level) at these repetition rates are desirable in a number of industrial and spectroscopic applications. In this frequency range and energy regime an ideal compromise is possible between the peak power necessary to enhance nonlinear optical processes and the ability to perform high-repetition-rate signal averaging.

Owing to the birefringence resulting from thermal effects and the acoustic ringing associated with the use of electro-optic crystals at high repetition rates, conventional cw pumped electro-optically switched regenerative amplifiers have been limited to repetition rates of the order of 1–6 kHz.9–11 Recent efforts to damp out the acoustic ringing have resulted in amplifier operation at repetition rates up to 10 kHz.12 In order to avoid the difficulties encountered with high-repetition-rate electro-optic switching, we have devised an all-acousto-optic (AO) switching scheme. Aside from the high speed and convenience of low-voltage operation, the substantially lower insertion loss of the AO devices compared with their electro-optic counterparts provides an important advantage for operation at repetition rates greater than the inverse storage time of the gain media. In this regime, cavity losses can dramatically affect the output pulse energy since the Q-switched system is operating much closer to threshold and shows a considerable reduction in gain compared with that found at low repetition rates.

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Using only AO devices, we have demonstrated stable regenerative amplification at pulse repetition rates in the 100-kHz range. Used as a synchronous pump source for our femtosecond dye laser amplifier, this device provides operation at repetition rates between that available with conventional electro-optically switched (0.5-10-kHz) solid-state regenerative amplifiers, or copper-vapor laser-based amplifiers (6-20 kHz), and megahertz dye amplifiers pumped by cavity-dumped ion lasers (1-4 MHz).

**EXPERIMENTAL SYSTEM**

An illustration of the regenerative amplifier is shown in Fig. 1. The amplifier cavity was formed from three high-reflectivity spherical mirrors, M1 (R1 = 10 cm), M2 (R2 = 20 cm), and M3 (R3 = 10 m), configured in a folded, astigmatically compensated resonator. For reasons to be discussed below, the optical length of the resonator was matched to within several hundred micrometers of the optical length of the 76-MHz master oscillator. A Spectron Systems 4-mm-diameter by 76-mm-long Nd:YAG rod/pump chamber assembly served as the gain medium. Using an optical cavity-design program employing the ABCD ray matrix method to calculate resonator parameters and cavity stability, we chose the mirror radii and distance between M1 and M2 to create an intracavity beam waist at the radius of M1 with a beam diameter of approximately 80-100 μm. The beam diameter in the YAG rod was selected to be of the order of 1.5-2 mm for optimum power and TEM00 transverse-mode quality. Computer analysis yielded two possible resonator configurations with regard to the position of the YAG rod assembly that possessed the desired resonator characteristics. The stability and characteristics of both resonator configurations were verified experimentally. Rod placement near M3 was found to be far less sensitive to misalignment, have much better beam pointing stability, and result in better overall mode quality. In addition, it permitted a convenient course adjustment of the intracavity beam waist and rod spot size over a wide range of values by selection of the M3 radius. Increasing the curvature of M3 allowed the spot size at the intracavity focus to be decreased with a corresponding increase in the spot size in the YAG rod. Small (2-cm) adjustments of the rod position over a range of 10-12 cm then permitted fine tuning and optimization of the resonator parameters.

A fused-silica AO Bragg cell (Harris H101) oriented at Brewster's angle was inserted at the beam waist near M1. The Bragg cell was used both to switch in the mode-locked seed pulse and to dump the amplifier output pulse. The relatively large spot size used in the cavity dumper allowed the anticipated energy density at the focus to be kept below the optical damage threshold of the cell. A second quartz AO device (Intra-Action AQS504A) was used to switch the amplifier simultaneously on pulse injection. We restricted oscillation to the TEM00 mode by inserting a limiting aperture approximately 1.5 mm in diameter in the cavity. Custom rf drivers and synchronization electronics for both AO devices were obtained from Camac Systems, Inc. In order to obtain the required diffraction efficiency at 1064 nm in the cavity-dumper Bragg cell, we boosted the rf output pulses from the Camac Systems cavity-dumper driver to 20-W peak power with an additional broadband rf amplifier (Amplifier for Research 10W100A).

The master oscillator in our experiment was a cw lamp-pumped, mode-locked, Nd:YAG laser. It was constructed from a 20-W cw Spectron Nd:YAG laser reconfigured in an asymmetric resonator with a 50-cm-high reflector and a 20% 4-m output coupler. The YAG rod and the mode-locker crystal were placed near the high reflector and the output coupler, respectively. An intracavity aperture placed between the high reflector and the YAG rod restricted oscillation to the TEM00 mode. The oscillator was amplitude modulated at 76 MHz with an actively stabilized standing-wave AO modulator (Newport EOS N10038) by using a Camac ML4000 2-W mode-locker driver system. The mode-locked system produced pulses at 1064 nm with 1-2% peak-to-peak amplitude stability and average powers of 15-20 W. Using a 20-ps rise-time Antel photodiode with Tektronix plug-in sampling units (7T11A, 7S11) and an S-6 sampling heat (30-ps rise time), we found the mode-locked pulses to be of the order of 50 ps FWHM after deconvolution of the detector response (see Fig. 2). Timing jitter between mode-locked output pulses from the master oscillator was minimized through an additional optoelectronic feedback system (Camac PS6000) based on a modified Cotter type21 phase stabi-
lization scheme. Dc coupling of the real-time phase error detection used in this system ensured stable operation over long time periods without the timing drift often associated with rf mixer-based phase stabilization electronics. Typical phase noise reduction was approximately 20 dB from dc to 500 Hz and decreased to 10 dB at 1 kHz. Long-term timing stability (of a several-hour time scale) with this approach was limited primarily by drift in the resonator length of the mode-locked oscillator. In principle, the maximum long-term stability achievable with this phase stabilization technique depends ultimately on the temperature stability of the emitter coupled logic components used in the feedback loop and the stability of the rf crystal oscillator used in the mode-locker driver.

Approximately 100 mW of the 1064-nm beam was used for injection seeding the regenerative amplifier. Synchronization between the mode-locked master oscillator and regenerative amplifier was ensured by deriving all the rf and timing signals from the same 38-MHz mode-locker frequency source.

AO injection was accomplished by mode matching the input beam to the amplifier resonator and propagating it along the same path as the diffracted output beam from the Bragg cell. A permanent-magnet Faraday isolator was used to separate the amplified and injected pulses and to decouple the master oscillator from the regenerative amplifier. Unlike in previous pulse-switching schemes that use an AO Q switch for pulse injection, the fast rise time of the Bragg cell permits single-pulse injection without the need for an additional pulse selector.

A critical parameter that one must consider when using this type of AO switching scheme is the spot size of the amplified beam in the Bragg cell. Given that it should not exceed the dimensions of the acoustic column, the optimum spot size is determined by a compromise between the maximum allowable energy density in the cell and the required Bragg cell rise time for single-pulse dumping. The use of a double-pass optical geometry with integer + 1/2 rf timing relaxes the spot size constraint by exploiting an optical interference effect to increase the single-pulse diffraction efficiency and suppress the preceding and trailing pulses. In the double-pass configuration, both the diffracted and the undiffracted portions of the incident beam are retroreflected back through the Bragg cell by the curved end mirror to interact a second time with the acoustic wave. The superimposed beams interfere to produce the diffracted output. The phase and frequency shifts accompanying the AO interactions result in an amplitude modulation of the diffraction efficiency with a beat frequency equal to twice the cavity-dumper acoustic frequency. Setting the carrier frequency of the rf driver for the Bragg cell equal to an integer + 1/2 of the mode-locker drive frequency allows the modulation envelope to be synchronized with the mode-locked pulse train such that the diffraction is maximum when the desired pulse from the mode-locked train is incident upon the Bragg cell. When this condition is satisfied, the preceding and trailing pulses are automatically centered at the diffraction minima. Theoretically, 100% of the selected pulse energy can be diffracted in or out of the amplifier cavity with a maximum single-pass diffraction efficiency of 50% by using this technique. An example of single-pulse selection by double-pass AO diffraction with integer + 1/2 timing is shown in Fig. 3. The diffraction efficiency is limited to 70–75% by the available rf drive power and the low acoustic figure of merit of fused silica. By overdriving the rf power amplifier we could increase the diffraction efficiency, but ringing in the rf amplifier distorted the rf pulse envelope, and the single-pulse contrast ratio was degraded.

RESULTS AND DISCUSSION

Actual operation of the regenerative amplifier can be described as follows: a rf pulse of sufficient duration and power is supplied to the AO Q switch to hold the amplifier below threshold until the inversion reaches its maximum value. As the amplifier is Q switched, a single 50-ps pulse from the master oscillator is injected into the resonator by supplying a short (<8-ns) rf pulse to the Bragg cell. When the internal pulse energy reaches its maximum, a second short rf pulse sent to the Bragg cell switches the energy out of the cavity. This sequence of events is illustrated in Fig. 4. The phase of the rf carrier and the timing of the RF pulse envelope used to drive the Bragg cell are optimized electronically to maximize the diffraction efficiency and single-pulse contrast of the injected seed pulse. The timing of the second rf pulse is controlled through an adjustable electronic delay, while the relative phase of the circulating pulse with respect to the acoustic field is controlled by the fine adjustment of the amplifier resonator length. Since the timing pulses are digitally derived from a synchronous timer driven by the 38-MHz crystal oscillator used in the mode-locker driver, drift in the setting of the electronic delay is negligible. An example of regenera-
Fig. 4. Timing sequence of events for acousto-optically switched regenerative amplification. At \(t_1\) the rf power to the Q switch is turned off; at \(t_2\) a seed pulse is injected into the amplifier resonator by application of a short, 8-ns rf pulse to the Bragg cell. The injected pulse is then amplified and cavity-dumped at \(t_3\) by application of a second rf pulse to the Bragg cell. At \(t_4\) the rf power to the Q switch is turned on. The transition time for the Q switch is 250 ns. All delays between events are electronically adjustable and optimized for operation at a given pulse repetition frequency.

Fig. 5. Oscilloscope trace of the intracavity leakage light through mirror M2 sampled by a fast photodiode, illustrating the Q-switch envelope during regenerative amplifier operation at 100 kHz without cavity dumping. The horizontal scale is 50 ns/division. The separation between pulses is the 13-ns round-trip time of the amplifier cavity.

Fig. 6. Simultaneous outputs from two fast photodiodes during regenerative amplifier operation at 100 kHz, including cavity dumping. Top trace: intracavity leakage monitored through M2 during cavity dumping. Bottom trace: cavity-dumped output pulse. Additional postpulses are primarily a result of photodiode ringing and distortion caused by overdriving the high-power rf amplifier for the Bragg cell. The scale is 50 ns/division.

Fig. 7. Oscilloscope traces of 100-kHz regenerative amplifier output with the horizontal scale expanded. Top trace: 2-ns/division scale illustrating the high-power contrast of a single output pulse. The cavity round-trip time is 13 ns. The preceding pulse was not detectable under the measurement conditions. Bottom trace: 200-ps/division scale illustrating detector-limited response to a single-amplifier output pulse.
under conditions in which the integrity of the rf pulse envelope was undistorted. The rf timing was adjusted to completely eliminate the prepulse. At this rf power level (65% diffraction efficiency) the postpulse at twice the round-trip time (26 ns) seen in Fig. 4 was also not observable. The use of a broadband high-power amplifier designed to deliver 30- or 40-W peak power pulses into a 50-Ω load should permit 100% of the amplified optical pulse to be cavity dumped with minimal distortion and maximum single-pulse contrast. Owing to the short rf pulse width and correspondingly low duty cycle used in this application, the overall thermal stability and performance of the cavity-dumper Bragg cell should not be compromised by this increase in rf power. Rf peak power levels as high as 100 W have been used in Nd:YAG cavity dumpers incorporating traveling-wave AO quartz modulators at repetition frequencies up to 2 MHz without adverse affects on dumper stability.29

The lower trace in Fig. 7 illustrates the detector-limited response to the amplified output pulse. Examination of the amplified output with a 20-ps rise-time Antel photodiode with Tektronix plug-in sampling units (7T11A and 7S11) and an S-6 sampling head yielded an oscilloscope trace essentially identical to that shown in Fig. 2 for the seed pulses. A more detailed investigation of the spectral and temporal properties of these pulses will be of interest. The high peak intensities encountered at the beam waist in the fused-silica Bragg cell may result in self-phase modulation and frequency chirping of the amplified pulses. Subsequent compression of the output pulses may then be possible. The feasibility of exploiting this phenomenon will certainly increase as the pulse energy is scaled to higher values or substantially shorter-duration pulses are injection seeded into the amplifier. (The gain bandwidth of YAG should support pulses of the order of 8–10 ps, although, alternatively, a totally different gain medium with a broader bandwidth could be used in the system.) Although the same intensity levels required for self-phase modulation can also cause spatial modulation of the pulse profile and self-focusing effects, the relative magnitude of this effect can be greatly minimized in a stable resonator constrained to oscillate in a TEM_{00} mode with an intracavity spatial filter. An estimate of the importance of these nonlinear-optical effects can be obtained by calculating the integrated nonlinear index of refraction along the beam path of the amplified beam. At a given pulse energy this can be done by evaluating the B integral.27,28

For high-power laser systems, the value of the B integral must be less than approximately 5 to prevent severe self-focusing effects. Above this value, high-spatial-frequency components are preferentially amplified and must be removed by spatial filtering to avoid optical damage. At the TEM_{00} mode intensities encountered in these experiments, the value of the multipass B integral is estimated to be less than or equal to 1.5 at the 100-μJ level. We do not observe any noticable degradation of beam quality either in the fundamental output of the amplifier at 1064 nm or in its externally generated second harmonic at 532 nm that would indicate any sign of spatial pulse distortion or self-focusing effects.

A plot of the output energy per pulse and the average power of the regenerative amplifier as a function of repetition rate in the range from 20 to 100 kHz is displayed in Fig. 8. As expected, the pulse energy decreases monotonically, while the average power remains essentially constant. Seventy-five percent of the available energy was switched out of the cavity with a peak-to-peak pulse stability on the order of four to five percent across the range. To avoid the possibility of damage while collecting the data for this plot, we reduced the average output power with an intracavity aperture to approximately 1.5 W at a 100-kHz pulse repetition rate. The average cw power, measured under these conditions by replacing M3 with a 20% output coupler and turning off the Q switch, was approximately 1.8 W. For stable operation the Q-switch duty cycle and relative timing between events were adjusted to maximize the pulse energy at each pulse repetition frequency. The slight decrease in average power with repetition rate below 70 kHz is believed to be correlated with the observation of non-phase-matched second-harmonic generation in the fused-silica Bragg cell. Ideally, this nonlinear process could be avoided by a slight increase in spot size as the repetition rate is reduced. The spot size was kept at approximately 80 μm for these experiments but could easily be optimized for each repetition rate by repositioning the pump chamber in the cavity.

![Fig. 8. Energy per pulse and average power of the regenerative amplifier as a function of repetition rate. Filled circles are the measured energy per pulse, and triangles are the average power.](image)
performance specifications for Spectron pump chambers in reasonable average power expectation based on proportional increase in output pulse energy. This is atracted from the amplifier resonator and result in a pro-TEMo, mode powers of the order of 10-20 W to be ex-
resent Spectron pump chamber should allow average
resonator. Use of a higher-quality Nd:YAG rod in the Q-switch pulse envelope was used as a diagnostic for
erably degraded. The observation of this modulation on
Fig. 9(b) and a uniform Q-switched pulse train amplitude.
Although the single-pulse output energy of the system is
put pulse train when the amplifier is allowed to run at 100 kHz
with multitransverse modes as a repetitively Q-switched oscillator. (b) Intracavity leakage monitored through M2 on a fast photodiode, illustrating the modulation of a Q-switched envelope when the multimode oscillator is injection seeded. Under this condition, pulse alternation is no longer observed in the relative output pulse amplitudes.
Modeling of the repetition-rate dependence of the output
pulse energy as a function of the amplifier parameters is
under way. It is anticipated that the pulse-energy-versus-
repetition-rate dependence will scale with cw output power in a manner similar to that found for continuously pumped, repetitively Q-switched lasers.29
In the current amplifier system, the maximum achievable pulse energy at a given repetition rate was severely limited by the small fraction of the available cw multimo-
mode power that was obtainable in the TEMoo mode. The unexpectedly low fundamental mode power appeared to be a manifestation of poor Nd:YAG rod quality. Without careful adjustment of the intracavity aperture, the amplifier had a strong tendency to run multimode. Manifestations of this behavior are shown in Fig. 9. The pulse-to-pulse amplitude alternation shown in Fig. 9(a) is a characteristic feature observed in high-repetition-rate Q switching of multitransverse mode lasers. This results from the existence of a subset of oscillating modes that compete effectively for gain only every other period of the driving cycle.30 The alternation does not occur in the case of a laser running in a single transverse mode. Injection locking the laser while it is running multimode results in the modulation of the Q-switched envelope shown in Fig. 9(b) and a uniform Q-switched pulse train amplitude. Although the single-pulse output energy of the system is increased several-fold under these conditions (for example, >100 mJ/pulse at 100 kHz), the overall stability is considerably degraded. The observation of this modulation on the Q-switch pulse envelope was used as a diagnostic for adjusting the TEMoo mode quality within the amplifier resonator. Use of a higher-quality Nd:YAG rod in the present Spectron pump chamber should allow average TEMoo mode powers of the order of 10-20 W to be extracted from the amplifier resonator and result in a proportional increase in output pulse energy. This is a reasonable average power expectation based on performance specifications for Spectron pump chambers in standard resonators with Nd:YAG rods specifically selected for cw TEMoo operation. At the pulse energies achievable at these average power levels, the amplifier output will probably be limited by optical damage to the surface of the fused-silica Bragg cell.
To demonstrate the general potential of the current ampli-
ifier system for use in femtosecond pulse amplification, the second harmonic was generated by using a 5-mm KTP crystal. Conversion efficiencies >40% were obtained in a high-quality TEMoo beam. Using only 3-4 μJ of the 532-
nm output at 100 kHz for synchronous pumping of a two-
pass dye-jet amplifier, we synchronously amplified the 50-fs, 610-nm output of a cavity-dumped antiresonant-
ring hybridly mode-locked dye laser to energy levels of the order of 150-220 nJ. At the 5-7% level of gain extraction efficiency, the dye-amplifier gain scaled linearly with the input pulse energy. Under these conditions, the amplified output pulses had essentially the same temporal and spectral profile as the unamplified dye-laser pulses. The dis-persion uncompensated 50-fs output from the dye amplifier was then focused into a 2-mm cell of water with a 10× microscope objective, and a stable white-light continuum was generated at a 100-kHz repetition rate. Essentially 100% conversion efficiency of the amplified dye pulse to the white-light continuum attested to the near-transform-limited character of the 50-fs amplified pulses and the general utility of the acousto-optically switched regenerative amplifier for high-repetition-rate femtosecond pulse amplification.
CONCLUSIONS
We have successfully demonstrated regenerative amplifi-
cation of 50-ps Nd:YAG pulses to the 20-100-μJ level at pulse repetition rates of the order of 100 kHz, using an all acousto-optically switched amplifier. At these high repetition rates, the pulse energy is limited by both the time required to reestablish the inversion and the intracavity loss. Consequently, the maximum achievable pulse energy is determined primarily by the average TEMoo power that the amplifier resonator can deliver. The major limitation of the current amplifier design with regard to energy scaling is a consequence of the spot size required for the amplified beam in the AO Bragg cell and the resulting potential for optical surface damage at high pulse energies. In these initial investigations all commercially available components were used. The use of custom-designed Bragg cells fabricated from fused silica with well-cleaned, highly polished surfaces would certainly have a large effect on this potential problem. An ion-milled piece of highly polished fused silica, for example, can have a surface damage threshold in the 50-100-J/cm² range31 compared with the 3-20-J/cm² range typical of most standard polished fused-silica surfaces.32 Despite these energy scaling considerations, we have established the feasibility and the general utility of solid-state regenera-
tive amplification at pulse repetition frequencies in the 100-kHz regime. The availability of new solid-state gain media along with rapid advances in electro-optical and acousto-optical switching technology promises to make high-repetition-rate solid-state regenerative amplification an important new technology.
REFERENCES AND NOTES

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