Power scaling of LED-pumped alexandrite : the road to high gain multipass amplifiers

Elio Thellier[1], Hussein Taleb[1], Catherine Le Blanc[1], Pierre Pichon[1], Frédéric Druon[1], Patrick Georges[1] and François Balembois[1]
1. Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127, Palaiseau, France

Abstract: Our experiment demonstrates that LED-pumping through luminescent concentrator enables sufficient pump power for viable alexandrite amplifier gain. In 10 passes we obtain a gain of 19 with 10 W output power, for 50 µs pulses at 20 Hz and 760 nm.

Alexandrite (Cr^{3+}:$BeAl_2O_3$) is a well-known laser crystal with interesting and unique properties. It presents a 100 nm wide emission spectrum centred on 755 nm, which can support ultra-short pulse amplification and tuneable laser systems [1]. This spectral range is of interest for LIDAR applications [2] including detection of water vapour, oxygen, potassium (770 nm) [3] and iron [4] after second harmonic generation. In addition, its emission located in the therapeutic window is potentially valuable for imaging through biological media [5].

Its broad absorption spectrum from 400 to 650 nm offers many pumping options : it has already been pumped by flashlamps in dermatology [6], red [7,8] and blue [9, 10] laser diodes. It has also been LED pumped via luminescent concentrator emitting in the yellow-orange [11]. Despite an intrinsically short lifetime of the higher-lying $^4T_2$ laser level (6.6 µs), its coupling with the metastable lower-lying level ^2E results in an effective radiative lifetime of 260 µs [12], allowing good energy storage for Q-switching operation or amplification. This level coupling also causes the small signal gain of alexandrite to increase with temperature up to 100°C facilitating high average power utilisation [12].

However, alexandrite is generally used in laser oscillators but rarely in amplifiers due to its low emission cross section. While a small signal gain of a few units can be achieved with flashlamp pumping, much lower values have been reported with semiconductor pumping [8-10]. The main limitation is related to the power available for red laser diodes, typically limited to hundreds of watts [4]. To reach a significant gain, it is then necessary to build multipass amplification. A gain of 2 in a four passes configuration has been previously reported [2] and a gain of 4 for an eight-passes one [11]. In this work we report the highest gain ever obtained with an alexandrite pumped by semi-conductors. The key point lies in the power scaling offered by LEDs that is several orders of magnitude higher than that of laser diodes.

In our setup, we use 3392 blue LEDs arranged in two panels in order to pump a Ce:YAG luminescent concentrator (LC) on its both large faces (Fig1.a insert). The Ce:YAG crystal absorbs blue (450 nm) power and its fluorescence is partially trapped by total internal reflections and guided towards the output face. Ce:YAG emits between 550 nm and 650 nm, matching perfectly the alexandrite absorption band. Its innovative output face cut at 45° (insert Fig1a) improves the LC optical efficiency by 30 % in comparison to the last report [11]. This face is directly glued to the alexandrite crystal leading to a robust transverse pumping. The pump power delivered to the alexandrite reaches 2.9 kW, more than twice higher than in the previous setup [11]. This LED pumping module has been designed to operate up to 100 Hz, with ceramic PCB for the LEDs and water cooling.

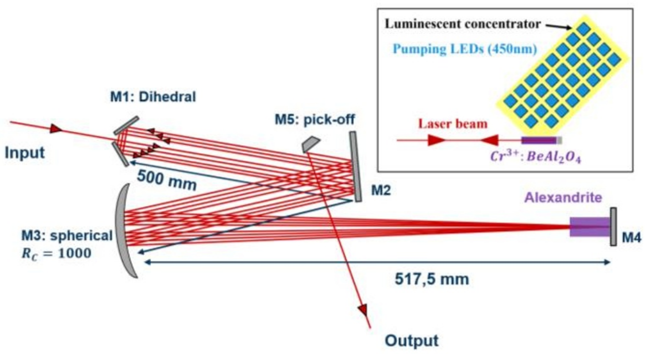

Figure 1a: Diagram of the folded confocal multipass amplifier. M1 to M5 are HR at 760 nm. In the insert: alexandrite LED pumped via luminescent concentrator with an optimized output face at 45° (surface of 1 × 20 mm)

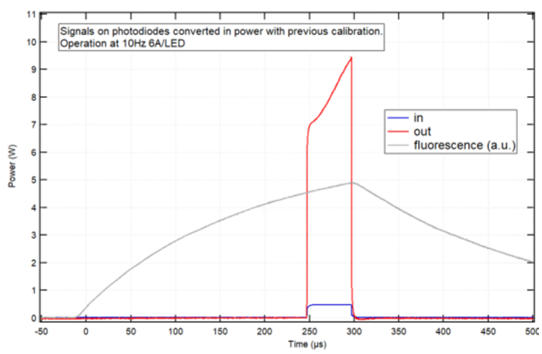

Figure 1b: Temporal signature of laser signal before (blue) and after (red) amplification. Fluorescence of alexandrite (grey) over pump duration is represented in arbitrary unit.

In order to increase the number of passes, we use a slab geometry for the alexandrite that opens the possibility for signal beams to propagate in a plane at different angles without constraints (Fig 1a). The dimensions of the alexandrite crystal are $1 \times 10 \times 25$ mm. The alexandrite amplifier is seeded by a single-frequency laser diode at 760 nm providing 0.5 W in continuous wave operation, which is temporally carved with an acousto-optic modulator. This setup enables synchronization of the seed at the end of the pulse pump where the gain is maximum (Fig 1b), and offers adaptability in pulse durations. The presented data are collected using 50 µs pulses at 20 Hz, (300 µs pump pulses at 2.9 kW) and gain is considered at the top of the signal (Fig 1b).

The gain (passive losses included) reaches 19 after 10 passes (Fig 2). Gain variation versus pump power fits with exponential, showing that we are still operating in small signal gain regime. At the output of the amplifier, we measure a peak power of 10 W at the end of the pump pulse corresponding to an output energy of 0.4 mJ integrated over the signal duration.

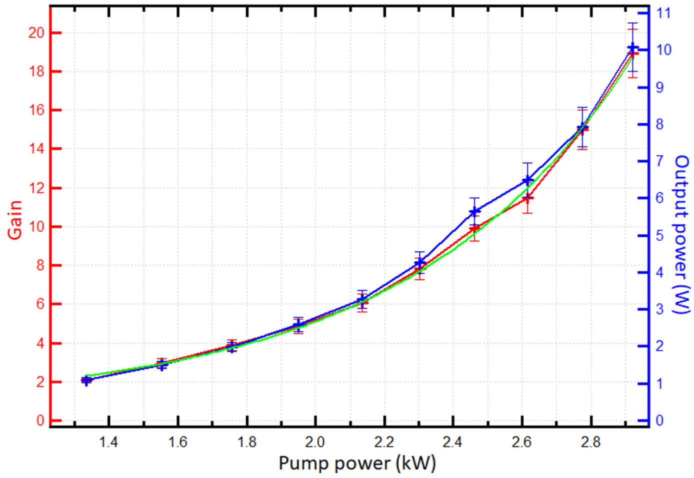

Figure 2: Gain versus pump power (in red). Output power versus pump power (in blue). In green, exponential fit.

In conclusion, we have developed a high gain alexandrite multipass amplifier. The single pass small signal gain reaches 1.44 and we obtain a gain of 19 after 10 passes in a geometrical multipass design. This performance can be improved by doubling the number of passes with a Faraday rotator and a polarization beam splitter. In the future we plan to increase the repetition rate from 20 Hz to 100 Hz corresponding to an average pump power of 100 W that is compatible with alexandrite thermal properties.

This new system could be used as amplifier for many laser sources with a large range of pulse duration: from femtosecond to nanosecond pulses and even with very long microsecond pulses. In this case, it has the potential to deliver single frequency pulses with a peak power of 100 W, 100 Hz repetition rate, and a typical duration of 100 µs. It could represent a breakthrough to push the depth penetration of acousto-optic imaging in scattering media by an order of magnitude.

Funding : Agence Nationale de la Recherche (project HULOT ANR-21-CE42- 0014).

References

[1] P. Bado, M. Pessot, J. Squier, G. A. Mourou, and D.J. Harter "Regenerative amplification in alexandrite of pulses from specialized oscillators" in IEEE Journal of Quantum Electronics, vol. 24, n°6, pp. 1167-1171 (1988)
[2] Coney, A. T., & Damzen, M. J. (2021). High-energy diode-pumped alexandrite amplifier development with applications in satellite-based lidar. JOSA B, 38(1), 209-219.
[3] A. Munk , S. Scheuer, M. Strotkamp, B. Jungbluth, J. Froh, T. Mense, A. Mauer, and J. Höffner "Energy-scaling of a diode-pumped Alexandrite laser and prototype development for a compact general-purpose Doppler lidar", in Applied Optics, vol. 62, No. 33 (2023)
[4] S. Scheuer, A. Munk, M. Strotkamp, C. L. Haefner, J. Höffner, and J. Froh "Efficient intra-cavity frequency doubled, diode-pumped, Q-switched alexandrite laser directly emitting in the UV" in Optics Express, vol. 32, No. 5 (2024)
[5] J.-B. Laudereau, E. B. à La Guillaume, V. Servois, P. Mariani, A. A. Grabar, M. Tanter, J.-L. Gennisson and F. Ramaz "Multi-modal acousto-optic/ultrasound imaging of ex vivo liver tumors at 790 nm using a $Sn_2P_2S_6$wavefront adaptive holographic setup", in Journal of biophotonics 1-8 (2014)
[6] K. Ash, J. Lord, J. Newman, and D. H. McDaniel, "Hair removal using a long-pulsed alexandrite laser dermatologic clinics", in Dermatologic Clinics, Vol. 17, Issue 2, 387-399 (1999)
[7] R. Scheps, B. M. Gately, J. F. Myers, J. S. Krasinski, and D. F. Heller "Alexandrite laser pumped by semiconductor lasers", in Applied Physics Letters 56 (1990)
[8] A. Teppitaksak, A. Minassian, G. M. Thomas, and M. J. Damzen "High efficiency> 26 W diode end-pumped Alexandrite laser" in Optics Express, 22(13), 16386-16392 (2014)
[9] M. Fibrich, J. Šulc, D. Vyhlídal, H. Jelínková, and M. Čech "Alexandrite spectroscopic and laser characteristic investigation within a 78–400 K temperature range" in Laser Physics, 27(11), 115801 (2017)
[10] H. Xiao, X. Jiang, and M. J. Damzen "Alexandrite lasers with blue-diode-pumping" in Optics Express, vol. 31, n°4 (2023)
[11] P. Pichon, A. Barbet, J.-P. Blanchot, F. Druon, F. Balembois, and P. Georges "LED-pumped alexandrite laser oscillator and amplifier" in Optics Letter vol. 42, n°20, pp 4191-4194 (2017)
[12] U. Demirbas, A. Sennaroglu, and F. X. Kärtner "Temperature dependence of Alexandrite effective emission cross section and small signal gain over the 25-450 °C range" in Optical Materials Express (2019)