Optical Cryocooler for Space Applications

An OSIP technology development activity

Executive Summary Report –21 July 2023

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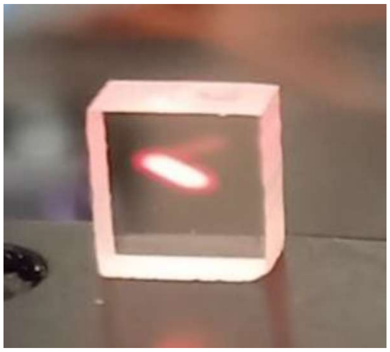

Lasing through Ho:YLF cooling medium inside a Tm:YAG laser cavity

Summary

Need for fully vibration-free, reliable and miniaturized cryocoolers

Almost all types of satellite sensors are actively or passively cooled, in many cases down to cryogenic temperatures. The goal is to suppress thermal noise in order to achieve the highest possible signal-to-noise ratio. Thus, cryocoolers are critical components in satellite systems, and in many cases *key enablers*.

For instance in Earth Observation (EO) systems, mechanical cryocoolers are preferred over passive ones. The reason is that passive radiators induce constraints on satellite orbit and attitude. This choice is often made to the cost of mechanical vibrations and increased electromagnetic perturbations induced by the motors. For small spacecrafts, microvibrations are difficult to suppress; this may cause *line-of-sight jitter* and limit optical system resolution. As a result, reduction of microvibrations has become one of the main challenges in the development of new spacecraft systems with ever increasing data requirements.

Several alternative cryocoolers readily exists; Joule Thomson cryocoolers with sorption compressors and Turbo-Brayton cryocoolers, for instance. However, while vibrations in these cryocoolers are significantly suppressed at high frequencies (for Joule Thomson cryocoolers) and low frequencies (Turbo-Brayton cryocooler), they cannot be considered as *truly vibration-free*. In addition, Joule-Thomson cryocoolers require precooling and are therefore of limited capability as a stand-alone cooler. Truly vibration-free solutions include passive coolers, cryogenic fluid storage, and thermo-electric coolers. They all have limitations, respectively on satellite attitude, mission duration, and achievable temperatures.

Despite significant improvements in the suppression of microvibrations, alternative truly vibration-free cryogenic cooling technologies are needed. This has been expressed for instance in the roadmap on space technology demands from the European-wide space sector conducted by ESA, the *European Space Technology Harmonisation Process*. One of the main driving forces is the growing market for high quality satellite data, serving a myriad of economic, scientific and societal goals. Whereas this trend has its origin in traditional, government funded space programs, the market is undergoing an exponential growth in number of, and activities by *New Space* technology companies. In addition to microvibration cancellation, the *New Space* trend will also require smaller, cheaper and more reliable cryocoolers. Hence *miniaturization, cost reduction* and *reliability* are also key challenges.

The proposed Early Technology Development activity addresses all these challenges by investigating a promising approach of *optical cryocooling*.

The optical cryocooling principle

Optical cryocooling provides a unique solution in that it is the *only active cryocooling technology that is truly vibration-free*, due to the absence of any moving parts *or* material transport. Since the first demonstration in 1995, this cooling approach has progressed steadily with current record low temperatures of 87 K. These advances were achieved with high quality Yb:YLF (using 5% Yb^{3+} with 16 ppm Tm^{3+} co-doping) crystals developed at the University of Pisa (UPisa), being one of the team members in the activity. Another relevant, previous, record is that of 91 K obtained with 10%Yb:YLF.

The principle of optical cooling relies on anti-Stokes luminescence, in which a cooling medium is being irradiated with a laser source of some optical frequency (energy, wavelength), part of which is being absorbed. In the case of anti-Stokes luminescence, the absorbed energy is re-emitted as radiation with on average higher energy (shorter wavelength). The cooling cycle occurs via the radiative transitions within Yb^{3+} ions or another optical active element. The difference between input and output photon energy, being on the order of 2% for Yb^{3+}, is being compensated by absorption of thermal energy from crystal lattice vibrations. This process can, under a set of constraints, lead to macroscopic cooling of the crystal. Crystal properties determine in large part the efficiency of the rare-earth ion cooling process; in particular ultra-pure fluoride crystals including YLF (yttrium-lanthanide-fluoride) are well suited for this purpose. Ultimately, the lowest temperature achievable with rare-earth doped dielectric materials is estimated to be in the range of 50 - 70 K. On the other hand, semiconductor cooling materials are considered to enable cooling down to 10 – 20 K. However, it has proven a significant challenge to fabricate semiconductor cooling materials, and truly ground-breaking results are yet to be obtained.

Scope of the activity; rational and assumptions of the proposed approach

One of the main challenges in the development of viable space-based optical cryocoolers is the improvement of overall wallplug efficiency of the cooler. For instance, analysis shows that current optical cryocooling approaches afford a wallplug efficiency that is about a factor 10-15 lower in comparison with pulse tube cryocoolers, at 150 K. For an end-user, such significantly lower efficiency may pose too high a burden on electrical power consumption aboard a space platform. In order to address this challenge, several approaches have been identified to significantly reduce this current imbalance and shift the overall Figure of Merit in advantage of optical cryocooling.

Objectives of the Activity

The main objective of the proposed activity is to validate a promising optical cryocooler concept that combines two advantageous features;

(1) a 2 μm (*two-micron*) Ho^{3+} cooling medium, and
(2) an intracavity (IC) laser cooling architecture.

Specifically, the objective is to demonstrate (1) the potential higher intrinsic cooling efficiency afforded by Ho-doped cooling media; and (2) optimal cooling media pumping afforded by the flexibility in cooling medium geometry, pumping beam parameters and wavelength in an intracavity scheme. In terms of cryocooler performance, this objective translates into demonstrating that the approach enables overall cryocooler performance surpassing currently best optical cryocooling approaches, by enabling a MAT << 90 K, wallplug efficiency >> 0.3% at 150 K, and cooling power >> 300 mW at 150 K.

The second objective is to enable a trade-off comparison of different cryocooling approaches, including 1 and 2 μm laser cooling media pumped with different (intracavity and extracavity) multipassing approaches. This trade-off analysis will be performed in the broader context of space implementation and includes a full system analysis, including power, size and weight of the different cryocooler approaches.

The technical readiness level (TRL) at the start of the activity was considered to be Level 2, and the aim of the activity was to elevate it to TRL 3.

Project Work Packages and Organisation

The activity was conducted by the following consortium:

- Lumium *optical systems*, (Dronryp, The Netherlands); prime contractor
- University of Pisa (Italy)
- MegaMaterials (Pisa, Italy)
- Air Liquide advanced Technologies (Grenoble, France)
- CNRS Institút Néel (Grenoble, France)

The project activity involved three main parts;

I. Ho^{3+} cooling media development and analysis

The first main activity was the development and analysis of high quality Ho^{3+}:YLF cooling media. This part was performed at University of Pisa and MegaMaterials and involved approximately 40% of the activity. Fabrication of Ho^{3+}:YLF crystals involved a state-of-the-art Czochralsky furnace specifically developed for growing fluoride crystals. Analysis of cooling materials involved (amongst others) optical diagnostics and local cooling performance tests on prepared Ho:YLF crystals.

II. Intracavity laser cooling system and cooling demonstration

The second main activity was the development of a 2 micron laser system and subsequent demonstration of optical cooling with the Ho^{3+} cooling media. This part of the activity represents approximately 40% and was performed by Lumium.

III. Trade-off analysis of multiple cooling approaches and space implementation

The third main activity involved (1) a refined trade-off analysis between various approaches involving Yb^{3+} and Ho^{3+} cooling media and the use of intra- and extra-cavity pumping schemes; and (2) development and first analysis of different space implementation concepts. This part represented approximately 20% of the project and was be performed mainly by Lumium (comparative analysis) and Air Liquide and Institut Néel (space implementations).

Conclusions and recommendations

The conclusions for this project are:

- **Cooling in Tm:YLF could be demonstrated.** While Tm:YLF may not have the same low temperature cooling potential in comparison to Ho:YLF, it has a slightly higher absorption coefficient in wavelength of interest, which makes cooling at RT slightly easier. It also serves the purpose of checking a number of experimental components. In any case, Tm:YLF should be considered as a viable alternative material as well.
- **At T = 120 K, Yb:YLF Intra-Cavity outperforms Extra-Cavity due to saturation**. Comparison of EC and IC configurations show that the impact of saturation increases with lowering temperatures, and impacts EC more due to use of a smaller diameter beam; Yb:YLF cooling performance at 150 K is relatively similar for EC and IC, whereas at 120 K the performance of IC appears a factor 2 improvement over EC. At lower temperatures, the difference in performance further increases.

- **Tm:YAG appears to be a suitable laser for intra-cavity cooling of Ho:YLF**; a Tm:YAG laser system was demonstrated with high stability and sufficient power for cooling testing and development.
- **Laser cooling system model capabilities were developed that allow more realistic performance analysis at high power operation.**
- **Ho:YLF has a lower saturation intensity** in comparison to Yb:YLF. This will require either lower intensity operating conditions, or a method to circumvent low saturation levels, such as working at longer wavelengths or co-doping schemes.
- **Cooling in Ho:YLF could not be demonstrated**, which is assumed to be due to a combination of factors: insufficient power in wavelength range of interest; possible contribution from ETU; possible contribution from impurities or crystal defects.

From those conclusions the hereafter recommendations are made:

- **Ho:YLF is a material of interest**, and further research is recommended. In particular, better insight into the influence of ETU and saturation is needed, as well as the potential for background absorption by impurity ions at 2 micron. It is recommended that such research also includes Tm:YLF materials.
- **A demonstration of IC cryocooling of Yb:YLF is needed**. Such a demonstration will allow validation of improved effective efficiency at T = 120 K, as predicted by analysis performed in current activity.
- **Current system models are too simplistic**, especially at low temperature and high power, significant improvement in model capability is needed.
- **Cooling in Ho:YLF is yet to be demonstrated** and required before this approach is elevated to TRL 3; i.e., the matureness will remain at TRL 2.