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Exail magazine

June 2023 | Photonics special issue

LASER FUSION
Reaching new performance limits

OPTICAL MODULATORS
En route for the New Space

QUANTUM KEY DISTRIBUTION
Unlocking its full potential

COLD-ATOMS BASED TECHNOLOGY
Pioneering the quantum era

BRUNO DESRUELLE

Vice-President Photonics

Exail is one of the key European players in the field of photonics, and is involved in 4 different activities: specialty fibers, modulation solutions, photonic systems, lasers and quantum systems. The company offers unique technologies that have proven their relevance for a large number of applications, and has established a strong position in a wide range of markets: sensors, lasers, communication, metrology, quantum, geosciences...

Exail's photonic activities have grown exponentially over the past years. This continued success is the result of our teams strong commitment that results in an extensive technological and industrial expertise. From the very beginning, innovation, risk-taking and customer satisfaction have been the core of everything we do. It led to the development of cutting-edge solutions, capable of delivering ultra-high performance. But while performance is key, this is not our only differentiator. Our technologies have been optimized for a wide range of environments – from temperature-stabilized laboratories, to deep space – and to reach the quality and reliability standards necessary to the most demanding operations.

Thanks to this, Exail offers top level modulation solutions, a wide range of advanced specialty optical fibers, ultra stable fibered micro-optical benches, laser systems offering unique spectral features and field-proven quantum gravity sensors.
Today, Exail has strong ambitions. Supported by an intense R&D activity, the company is developing tomorrow's technologies, coming up with disruptive photonics solutions. In the next pages, you will discover a wide range of examples of innovations on which the Exail photonics teams are currently working. You will learn about the latest developments conducted by our team in advanced doped and rad-hard fibers, modulation solution, photonic systems and lasers. Through a number of customer stories, you will understand how these developments lead the way for technological breakthrough in the fields of space optical communication, secured quantum communication, high energy laser, but also in defense, LIDAR for automotive and bio or medical imaging.

After all these years, our passion and conquest spirit haven't vanished, and we are thrilled to address new technological challenges. We are convinced that photonics will be at the heart of our World's mutations, and we believe our technologies will play a key role to further explore the potential offered by the control of light and to transform the future. Be sure that you can rely on our full commitment to make this happen! ■

» TODAY, EXAIL HAS STRONG AMBITIONS. SUPPORTED BY AN INTENSE R&D ACTIVITY, THE COMPANY IS DEVELOPING TOMORROW'S TECHNOLOGIES, COMING UP WITH DISRUPTIVE PHOTONICS SOLUTIONS.

01 PRODUCT news

P.8
Optical Modulators
En route for the New Space

P.14
Coherent Beam Combination
For Directed Energy Laser

P.20
New Er/Yb doped fibers
Enhancing high-power lasers

P.26
Neodymium doped fibers
Powering multi-photon microscopy

P.32
Cold-atoms based technology
Pioneering the quantum era

02 CUSTOMER stories

P.42
Bringing quantum processors
To industry standards

P.46
Quantum Key Distribution
Unlocking its full potential

P.52
High Energy Laser
Enhancing their capabilities

P.56
Laser Fusion
Reaching new performance limits

P.62
2 µm fiber laser sources
Delivering new defense innovations

P.66
LISA mission
Supporting NASA and CNES

01

PRODUCT news

P.8
Optical Modulators
En route for the New Space

P.14
Coherent Beam Combination
For Directed Energy Laser

P.20
New Er/Yb doped fibers
Enhancing high-power lasers

P.26
Neodymium doped fibers
Powering multi-photon microscopy

P.32
Cold-atoms based technology
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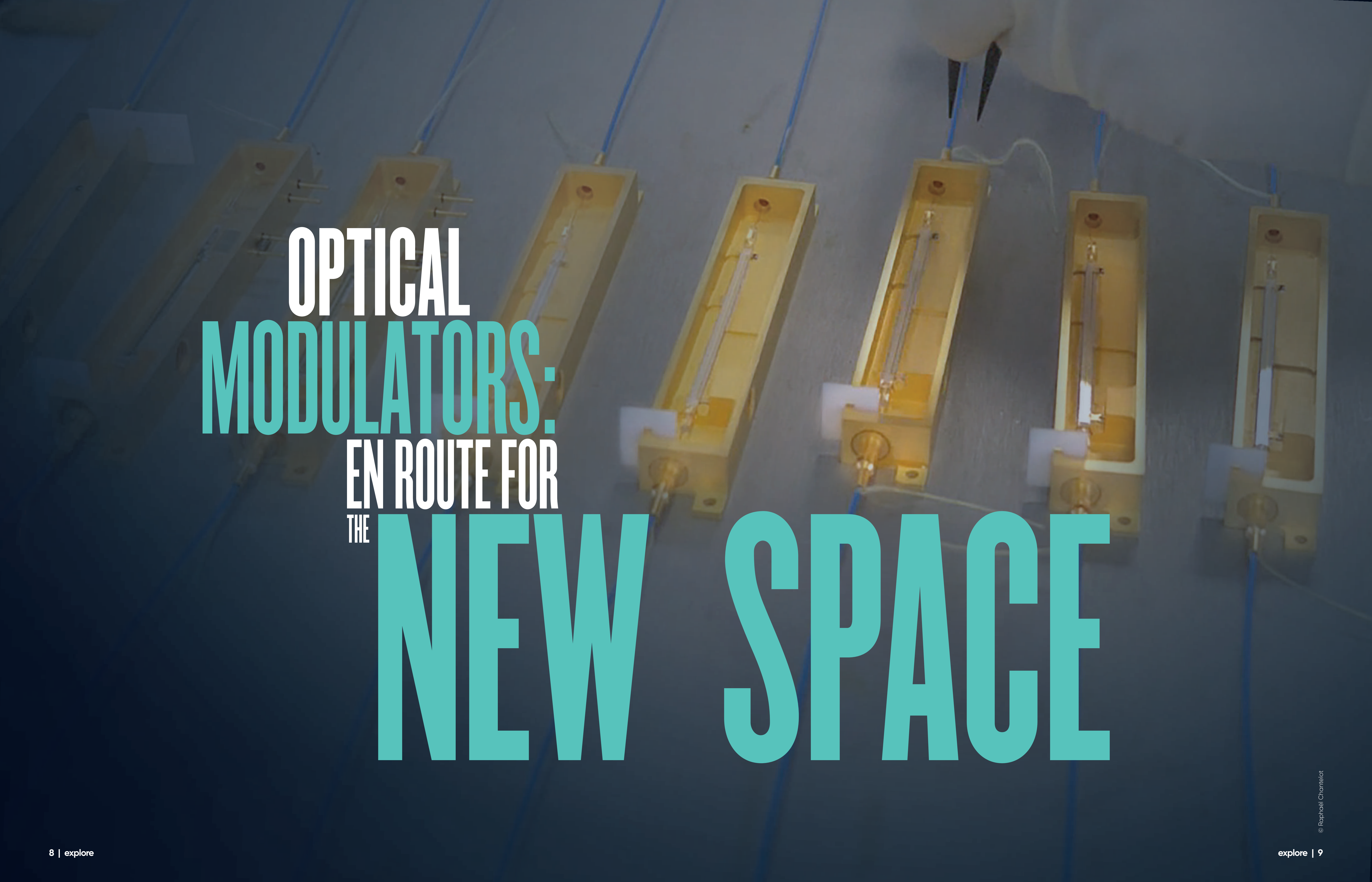

OPTICAL MODULATORS: EN ROUTE FOR THE NEW SPACE

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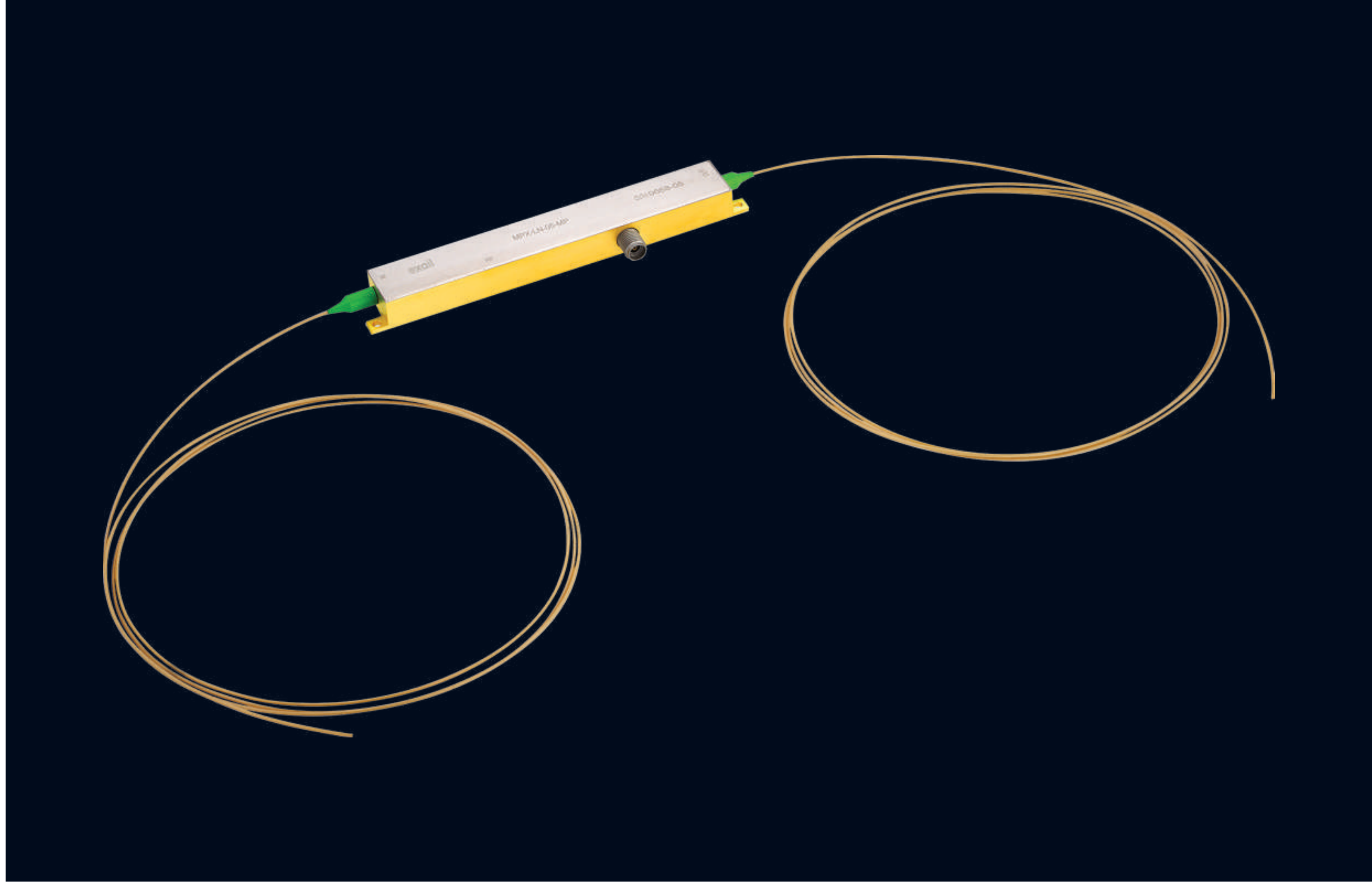


Example of Flight Model $LiNbO_3$ Modulator

EXAIL IS A DESIGNER AND A MANUFACTURER OF SPACE GRADE OPTICAL COMPONENTS, NOW AVAILABLE IN A NEW COMMERCIAL-OFF-THE-SHELF PRODUCT LINE.

The company especially masters the manufacturing of optical $LiNbO_3$ modulators dedicated to space applications, with a track-record of successful missions embarking its "flight proven" components (see the Customer Story on page 66 about the LISA Mission). Their robustness and reliability even under extreme conditions are appreciated. They are at the core of state-of-the-art technologies in development at Exail for the space domain: optical transceivers for space communications (in space and between space and ground stations), but also QKD systems that could one day fly on-board telecommunication satellites.

Today, Exail offers its space-grade $LiNb0_3$ optical phase modulator within new standardized Commercial-off-the-shelf (COTS) product lines.

Hundreds of Exail $LiNb0_3$ modulators already delivered for space missions

The $LiNbO_3$ modulators offer a unique combination of performance that makes them prime candidates to satisfy the optical system specifications, and to meet the tough requirements of space operations. Today, many embarked space photonic systems use such modulators as key components to achieve intensity or phase modulation. Many space projects already involve Exail's TRL9 modulators, for a total of more than 300 units delivered. They are amplitude and phase $LiNbO_3$ modulators in the 850nm, 1064nm and 1550nm ranges, offering several options such as high extinction ratio or low $V\pi$. They are deployed either onto the Geostationary Earth Orbit (GEO), or onto the MEO (Medium Earth Orbit) and LEO (Low Earth Orbit) satellites. The GEO imposes the most stringent operating conditions as systems have to operate during at least 20 years (average GEO satellites life expectancy) and have to sustain extreme temperature variations (they can sustain temperatures from -40°C to 85°C, and operate at full performances between 0°C and 70°C). The instruments and components are also exposed to strong vibrations and shocks during the spacecraft take-off and while flying through the atmosphere in the satellite deployment phase, the space vacuum and the dangerous solar radiation.

The reliability of Exail modulation solutions in space environment, especially in GEO orbit, comes from the company core business which is the development of Inertial Navigation Systems (INS) based on Fiber-Optic Gyroscopes (FOG). The FOG principle is a patented technology, based on an optical fiber coil. The coil diameter & length determine the rotation precision. A phase modulation solution developed by Exail is used to bias the system. The technology allows to get very close to theoretical performances, reaching the high requirements in difficult environment from subsea to space, for instance. For over 20 years, Exail has been partnering with Airbus Defence & Space for the delivery of its FOG system "Astrix", to equip more than 30 satellites, counting more than 6 million hours in orbit (in GEO) without incident.

Exail flagship $LiNb0_3$ modulators now available in Engineering Model, New Space Flight Model and Flight Model

The NIR-MPX-LN-0.1 phase is an electro-optical phase modulator featuring a wide bandwidth from DC to more than 300 MHz. Like all Exail Near InfraRed (NIR) modulators, it uses a proton exchanged based waveguide process that confers them an unparalleled stability even when operating at high optical power and over a wide range of temperatures. The NIR-MPX-LN-0.1 phase modulator comes with high Polarization Extinction Ratio (PER) and Low Insertion Losses (LIL). Its main features are (on top of being qualified for harsh environments), its optical power up to 20 dBm, its high impedance, its low insertion losses and its low $V\pi$.

The NIR-MPX-LN-0.1 phase modulator exists in a Terrestrial Grade version perfectly suited for laser applications such as Directed Energy Laser applications, with the Beam Combining Technique. A TRL9 version of the NIR-MPX-LN-0.1 phase modulator has already been used in successful space missions such as the NASA Mission "Grace Follow On" since 2018.

Leveraging this extensive experience, Exail is now offering the space-grade "NIR-MPX-LN-0.1" under three different versions according to customer's requirements in terms of qualification. The product having already been submitted to a thorough qualification and having been embedded into satellites (TRL9), the COTS NIR-MPX-LN-0.1 product line is now offered to answer the current needs of the space industry, with the rise of New Space.

The standardized versions of Exail's space-grade phase modulators are cost-effective solutions with different levels of customizations possible according to each customer requirements:

The Engineering Model (EM) version is flight representative in form, fit and function. It is manufactured exactly like a TRL9 modulator, but no batch unicity nor space compacity checks are performed during the assembly process, neither any further screening nor space qualification tests, as long as specifications of the products are met in terms of performance. This EM NIR-MPX-LN-0.1 is the ideal cost-effective version for a customer willing to test the performance of a TRL9 component for a given space system design, when working on the final validation.

They are used for functional qualifications, except redundancy verification, failure survival demonstration and parameter drift checking.

The New Space Flight Model (NS-FM) version is a flying version based on its qualification heritage (available on request), which is ideal for New Space low costs developments. This already-flight proven product is designed and manufactured like a flight hardware and is sampled after screening test to eliminate items whose behavior doesn't meet the specifications during temperature tests. Such a NS-FM NIR-MPX-LN-0.1 is thus relying on qualifications performed for previous TRL9 components that successfully flew in space, following the same manufacturing and assembling process, and including some basic screening tests.

The high reliability Flight Model (FM) is the flying version based on legacy space standards: these modulators are assembled from a unique batch and are submitted to acceptance-level testing (Lot Acceptance Tests corresponding to a relaxed qualification tests program) after preliminary selection by temperature screening tests. Such a FM NIR-PMX-LN-0.1 is delivered with its full documentation and test reports, ensuring to the customer that the modulators are flight-proven.

"If the New Space Flight Model (NS-FM) modulators are flying versions based on qualification heritage, the high reliability Flight Model (FM) modulators are coming from the same batch of fabrication and are following a dedicated relaxed qualification program (or lot acceptance test). This qualification program can be discussed with the customer depending on mission specifications. Some components from the same batch will be selected for a more drastic qualification program to validate the entire batch. The most drastic qualification program is described in Reliability assurance guideline for lithium niobate-based electro-optical modulators (available on demand). However, based on Exail heritage & background, the number of components for qualification can be reduced, and the qualification program simplified." Explains Clement Guyot - Space product line manager at Exail.

Towards a broader offer of space-grade COTS optical components

The radiation hardened (rad-hard) fibers and their matching Fiber Bragg Gratings (FBGs), the fiber sources, the low noise optical amplifiers, the Multiplexer/Demultiplexer and other micro-optics assemblies are other space-grade components and sub-components offered by Exail. For example, the optical transceiver developed by the company, in close collaboration with Airbus (its demonstration model TELEO is flying onboard the telecommunication satellite Arabsat BADR-8 launched in May 2023) is made of a compact Optical Channel Emitter (OCE) integrating a $LiNbO_3$ modulator and a RF amplifier designed by Exail. Several OCEs can be multiplexed by a Mux produced in-house with the expertise in manufacturing robust micro-optics assemblies. And the reception channel integrates a proprietary LNOA (Low Noise Optical Amplifier) designed and assembled by Exail.

All those components will soon be available in dedicated COTS product lines, starting with the RF amplifier designed for the transceiver OCE. And among the $LiNbO_3$ phase and intensity modulators, the next reference that will be available in space-grade COTS are the NIR-MPZ-LN-20, a phase modulator adapted to high frequency thanks to its low Vπ, and the MXER-LN-10, an intensity modulator in 1500nm with high contract (more than 30dB). ■

EM/NS-FM/FM/-NIR-MPX-LN-0.1

1000 nm BAND 300 MHz ENGINEERING MODEL / NEW-SPACE FLIGHT MODEL / FLIGHT MODEL PHASE MODULATOR

NIR-MPX-LN-0.1 PERFORMANCE HIGHLIGHTS

Parameter	Min	Typ	Max
Operating wavelength (nm)	950	1060	1150
Usable EO bandwidth (MHz)	-	300	-
Vπ RF @50 kHz (V)	-	1.5	2
Insertion loss (without connector) (dB)	-	2.5	4
RF port input impedance (Ω)	-	10,000	-

SPACE GRADE MODULATOR VERSIONS AND DEFINITION

Modulator grade		Terrestrial Grade TG	Engineering Model EM	New-Space Flight Model NS-FM	Flight Model FM
	Flight compatibility	x	x	●	●
Assembly	Space compatible raw material	x	●	●	●
	Batch unicity	x	x	x	●
	Space compatible assembly process	x	x	●	●
Test	Screening test	Partial	Partial	●	●
	Space qualification test	x	x	●	●
	Lot acceptance test	x	x	x	●
	Qualification program	x	x	x	●
Documentation	Acceptance test report	●	●	x	x
	Interface control document	x	●	●	●
	Certificate of conformity	x	●	●	●
	Screening test report	x	x	●	●
	Lot acceptance test report	x	x	x	●
	Handling manual	●	●	●	●

● Apply
x Does not apply

COHERENT BEAM COMBINATION FOR DIRECTED ENERGY LASER

EXAIL OFFERS AN OPTIMIZED SOLUTION FOR THE ACCURATE, ADJUSTABLE, AND RELIABLE PHASELOCK MODULATION BETWEEN SEVERAL LASER BEAMS, USING THE COHERENT BEAM COMBINING TECHNIQUE: THE MODBOX CBC.

THE COHERENT BEAM COMBINING TECHNIQUE IS THE MOST EFFICIENT SOLUTION TO GAIN POWER WITH SEVERAL COMBINED LASER BEAMS

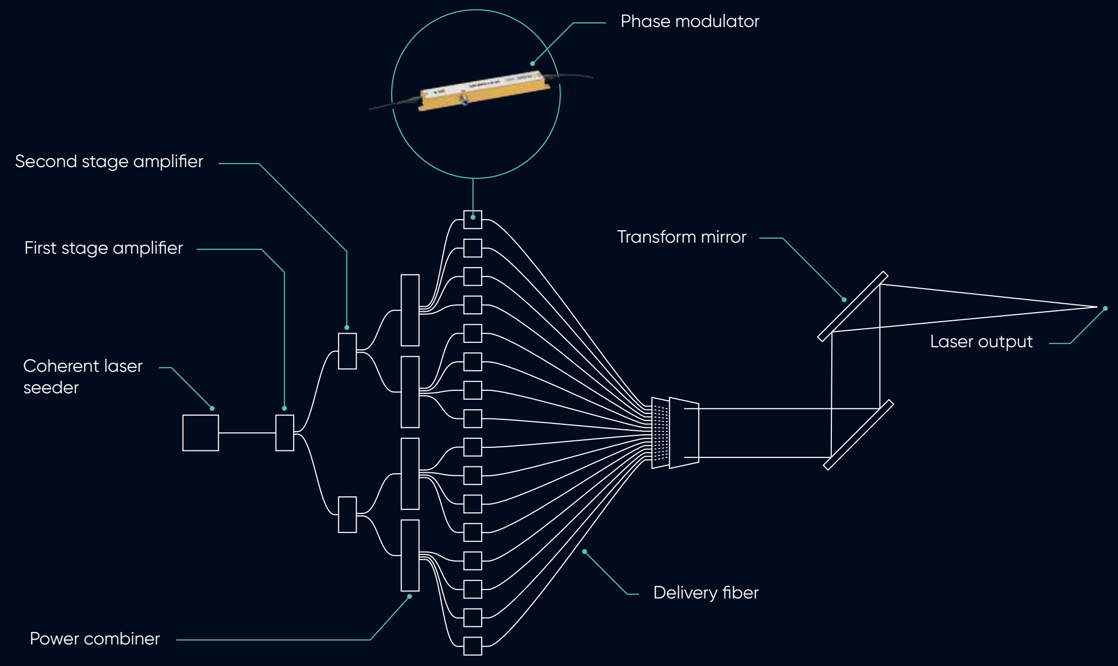
The development of Directed Energy Lasers (DEL) for defense applications is accelerating tremendously. High power fiber lasers have many advantages over chemical or solid-state lasers for such applications: compactness, lower mass for easier deployment, lower production and operating costs, higher reliability over time, resistance to severe and even extreme environments, etc. Today, phasing multiple fiber sources of several kilowatt by optical combination can already result in laser architectures delivering powers of up to tens of kilowatts. Ongoing works are carried out to expend this power to several 100 kW which is the estimated power required for defense applications.

The Coherent Beam Combining (CBC) technique is the most efficient solution to gain power with several combined laser beams as it ensures the combination of several lasers by real-time control of their relative phases. It thus allows to permanently maintain constructive interferences and thus guarantee maximum power efficiency during the combination, a crucial requirement to develop lasers powerful enough to disrupt a drone for example.

An integrated solution to combine several beams with individual phase adjustments

The Modbox CBC-1064 nm is an optimized multi-channels phase modulation solution for multibeam coherent combination. The ModBox CBC integrates up to 8 independent channels with phase and delay tuning capabilities. Each channel allows to adjust the temporal phase for synchronization of the different laser beams. The design integrates – in each channel – Exail proprietary low frequency phase modulator with its matching RF electronic (Exail driver DR-VE) as well as a tunable optical delay line that is selected for high accuracy and a wide delay adjustment range. Special care is taken for the assembly of the ModBox: the Exail electro-optical phase modulators integrated into each system are screened from the company regular production to ensure very low insertion loss, high polarization extinction ratio, low residual amplitude modulation, and high phase modulation stability. The selection of high-grade modulators also secures a reduced optical path between the different optical channels, thus ensuring high optical performances. The phase modulators are also locked in temperature, to ensure a lower drift over time and to limit the photorefractive effect.
Additionally, Exail phase modulator is well known to be the best planar phase modulator in the NIR featuring the highest

Coherent combination of laser beams



optical input power handling capability. The NIR-MPX-LN (Near InfraRed – Modulator Phase with X-cut, on $LiNbO_3$) is widely used and represents a commercial success for such applications.

Exail's Modbox CBC integrates the optical delay lines (Variable Optical Delay Line – VODL) as an option. It is a patented technology based on micro-optic assemblies used to align the optical paths of the different laser channels, thanks to a very precise and stable control of the optical delay (from 0 ps to 600 ps, with a resolution of a few femtoseconds). The optimal optical delay between channels (only tenths of picoseconds of variation) is also ensured by a fine tuning of the fibers lengths of each channel within the system. The ModBox-CBC is coming with a Graphical User Interface (GUI) allowing to control Optical Delay Lines delays. Each channel can be adjusted individually.

Companies manufacturing laser architectures for applications in DEL can rely on Exail ModBox CBC as a proven and reliable solution to develop and test their first prototypes. They can then integrate the sub-components, the phase modulator, the RF driver and the tunable optical delay line, into their own system that can count up to hundreds of channels to reach the kilowatts of power required. "Already a number of companies chose Exail modulation solutions to develop their DEL laser applications." highlights Nicolas Bourriot, product line manager at Exail.

Modbox CBC-2000 nm for the development of Directed Energy Laser using fiber lasers at 2 µm

Today, new applications are rising for high power fiber lasers in the 2 µm range, which has driven recent innovations in specialty fibers technology. Even if still more expensive than the 1 µm or 1.5 µm lasers, the 2 µm lasers offer a considerable asset for applications in Directed Energy Laser applications, as it is "eye-safe", meaning that our eye is sensitive to its beam and instinctively closes itself when touched. That is not the case with thinner laser beams that can reach deep inside our eyes and damage it irreversibly, even after being reflected from a reflective surface. It makes any Directed Energy Weapons (DEW) at 2 µm less dangerous to handle. The ModBox CBC is available in the 2000 nm range.

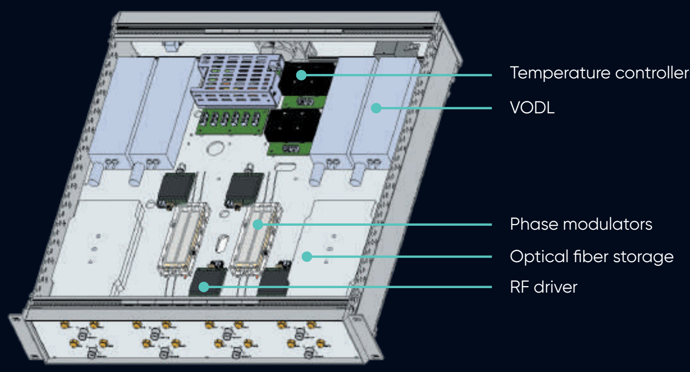
Exail also offers a wide range of specialty fibers for the development of 2 µm fiber lasers for DEL (see Customer Story on page 62 about the partnership with the French-German Research Institute of Saint-Louis – ISL). They are co-doped fibers with Thulium (Tm), Holmium (Ho), or both (Tm/Ho), with on demand customization: any core size (4 µm to 25 µm), one-two or three claddings, any kind of coating (including innovative ones for high temperature or harsh environment) and any kind of doping level. The fiber can also contain a polarization-maintaining (PM). Matching passive fibers are available too. ■

ModBox-CBC-1064 nm-CH

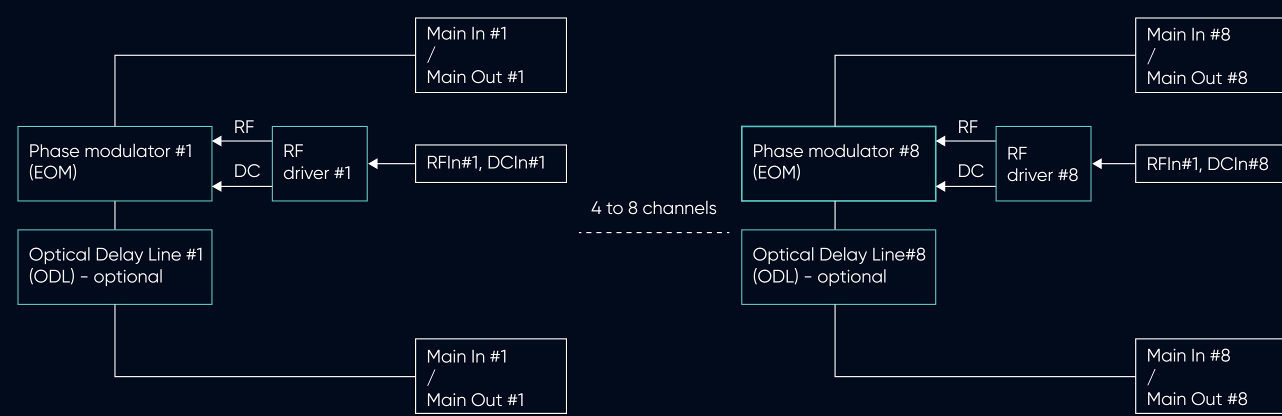
MODBOX 1064 nm 4 OR 8 CHANNELS WITH PHASE MODULATION CONTROL

PERFORMANCE HIGHLIGHTS

Operating wavelength	1064 nm	2000 nm
Insertion loss	< 5 dB	< 5 dB
Polarisation extinction ratio	> 25 dB	> 25 dB
Adjustable delay range	600 ps	600 ps
RAM	Adjustable	Adjustable



MODBOX-CBC FUNCTIONAL BLOCK DIAGRAM



The ModBox CBC exists in 1U (4 channels combined, no VODL) or in 2U (4 to 8 channels, VODL in option)

NEW ER/YB DOPED FIBERS FOR HIGH-POWER LASER

WITH ITS EXTENSIVE KNOW-HOW IN DESIGNING AND MANUFACTURING ERBIUM YTTERBIUM DOPED OPTICAL FIBERS. EXAIL CAN ADDRESS SPECIFIC REQUIREMENTS FOR THE ASSEMBLY OF HIGH-POWER FIBER AMPLIFIERS AND LASERS.

High-power lasers are used today as LIDAR laser sources dedicated to autonomous vehicles (in pulsed regime) for the mapping of their environment, or to equip ground-base stations with high-power amplifiers for ground to space optical communication links (in quasi continuous-wave regime). Exail's process techniques for the manufacturing of specialty fibers keep being optimized to enable high power laser systems with higher efficiency and lower 1µm parasitic optical noise.

With high power range, the limited quantum efficiency leads to a significant heat increase in erbium ytterbium (Er/Yb) fibers. The temperature of acrylate coating, used in most Er/Yb fibers, is limited to 85°C. Managing the pumping signal interaction with the fiber coating is thus an important challenge. In the environment of a compact LIDAR laser source embedded in an autonomous vehicle, the external heat, which can rise up to more than 100°C, is an additional challenge.

In 2023, Exail has added new references of Er/Yb doped fibers to its portfolio, offering new solutions to ensure a high-power laser transmission even under high temperatures, with larger core and polarization maintaining capability. "Those new references can address the requirements for the assembly of lasers with higher peak energy, meaning laser systems with a larger range." Explains Arnaud Laurent, Specialty fiber product line manager at Exail.

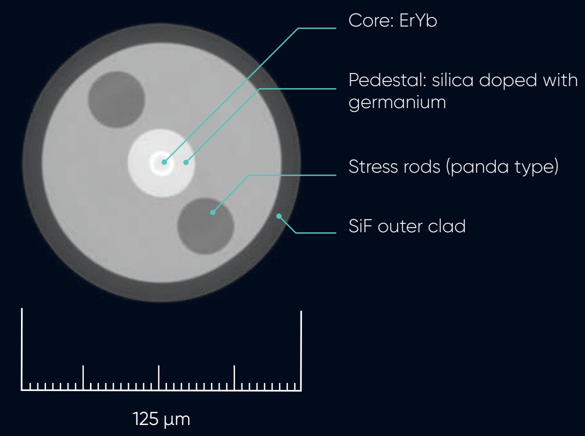
Those developments benefit from the recognized trademark of Exail Er/Yb co-doped fibers developed over the past 10 years.

Enhancing Er/Yb doped fibers for LIDAR applications

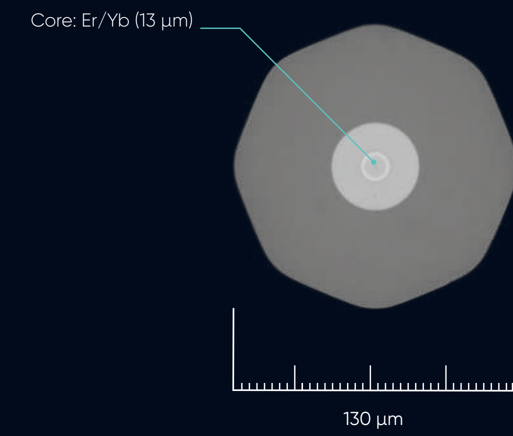
Exail already offers Er/Yb doped fibers with a High Temperature dual layer acrylate Coating (HTC), used to increase the long-term operational temperature range up to 125°C. Those are available with polarization maintaining design. To avoid any issue regarding the interaction of the pumping laser with the fiber coating, Exail also recently developed the All Glass Er/Yb. The Er/Yb core of this fiber is surrounded by a double (or even triple) cladding. Between the two claddings is a Fluorine doped Silica (SiF) material with lower index, meaning that the laser beam interacts only with glass within the fiber, making it very reliable and optically insensitive to acrylate damage.

The most recent improvements in the manufacturing process have enabled to develop Er/Yb doped fibers with larger core and higher reliability, which is key for the implementation of a compact LIDAR laser source for automotive environments. The Double Clad Er/Yb doped fiber with a core of 10µm is now offered as a single mode fiber with a Mode Field Diameter (MFD) of 11.5µm, for an external diameter of 130µm. It exists with High Temperature acrylate coating. It has been designed for applications in LIDAR laser sources requiring high power.

New Er/Yb fibers cross-sections



Cross-section view of the double clad All Glass PM Er/Yb fiber with 12 µm core diameter (IXF-2CF-AG-EY-PM-12-105-125-HTC). The core is surrounded by a pedestal, allowing a 0.11 NA value and a monomode laser transmission.



Cross-section view of the double clad Er/Yb fiber with 13 µm core diameter (IXF-2CF-EY-O-130-HTC). It has a low 0.09 NA, high efficiency, low 1 µm parasitic emission, high temperature, and an easy to splice 125 µm diameter geometry.

> Exail has added new references of Er/Yb doped fibers to its portfolio, offering new solutions to ensure a high-power laser transmission even under high temperatures, with larger core and polarization maintaining capability.
>
> ARNAUD LAURENT, SPECIALTY FIBER PRODUCT LINE MANAGER AT EXAIL

And the All Glass Er/Yb doped fiber is now available with a core of 12 µm (5 µm or 9 µm in previous versions), for an external diameter of 125 µm. It also has a Polarization Maintaining capability. The core composition has been carefully selected to provide high efficiency and long-term reliability which are key advantages for harsh environments, with reduced system cooling requirements.

"With those updates, the new Er/Yb All Glass PM fiber is unique with its 12 µm singlemode core design. This new reference of PM Er/Yb All glass allows the LIDAR manufacturers to develop systems with highest pulse energy and thus a larger range. It will be possible to recover more data from a larger range around the LIDAR" according to Arnaud Laurent.

› Er/Yb doped fibers with large core for high power amplifier in ground-based stations for optical space telecommunication

High-power continuous-wave fiber lasers, for example for ground to space optical communication links rely on fiber with large core diameter, where most of the light power is transmitted. Fibers currently available on the market for these applications have large core (25 µm) but also a large external diameter (250 µm in total). They are difficult to cleave and splice, more sensitive to bending and thus difficult to manipulate and assemble. Matching components are also more difficult to develop and more expensive. Fibers with smaller core exist for high power amplifier application, but they are multimode which can create power instabilities in a compact system, and they also present reduced Mode Field Diameter (MFD) at 1.55µm.

With its industrial capabilities and state-of-the-art technology, Exail could develop a monomode fiber with a large core as an ideal compromise among the existing products for high-power CW fiber laser: the Er/Yb Double Clad doped fibers with a large core of 13µm. It is a single mode fiber at 1.5µm, with a large MFD (13.5 µm-15.5 µm), High Temperature and a low 1 µm parasitic emission (thanks to a specific design of the matrix).

The most recent tests show an excellent behavior of the fiber at 40 W in continuous mode over several days without any power loss. The matching passive fibers developed by Exail, both single clad and double clad are available and in stock. Moreover, the fiber is easy to handle, bend and splice. A version with Polarization Maintaining design will be available soon. ■

Er/Yb Fibers, All Glass 9 or 12 µm, Double Clad 10 or 13 µm

IXF-2CF-AG-EY-O-9-105-125-HTC
IXF-2CF-AG-EY-PM-12-105-125-HTC
IXF-2CF-EY-O-10-130-010-HPA
IXF-2CF-EY-O-13-130-009-HPA

PARAMETERS

Part number	IXF-2CF-AG-EY-O-9-105-125-HTC	IXF-2CF-AG-EY-PM-12-105-125-HTC	IXF-2CF-EY-O-10-130-010-HPA	IXF-2CF-EY-O-13-130-009-HPA
Core diameter (µm)	8.5 ±0.5	11.5±1	10 ±1	13 ±1
Inner clad diameter (flat-flat) (µm)	105 ±4	105 ±3	NA	NA
Inner clad shape	Octagonal	Circular	NA	NA
Clad diameter (µm)	125 ±3	125 ±3	125 ±3	125 ±3
Outer clad shape	Circular	Circular	Octagonal	Octagonal
Core-clad offset (µm)	<1	<1	<1	<1
Coating diameter (µm)	210 ±15	210 ±15	210 ±15	210 ±15
Coating Material	HTC*	HTC*	HTC*	HTC*
Core NA	0.14 ±0.015	0.11 ±0.01	0.10 ±0.01	0.085 ±0.01
Inner clad NA	≥0.22	≥0.22	NA	NA
Outer Clad NA	≥0.40	≥0.40	≥0.46	≥0.46
MFD @1550nm (µm)	9.5	12.5	12	14.5
Clad absorption @915nm (dB/m)	2.8±0.5	3 ±0.7	2.5 ±0.5	3 ±0.7
Clad absorption @976nm**, Typ. (dB/m)	11	12	10	12
Core absorption @1536nm (dB/m)	>60	>40	>40	>50
Multimode background losses (dB/km)	<20	<20	<20	<20
Proof test level (kpsi)	100	100	100	100
Minimum fiber bending diameter (mm)	50	50	50	60
Birefringence	NA	$\geq 0.5.10^{-4}$	NA	NA

* HTC: High Temperature acrylate Coating
** Calculated from 915 nm absorption value

POWERING MULTI-PHOTON MICROSCOPY WITH NEODYNIUM DOPED FIBER LASERS

LASER SOURCES BASED ON NEODYMIUM-DOPED FIBER IS AN UNRIVALED TECHNOLOGY FOR FLUORESCENCE IMAGING.

EXAIL'S PORTFOLIO NOW COUNTS NEODYMIUM-DOPED FIBERS PERFECTLY ADAPTED TO "TWO-PHOTON MICROSCOPY" IN THE 920 nm REGION.

Bio or medical imaging relies on the ability to image, in real-time and with ultimate high-resolution, living biological materials (i.e cellular tissues at depths of about one millimeter), while being totally non-invasive. Laser sources are used in a technique called "two-photon fluorescence excitation microscopy". It requires ultrafast pulsed lasers capable of producing high peak power with low pulse energy to avoid degradation of living cells. Fiber based lasers are ideal solutions for this application. They are much easier to install and to maintain than solid state lasers.

920 nm is one of the main wavelengths used for this application, the linewidth where scattering loss is reduced and where fluorescent proteins are available. Laser sources based on neodymium-doped (Nd-doped) fiber can be used as femtosecond pulsed lasers in the 920 nm region for "two-photon microscopy".

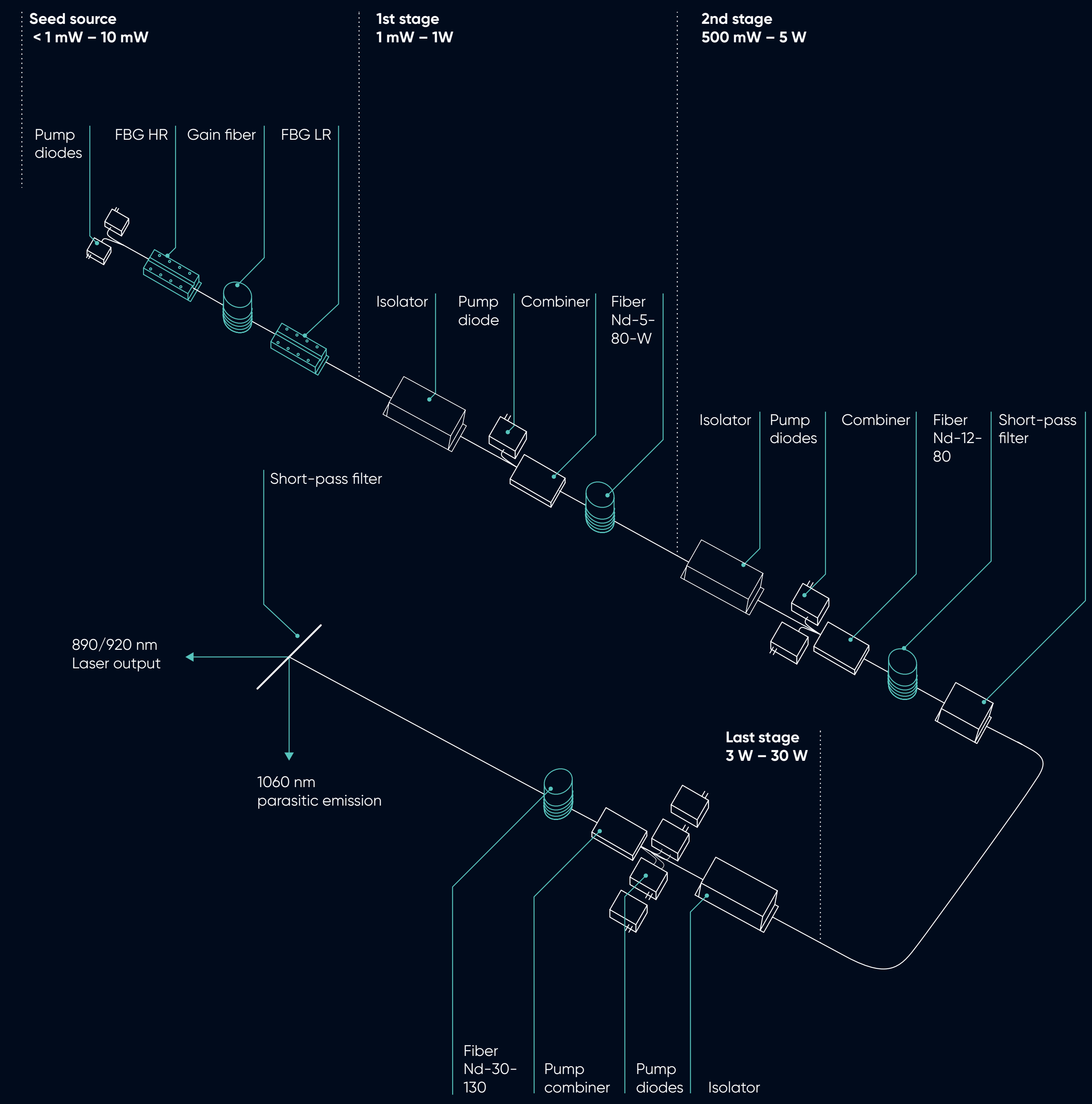
For over a decade, Exail has been engaged in a fruitful collaboration with the team of Mathieu Laroche, researcher at the CIMAP lab in Caen (a joint research lab of CNRS/CEA/ENSICAEN/Univ. of Caen-Normandie) aiming to develop new laser sources based on Nd-doped optical fibers for short infrared and blue/deep-UV wavelength laser emission. Exail's portfolio now counts Nd-doped fibers perfectly adapted to these applications.

The sole industrial reference of Nd-doped fiber dedicated to 920 nm laser sources

Lasers based on ytterbium doped optical fibers are quite common today and efficient in the 1000-1100 nm region. However, among all silica-based fiber lasers, only the one based on Nd-doped optical fibers can efficiently reach shorter wavelengths, in the 900 nm range. The development of Nd-doped fiber lasers is challenging. There is a competition between two transitions of neodymium in the doped core, the transition at 910 nm (3-level scheme) and at 1060 nm (4-level scheme). The latter is much more efficient and must be attenuated to foster the emission at 900 nm. A second major challenge is the non-linear effects appearing, in pulsed regime and single-frequency regime, when the power increases in the optical fiber. The last challenge comes from clustering effect of neodymium ions, leading to ion pairs inducing non-radiative energy transfers highly reducing the fiber efficiency.

The different technological challenges towards the industrialization of the Nd-doped fibers were successfully overcome by Exail, leveraging its manufacturing know-how of specialty fibers developed over the past 10 years. In particular a "W-profile" shaping of the index developed during the collaboration with Mathieu Laroche team was used to obtain a controlled leak for emission above 1 μm. This was a crucial technological step because with the "W-profile" a high gain (up to 25 dB) in the 890-930 nm range can be obtained by suppressing the parasitic emission in the 1000-1100 nm range. The fiber cladding size is reduced to 80 μm to reduce the

MOPA configuration for a laser source based on Nd-doped fibers



neodymium concentration (and thus the clustering) while maintaining the pump absorption level. The double clad fiber ("IXF-2CF-Nd-PM-5-80-D1") has a 5 µm core and a panda polarization maintaining design needed for most applications. This product is highly efficient to amplify low input power, the main limit being the nonlinear effects in single frequency or short-pulse regime.

Exail overcame this limit by extending the core size and using a reduced clad-to-core ratio to favor gain around 920 nm. The fiber core is single mode, and the clad-to-core ratio has been designed to optimize gain of the 3-level transition from 890 nm to 930 nm. A Double Clad neodymium PM fiber with 12 µm core, 80 µm cladding diameter (IXF-2CF-Nd-PM-12-80) is now available for implementation within a MOPA configuration. The first limit of this fiber is the 1060 nm parasitic emission which is dependent on the input power, this technology can amplify signal in the 890-930 nm region to more than 5 W.

To further increase the output power or the pulse energy of 890-930 nm lasers, a very large mode area (VLMA) fiber has been developed with a 30 µm core and 125 µm cladding diameter. The clad-to-core ratio of 4 has been carefully selected to optimize the gain in the region of interest and can produce high power of few tens of watt. The fiber core numerical aperture (NA) has been reduced to ensure good beam quality.

The Nd-doped fiber family produced by Exail is the only industrial reference of the market dedicated to applications using 920 nm laser sources. It has been optimized for the 890-930 nm region and 3 different designs have been developed to address a wide power range from a few mW to tens of watt in short pulse or single frequency regime. All the fibers have a polarization maintaining design. Single clad fibers are also offered and would be ideal to build seeder sources. The different fibers can also be delivered integrated with components such as fibered pump combiners perfectly matching Exail fibers.

Towards watt-level deep-UV and blue lasers for quantum technology and other applications

Nd-doped fiber laser sources can emit at high power (more than 80 W) near 900 nm which is useful in many scientific or technological applications requiring accuracy as much as strict power. Another advantage of the Nd-doped fiber laser is the possibility to double or even quadruple its frequency via non-linear crystals, to obtain several watts of power in the blue region (450 nm) or around a watt in even shorter wavelengths (in deep-UV around 225 nm).

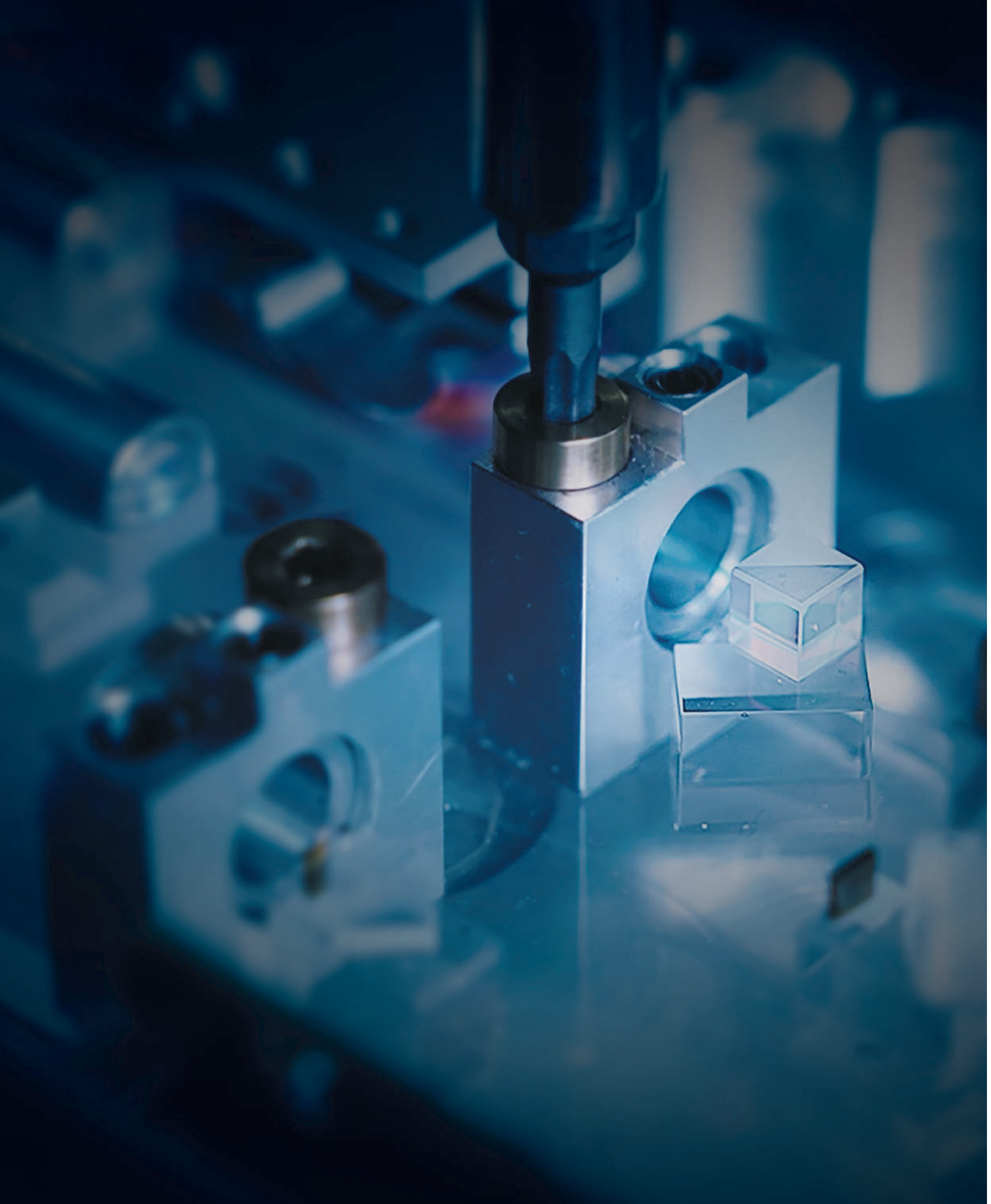
As a source of continuous-wave single-frequency in the blue domain (frequency doubled), they can be used to cooldown strontium atoms for quantum applications. But Nd-doped laser sources can also serve as lasers emitting in the deep-UV to fasten the material processing/characterization (due to their high energy and accuracy), to replace excimer lasers (i.e Fiber Bragg Gratings inscription) or to generate laser induced fluorescence to detect explosive devices (at around 230 nm). ■

Neodymium doped Fibers

IXF-2CF-ND-PM-12-80

Part number	IXF-2CF-ND-PM-12-80
Core diameter	12 µm
Clad diameter	80 µm
Outer clad shape	Circular
Core-clad offset	< 1.0 µm
Coating diameter	165 µm
Coating Material	Acrylate
Core NA	0.06
Inner clad NA	≥ 0.46
MFD @920 nm	13.0 µm
Clad absorption @808 nm	1.6 dB/m
Multimode background losses	< 50 dB/km
Proof test level	100 kpsi
Birefringence	1.8×10^{-4}

* Calculated from 915 nm absorption value
** Following XFS/080301ARL procedure



PIONEERING COLD-ATOM BASED QUANTUM TECHNOLOGIES

THE QUANTUM SENSING ACTIVITY OF EXAIL, STARTED 12 YEARS AGO IN THE VERY FOOTSTEPS OF ALAIN ASPECT, 2022 PHYSICS NOBEL PRIZE, IS THE WORLD'S LEADER IN INDUSTRY-GRADE QUANTUM SENSORS BASED ON LASER COOLED ATOMS.

Today, Exail quantum sensors are operated worldwide by non-specialists, from the top of Mount Etna to Antarctica. The development of dedicated intelligent frequency-stabilized laser systems (ILS) and Integrated micro-optics benches (iMOB) holds the key to such success. This state-of-the-art range of technologies is now available for a broader range of users.

Beyond quantum sensors, Exail's photonics solutions enable real applications in all quantum technology fields, both for academic laboratories and for the industry. Following the outstanding developments and field deployments of quantum gravity sensors, laser-cooled atoms are today one of the most mature and promising physical platforms to implement quantum computing and long-distance quantum communication.

Exail's ILS now stands as a flagship solution for quantum systems manipulation. It indeed integrates a range of in-house components and sub-systems (iMOB), offering innovative and reliable solutions to unleash the use of quantum technology platforms. From design to manufacturing, Exail masters the complete production chain of such integrated ILS laser systems.

The company also provides specialty fibers, bragg gratings, high speed modulation solutions and micro-optics assemblies. Exail leverages on both this industrial capacity and on the fruitful collaborations with leading research labs it has nurtured over the years.

Exail's field-proven solutions now cover a wide range of quantum applications, from the deep sea (In 2022, Exail and researchers from the LP2N lab demonstrated the first 3-axis quantum inertial sensor that allows to continuously measure the acceleration in 3 dimensions and for any orientation of the sensor, an important step towards the development of a drift-free inertial navigation system) to outer space (Exail is involved in the CARIOQA-PMP European project which aims at developing a space grade quantum gravimeter for Earth and climate monitoring).

Efforts deployed by academic laboratories and companies worldwide to develop quantum processors are tremendous. Exail's innovative and reliable photonics components and systems are there to ensure faster development, from fundamental research to commercially available machines, and allows increasingly complex set-ups to be developed and ran. Whether they rely on photons, neutral atoms, trapped ions, NV-centers to implement quantum computing or quantum simulation, Exail's iMOBs and modulation solutions will help reach the most ambitious goals.

Turn-key laser systems for quantum technologies and laser-cooled atoms

Exail intelligent laser systems (ILS) is a new generation of compact and agile laser system offering precise control of lasers amplitude, phase, and absolute frequency with fast tunability. The ILS laser Series is mainly dedicated to manipulating rubidium atoms with 780 nm laser light. However, other wavelengths for other species can be addressed and a wide variety of configurations are available.

The laser architecture is based on the use of slave lasers, phase-locked to a master laser whose frequency is actively stabilized on an atomic transition using saturated absorption spectroscopy.

The laser systems are equipped with dedicated ultra-low-noise electronics developed by Exail, on-board computer and power supply to offer ultra-low noise laser light, agile and precise frequency control, industry-grade integration and remarkable robustness, and user-friendly operation. These laser systems can also integrate an ultra-low noise microwave synthesizer.

The ILS systems are based on C-band fibered telecom optical components (i.e seed lasers), a proven robust and reliable technology. The laser light at telecom wavelength (around 1560 nm) is amplified and frequency-doubled to generate the required wavelength. This approach gives access to a wide variety of high performance fibered optical components, originally developed for high-bit-rate optical communication systems.

The laser systems provided by Exail feature state-of-the-art optical performances that meet the stringent demands of cold-atom physics and atom interferometry. On the optical domain, careful measurements show a typical linewidth of 50 kHz at 780 nm and a typical frequency stability of the different slave lasers of 50 kHz rms over days.

With Exail's ILS, the performances of state-of-the-art quantum physics experiments can be accessible to a much broader spectrum of users outside of academic laboratories. Indeed, no optical alignment, no mechanical assembly, no manual adjustment is required prior to operation and the installation can be done in 10 minutes. The frequency locking of the master laser and the phase locking of the slave lasers are automated and managed by the on-board computer. The frequency lock and the phase locks remain locked for months without any action required from the user. It is robust with regard to temperature variations and vibrations.

The dedicated and user-friendly data acquisition and system controller software allows an easy access to automated starting and self-calibration procedures, and to remote access and real-time data retrieval. The final asset of the ILS system is its small footprint, as it can be integrated in 19" rack cabinets and feature output fibers whose length can be of several meters.

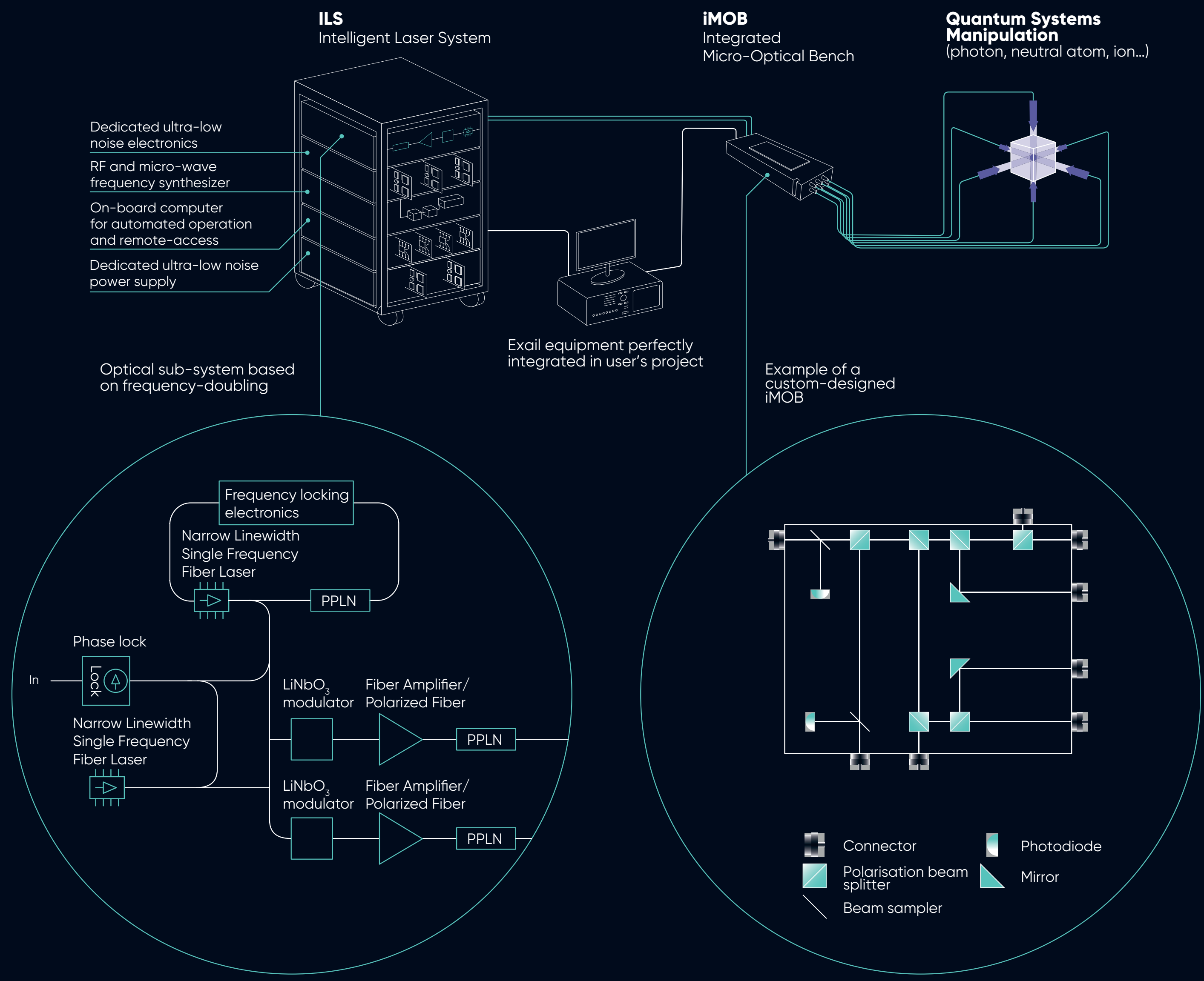
Turning your photonic lab experiment into a compact and robust system with the iMOB Series

It is well known, photonic laboratory experiments can be tricky to handle as they require regular realignment, in particular when turned on and when the system is heating up. Exail has developed the iMOB to help researchers in this situation. iMOB is a free-space micro-optical bench (fibered in entrance and output) built using a fully active alignment method that has been proven reliable for telecom application, space application, and that is perfectly suited for laboratory applications. iMOB systems offer stability and reproducibility of the measurements, while being compact and transportable, and they can integrate a wide range of optical functionalities.

One of the biggest challenges in optics is to manage the light once it has been emitted. Optical fiber is often the preferred solution as it is the easiest way to manage a laser beam. Still though, depending on the application's wavelengths, free space optics might be necessary in order to perform the effect needed for certain functionalities that are not easily compatible with a fiber. Exail micro-optics technology was developed and was first acknowledge by a Telcordia norm to be compatible with telecom applications. Exail leverages this know-how in the 1550 nm wavelength range and offers today the iMOB series as an answer to the markets needs of today.

Exail expertise in the direct assembly of micro-optics makes it easy to integrate switches, frequency shifters, or splicing combining functions in iMOB benches. It can perform the requested functions by using quarter waveplates, half waveplates, acousto-optics modulators, shutter blades, mirrors and of course lenses. As the laser beam is collimated with our own methods, powers up to a few Watts can be handled. iMOB also relies on Exail's gluing technology which was Telcordia approved, and more recently qualified for space applications in the 1550 nm range. ■

Quantum systems manipulation: form components to laser systems



ILS Series

FREQUENCY-CONTROLLED LASER SYSTEMS DEDICATED TO ATOM COOLING AND TRAPPING

A WIDE VARIETY OF CONFIGURATIONS AVAILABLE

- Up to 4 independent frequency-stabilized laser heads operating at 780.23 nm
- Tunability frequency range up to 1 GHz
- Sideband generation
- Fast beam extinction and power modulation
- Phase-locking of laser outputs
- Power splitting to 3 or 6 output fibers per laser head, with power control adjustability.

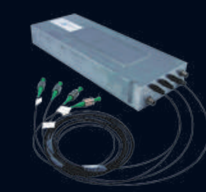
OPTICAL CHARACTERISTICS

Operating wavelength	780.23 nm (D2 line of 87 Rb and 85 Rb)
Output power	> 300 mW per laser head (direct use for atom manipulation)
Linewidth	< 60 kHz
Tunability range	up to 1 GHz
Sweeping rate	> 250 MHz/ms typ.
Polarization	30 dB typ.
Beam quality	TEM_{00} M2 < 1.1
Rise/fall time	< 1 µs
Frequency stability	< 100 kHz rms at 1 day

GENERAL CHARACTERISTICS

Dimensions	19" rack, 500 mm depth, from 6 to 14 U, depending on the laser configuration
Supply voltage	100-240 VAC, 50-60 Hz
Electrical power consumption	< 250 W typical, depending on the laser configuration

iMOB Series



INTEGRATED MICRO-OPTICS BENCHES FOR BEAM SPLITTING/BEAM COMBINING

BENEFITS & FEATURES

- Many configurations available: 1 or 2 inputs, up to 12 outputs
- Wide choice of operating wavelength from 400 nm to 2000 nm
- Input power up to 2 W

APPLICATIONS

- Quantum technologies (sensing, communication, simulation, computing)
- High-precision measurement
- Spectroscopy

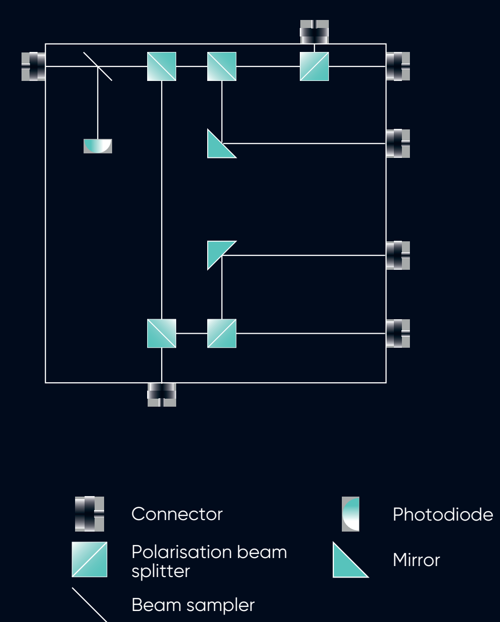
OPTIONS

- Variable splitting stage, mechanical shutters, AOMs
- Choice of fibers and connectors
- Ditherless version

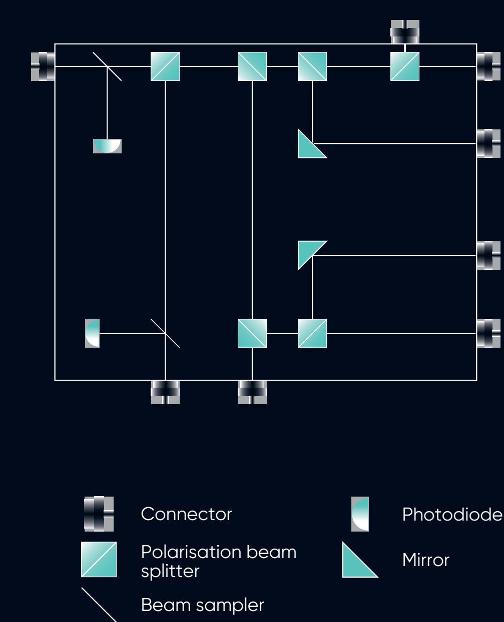
SPECIFICATIONS

Wavelength	from 400 nm to 1600 nm
Maximum Input Power	2 W
Insertion Loss	< 2.5 dB (depending on configuration)
Insertion Loss variation over Operating Temperature Range	< 0.7 dB
Operating Temperature Range	[10°C ; 50°C]
PER out	> 25 dB (30 dB typ.)
Number of output fibers	On demand, between 2 and 12 typically
Dimensions	250 mm x 110 mm x 35 mm (depending on configuration)

In addition of the fantastic flexibility of optical design, the iMOB Series can be customized at will to meet a great variety of optical designs (number of input and output fibers, type of fibers, fiber lengths, connectors).



› Optical power splitting
1 input into 6 outputs



› Optical power combining & splitting
2 inputs into 6 outputs

02

CUSTOMER stories

P.42
Bringing quantum processors
To industry standards

P.46
Quantum Key Distribution
Unlocking its full potential

P.52
High Energy Laser
Enhancing their capabilities

P.56
Laser Fusion
Reaching new performance limits

P.62
2 µm fiber laser sources
Delivering new defense innovations

P.66
LISA mission
Supporting NASA and CNES

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BRINGING PASQAL QUANTUM PROCESSORS TO INDUSTRY STANDARDS

FOR A FEW YEARS NOW, QUANTUM COMPUTER STARTUP PASQAL HAS PARTNERED WITH EXAIL TO DEVELOP CUTTING EDGE LASER AND CONTROL SOLUTIONS WITH THE AIM OF PUSHING THE TECHNOLOGICAL BOUNDARIES OF QUANTUM COMPUTING.

› Quantum Processing Units out of atomic arrays

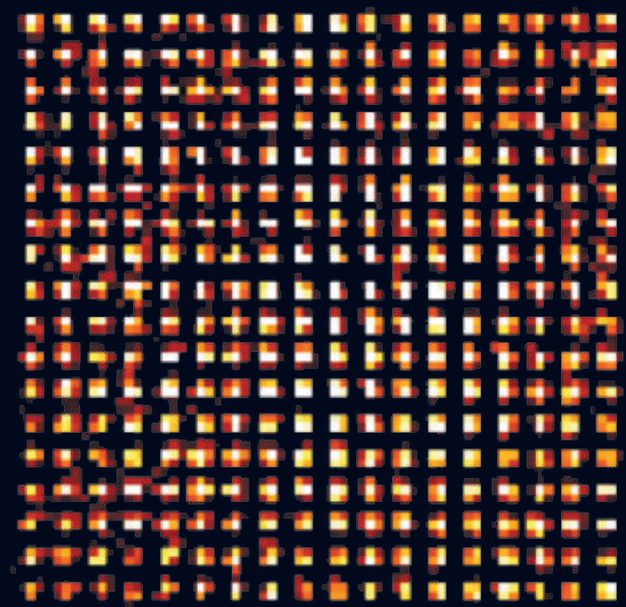
PASQAL is a French company developing quantum processors built out of atomic arrays. Co-founded by Alain Aspect, 2022 Physics Nobel Prize, the company exploits a laser-cooled neutral atoms technology to develop its quantum solutions. The quantum property of such neutral atoms makes it possible to use them as quantum bits, a two-level system ruled by the superposition principle. When a classical bit can only store 2 combinations (0 and 1), a qubit can store multiple combinations (0, 1 and combinations in between). The qubits can then be used in digital quantum gates for processing tasks. PASQAL has already sold quantum processors counting 200 qubits and aims at delivering, by 2024, a quantum processor with 1000 qubits, accessible via the Cloud.

The manufacturing of quantum processors can rely on different platforms for the manipulation of quantum systems (photons, ions, atoms, etc.), each one of them facing specific challenges. Quantum processors based on superconducting qubits, for example, rely on a long engraving process of a chip in a cleanroom environment. The quantum systems used by PASQAL to perform its quantum processing are neutral atoms. With this platform, implementing a quantum processing requires going through three distinct phases. First, the preparation of an atomic array, called qubit register. The register is made by cooling and trapping atoms (rubidium atoms) one by one from an initial cloud of atoms. Then, optical tweezers are used to place each atom in a particular geometrical shape for the calculation. Such a grid formed by individual and identical atoms is generated for each new cycle of calculation. For the last phase, consisting in processing the qubits (atoms trapped in optical tweezers), lasers are used to manipulate the states of the atoms and to generate entanglement. It is then possible to implement a quantum algorithm. The entanglement required to implement quantum processing is a key step for which PASQAL is planning further collaboration with Exail to co-develop more powerful types of lasers, dedicated to this processing phase.

› Improving reliability of PASQAL quantum processors with intelligent laser systems

Preparing a register with many qubits without any defects is a real challenge. With the goal to reach a quantum processor counting 1000 qubits, it is important for PASQAL to rely on its sub-systems, and in particular in the laser system that prepares the qubit register. Adrien Signoles, Deputy-CTO at PASQAL, adds that "having laser systems that are truly reliable and robust over time is a crucial point for us on the road to reach industrial-scale quantum processors for the quantum computing market".

Exail had worked for more than a decade on the industrialization of complex systems to manipulate cold atoms to develop quantum gravimeters. "We knew that both their laser system, their system to trap atoms and their integration capability were reliable enough to operate a quantum gravimeter from the top of Mount Etna to Antarctica." explains Adrien Signoles. The intelligent laser systems used to operate the quantum gravimeter was adapted to improve PASQAL's



We rely on Exail's laser system on the first step of our process, to cooldown millions of atoms into a cloud, before trapping them one by one.

ADRIEN SIGNOLES, DEPUTY-CTO AT PASQAL

PASQAL unveiled a new quantum processor architecture with a record 324 atoms in September 2022.

quantum processors reliability. "Our goal at PASQAL was to go through the same path for the industrialization of our own quantum technology: quantum processors based on neutral atoms." Exail has been more than a supplier, it has been a partner to develop complex quantum systems based on cold atoms with industry standards. The team of PASQAL has also given feedback along the way so that the laser system could be improved for such a complex technology.

According to Adrien Signoles: "We rely on Exail's laser system on the first step of our process, to cooldown millions of atoms into a cloud, before trapping them one by one. This is quite a similar process to what is done inside Exail's quantum gravimeter where a cloud of rubidium atoms laser-cooled close to absolute zero is used as the test mass, to sense minute variations of gravity. At PASQAL we use the same laser wavelength - 780 nm - to cooldown the atoms and manipulate the same type of atoms. It is based on a doubled wavelength - 1560 nm - usually used for telecom applications, which means that all the technology developed at this wavelength have proved its robustness".

The intelligent laser system acquired by PASQAL is customized, but easy to integrate as it is fibered and ready to operate PASQAL's quantum processor at the correct wavelength. It is a crucial step towards the industrialization of their system, initially developed in an academic environment where a large optical bench in free space with many optical different devices was needed to shape the laser beams as required. "The laser systems supplied by Exail are now integrated, rack by rack into the PASQAL quantum processor" sums up Adrien Signoles.

Developing next-generation HPC (high performance computing) solutions

There is high interest in intelligent laser systems (ILS Series), able to operate cold-atom based quantum technologies such as PASQAL's quantum processors. HPC centers, for example, are interested in installing quantum processors directly in their supercomputer. The computing capability can then be delivered to answer the needs of large industry companies. Future quantum processor units (QPUs) could soon be incorporated into supercomputers to solve some specific problems that can't be solved by classical processors. Optimization problems are often taken as applications for which a quantum computer could find much better approximate solutions. Optimizing the charging of electric vehicles is an example on which PASQAL is already working with EDF (Electricity of France). But the quantum processing capabilities offered by PASQAL is also interesting banking companies to improve their predictable models and to deal with other types of machine learning algorithms. ■

UNLOCKING QUANTUM KEY DISTRIBUTION

EXAIL AND THALES PARTNER ON NEW QUANTUM COMMUNICATIONS HARDWARE, FOR THE DEVELOPMENT OF EUROPEAN READY-TO-DEPLOY QKD SYSTEMS.

The EuroQCI initiative (European Quantum Communication Infrastructure), which aims to deploy a quantum communication infrastructure for EU member states within three years, started in January 2023, funded by the European Commission. Indeed, by 2040, quantum computers could use their unprecedented computational power to decode encrypted data, incomparably threatening the security of even the best-protected communication systems. EuroQCI aims to counter that threat by developing sovereign systems to protect the communications and data assets of critical infrastructure providers and government institutions.

As an answer to the current lack of established QKD hardware suppliers to protect the EU strategic digital autonomy, QKISS (Quantum Key Industrial SystemS) project started, aiming at producing high-performance, secure and certifiable European Quantum Key Distribution (QKD) systems by 2025. The objective is to implement a complete and qualified telecom link that allows encrypted communications protected by the fundamental laws of physics.

Led by Exail, QKISS leverages the extensive expertise of the 4 partners involved, two high-tech industrial groups, Exail and Thales, and two leading academic: team of Prof. Philippe Grangier at Institut d'Optique Graduate School (Univ. Paris-Saclay/CNRS) and team of Dr. Eleni Diamanti at LIP6 laboratory (Sorbonne Univ./CNRS). The project will include the manufacturing of opto-electronic components, the development of specialized signal processing and coding algorithms, and go up to full system integration and field demonstrations. QKISS will also produce field evidence of compatibility with telecom network systems, with the QKD systems functioning together with Mistral encryptors from Thales (a turnkey network encryption system including a centralized management software, adapted to the specific QKD framework).

› Exail provides reliable components (modulators, VOA, COH) and sub-systems (LAZ-LAB-NL) to implement CV-QKD, both for the transmitter side and the receiver side.

Baptiste Gouraud, R&D engineer and project manager for Exail, states: "In practice, QKISS will consist in the implementation of a laser-telecom link between a transmitter called "AliX" and a receiver called "BeatriX" thanks to optical fibers. Using the same technique as in long-haul optical communications, information will be transmitted through coherent modulation of light: it will be encoded in the amplitude and phase of the electromagnetic field but will be protected by the quantum detection noise. Coherent homodyne or heterodyne detection will be used to retrieve the quadrature value of the signal to read the key into it. The communication will thus be fully encrypted and protected by the fundamental laws of physics."

"Thales teams are eager to strengthen collaborations with partners within QKISS. The Group will contribute to meeting the high technical expectations of this project, by providing their expertise in specific signal processing for QKD, system design, security analysis and dedicated encryptors." adds Stéphanie Molin, R&D project leader at Thales. According to Philippe Grangier "The QKISS project builds upon a long experience of academic research on continuous-variable quantum key distribution (CV-QKD), starting with a highly-cited article published in 2003 (F. Grosshans and al., Nature, 421). After tremendous progress over the years, involving both academic and industry partners, the technology is now mature enough for industrial deployment."

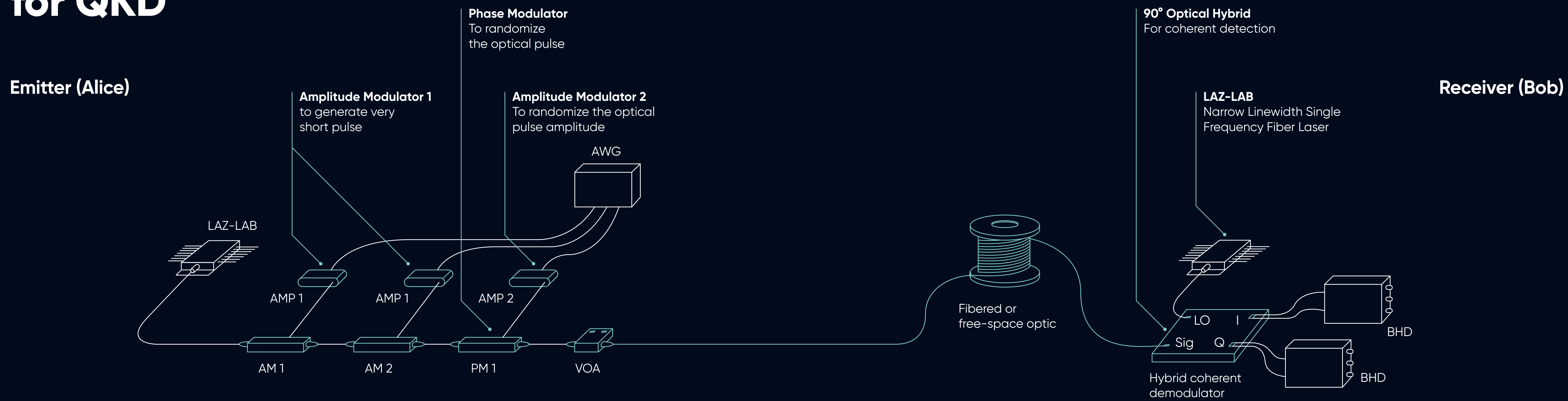
"QKISS leverages and builds on the important recent developments and synergies pursued in the QKD field in the context of EU-funded projects (for instance, CiViQ and OpenQKD)", adds Eleni Diamanti.

The project targets a low-cost and high-rate implementation suitable for metro use-cases with very high speed of communication: modulation rate in hundreds of megabaud (MBd) and secure key rate in megabits per second (Mbit/s). After an industrialization phase, QKISS systems will be available for deployment in the EuroQCI and applications relying on private communications: e-banking, e-health, government communication or the management and protection of critical infrastructure.

› Leveraging more than 5 years of expertise in designing and manufacturing reliable optical components for leading QKD players

There are two different approaches to implement QKD. One focuses on discrete variable (DV-QKD) and relies on single photons with encoded random data. The other one (CV-QKD) plays on the wave nature of light with information encoded in the quadrature of its electromagnetic fields. Coherent homodyne or heterodyne detection is used to continuously retrieve the quadrature value of the signal to read the key into it. Exail has been delivering its reliable optical components to the main industrial leaders for both DV-QKD and CV-QKD.

Modulators with their matching components and demodulator for QKD



In practice, QKD is achieved with optical telecommunication links, either via optical fibers or via the propagation of light in vacuum (or in the atmosphere) for satellite links, where Exail's solutions are used.

For example, Exail has collaborated since 2019 with Quside, a European designer and manufacturer of innovative quantum randomness solution suitable for cryptographic key generation. Quside has been developing innovative solutions for quantum secured space-based communication (space-QKD) and relied on Exail solutions such as the space grade TRL9 Lithium niobate modulators to build a highly integrated high-speed quantum secure communication system. "Exail has helped us accelerate our capabilities within the space sector and we look forward to developing our mutually beneficial relationship into the future" states Quside.

Implementing telecom standard CV-QKD with the optical IQ modulator MXIQER

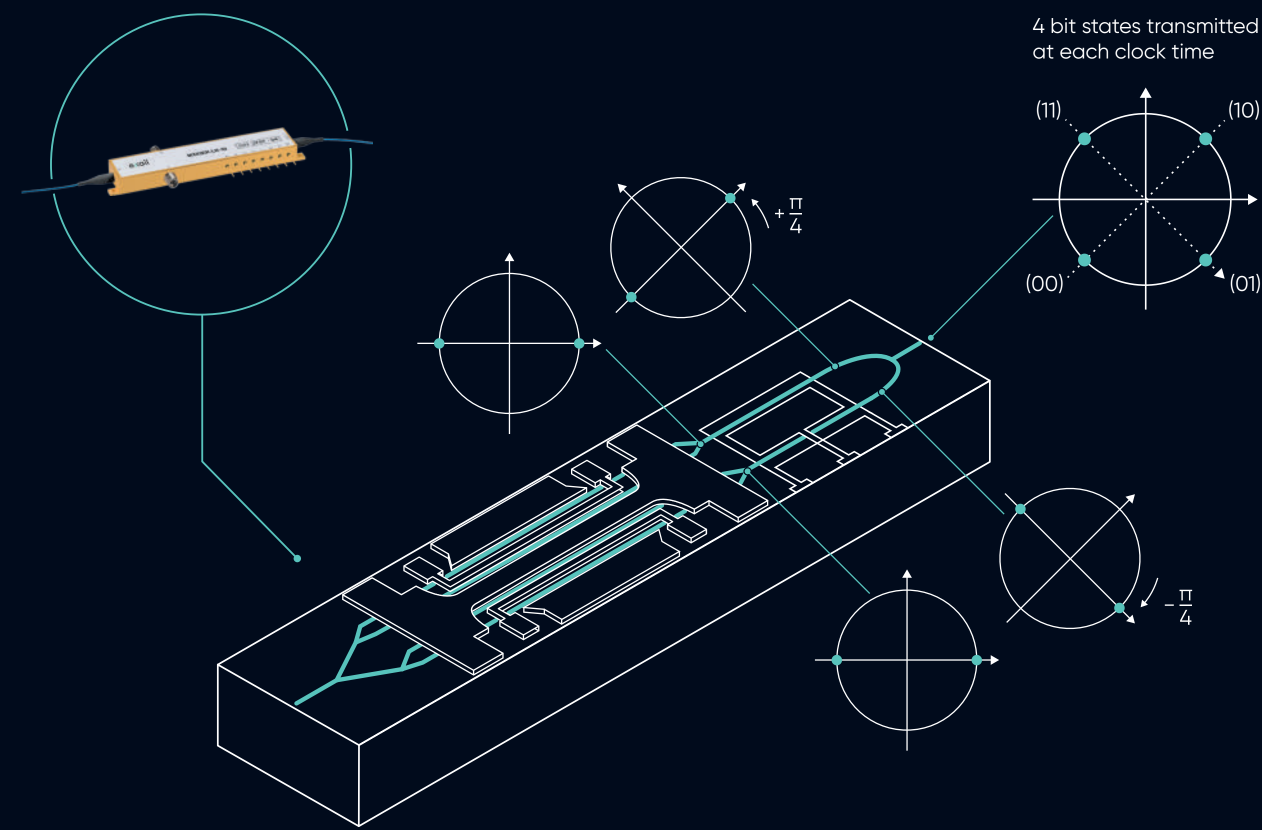
In a CV-QKD system, information is encoded in both the amplitude and the phase of laser pulses using modulation solutions such as the one offered by Exail. Using an Arbitrary Waveform Guide (AWG), a first modulation block can be used to generate short optical pulses. Using Exail's NIR-MX800, MXER1300 and MXER high contrast and wide bandwidth amplitude modulators, very short optical pulses width from 70 ps can be achieved at 850 nm, 1310 nm and 1550 nm respectively. The modulator can be combined with the driver DR-VE-10-MO which can be set either as a limiting or linear amplifier for either square or gaussian pulse waveforms. Using Exail's bias controller MBC-DG-LAB, a high pulse contrast stability can be obtained for frequency repetition rates up to several GHz.

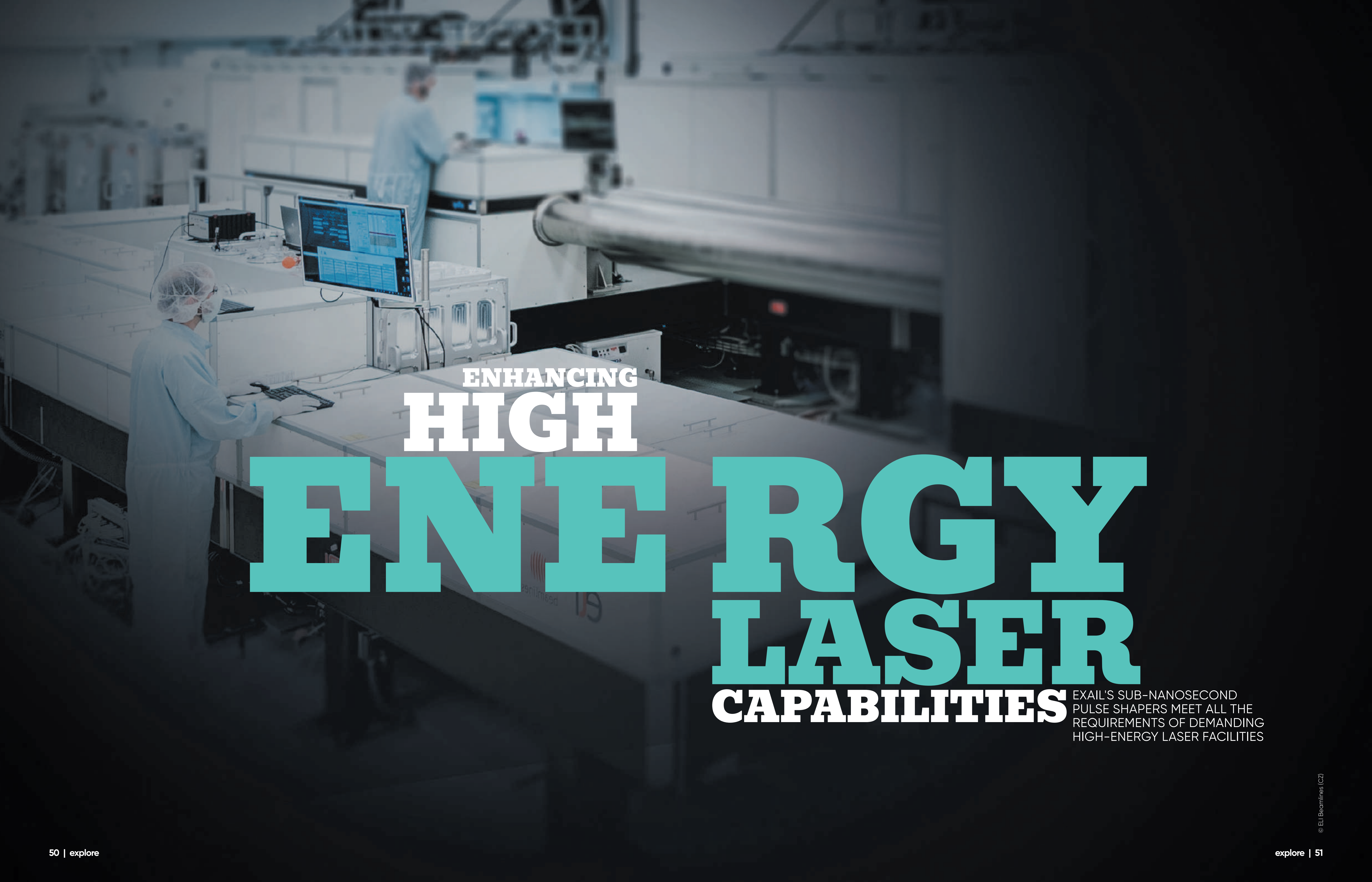
Two separate modulators are often used for the phase modulation (Exail's MPX-MPZ Series) and the amplitude modulation (Exail's MXER Series). But few know that Exail is offering a modulation solution integrating simultaneously the phase and amplitude modulation functions into one unique component. This component, called the Optical IQ Modulator or "MXIQER", modulates via two RF inputs the in-phase (I, or real part) and the quadrature (Q – or imaginary part) components of the transmitted light.

The MXIQER-LN-30 optical IQ modulator is a wide bandwidth, low insertion loss and high extinction ratio Dual Parallel Mach-Zehnder Modulator. Using Exail's MXIQER offers many advantages compared to a phase modulator and an amplitude modulator used separately. It offers compacity as the two functions are integrated into a modulator as large as any Exail's modulators (only it has more connectors – see picture/scheme attached). If the theoretical performances of both setups are similar, using a unique component especially offers greater efficiency. Indeed, less voltage (low Vπ / low arbitrary tension) is required to apply important phase modulation shifts with the MXIQER than with a separate phase modulator. It is thus the most recommended solution for the implementation of a CV-QKD system with telecom standards, exploiting Exail's extensive know-how in manufacturing modulation solutions based on Lithium Niobate ($LiNbO_3$).

The MXIQER is an optical IQ modulator enabling coherent modulation of light on the transmitter side of the communication (Alix) in CV-QKD, when Exail's COH 90° offers an ideal solution for coherent demodulation on the receiver side (Bob). ■

Simultaneous integration of the phase and amplitude modulation functions into one unique component





ENHANCING HIGH ENERGY LASER CAPABILITIES

EXAIL'S SUB-NANOSECOND PULSE SHAPERS MEET ALL THE REQUIREMENTS OF DEMANDING HIGH-ENERGY LASER FACILITIES

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IN THE LAST DECADES, THE UNITED KINGDOM GOVERNMENT AGENCY "SCIENCE AND TECHNOLOGY FACILITIES COUNCIL (STFC)" HAS INVESTED IN THE DEVELOPMENT OF NEW LASER TECHNOLOGIES THROUGH ITS CENTRAL LASER FACILITY (CLF).

It has aimed at keeping its laser capability at the international forefront until today, principally through the development of a world leading laser architecture called DiPOLE, a new high energy, high repetition rate and high efficiency pulsed laser technology. Being able to generate accurate impulsions with reliability over time is a challenge for such a demanding laser facility. Exail could meet all the requirements with its ModBox Front-End, a versatile sub-nanosecond laser pulse generation transmitter based on unparalleled $LiNbO_3$ modulator design.

The STFC CLF won several contracts in the high energy field with this new DiPOLE architecture. It includes the construction of the first 100 J / 10 Hz laser system provided for HiLASE Center in Czech Republic, for the development of pulsed nanosecond diode-pumped solid-state laser. A similar system was constructed for the European XFEL in Germany, a large high energy infrastructure for the generation of extremely intense X-ray flashes. CLF also delivered parts of an amplifier head to ELI (Extreme Light Infrastructure), in Czech Republic, which aims at being the world's largest and most advanced high-power laser infrastructure.

For all these developments, the STFC CLF works with industrial partners to facilitate solutions to real-world problems. The optical pulse shaping solution of Exail, the "ModBox Front-End", was selected as an industrial turn-key solution to facilitate the exploitation of such an extensive technology.

› DiPOLE, a technological reference in the high energy laser field

DiPOLE is the first cryogenically gas cooled, diode-pumped, solid-state laser (DPSSL) system, initially conceived as a prototype. The DiPOLE laser architecture provides a scalable concept design for efficient, high-energy, high-repetition rate. This complex technology was proven mature and established as a reference in the field. It relies on an innovative laser diode pumping system and a powerful cryogenic cooling system, based on intense gas bursts. It also has a multi-slab amplifier head. The DiPOLE laser system is designed for operation from 10 Hz to 100 Hz pulse repetition rate, with pulses at high energy. In comparison, the repetition rate of most high energy facilities in operation in the world today is often lower than one pulse per minute. Real-world applications exploiting ultra-high intensity light-matter interactions will require development of lasers and technology, capable of operating at high pulse energy and repetition rate.

Currently, DiPOLE features an automatic beam alignment system, an adaptive optic system, and thanks to Exail's ModBox the ability to easily generate and modify temporal pulse shapes.

› Reaching state of the art temporal pulse shaping performance using ModBox Front-End

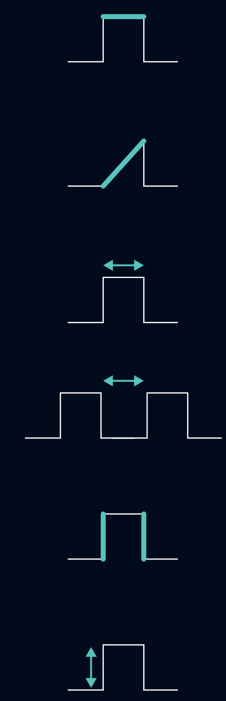
Exail's ModBox Front-End was selected as a solution in the DIPOLE laser architecture. It is used for the optical shaping of the initial laser impulsion, which is amplified a billion times within the system, from several nJ to 150 J. The ModBox offers accurate control of the temporal shaping of each laser impulsion, with its capability to correct the pulse characteristics even at high repetition rate. It is a crucial tool to optimize the performance of a high energy laser facility. "The stability, the reproducibility and the quality of the impulsions generated by the ModBox were some of the most important criteria in the strict specifications of STFC, as well as the reliability over a period of several months" explains Alexandre Soujaeff, ModBox Business Engineer at Exail.

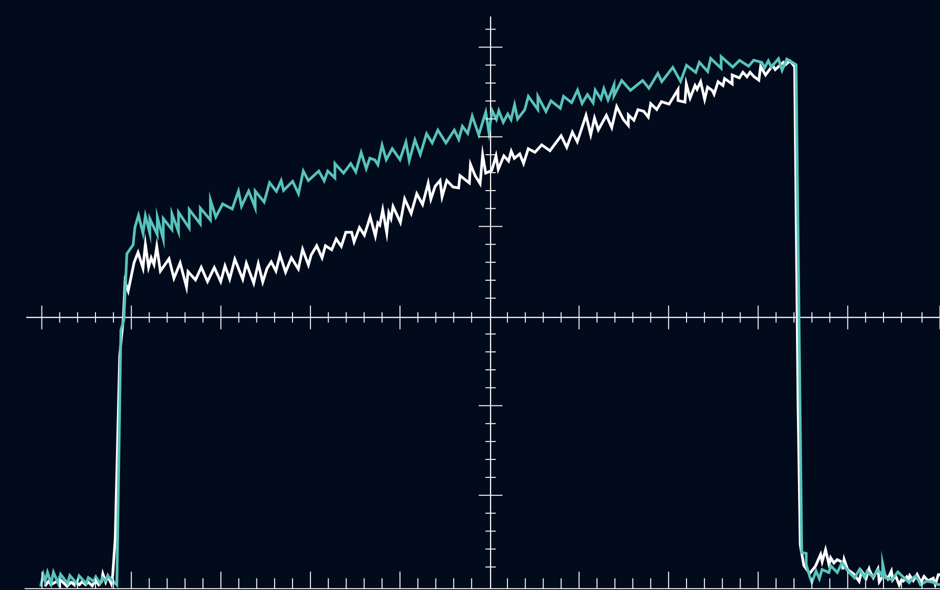
The ModBox Front-End selected to equip the DIPOLE laser systems is an industrial turnkey system, based on Exail's unique know-how in designing and manufacturing $LiNb0_3$ modulation solutions. The company has built up a strong experience in such systems and successfully installed them in many research laboratories over the world, and in industrial companies. Exail know-how in the modelization of complex electro-optic system in the RF domain enables advanced correction capability (see experimental curve). With this feature, ModBox users can easily perform pulse shaping with a high level of fidelity.

Exail indeed masters all three key components needed for optical pulse shaping application: the Electro-Optical Modulator (EOM) based on lithium niobate technology, the high speed and high voltage linear driver for EOM modulators and the modulator bias control (MBC) board.

Each new customer request and each new challenge has led to an improvement of Exail expertise, leading to the most recent products currently in the company portfolio. The ModBox-FrontEnd is challenging the state of the art of temporal pulse shaping performance, as Alexandre Soujaeff, describes it: "With the ModBox FE we are able to generate laser pulses with any kind of temporal shape. And compared with a simple modulation solution, an integrated ModBox solution offers unique performance in term of contrast and stability". ■

Generation of laser pulses with any kind of temporal shape

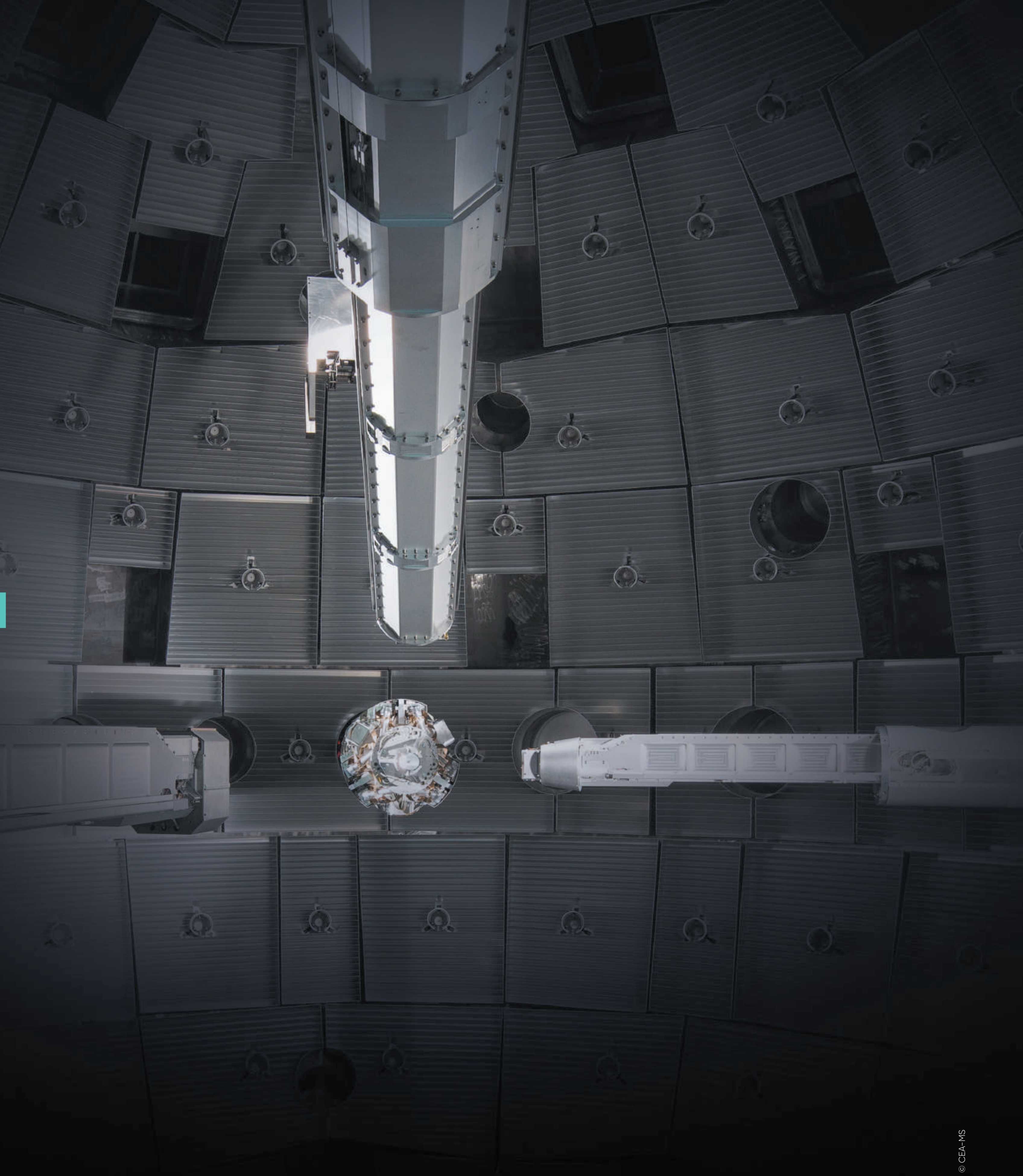




› Exail ModBox FE drastically improves the signal linearity of a high energy or a high power laser experiment. In green is the pulse shaping resulting from Exail advanced correction system, compared to the grey curve where no correction is applied.

BEYOND LASER FUSION FRONTIERS

IN A DECADE, EXAIL HAS BECOME THE SOLE SUPPLIER OF RADIATION RESISTANT DIAGNOSTICS OPTICAL FIBERS, ENABLING THE NATIONAL IGNITION FACILITY (NIF) IN THE US AND THE LASER MEGAJOULE (LMJ) IN FRANCE TO REACH NEW LIMITS IN TERMS OF PERFORMANCE.



In December 2022, the team of NIF at Lawrence Livermore National Laboratory (LLNL) performed the first fusion ignition experiment - with more energy released from the fusion reactions (3.15 MJ) than the laser energy (2.05 MJ) used to trigger them. France built its equivalent of the LLNL-NIF, the Megajoule Laser of the *Commissariat à l'Energie Atomique et aux Energies Alternatives** (CEA-LMJ). Commissioned at the end of 2014, it is primarily used to ensure the safety and reliability of nuclear weapons for deterrence. Accurate diagnostics are crucial to reach thermonuclear gain fusion with high energy lasers. The teams of both facilities have had strong interactions over the years, facing similar challenges and sharing their technical knowledge and competency, in particular around diagnostics optical fibers able to resist intense levels of radiation.

The CEA-LMJ and LLNL-NIF are huge facilities: hundreds of pulse laser beams, with a duration of around a nanosecond, are targeted on a millimeter-sized microsystem. Once combined, the laser beams reach an ultraviolet laser energy of 1.2 MegaJoule (more than 2 MegaJoules at LLNL-NIF) in a luminous flash producing hundreds of terawatts (thousand billion Watts). By accurately synchronizing the laser beams, it is possible to carry out extremely complex laser-matter interaction experiments with an incredibly high level of homogeneous compression.
The target is designed to reproduce, after having received the MegaJoule of energy, a phenomenon of the same nature as that occurring in weapons, or in the core of stars. The most complex experiments are those leading to thermonuclear gain fusion (the nuclear energy released by the fusion reactions is greater than the laser energy invested to trigger these reactions) by inertial confinement of a deuterium-tritium mixture in the micro-target. Creating and accurately controlling such extreme physical parameters also opens the doors for new physics. "We receive more and more requests from scientific researchers wanting to use our laser facility to explore laser-matter interactions" Nicolas Beck, research engineer at CEA-LMJ. The extremely accurate synchronization of the pulse laser beams is made possible by measurement diagnostics, which are specialized state-of-the-art measuring instruments collecting data from the experiment in real-time.

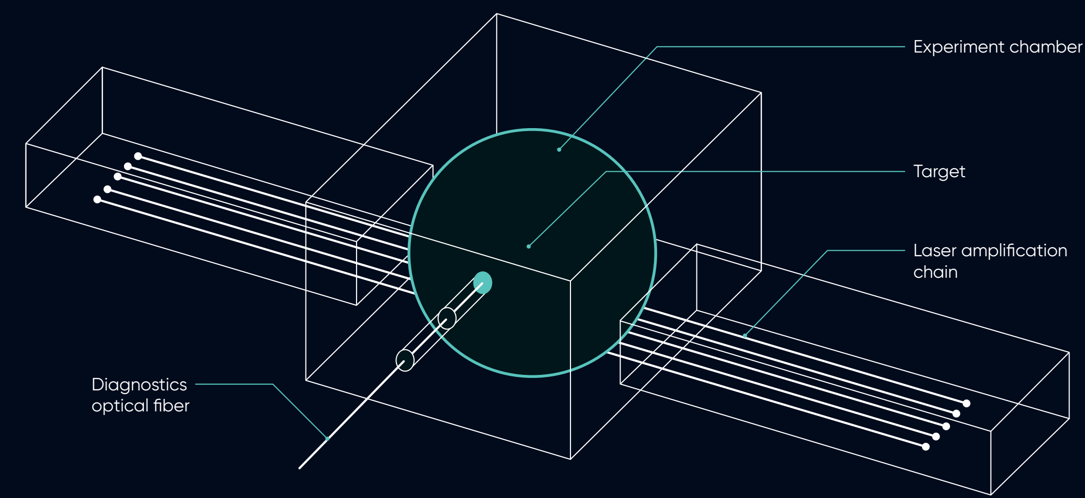
Exail, a unique supplier for reliable radiation resistant diagnostics optical fibers

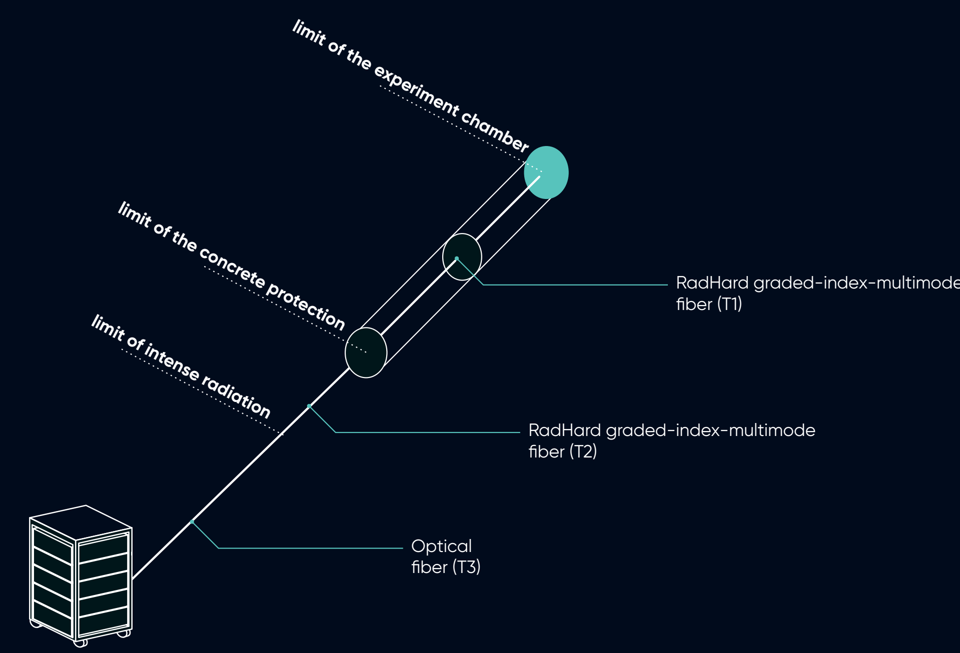
At NIF and LMJ, an optical network is connected to the experimental chamber to recover data of the laser beams through the measurement of their energy, their temporal and their spectral characteristics. The diagnostics optical fibers used to transmit the data within the 30 m close to the target (within the concrete protection) must stay operational despite the extreme conditions and at a high-speed (bandwidth is ~1 ps): it must ensure that the temporal shaping of the laser beam remains unaltered, and the optical attenuation must be extremely low to assure a good transmission of the measurement data. But the most critical aspect is the resistance to radiation involved in the experiment process, that usually damages, or darkens diagnostics optical fibers.
This is where Exail expertise in specialty fibers come into play. Its radiation resistant optical fibers are able to perform reliable diagnostics up to the experiment chamber, where radiation is the most intense. They have become mandatory components for both LLNL and CEA facilities to reach new limits such as fusion ignition or thermonuclear gain fusion.

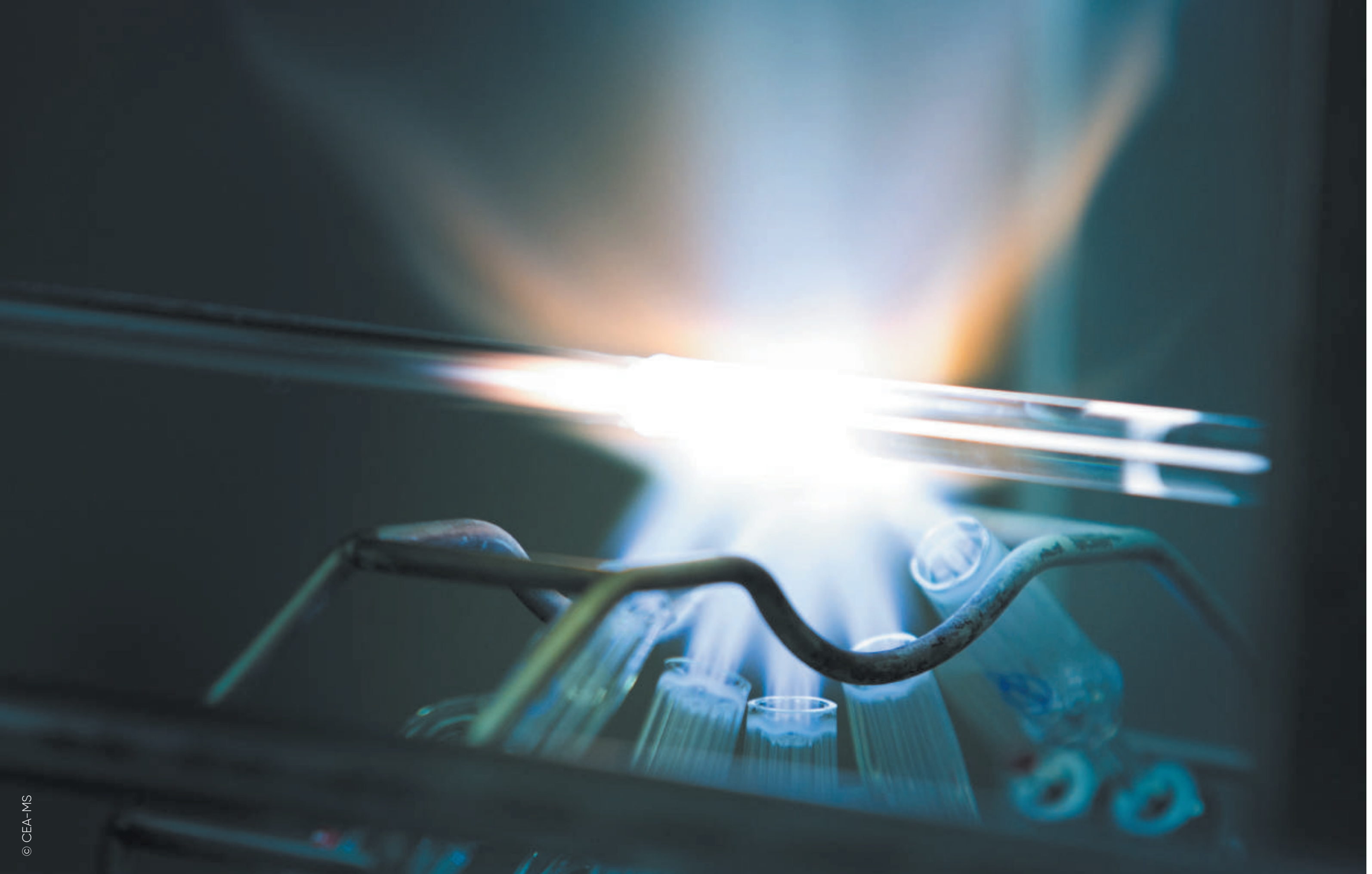
Leveraging a decade of academic-industry collaboration

Exail develops optical fibers for radiation monitoring in radiation-rich mixed environments typically present in the Megajoule class laser facilities. For the laser diagnostics, multimode optical fibers with "graded-index refractive-index profiles" have to be used, to reduce the dispersion impact on measurement quality. In classic step-index multimode optical fibers, the signal is propagated through different optical modes that travel at different speeds. Thus, the temporal information of a given signal is not preserved through propagation. This is of the utmost importance when the light is carrying diagnostics data related

Diagnostics optical fibers operating up to the experiment chamber at CEA-LMJ







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> With the radiation resistant fiber and the modulator for the temporal shaping, you can actually consider that Exail is on the right track to deliver two key components to the main high-energy laser facilities in the world. It shows the company can deliver cutting-edge technology for the high-energy laser field.
>
> NICOLAS BECK, RESEARCH ENGINEER AT CEA-LMJ

Exail develops optical fibers for radiation monitoring in radiation-rich mixed environments typically present in the Megajoule class laser facilities.

to a thermonuclear reaction you want to monitor. Fortunately, "graded-index" multimode optical fiber ensures that each mode injected into the fiber reaches the diagnostic sensor at the other end at the exact same time.

Thanks to a decade of investment in R&D and research collaborations between Exail and Prof. Sylvain Girard (former researcher at CEA, now Professor at St-Etienne Univ. and co-manager of the LabH6 joint laboratory**), the development of a highly specific type of optical fibers became possible. This large core diameter (400 μm) multimode fiber is highly transparent to UV light (thanks to specific treatments of the silica) in order to capture and transmit the maximum of data, while exhibiting both unique radiation-resistance and low temporal dispersion. This diagnostics fiber was designed and is now produced at the Lannion site of Exail. It was qualified and installed at CEA-LMJ in summer 2019.

"Before Exail, only a laboratory had succeeded in producing graded-index fibers matching all our strict specifications, but the fibers were not radiation hardened. With Exail's radiation resistant fibers, we can now guarantee the quality and accuracy of the data collected at any point of the experiment, in particular in the experiment chamber where radiation levels are extreme. It gives us a much clearer diagnostic of whether the experiment is conducted smoothly or not, when experiments were mostly conducted "blindly" before due to the poor information we could recover from the target" explain Nicolas Beck.

During the historic fusion ignition experiment on December 5th, 2022 at the NIF, about 10^{18} (a quintillion) of high-energy neutrons were released. Under this harsh environment, the UV Exail fibers used to transport the laser power signal behaved very well as no significant attenuation was observed. Over the past months, the NIF obsolescent fibers were replaced with several kilometers of Exail radiation resistant UV fibers, thanks to a collaboration between Exail, CEA-LMJ and LLNL-NIF.

Towards new applications for radiation hardened fibers

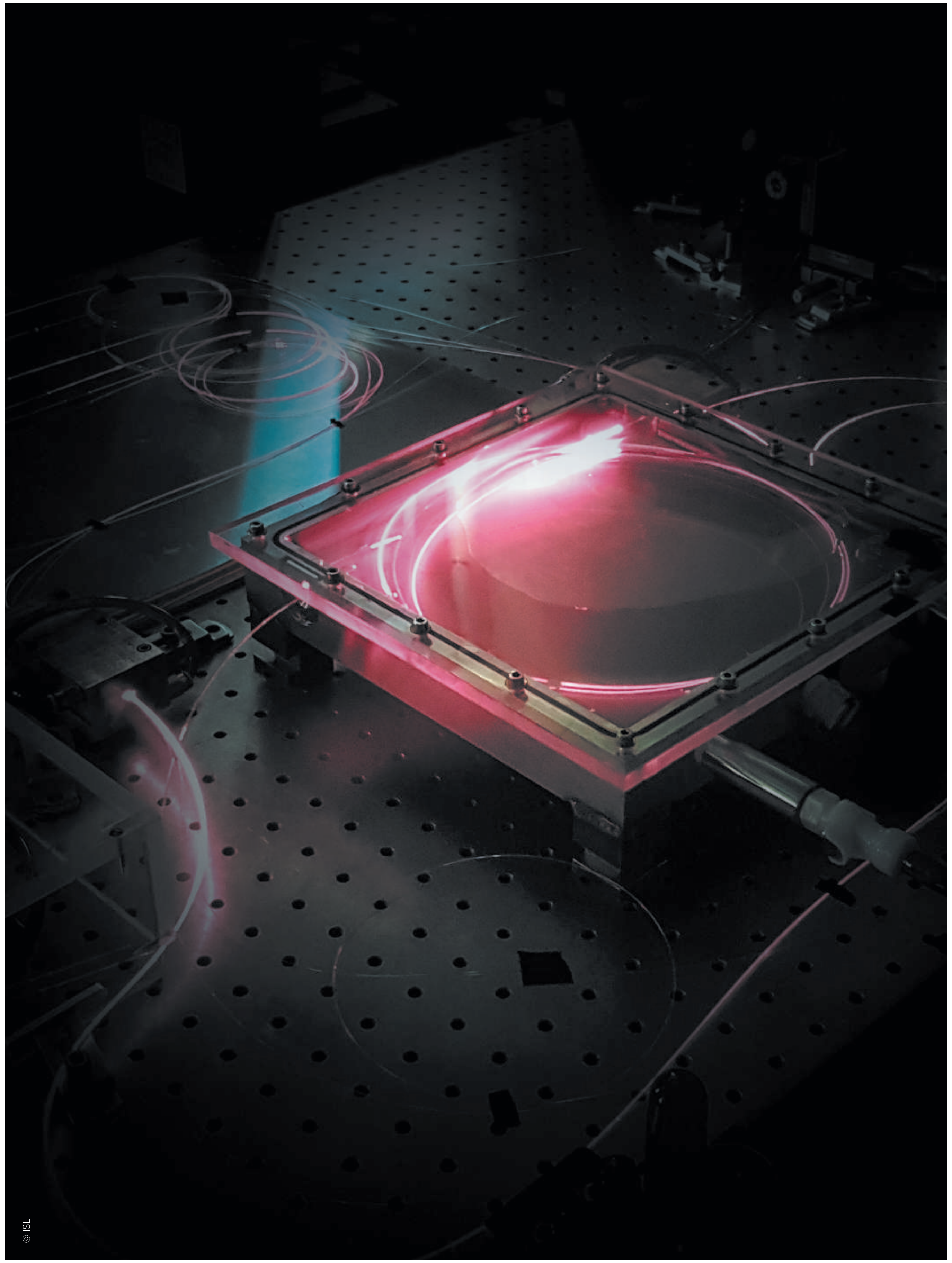
After such a strong and successful collaboration around Exail's diagnostic optical fiber in both the CEA-LMJ and LLNL-NIF facilities, the modulation solutions of Exail (mainly the $LiNbO_3$ optical modulator for the pulse shaping of the laser beam), already used at CEA-LMJ, are now also being qualified for use on the LLNL-NIF.

According to Nicolas Beck "With the radiation resistant fiber and the modulator for the temporal shaping, you can actually consider that Exail is on the right track to deliver two key components to the main high-energy laser facilities in the world. It shows your company can deliver cutting-edge technology for the high-energy laser field. As our specifications are extremely high, it means the same technology can meet the demand of other fields, including the dosimetry in nuclear power plants."

The R&D efforts deployed by Exail and the LabH6 joint laboratory on optical fibers for harsh environments have paved the way for new type of applications, beyond the high-energy laser field. Exail now counts in its portfolio 10 different references of space grade fibers with a guaranteed "Radiation Induced Attenuation" (RIA). New hardening techniques identified, in particular on the occasion of a research collaboration with the French Space Agency (CNES), have also opened horizons for applications in radiation sensing (radiation dosimetry), useful in space (LUMINA project) and in nuclear power plants. ■

* French Alternative Energies and Atomic Energy Commission (CEA)

** LabH6 is a joint laboratory between Exail and the Hubert Curien Laboratory (Jean Monnet Univ. St-Etienne / CNRS / IOGS) focusing on the study of optical fibers and optical fiber-based sensors in harsh environments. Joint laboratories are partnership research collaborations built between Exail and academic laboratories around a shared scientific theme. They respond to both the needs of ambitious research and long-term industrial challenges. They offer a structural, flexible, and enduring framework, allowing leverage on the complementary strengths of both partners and allowing potential technological breakthroughs.



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NEW 2 µm FIBER LASER SOURCES FOR DEFENSE

FOR MANY YEARS NOW, THE FRENCH-GERMAN RESEARCH INSTITUTE OF SAINT-LOUIS (ISL) HAS BEEN A PARTNER OF EXAIL IN THE RISING FIELD OF 2 µm FIBER LASERS. EXAIL SUPPORTS THE EMERGENCE OF INNOVATIONS IN THIS FIELD WITH ITS EXTENSIVE EXPERIENCE AND PORTFOLIO.

The ISL is a bi-national institute jointly operated by the French Republic and the Federal Republic of Germany. The mission of the ISL is to develop technical innovations in the fields of defense and security, from basic research to the development of preindustrial prototypes that can be integrated in operative equipment (TRL from 1 to 6). A large proportion of its research contracts are concluded with the DGA (General Directorate for Armament) and the BAAINBw (Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support) as well as with industry at national and international levels.

Among other activities, the Institute focuses on “Controlling the effects of projected energy and increasing its precision”. It includes the development of new laser sources emitting in the wavelength range from 2 µm - 5 µm for defense applications, based on new lasing materials such as silica doped fibres (thulium - Tm, holmium - Ho). The ISL obtained in 2021 some very interesting results using an Exail optic fiber: a monolithic laser source with Tm-Ho co-doped fiber in single oscillator emitting 195 W at 2090 nm in continuous mode (A. Motard and al. Optics Express, 2021. This result obtained at the occasion of a research program with the DGA opened new horizons for the development of Directed Energy Laser (DEL) in the 2 µm range using laser architecture based on Tm/Ho doped fibers.

Exail leverages 20 years of experience in manufacturing doped fibers at its Lannion site. Its portfolio counts a range of Tm & Ho doped fibers for amplifiers and fiber lasers addressing the 2 µm market, but also high-performance modulation solutions ($LiNbO_3$ modulators and ModBox) and integrated micro-optics benches adapted to this wavelength range. The main products delivered by Exail on which the ISL relies to develop its research are the Tm doped fibers, the Tm-Ho doped fibers and the Fiber Bragg Gratings (FGBs), for the design of fiber laser cavities in specific wavelengths. They are key components for the development of laser architecture in the 2 µm range that are as efficient as possible, and that can deliver high power (around 200 W).

Fibered laser systems have plenty of advantages for defense applications: they are compact and robust, and resist to vibrations, which is key for embedded applications. In the past five years, fibered components such as doped fibers and FBGs have become the most adapted technologies to develop more powerful laser systems.

“FBGs in particular have been improved considerably in the recent years to adapt to the high-power laser applications, in the 2 µm range but also in other wavelengths (see graph). The new generation of Exail’s FBGs are now perfectly fitted for integration into this type of laser architecture” highlights Anne Dhollande, Head of Laser Development group at the ISL.

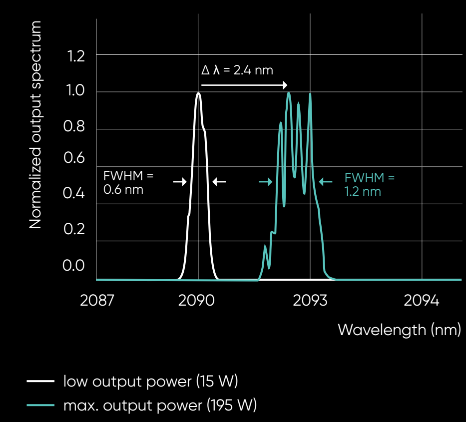
High energy laser emitting in the sub-2 µm range (between 3 and 5 µm when combined and converted) also find application in the Directional Infrared Counter Measures (DIRCM) field, which consists in targeting surface-to-air missiles optoelectronic system with a high efficiency and high-power laser beam. A relatively small device, such as a compact and stable fiber laser system installed on an aircraft, can disrupt the missile seeker by focusing all of its infrared output on it. This effective method of jamming infrared missile seekers through the sensor confuses the missile guidance system with pulsing flashes of infrared energy. It prevents the tracking of the targeted aircraft which rely on the accurate tracking of the infrared emission coming from the thermic signature of the target.

In the air, the water molecules will absorb infrared light in one specific wavelength at 1940 nm. It is thus important to ensure that any laser source developed for such applications in free-space emits over 2000 nm. In Spring 2023, new results were published by Exail and the ISL, this time with a Single-Oscillator Monolithic Thulium-Doped Fiber Laser, allowing high-efficiency emission at 2.09 µm, reaching 193 W (see figure).

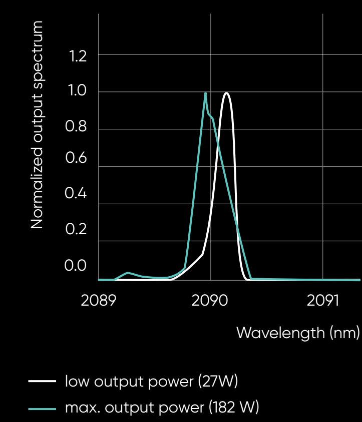
“It is the first time that a laser architecture only based on thulium doped fibers show such an efficient emission, opening the way for developments relying only on thulium ions” adds Anne Dhollande.

Exail and the ISL are already working on a new type of fiber laser architecture aiming at reaching powerful emission for DEL applications, in the framework of a research project with French ONERA and funded by DGA. The laser architecture is based on a Tm doped fiber monolithic continuous source at 1940 nm, pumping a holmium-doped triple clad fiber emitting at 2.12 µm (delivered by Exail). Such a specific architecture should allow to increase the laser power while avoiding heat in the second inner cladding, and thus protecting the acrylate cladding. ■

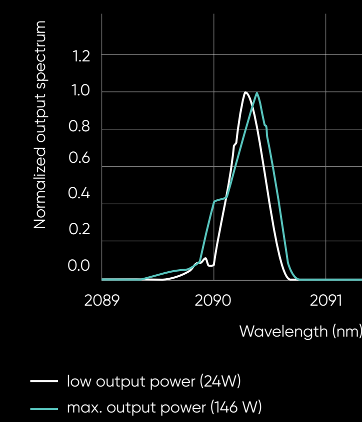
Exail high power FBG optimization



› HR FBG

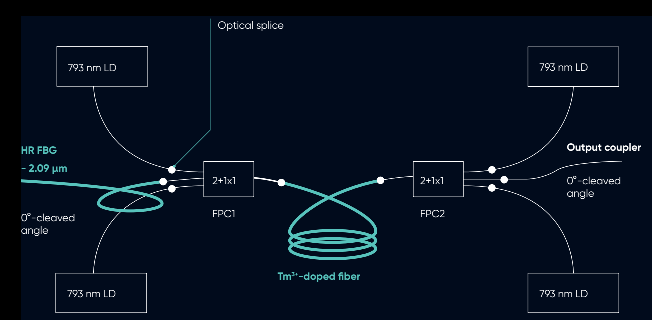


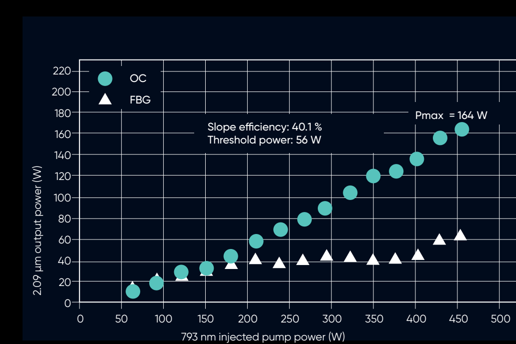
› HR FBG cooled in deionized water at 17°C



› HR FBG with dissipative packaging cooled by a copper plate to achieve a thermal slope better than 1,5°/W

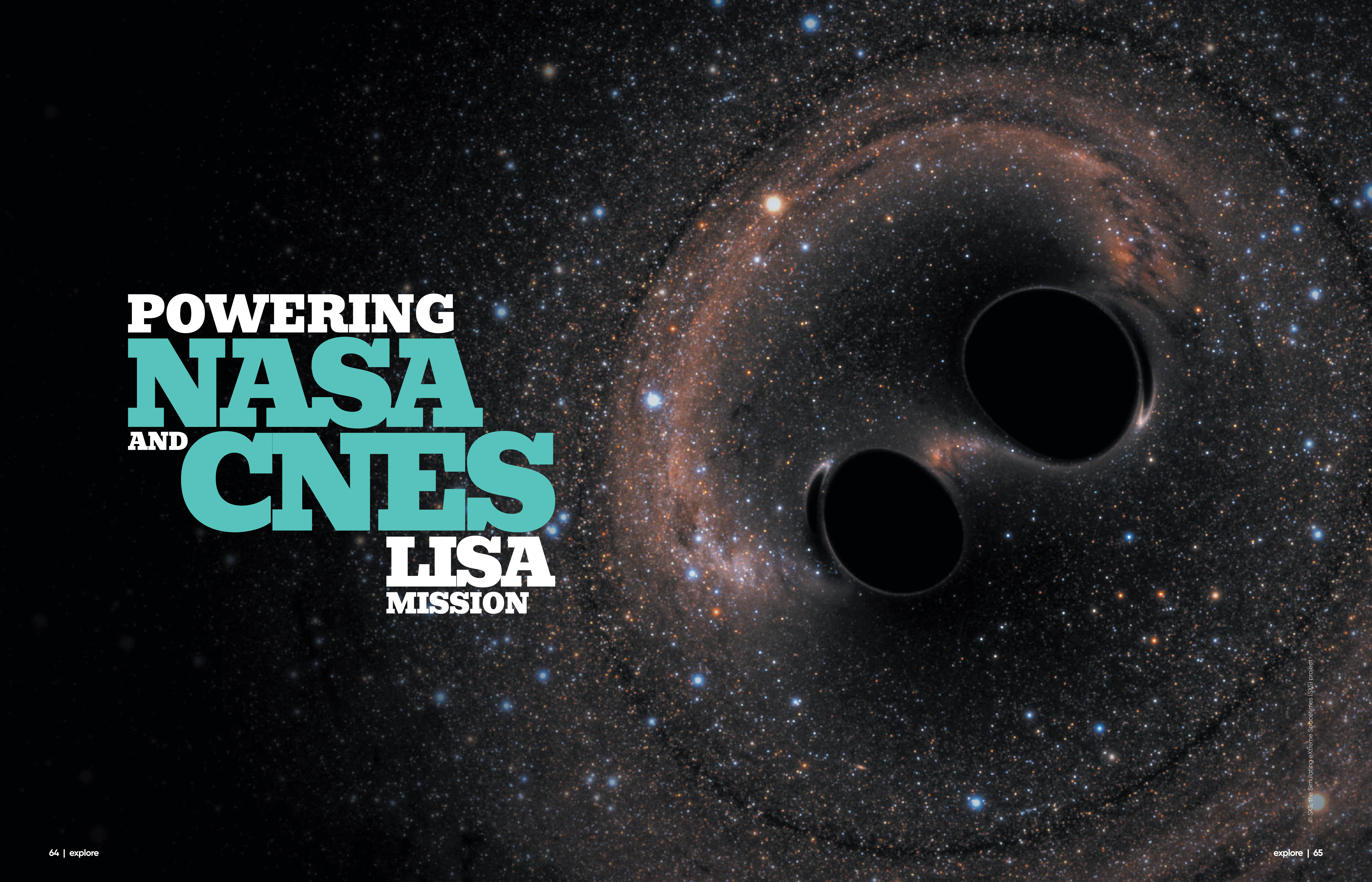
Thulium-doped fiber laser source show efficient emission





› C. Louot and al. IEEE Photonics Technology Letters, 2023

POWERING NASA AND CNES LISA MISSION



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LISA, for Laser Interferometer Space Antenna, is a challenging mission aiming at deploying a space-based gravitational wave observatory to study gravitational waves. Exail could answer some of the requirements of the American and the French space agencies with its space-grade phase modulators, gained fibers and its expertise in designing and manufacturing integrated micro-optical systems.

Detecting and studying gravitational waves require ultra-stable laser sources.

Jointly funded by ESA and NASA, LISA mission is set to launch in mid-2030's and is expected to make groundbreaking discoveries in the field of astrophysics, fundamental physics and cosmology. Indeed, one big issue faced by current ground-based detectors like LIGO (US) and Virgo (Italy) is that the frequency range at which they are sensitive to gravitational waves is limited due to noise in the terrestrial environment. By moving to the quieter space environment and expanding the size of the detector by a factor of nearly a million, LISA will be sensitive to gravitational waves at low frequencies, between 0.1 MHz and 100 MHz, where a rich and diverse set of astrophysical sources are expected.

Gravitational waves passing through the LISA constellation will manifest themselves through tiny changes in the phase of the beat notes produced by pairs of laser beams traversing the LISA arms. But how to be sure that such a tiny shift is caused by a gravitational wave or by a frequency drift from the lasers? Clearing this doubt is possible using ultra-stable lasers, reaching equivalent performances as the one in the ground-based detectors while being robust and reliable for the space environment. Exail could meet those requirements with its expertise in the design and manufacturing of state-of-the-art optical solutions.

Exail's space-grade phase modulators and gain fibers evaluated by NASA as potential components for the LISA laser transmitter

Anthony Yu, a laser scientist at NASA Goddard Space Flight Center with over 30 years of experience in space-based laser development, leads the laser transmitter development for LISA. According to him "The reliability and longevity of the laser system components is key to make the mission successful."

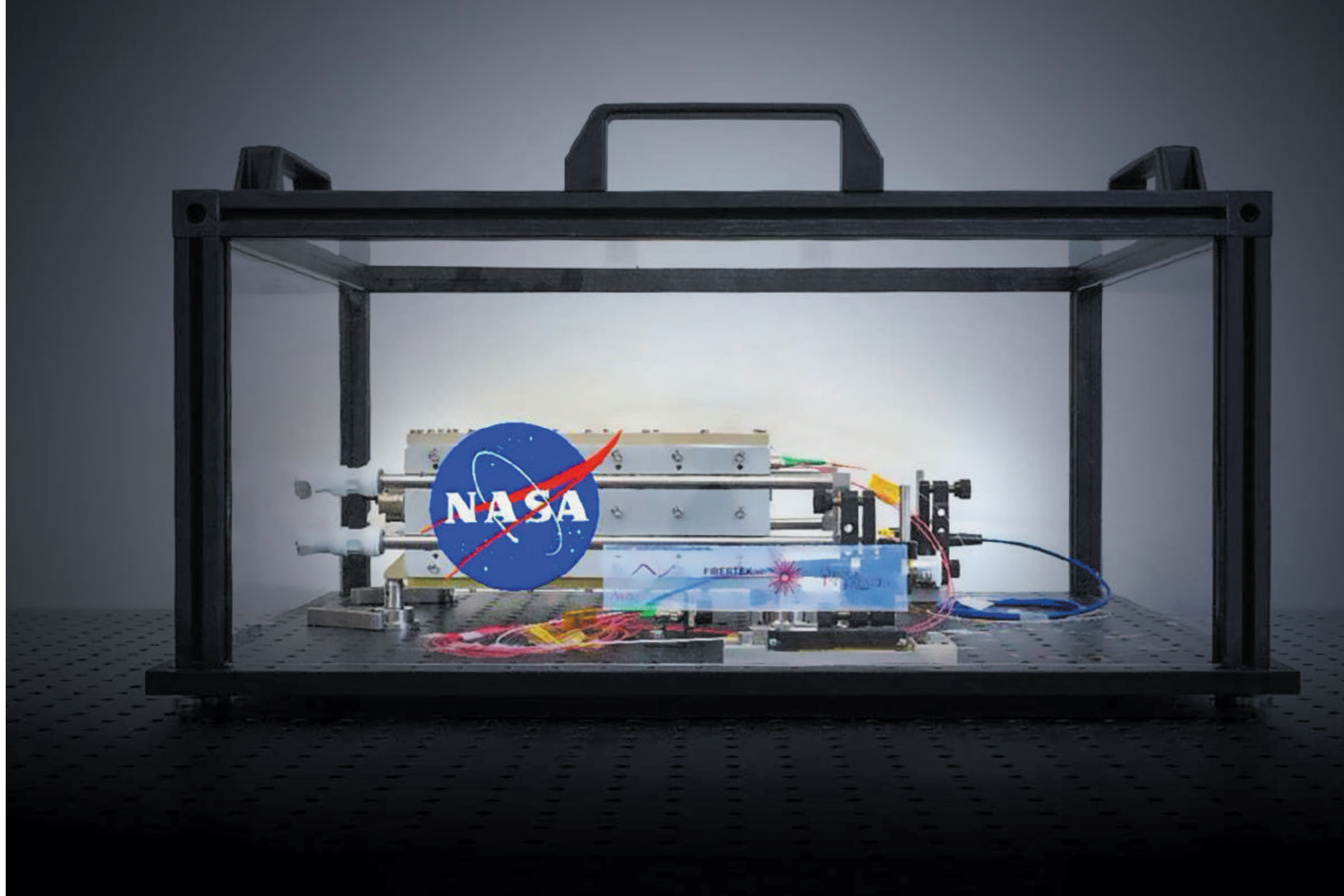
LISA Mission has challenging requirements: To measure picometer-level length change over 2.5-million km with the low received power, the laser system must be extremely quiet in terms of noise (including intensity, frequency and phase noise). Also, the laser system must be able to operate over a long period to meet the LISA mission lifetime requirement which is over 12 years when adding up ground operations, launch, and deployment.

NASA Goddard Space Flight Center developed a Master Oscillator Power Amplifier (MOPA) architecture for the LISA mission, with a low-power laser (Nd:YAG laser) meeting all frequency noise requirements, enhanced by a fiber-optic amplifier. For the development of this laser architecture, the NASA team has built upon some of the technologies used in NASA's GRACE (Gravity Recovery and Climate Experiment)- Follow-On mission from 2002 to 2018 where Exail $LiNbO_3$ phase modulators was chosen for use with the optical reference cavity. The relevance and reliability of high input power handling version of the Exail phase modulators to generate sidebands and lock the laser frequency to the cavity is being evaluated for use in the LISA laser.

A requirement of the LISA laser system is to transmit reference clock information between spacecrafts. An electro-optical phase modulator is used to provide that clock information along the optical path. A phase-modulation sideband at around 2,4 GHz is necessary to format the optical signal. Without the clock transfer, the tiny gravitational wave signal would be buried in the clock noise on the three spacecraft. In the NASA MOPA architecture, the phase modulator is used between the Master Oscillator and the Power Amplifier. The Master Oscillator (Nd:YAG laser) is coupled to a fiber and the rest of the architecture, the phase modulator and the fiber amplifier is monolithic. This means that the phase modulator must accommodate a high optical power input coming from the Master Oscillator. If the optical throughput changes in time, the power entering the power amplifier will change in time that could cause problems and must be to be avoided, especially in the case of a space mission.

Anthony Yu highlights a potential technical advantage of the $LiNbO_3$ phase modulation design offered by Exail: "One intrinsic problem of phase modulators based on lithium niobate waveguide is the photorefractive effect. It is a change of refractive index within the media which can change over time, due to the incident optical power. If the photorefractive effect is triggered, it will decrease the optical signal transmission through the waveguide."

After NASA had evaluated different products over many years, Exail, as a pioneer and expert in the design and manufacturing of such $LiNbO_3$ modulators, was one of the handful of manufacturers worldwide able to meet the new requirements for the reference clock transmission functionality. NASA is also working with Exail on the qualification of radiation hardened ytterbium fibers for the design of the power amplifier. These fibers have met the LISA laser requirements after a testing under gamma radiation (reaching 40 krad).



© European Space Agency/CSEM

The first prototype of a laser sits on a testbed at the Swiss Center for Electronics and Microtechnology (CSEM), headquartered in Neuchâtel, Switzerland, (2021) integrating $LiNbO_3$ phase modulator delivered by Exail.

An early LISA laser prototype meeting the LISA performance requirements was delivered to the Swiss Center for Electronics and Microtechnology (CSEM) at the end of 2021 for tests and characterizations. Environmental tests of a ruggedized laser model (including shock/vibrations, thermo-vacuum cycling and radiation tests) are to be performed in late summer 2023 to demonstrate the qualification of the laser design for the space mission, so production can then start within a few years, for a delivery to ESA in the late 2020s.

An ultra-stable compact and transportable laser for the LISA mission ground operations

The ultra-stable cavity stabilized Nd:YAG laser developed by NASA and chosen for the LISA mission is a space proven solution, but it won't be ready soon enough for the qualification tests of the different LISA mission modules. Moreover, if it is space proven, it is also quite sensitive and difficult to transport. The French CNES, leader for these LISA mission tests (AIVT for Assembly, Integration, Verification and Testing), thus decided to order an alternative ultra-stable transportable laser source to play the role of frequency reference, during the mission ground operations. An iodine-stabilized telecom laser was chosen.

Alexis Mehlman has been pursuing a joint PhD at SYRTE Laboratory in Paris (LNE / CNRS / Observatoire de Paris) and Exail since 2020 for the development of such an iodine-stabilized telecom laser that is compact, flexible and robust. It leverages 20 years of experience of SYRTE on optical frequency metrology (that has also benefited the performance of Exail's lasers for quantum technology), and in Exail's know-how to design, develop and integrate compact and industry-grade micro-optics setups. The developed laser system also benefits from the many advantages of fibered telecom lasers, which are cost-effective, robust, space proven and thus reliable enough for new laser applications.

If the setup will most certainly find other applications in metrology in the future, the first prototype has started to be deployed in Spring 2023 by CNES in various French and European labs where LISA modules have to be tested.

Turning a lab experiment into a compact and transportable laser system

The setup that will be delivered to the CNES will be made of two Nd:YAG laser, simulating the two lasers mixed into each spacecraft of the LISA mission. The two lasers are phase-locked to each other, to keep their interferences (optical beat-notes) as regular as possible. Both master lasers will have their frequency phase-locked to the telecom laser, which is itself permanently stabilized on iodine. The whole system is thus stabilized on the physical properties of an iodine vapor (see figure).

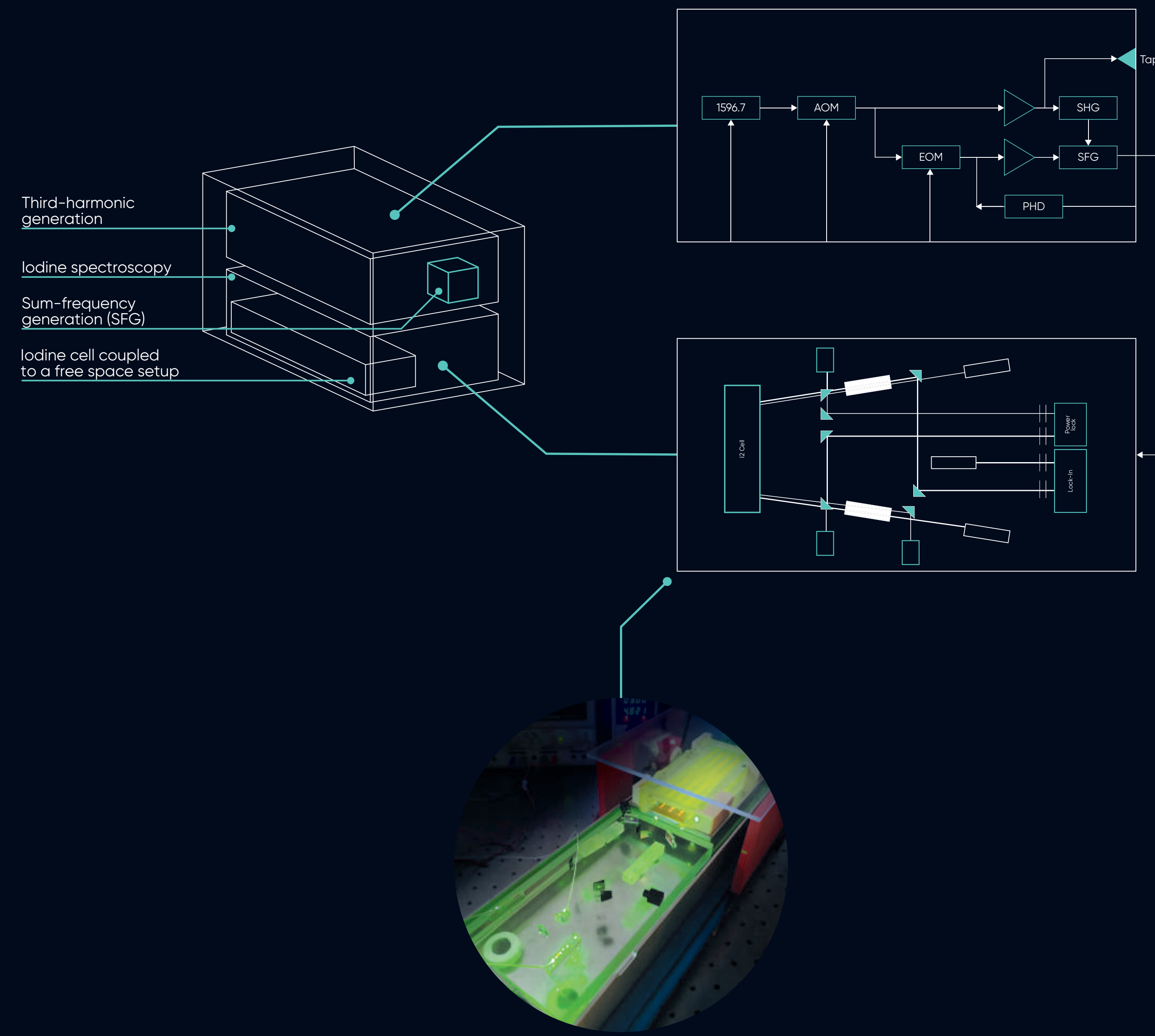
Non-linear optic modules (Second Harmonic Generation – SHG, and Sum Frequency Generation – SFG) are used to create optical beat-notes with lasers at different wavelengths by matching the frequencies of interest. Most of the optical components required for the system, including the SHG, are already existing products, easy to integrate into a compact system. During his thesis Alexis Mehlman has worked on the design and manufacturing of two main critical modules for such operations: the iodine spectroscopy module and the Third Harmonic Generation (THG) module (including a dedicated SFG component). The first one existed in a room size lab experiment at SYRTE before the thesis of Alexis, and the other one had never been developed within a such compact fibered system.

Exail's expertise in the direct assembly of micro-optic assemblies was key to turn the complex SYRTE iodine spectroscopy module into a transportable fibered system (see figure). An iodine cell could be assembled to the module with a "multipass scheme" ensuring a greater interaction length between the light and the atoms, as well as some electronics modules. The THG module includes key building blocks developed in-house by Exail, in particular the phase modulator, and the SFG. If SHG are quite common, no industrial player is currently producing SFG with telecom fiber technology. An extremely accurate integration of micro-optics in free-space, and their connection with optical fibers, enabled to develop such a telecom fibered SFG module (size of around 100 cm^3), integrating a PPLN (periodically polarized Lithium Niobate) crystal.

Based on this prototype for LISA, a first commercial frequency tripler was produced by Exail in 2023 and sold to the Royal Institute and Observatory of the Spanish Navy (ROA). It will be integrated into an iodine spectroscopy setup, similar to the one developed by Exail for the LISA mission. It is the first commercially available compact fiber system for 515 nm generation, with state-of-the-art performance in terms of green power generated. Potential users may be interested in buying the module alone, meaning a small component with fibers inputs/outputs.

By adding the various photonics skills mastered by Exail, it would be possible to provide a complete turnkey laser source in similar wavelength ranges. There is indeed a large interest, in being able to produce lasers at new wavelengths, in particular for quantum applications. With this new frequency tripler, Exail has everything to answer these growing needs. ■

Schematic of the laser setup, including SFG and iodine spectroscopy modules



LATEST SCIENTIFIC PUBLICATIONS

Exail partners with major laboratories and organizations to push the limits of science in our fields of expertise. The following publications reflect this desire to always go further to meet our customers ever increasing demanding requirements.

2 µm FIBER LASERS

Optimizing the performance of a monolithic Tm^{3+}, Ho^{3+}-codoped fiber laser by FBG reflected wavelength and fiber gain matching
Optics Express Vol. 31, Issue 12, pp. 18939-18948 (2023)
Co-written with Saint-Louis Research Institute (ISL) and CELIA Lab (CNRS/CEA/Univ. Bordeaux)

High-Efficiency 2.09 µm Single-Oscillator Monolithic Tm-Doped Fiber Laser
IEEE Photonics Technology Letters (May 2023)
Co-written with Saint-Louis Research Institute (ISL)

High Efficiency of a Ho doped fiber laser in clad-pump configuration
Presented at Fiber Lasers XX: Technology and Systems (March 2023)
Co-written with ONERA

Passive Fiber with Pedestal in a 213-W Continuous Wave Monolithic Tm^{3+} doped fiber laser at 1.94 µm
Presented at Adv. Solid-State Lasers (ASSL) 2022
Co-written with Saint-Louis Research Institute (ISL)

Gain-controlled broadband tuneability in self-mode-locked Tm-doped fiber laser
Communications Physics (Sept. 2022)
Co-written with Leibniz Institute of Photonic Technology and Novosibirsk State University

ATOMIC CLOCK

Cold-atom-based Commercial Microwave Clocks at 10^{-15} Relative Instability Over More than One Month
Presented at the Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS) 2022
Co-written with LNE-SYRTE

DEEP-UV LASERS BASED ON NOVEL ND-DOPED FIBERS

Watt-level deep-UV sub-ns laser system based on Nd-doped fiber at 229 nm
Optics Letters (Feb. 2023)
Co-written with CIMAP

83 W efficient Nd-doped LMA fiber laser at 910 nm
Presented at Fiber Lasers XIX: Technology and Systems (March 2022)
Co-written with ENSICAEN and Institut d'Optique Graduate School

METROLOGICAL FIBER NETWORK

Coherent Optical-Fiber Link Across Italy and France
Phys. Rev. Applied 18, 054009 – Nov 2022
Written by LNE-SYRTE, LPL and INRIM, using Exail's products

QUANTUM GRAVIMETER & GRADIOMETER

Detecting Volcano-Related Underground Mass Changes With a Quantum Gravimeter
Geophysical Research Letters e2022GL097814, (2022)
Co-written with INGV

Compact differential gravimeter at the quantum projection-noise limit
Phys. Rev. A 105, 022801 (2022)
Co-written with LNE-SYRTE

QUANTUM LASER

Efficient 2D molasses cooling of a cesium beam using a blue detuned top-hat beam
The European Physical Journal D, Vol 76, Article N°35 (2022)
Co-written with LP2N, LAC, AzurLight Systems, Orsay Physics using Exail's laser at 852 nm

Plug-and-play generation of non-Gaussian states of light at a telecom wavelength
Optics Express Vol. 30, Issue 25, pp. 45195-45201 (2022)
Written by INPHYNI, LENS, CNR-INO, using Exail's USML 1560/780 nm

QUANTUM SENSING

Tracking the vector acceleration with a hybrid quantum accelerometer triad
Science Advances (Nov 2022), Vol 8, Issue 45
Written with the iXAtom joint laboratory (Exail/LP2N lab)

SPACE

WDM Optical Front End for GEO-Ground Digital and Analog Telecommunications
Presented at EPIC Meeting on Photonics at the Final Frontier at ESA (Sept. 2022) and at the International Conferences on Space Optics (ICSO 2022)

Radiation tolerant frequency comb fiber laser for space applications
Presented at Photonics West 2022
Co-written with Menlo Systems and Fraunhofer INT

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