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REPETITIVELY PULSED Cr:LiSAF LASER FOR
LIDAR APPLICATIONS

Author(s):

Tsutomu Shimada, CST-5
James W. Early, CST-6
Charles S. Lester, CST-5
Nigel J. Cockroft, CST-6

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**Tsutomu Shimada, James W. Early, Charles S. Lester and
Nigel J. Cockroft**

**Chemical Science and Technology Division
Los Alamos National Laboratory
MS-E535, P.O.Box 1663
Los Alamos, NM 87545
Phone: (505)-667-8391
Fax: (505)-665-4637**

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Abstract:

A Cr:LiSAF laser has been successfully operated at time averaged powers up to 11 W and at pulse repetition rates to 12 Hz. During Q-switch operation, output energy as high as 450 mJ (32 ns FWHM) was obtained. Finally, line narrowed Q-switched pulses (<0.1 nm) from the Cr:LiSAF laser were successfully used as a tunable light source for lidar to measure atmospheric water content.

Introduction:

Cr:LiSAF as a flashlamp pumped laser material^{1) -3)} has received considerable attention recently due mainly to 1) its broad gain bandwidth which provides wide lasing wavelength tunability and ultrashort pulse amplification and 2) a reasonably long lifetime (67 μ s) which supports Q-switched operation.

In a particular application such as lidar for remote sensing, the laser is required to operate with a reasonable repetition rate to provide reliable information by averaging over many pulses. We have been developing a repetitively pulsed tunable Q-switched Cr:LiSAF laser system especially for lidar applications.

Experiments:

A Cr:LiSAF rod with a length of 10 cm and a diameter of 0.635 cm was used for these experiments. The rod was doped to a Cr concentration of 1.5%. A dual xenon flashlamp pump cavity, containing a Pyrex insert surrounded by BaSO₄ to provide a broadband, diffusively reflecting surface to the flashlamp light, was used to pump the rod.

The flashlamp power supply was designed to produce a 60 μ s(FWHM) wide current pulse into the two flashlamps connected in series. Pump length was limited to 8.9 cm (3.5 in) due to the dimensions of the pump cavity and the discharge gap of the flashlamps. The laser resonator consists of a 2-m radius of curvature, high reflectivity, dielectric mirror and a flat, dielectric output coupler. A cavity length of 61 cm was used. We used 1 to 3 plate birefringent tuner for the wavelength tuning, Pockells' cell for Q-switching and 2 etalons for narrow linewidth operation. Block diagram of the laser setup with all the intracavity optics are shown in Fig.1.

It should be noted that we used a pH-7 buffer solution as a cooling water to minimize the weight loss of the Cr:LiSAF crystal due to the dissolution to the cooling water, and we have not seen any measurable weight loss of the Cr:LiSAF crystal over six month period.

Figure 1. Block diagram of the typical laser setup when all the intracavity optics are placed.

Results and Discussions:

i) Free Running Mode

Figure 2 shows the dependence of laser output pulse energy on the stored electrical energy at the capacitor for several different reflectivities of output coupler. The laser was operated at a 1 Hz repetition rate in the free lasing mode at a wavelength of 853 nm without any intracavity dispersive elements. As shown in the Fig.2, increasing the reflectivity of the optical cavity, decreases oscillation threshold input energy, whereas, slope efficiency becomes maximum at a output coupler reflectivity about 60%. A maximum output energy of 3.1 J was obtained with an electrical energy input to the flashlamp of 80 J. A maximum slope efficiency of 4.9% and an over all efficiency of 3.8% was obtained using the 60% reflective output coupler. Maximum laser output energy obtained shown in Fig.2 is not limited by the optical damage of the crystal nor the optical elements of the cavity used, so that one will be able to obtain much higher output energy and better overall efficiency with a higher input energy. Typical waveforms observed for free running mode had a gain Q-switched pulse followed by a 30-50 μ s long relaxation oscillation depending on the pump energy.

Figure 2. Output energy dependence on stored energy for various reflectivities of output coupler. (free running mode, @ 853 nm)

We have also measured the dependence of average laser output power on pulse repetition rate for electrical energy input to the flashlamps of 40 J/pulse and 75 J/pulse (see Fig.3). When compared to the output pulse energy at a 1 Hz rate, we typically observe a reduction in pulse energy at higher pulse rates for both input energy case as shown in Fig.3. However, compared to the output energy at a 1 Hz pulse rate, the pulse energy at 5 Hz dropped to 80% (2.05 J compared to 1.64 J). At

a higher pump energy of 100 J, an average output power of 11 W (2.2 J/pulse) was obtained during 5 Hz operation (a reduction in pulse energy of 24% from that measured at 1 Hz). We also operated the laser at repetition rates up to 12 Hz with a lower pump energy of 40 J. With the same cavity optics, a maximum average output power of 4.3 W was obtained (a 37% reduction in pulse energy compared with the 1 Hz operation). We attribute the decrease in pulse energy at higher repetition rates to increased diffraction losses within the cavity due to thermal lensing in the Cr:LiSAF rod, which can be compensated by the proper cavity design. Although energy lifetime shortening and subsequent gain reduction in the Cr:LiSAF rod can occur at high thermal loading, measurements of the small signal gain as well as the fluorescence waveform show no dependence on repetition rate up to our maximum time averaged pump power of 480 W.

After the repetitive high average power experiments, we observed a couple of micro-crack formations in the Cr:LiSAF crystal due to the high thermal loading. This thermal fracture considered to be occurred during average flashlamp input power of 480-500 W. In spite of the micro-crack formation, we could not see any changes in the laser performances during experiments.

Figure 3. Average power dependence on repetition rate for different stored energy (free running mode @ 853 nm). Maximum average power obtained was 11.3 W, (Estored=100 J, 5 Hz, R=40%).

Spectral measurements of the flashlamp's output transmitted through the Pyrex insert of the pump chamber showed a peak emission at the wavelength of 450 nm. The peak wavelength was found to be independent of lamp energy over the 35-100 J range of lamp energy investigated. This is due mainly to the 350 nm uv transmission cut-off which is exhibited by Pyrex insert. We did observe, however, a rapid increase in the emission at 450 nm relative to that at 650 nm as

lamp energy increased. This may result adversely in increased thermal loading to the Cr:LiSAF crystal due to multiphonon relaxation between the $^4T_{1g}$ and $^4T_{2g}$ levels. Considering the lower thermal fracture limit of Cr:LiSAF crystal (4.5 W/cm^2)⁴⁾, improvements of the flashlamp color temperature match with the Cr absorption bands, especially to the 650 nm band, is needed to reduce a thermal loading for the higher average power operation. This may also be accomplished without significant degradation to the pumping efficiency by utilizing a large bore flashlamp and/or fluorescence converter.

ii) Q-Switched Mode

In addition to the repetitive, free-lasing operation of the Cr:LiSAF laser, we have successfully demonstrated Q-switched lasing. Q-switched pulses with an energy of 450 mJ and a pulsewidth of 32 ns (FWHM) were obtained during 1 Hz operation for an electrical input of 45 J/pulse to the flashlamps. Output energy stability was better than 5.0%. The Q-switched laser was also operated at a repetition rate of 5 Hz to provide an output energy of 90 mJ/pulse at a lower pump energy. However, we observed optical damage in the form of seriesed void formation in the crystal as Richardson et.al. reported⁵⁾ when the electrical input energy to the flashlamp was increased to 50 J.

Figure 4. Q-switched output energy and pulsewidth dependence on stored energy for different wavelength. (with a birefringent tuner without etalon).

Tuning of the laser's output was also demonstrated over the wavelength range of 820 to 890 nm using a single and triple plate birefringent tuner, and this was limited by the coating of the optics used for the laser cavity centered at 850 nm. Figure 4 indicates Q-switched output energy and pulsewidth dependence on the stored energy at two different wavelengths. Since small signal gain peak locates in the vicinity of 850 nm, higher

output energy and shorter pulse width were obtained at 845 nm than at 820 nm with a same stored energy. However, pulsewidth at both wavelengths were to be the close value of 30 ns when the laser was operated at stored energy of more than 40 J. Typical linewidth with a birefringent tuner was 3 nm for single plate tuner and 0.7 nm for 3 plate tuner, respectively. Linewidth as narrow as less than 0.1 nm was measured with an additional set of intracavity etalons.

iii) Diode Injection Seeded Q-Switched Mode

For further narrower linewidth operation, we have worked on single mode diode injection seeding experiment. A single mode CW output (@890 nm, 8 mW) from the diode laser was introduced into a Cr:LiSAF laser cavity through the output coupler. Cr:LiSAF laser for this experiment consists of an output coupler ($R=40\%$), 1 mm ϕ aperture for a single transverse mode, Cr:LiSAF rod, E/O switch, polarizer, birefringent tuner and HR(2m C.C).

To avoid an optical damage and wavelength instability of the diode laser due to the feed back light from the Cr:LiSAF laser, we used a pin hole spatial filter and 2 Faraday isolators in series (2 x 30 db). Spatial filter also was used to match the mode sizes of the two lasers. By carefully observing the Q-switched laser waveforms with injection, we could see the two mode beating with a frequency of longitudinal mode spacing (modulation depth of 30-40%) at the intracavity injection power range from 40 μW to 330 μW . Although we did not measure the linewidth precisely, an etalon with 30 GHz free spectral range showed Cr:LiSAF laser linewidth was comparable to that of single mode diode laser we used. Typical laser output energy during this experiment was 10 mJ/pulse with a pulsewidth of 50 ns (FWHM).

It may be well worth to mention that we observed optical damages during Q-switch operation; one case with a multiple transverse mode operation without intracavity aperture at an output energy of more than 450 mJ (beam diameter : 6.35 mm ϕ) as mentioned before, the another case with a single transverse mode operation at an output energy of 12 mJ (beam diameter : 1.0 mm ϕ). For both cases, a damage threshold fluence was about 1.5 J/cm^2 for the laser pulses with a pulsewidth of 30-50 ns (FWHM).

iv) Cr:LiSAF Lidar Demonstration

A LANL miniature lidar system which normally operates at 1.06 μm was used as the Cr:LiSAF lidar receiver. Laser photons scattered backwards towards the lidar by the atmospheric aerosol particles are collected by an 8" diameter, f/10 telescope and focused onto a silicon avalanche photodiode (APD) mounted on the back of the telescope. A 10-nm bandpass filter (at 820- or 830-nm) was used to block out solar background, and this allowed night and day time operation. In this configuration, the miniature

lidar telescope was aligned with the optical axis of the Cr:LiSAF transmitter giving a single line-of-sight with which to make measurements. By recording single line-of-sight data as a function of time (referred as "time-domain" scans) one can monitor the temporal changes in atmospheric aerosol load over the spatial range of interest. This lidar system was operated to evaluate its performance characteristics such as (1) determining the lidar detection range and sensitivity by monitoring atmospheric changes at a fixed wavelength, and (2) measuring the atmospheric water content by tuning the laser wavelength in 818 to 870 nm region.

With transmitter output pulses of 100 mJ, 50 ns (FWHM), we could detect the back scattered signal as far as more than 100 km during the daytime with a relatively high elevation angles. For the narrow linewidth transmitter configuration (35 mJ, 65 ns, linewidth < 0.1 nm), measured results indicate return signal at 820.1 nm (on resonant to the water absorption line) from the mountain at 12 km was about 1/16 of the signal measured at 824.0 nm (off resonant to the water absorption line) whereas measurements with a line width of 0.7 nm gives an extinction of only 1/2. Further lidar experiments are now under way.

Table 1. Summary of the demonstrated values of Cr:LiSAF laser system.

(rod dimension : 1/4" ϕ x 4", [Cr ³⁺]=1.5%)		
Single Pass Gain at 850nm	5.2	(@ 1 Hz, 100 J/pulse)
<u>Free Running Mode:</u>		
Output Energy	3.1 J	(@ 1 Hz, 80 J/pulse)
Slope Efficiency	4.9 %	
Repetitive Operation	4 W	(@ 12 Hz, 40 J/pulse)
	11 W	(@ 5 Hz, 100 J/pulse)
Pulse to Pulse Stability	< +/-2 %	
<u>Q-Switch Mode:</u>		
Output Energy	450 mJ	(@ 1 Hz, 45 J/pulse)
Pulsewidth	32 ns	(@ 1 Hz, 45 J/pulse)
Linewidth	3.0 nm	(1 plate birefringent tuner)
	0.7 nm	(3 plate birefringent tuner)
	<0.1 nm	(2 additional etalons)
<u>Diode Laser Seeded Q-Switched Mode:</u>		
(Single Transverse Mode Operation at 890 nm)		
Power of the Seeder	8 mW	(40 to 330 μ w inside of the cavity)
Output Energy	10 mJ	
Pulsewidth	50 ns	
Linewidth	< 1 GHz	(2 mode beating was observed)

Conclusions:

We have successfully designed and developed a repetitively pulsed, tunable, Q-switched Cr:LiSAF laser system for lidar applications, and performances of the Cr:LiSAF laser system are summarized in table 1. To our knowledge, this is the first flashlamp pumped Cr:LiSAF laser system used as a tunable light source for lidar application. We observed a thermal fracture of the Cr:LiSAF rod in the form of micro-crack formations

with a average flashlamp input power of ~ 500 W. Optical damages were observed in the Cr:LiSAF crystal during a Q-switch operation (pulsewidth : 30~50 ns) and its threshold fluence was about 1.5 J/cm². For the higher average power and/or higher intensity Q-switched operation, design parameters such as thermal lensing effect, thermal fracture limit and optical damage threshold value are the ones of the most important issues for a Cr:LiSAF laser system design.

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