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Quasi-continuous-wave and actively mode-locked diode-pumped Cr^{3+}:$LiSrAlF_6$ laser

François Balembois, Patrick Georges, and Alain Brun

Institut d'Optique Théorique et Appliquée, Unité de Recherche Associée au Centre National de la Recherche Scientifique No. 14, Université Paris-Sud, B.P. 147, 91403 Orsay Cedex, France

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We have developed a 500-mW cw diode-pumped Cr^{3+}:$LiSrAlF_6$ laser that produces 72-mW, quasi-continuous-wave output at 850 nm. In actively mode-locked operation, we obtained 100-ps pulses at 860 nm with 30 mW of average power. Pulses with durations of less than 130 ps have been measured between 820 and 880 nm.

Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) crystal has proved to be a useful crystal in the ultrashort-pulse domain. Its large emission band (800–1000 nm) has permitted the generation of femtosecond pulses by the Kerr-lens mode-locking technique.[1,2] Its high saturation fluence and its long fluorescence lifetime (67 μs) have permitted the amplification of ultrashort pulses up to the 150 mJ level in a flash-pumping scheme.[3] Moreover we have recently reported a cw krypton-laser-pumped regenerative Cr:LiSAF amplifier working at a high repetition rate (5 kHz) and producing 5-μJ energy pulses.[4] Unlike Ti:sapphire, Cr:LiSAF crystal has a red absorption band (600–700 nm), making it suitable for pumping by recently developed visible red diodes. Two methods of diode pumping have already been investigated. The first used an AlGaInP laser diode emitting near 670 nm to pump the crystal at the maximum of its absorption band. The best performance reported to date was roughly 20 mW of output power for 100 mW of cw pump power.[5] The second method, called wing pumping,[6] consists of pumping a highly doped Cr:LiSAF crystal (doping ratio higher than 33%) near the limit of the absorption band in order to use AlGaAs diodes emitting near 800 nm. Typical performances are 0.5 mW for 18 mW of input pump power from a GaAlAs diode emitting at 779 nm.[7]

The development of new high-power AlGaInP laser diodes (500 mW and now 3 W by Spectra Diode Laboratories) opens up new areas in the study of diode-pumped Cr:LiSAF lasers. The higher available pump power will permit greater passive losses of such lasers and thus make the addition of intracavity elements possible. The diode-pumped Cr:LiSAF laser can now enter the short-pulse domain. Preliminary results on a tunable, actively mode-locked, diode-pumped Cr:LiSAF laser have been reported by French *et al.*[8] However, their laser had a relatively low efficiency and produced only a few milliwatts of average power with a pulse duration of 300 ps.

In this Letter we report a quasi-cw diode-pumped Cr:LiSAF laser producing 72 mW of power at 850 nm and tunable from 810 to 900 nm. By adding an intracavity acousto-optic modulator, we have obtained pulses as short as 100 ps at 860 nm with 30 mW of average power in active mode locking.

The laser diode (Spectra Diode Laboratories 7432) used is a single-stripe model, with a surface area of 250 μm × 1 μm, emitting a cw power of 500 mW at 668 nm. The output beam is nearly diffraction limited in the direction perpendicular to the junction but 20 times diffraction limited in the direction parallel to the junction. This shows that it is difficult to focus the pump beam tightly while maintaining a good overlap between the pump mode and the cavity mode. For this problem to be solvable, the pump absorption length must be as short as possible. In this experiment we used the most highly doped commercially available Cr:LiSAF crystal (5.5% in weight) from Lightning Optical Corporation. Moreover, through numerical calculations, we have attempted to find an optimal compromise between the spot size at focus and the divergence of the pump beam in the crystal. Our solution has led to a pump volume that stays inside the cavity mode along the absorption length. However, the use of a thin crystal inhibits efficient cooling, which will introduce thermal effects that we have to take into account.

The pump optics is illustrated in Fig. 1. An initial objective (f = 15 mm, numerical aperture 0.6) collimated the diode beam. An afocal cylindrical system with a magnification of 12 modified the beam in the direction parallel to the junction of the diode. A second objective (f = 50 mm, numerical aperture 0.5) focused the beam into the 2-mm-long Cr:LiSAF crystal. The overall transmission of the pump optical system is 76%. The cavity consisted of three mirrors. The first (highly reflecting at 760–960 nm,

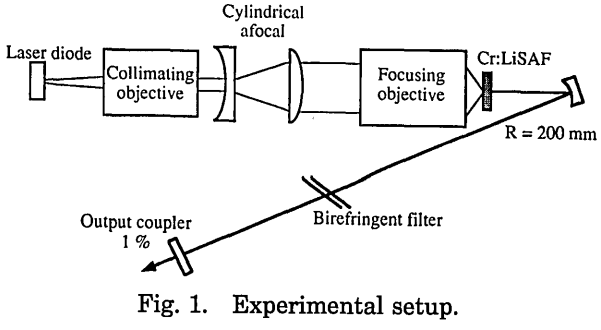

Fig. 1. Experimental setup.

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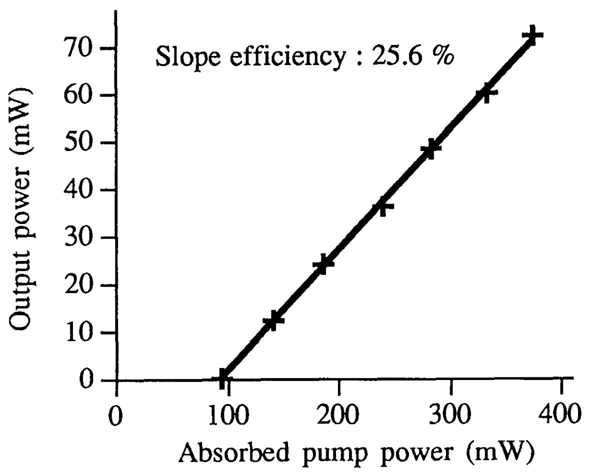

Fig. 2. Output power versus absorbed pump power in quasi-cw operation.

antireflecting at 670 nm) is directly coated onto the Cr:LiSAF crystal. The second is a curved mirror (highly reflecting at 800–900 nm) with a radius of curvature of 200 mm. The third is a plane output coupler with 1% transmission between 800 and 900 nm. The distance between the Cr:LISAF crystal and the curved mirror is 110 mm. The laser cavity configuration leads to a collimated beam between the curved mirror and the output coupler, making it possible to add intracavity components such as a birefringent filter or an acousto-optic or electro-optic modulator.

We operated the pump laser diode in quasi-cw operation (duty cycle 1/6, frequency 100 Hz) in order to avoid thermal effects in the crystal. In quasi-cw operation, this laser provided 72 mW of power at 850 nm for 376 mW of absorbed pump power with a threshold of 95 mW (Fig. 2). Note that the laser wavelength is shifted in the infrared compared with the maximum of the emission cross section of Cr:LiSAF (830 nm). We attribute this fact to the antireflection coating on the crystal, centered at 850 nm. The slope efficiency η_S is 25.6%. In order to compare the performance of this diode-pumped laser with that of a krypton-pumped Cr:LiSAF laser, we calculated the intrinsic slope efficiency[9] η_0,

$$\eta_0 = \eta_s(T + L)/T\,, \qquad (1)$$

where T is the transmission of the output coupler and L represents the passive losses per round trip. L is determined from the analysis of Findlay and Clay[10] and is found to be equal to 0.85%. We obtained an intrinsic slope efficiency of 47%, which is close to that obtained with a krypton-pumped Cr:LiSAF laser (53% reported[9]). The laser output is linearly polarized, parallel to the c axis of the crystal. The output beam is TEM$_{00}$ but slightly elliptical as a result of uncompensated astigmatism introduced by the off-axis curved mirror. The ratio between the two dimensions of the ellipse is 1.3. We achieved tunability by adding a two-plate birefringent filter inside the cavity. The laser was tunable between 810 and 900 nm and was limited in the long-wavelength range by the coating on the curved mirror.

In order to obtain picosecond pulses, we added an acousto-optic modulator to the cavity. This modulator worked at 125 MHz while the cavity frequency was adjusted to 250 MHz. In the first 100 μs of laser operation, the pulse amplitude was modulated by relaxation oscillations. After this, the pulse amplitude was stable over the entire 1.6-ms pumping window. A typical autocorrelation trace is given in Fig. 3. Each line of the experimental autocorrelation represents laser operation over a pumping window. The sweep frequency of the autocorrelator is 1 Hz. Assuming a Gaussian pulse profile, we measured a pulse duration of 100 ps at 860 nm. The difference between the experimental results and the theoretical fit in the wings of the autocorrelation was certainly due to the transient regime in the first 100 μs, where the buildup time of the pulses from nanosecond to 100-ps duration must be taken into account. The average power was then 30 mW for 376 mW of absorbed pump power, and the threshold was 140 mW. We achieved tunability from 820 to 890 nm (Fig. 4). The pulse duration varied between 100 and 150 ps in this wavelength range (Fig. 5).

In conclusion, we have demonstrated a Cr:LiSAF laser pumped by a 500-mW red laser diode. The slope efficiency obtained in quasi-cw operation is similar to that obtained with Cr:LiSAF pumped by a

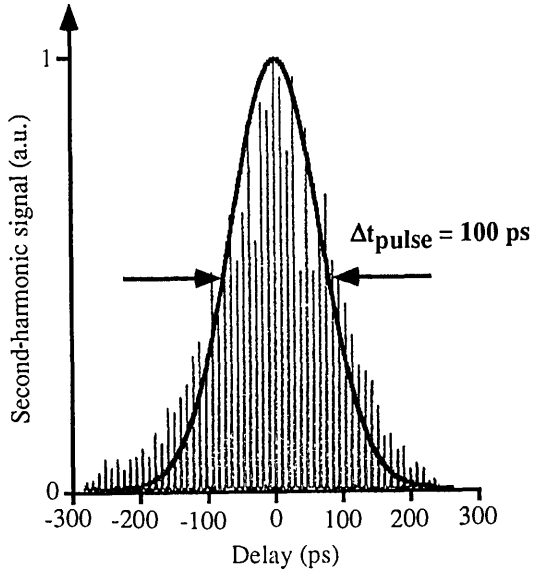

Fig. 3. Autocorrelation trace.

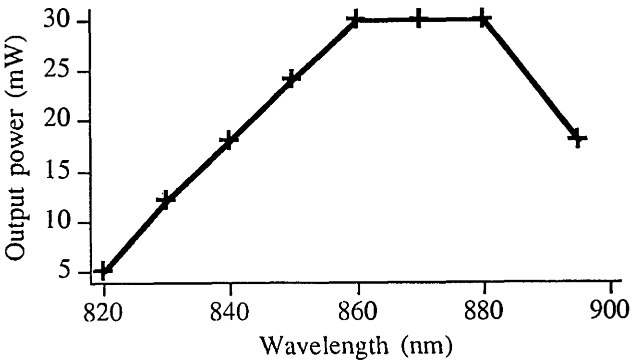

Fig. 4. Tunability in mode-locked operation.

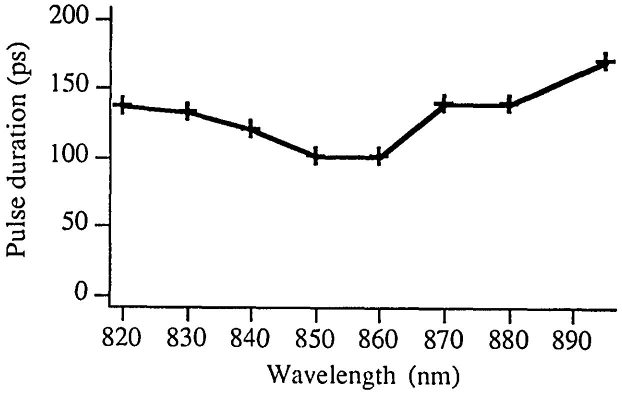

Fig. 5. Pulse duration versus the wavelength.

krypton laser. This fact shows that the poor quality of the diode beam is not a limitation for high-power diode-pumped Cr:LiSAF lasers. In this Letter we presented a tunable actively mode-locked diode-pumped Cr:LiSAF oscillator. This laser provided pulses near 100 ps with 30 mW of average power at 860 nm with a tunability over 70 nm. These experimental results show that this compact all-solid-state source of short pulses could be useful for many applications, including spectroscopy experiments. These results also suggest that it will be possible in the near future to produce femtosecond pulses by using the Kerr-lens mode-locked technique in an all-solid-state diode-pumped laser.

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