International Conference on Space Optics—ICSO 2020

Virtual Conference

30 March–2 April 2021

Edited by Bruno Cugny, Zoran Sodnik, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2020, edited by Bruno Cugny, Zoran Sodnik,
Nikos Karafolas, Proc. of SPIE Vol. 11852, 118526S · © 2021 ESA and CNES
CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2600321

GALACTIC – High Performance Alexandrite Crystals and Coatings for High Power Space Applications

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ABSTRACT

Spaceborne Earth observation based on laser instruments provides new technologies to monitor the atmosphere or our planet's surface. Space-qualified Alexandrite laser crystals show convincing properties as a laser-active medium in high power laser systems for space-based missions, e.g. the wavelength tunability and the excellent material properties, such as high thermal conductivity and a good breaking strength. Therefore, the Horizon 2020 project GALACTIC was initiated to realize space-qualified, high-quality coated Alexandrite crystals relying on a purely European-based supply chain. The project consortium will push the development of Alexandrite crystals and coatings within the EU from the current Technology Readiness Level (TRL) 4 up to TRL 6.

Keywords: Alexandrite, TRL 6, Earth observation, Remote sensing, Lidar, Diode-pumped laser, Solid-state laser, Space qualification, Crystal growth, Crystal treatment, Advanced coatings

1. INTRODUCTION

Alexandrite (Cr^{3+}-doped chrysoberyl, $Cr^{3+}:BeAl_2O_4$) laser crystals as laser-active media in spaceborne Earth observation missions have aroused a lot of interest in recent years. Up to now most laser systems for space-based missions, e.g. LIDAR instruments, rely on the well-established and proven Nd:YAG laser crystal technology[1]. Nevertheless, Alexandrite laser crystals with their inherent tunable output wavelength (700 – 860 nm) show convincing benefits as potential alternative[2]. Laser sources with Alexandrite as laser-active medium only need a single nonlinear frequency conversion process to directly reach the blue/UV spectral region. Besides, the broad spectral bandwidth yields the potential to generate sub-20-fs pulses. The high hardness (around 200 kg/mm²), high thermal conductivity (23 $Wm^{-1}K^{-1}$)[3] and good breaking strength are excellent Alexandrite material properties, which are advantageous for high power space applications. Furthermore, Alexandrite has a high optical efficiency due to the small quantum defect, especially if used in laser-diode pumped systems. High power laser diodes, which emit in the red spectral region, were enhanced in the last years, which also pushed forward the research of Alexandrite laser instruments for space-based missions. However, specific space missions have not been defined yet by space agencies like ESA or NASA. Likely mission scenarios are Earth observation missions like vegetation monitoring[4] or potassium Doppler LIDAR missions[5,6] based on a frequency-doubled Alexandrite laser system. A lot of investigation is ongoing in both fields to develop Alexandrite-based laser systems, which fulfill the general laser requirements for these remote sensing types. However, the systems themselves currently do not exceed TRL 4 to TRL 5[7].

The Horizon 2020 project GALACTIC[8,9] ("High Performance Alexandrite Crystals and Coatings for High Power space applications") aims at pushing the Alexandrite laser crystal technology within the EU up to TRL 6, and at establishing a fully European-based supply chain for high quality functionally coated Alexandrite laser crystals. To reach the GALACTIC goals, the project partners Optomaterials S.r.l., Altechna Coatings and Laser Zentrum Hannover e.V. will work closely together to enhance the European state-of-the-art Alexandrite crystal and crystal coating technology. Therefore, Optomaterials S.r.l. will continuously refine the crystal growth process and improve the bulk crystal material as well as the machining and polishing quality step by step. Furthermore, Altechna Coatings will develop high quality, low loss and high-laser induced damage threshold (LIDT) coatings specifically tailored for deposition onto Alexandrite laser crystals. The performance of the shaped and coated Alexandrite crystals is assessed by implementing them in typical laser systems. The Laser Zentrum Hannover e.V. will set up laser demonstrator prototypes, whose output parameters mimic typical Earth observation laser source requirements.

Finally, the GALACTIC consortium will characterize and qualify the coated laser crystals according to a detailed component test plan based on own experiences with space-related qualification tests[10], on collaborating with external partners from the European space industry and by deriving the requirements from typical Earth observation space missions. TRL 6 of the coated laser crystals will be proven via an environmental test campaign comprising thermal cycling and irradiation tests of the crystal samples.

2. TOWARDS HIGH QUALITY ALEXANDRITE LASER CRYSTALS

The overall goal of the GALACTIC project is to realize and qualify high-performance coated Alexandrite laser crystals for space applications. For this purpose, TRL 6 shall be reached for the coated crystal components. The TRL is defined in the space industry to assess a particular technology or instrument's maturity level and was introduced by NASA in the 1970s. The general definition according to the Horizon 2020 work program was adopted for the implementation of the GALACTIC project[11]. Here, TRL 6 is equivalent to "demonstrating the critical function of the element in a relevant environment". For a more detailed perspective on the respective status of the element definition and the performance requirements accompanied by the necessary work achievement, the ISO16290:2013[12] is used as well (see relevant TRL 6 definition in Table 1).

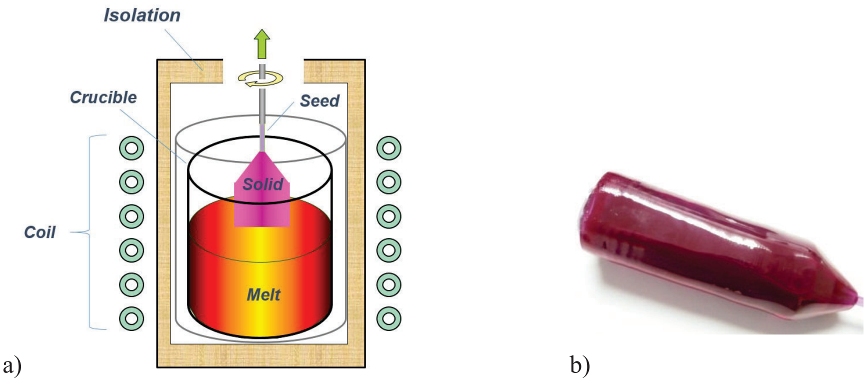
Table 1: TRL 6 definition and working plan adopted from ISO16290[12].

Technology Readiness Level 6	Milestone achieved for the element	Work achievement (documented)
Model demonstrating the critical functions of the element in a relevant environment.	Critical functions of the element are verified, performance is demonstrated in the relevant environment and representative model(s) in form, fit and function.	• Definition of performance requirements and of the relevant environment. • Identification and analysis of the element critical functions. • Design of the element, supported by appropriate models for the critical functions verification. • Critical function test plan. • Model definition for the critical function verifications. • Model test reports.

The working steps to achieve TRL 6 can be broken down into several subtasks. In the first step, the performance requirements and the relevant environment have to be defined, and a critical function test plan has to be compiled and implemented. A description of the derived test parameters and the test campaign to be performed within the scope of the GALACTIC project can be found in Chapter 3. However, before the manufactured Alexandrite crystals can be tested against space mission relevant parameters, e.g. temperature range and ionizing irradiation levels, the crystal growth and machining processes as well as the crystal surface pre-treatment prior to coating deposition and the coating deposition itself have to be improved to guarantee the necessary quality level of the components and a reliable and reproducible production (described in Section 2.1). Furthermore, the laser demonstrators have to be designed, assembled and characterized to test the laser performance of the crystals before and after the environmental tests (Section 2.2).

2.1 Manufacturing high-quality, high damage threshold coated Alexandrite laser crystals

The synthesis of single crystals is the starting point of manufacturing high-quality Alexandrite laser crystals and one of the most critical parts of the production chain. The Alexandrite laser crystals produced within the scope of the GALACTIC project are grown using the Czochralski method. The Czochralski method is one of the most utilized techniques for synthesizing inorganic single crystals and guarantees the possibility to extend a product from a laboratory environment to mass production with a high level of reproducibility. A detailed explanation of this method is given in literature[13,14]. To reach a high TRL, the quality of available crystals has to be improved by determining the best experimental conditions for a low number of defects – i.e. minimizing bubbles, defect sites and cracks – and low mechanical stress, while ensuring a reproducible manufacturing process of the products. For that, several crystal boules will be synthesized with modified growth parameters, e.g. gas pressure, pulling and rotation speed and doping concentration. Afterwards, they will be characterized regarding their optical and spectroscopic properties e.g. by measuring the absorption and transmittance. Furthermore, the physical properties, such as the size and tolerances, geometric profile and angular shaping, parallelism, perpendicularity, interferometric wavefront distortion, surface flatness, curvature and surface quality (scratch/dig), barrel finish and bevels, are verified. Lattice and vibrational characterization by X-ray and Raman spectroscopy are also performed to validate the correct crystal phase and monitor the crystal structure's stress and deformation.



a) b)

Figure 1: a) Sketch of the Czochralski crystal growth method; b) Example of an Alexandrite crystal boule.

The last steps in the optical element production are the crystal surface pre-treatment prior to coating deposition and the coating deposition itself. Therefore, defects such as scratches, digs, microcracks and residual polishing compounds, which are induced by or remaining after the polishing process, have to be removed by optimization of the surface pre-treatment process[15]. To obtain high LIDT values, the pre-treatment process must substantially reduce these scratches and subsurface defects. Therefore, several crystal pre-treatment experiments will be carried out, including different ultrasonic cleaning procedures and radio frequency (RF) plasma etching with different types of ions, varying etching rates and depths (see "ClusterLineRAD" shown in Figure 2). This etching procedure has tenfold increased the LIDT of commercial polished fused silica substrates and has cleaned out the subsurface damages[16]. Hence, also a significant increase of the LIDT of the Alexandrite crystals can be expected.

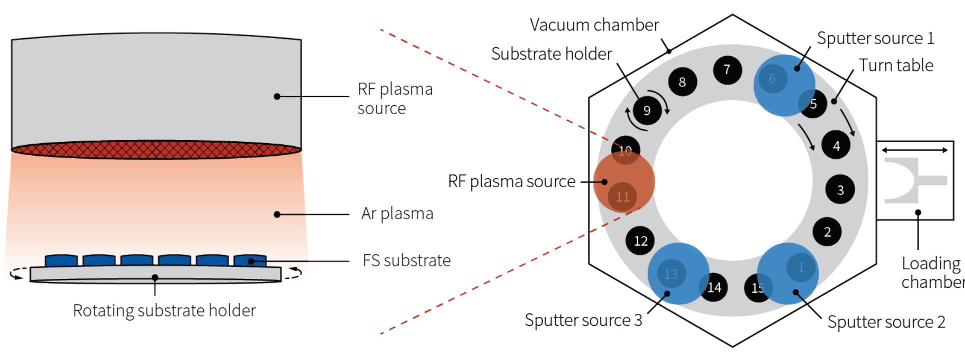


Figure 2: Schematic diagram (left) and ClusterLine RAD sputter platform (right) showing etching procedure.

After a successful pre-treatment of the crystals' end facets, two different state-of-the-art deposition techniques will be used for coating the crystals with anti-reflective (AR) and high-reflective (HR) coatings, namely ion beam sputtering (IBS) and reactive magnetron sputtering (RMS). Thereby, the variation of the deposition technology and the coating materials will lead to the best candidates for coating the Alexandrite crystals for space applications (see Table 2). Two sets of optical interference coatings on both end surfaces of the crystal will be designed and realized, whose specifications are listed in Table 3. To finalize the coating process, the optical coatings will be tested regarding transmission, reflection and absorption properties, the resistance to laser radiation (LIDT test), the adhesion strength and durability (tape-lift test) and finally, the laser performance in the demonstrator systems developed within the project.

Table 2: Variation of deposition technologies and coating materials explored in this project.

Technology	Reactive magnetron sputtering (RMS)	Ion beam sputtering (IBS)
Materials	$Ta_2O_5 – SiO_2$	$Ta_2O_5 – SiO_2$, $HfO_2 – SiO_2$
Deposition rates, Å/s	2 – 6	1 – 3
Properties	High environmental stability, near bulk-like density	

Table 3: Two designs of optical interference coatings.

	AR-HR coated crystal	AR-AR coated crystal
1^{st} surface	AR < 1 % @ 638 ± 20 nm + AR < 0.25 % @ 760 ± 20 nm, AOI = 0°	AR < 1 % @ 638 ± 20 nm + AR < 0.25 % @ 760 ± 20 nm, AOI = 0°
2^{nd} surface	HR > 99.5 % @ 760 ± 20 nm + HT > 95 % @ 638 ± 20 nm, AOI = 0°	AR < 1 % @ 638 ± 20 nm + AR < 0.25 % @ 760 ± 20 nm, AOI = 0°

2.2 Laser demonstrator systems

Two laser demonstrators will be set up within the GALACTIC project with the focus on the development, assembly and testing of breadboard-level Alexandrite laser systems with two different operational regimes. Both demonstrator setups are designed to test and verify the laser crystal related functional limitations that are influenced by the overall laser crystal and coating manufacturing process. The systems are derived from two typical applications of remote sensing: atmospheric space-based LIDAR and altimetry or vegetation monitoring. For atmospheric sensing from a satellite-based platform, e.g. wind or resonant backscatter LIDAR systems, high laser pulse energies in the range of multi ten mJ are required because of the low signal return. Pulse durations can be long in the range of multi ten up to around ~100 ns[4,17]. Satellite-based lasers for vegetation monitoring require less laser pulse energy because of the better signal return from the ground compared with the signal return in atmospheric sensing applications. Here, short pulses in the nanosecond range are necessary (e.g. a pulse duration of 1 ns corresponds to a roundtrip resolution of 15 cm in height profiling). Besides, a higher pulse repetition rate (multi-kHz) compared to atmospheric sensing (> 150 Hz) is desirable for a good lateral spatial resolution and a high sampling rate[4]. The design driving laser parameters pulse energy and pulse repetition rate can therefore be split into two regimes. The first demonstrator will reach a high pulse energy at a low repetition rate and will be realized by an actively q-switched Alexandrite laser system (see Figure 3 a). The second demonstrator, consisting of a cavity-dumped and actively q-switched Alexandrite laser system (see Figure 3 b), will be realized with low pulse energy but with a high repetition rate.

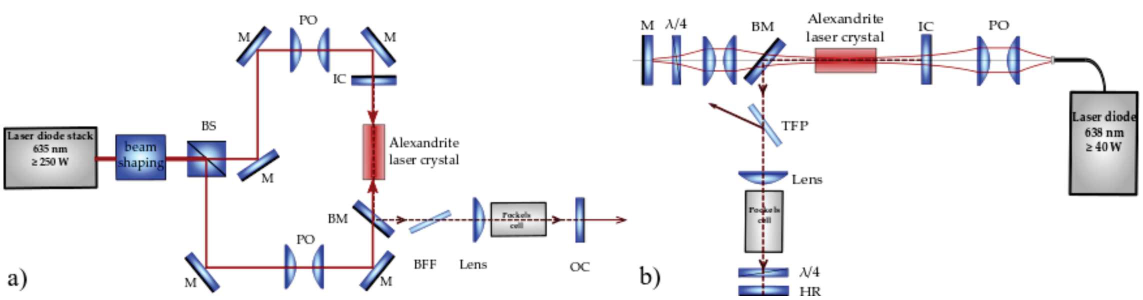


Figure 3: a) high pulse energy - low repetition rate laser demonstrator system; b) low pulse energy - high repetition rate laser demonstrator system. Abbreviations: BS = Beam splitter, M = Mirror, PO = Pump optics, IC = Input coupler, BM = Bending mirror, OC = Output coupler, BFF = Birefringent filter, TFP = Thin film polarizer, HR = Highly reflecting mirror.

The intended laser output parameters to be realized in both systems at the end of the project are summarized in Table 4. The parameters are derived from the laser requirements of the two applications of space-based remote sensing.

Table 4: Intended laser output parameters of the demonstrator setups within the GALACTIC project.

	System 1	**System 2**
Pulse energy	> 3 mJ	≥ 200 µJ
Pulse duration	~ 100 ns	< 10 ns
Pulse repetition rate	50 – 500 Hz	≥ 5 kHz
Laser wavelength	750 – 770 nm	

3. SPACE-QUALIFIED ALEXANDRITE LASER CRYSTALS

The coated Alexandrite laser crystals will be tested to withstand space mission relevant environmental conditions on component not system level leading to TRL 6. This means that the crystals will be tested considering typical mission-specific non-operational thermal conditions combined with laser material temperature constraints and typical mission radiation requirements independent from their specific integration in the individual space hardware. In this context, it should be clarified, that the GALACTIC breadboard demonstrators, which were described in the previous section, will not be developed as a space-suitable or space-qualified system, and the laser demonstrator will only be operated in a laboratory environment. The same applies to the opto-mechanical interfaces (e.g. the crystal mounts) developed in the project.

Space mission environmental conditions vary depending on where the mission is operated in space, the desired lifetime, and where the relevant component/system is integrated within the space hardware (satellite). Within the scope of the GALACTIC project, the focus is on LEO (Low Earth Orbit) Earth observation missions to define a plausible and realistic test scenario. An assessment of typical requirements for such missions allows defining likely environmental conditions as a basis for the TRL 6-relevant tests to be applied to the developed coated Alexandrite laser crystals. Figure 4 gives an overview of the planned environmental test campaign

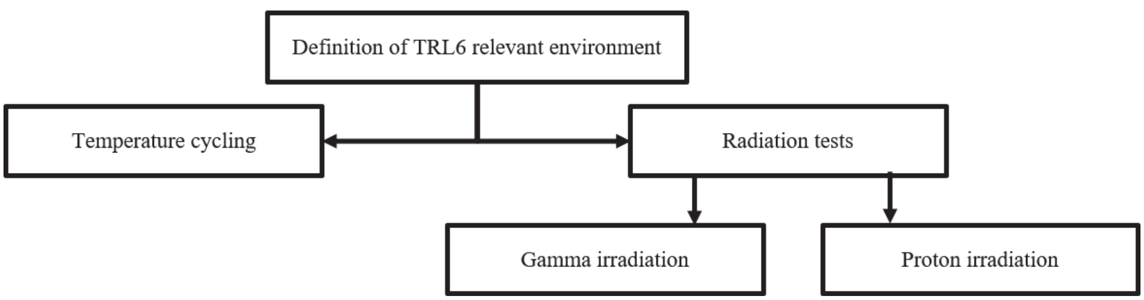
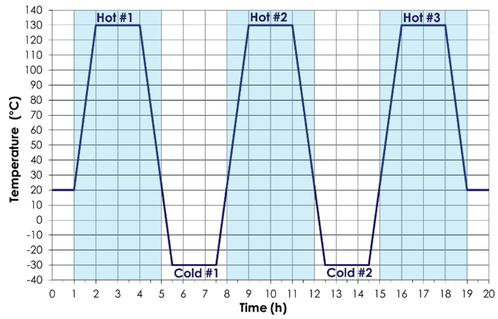


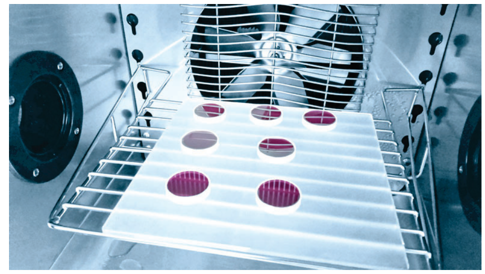
Figure 4: Overview of the planned TRL 6 relevant environmental test campaign within the GALACTIC project.

3.1 Temperature cycling tests

To define the thermal cycling test conditions for TRL 6 verification, typical mission temperature requirements, laser material characteristics, the MIL-C-48497A[18] ("Requirements for coating durability") norm and internal testing standards for high-quality optical components are considered. Due to the material characteristics of Alexandrite, two different derivations were used to specify the lower and the upper thermal cycling limit.



a)



b)

Figure 5: a) Thermal cycling test sequence (schematic); b) Climatic chamber (ESPEC SH-262) for thermal durability tests.

The efficiency of Alexandrite can be optimized by operating the crystals at elevated temperatures around 100 °C[6]. This value is far beyond typical maximum non-operational temperatures for space-based laser systems. Because of this specific characteristic, the maximum temperature is defined by the expected operational limit plus a sufficiently high margin instead of applying a typical maximum non-operational temperature. For the lower thermal cycling limit, literature values are consulted. Typical temperature test ranges for LEO missions have been reported e.g. for the GLAS laser as part of the LEO Earth observation ICESat[19] as well as the ATLAS instrument for ICESat-2 (0 °C up to +50 °C)[20], for the ALADIN laser onboard the ADM-Aeolus mission (-15 °C up to +50 °C)[21] and for the FULAS laser developed for a future high power space-based LIDAR system (-30 °C up to +50 °C)[22]. Thus, the test parameters for the thermal cycling within the GALACTIC project result as follows:

- Temperature min/max values: -30 °C to +130 °C
- Temperature hold time: 2 h
- Temperature ramp time: < 2.2 K / min
- Number of temperature cycles: 3 hot and 2 cold cycles
- Thermal cycling tests performed under non-condensing environmental conditions at ambient pressure

Thermal durability tests are carried out in a climatic chamber (ESPEC SH-262) with non-condensing, dry conditions setting no humidity (see Figure 5 b).

3.2 Gamma and proton irradiation tests

The radiation environment relevant for LEO missions is dominated by high energetic charged particles trapped in the inner van-Allen belt. Radiation tests with optical components for space missions are typically performed separately on the one hand with protons for considering Total Non-Ionizing Dose (TNID) effects (displacement damages) and on the other hand with gamma radiation for Total Ionizing Dose (TID) effects. Co-60 sources providing gamma radiation with characteristic energies of 1.173 MeV and 1.332 MeV are typically used for TID testing, whereas proton beams usually generated in cyclotrons are used for TNID testing.

In literature, a typical gamma irradiation dose of 1-2 krad per year for a LEO orbit assuming a 4 mm aluminium shielding[23], a total gamma dose of 5-10 krad for laser systems for LIDAR applications[24] and 30 krad for the GLAS as well as the ATLAS laser[19,20] development is reported. Therefore, the parameters for the gamma radiation test to be applied within GALACTIC are:

- Gamma radiation dose levels: 10 krad and 30 krad
- Gamma radiation dose rate: 4 krad/h

The gamma radiation test will be performed with two total dose levels to cover uncertainties because no specific space mission for Alexandrite lasers has been defined yet.

Regarding the total proton flux relevant for LEO missions, the literature[24] reports a range of 10^{11} protons/cm^2 to 10^{12} protons/cm^2. Furthermore, proton irradiation tests with non-linear optical crystals were performed with proton energies of 8, 70 and 300 Mev[25]. If the proton irradiated test item is susceptible to displacement damage, what is unknown for Alexandrite laser crystals, several proton energies up to 200 MeV should be tested[24]. Here, the used test parameters for the proton radiation tests will be

- Proton flux: 10^{12} protons/cm^2 with 8 MeV equivalent protons and 10^{12} protons/cm^2 with 70 MeV equivalent protons
- Proton flux rate: $8 \cdot 10^7$ protons/(cm$^2 \cdot$ s)

Different parts will be used to test the two gamma radiation dose levels and the two proton energies.

4. SUMMARY

The Horizon 2020 project GALACTIC was initiated to realize space-qualified high-quality coated Alexandrite crystals relying on a purely European-based supply chain and to push the development of Alexandrite crystals and coatings within the EU up to TRL 6. Up to now, the Alexandrite laser crystal technology and resulting laser systems do not exceed a TRL of 4 to 5. By improving the crystal growth and treatment processes as well as the coating technology, the GALACTIC consortium will develop high-quality Alexandrite crystals and high damage threshold coatings. TRL 6 will be achieved by testing the developed crystals' properties against mission-specific environmental conditions, e.g. temperature variation and radiation. To conclude the GALACTIC goal and the qualification according to TRL 6, the Alexandrite laser crystals will be investigated in typical laser configurations before and after the environmental testing.

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