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Tunable and High-Energy Q-Switched Operation of an Alexandrite Slave Ring Laser

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Abstract. Narrow bandwith tunable Q-switched operation of an alexandrite oscillator was used for injection-locking of a high-energy alexandrite slave ring laser. Pulses with up to 600 mJ in energy over a 600 cm^{-1} tuning range were obtained.

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Laser sources tunable in the visible spectrum have demonstrated their great usefulness in a lot of chemical and physical applications. Furthermore, they provide primary sources to extend the frequency tunability both in the ultraviolet and infrared regions. In the high-energy pulsed domain, the most common system is obtained by pumping a dye laser by a powerful fixed-frequency laser. More recently tunable solid-state vibronic lasers operating at room temperature have been demonstrated to be of practical interest. Among them alexandrite ($BeAl_2O_4:Cr^{3+}$) [1] showed very attractive characteristics. Indeed, both the mechanical properties and the long storage time (260 μs) of alexandrite permit to obtain an efficient tunable Q-switched operation.

In order to achieve a high repetition rate high intensity Raman laser tunable in the infrared, one of the best solution consists in starting from a high-power tunable alexandrite laser. Such high powers can not be easily reached with only one oscillator cavity [2], and therefore an oscillator-amplifier chain is required. Furthermore, the alexandrite laser gain being low [3], energy extraction from an amplifying rod is only possible by using an intracavity amplification scheme. Consequently, a simple technique seems to be a frequency selection with a low-energy master oscillator using low-damage threshold highly dispersive elements and an extraction of the energy from a high-energy slave laser.

In this paper, we present the experimental results obtained by applying the injection-locking technique [4] to the case of alexandrite lasers. A high-energy ring alexandrite laser is forced to oscillate on the well-defined frequency of an injected low-energy pulse traveling from a master alexandrite oscillator. Thus a very simple and efficient technique for decoupling the two cavities is demonstrated.

The experimental set-up is presented in Fig. 1. Basically the master oscillator was an Allexite 7511 Model from Apollo Laser, Inc., but except for the laser head and the Pockels cell, all the laser cavity has been modified. The double elliptical laser head incorporated two linear Xenon flashlamps and an alexandrite rod (5 mm in diameter and 10 cm long). In order to obtain the widest tunability, the alexandrite rod was maintained at 60 °C by means of a desionized water cooling unit.

The lab-made laser resonator (120 cm in length) consisted of an output dielectric mirror and a littrow-

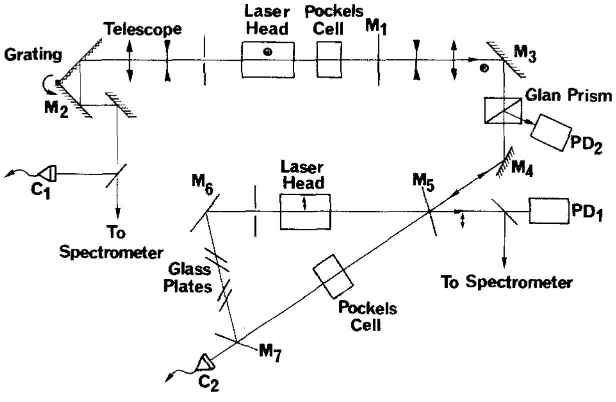

Fig. 1. Experimental setup. The polarizations of the beams are indicated by ⊙ and ↕ for vertically and horizontally polarized beams, respectively

mounted diffraction grating. The output coupler ensured a 75% reflectivity and a 85% reflectivity was estimated for the first-order reflection of the grating (1224 grooves per mm). The zero-order reflection was used as a second output for the cavity through reflection on mirror M_2 placed at a right angle to the grating. The rotation axis of the entire system was chosen at the intersection between mirror and grating planes, thus ensuring the same output beam whatever the laser wavelength. Furthermore, a telescope ($f_d = -50$ mm, $f_c = 250$ mm) permitted to increase the beam cross-section on the grating. A Pockells cell with longitudinal field operating in the quarter-wave regime was used to Q-switch the cavity. Switching the voltage off permitted the laser action to be created with a defined polarization (vertical in our case) because of the gain dichroism. A 3.5 mm hole limited the beam in the cleanest spatial region of the rod.

The master oscillator pulse was injected into the slave ring cavity through the mirror M_5 by means of mirrors M_3 and M_4. The ring cavity (110 cm in length) consisted of three mirrors, one of them (M_5) having a 77% reflectivity and the two others (M_6 and M_7) being totally reflecting. The laser head from Apollo Laser, Inc. contained two simmered flashlamps in the same geometrical configuration as the master-oscillator laser head. The alexandrite rod was 9.52 mm in diameter and 10 cm long. In fact, the total beam diameter was limited to 7 mm because the rod quality was not good enough to use its whole cross section. A telescope ($f_d = -100$ mm, $f_c = 250$ mm) placed between the two cavities matched the slave laser-beam cross section. The lab-made pulse forming network could yield 215 J per flashlamp with the duration of electric pulses of 190 μs at 90% energy. The present repetition rate (0.5 Hz) was only limited by the 500 W power supply. The master oscillator was temporally synchronized to the slave laser in order to ensure the best laser energy output. The desionized water-cooling unit used for the master oscillator also provided a 60 °C temperature for the flashlamps while a second water cooling unit maintained a 80 °C temperature for the alexandrite rod, thus increasing the gain.

The ring cavity also contained a Pockels cell with longitudinal field and four glass plates at the Brewster angle which provided 75% losses for the vertical polarization while the alexandrite rod was oriented for a maximum gain on the horizontal polarization. A 2330 V quarter-wave voltage was sequentially applied before laser triggering to one electrode of the Pockels cell, the other one being grounded. This allowed for blocking laser action. A high speed photodiode (C_1) detecting the master-oscillator pulse permitted to Q-switch the slave laser with a suitable delay. Q-switching was accomplished by applying on the other electrode of the Pockels cell a 50 ns rise-time step electrical pulse having exactly the 2330 V voltage. In this way the voltage difference was zero between the electrodes of the Pockels cell and lasing could occur.

The key point in such master-slave lasers was to achieve the best decoupling between the two cavities. The ring cavity had the obvious advantage to spatially decouple slave and master cavities during injection – locking operation: indeed, in this case, the output of the ring cavity was uni-directionnal. Without injection – locking, the ring laser cavity had two equivalent output directions: one of the two beams could induce optical damages in the master-oscillator cavity. In both cases the output energy of the ring cavity was horizontally polarized. The decoupling was achieved by means of a Glan prism placed between the two cavities. The output energy of the vertically polarized master-oscillator beam was transmitted through the Glan prism, whereas the horizontally polarized beam from the slave laser was totally deflected. Storage of the master oscillator vertically polarized energy in the slave cavity was made possible since it was occuring before Q-switching of the slave laser and after passing through the Pockels cell which acted as a quarter-wave plate.

A joulemeter PD_1 and a photodiode C_2 provided energy and pulse duration measurements for the output laser pulse. Another joulemeter PD_2 permitted to measure after deflection on the Glan prism the energy eventually directed back towards the master oscillator. A spectrometer and a photodiode array were used for the frequency measurements of both oscillators. A IBM Personal Computer recorded photodiode array signals, thus providing a frequency spectrum for each shot. Furthermore, this computer was coupled to a stepping motor in order to frequency scan the whole laser system via grating rotation.

The output characteristics of the master and slave oscillators are listed in Table 1. For the master oscillator, the tuning range is indicated for a minimum output energy of 5 mJ which represented the energy for an efficient injection-locking of the slave oscillator. The present limitation of the tuning range on the red side of the spectrum was due to an increase of 15% in losses between 0.76 and 0.78 μm because of inadequate coating of the optical elements. Pulse energies delivered by the slave laser were plotted versus wavelength and electrical pumping rates of 1.28 and 1.43 times the threshold value (280 J) (Fig. 2). Measurements were performed only for energies smaller than 600 mJ in order to avoid optics damage. 80% of this energy was contained in a 0.5 mrad total divergence angle, which was a few times larger than the diffraction limited angle for our 7 mm diameter beam. This limitation was probably due to the alexandrite-rod

Table 1. General characteristics of the master-slave system. (λ: wavelength; E: energy per pulse; Δt: pulse duration at FWHM; $\Delta\sigma$: spectral bandwidth at FWHM; θ: total divergence angle at 80% energy; ϕ: beam diameter)

	λ[μm]	E[mJ]	Δt[ns]	$\Delta\sigma$[cm^{-1}]	θ[mrad]	ϕ[mm]
Master oscillator	0.725–0.775	>5	250–300	0.2	1	3.5
Slave oscillator	Fig. 2	Fig. 2	120–200	0.2	0.5	7

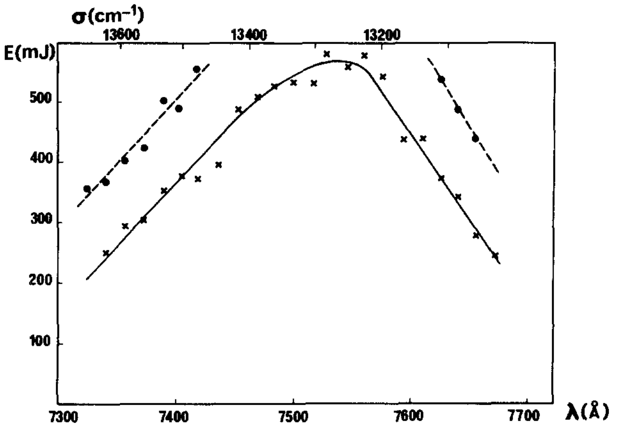

Fig. 2. Energy output of the whole system during injection – locked operation versus wavelength. Solid and dashed lines are for 1.28 and 1.43 times the threshold pumping energy, respectively

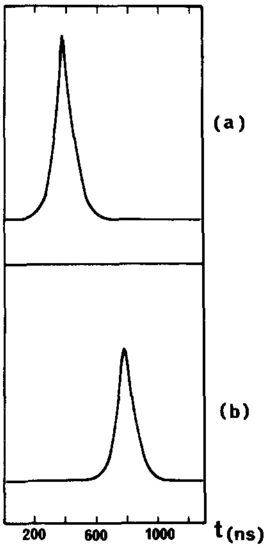

Fig. 3a and b. Buildup time of the pulse in the ring cavity (a) good injection – locking (b) free-running

inhomogeneities. The tuning range was limited to a 618 cm^{-1} spectral region between 7325 and 7673 Å. For shorter or longer wavelengths, the gain-losses ratio was greater than 1 at the band center and not at the injected wavelength. Broadband operation around 7515 Å was consequently observed with the same amount of energy in the two directions of the ring cavity: indeed, the laser gain at 7515 Å is about twice the gain at 7325 Å [3]. The tunability could easily be increased by means of a low dispersion element in the ring cavity such as a prism, for instance. In this case the tuning range would be close to that of the master oscillator. It must also be noted that for all wavelength a 10 mJ energy was emitted is the opposite direction during injection-locking operation. It was probably due to backscattering on the optical elements placed inside the ring cavity. Accordingly to the rate equations, the pulse duration at FWHM depended on the amount of energy extracted from the laser cavity. 200 and 120 ns pulse durations corresponded to 200 and 500 mJ slave energies, respectively, while a longer duration (250–300 ns) was observed for the low-energy master oscillator. The buildup time of the laser pulse in the slave cavity is shown in Fig. 3. In agreement with the rate equations it was shorter for the injection-locking operation (Fig. 3a) than in free-running operation (Fig. 3b). The spectral bandwidth of both master-oscillator and slave-laser pulses was measured with a Fabry-Perot interferometer and found identical (0.2 cm^{-1}). It could be reduced by putting a Fabry-Perot etalon in the master oscillator cavity. The injection-locking rate was also measured at 7325 Å by comparing the broad-band spectrum around 7515 Å with and without injection – locking. A minimum value of 99% was found limited by the measurement precision.

In conclusion, a simple experimental setup consisting of a master alexandrite oscillator and a slave ring alexandrite laser has been tested: pulses with an energy as high as 600 mJ have been generated with a tuning range of 618 cm^{-1} which could be greatly increased by using a prism in the slave cavity. Work is presently in progress to replace the simmer, power supply and the pulse-forming network system of the slave laser in order to increase the present 0.5 Hz pulse repetition rate up to 10 Hz.

This 600 mJ source will then act as a pump for an infrared intense laser source of nanosecond duration pulses continuously tunable in the infrared. These pulses will be obtained through pulse compression via Raman Induced Cavity Dumping described elsewhere [5, 6]. Working at a 10 Hz pulse repetition rate, this source will multiply by 150 times the pulse repetition rate of our present infrared source formed by a rubypumped dye laser, frequency down-shifted by stimulated Raman scattering [7].

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