Solar Pumped Optical Cryocooling (SPOC)
with electrical power recuperation

a system and feasibility analysis

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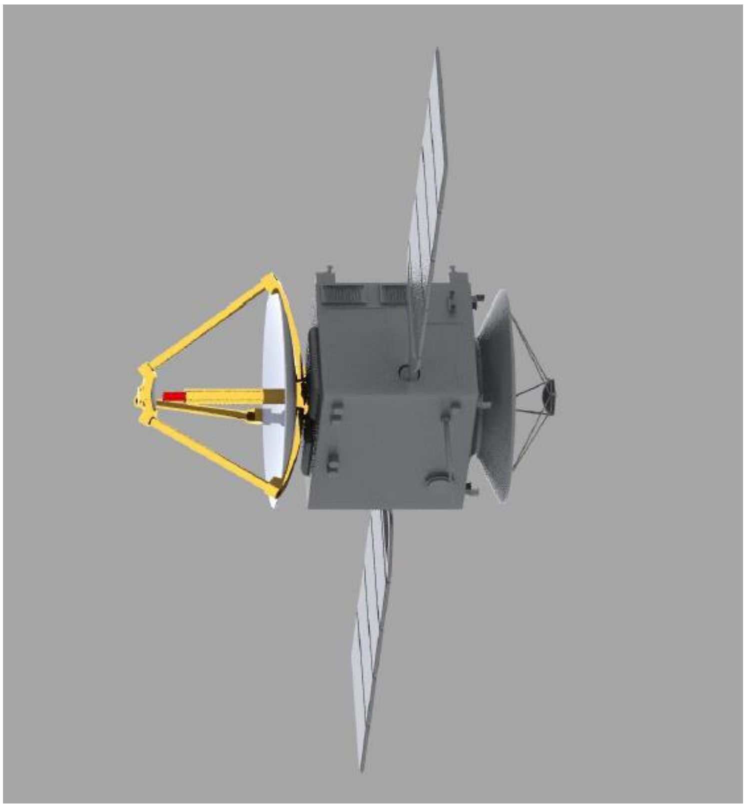

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Summary

A broad range of satellite sensors for Earth Observation and Science Missions require active cooling in order to reduce the effects of thermal noise, often to cryogenic temperatures. However, the main requirements for cryocoolers in almost any space application – high electrical-to-thermal efficiency, minimal to zero vibrations, miniaturization and high reliability – are not met by any of today's active cryocooling methods. The relatively novel technique of optical cryocooling provides a unique solution in that it is the only active and stand-alone cryocooling technology that is truly vibration-free, due to the absence of any moving parts *or* material transport. Since the first demonstration in 1995,[1] the state-of-the-art is a record low temperature of 87 K achieved with a fluoride crystal of composition Yb(5%)Tm(16ppm):YLF.[2] 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.

The efficiency of current optical cryocooling approaches is, however, still relatively low in comparison to mechanical cryocoolers. While this may be favourably offset by smaller volume and weight, further enhancement in optical cryocooling efficiency may be needed to compete with existing cryocooling technology in a broad range of applications.

One such approach is analysed here, and consists of a direct solar pumped laser (SPL) that drives the optical cryocooling process. In comparison to an indirectly powered laser, which requires two intermediate steps – i.e., photovoltaic (PV) conversion of solar radiation to electrical power, followed by conversion of electrical power back to optical (laser) radiation –, a direct solar pumped laser eliminates these two conversion losses. Thus, from a thermodynamic point of view, direct solar-pumped lasers may be possible to operate at significantly higher efficiency in comparison to indirect solar powered lasers. The prospect of higher efficiency is thus of interest in space applications, where power budget constraints may be important. The approach investigated is an inversion of the chain of thermal and electrical processes on-board spacecraft: instead of first converting solar radiation to electricity for powering the satellite instrumentation and cooler, the proposed approach is to use solar radiation first for optical cooling, followed by the recuperation of waste radiation to generate electrical power. The potential advantages that may be achieved with this approach is not only higher cooling efficiency, but in effect also more efficient generation of electrical power with compact PV modules, and a reduction in overall system mass. If successfully implemented, this approach may open the way to miniature, efficient, truly vibration-free, reliable, combined cooler-electrical power generators.

System analysis – key findings on the potential of SPOC and development needs

The conceptual solar pumped optical cryocooler (SPOC) system consists of 4 main components: (1) solar concentrator; (2) solar pumped laser (SPL); (3) laser cryocooler; and (4) PV electrical recuperation. One of the main development requirements for such a system to be of interest is a performance increase in SPLs well beyond the state-of-the-art. Today's record overall solar-to-laser power efficiency is on the order of 5% (excluding the concentrator efficiency; 3% when

including the concentrator).[3] However, considering that the thermodynamic limiting value is estimated to be on the order of 30%,[4,5] there is plenty of room for improvement.

In comparison, the conventional PV-route of generating diode-pumped solid state laser radiation has an overall efficiency on the order of 6% at beginning of life (BOL) and under realistically optimized conditions, including some unavoidable losses. This is based on using current state-of-the-art triple junction (3J) PV cells with efficiency of 32%, laser diode efficiency of 70% and diode-pumped solid state laser efficiency of 50% and some typical thermal, optical and material losses. Without these losses, the limiting value is on the order of 10%, i.e., far below the thermodynamic limit of direct SPL. Also, contrary to SPL, the room for further efficiency improvement of this route is likely to be limited, given the technological advancements in both PV and diode pumped solid state laser systems already made. Thus, it is of interest to investigate how solar pumped lasers may be improved to outperform conventionally powered lasers.

In this project, three specific improvements over current solar powered lasers were identified; (1) the use of an aberration-free concentrator to increase the focus intensity; (2) the use of radiation trapping and concentration in the gain medium; and (3) the use of co-doping and efficient energy transfer to capture a broader part of the solar spectrum and converting it into laser radiation. The challenge of increasing the SPL performance seems considerable, given the long history of development of solar pumped lasers and the slow increase in overall efficiency. On the other hand, the thermodynamic limit of over 30% clearly points to significant room for improvement. Furthermore, the three presented improvements offer support to the feasibility of more than a factor 3 enhancement in SPL operation. In the end, the potential benefits of more than doubling the solar-to-laser conversion efficiency of current PV-route systems may outweigh the development challenges.

Space implementation opportunities and constraints for solar pumped lasers

In addition to technical challenges of developing advanced solar-pumped lasers, implementation of solar-based lasers has specific advantages and disadvantages depending on the type of application. The envisioned SPOC system inherently favours constant exposure orbits, such as sun-synchronous dawn-dusk orbits. In the case of orbits with an eclipse, a back-up laser and battery system would be needed for continuous availability of a laser source. This would add weight and volume, yet a storage battery would be needed for other systems as well. The SPOC system would also need an additional diode laser, which thus would slightly offset the benefit of reduced weight gained in the first place. However, the SPOC system also potentially generates sufficient electrical power by recuperation of un-used and recycled radiation, such that it could sustain powering a back-up laser during eclipses. Even with the additional weight of a power storage unit, a SPOC system could still be of interest in such cases, for being truly vibration-free.

For the application of optical cryocooling, the main competitive areas would be cooling of LEO instrumentation in the temperature range of 90 K and below, where passive cooling becomes in-efficient. Other implementation areas of interest would be inner solar system missions to Venus and Mercury, where higher solar radiation levels make passive radiative coolers less efficient and at the same time make a solar pumped laser more efficient.

In general, the prospect of improved SPL efficiency could be of interest to a broader set of space-based laser applications. Typical current applications of lasers in space are remote sensing, navigation and optical communication. In cases where such applications operate in full solar orbit, where eclipse down-time can be tolerated or where additional back-up power for operation during eclipses can be accommodated, replacement of conventional PV driven diode pumped lasers with solar-pumped lasers may thus be of interest. Another main application of interest is highly directional wireless energy transmission via laser to remote locations,[6] such as on the Moon,[7] Mars or Earth, or between and to satellites. Although such ideas have been considered for some time, the prospective enhancement in direct solar-powered laser efficiency may lead these to be more viable options. Thus, the development of a high efficiency SPL may have multiple benefits in the sense of it either being applied in an engine like SPOC, or as a stand-alone system for power transmission or other space-based laser application.

Furthermore, a third interesting prospect is that electrical power can be generated in an SPL-driven system like SPOC with similar and possibly even higher efficiency in comparison to the use of conventional solar panels. This would be using a fraction of solar panel surface area, at the expense of using a solar concentrator. While the weight and volume of a solar panel and a solar concentrator may be comparable under similar power demands, the use of compact ultra-high efficiency multi-junction solar cells in the SPOC system may push the efficiency higher at a fraction of the cost. Thus, if electrical power generation in SPOC can be of similar magnitude, this means that the optical application (i.e., stand-alone SPL or SPOC) can be operated "for free", in contrast with conventional PV-driven systems, where the electrical power is consumed for that specific purpose.

In summary, the project has sought to demonstrate sufficient grounds for the feasibility of

1. a SPL laser system that could offer more than a factor 3 higher power transmission efficiency in comparison to conventional PV-driven laser systems, and a similar reduction in mass;
2. a SPOC system with overall equivalent system mass & volume that is comparable to or lower than that of a mechanical cryocooler, in addition to being truly vibration free;
3. an electrical recuperation subsystem that could generate similar amount of power per input solar power, at a fraction of the PV area.

This Executive Summary is the introduction part of the Final Report, which in turn is a condensed version of a more complete analysis conducted in the project. More in-depth analysis is being prepared for publication. For questions, please contact the author at bheeg@lumium.nl.

References

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[1] R.I. Epstein, M.I. Buchwald, B.C. Edwards, T.R. Gosnell, and C.E. Mungan, "Observations of laser-induced fluorescent cooling of a solid," *Nature* 377, 500 (1995).

[2] A. Volpi, J. Meng, A. Gragossian, A.R. Albrecht, S. Rostami, A. Di Lieto, R. Epstein, M. Tonelli, M.P. Hehlen and M. Sheik- Bahae, "Optical refrigeration: the role of parasitic absorption at cryogenic temperatures", *Opt. Expr.* 27, 29710 (2019).

[3] D. Liang, J. Almeida, C.R. Vistas, E. Guillot, "Solar-pumped Nd:YAG laser with 31,5 W/m^2 multimode and 7.9 W/m^2 TEM$_{00}$-mode collection efficiencies", *Sol. En. Mat. & Sol. Cells* 159, 435 (2017).

[4] C.B. Roxlo and E. Yablonovitch,"Thermodynamics of daylight-pumped lasers", *Opt. Lett.* 8, 271 (1983).

[5] S. Nechayev and C. Rotschild, "Detailed balance limit of efficiency of broadband-pumped lasers", *Sci. Reports* 7, 11497 (2017).

[6] L. Summerer, O. Purcell, "Concepts for wireless energy transmission via laser", ESA Advanced Concepts Team (ACT) document ACT-RPR-NRG-2009-SPS-ICSOS (2009).

[7] R. Ramasamy, D. van Paridon and L. Summerer, "Solar power satellites for lunar rover exploration" 69th *Int. Astronautical Congress*, IAC-18-C3.4.10 (2018).