NEWSLETTER N°5

MAY 2022

Welcome to the LEMON project newsletter n°5

The overall objective of LEMON is to provide a new Differential Absorption Lidar (DIAL) sensor concept for greenhouse gases and water vapour measurements from space, based on a versatile transmitter.

Editorial by the Coordinator

After the promising DIAL results obtained with the laboratory breadboard WAVIL, the LEMON project entered a few months ago a new challenging phase, marked by the airborne instrument manufacturing and assembly.

This newsletter is thus the occasion to present the status overview of the LEMON emitter manufacturing, in line with our objectives to be able to target several species, along with an updated list of the LEMON Key Exploitable Results (KER). These KER cover a wide range of subjects, from the overall DIAL system to the key components at its core, along with the calibration methods. For these KER we also explain how they are paving the road towards a multi-species spaceborne instrument.

This newsletter is completed by an interview of Valdas Pasiskevicius from KTH, who is involved in LEMON through the development of LEMON nonlinear crystals, which are a key component of the emitter.

Enjoy reading us!

Dr. Myriam Raybaut

Research engineer at ONERA – France

NEWS & EVENTS

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Status of the LEMON emitter manufacturing

After the successful Optical and Mechanical Readiness Report as an output of the design phase, the LEMON project entered the next stage with the start of the manufacturing of the various subsystems. The main subsystems that define the performance of the DIAL system are the transmitter TREE, the receiver ARM and the frequency reference unit FRUit. The mechanical designs and particularly the interfaces ensure a stable beam delivery between the subsystems, even for the challenging environment during the measurement flights.

Here, we will focus on the latest emitter developments. We recall that the emitter consists of:

- a first housing, comprising a pump laser emitting at 1 µm, and supplying the energy for two OPOs, which generate the targeted wavelengths;
- a second housing, including an OPA stage that amplifies the targeted wavelength to high pulse energies.

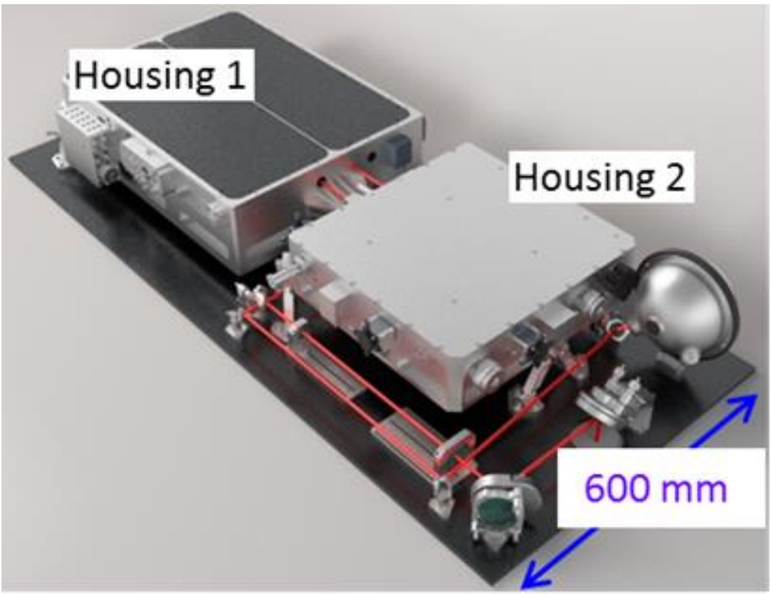

Figure 1: The two housings of the LEMON emitter.

The first housing was successfully delivered by Innolas to Onera, with the following characteristics. The laser system delivers a pulse energy of >250 mJ at a center wavelength of 1064 nm with a Gaussian beam profile, a beam quality factor of M2 = 1.4 and a pulse duration of 10 ns. The pulse-to-pulse energy stability was measured to be <0.2 % (RMS) and the polarization purity to be better than 93 %. All requirements are so fulfilled and the laser will be delivered to ONERA, where the OPOs will be included.

Two OPOs were aligned using specific alignment tools. Indeed, the OPO cavities are designed to operate in a Nested Cavity configuration, allowing single frequency emission, with no seeder, in the nanosecond regime. The two cavities consist of a temperature-controlled nonlinear crystal with two entangled cavities built with two mirrors, which positions are controlled with lownoise piezoelectric transducers. It is built around an ultra-low expansion glass (zerodur) frame to minimize the cavity displacements and misalignment due to temperature gradients.

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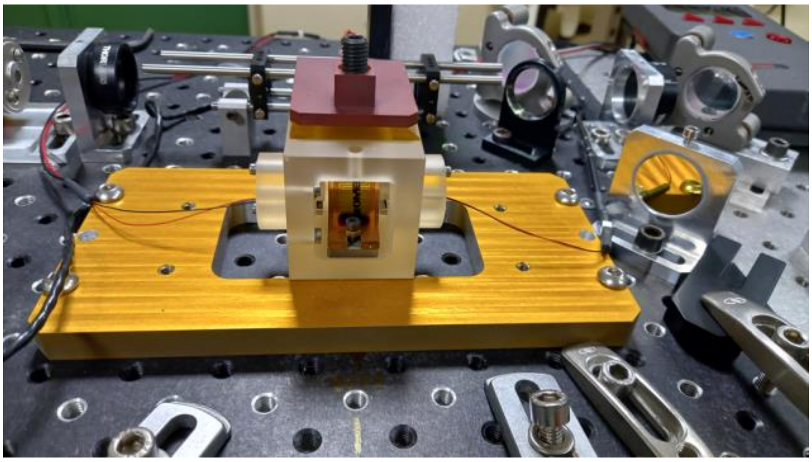

Figure 2: Nested Cavity OPO zerodur cavity once aligned. The crystal is placed in the copper oven in the center, and the mirrors are aligned by translation on the zerodur body.

Two OPOs were thus assembled at Onera, in line with the LEMON project goals to demonstrate that it is possible to address several species with a single set-up:

- A first OPO targets CO_2 and H_2O, allowing to emit wavelengths in the 2.05-2.06 µm range.
- A second OPO targets H_2O and HDO in the 1.982 µm region, with an idler emission in the 2.3 µm range (in the vicinity of methane absorption lines, which are too weak for an airborne integrated measurement or a ground based range-resolved measurement, but could be of interest for space integrated measurements).

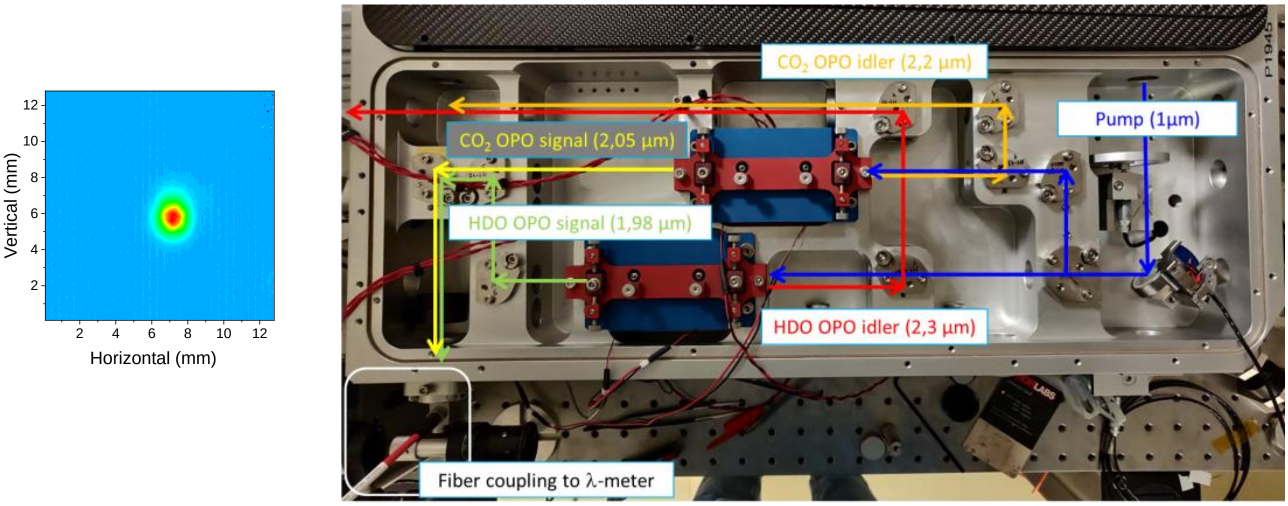

Figure 3: First housing after integration of the two OPOs (Beam paths and wavelengths combinations are indicated) and OPO output beam (left).

The first housing was then delivered to Fraunhofer ILT, to be able to continue with the housing 2 alignment, including the specific nonlinear OPA crystals developed by KTH.

Written by Myriam Raybaut (ONERA)

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LEMON preliminary Key Exploitable Results towards a multispecies spaceborne instrument

Following the latest results obtained on various topics along the LEMON project, such as:

- Preliminary DIAL testing with the laboratory bench Wavil,
- Development of in-situ sensors calibration methods,
- Realization and tests of specific PPKTP nonlinear crystals,
- Latest results on the emitter first housing integration,
- Preliminary testing of a zero cavity backward OPO concept,
- Design and realization of a generic DIAL receiver base-plate for airborne measurement, which could welcome different emitters, and based on a fiber coupled telescope,
- Design and realization of new frequency measurement methods and instrumentation,

We are now able to derive a first list of key exploitable results (KER), even if the project is still running for one year, which means that the list is in a preliminary shape. Some of these KER were already the subject of a publication.

Where relevant, for some KER we also explain how they are paving the way towards a multi-species spaceborne instrument, which is the main expected impact of the LEMON project.

Table 1: Key Exploitable Results of LEMON at M42.

#	Key Exploitable Result	Applications and main beneficiaries
1	**1 µm laser system, enhanced in terms of robustness and stability**	**Applications:** Application in ground based/airborne/spaceborne LIDAR experiments and/or further experiments sensitive to high laser pointing stability like for example long range PIV experiments. **End-users:** Lidar instrument scientific developers or companies, PIV scientific developers or companies, airborne/spaceborne laser users.
2	**Frequency reference unit: significant enhancement of addressable frequency range in one unit, rugged design**	**Applications:** Global space GHG monitoring (able to be used for different trace gas missions, thereby significantly reducing the cost of mission development). Laser characterisation and locking. Compact optical clocks for space (GNSS), Astronomical spectrometer calibration. **End-users:** Lidar instrument scientific developers, Laser developers, frequency reference developers. **Towards a multispecies spaceborne instrument:** The frequency reference is able to operate on a wide wavelength range, and thus to be used for different trace gas missions, thereby significantly reducing the cost of mission development.
3	**Rugged, mJ energy level emitter able to address CO_2, H_2O, HDO and CH_4**	**Applications:** Application in GHG ground based/airborne/spaceborne LIDAR experiments. Airborne control system of natural gas pipelines and fields and CO_2 pipelines in the chemical industry **End-users:** Atmospheric physicists, companies for pipeline services. **Towards a multispecies spaceborne instrument:** This emitter is able to address the CO_2, H_2O, HDO and CH_4 lines, which can be used

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#	Key Exploitable Result	Applications and main beneficiaries
		for an IPDA spaceborne measurement (for CH_4, a mere change of filters is needed within the amplifier stage).
4	**Rugged, DIAL instrument able to perform range-resolved CO_2, H_2O, HDO**	**Applications:** Application in GHG ground based/airborne/spaceborne LIDAR experiments. **End-users:** Atmospheric physicists. **Towards a multispecies spaceborne instrument:** First tests were already performed on H_2O, HDO with Wavil laboratory breadboard, even higher sensitivities are expected with LEMON. Ground based DIAL measurements can be used for other missions CAL/VAL.
5	**DIAL instrument model and DIAL data retrieval for CO_2, and multi-species H_2O and HDO measurement**	**Applications:** Application in GHG ground based/airborne/spaceborne LIDAR experiments. **End-users:** Atmospheric physicists, lidar developers. **Towards a multispecies spaceborne instrument:** Simultaneous measurement of water vapour with HDO and CO_2 can help reduce the bias on these measurements, and a multi-species instrument model is thus necessary.
6	**Rugged, fibered, receiver Lidar platform for airborne experiments, able to be used for different lidar system**	**Applications:** Airborne Lidar experiments. **End-users:** Lidar instrument scientific developers, Lidar companies. **Towards a multispecies spaceborne instrument:** The platform is designed to be implemented in the ATR-42 aircraft, for space mission CAL/VAL or other scientific campaigns, it can be plugged with other emitters than LEMON. Fibered telescope coupling allows for an easy change of detector if other emitters are plugged, or if other detectors have to be tested.
7	**High aperture PPKTP nonlinear crystals**	**Applications:** parametric sources development, quantum communications, quantum imaging. **End-users:** Laser scientists, laser companies, system integrators. **Towards a multispecies spaceborne instrument:** Periodically poled crystals allow for a more generic and stable design than classical birefringence crystals (no angle tuning needed). This high-aperture crystal display has a high damage threshold, well suited for high energy applications as required for space remote sensing, and were successfully radiation-tested.
8	**Calibration procedure for airborne local gas sensors**	**Applications**: Application in GHG ground based/airborne/spaceborne local sensing experiments. **End-users**: Atmosphere physicists, local gas sensors developers, remote sensing products validation users.

#	Key Exploitable Result	Applications and main beneficiaries
9	**Rugged NesCOPO design**	**Applications**: parametric sources development. **End-users**: Laser scientists, laser companies **Towards a multispecies space-borne instrument :** Such OPO design allows single frequency emission with no need for injection seeding, which simplifies the emitter set-up Preliminary vibration testing was realized, within a rugged, thermally robust design (zerodur glass cavity)
10	**Cavity-less (BWOPO) OPO concept**	**Applications**: parametric sources development, quantum communications. **End-users**: Laser scientists, laser companies, system integrators **Towards a multispecies space-borne instrument :** Such OPO design has a lower TRL than the previous one, but allows single frequency emission with no need for injection seeding and no cavity, which simplifies even further the emitter set-up Its thermal stability is also very promising, spatial-spectral coupling properties have to be further investigated
11	**New cavity-less OPO concept (BWOPO) testing with a tunable pump source**	**Applications**: Application in ground based/airborne/spaceborne GHG LIDAR experiments. **End-users**: Atmospheric physicists, lidar developers **Towards a multispecies space-borne instrument :** Pump frequency tuning of a BWOPO could be a very primising emitter concept, based on a hybrid fiber/bulk amplifier laser, followed by a zero-cavity OPO. The TRL of the pumpshould be enhanced (proof of concept performed)
12	**Lac d'Annecy scientific campaign results – L-WAIVE (June 2019)**	**Applications:** GHG measurements and experiments with (ultralight) aircrafts. Experimental investigation of the stable water isotope distribution in an Alpine lake environment, using ground-based and airborne lidars as well as an airborne cavity ring down spectrometer. **End-users:** Atmosphere physicists, meteorological agencies.
13	**Aubenas campaign results (September 2021)**	**Applications:** GHG measurements and experiments with (ultralight) aircrafts. Data assimilation experiments with airborne/remote sensing/regional circulation models. Qualification of the H2O and HDO measurements performed with the LEMON demonstrator system WaVIL using a ground-based water vapor lidar, radiosondes as well as an airborne cavity ring down spectrometer. **End-users:** Atmosphere physicists, meteorological agencies

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GET TOGETHER

In this chapter you will find a selection major conferences, exhibitions and other events which are of interest for the LEMON community.

CLEO 2022: CONFERENCE ON LASERS AND ELECTRO-OPTICS, SAN JOSE, CALIFORNIA, US, 15-20 MAY 2022

CLEO is the world's premier international forum about innovative advances, research and new technologies from the laser science industry. CLEO 2022 highlights the latest research, applications and market-ready technologies in all areas of lasers, optics and photonics.

Two presentations were given by LEMON partners.

ONERA presented the paper "Demonstration of range-resolved detection of stable water isotopologues by differential absorption lidar", in collaboration with **CNRS**, based on the results of the first lidar DIAL measures by WAVIL system performed during the LEMON campaign in September 2021 in Aubenas.

KTH presented the joint KTH-ONERA paper entitled "Tunable narrowband MIR ns-pulses at 5 kHz repetition from a 70% efficient backward wave OPO pumped at 1030 nm", as a result of a side project between the two partners and LCF.

Website: https://www.cleoconference.org

OPTIQUE NICE 2022 CONGRESS, NICE, FRANCE, 4-8 JULY 2022

Optique Nice is the largest international French speaking congress organised by the French Optics Society (*Société Française d'Optique*). The congress will deliver a global view of research, from fundamendal to applied research in the field of optics.

Partners from the LEMON project will attend the congress to disseminate the project results.

Website: https://www.sfoptique.org/pages/congres-optique/optique-nice-2022/

NONLINEAR PHOTONICS CONFERENCE 2022, MAASTRICHT, NETHERLANDS, 24-28 JULY 2022

The Nonlinear Photonics conference is an event organised by Optica. It covers various areas of Physique including Optics and Lasers, with a focus on fundamental and applied nonlinear photonics.

KTH will present the paper "Low-threshold highly efficient backward wave OPO", which is the result of a collaboration with **ONERA**.

Website: https://www.optica.org/en-us/events/congress/advanced_photonics_congress/program/nonlinear_photonics/

SPIE REMOTE SENSING 2022, BERLIN, GERMANY, 5-8 SEPTEMBER 2022

SPIE Remote Sensing is the leading leading European conference for researchers and scientists involved in emerging sensor and photonic technologies that enable satellite-based atmospheric monitoring and observation of the Earth's ecosystems.

Partners from the LEMON project will attend the congress to disseminate the project results.

Website: https://spie.org/conferences-and-exhibitions/sensors-and-imaging/programme/conferences/remote-sensing?SSO=1

73RD INTERNATIONAL ASTRONAUTICAL CONGRESS 2022, PARIS, FRANCE, 18-22 SEPTEMBER 2022

The IAC is a yearly congress where all global space actors come together, attracting more than 6000 participants each year. Covering all space sectors and topics, it offers the latest developments in the field of space in academia and industry, networking opportunities, contacts and potential partnerships. The audience is composed of researchers, aeronautic and space engineers, agency officials, industry representatives, policy-makers, astronauts, press members and general public. The 2022 issue of the IAC will take place in Paris.

The **LEMON** project, in collaboration with the related and complementary H2020-funded projects SCARBO (GA n°769032) and HOLDON (GA n°776390), have decided to jointly submit abstracts to the IAC 2022, with the

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aim to gather together at the congress, jointly present the project results, and discuss about any possible future cooperations in the framework of Horizon Europe. The LEMON abstract was submitted to the B1.3 session called "Earth Observation Sensors and Technology".

Website: https://iac2022.org/

ICSO 2022: INTERNATIONAL CONFERENCE ON SPACE OPTICS, DUBROVNIK, CROATIA, 3-7 OCTOBER 2022

ICSO 2022 is the 14th edition of the largest meeting worldwide of experts working in all disciplines of Optical, Optoelectronic and Photonic Technologies for Space Applications.

This is a key event for the LEMON project and its key target audience. Partners from the LEMON project will attend the congress to disseminate the project results.

Website: https://atpi.eventsair.com/icso2022

Figure 4: The LEMON consortium at the General Assembly meeting in January 2022, with the EC Project officer, Florence Beroud, and the external reviewer, Maria Losurdo.

The LEMON consortium partners look forward to meeting you!

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Interview

In this LEMON Newsletter issue, you will read an interview with Valdas Pasiskevicius, Professor of Applied Physics at KTH, the Royal Institute of Technology (Stockholm, Sweden). Valdas Pasiskevicius received the M.S. degree from Vilnius University and the Ph.D. degree from the Institute of Semiconductor Physics (both in Vilnius, Lithuania). Valdas is currently Professor of Applied Physics at KTH, the Royal Institute of Technology (Stockholm, Sweden), as well as the Head of the KTH Laser Laboratory facility and a coordinator of the Laser Laboratory Stockholm node of the Laser Laboratory Sweden network. He has a long-lasting and recognized research experience in the fields of lasers, nonlinear optics and nonlinear optical materials, which brought him to author more than 200 papers in several journals and conferences over the past decades. Furthermore, he has chaired and co-chaired a number of international conferences, as well as served as topical editor for several journals. Finally, he is a Fellow of the Optical Society and a member of the European Physical Society, as well as a Board Member of the Quantum Electronics and Optics Division of the European Physical Society since 2014. Within LEMON, Valdas is the leader of three tasks in different work packages, responsible for the design, fabrication and radiation testing of the nonlinear crystals.

VALDAS PASISKEVICIUS, PROFESSOR OF APPLIED PHYSICS AT KTH, THE ROYAL INSTITUTE OF TECHNOLOGY (STOCKHOLM, SWEDEN)

Question (Q) 1: Valdas, how did you become passionate about lasers, which are the red wire in your brilliant career and which make of you a reference researcher in this field, at European but also international level?

Answer (A) 1: I started my research by working on solid-state materials for ultrafast optoelectronic applications. The applications concerned semiconductor detectors capable of high-frequency response, typically in the THz range. For testing such structures, there was a need to use appropriate laser sources both in the THz frequency range and femtosecond lasers in the near-infrared and visible. There were no suitable commercial lasers available at the end of the 1980s and the beginning of the 1990s. So, the solution was to learn how to make such lasers and just make our research tools. How hard can it be? Thus, we made our own p-Ge THz laser operating at 4 K temperature and our own colliding pulse mode-locked femtosecond dye laser. Obviously, it proved to be harder than planned. One can go far just on enthusiasm alone. While reading around and talking to knowledgeable people, it became clear that the fields of solid-state lasers and nonlinear optics were experiencing a paradigm shift with the advent of diode pumping and new concepts of engineered laser and nonlinear optical materials. They brought the prospect of much higher efficiencies, higher powers, and higher intensities. That opened up a whole new world of possibilities by replacing the legacy laser technologies and finding new application areas. One of the most exciting aspects of laser and nonlinear optics fields is a relatively fast rate of technology transfer from promising research concepts to the commercial exploitation domain. Barriers to entry are not as high as in many other technology fields. That makes this research area very dynamic and, in turn, such dynamism tends to attract young people. In some sense, I was sucked into it right after my Ph.D. It offered a great opportunity to combine my knowledge in solid-state physics and my experience in designing and building lasers.

Figure 5: Valdas Pasiskevicius.

Q2: Valdas, how were you involved in the LEMON project?

A2: The LEMON project has prehistory of our fruitful collaboration with ONERA on developing nonlinear optical devices for frequency conversion into the mid-infrared spectral range. ONERA has an outstanding and versatile team with proven capability of designing and building LIDAR systems. I would mention MICLID and GENUIN joint projects with ONERA, which the EDA and ESA, respectively, funded. Those and other projects gave us the impetus for developing nonlinear material fabrication processes suitable for scaling up the output powers required for long-range LIDAR systems. Previous projects allowed testing certain concepts and gave us confidence in achieving the necessary parameters for the satellite-based greenhouse gas concentration mapping instrument. Therefore, we were glad to see the announcement of the Horizon 2020 call dedicated to the development of such Earth observation technology with potential for future space missions. I believe the team's strength with proven and relevant capabilities was crucial for the EC deciding to award the grant to LEMON collaboration.

Q3: Within the LEMON project, KTH is the leader of three tasks linked to the nonlinear crystals, in which you are responsible for their design,

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fabrication and radiation testing. What are the challenges of these activities towards the set-up of the LEMON DIAL instrument?

A3: The LEMON instrument contains nonlinear optical frequency converters and, more specifically, optical parametric amplifiers, which are supposed to deliver the needed pulse energy at several wavelengths in the infrared spectral range, corresponding to the absorption spectrum of the greenhouse gasses. In these converters, we employ engineered nonlinear materials, which give flexibility in terms of wavelength tuning and can reach high efficiency under understandable power budget constraints of a mobile LIDAR system. The engineered nonlinear materials can be understood as consisting of a stack of crystalline layers with periodically varying crystal orientation. By precisely designing the periodicity, one can precisely target the output wavelength. Typically, the periods are of the order of twenty-thirty microns, while the length of the stack is a couple of centimeters. So the stack is rather long and contains about 2000 layers. The structure has to be uniform throughout the volume and accept large and powerful laser beams. It is challenging to produce such large-aperture structures. We at KTH spent a couple of decades working on the understanding and tailoring of nonlinear material properties, which led to the development of the needed fabrication techniques. Substantial investments were made in this field at KTH. We are glad to be able to offer cutting-edge nonlinear converters for high-energy pulses suitable for the LEMON instrument. Targeting space applications poses specific challenges to all materials, including nonlinear frequency converters. At the outset of the project, the radiation hardness was not a proven fact. There was some understandable uncertainty regarding the robustness of the structured materials. The tests, performed together with ONERA, proved that these materials could be safely employed in a typical low-Earth orbit mission. So the project raised the TRL level of these engineered nonlinear materials for space applications.

Q4: What are KTH key assets to perform these activities?

A4: The main asset at KTH are the people with knowledge and know-how related to the design, fabrication, and testing of custom nonlinear optical crystals. As in all materials engineering pursuits, a large part of knowledge is difficult to codify in the form of patents or instructions, however detailed. Therefore, people with expertise are key. Purely technically, we enjoyed access to the research infrastructures at KTH Nanofabrication facility and KTH Laser Lab. These research infrastructures provided all required equipment for fabrication processes and testing of the custom-designed structured nonlinear materials.

Q5: What does the LEMON project bring to nonlinear optics? To what extent is the LEMON project innovative in this domain?

A5: Molecular-specific optical sensing needs to target particular wavelengths corresponding to absorption features of those molecules. Different laser technologies allow doing that typically at low powers and low pulse energies. At high energies, as required for long-distance sensing, e.g., from satellites, the traditional laser technologies can offer only a few choices of target wavelengths. Therefore, using conventional laser techniques, multispecies remote sensing would be impossible. Nonlinear optical frequency converters provide help here. However, the solution is not simple. The challenge is generating high spectral purity and high-energy radiation with rapid wavelength tuning. The LEMON project has shown that all-nonlinear optics solution combining nested cavity optical parametric oscillator and optical parametric amplifier comprises a robust platform with performance corresponding to the requirements of mobile multispecies LIDAR. New concepts in frequency tuning and locking, which we are exploring in the LEMON project, will have the potential to increase the performance even further concerning overall system simplicity and reliability. Those are the novel developments needed to make the technology suitable for operating low-Earth orbit satellites.

Q6: Valdas, you are very active in your research field, as you chaired a number of international conferences, served as topical editor for several journals, and on top of that you are a Fellow of the Optical Society and a Board Member of the Quantum Electronics and Optics Division of the European Physical Society. This experience gives you a broad view on the ongoing innovations in Optics and Laser fields. Based on this, how would you assess the potential of exploitation of the LEMON project results?

A6: The LEMON instrument is a rather complex optical system comprising a laser, optical parametric oscillators, an amplifier chain, precision frequency measurement, and locking. The system is brought together in a carefully designed and mechanically robust while compact package, which can sustain required operation parameters in airborne conditions. To reach such performance, the TRL level of all subsystems had to be increased. Moreover, the space readiness of the critical components has been proven. These developments increase the potential for commercial exploitation of the technologies used in the LEMON instrument.

DISCLAIMER: The information, statements and opinions in the above interview are personal views of the individuals involved in the LEMON project and do not necessarily reflect the views of the LEMON consortium as a whole, nor of the European Commission. None of them shall be liable for any use that may be made of the information contained herein.

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