High repetition rate 300 ps pulses ultraviolet source passively Q:switched microchip laser and a multipass amplifier

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High-repetition-rate 300-ps pulsed ultraviolet source with a passively Q-switched microchip laser and a multipass amplifier

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We demonstrate a new kind of picosecond laser source in the UV at a high repetition rate of −45 kHz, using only passive, compact, and simple elements. This system is based on a microchip laser and a very efficient multipass amplifier, both pumped with recently developed high-brightness laser diodes. The system has been optimized to deliver, at a high repetition rate, subnanosecond pulses at the wavelength 355 nm with an energy per pulse of close to 1 μJ (38-mW average power). This source is to our knowledge the first totally passive 300-ps UV laser source at this high repetition rate.

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In many domains of application, especially in biology, there is intense interest in simple, all-solid-state pulsed UV sources. For example, in applications such as fluorescence-lifetime measurement both short duration and high repetition rate are shown to be crucial. In fact, the chemical-process dynamics of biological molecules such as NADH often occur on the nanosecond time scale, which implies that subnanosecond pulses must be used to analyze them. Second, the techniques of measurement of these dynamics require a high repetition rate for a fast acquisition process. The common method[1,2] of producing such pulses consists of using a mode-locked oscillator that produces ultrashort pulses at a very high repetition rate (typically 100 MHz). This pulse rate is then decimated to the accurate slower repetition rate of the amplifier (1 to 250 kHz). However, this technique has several disadvantages. The repetition rate of the oscillator is so high that almost all its power—more than 99.99%—is unavailable for the amplification process. Moreover, the selection of a pulse implies a complex setup whose repetition rate is then limited by the speed of the active elements. All these requirements lead to complex systems for both the oscillator and the amplifier stage.

Another method of obtaining a simpler, more-efficient source without repetition-rate limitation consists of starting directly with an oscillator operating at the right repetition rate. The use of passively Q-switched diode-pumped microchip lasers seems to be very accurate.[3–5] Moreover, this monolithic device is simple to use because of its totally passive process and compact because of the small sizes of the microchip and the diode-pumping system. However, the main disadvantage is the difficulty of achieving high-repetition-rate, short pulses and enough energy per pulse for nonlinear conversion to the UV within the same device. To overcome this problem, and to obtain a high repetition rate with a microlaser producing short pulses, we use a high-brightness pump laser diode (LD). Afterward, we amplify the output pulses in a gain medium inserted into a simple, totally passive multipass amplifier.

Our experiment was performed with a microchip laser[6] composed of a 750-μm piece of gain medium (Nd^{3+}:YAG) on which a 60-μm layer of saturable absorber (Cr^{4+}:YAG) was grown by liquid-phase epitaxy. We conceived this passively Q-switched laser to produce subnanosecond pulses. Actually, the predicted pulse duration given by the theory[9–11] for this device was 520 ps. This value was in good agreement with our experimental measurement of 500 ps, obtained with a fast photodiode. This kind of short-pulse-duration microchip laser is usually pumped with a fiber-coupled cw LD and then produces pulses at a relatively low repetition rate. For example, with a 0.85-W 100-μm core-diameter fiber-coupled diode, the repetition rate is 5.9 kHz and the average power is 15 mW (Table 1). In fact, for production of 500-ps pulses, our microchip concept consists of having both a short length of gain medium (usually less than its absorption length) and a saturable absorber with a high ion concentration, both of which are incompatible with a high repetition rate.

For a higher repetition rate, a first idea would be to modify the microchip laser structure. But to keep the pulse duration short one should make this modification for the Nd concentration, which requires a different technology. An alternative method of achieving a higher repetition rate is to optimize the pumping system. Actually, the repetition rate (P_{rf}) depends linearly on the small-signal gain. Moreover, the small-signal gain is proportional to the pump intensity integrated over the crystal. So, to obtain a high repetition rate we must have a brighter pump beam, which is equivalent to having both a high pump intensity and a long Rayleigh length. When the pump beam is non-diffraction-limited and elliptical, we define a generalized Rayleigh length, where the beam is double the one at its waist. At the optimum repetition rate (when the generalized Rayleigh length fits the crystal length), P_{rf} can be considered a linear function of the intensity and the generalized Rayleigh length. Because this product depends on only the brightness of the diode, it can be expressed as a function of pump power P_p and the M^2 factor.[12] The repetition rate is then given by

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Table 1. Influence of the Pump System Brightness on Microlaser Performance

Pump at 808 nm	LD [0.85-W fiber-coupled 100-μm (ϕ)	Ti:Sapphire	LD (1-W, 1 μm × 100 μm)	LD (1-W, 1 μm × 50 μm)	LD (2-W, 1 μm × 100 μm)
Incident pump power (W)	0.85	0.67	0.9	0.9	1.8
M^2 factor	18	1	10	5	10
Pump spot size in the microchip (μm)	100 (ϕ)	25 (ϕ)	15 × 170	20 × 50	15 × 180
Repetition rate (kHz)	5.9	101	21	41	45
Energy per pulse (μJ)	2.5	0.28	0.58	0.37	0.89
Average power (mW)	15	28	15	15	40

$$P_{\mathrm{rf}} = C\zeta P_p/M^2, \tag{1}$$

where C is a constant that is characteristic of the microchip, independently of the pump condition, for our microchip laser. C is $0.145 \times 10^6\ \mathrm{W}^{-1}\ \mathrm{s}^{-1}$ and ζ is a factor depending on the pump system. ζ is introduced to take into account the fact that for a diode junction the usually defined M^2 factor corresponds to the divergence of the beam in the parallel direction. When M^2 is much larger in one direction than in the other, we can consider, with a simplistic approximation, that $\zeta = \sqrt{3}$. On the other hand, if M^2 is the same in both directions (a diffraction-limited or a fiber-coupled beam), $\zeta = 1$.

To estimate the repetition-rate upper limit we pumped the oscillator with a diffraction-limited beam from a cw Ti:sapphire laser. The highest repetition rate that we obtained was 101 kHz at 0.69-W incident pump power (Table 1). This pump power corresponded to the limit for single-longitudinal-mode operation with a stable train. With a higher incident power, multiple longitudinal modes began to appear, and the pulse train became erratic.

We investigated experimentally the influence of the pump-diode brightness on repetition rate (Table 1). First, we used a standard 1-W power 1 μm × 100 μm junction cw LD whose beam was reshaped by cylindrical lenses that were optimized for the repetition rate. This technique allowed, with approximately the same incident power, a gain in repetition rate of 3.6 [3.3 according to Eq. (1)] compared with a gain with a fiber-coupled diode. The second step was to use very high-brightness diodes. We used a 1-W 1 μm × 50 μm LD, and this improved the repetition rate to 6.9 [6.6 according to the Eq. (1)]. Finally, we pumped the oscillator with a 2-W 1 μm × 100 μm cw LD from SDL, Inc., especially designed for our application. Because the brightness of this LD was the same as that of the 1-W 1 μm × 50 μm diode, the repetition rate was nearly the same. However, the power was twice as great, which allowed a higher average power of 40 mW for the 2-W 1 μm × 100 μm diode.

To validate these experimental results with our theory we plot in Fig. 1 the theoretical repetition rate versus the pump power corrected by the brightness factor ζ/M^2 by use of Eq. (1). This theoretical curve shows very good agreement with the experimental results for both diffraction-limited Ti:sapphire pumping and non-diffraction-limited diode pumping. The good fit between the experimental results and the theory corroborates the use of a very high-brightness diode pump system to obtain a significant increase of the repetition rate.

However, pumping with a high-brightness diode also reduced the energy per pulse (Table 1). To solve this problem we decided to add an amplifier stage to the system.

To increase the energy per pulse without reducing the repetition rate we used a geometric multipass amplifier configuration. The main advantage of a multipass amplifier was its totally passive process, which induced no repetition-rate limitation.[11] For simplicity, efficiency, and compactness we chose a Nd:YVO_4 crystal because of its high emission cross section at the 1064-nm emitted wavelength of the microchip, which favored good energy extraction even in a few-round-trip configuration. Moreover, to reduce thermal effects we used a composite crystal[12] made from a 1-mm-long undoped YVO_4 crystal bonded to a 1%-doped 3-mm-long Nd:YVO_4 crystal. As the injection from the microchip lase had significant energy (hundreds of nanojoules), the energy stored in this crystal could be extracted in only four passes. The experimental setup is shown in Fig. 2.

For high gain per pass and thus to increase further the extraction efficiency of the amplifier, we used a

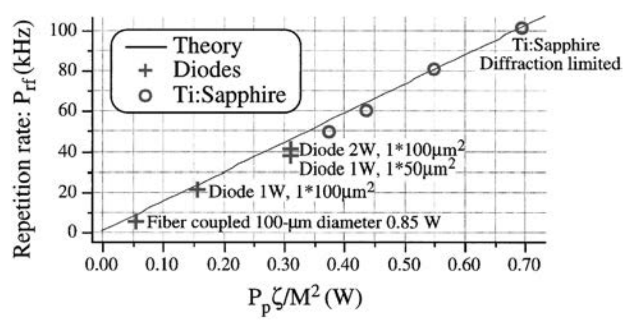

Fig. 1. Repetition rate versus pumping-system brightness.

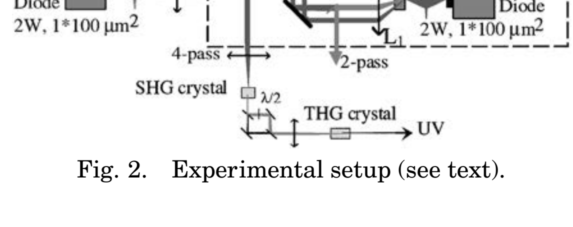

Fig. 2. Experimental setup (see text).

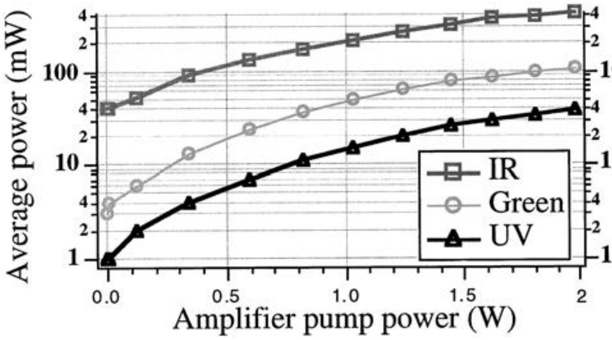

Fig. 3. Output power of the source for the fundamental and the harmonic waves.

high-brightness (2-W, 1 μm $\times$ 100 μm) pump diode. The use of very bright diodes seemed to be accurate for an efficient multipass amplifier. For example, after two passes the gain obtained with a more-powerful but less-bright (4 W, 1 μm $\times$ 500 μm) diode was 2.5 times lower than that of the brighter diode. Despite a higher amount of energy deposited in the crystal with the 4-W diode, the maximal (after four passes) energy extraction remained almost the same as with the high-brightness diode.

Finally, the average output power (Fig. 3) was 408 mW after two passes and 510 mW after four passes. We also recorded the beam profiles and the average output power for the two- and four-pass configurations. The beam profile shrank in the horizontal direction during the third and fourth passes. This could be explained by the fact that the shifted signal beam of the third and fourth passes was amplified at the edges of the gain area. The shrunken amplified beam was astigmatic, but M^2 was almost unchanged, from 1.21 to 1.27 for the horizontal direction and from 1.26 to 1.3 for the vertical one. The choice between the four-pass configuration, which delivered the maximum output power, and the simpler two-pass configuration, which delivered less energy but with a more circular beam profile, was made with the efficiency of harmonic generation by nonlinear processes taken into consideration.

For the nonlinear processes we first used a 5-mm-long type II KTP crystal for second-harmonic generation (SHG) and an 8-mm-long type II LBO crystal for third-harmonic generation (THG). The output green power (at 532 nm) was as much as 180 mW (4 μJ/pulse and 37% conversion efficiency) in the four-pass configuration and 120 mW (2.33 μJ/pulse and 31% conversion efficiency) in the two-pass configuration. To obtain a circular beam profile in the UV (at 355 nm) we used the angular acceptance of the LBO crystal to reshape the distorted IR beam profile delivered by the multipass amplifier. An output power of 38 mW (10% efficiency) for the two-pass configuration was obtained, compared with output power of 35 mW (7.2% efficiency) for the four-pass configuration. Actually, because of its ellipticity, after four passes the output beam did not allow an efficiency as high as that after two passes. The optimal system in terms of both simplicity and efficiency in the UV was thus the one with the two-pass amplifier. The M^2 of the UV beam in this case was 1.34. This UV source delivered 0.84-μJ pulses (Fig. 3) at 45 kHz, with a pulse duration shortened to 300 ps by nonlinear conversion.

We have demonstrated that using a high-brightness diode to pump the oscillator allowed us to increase the repetition rate compared with the rate obtained with standard use. Moreover, by adding a two-pass amplifier that was also pumped with a high-brightness diode we increased the repetition rate sufficiently to obtain efficient harmonic generation. This new kind of high-repetition-rate source has several advantages: It is simple, compact, and totally passive, does not have repetition-rate limitations owing to the electronic devices used, and is efficient and stable. Actually, the stability of the UV beam power measured during 4 h showed fluctuations of only 6% (peak to peak). An inconvenient aspect of this device is the temporal jitter between pulses, but this problem can be solved by optical synchronization. All these advantages make this source easy to use. We are looking forward to using this fast and compact Microlaser Amplified by a Multipass with an Output in the Ultraviolet using Third Harmonic generation (MAMOUTH) source for fluorescence-lifetime measurement.

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References

1. F. Salin, J. Squier, G. Mourou, and G. Vailancourt, Opt. Lett. **16,** 1964 (1991).
2. T. B. Norris, Opt. Lett. **17,** 1009 (1992).
3. J. J. Zayhowski and C. Dill III, Opt. Lett. **17,** 1201 (1992); **19,** 1427 (1994).
4. J. J. Zayhowski, in *Conference on Lasers and Electro-Optics*, Vol. 9 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), p. 236.
5. S. Zhou, K. K. Lee, Y. C. Chen, and S. Li, Opt. Lett. **18,** 511 (1993); Y. C. Chen, S. Li, K. K. Lee, and S. Zhou, Opt. Lett. **18,** 1418 (1993).
6. L. Fulbert, J. Marty, B. Ferrand, and E. Molva, in *Conference on Lasers and Electro-Optics*, Vol. 15 of 1995 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1995), p. 176.
7. A. Szabo and R. A. Stein, J. Appl. Phys. **36,** 1562 (1965).
8. J. J. Zayhowski and P. L. Kelley, IEEE J. Quantum Electron. **27,** 2220 (1991).
9. J. J. Degnan, IEEE J. Quantum Electron. **31,** 1890 (1995).
10. A. E. Siegman, IEEE J. Quantum Electron. **27,** 1146 (1991).
11. C. Larat, M. Schwarz, J. P. Pocholle, G. Feugnet, and M. R. Rapuchon, Proc. SPIE **2381,** 256 (1995).
12. M. Tsunekane, N. Taguchi, and H. Inaba, Electron. Lett. **32,** 40 (1996).