Tunable picosecond blue and UV pulses from a diode-pumped laser system seeded by a gain-switched laser diode

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Picosecond pulses emitted from a gain-switched laser diode have been amplified in a Ti:sapphire regenerative amplifier indirectly pumped by a 4-W laser diode. This all-solid-state system produced microjoule pulses tunable from 803 to 840 nm at repetition rates up to 25 kHz with durations of 70–100 ps. By frequency doubling and tripling the output, we generated blue and UV pulses tunable from 401 to 420 nm and from 268 to 280 nm, respectively. Average powers larger than 4 mW were reached in these two wavelength regions.

OCIS codes: 140.0140, 140.3480, 140.3280, 140.3580, 140.3590, 140.3600.

1. Introduction

In the past few years there has been a considerable effort to develop compact high-power laser sources capable of producing pulses in the picosecond and femtosecond ranges. The basic scheme consists of a short-pulse oscillator with an energy of a few nanojoules or less and an amplifier whose output can reach the microjoule or millijoule level. One key to the optimization of these sources stems from the use of laser diodes as either primary or pump oscillators because laser diodes are both highly efficient and highly compact. For example, diode-pumped mode-locked oscillators that produce picosecond or femtosecond pulses have been used in conjunction with diode-pumped regenerative amplifiers.[1–3] Still simpler and more-compact systems have recently been achieved in which the mode-locked oscillator itself was an external-cavity laser diode producing femtosecond pulses[4]: Mode-locked pulses were used to seed a flash-lamp regenerative amplifier. For generation of picosecond pulses it is easier to operate the laser diode in the gain-switched regime. Seeding of an erbium-doped fiber amplifier with gain-switched laser-diode pulses near 1.5 μm has been reported.[5] A Ti:sapphire regenerative amplifier, pumped by a flash-lamp frequency-doubled Nd:YAG laser, and a flash-lamp-pumped alexandrite regenerative amplifier were both injected by a picosecond gain-switched laser diode.[6–7] Energy that reached the millijoule level at a few-hertz repetition rate was reported.

However, many applications, such as tissue ablation[3] and time-resolved spectroscopy, require ultrashort pulses with a lower energy level (in the microjoule range) but at a higher repetition rate (in the kilohertz domain) with excellent pulse-to-pulse stability. To this end, we have developed an indirectly diode-pumped Ti:sapphire regenerative amplifier operating at a repetition frequency up to 25 kHz and injected by a gain-switched laser diode. The system is shown to produce 70-ps pulses at 812 nm with an energy of 4.5 μJ at 10 kHz. Moreover, a simple technique is implemented to make the system tunable from 803 to 840 nm.

To make our system suitable for time-resolved biological studies we frequency double and triple the output of the regenerative amplifier, because biological media have absorption bands in the blue–UV domain. Tunable blue and UV picosecond pulses (from 401 to 420 nm and from 268 to 280 nm) are then obtained. To our knowledge, this is the first time that tunable picosecond pulses have been produced in

F. Balembois, M. Gaignet, P. Georges, and A. Brun are with the Institut d'Optique Théorique et Appliquée, Unité de Recherche Associée 14 du Centre National de la Recherche Scientifique, Université de Paris-Sud, B.P. 147, 91403 Orsay, France. N. Stelmakh and J. M. Lourtioz are with the Institut d'Électronique Fondamentale, Unité de Recherche Associée 22 du Centre National de la Recherche Scientifique, Bâtiment 220, Université de Paris-Sud, 91405 Orsay, France.

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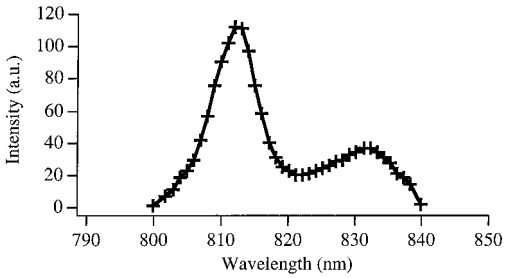

Fig. 1. Spectrum of picosecond laser-diode pulses.

these wavelength ranges by use of such a compact diode-pumped system.

2. Experimental Setup

The laser diode consisted of a separate-confinement single-quantum-well structure with a 170-Å GaAs active layer in an AlGaAs waveguide. The laser stripe was 5 μm wide and 2 mm long, and lasing occurred on a single transverse mode. To increase the output efficiency, the front face was antireflection coated (reflection coefficient of 1%) and the back face was high-reflection coated (reflection coefficient of 95%). We reached the gain-switching regime by pumping the laser diode with a pulsed generator capable of delivering 200-ps current pulses at repetition rates of as much as 100 kHz.[8] Under these conditions the laser output spread over many longitudinal modes. Because of the chirping effects of each longitudinal mode, the pulse spectrum was quasi-continuous and spanned 800–840 nm, with a maximum amplitude at 812 nm (Fig. 1). The pulse duration was 200 ps, and the pulse energy was 22 pJ.

The experimental setup is shown schematically in Fig. 2. The picosecond laser-diode output beam was collimated with a high-numerical-aperture objective, L_1 (N.A., 0.5; focal length, 8 mm). Two cylindrical lenses with focal lengths of +100 mm and −25.4 mm, respectively, were used to reshape the output beam and match the beam profile to the regenerative amplifier. The latter comprised a classic L-shaped cavity (mirrors M_1–M_3 in Fig. 2) with a 13-mm-long Ti:sapphire crystal (absorbing 80% of the pump power), a Pockels cell, and a polarizer. A prism was inserted into the cavity for selection of the operating wavelength.[2] A two-way switch consisting of a Faraday rotator, a half-wave plate, and a polarizer was used to separate the ejected beam from the injected beam. As the isolation provided by this system was not enough to prevent all feedback from the amplifier to the laser diode, we added a Faraday isolator. The overall transmission from the amplifier to the picosecond laser diode was then 1.1×10^{-6}.

The pump laser of the amplifier consisted of a three-mirror cavity, with a Nd:YVO_4 crystal pumped by a 4-W laser diode (Spectra Diode Laboratories 2348), a $KTiOPO_4$ (KTP) crystal, and an acousto-optic modulator for Q switching, as described previously.[2] The laser emitted 40-ns green pulses with an energy of 40 μJ at 10 kHz.

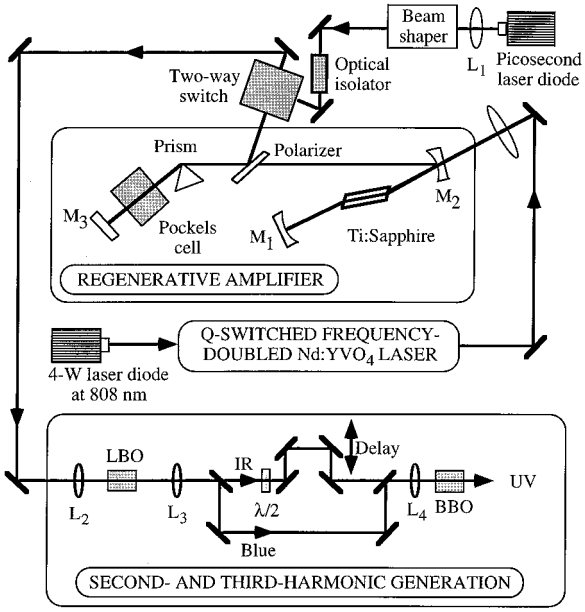

Fig. 2. Experimental setup of the tunable picosecond laser system. The focal lengths of lenses L_1, L_2, L_3, and L_4 are 8, 200, 100, and 90 mm, respectively. LBO, LiB_3O_5; BBO, β-BaB_2O_4.

All the devices were synchronized with the internal clock of the Pockels cell driver (MEDOX Electro-Optics). A first voltage step was applied to the driver of the acousto-optic modulator to trigger the pump pulse at 532 nm. A second voltage step was applied to the pulsed generator of the picosecond laser diode. The delay between the two voltage steps was adjusted to synchronize the picosecond laser-diode pulse injected into the regenerative amplifier with the green pump pulse. Two high-voltage steps were applied to the Pockels cell. The first voltage step was used to trap the picosecond pulse inside the cavity. The second one was used to eject it, once the amplification process had reached its maximum.

3. Performance of the Amplifier

Because of the presence of a prism in the regenerative amplifier cavity, only a small window of ≈5-nm FWHM was selected in the spectrum of the picosecond laser diode. We could adjust the central wavelength simply by rotating plane mirror M_3 of the amplifier. By considering the transmission of the different optics and the shape of the laser-diode spectrum (Fig. 1), we estimated that the energy actually injected into the amplifier was 1.6 pJ at 812 nm (i.e., at the laser-diode spectrum maximum), whereas it was only 0.3 pJ at 803 nm (at the edges of the laser-diode spectrum). Figure 3 compares the amplification process at these two wavelengths, obtained by a fast photodiode (rise time, 1 ns) monitoring the leakage of the regenerative amplifier. The measured signal-to-background ratio (SBR) was 22 at 812 nm [Fig. 3(a)] and 3 at 803 nm [Fig. 3(b)]. The actual SBR must be corrected from the photodiode rise time.[9] It is equal to the measured SBR multiplied by the ratio of the FWHM response of the photodiode

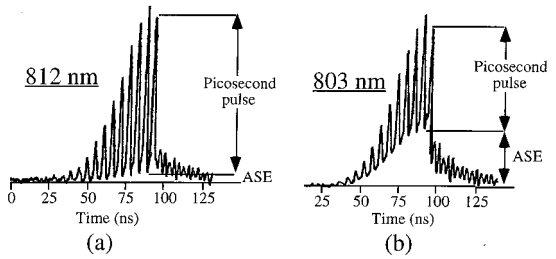

Fig. 3. Pulse responses at 803 and 812 nm monitored by a fast photodiode (1-ns rise time) monitoring a leakage of one mirror of the regenerative amplifier.

to the actual pulse width. Here the corrected value was 314 at 812 nm, of the same order of magnitude as those previously obtained in the research reported in Ref. 9, showing that the amplifier was correctly seeded. At 803 nm, the actual SBR was 43. Despite its higher sensitivity to alignment at this wavelength, the amplifier could easily be injected. Moreover, once the alignment was achieved, the SBR remained the same during all our experiments (2 h).

To obtain the injection threshold of our amplifier we decreased the energy emitted by the laser diode until the measured SBR was equal to 1. We measured the average power emitted by the laser diode at the input of the amplifier. By taking into account the spectral window of 5 nm (selected by the prism inside the amplifier), we estimated that the injection threshold was 0.2 pJ/pulse at 812 nm.

At this wavelength, the pulse energy was high enough to saturate the amplifier, but a different situation occurred at 803 nm. Spontaneously emitted photons were amplified in competition with those emitted from the picosecond laser diode. Therefore the amplifier output pulse consisted of two parts: an amplified picosecond pulse and a pulse of amplified spontaneous emission (ASE) with a duration of 5 ns that corresponded to one round trip in the amplifier cavity. Figure 4 shows that, despite the ASE, it was possible to generate picosecond pulses at a 10-kHz repetition rate with an energy of 1 to 4 μJ and a tuning range from 803 to 840 nm.

The temporal width of the amplified pulses was measured with a sampling oscilloscope (30-ps rise time) and a high-speed photodiode (25-ps rise time). A value of 70 ps (no deconvolution) was found for the

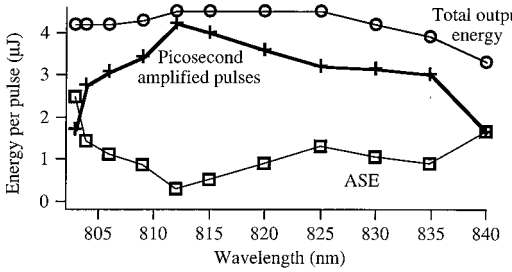

Fig. 4. Tunability of IR pulses near 820 nm. Circles, total energy extracted per pulse from the amplifier (including ASE); crosses, energy of the amplified laser pulses; squares, ASE.

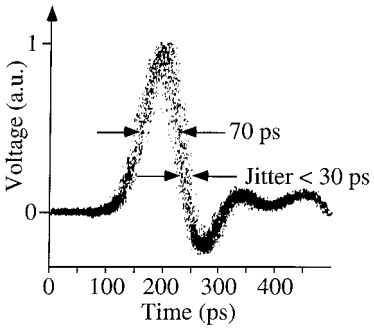

Fig. 5. Shape of the amplified pulse measured with a sampling oscilloscope.

amplified pulse width at 812 nm (Fig. 5). As we tuned the amplifier, we observed that the pulse width remained between 70 and 100 ps. Note that the amplified pulses were shorter than those emitted by the laser diode (200 ps). This result actually reflects the spectral selectivity of the amplifier: As the different wavelengths are emitted at different times during the laser pulse, selecting a wavelength is just equivalent to selecting a temporal window in the gain-switched pulse. The sampling oscilloscope was triggered by an electrical signal delivered by the power supply of the picosecond laser diode. The pulse jitter deduced from the trace thickness (Fig. 5) was within the measurement accuracy (≈30 ps). In fact, timing jitter of less than 1 ps can be expected from a gain-switched laser-diode system. Present results show that the amplified optical pulses can be precisely synchronized with an electrical signal. This effect could be useful in multiple optoelectronic applications.

4. Frequency Conversion to Blue and Ultraviolet

The amplified pulses were frequency converted in the blue and the UV by harmonic generation. We used an experimental setup (Fig. 2) that was similar to the one described in Ref. 10. The frequency doubling was obtained in a LBO crystal (8-mm length) cut for second-harmonic generation at 850 nm in type I phase matching. The third harmonic was generated in a BBO crystal (8-mm length) cut in type I for sum-frequency generation of 780 and 390 nm. We introduced a delay line to finely adjust the optical path length of the IR beam to that of the blue beam. The accuracy of the path length in the harmonic generator needed to maximize the UV signal was ~2 mm.

Spectra with FWHM of 1 and 0.3 nm were measured in the blue and the UV, respectively, which can be compared with the 5-nm FWHM spectrum of the IR pulses. Clearly, spectral widths were limited by the spectral acceptance of the two nonlinear crystals. Although the LBO and BBO crystals were not optimized for the operating wavelength range (803–840 nm), we obtained good conversion efficiency, reaching 30% from IR to blue and 12% from IR to UV. We achieved a tunability of more than 15 nm in the blue

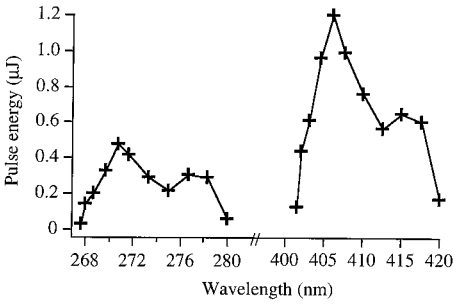

Fig. 6. Tuning curves for the second-harmonic generation (on the right) and the third-harmonic generation (on the left).

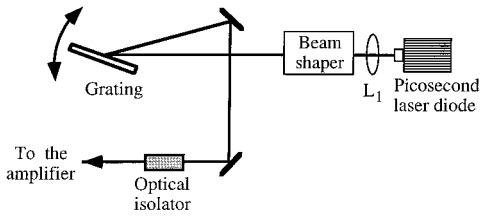

Fig. 7. Setup for injection seeding with a grating.

and of more than 10 nm in the UV (Fig. 6). In both cases the pulse energy was above 0.1 μJ. For a 10-kHz repetition rate, average powers larger than 11 and 4 mW were achieved at 406 and 271 nm, respectively.

To estimate the maximum contribution of ASE to the UV signal, we operated the amplifier in free-running mode (i.e., without seeding) with an output energy per pulse of 4 μJ. We measured a UV energy per pulse of less than 2 nJ, that is, more than 2 orders of magnitude less than the energy of picosecond UV pulses. Thus, by means of the nonlinear conversion process, the pulse was removed from its nanosecond ASE background.

The output level in the UV (at 271 nm) was monitored for 2 h. Over this period, the seeding of the amplifier remained unchanged and the SBR remained at its initial value of 314 (at 812 nm). Peak-to-peak fluctuations were found to be of ±2.5%, corresponding to IR fluctuations of less than ±0.8%. Such good stability obtained in spite of a nonlinear conversion process reflects the good reproducibility of pulses emitted by the gain-switched laser diode as well as the stable pumping of the regenerative amplifier by a cw laser diode.

The repetition frequency was increased to 25 kHz, which was the maximum value acceptable for our Pockels cell. Because of the long fluorescence lifetime of the Nd^{3+} ion in the vanadate matrix (115 μs), the frequency-doubled Nd:YVO_4 laser then emitted green pulses of lower energy (18 μJ at 25 kHz instead of 40 μJ at 10 kHz). However, we still obtained 1-mW average power in the UV at 271 nm.

5. Improvement of the Spectral Quality

Harmonic conversion efficiency was limited by the wide spectrum of the IR pulses (5 nm FWHM). Moreover, it could be useful for spectroscopic applications to emit pulses with narrower spectra. For these reasons we modified the injection setup as shown in Fig. 7. We used a 2000-groove/mm grating, which spatially dispersed the beam of the gain-switched laser diode. As the injection was highly sensitive to alignment, we could rotate the grating to finely select the wavelength of the pulses seeded into the amplifier. The optical path length between the grating and the input of the regenerative amplifier was 140 cm. With this setup the amplified spectrum was less than 1 nm FWHM, compared with 5 nm FWHM in the former experiment. The pulse duration remained the same as previously, 70–100 ps.

At 812 nm, corresponding to the maximum of seeded energy, the SBR was equal to 43. It was lower than previously (314) because the energy seeded in the amplifier was only 0.3 pJ (compared with 1.6 pJ). In fact, a smaller part of the diode spectrum was selected, and the transmission of the grating was only 80%.

We also compared the frequency conversion in the two cases, with and without the grating. At the same injection level (with a SBR of 43) and at the same wavelength (271 nm) we obtained an UV average power of 3.4 mW with the grating and of 1 mW without the grating. As expected, the spectral narrowing of the fundamental wavelength increased the nonlinear conversion efficiency.

We achieved tunability by simultaneously rotating the grating and the back mirror of the regenerative amplifier (Fig. 2) to match the wavelength of the injected beam with the wavelength of the beam propagating inside the amplifier. The system was tunable from 810 to 817 nm with a SBR of 20–43. The UV average power was 1 mW–3.4 mW in the spectral range 270–272.3 nm. The performance quality was less than previously because more than the half of the energy ejected from the amplifier was lost in ASE. However, the average powers obtained were sufficient for time-resolved spectroscopic studies such as those performed on biological media.

6. Conclusion

In conclusion, the amplification of gain-switched laser diode pulses in a Ti:sapphire diode-pumped regenerative amplifier has been proved to be a simple and efficient technique to produce tunable picosecond pulses at a high repetition rate in the IR (near 820 nm). By frequency conversion in LBO and BBO crystals, average powers larger than 11 and 4 mW were achieved at 406 and 271 nm, respectively. Gain-switched laser diodes, which are of simpler design and are more compact than conventional mode-locked oscillators, exhibit broad emission spectra. This technique has been used to achieve more than 35-nm tunability in the IR and 12 nm in the UV. Our system has an excellent electrical-to-optical conversion efficiency and the unique advantage of direct electrical control of the optical timing with low jitter. This compact all-solid-state system promises to have

many potential applications in the domains of time-resolved spectroscopy and optical sampling.

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