3.C Kilohertz, Synchronous Amplification of 85-fs Optical Pulses

In recent years significant advances have been made in the generation and amplification of ultrashort optical pulses. The amplification of ultrashort pulses allows high (gigawatt) peak powers to be obtained, making it possible to investigate nonlinear phenomena occurring on the picosecond or femtosecond (fs) time scale. Of particular interest is the generation of the white-light continuum, which is obtained by focusing a laser pulse with intensities in excess of 10^{11} W/cm^2 in a clear liquid such as water or ethylene glycol.[1] The continuum is useful as a source of ultrashort pulses in the spectral range from the near IR to the near UV.

Two general schemes have been reported for providing ultrashort, amplified femtosecond laser pulses. In one method, pulses of duration of the order of 100 fs are generated in a cw-pumped and colliding-pulse mode-locked (CPM) dye laser.[2] The pulses are then amplified to the 100-μJ level by pumping an amplifier chain with nanosecond pulses from a frequency-doubled Q-switched Nd:YAG laser.[3] Since the pump pulses are much longer than the storage time of the dye amplifier medium, there is no severe requirement for synchronization between the oscillator pulses and amplifier pump pulses. In the second method, the subpicosecond pulses are generated in a synchronously pumped, passively mode-locked dye laser,[4] and are amplified by 90-ps pump pulses that are synchronized to the dye laser pulses[5,6] to within about 40 ps. Because the pump pulses are now of duration of the order of the dye storage time, a strict synchronization is required between the oscillator and pump pulses. Only a synchronously pumped oscillator-amplifier configuration is capable of satisfying this condition. The advantages of pumping the amplifier chain synchronously with short ($<$ 100-ps) pump pulses include increased efficiency, stability, and energy contrast between the amplified pulse and amplified spontaneous emission. Both methods are capable of producing peak powers of a few gigawatts at repetition rates of about 10 Hz.

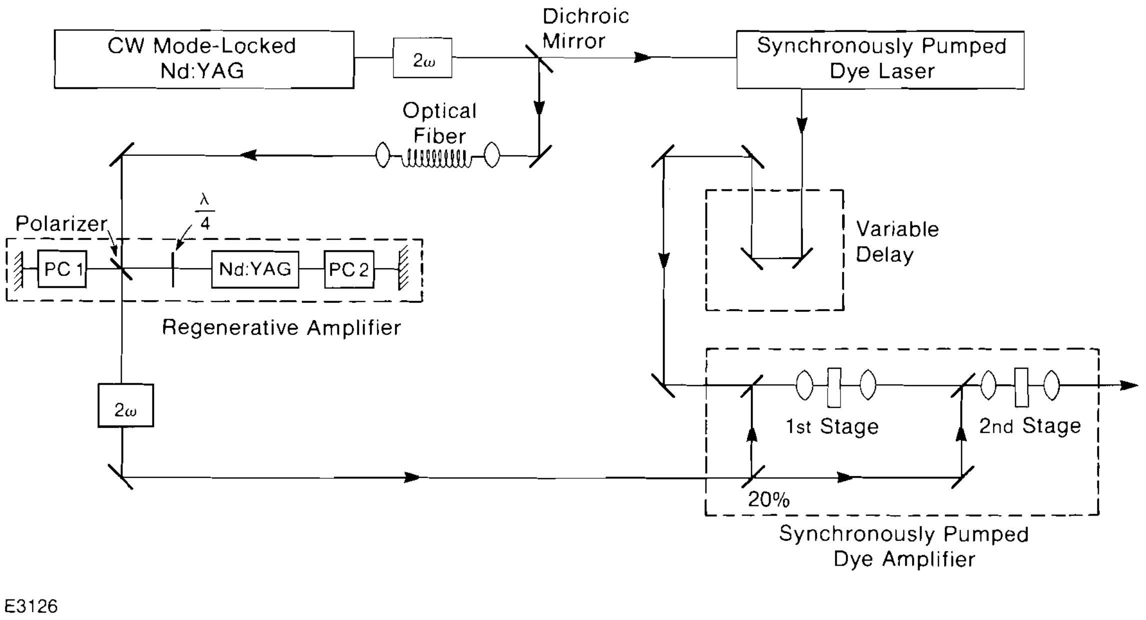
Here we report the development of an oscillator-amplifier system that offers two significant advantages over the systems discussed above. We have developed a dye laser that is both synchronously pumped and colliding-pulse mode locked, making synchronous amplification of a CPM laser possible for the first time.[7] Second, we have developed a cw-pumped regenerative Nd:YAG amplifier that can produce 1-mJ, 100-ps pulses at a repetition rate of 1 kHz. In this oscillator-amplifier system, the CPM dye laser is synchronously pumped by the frequency-doubled output of a cw mode-locked Nd:YAG laser. The Nd:YAG laser is also used to seed the regenerative amplifier. The output of the regenerative amplifier is frequency doubled and is used to pump a two-stage dye amplifier chain. Timing between the oscillator and pump pulses is achieved using an optical delay line. With this system, we have succeeded in amplifying the 85-fs CPM pulses to the microjoule level, sufficient to produce the white-light continuum at a 1-kHz repetition rate. In what follows we discuss in detail the two new amplifiers: the regenerative Nd:YAG amplifier and the dye amplifier chain.

Nd:YAG Regenerative Amplifier

The pump source for the new dye laser amplifier is the output of a recently developed Nd:YAG regenerative amplifier.[8] In the past the repetition rate of Nd:YAG amplifiers has been limited to about 30 Hz by the flashlamps and power supplies. Alternatively, a cw mode-locked and Q-switched laser could be used as the dye amplifier pump source; however, the selection of a single pulse from the Q-switched pulse train reduces the available energy to about 100 μJ. In addition, the repetition rate of such a system is limited to 500 Hz to ensure good stability. All of these limitations can be overcome by using a cw Nd:YAG operated as a regenerative amplifier.

The configuration of a system in which such an amplifier is integrated as the source for a dye amplifier is shown in Fig. 21.24. The input pulse is a portion of the 1.06-μm radiation from the cw mode-locked Nd:YAG laser that is used to pump the dye laser. These pulses are then injected into a fiber for transport to the regenerative amplifier. The use of a fiber not only decouples the alignment of the two lasers, but also allows the oscillator and amplifier to be in different locations (tables or even rooms) without need for long beam paths. A 4% reflector follows the fiber to isolate the cw mode-locked Nd:YAG from the amplifier. The reflector also serves to protect the fiber from being damaged by leakage from the amplifier. The injected pulses are of approximately 10-pJ energy and 100-ps duration. A quarter-wave plate is placed in the cavity both to frustrate cw lasing and to reject the injected pulses after two round trips. The amplifier is triggered by applying a voltage sufficient for a quarter-wave rotation to the injection Pockels cell (PC 2) to compensate

Fig. 21.24
Synchronous dye amplifier system. The Nd:YAG regenerative amplifier configuration is detailed inside the dotted line. The Nd:YAG amplifier can produce 1-mJ, 100-ps pulses at 1 kHz. The dye amplifier produces 170-fs pulses with energy 1.5 μJ, or 1.7-ps pulses with energy 5 μJ.



for the quarter-wave plate. This action not only Q-switches the laser but also traps one of the injected pulses in the cavity. Following approximately 45 round trips (500 ns), the cavity-dumping Pockels cell (PC 1) is triggered and the pulse is rejected from the cavity.

The system can currently be triggered at any repetition rate up to 1.6 kHz, limited by the Pockels cell driver power supply. A plot of output pulse energy versus repetition rate is shown in Fig. 21.25. It is expected that the pulse energy will remain constant until the repetition rate approaches the inverse storage time of the Nd:YAG (5 kHz). This would indicate that the rolloff at 1 kHz present in Fig. 21.25 is due to either uncertainty in the measurement or a thermal effect in the Pockels cells. The output pulse energy is 0.8 mJ in routine operation, although values as high as 1.1 mJ have been obtained at 1 kHz. This limit is due to the high-contrast dielectric polarizer which must be inserted in the cavity.

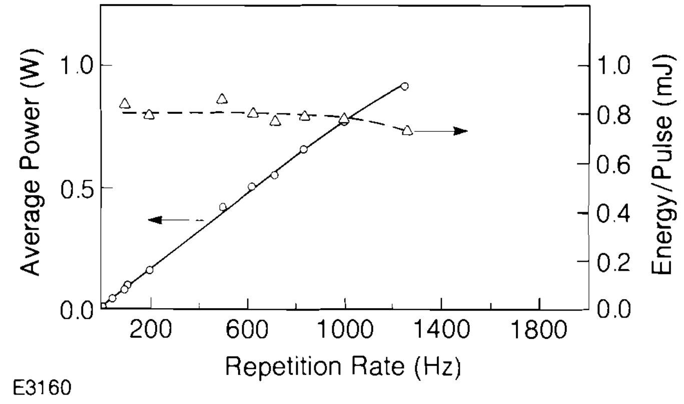


Fig. 21.25
Energy per pulse and average power vs repetition rate for the cw-pumped Nd:YAG regenerative amplifier.

Since the amplifier is used as a source of pump pulses for the dye amplifiers, the 1.06-μm pulses were frequency doubled using a 3-mm KTP crystal. Energies of 250 μJ at 532 nm are obtained (30% efficiency). Efficiencies as high as 50% have been observed, but this resulted in damage to the KTP crystal. The output energy stability of this system is shown in Fig. 21.26, which is a histogram of the doubled energy output of the Nd:YAG regenerative amplifier. The full width at half maximum of the energy distribution is 2.3%, with 99% of the shots falling within ± 2.7%.

Dye Amplifier

The dye amplifier is configured as a standard two-stage, collinearly pumped amplifier, as shown in Fig. 21.24.[5] The stages are 1 cm in length, with flowing Kiton Red of 4×10^{-5} Molar concentration in water. The spot sizes in the first and second stages are 25 μm and 150 μm, respectively. The first stage is pumped by 20% of the green energy. The input dye laser pulse energy is from the synchronously pumped CPM laser, with a pulse width of 85 fs.[7] After transport to the amplifier, the pulse energy is approximately 350 pJ. After the losses of the unpumped amplifier chain, the transmitted energy is 150 pJ. The combined gain of the two stages is 10^4, resulting in an output energy of 1.5 μJ.

An autocorrelation of the amplified dye laser pulses is shown in Fig. 21.27. The trace indicates a pulse width of 170 fs, assuming a sech^2 pulse shape. The presentation of the autocorrelation trace as points is due to the limitation of our computer-controlled data acquisition and

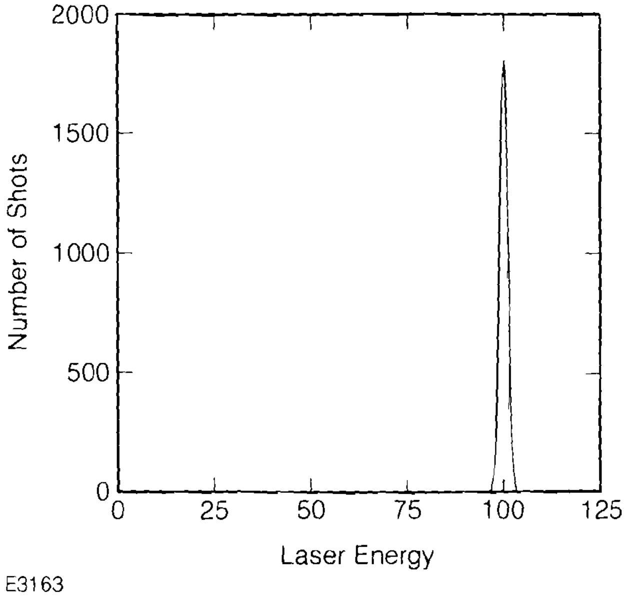


Fig. 21.26
Histogram of the energy of the frequency-doubled output of the Nd:YAG regenerative amplifier. Ninety-nine percent of the pulses lie within ± 2.7%.

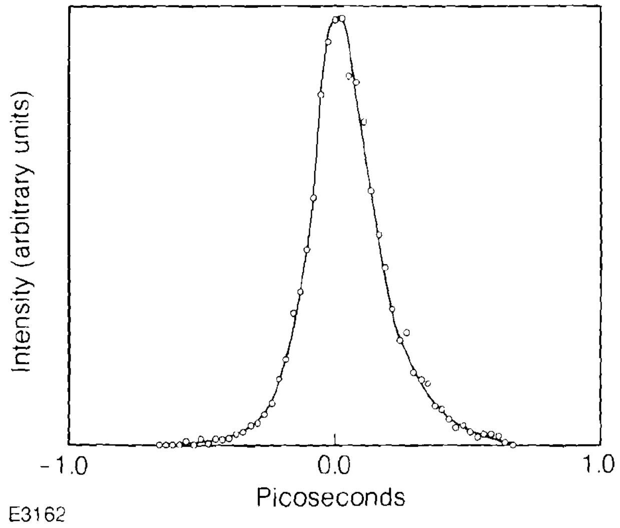


Fig. 21.27
Autocorrelation of the amplified dye pulses. For an input pulse width of 85 fs, the output pulse width was 170 fs, assuming a sech^2 pulse shape. No saturable absorber or grating pair was used to limit the pulse broadening.

not caused by the repetition rate of the laser. Some form of gating of the collection scheme is required in order to remove the background signal from the cw dye laser output. Broadening of the pulse is caused by both dispersion in the amplifier chain as well as saturation of the gain. The unamplified beam, if allowed to propagate through the amplifier chain, shows broadening due to dispersion to approximately 120 fs, which presumably could be removed with a grating pair. The remaining broadening is due to gain saturation. This was confirmed by observing that the amplified pulse width became 120 fs if the dye input energy was reduced significantly. No saturable absorbers or negatively dispersive elements were used to reduce the output pulse width.

It was found that the white-light continuum could be generated in water with as little as 250 nJ when a 7x objective was used for focusing. This low threshold indicates that the beam quality (focusability) of the amplified pulses is very good, as is expected from a longitudinally pumped amplifier.

When the saturable absorber jet in the dye laser was removed so the pulse width was 1.7 ps and the laser was tuned to the peak of the Kiton Red gain, the output energy increased to 5 μJ. It is interesting to note that when the spectrum of the amplified pulse and ASE were examined, the ASE energy decreased by a factor of 3 when the dye laser was being amplified compared to when the dye laser was blocked. This would indicate that all energy measurements are underestimated if the ASE is determined by blocking the dye laser input.

Conclusion

Development of a kHz Nd:YAG regenerative amplifier and a synchronously pumped CPM dye laser has enabled the high-repetition-rate amplification of ultrashort optical pulses to the microjoule level. The pulse width broadens from 90 fs to 180 fs due to gain saturation and dispersion in the amplifier chain.

Two improvements to the system are planned in the near future. First, a saturable absorber will be inserted between the two dye amplifier stages to suppress the ASE and to control the preferential amplification of the leading edge of the pulse due to gain saturation. Second, temporal broadening due to dispersion will be removed by use of a dispersive delay line consisting of a grating pair. With these additions, the amplifier should produce megawatt pulses shorter than 100 fs at kHz repetition rates.

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