2.B Regenerative Amplification in Alexandrite of Pulses from Specialized Oscillators

In a variety of laser sources capable of reaching high energy levels, the pulse generation and the pulse amplification are physically divided among two or more subsystems. An oscillator generates a low-energy seed pulse with the appropriate temporal and spectral features; then, an amplifier stage increases the seed pulse to the desired energy level. When large gains are desired, numerous amplification stages may be required.

Regenerative amplification is an attractive way of limiting the size of the amplifier chain. A seed pulse is injected into a laser resonator that contains a gain medium. The pulse is amplified over many passes through the medium until the gain reaches saturation, and the pulse is then switched out of the resonator cavity. Ideally, the pulse's spectral and temporal characteristics are determined by the oscillator, while the energy output is a function of the regenerative amplifier alone. This technique has been applied to numerous laser media, either flash pumped[1-3] or cw pumped,[4,5] over the last decade. This article describes the use of an alexandrite flash-pumped regenerative amplifier to increase the energy of the output from various specialized oscillators.

Regenerative Amplifier

Alexandrite is a solid-state lasing medium with an output wavelength that can be continuously tuned over 700–810 nm.[6] Due to its very broad pump bands, long fluorescent lifetime (250 μs at 300°K), high saturation fluence (20 J/cm^2),[7] and low stimulated emission cross section (7×10^{-21} cm^2 at 300°K), alexandrite can store large energy densities efficiently. In addition, with its large lasing bandwidth it should be capable of amplifying pulses as short as 8 fs. Another favorable property of alexandrite is its low refractive index dispersion near the center of the lasing band.[8] However, because of the low stimulated emission cross section, it is difficult to obtain high gain. Single-pass gain of a typical alexandrite amplifier is between 2.0–6.0. In order to have a large overall gain, many passes through the active alexandrite medium are necessary. Regenerative amplification is one of the most elegant multipass configurations. This technique was first used to amplify low-energy mode-locked pulses in Nd-doped materials.[1,9]

Our regenerative amplifier consists of two high reflectors, the laser medium, a thin-film polarizer, a static quarter-wave plate, and a Pockels cell. For wavelength tunability off gain center, the alexandrite regenerative amplifier also incorporates a birefringent tuner or a pellicle. The 1.5-m-long resonator has a large TEM_{00} mode with a beam radius w_0 of approximately 0.5 mm. The amplifier could be operated at repetition rates as high as 30 Hz.

A single Pockels cell controls the injection of the seed pulse and the cavity dumping after amplification. The Pockels cell driver is described elsewhere.[10] The intracavity polarizer has a broadband coating (50 nm) and can be used in either transmission or reflection. For some experiments the static quarter-wave plate was found to produce a strong etalon effect. To overcome this, the Pockels cell alignment was adjusted to provide a quarter wave of static birefringence, removing the need for the separate quarter-wave plate.

Switching the Pockels cell to its quarter-wave voltage (double-pass retardation equal to half wave) injects a single pulse inside the cavity. The pulse is trapped between the two high reflectors and is amplified for 50 to 500 round trips. The pulse remains in the resonator until the signal from a photodiode that detects light transmitted through one of the end reflectors reaches a predetermined threshold value. A second voltage step is applied to the Pockels cell to cavity dump the amplified pulse.

Amplification of Nanosecond Pulses from a Narrow-Linewidth Dye Laser

To obtain very stable frequency output, cw pumping is usually required. The amplification of the low-power output from cw-pumped sources to power levels comparable to those obtained from pulsed solid-state lasers is in many cases desirable. To reach this goal, 5-ns slices from a cw dye laser were amplified in the alexandrite regenerative amplifier. A diagram of the experimental setup is shown in Fig. 34.25.

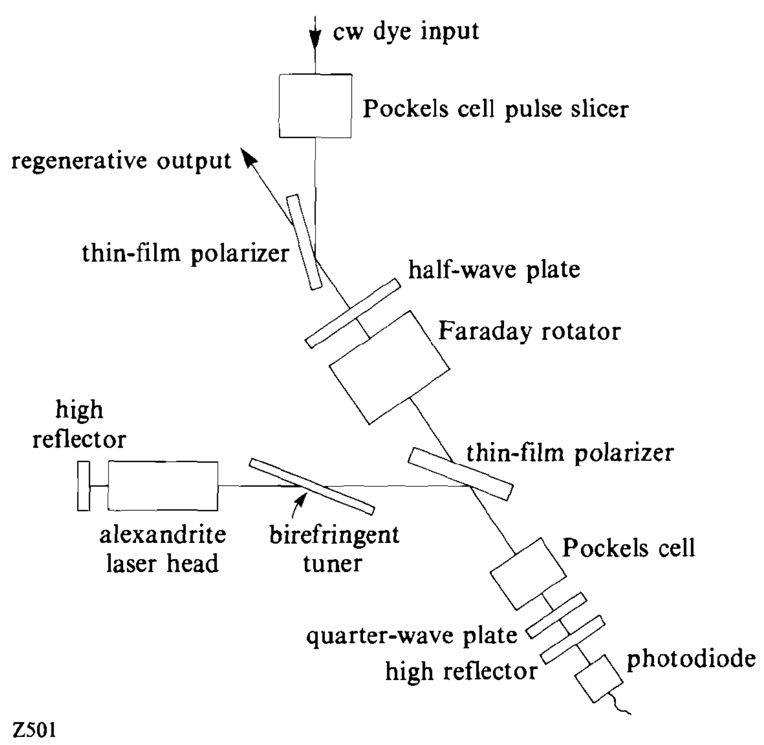


Fig. 34.25
Experimental setup for narrow-linewidth regenerative amplification.

The pulse slicer in Fig. 34.25 is a Pockels cell positioned between two polarizers; it provides a 5-ns transmission window. This device was found necessary since the intracavity Pockels cell does not provide sufficient contrast to prevent some light from the cw laser from leaking into the regenerative amplifier. This leakage forces the laser to operate as an injection-seeded oscillator rather than as a regenerative amplifier. The difference between these two processes is illustrated in Figs. 34.26(a) and 34.26(b). The temporal profile shown in Fig. 34.26(a) is typical of the alexandrite laser operating as a regenerative amplifier. The pulse, which is shorter than the cavity, is shown being amplified at each pass through the resonator, with a total single-pass amplification of 1.06.

If a fraction of the cw dye laser leaks into the resonator for a period longer than the time for a single-cavity round trip, then injection seeding occurs instead of regenerative amplification. In the injection-seeded mode, the pulse is longer than the cavity round-trip time, which creates a standing wave inside the resonator at one (or two) of the resonator modes. The spectrum of the output pulse is then governed by the resonator and is centered at one (or two) of the resonator axial modes. Injection seeding gives a long, smooth pulse buildup, as is shown in Fig. 34.26(b). The addition of the pulse slicer completely eliminates this injection seeding.

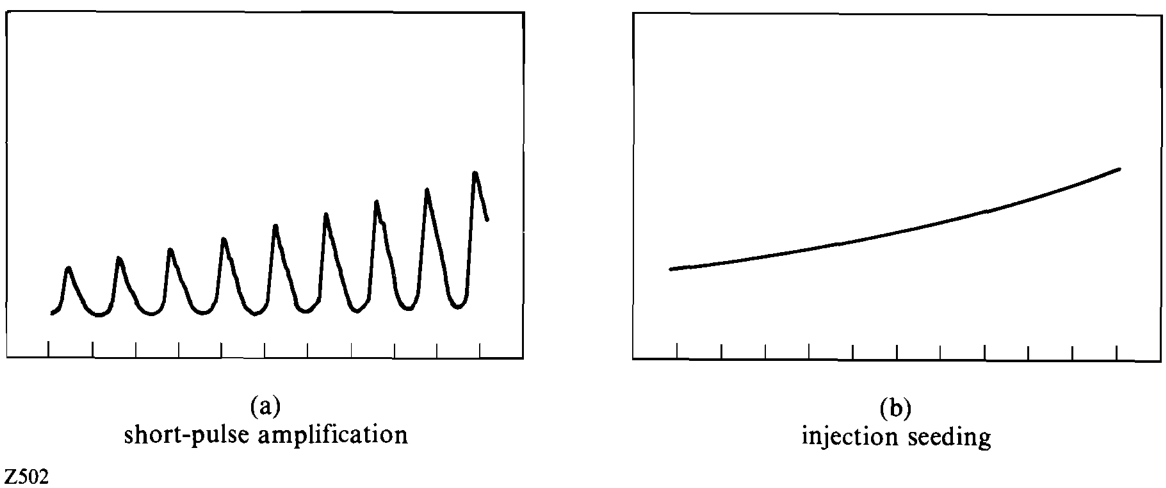
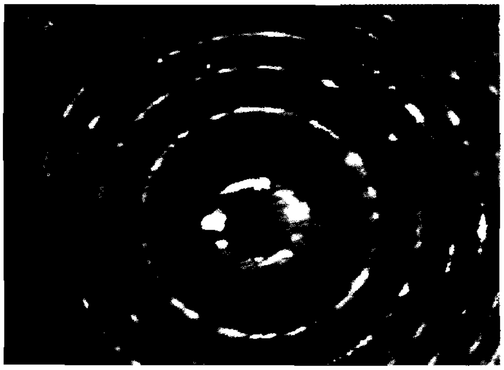


Fig. 34.26
Temporal output from narrow-linewidth regenerative amplifier.
(a) Light transmitted through one of the end mirrors showing the input pulse being amplified in the resonator.
(b) Smooth buildup is observed when the resonator is injection seeded.

The temporal pulse output has a pulse duration (FWHM) of approximately 5 ns. The Fourier transform limit for a 5-ns Gaussian pulse is 88 MHz. The spectrum of the amplified pulse as monitored by an air-spaced Fabry-Perot with mirror spacing of 10 cm is shown in Fig. 34.27. The spectral width was measured to be 100 ± 15 MHz.

The input energy of the pulse was approximately 1 nJ, while the output energy is 5 mJ in a clean TEM_{00} mode. Input energies as low as 10 pJ were amplified. All measurements were done initially at 755 nm, near the peak of the gain curve. When the frequency of the dye laser is tuned, the output of the regenerative amplifier follows. However, in order to tune far from the gain center of alexandrite, an intracavity broadband tuner, or a more energetic dye laser input than was available, is necessary.

Injection seeding[11,12] is one of the more common alternatives for obtaining reliable narrow-frequency output. This approach requires active feedback, however, and will probably have a lower frequency stability than our technique.



(a)
with narrow-linewidth input from a dye laser

(b)
without input

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Fig. 34.27
Spectral output from narrow-linewidth regenerative amplifier from air-spaced Fabry-Perot with 10-cm spacing: (a) with narrow-linewidth input from a dye laser; (b) without input.

Amplification of Picosecond Pulses from a Gain-Switched Diode Laser

We have also used our regenerative amplifier to amplify low-energy pulses from a gain-switched laser diode[13] (Sharp, model LT030MD) that lases at 755 nm. Streak-camera measurements of the diode pulse width show that the duration could be varied from 35 to 100 ps by changing the ratio of the RF input to the dc voltage bias. For this experiment, the pulse width was approximately 50 ps, as illustrated in Fig. 34.28.

Typical pulse energies from the diode were 1 pJ. The regenerative amplifier increased the pulse energy by ten orders of magnitude to 10 mJ. Energies as low as 100 fJ could be amplified but somewhat less reliably. The experimental setup was similar to that shown in Fig. 34.25, except that the single-frequency dye laser was replaced by the gain-switched laser diode and a second Faraday rotator and polarizer were also added. The laser diode is quite susceptible to optical damage from amplifier feedback; the two Faraday rotators are necessary to protect the diode. For 10 mJ of output energy, the required alexandrite flash-lamp input energy was 75 J. Better efficiency could be obtained if one of the end mirrors, which was an 80% reflector, were replaced with a higher reflector. The 80% reflector transmitted sufficient light for diagnostic purposes.

An alternative means of obtaining tunable 10- to 30-ps pulses in the millijoule range is by passively mode-locking alexandrite.[8,14] However, passive mode-locking is inherently noisy, while the regenerative amplification of a well-defined seed pulse can be controlled to a much greater extent. The regenerative amplifier is also more efficient than a passively mode-locked laser. It contains fewer intracavity elements and all the energy is accumulated in a single pulse rather than in a train of pulses.

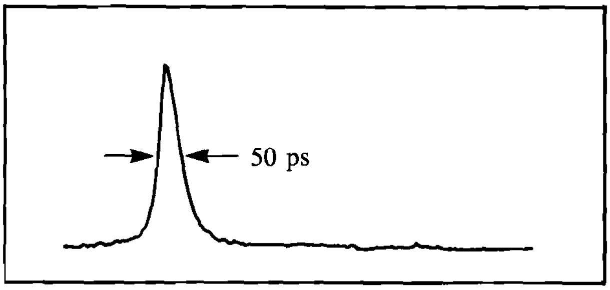

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Fig. 34.28
Temporal pulse shape from gain-switched diode measured with streak camera; FWHM of pulse is ~50 ps.

Amplification of Femtosecond Pulses from a Synchronously Pumped Dye Laser

Finally, we amplified subpicosecond pulses generated by a synchronously pumped, passively mode-locked dye laser. Traditionally, the amplification of ultrashort pulses has been based on the use of organic dye or excimer amplifiers. These systems offer the broad bandwidths needed to amplify subpicosecond pulses but suffer from low saturation fluences of the order of a few mJ/cm^2. The low saturation fluence restricts the utility of these media to low energy levels—although, in the case of excimer systems, scaling up of the aperture has allowed the generation of pulses approaching a terawatt.

Solid-state media such as Nd:glass or alexandrite have rather large saturation fluences, of the order of 5 to 20 J/cm^2. Coupled with their relatively long upper-state lifetimes, these materials have excellent energy storage capabilities. Until recently, however, ultrashort pulses could not take advantage of this capability of solid-state media. The high peak powers produced with subpicosecond pulses can quickly exceed the threshold at which nonlinear effects become significant and distort the spatial and temporal profiles of the pulses. This limits operation to fluence levels well below the saturation fluence. Consequently, the energy extraction efficiency of such systems has traditionally been low.

With the recent development of chirped-pulse amplification,[15] it is now possible to extract efficiently the energy stored in solid-state materials. Briefly, the peak-power limitation is overcome by stretching the pulses prior to amplification. These long pulses can then be amplified to saturation while a relatively low peak power is maintained. After amplification, the pulses are recompressed to their Fourier transform limit.

A schematic of this system is shown in Fig. 34.29. It consists of four subsystems: the dye laser, to provide the seed pulse; a pulse expansion system; the alexandrite regenerative amplifier; and a pulse compression system.

A detailed description of the dye laser is given elsewhere.[16] The dye laser oscillator uses LDS 722 (Pyridine 2) and cryptocyanine as the gain and absorber media, respectively. This laser was pumped by the 850-mW output of a cw mode-locked frequency-doubled Nd:YAG, at a 100-MHz repetition rate.

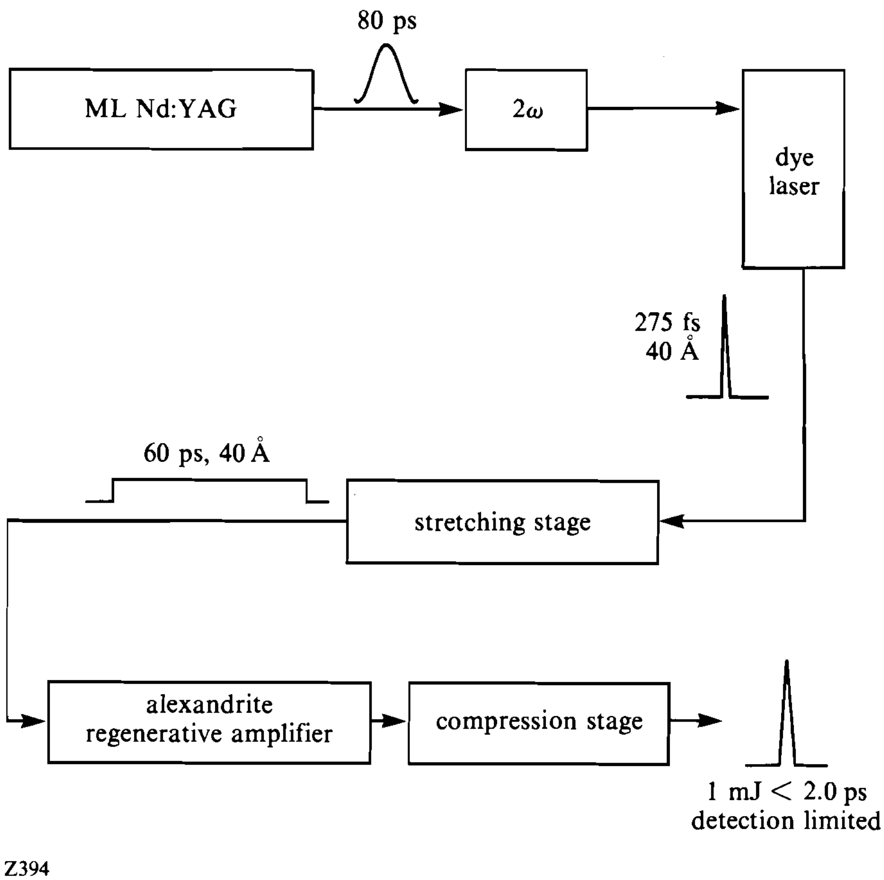

Fig. 34.29
Experimental setup for femtosecond-pulse amplification.

Optimization of the cavity yielded pulses as short as 197 fs. On a day-to-day basis, the dye laser generated 275-fs pulses. Output power of the laser was ~30 mW.

Tuning the alexandrite rather than the dye laser allowed us to work with shorter output pulses from the dye laser. A 6-μm-thick pellicle was used inside the alexandrite cavity to tune the peak gain to the dye laser's operating wavelength. Extreme care was taken to mode match the input to the regenerative amplifier cavity, and the alexandrite laser operating wavelength was carefully tuned to coincide with that of the dye laser. Under these conditions, energies as low as 1.0 pJ were sufficient to reliably seed the amplifier. Somewhat higher (5- to 10-pJ) energies were needed if the dye laser was detuned from gain center by ~5 nm.

The pulse expansion system consists of two 1800-line/mm gratings in an antiparallel configuration. Between the gratings are two lenses forming a telescope with unit magnification. This grating configuration has previously been shown to provide a net positive GVD.[17,18] A 275-fs, 40-Å (FWHM) input pulse to the expansion system is transformed into a positively chirped pulse of 60-ps duration. After expansion, the pulse is amplified in the regenerative amplifier. Finally, a standard double-pass grating compressor can then be used to compress the pulse back to nearly its original duration. If the gratings used in the expansion and compression are identical, the result is a net-zero dispersion to all orders.

Figures 34.30(a)–34.30(c) show the input dye laser spectrum before and after amplification, and the spectrum of the free-running alexandrite laser. There is no evidence of gain narrowing or of any other bandwidth-limiting effects. The output energy at this stage is 2 mJ. Double passing the high-energy chirped pulse through a standard grating compressor yields a streak-camera-limited pulse width of less than 2 ps. In order to realize the full potential that this system holds, we note that at the energies achieved here, the fluence within the amplifier (250 mJ/cm^2) is still well below the saturation fluence of the medium. Once optimized, this laser source is expected to deliver 20-mJ pulses.

Conclusion

We have shown that an alexandrite regenerative amplifier is a versatile source capable of amplifying by six to ten orders of magnitude short pulses from various oscillators. The amplifier was used to amplify 5-ns slices from a line-narrowed cw dye laser and 50-ps pulses from a laser diode to the 10-mJ range. We have also combined the technique of chirped-pulse amplification with our alexandrite laser to amplify femtosecond pulses. By using diffraction grating expansion/compression techniques, we have produced subpicosecond pulses with peak powers as high as 2 GW. This source is tunable across a wide bandwidth, limited presently by the dye laser seeding the amplifier, and could serve as a source for continuum generation in the near infrared, or for high field strength studies in atomic physics.

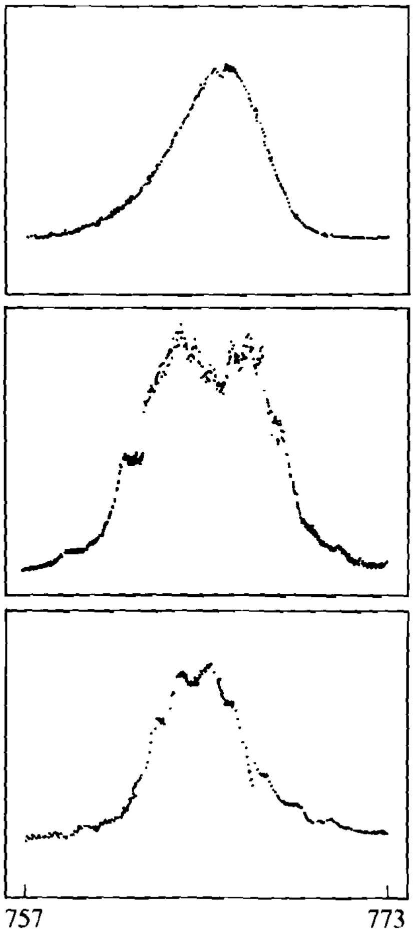

Fig. 34.30
Spectrum of the synchronously pumped dye laser (a) before amplification, (b) spectrum of the free-running alexandrite, and (c) after amplification.

ACKNOWLEDGMENT

This work was done in cooperation with Dr. Donald J. Harter, Allied Signal Inc., Morristown, N.J.

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