

Compact LiF:F_2^- laser emitting at $1.14 \mu\text{m}$ using a passively q-switched Nd:YLF diode-pumped laser as excitation source

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Abstract --- The LiF:F_2^- laser has a unique, smoothly tunable emission spectra which ranges from 1050nm to 1310 nm and when frequency doubled, covers all frequencies in the visible spectra from the green to the red. Due to its tuning range, this laser has important applications in telecommunications. This is to our knowledge the first time that a diode pumped Nd:YLF laser is used as a pump source for this color center laser.

Key words --- Solid-state lasers, laser crystals, diode-pumped lasers.

I. INTRODUCTION

Color center laser have some very distinct advantages over other solid-state lasers like large and very smooth tunability and very high gain. The LiF:F_2^- color center laser was operated for the first time at room temperature in 1977 [1]. Today it is still one of the only stable color centers which is relatively easy to fabricate. It has a broad tuning range from 1070 to 1310 nm [2] and a conversion efficiency of up to 40% when pumped by a Nd:YAG laser. Its unique spectral range of lasing is important for optics communications. When frequency doubling is employed, this laser is capable of generating a smoothly tunable output from the green to the red (540nm – 655nm) with almost constant power [3,4]. A commercial version of this laser is fabricated in Russia [5].

Recent improvements in the long term stability of this color center have shown that this crystal is very effective as q-switcher for neodymium doped crystals lasers which are pumped by diode lasers. A very compact, simultaneously q-switched and self mode-locked high power Nd:YVO₄ laser was recently achieved by using a folded cavity with LiF:F_2^- color centers as passive absorbers [6].

The crystal has a very strong and broad absorption band peaked at 960 nm. Therefore, it can be pumped by a variety of sources like neodymium doped lasers, high power diodes emitting at 960 nm [7] and, more recently, ytterbium doped lasers [8]. Until 1995 there has been a strong effort to achieve cw lasing in this medium but most researchers only achieved quasi-cw operation and the best results so far are 0.2 % optical to optical efficiency [9] in cw operation. A very thoroughly conducted research in 1997 was not able to

establish the reason for the crystal's cw-incapability [10]. The general opinion is that there must exist a "bottleneck" in the center's pumping cycle which is due to some very long lived excited state [7,10]. This discovery led to the first directly diode pumped LiF:F_2^- laser [7]. In order to avoid long pump pulses, a 60 W, 976 nm diode laser bar was impedance matched to a pulsed diode driver by specially developed strip lines of a specific length, generating 100 ns pulses. An optical to optical efficiency of 4% was achieved. In the absence of this special technique, diode pumped neodymium and ytterbium lasers are still the most efficient and compact pump sources for LiF:F_2^- color center lasers. This is to our knowledge the first time that a diode pumped Nd:YLF laser is used as a pump source.

II. THE Q-SWITCHED ND:YLF LASER

We used a 20 W diode bar emitting at 797 nm as a pump source [11]. It has a total width of 1 cm which comprises 24 emitters, each measuring $1 \mu\text{m} \times 200 \mu\text{m}$ (height x width), with center to center spacing of 400 μm . The emitted beam is collimated in the fast direction (x-axis) by a factory installed, AR-coated non-cylindrical fiber lens of 440 μm diameter. A two-mirror beam-shaper [12] was used, to reconfigure the diode emission into a more circular beam with approximately equal M^2 factors in the x- and y-direction. A significant amount of diode array curvature was detected, which could be partially corrected with the help of the cylindrical, slow divergence axis (y-axis) collimating lens, inserted parallel to the fast axis in front of the diode [13], as shown in Fig. 1.

The temperature of the diode was fixed at 23.6 °C by means of a thermoelectric cooling plate connected to a closed loop temperature stabilization circuit of ± 0.1 °C precision. Heat was removed from the crystal and the diode's thermoelectric cooler by means of copper heat sinks with circulating chilled water from a commercial chiller. The final beam quality at the Nd:YLF crystal position was $M^2 = 61$ in the x-direction and $M^2 = 42$ in the y-direction with a maximum power of 16.8 Watt.

The single crystal was grown by the Czochralski technique under high purity argon atmosphere. It had a relatively low dopant concentration of only 0.8 mol%, generating peak absorption of 8 cm^{-1} at 792 nm for π polarized light (light polarized parallel to the crystals c axis). Due to the large

bandwidth of diode bars, their overlap with the small absorption features of the crystal is relatively poor. In our case we calculated an effective absorption of 4.8 cm^{-1} at the crystal pump face, which rapidly becomes smaller and is of 3 cm^{-1} at the end of the 9 mm long crystal sample. The small absorption coefficient makes it necessary that good mode matching is maintained between pump and laser in order to achieve a high coupling efficiency. The crystal sample was Brewster cut for π -polarization in order to minimize reflection losses at the laser entrance and exit facets.

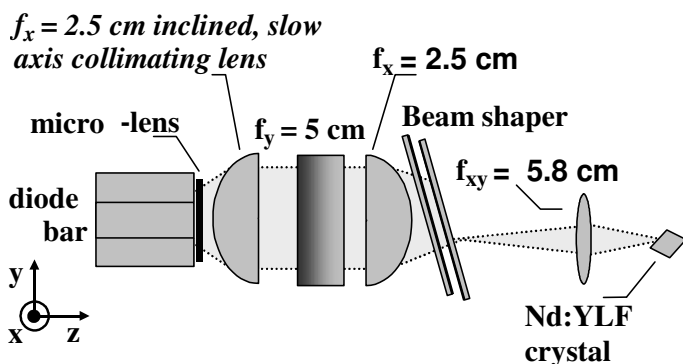


Fig. 1: pump set-up for the Nd:YLF crystal

The Nd:YLF laser cavity had a 1 m radius of curvature, high reflector mirror for $1.05 \mu\text{m}$ at the pump side with 80% transmission for the pump wavelength. Using a flat output coupler with 9% transmission, this cavity generated 3.6 watts for 12 Watt of incident pump power at the crystal face.

A 8 mm long LiF:F_2^- crystal sample was positioned next to the YLF crystal for passive q-switching as shown in Fig. 3. The saturable absorber had an optical density of 0.2 at the pump wavelength as shown in Fig. 4. The cavity length was optimized in order to achieve a pulse duration of the order of the excited state life time of the color center which is $\tau = 60 \mu\text{s}$. Increasing the cavity length generates a longer pulse duration but smaller peak power. For 12 cm of cavity length, the pulse duration was 32 ns and the peak power 800 kW/cm^2 . Smaller pulse durations and higher peak power can easily be achieved with a smaller cavity, but this may lead to damage in the color center crystal. At 5 cm cavity length the peak power was 3.6 MW/cm^2 and the pulse duration 14 ns. We experienced damage at the crystal surface at 3.6 MW/cm^2 .

A good compromise was achieved with an overall cavity length of 11.5 cm that generated a pulse duration of 25 ns at 142 Hz. The repetition rate was dictated by the diode driver which operated in the quasi-cw-regime for the reason described below. The average output power was 25 mW, the pulse energy $176 \mu\text{J}$ and the peak intensity 1.25 MW/cm^2 . This is about eight times above the saturation intensity of

LiF:F_2^- , ensuring therefore efficient lasing action of the color center in the coupled cavity.

In a passively q-switched pulse train, the first pulse has unique features like constant amplitude and time delay to the pump pulse, whereas the following pulses generally show large amplitude fluctuations and timing jitter. To achieve stable output pulses, the diode laser was operated at $380 \mu\text{s}$ pulse duration. This generated one single q-switched pulse of the Nd:YLF laser 40 μs after the diode laser emitted its pulse. Maintaining the diode's pulse duration just long enough to allow for one single q-switched pulse of the Nd:YLF laser permits very stable output with no timing jitter between the pulses as shown in Fig. 2.

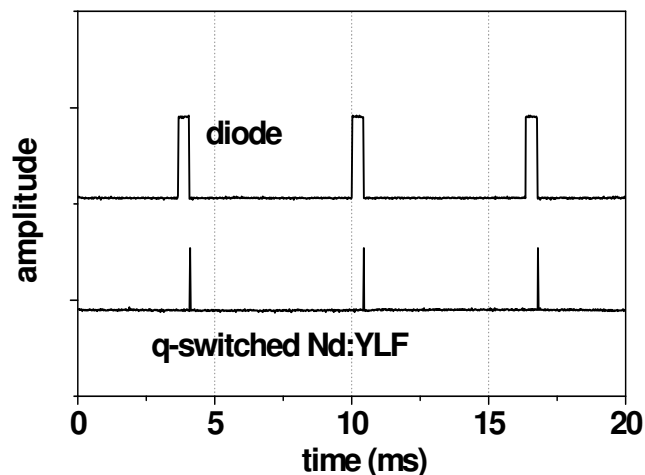


Fig. 2: Generation of q-switched pulses with no timing jitter by adjustment of the diodes pulse length.

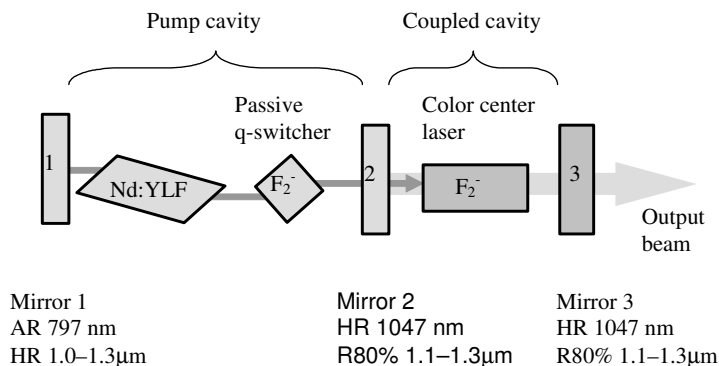


Fig. 3: Nd:YLF cavity with q-switcher and coupled LiF:F_2^- cavity.

III. THE LiF:F_2^- LASER AND SAMPLE PREPARATION

A 25 mm long LiF:F_2^- crystal was used as the gain media for 1.14 μm radiation inside a 3.5 cm long coupled cavity (see Fig. 3). The sample without antireflection coatings on its entrance and exit facets absorbed 25% of the pump power. A coupling mirror with 66% reflectivity for 1.05 μm and highly reflective for 1.14 μm was used. The output mirror had 2.7% transmission at 1.14 μm and was highly reflective at 1.05 μm in order to obtain a second pass for the non absorbed pump radiation inside the gain media.

It should be mentioned that the color center crystal in the coupled cavity has been prepared almost 10 years ago, demonstrating clearly that color centers can be stored and used over a very long period of time without fading away, when handled properly. This means basically maintaining the crystal at temperatures beneath 25 degrees and completely isolating it from UV light.

The smaller crystal, used to passively q-switch the Nd:YLF laser had been prepared specifically for this experiment. The F_2^- color centers of this crystal had been prepared in three different ways: 1) with the help of a ^{60}Co gamma radiation source, 2) using gamma radiation and neutrons from a nuclear reactor core (IEA-R1 from IPEN/SP) and 3) close to the core of the nuclear reactor. All samples came from the same crystal boule. Best results were obtained in the second case, where the temperature of the crystal can be controlled during irradiation (see Fig. 4). A residual absorption of 10% \pm 5% at the pump wavelength was measured and is probably due to parasitic centers. The effects of this residual absorption can be clearly seen at 1200 nm. Temperature is a crucial factor during irradiation and should be kept around 2 $^\circ\text{C}$. In the third case the temperature is no more controllable and the high dose of neutrons introduces high residual loss as can be seen in Fig. 4. Finally, in the first case, we also had no technical possibility to refrigerate the crystal which led to an increase of residual losses.

Although the results with the sample of case 2) were satisfactory, constant changes in the power of the reactor made it difficult to control the irradiation variables. We therefore searched for a new alternative. The last crystals were irradiated by a private company (Embrarad Ltda.) which uses gamma radiation from a ^{60}Co source but with controlled temperature and stable power. In Fig. 4, the bold trace represents irradiation with the ^{60}Co source under temperature controlled condition, the light trace the non-temperature controlled sample. It is clearly seen how much more centers are present in the main absorption band centered at 960 nm and how much less residual loss is present at 1200 nm.

Cavity output was detected with a pin photo diode of 100 ps rise time coupled to a digital oscilloscope [14] of 1.75 ns rise time. The output pulse is shown in Fig. 5. An approximated estimate of the pulse duration was done by fitting the signal with two Gaussians.

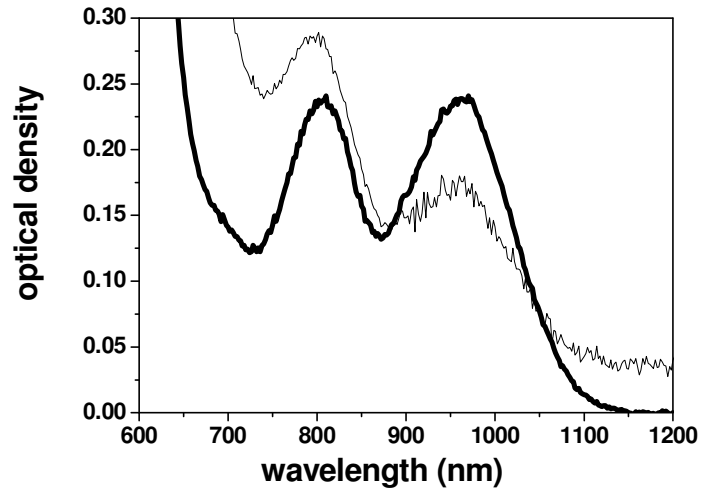


Fig. 4: Absorption spectra of the 8 mm long LiF:F_2^- sample irradiated with a ^{60}Co source. The bold trace is with irradiation at Embrarad Ltda and the light trace represents the irradiation at IPEN/SP.

The values were corrected by de-convoluting each Gaussian with the finite rise time of the oscilloscope. The final, calculated pulse duration at 1.14 μm is 4.7 ns (FWHM) with a delay of 8.8 ns to the 1.05 μm pump pulse.

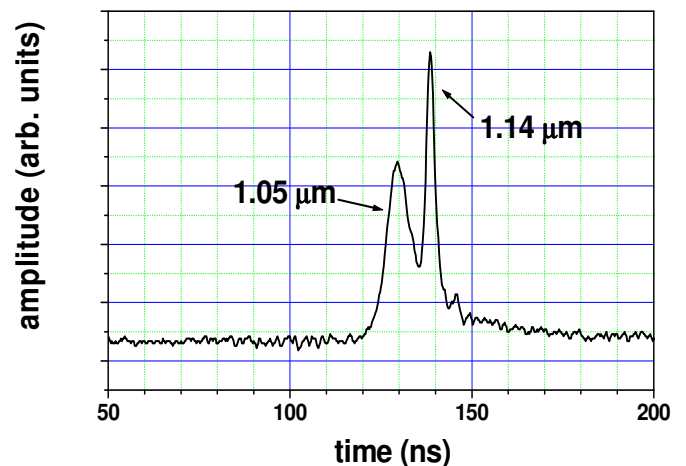


Fig. 5: Oscilloscope trace of the output pulse.

Measurement of the average output power was limited by the resolution of our power meter and was $2\text{mW} \pm 1\text{mW}$. The fact that the optical efficiency is less than 40% can be attributed to residual losses in the color center crystal. Although, this crystal

has proven very good long term stability, some of the F_2^- centers always migrate and end up as parasitic centers increasing the residual losses and diminishing the number of active centers. Certainly, a newly irradiated crystal would have achieved higher efficiencies, but at the time we did not have any long crystals for irradiation. The shorter crystals used for q-switching in the pump cavity are too short as to achieve enough inversion population for the lasing action.

Due to the proximity of the pump and lasing wavelength we were not capable to measure the energy of the 1.14 μm pulse separately from the 1.05 μm pulse. But from the fact that the responsivity of the PIN detector at 1140 nm is approximately a factor 10 lower than at 1047 nm, we can assume that more than 95% of the measured energy is contained in the 1.14 μm pulse. This corresponds to an estimated peak power of 2.2 (± 1.1) MW/cm².

IV. CONCLUSIONS

A LiF:F₂⁻ laser has been operated, pumped for the first time by a diode pumped Nd:YLF laser. The peak output power is more than enough in order to achieve efficient frequency doubling. Higher output powers can be achieved with crystals, presenting higher center density and lower residual losses.

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