Gain-switched, all-acousto-optic, femtosecond pulse amplifier

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The design and performance of a gain-switched, all acousto-optic (AO) Ti:Sapphire regenerative laser amplifier is presented. An AO Bragg cell is used to send pulses into and out of the amplifier cavity, and an AO modulator serves as an active isolation device. Pumping the high-*Q* amplifier with a short duration (~40 ns) 532 nm pulse allows gain-switched operation in which the seed pulse dominates the amplified spontaneous emission; no *Q* switch is required. The amplified pulse energy is >110 μJ at a 4 kHz repetition rate, and the compressed pulse duration is ⩽50 fs. Detailed measurements are reported demonstrating that this design facilitates low-noise operation. [DOI: 10.1063/1.1619581]

Titanium-doped sapphire has been the workhorse laser and amplifier medium of ultrafast spectroscopy since the recognition of its suitability in the 1990's. The latest generation of amplified Ti:Sapphire laser systems produces terawatt peak powers, generating sub-20 fs pulses with energies in the millijoule range[1–3] at multikilohertz repetition rates.[4] The development of such systems has been driven by ultrafast high-harmonic/x-ray generation, high-field measurements, and now attosecond science.[5] While many can fit on a "table-top," most are multistage systems with sophisticated pulse compression schemes. Conversely, the technological requirements for ultrafast electronic spectroscopy[6,7] are decidedly more modest: the laser system should be as simple and as flexible as possible, generate sufficient energy to perform basic frequency conversion processes, maintain short pulse durations, and provide low-noise operation.

This note presents a unique Ti:Sapphire regenerative amplifier that attains these characteristics. The design is modeled after a cavity-dumped oscillator,[8] combining the simplicity of that cavity design with the flexibility of regenerative amplification. Gain-switched operation and use of acousto-optic (AO) devices minimize the number of optical elements inside the amplifier cavity and actively isolate the amplifier from the seeding laser. The amplifier is pumped with a low-noise diode-pumped, frequency-doubled Nd:YAG laser. The system provides modest per pulse energies (~100 μJ) and operates at a 4 kHz repetition rate so that signal averaging techniques, such as lock-in amplifier detection, can be utilized in experiments. The compressed pulses have energies sufficient for white-light continuum generation and frequency doubling, permitting pump–probe studies of samples absorbing from the near-UV to the near-IR with sub-50 fs time resolution.

Two AO devices are employed. First, an AO Bragg cell replaces the commonly used Pockels cell/thin-film polarizer combination to inject the seed pulse into and eject the amplified pulse from the cavity. This configuration presents several advantages.[9,10] Reflection losses in the amplifier are minimized since the Bragg cell is used at Brewster's angle. Furthermore, dispersion is reduced since a typical Bragg cell has a shorter material path length and is made of fused silica, a low refractive index material. Second, an AO modulator supplants the conventional passive isolation scheme—a Faraday rotator and polarizers—for directional rather than polarization-based discrimination of incoming and outgoing beams. The AO modulator is composed of a flint glass (SF8) that has lower and more well-determined dispersion than the terbium gallium garnet used in Faraday rotators (see EPAPS material[11] for a table comparing material dispersion in different amplifier designs).

The use of a diode-pumped, frequency-doubled, Nd:YAG laser as a pump laser further optimizes the amplifier. Shot-to-shot noise specifications of <1% can be achieved by diode-pumped systems. In addition, the short duration pulses (<40 ns) from diode-pumped lasers create rapid gain buildup that facilitates gain-switched, rather than *Q*-switched, amplifier operation. While a *Q* switch suppresses amplified spontaneous emission (ASE), it also introduces reflection losses inside the amplifier, thereby reducing the efficiency. Gain-switched operation also affords a further reduction in material dispersion; this design leaves only two transmissive optics in the cavity.

A schematic of the laser system is shown in Fig. 1. The seed pulse for the amplifier is provided by a four-mirror Ti:Sapphire oscillator (KM Labs TS-Laser) pumped by a frequency-doubled Nd:YVO_4 laser (Spectra Physics Millennia). The oscillator produces a 91 MHz train of 22 fs pulses with spectra centered at 800 nm. The pulses first pass through an all-reflective, single-grating stretcher with gold-coated optics. The gratings in the stretcher and compressor

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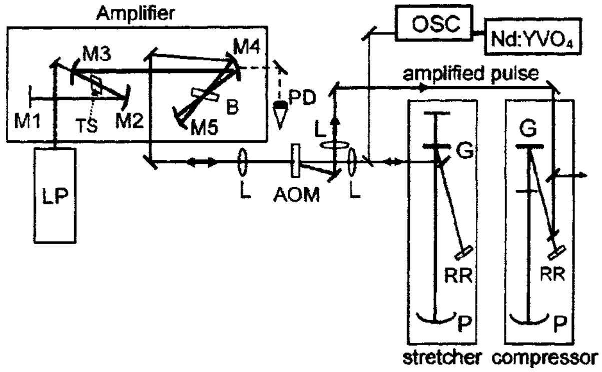

FIG. 1. Schematic of all-AO regenerative amplifier. M1—flat mirror. M2–M4—20 cm concave radius of curvature (ROC) mirror. M5—10 cm concave ROC mirror. TS—Ti:Sapphire crystal. B—Bragg cell. L—50 cm focal length (f.l.) lens. PD—photodiode. AOM—AO modulator. G—grating. P—17 1/2 in. f.l. parabolic mirror. RR—90° roof reflector. LP—Nd:YAG pump laser. $Nd:YVO_4$—$Nd:YVO_4$ pump laser. OSC—Ti:Sapphire oscillator.

have groove densities of 600 mm^{-1} and are blazed at 13.9° (Richardson Gratings). The stretcher and compressor designs are similar to those previously reported by Wynne *et al.*,[12] except that paraboloidal, rather than spherical mirrors, are used to eliminate spherical aberrations, and both are operated in an off-Littrow angle configuration to reduce clipping of the beam. A 90° roof reflector (PLX Inc.) is employed to reduce vertical spatial chirp by minimizing the deviation of the reflection angle from the grating normal. The stretched pulse length is ~90 ps.

After passing through the stretcher, the beam is gently focused into the AO modulator (Intra Action AOM 125). The diffraction efficiency of the AO modulator is 70% at full rf power. The gating window is ~75 ns long and is limited by the acoustic transit time across the diameter of the focused laser spot. The diffracted beam is collimated with a lens, identical to the focusing lens that mode-matches the size of the seed beam to that of the amplifier.

The regenerative amplifier cavity design is similar to that of a cavity-dumped oscillator,[8] but lacks a prism sequence.[9,10] All mirrors in the amplifier are broadband, low-dispersion dielectrics (CVI TLM2-800). The Bragg cell is placed at the focus of the M4–M5 mirror pair terminating the long arm of the cavity. ABCD matrix calculations show that this position allows a tight focus in the Bragg cell, yielding efficient diffraction and small pre- and post-pulses.[8] The amplifier is pumped by a Q-switched, diode-pumped, frequency-doubled Nd:YAG laser (Lightwave Electronics 210G) that produces pulses ~40 ns in duration. The pump pulse energy at 4 kHz is ~525 μJ.

The timing sequence of the rf and laser pulses is depicted in Fig. 2. The master frequency needed for synchronization of the amplifier electronics is established by the oscillator; light leaked through the high reflector end mirror is monitored by a fast photodiode. The repetition rate of the amplifier is set by a timing system (Camac TS 2004) that independently triggers the pump laser, AO modulator, and Bragg cell driver (Camac CD 5000) with rf power amplifier (Camac PB 1800). Independent phase control of the injection and ejection rf pulses sent to the Bragg cell is important for obtaining maximum amplified power and is achieved with a home-built circuit. In addition, properly timing the arrival of the pump laser pulse relative to seed pulse injection allows suppression of ASE. The pulse is ejected from the amplifier cavity after the maximum gain is achieved—in this case, after ten round trips. It is spatially separated from the incoming seed pulses as it passes through the AO modulator; on this pass, the modulator is off and the beam is therefore not deflected, allowing 100% of the amplified pulse energy to proceed to the compressor.

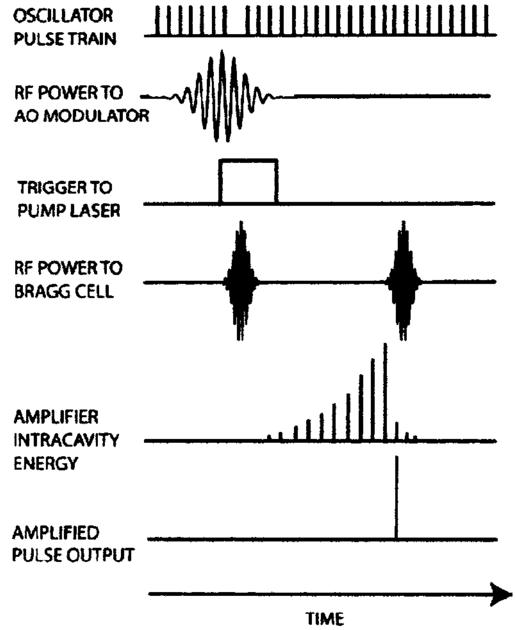

FIG. 2. Relative timing sequence for amplifier operation.

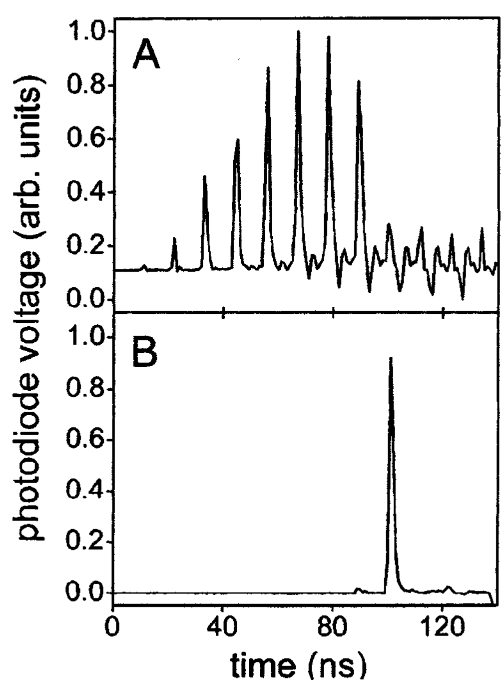

FIG. 3. (A) Amplified pulse profile in the amplifier cavity. (B) Profile of amplified pulse with contrast ratio of 37:1 (main to post-pulse). Data is normalized to a maximum of one.

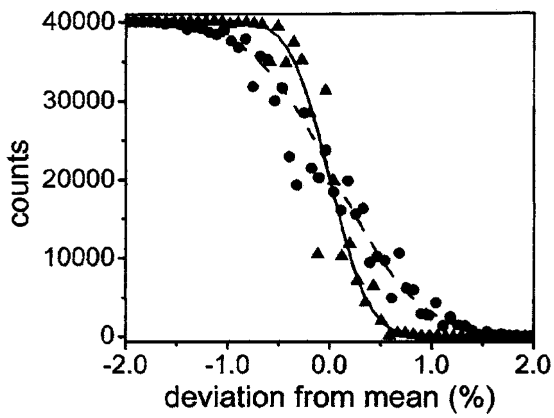

FIG. 4. Noise characterization of amplified and Lightwave pump pulses. Circles: Lightwave counts. Triangles: amplifier counts. Lines are fits of the deviation from the mean [as given by Eq. (1)]. Solid: Fit to amplified pulse data. Dashed: fit to Lightwave pulse data.

Light leaked through the dog-leg fold mirror is monitored by a fast photodiode; the intracavity pulse train is shown in Fig. 3(A). An ejection efficiency of 65% is observed in this case; efficiencies as high as 70% have been obtained. The contrast ratio between the main pulse and pre-/post-pulse is typically $\geqslant$35:1, as shown in the photodiode trace of an amplified pulse in Fig. 3(B). The ejected pulse energy of more than 110 μJ represents >30% gain extraction of the absorbed pump pulse energy and a gain factor of $>3\times 10^4$.

Amplified pulses then pass through a pair of BK7 prisms after the compressor for readily tunable compensation of group velocity dispersion and third-order dispersion (TOD) imparted by the stretcher and materials in the amplifier. This strategy is feasible due to the reduction of material dispersion by the all-AO design. For more dispersive amplifier designs, the required prism separation would be several meters long, necessitating the use of grating angle adjustments in the compressor for TOD minimization. The final pulse energy after recompression exceeds 30 μJ. The amplified pulses were characterized by self-diffraction frequency-resolved optical gating,[13] yielding durations of ~50 fs.

To characterize the intensity stability of the amplifier, the pulse intensity distribution was measured with a fast photodiode and a gated photon counter with a discriminator (Stanford Research Systems SR400).[8] The total number of pulses counted at each discriminator voltage yielded a distribution of pulse intensities; distributions for both the Lightwave and amplified pulses were measured. The counts are fit to the integral of a normal distribution, as shown in Fig. 4. The deviation of the counts from the mean is fit to the function:

$$F(x)=N\,\mathrm{erfc}\left[\frac{x-a}{b}\right], \tag{1}$$

where erfc is the complementary error function, N is the maximum number of counts, a is the mean, and b is the standard deviation. The standard deviation is 1.0% for the Lightwave pump laser and 0.5% for amplified pulses. That the amplifier shows less pulse intensity noise than the pump source suggests that saturation is achieved. The noise figure of the amplifier exceeds the stability of commercially available Ti:Sapphire regenerative amplifiers, which typically specify root-mean-square energy stabilities of $\pm 1\%$.[14]

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[11] See EPAPS Document No. E-RSINAK-74-035311 for a table comparing material dispersion in electro- and AO amplifiers. A direct link to this document may be found in the HTML reference section of the online article. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html) or from ftp.aip.org in the directory/epaps. See the EPAPS homepage for more information.
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