iXnews

IXBLUE | APRIL 2022 | PHOTONICS SPECIAL ISSUE

LASER COMMUNICATION IN SPACE
A space grade transceiver

2µM FIBER LASERS APPLICATIONS
iXblue extensive components portfolio

LASER FOR QUANTUM TECHNOLOGY
Turn-key frequency-stabilized laser systems

FREE-SPACE MICRO-OPTICS
A ground-breaking approach to integrate optical setups

iXblue is on track to create a new European leader in photonics and quantum technologies. Its Photonics Division was already rich in two historical activities in the field of ultra-fast optical modulators based on lithium niobate technology and in the field of special optical fibers. It has known an important development in Spring 2021 with the acquisition of the two technological gems Muquans and Kylia.

MuQuans (µQuans), specialized in quantum sensors based on laser-cooled quantum manipulation techniques, is the first company to commercialize on an industrial scale a compact and transportable cold atoms gravimeter. MuQuans' Absolute Quantum Gravimeters are now deployed and operational in various environments, such as volcanoes (Mount Etna), for permanent monitoring. MuQuans also offers Gradiometers and Atomic clocks.
In addition its know-how led to the development of a new generation of compact and agile intelligent laser systems able to operate the emerging quantum technologies based on cold atoms, such as Quantum Computing.

As for Kylia, the company is internationally recognized for its expertise in the integration of complex photonics functions carried out by a dynamic and ultra-precise assembly of free-space optical components on micro-benches. The company develops components or subsystems both compact and extremely stable. Kylia's portfolio offers a large range of wavelength filters for multiplexing/demultiplexing for telecom applications, but also a wide variety of optical delay lines, fixed or variable. Interferometers for the demodulation of modulation formats such as DPSK (Differential Phase Shift Keying) or even 90° hybrid circuits for complex phase-amplitude coding demodulations at very high bit rates (>100 Gb/s) are among the other Kylia' flagship products.

All the photonics solutions offered by iXblue can now address a wide range of markets (sensors, fiber lasers, communication, metrology, quantum technologies, geosciences) and applications: distance measurements, automotive LIDAR, high-energy or high-power scientific laser facilities, industrial lasers (cutting, marking), optical communications, laser communications in space, time-frequency solutions, Quantum Key Distribution.

> "WITH STRONGER AND MORE ESTABLISHED PRESENCE, THE AIM IS TO BECOME A EUROPEAN LEADER IN PHOTONICS."

Henri Porte
VP Photonic Solutions Division

This external growth took place in the French New Aquitaine region, which offers a particularly favorable and dynamic photonics-oriented ecosystem. Synergies between our different photonics teams are being established. As such, space activity comes as an evidence. Indeed we have invested a lot of time and effort in this field in recent years. It is an opportunity to highlight our space qualified products, our know-how in hardening the components for the space environment, and proven project management that can be applied to each of our photonic activities.

Thus, our ambition lays clearly: to become a player in quantum technologies, particularly on key markets such as "Quantum Computing", Quantum Key Distribution and quantum inertial sensors. With stronger and more established presence, the aim is to become a European leader in photonics. ■

01 PRODUCT NEWS

02 APPLICATION CASES

01

PRODUCT NEWS

A NEW GENERATION OF PHASE MODULATORS FOR HIGH-POWER FIBER LASERS

GAINING POWER WITH SEVERAL COMBINED LASER BEAMS CAN BE DONE BY SUPERIMPOSING LASERS OF DISTINCT WAVELENGTHS IN A UNIFORM LASER OUTPUT.

High-power fiber lasers for defense and industry

Demand for high power fiber lasers has increased tremendously in the last 10 years. These lasers are used today in an increasing variety of fields such as industrial machines (marking, welding, cutting), LIDAR systems, intense laser systems (inertial fusion, plasma), and recently in optical systems that can deliver very high power for defense applications. With the growing presence of drones on the battlefield, the development of offensive laser applications, such as anti-structure laser weapons, have been accelerated. The fiber lasers are the ideal candidate of laser Directed Energy Weapons (DEW) in the field.

Until recently, chemical lasers or free-electron lasers, then solid-state lasers, were mainly considered as Directed Energy Weapons (DEW). However, these technologies are particularly expensive and complex to implement. On the opposite, high power fiber lasers offer a new alternative thanks to their compactness, lower mass allowing easier deployment, lower production and operating costs, higher reliability over time, resistance to severe and even extreme environments, etc. Thus, they are perfectly suited to operational environments, for example embarked on moving vehicles or ships.

Indeed, phasing multiple fiber sources of several kilowatt by optical combination can result in laser architectures delivering powers of up to tens of kilowatts today. Ongoing works are carried out to expend this power to several 100 kW which is the estimated power required to disable a drone. These laser architectures, developed for the defense market, can also be used for industrial cutting laser, and future applications when a new optical modulation technique will be available.

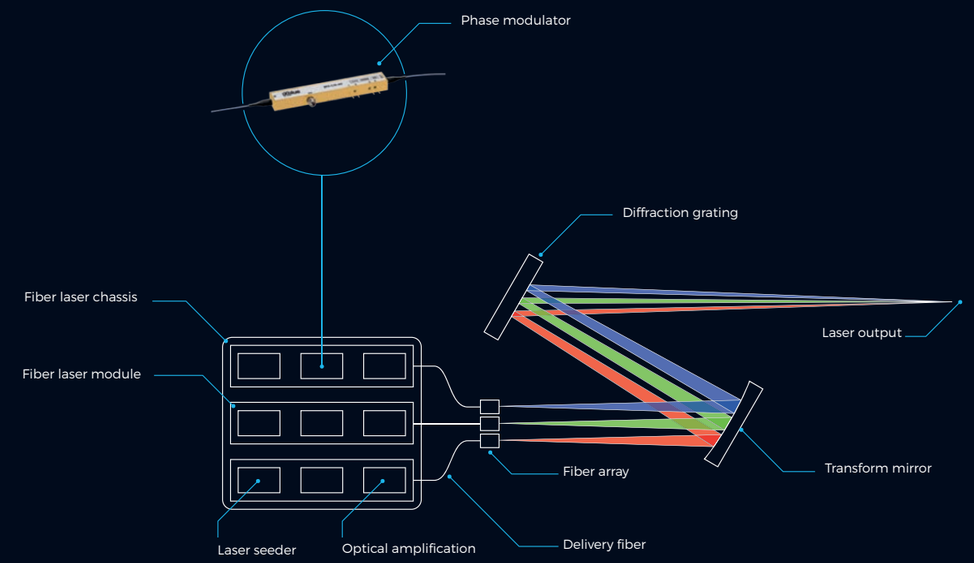
Gaining power with combined laser while dealing with the non-linear Brillouin effects

Gaining power with several combined laser beams can be done by superimposing lasers of distinct wavelengths in a uniform laser output. It can be done using the Coherent combination of laser beams technique (CBC), where the combination of several lasers by real-time control of their relative phases allows to permanently maintain constructive interferences and thus guarantee maximum power efficiency during the combination (iXblue NIR-MPX-LN-01 modulator and its matching amplifier DR-VE-0.1-MO are both ideal for high-power coherent beam combining applications). And it can also be done with the Spectral Beam Combination technique (SBC) where different laser beams emitting a continuous signal, centered on distinct wavelengths, are superimposed by adaptive optics. The result of the laser system is a uniform intensity distribution and an optical signal with a power proportional to the number of laser beams combined.

However, the maximum transmitted optical power in each fiber amplifier is severely constrained by the non-linear Brillouin effect. This effect, also called Stimulated Brillouin Scattering (SBS) can be mitigated by broadening the laser linewidth (to spread the spectral power density some GHz around the central wavelength) by the mean of an electro-optical phase modulator.

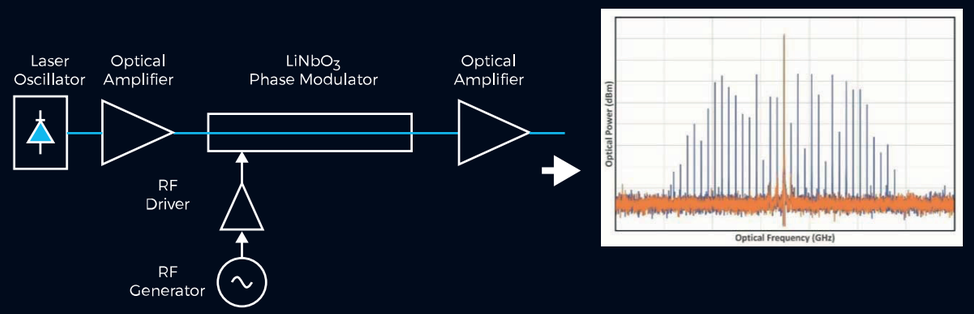
To create these side bands, three different RF source can be combined with the electro-optical phase modulator. A sinusoidal electric signal, a “white noise” or a telecom “PRBS – Pseudo-Random-Bit-Sequence”. With this technique, optical output higher than a kilowatt continuous signal can be reached, spectrally modulated, and combined with other fiber amplifiers to obtain the final and expected laser power level.

Spectral Combination of Laser Beams

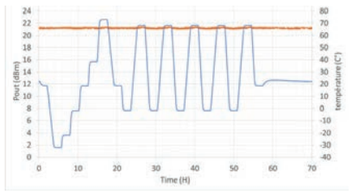


Spectrum broadening set-up

BASED ON ELECTRO-OPTICAL PHASE MODULATOR MEAN



A NEW GENERATION OF MODULATORS IS EMERGING IN IXBLUE PORTFOLIO IN EARLY 2022, DEDICATED TO THE HIGH FREQUENCY RANGE (UP TO 40 GHZ).



The NIR-MPZ series proves an excellent stability in temperature (< 0,3 dB), equivalent to the best X-cut generation.

iXblue modulation solution for high frequency range, insensitive to pyroelectric and photorefractive effects

Gaining in modulation efficiency in a high-power fiber laser, while lowering the electrical power consumption, means lowering the driving voltage (Vπ) of the phase modulator. iXblue has developed key building blocks to master the production of modulators. They benefit from the technological mastery of the "Annealed Proton Exchange" (APE) waveguide manufacturing process, the same process deployed for modulators integrated in iXblue gyroscopes.

A generation of iXblue phase modulators is now widely used and represents a commercial success: the NIR-MPX-LN (Near InfraRed – Modulator Phase with X-cut, on $LiNbO_3$ fiber), also proposed with their matching RF amplifier. iXblue components have certainly the best output performance and have proven the best behavior: low fluctuations and very good stability despite wide temperature variations (products have been tested from -40 to 85 °C and proved over 10 years' time, in CW mode) and high CW optical power to 300 mW.

A new generation of modulators is emerging in iXblue portfolio in early 2022, dedicated to the high frequency range (up to 40 GHz). For lower RF power consumption, an efficient RF to optical transmission is required, while maintaining stability even under important outdoor temperature variations. With the NIR-MPZ-LN-20, based on a "Z-cut*" $LiNbO_3$ crystal orientation structure, iXblue has developed a novel generation of phase modulators. They gain 40 % on Vπ efficiency, and as an accomplishment reach the same optical stability versus temperature variation and high optical input power than in the "X-cut" modulation design which is considered as the reference.

Spectral Beam Combination applied with such NIR-MPZ-LN-20 new generation of phase modulators are reaching large bandwidth up to 40 GHz and low driving voltage of 3,5 V, together with high optical input power up to 300 mW, high RF input power, with still high optical stability whatever the optical and temperature operating condition.

The efficiency of the modulation is proven with this new generation of Z-cut, while the stability in severe external conditions and optical power handling is perfectly maintained. iXblue proves its ability to solve technical challenges thanks to its expertise and experience over different markets. iXblue portfolio covers now the whole frequency range with solutions of high stability:

- NIR-MPX-LN-0,1 for up to 300 MHz;
- NIR-MPX-LN-0,2 for up to 5 GHz;
- NIR-MPZ-LN-20 for up to 40 GHz.

The plan is now to offer an ultra-low Vπ, 10 GHz version in the near future, by using the same Z-cut generation of phase modulators. Every technical step reached, and mastered, paves the way for the development of future new products.

With its large experience in the field of electro-optic manufacturing, iXblue has the capacity to industrialize a new idea or a new technology, into a process, to master it and then deliver it as a final product, in hundreds or thousands of samples. Today, iXblue is now working on the complete integration of different components into packaged product. ■

*iXblue has become expert in the whole process of fabrication of the Lithium Niobate phase modulators: from the design to the microfabrication in clean room environment, until the integration and testing before packaging. The Z-cut, given for the design of the $LiNbO_3$ "birefringent" cristal architecture used to fabricate the modulator, counts new optimized steps in the fabrication process.

NIR-MPZ-LN-20

NEAR INFRARED – MODULATOR PHASE WITH Z-CUT, ON $LINBO_3$ FIBER

ELECTRICAL

Electro-optic bandwidth S_{21} @-3 dB, from 2 GHz	GHz	Typ 16
Usable electro-optic bandwidth S_{21} (1)	GHz	Typ 30
Electrical return loss S_{11} 0 - 20 GHz	dB	Typ -13
Vπ RF electrodes @ 50 kHz	V	Typ 3.5
Vπ RF electrodes @ 20 GHz	V	Typ 6
RF ports impedance matching	Ω	Typ 50

(1) No sharp dips in the S21 response.

OPTICAL

Crystal	Lithium Niobate Z-Cut Y-Prop			
Wavelength of operation	nm	950	1060	1150
Insertion loss, @ max of transmission, w/o connectors	dB	-	3	4
Polarization extinction ratio	dB	20	-	-

OPTICAL INTERFACES

Input and output fibers	Polarization maintaining 980 nm, Corning PM 98-U25D length: 1.5 meter, buffer diameter 900 µm
Package size (L x l x H)	85 x 15 x 9.65 mm3
Input RF connector	Female K
Optical connectors	FC/APC (slow axis parallel to the connector key)

ENVIRONMENTAL

Operating temperature	-30 °c to +70 °C
Storage temperature	-40 °C to +85 °C

MAXIMUM RATINGS

Maximum RF input power	+33 dBm
Maximum optical input power	+25 dBm

OPTICAL TRANSCEIVERS FOR HIGH-SPEED SPACE COMMUNICATIONS: EN ROUTE FOR THE NEW SPACE

TODAY, MANY EMBARKED SPACE PHOTONIC SYSTEMS USE IXBLUE MODULATORS AS KEY COMPONENTS TO ACHIEVE INTENSITY OR PHASE MODULATION.

In space, the standard transmission solutions using RF technology are limited to a data-rate of hundreds Mbit/s, at best. The need for high-speed communications, reaching the range of hundreds of Gbit/s creates an opportunity that can be addressed by photonics-based solutions. The added advantages of photonics solutions in space are also reliability, even under harsh environment, scalability (modulations schemes, numbers of optical channels, ...) as well as smaller payload that reduces satellite consumption.

iXblue is a designer and a manufacturer of space grade optical components. The company masters the manufacturing of TRL9 optical components, with a track-record of successful missions embarking its "flight proven" components, such as: optical $LiNbO_3$ modulators, radiation hardened (rad-hard) fibers and their matching Fiber Bragg Gratings (FBGs), fiber sources, low noise optical amplifiers, Multiplexer/Demultiplexer and other micro-optics assembly for the receiver. Our expertise in the telecommunication domain, experience in assembling complex systems as well as our space background allow us to provide fully integrated optical transceivers for the space markets.

iXblue delivers TRL9 optical solutions for the Space market

The idea of the new space satellites network is to provide higher throughput at affordable cost. The satellites constellation needs to build a mesh coverage of Earth to share/deliver data even in the most remote places, including above the oceans and poles. Laser based inter-satellite links deliver highspeed data across the globe with a high level of security end-to-end communication services. 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 operation. Today, many embarked space photonic systems use iXblue modulators as key component to achieve intensity or phase modulation.

iXblue involvement in space is already substantial: with hundreds of TRL9 $LiNbO_3$ modulators, more than 1000 km space qualified fibers currently flying, and the Astrix gyroscopes recording more than 6 million hours in orbit. Our products are either used onto the Geostationary Equatorial Orbit (GEO), or onto the MEO and LEO satellites. The GEO imposes the more stringent operating conditions and has to operate during at least 20 years (average GEO satellites life expectancy), sustaining extreme temperature variations. 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 radiations.

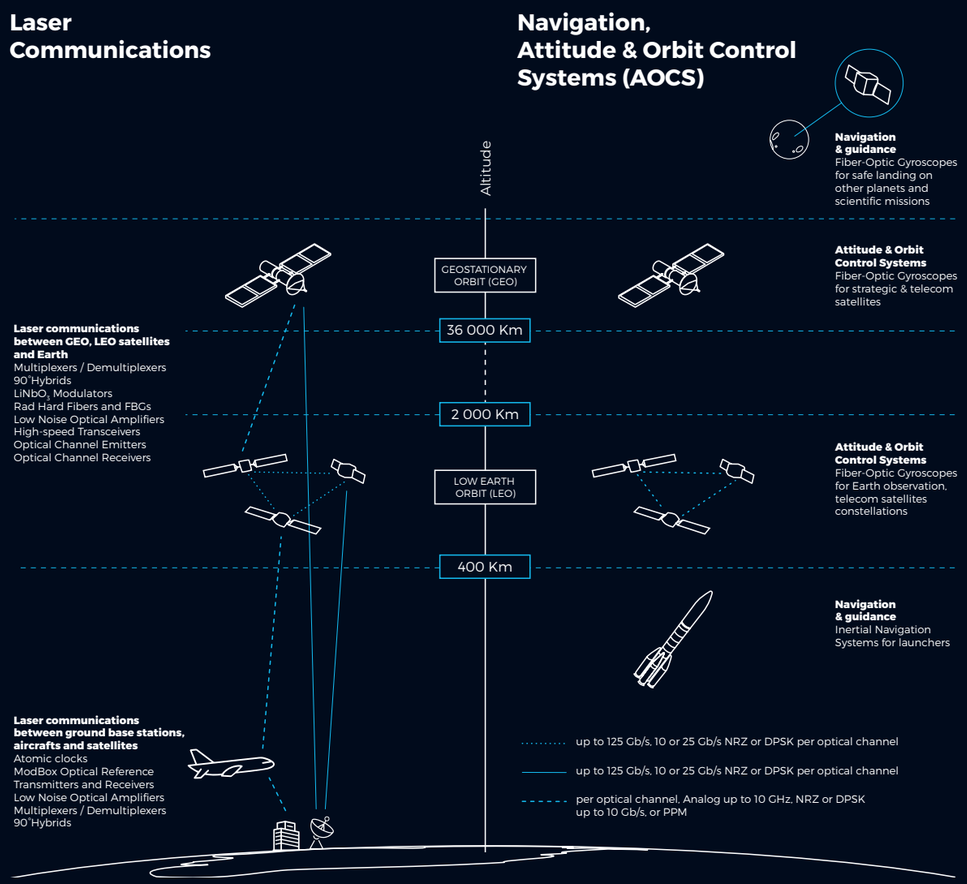
With a dedicated team for space products, iXblue has already supplied numerous key space players. These space stamped products were successfully qualified with the following ECSS and MIL standards. iXblue has an end-to-end control of its value chain, from the R&D carried out in its engineering offices through manufacturing in the company's own production shops and quality control. Production sites have large clean rooms for the manufacturing of space components and systems. Numerous skillful experts are available together with all the required environmental means to develop, test and qualify products.

iXblue products for laser space communications, robust by design and based on proven technology, do fit many needs of the New Space market. The company also has the capacity to be cost effective in their integration in complete transceiver systems.

From devices to fully integrated optical transceivers: the FOLC project

iXblue is involved in several EU projects to prove the ability of its components to address the need of space communications. One of them is the Feeder for Optical Link Constellation (FOLC[1]) project, started in 2017. Funded by ESA, supported by the French CNES, and with Airbus Defence and Space as a partner, it aims at building the telecommunication devices for future satellites constellation. It includes

iXblue flight proven optical solutions for space applications



iXblue delivers flight proven (TRL9) optical solutions for the Space market, but also atomic clocks and modbox reference transmitters and receivers for ground base stations.

iXblue has been one of the first companies in the world to develop the Fiber-Optic Gyroscope (FOG) technology. iXblue is now a recognized leader in this market. The Astrix series is a high-performance space grade 3-axis FOG. It has been developed in partnership with Airbus Defence & Space for more than 20 years, and now the Astrix is embedded in more than 30 satellites.

THE FOLC PROJECT LED TO THE DEVELOPMENT OF A GENERIC SOLUTION OF TRANSCEIVER AVAILABLE TO ANY IXBLUE CUSTOMER, WITH A TRANSMITTER BASED ON 1 TO 6 EMISSION CHANNELS AND A RECEIVER BASED ON 1 TO 8 RECEPTION CHANNELS.

the links between satellites in low Earth orbit (LEO <> LEO), the links between LEO satellites and a GEO satellite, and the links between LEO/GEO satellites and Earth. The complete telecommunications network has the goal to reach data transmission rates higher than 1 Tb/s. The project involves iXblue for the development of embedded optical communication and ground ModBox terminals while Airbus is dealing with the electronics components. iXblue has thus developed the first generation of space grade transceivers for the shaping of the laser signal transmitted through space. The transceiver is based on one transmitter emitting the optical data-signal via external modulation, (before emission) and a receiver module (see synoptic of transceiver & optical communication chain P.19).

For the first part of the project (FOLC[1]), that lasted until 2019, iXblue built a Reference Transmitter and Receiver ModBox with 12 transmission (Tx) and reception (Rx) channels for an in-lab demonstration. This study was required to define the level of performance of the Tx and the Rx: the modulation schemes, sensitivity of the photo-receiver, optical power budget, etc.

The second part of the project, FOLC[2] (Feeder Optical Link Communication Chain), started in 2020 is to produce a Demonstrator Model Transceiver: a ready to flight model transmitter and receiver for a data transmission rate of 20 Gbit/s – a first step toward higher data rates. It delivered in 2022 and embarked on a geostationary telecom satellite in 2023. As a "hosted payload", it will be tested in real space conditions for interconnections between the satellite and Earth.

The transceiver and its space qualified sub-components

The FOLC project led to the development of a generic solution of transceiver available to any iXblue customer, with a transmitter based on 1 to 6 emission channels and a receiver based on 1 to 8 reception channels. Parameters as the total weight of the device and its maximal power can be adapted according to the customer needs. iXblue can provide transceivers for constellations counting between 2-3 to thousands of satellites.

The transceiver's Tx is composed of iXblue sub-components that have been fully space qualified. The Compact Optical Channel Emitter (OCE) is composed of a laser (commercial one) and proprietary $LiNbO_3$ modulator and a RF amplifier designed by iXblue. Several OCEs can be multiplexed by a Mux. Transceiver's Rx possesses a proprietary LNOA (Low Noise Optical Amplifier) and commercial grade high-speed photoreceivers.

An optical multiplexer/demultiplexer produced by iXblue for other markets is also expected to obtain a space qualification in a near future, enabling its integration to the whole transceiver system.

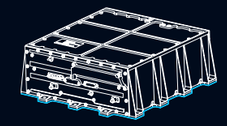
To the next generation of ultra-fast space telecommunications

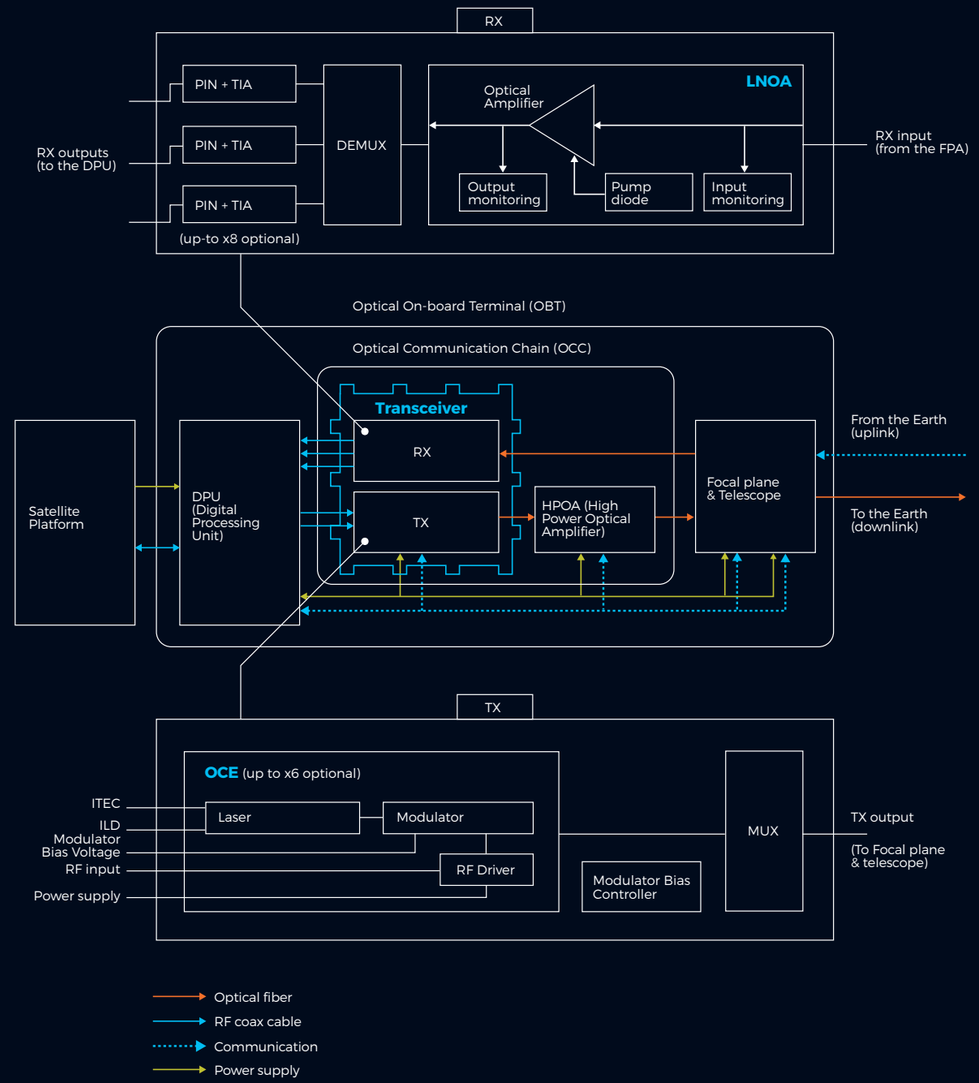
Another demonstrator is already being manufactured for a LEO orbit satellite dedicated to Earth imaging and will allow the transfer of ultra-high-resolution images of our planet taken from the orbit.

iXblue transceivers with proven robustness and reliability will be qualified for this new project, and our teams are already anticipating the next generation of ultra-fast space telecommunications, beyond the terabits/s range.

To conclude, iXblue space-grade transceivers have several main advantages. First, two modulation downlink modes (OOK -On-Off Keying- and DPSK -Differential Phase-Shift Keying-) of 10 Gbit/s or 25 Gbit/s are available, for a maximum reachable data rate of 125 Gb/s (with adapted design). Second, an uplink analog modulation or 10 Gb/s digital modulation is available, for a maximum reachable data rate of 125 Gb/s (with adapted design). Finally, the transceiver design (size and weight) can be customized according to the customer needs, with same level of space qualification. ■

Synoptic of transceiver & optical communication chain





Space Grade Transceiver

OPTICAL TRANSCEIVER FOR HIGH-SPEED SPACE COMMUNICATIONS
CO-DEVELOPED WITH AIRBUS DEFENCE & SPACE

TX ELECTRICAL INPUT

		Min	Typ	Max
Modulation format		NRZ-OOK or DPSK		
RF input connector		Single ended 2.92mm (K) connector – female		
Data rate	Gb/s	-	10	12.5
RF input power – single output	mVpp	150	200	400
Bias voltage control range	V	-8	-	+8

TX OPTICAL OUTPUT

Tx input fiber		PM1550-U25D fiber + PEEK jacket space-grade mini-avim FC/APC connector		
Number of Tx optical channels		2	-	6
Operating wavelengths	nm	1530	1550	1580
TX optical output with space grade mini-avim connector – one active channel in DPSK	dB	6	6.5	7
Polarization Extinction Ratio	dB	16	-	-
Tx sensitivity (10^{-3} BER without signal amplification, 10 Gb/s, PRBS 2^{31}-1)	dBm	-	-15	-

RX OPTICAL INPUT

Rx input fiber		SMF 28e+ fiber + PEEK jacket space-grade mini-avim FC/APC connector		
Number of optical channels		2	-	8
Operating wavelengths	nm	1530	1550	1580
RX optical input	dBm	-80	-	-20
Digital data rate	Gb/s	-	10	12.5

RX ELECTRICAL OUTPUT

Modulation format		NRZ-OOK or Analog		
Rx output connector		Differential output SMPM (GPPO) - male		
RF output signal – single output	mVpp			1200
Rx digital sensivity – (BER 10^{-3}, 10 Gb/s, PRBS 2^{31}-1)	dBm	-	-41.5	-

TRANSCEIVER ELECTRICAL INTERFACES

		Min	Typ	Max
DC supply	V	-	100	-
DC Supply connector		MMCS 4 pin D-click		
TM TC connector		MDSA 31 pin D-click		

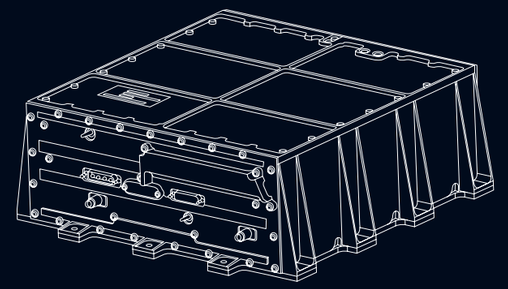
LAUNCH AND IN-ORBIT ENVIRONMENT

Orbit				LEO / GEO	
In-orbit mission lifetime after environmental stresses, pre-launch activities (1000 operating hours) and orbit injection phase. ** longer mission lifetime will require delta qualification process at component level (radiations, ageing).		years	-	-	2**
Operating temperature at TRP	**Qualification**	°C	5	-	55
	Acceptance	°C	10	-	50
	Mission	°C	15	-	45
Start-up temperature at TRP		°C	5	-	-
Non-operating temperature at TRP		°C	-35	-	65
In-orbit pressure		Pa	-	-	1.3 10^{-3}

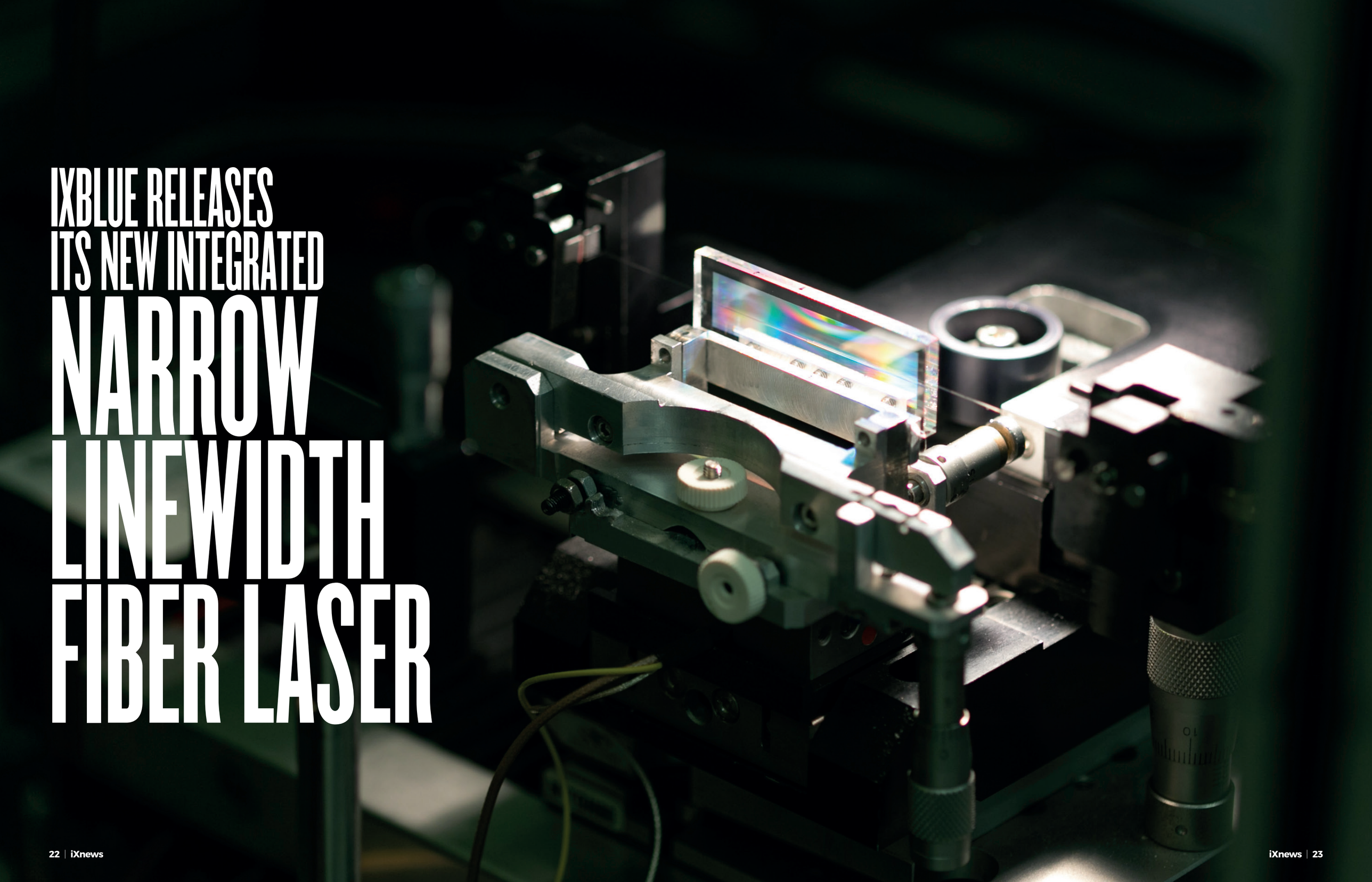
Mechanical	**Sine vibrations (3 axes)**	5-100Hz, 4 oct/min, 20g
	Quasi-static vibrations (3 axes)	35Hz, 10s, 20g

	Random vibrations	• Vibration levels:
		  • perpendicular to the mounting plane: 18.3 g rms
		  • parallel to the mounting plane: 9.5 g rms
		• Vibration duration: 1 min.

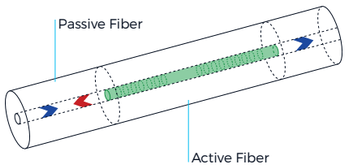
	Shocks	1300g 10000Hz
Radiations	**Total Ionizing Dose**	50 krad, source: Co60
	Total Non-Ionizing Dose	2×10^{11} p/cm^2, 60 MeV
	Single event	No sensitive EEE and optical components to single events



IXBLUE RELEASES ITS NEW INTEGRATED NARROW LINEWIDTH FIBER LASER



iXblue know-how in specialty optical fibers led to the development of single-frequency fiber lasers based on UV Bragg grating technology written into active rare-earth photosensitive fibers. Short cavity length and phase-shifted design permit an ultra-narrow linewidth, robust mode-hop-free and single longitudinal mode laser operation.



Such single-frequency fiber lasers, also called "Narrow Linewidth Fiber Laser" or "Distributed Feedback Fiber Lasers" (DFB-FL) are ideal for various emerging applications including LIDAR and cold atoms. Due to the extremely narrow linewidth, low noise and compactness, these fiber lasers can be used in applications such as interferometric sensing, in seismology for example. Several millimeters in length as a sensing element, lead to a robust single mode operation, without mode hop even when thermal and vibration environment are uncontrolled. That is why, these fiber lasers can also be used as hydrophones. One of their key advantages lies in the very low intrinsic noise, suitable for level with "Deep Sea State Zero" which means, the capabilities of an acoustic signal detection as low as the level of the acoustic noise floor of a quiet ocean. Finally, these fiber lasers are also useful for scientific research (i.e spectroscopy), or as continuous / pulse laser seeders.

Reaching a measurement with very low noise is possible when both FBGs and optical fibers design and manufacture are mastered. Based on its expertise in optical fibers and in photo-writing, iXblue is able to design matched active and passive fibers dedicated to such solutions. Armed with several years' experiences in the Fiber Bragg Grating (FBG) technology, iXblue shapes continuously FBGs and therefore improves fiber laser performances.

Today narrow linewidth fiber lasers can be applied to a variety of applications at several frequency or wavelength ranges: coherent pulse laser source for LIDARs, continuous laser for cold atoms, etc. They can replace semiconductor lasers having output powers of only few mW, with linewidths not suitable for coherent lightwave systems.

A new compact and integrated solution

With the aim to develop a fully integrated system, iXblue is adding to its portfolio a new compact solution integrating the narrow linewidth laser, the IXC-CLFO-LN-BT at 1.5µm. It houses the 1.5µm iXblue single-frequency fiber laser (FBG on active doped fiber) and an iXblue pump driver, but also an optical amplification stage. The output laser is a continuous polarization maintaining laser signal up to 40 mW, 0,1 kHz linewidth range and a tunability over 1nm. In this turn-key benchtop solution, iXblue guarantees the power amplification, the high stability and the quality of the narrow linewidth fiber laser. The DFB fiber laser sub-component is also available by itself, for 1.5µm. Thanks to its know-how at 1.5µm, iXblue opens new emerging applications, with its fiber laser at 2µm, based on the specialty Thulium doped fibers. ■

The compact turn-key benchtop solution housing the 1.5µm DFB with 40 mW output power released at Laser World of Photonics 2022.

IXC-CLFO-LN-BT

NARROW LINEWIDTH SINGLE FREQUENCY FIBER LASER

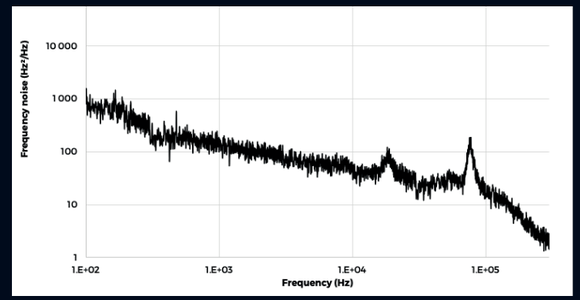
FEATURES & BENEFITS

- Narrow linewidth < 0,1 kHz
- Low intrinsic phase noise
- Single longitudinal mode
- Output power up to 40 mW
- Linear polarization
- Mode-hop-free
- 1 nm range tunability

APPLICATIONS

- Sensing
- Coherent LIDAR
- Hydrophone
- Cold atoms
- Laser seeder
- Interferometry
- Spectroscopy

Wavelength	1560 nm Other wavelengths available in C band
Wavelength tuning range	1 nm
Laser output power tunability	1 to 40 mW
Output power stability [1]	< 1 %
Linewidth [2]	< 0,1 kHz
Frequency noise @ 100 Hz	750 Hz²/Hz
Frequency noise @ 1 kHz	130 Hz²/Hz
Frequency noise @ 10 kHz	30 Hz²/Hz
RIN peak range	~75 kHz
RIN @ peak frequency	<-80 dBc/Hz
Rin @ 10MHz	<-130 dBc/Hz
Output fiber type	Panda
PER	> 23 dB
Operating temperature range	18-35 °C
Power supply	110 - 220 VAC
Com. interface	RS232 over USB
Dimensions	270 x 270 x 59 mm
Weight	5 Kg



1: over 12 h, maximum output power, 23°C room temperature
2: intrinsic linewidth

A NEW "ALL-GLASS" DOPED FIBER SOLUTION FOR HIGH-POWER LASER IN PULSED REGIME

iXblue offers a wide range of Erbium Ytterbium doped optical fibers designed for the assembly of high-power continuous-wave or pulsed fiber amplifiers and lasers. Recently, its Erbium Ytterbium doped fiber has been optimized to address the specific requirements of high efficiency and low noise for high power fiber lasers.

THE ALL-GLASS DESIGN PRESERVES EXTERNAL COATING TO BE IN CONTACT WITH THE PUMP SIGNAL, ENSURING A LONG-TERM OPERATION IN CRITICAL ENVIRONMENT.

There is today a new market for high-volume compact LIDAR lasers with high-power laser sources (up to several Watts in pulsed regime). They are used in autonomous vehicles to map their environment. The pumping signal of such high-power laser is guided in a fiber through a multimode guide of pure silica. With high power, the pumping laser will eventually interact with the acrylate coating of the fiber. It will spread energy in its small defaults, increasing heat and eventually damaging it and burning it. A first answer to that issue was to produce a fiber with a heat resistive acrylate coating (up to 125°C, when damages occur from 85°C). But today iXblue offers an ultimate solution: a fiber in which the pumping signal will not interact anymore with the fiber coating and the laser transmission will be the same whatever the temperature.

This new product, based on iXblue extensive know-how in Er/Yb fibers and some patented new process techniques, is the "IXF-2CF-AG-EY" (IXF – Double Clad – All-Glass Erbium-Ytterbium): a fiber co-doped in its core with Er-Yb, surrounded by a double (or even triple*) cladding. In 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 insensitive to temperature (up to 200°C).

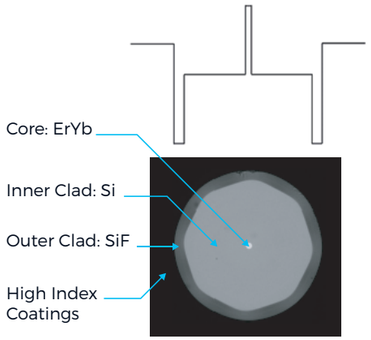
The core composition has been carefully selected in order to get high efficiency (Power Conversion Efficiency tested on every new fiber is higher than 40 %) and low 1 µm parasitic emission, which are the recognized trademark of iXblue Erbium-Ytterbium co-doped fibers developed over the past 10 years.

The All-Glass design preserves external coating to be in contact with the pump signal, ensuring a long-term operation in critical environment. The enhanced longer-term reliability and higher operational temperature possible are key advantages for harsh environments, with reduced system cooling requirements.

"A High Temperature dual layer acrylate Coating (HTC) is used to increase the long-term operational temperature range up to 125°C making it the ideal solution for 1.5 µm LIDAR in severe environments." explains Arnaud Laurent, Product Line Manager at iXblue

The All-Glass fibers are well adapted for high-volume fiber lasers manufacturers, in free-space or hybrid (fibered/free-space) architectures. The fiber has a diameter of 125 µm, with a core of 5 or 9 µm.

The octagonal shaping of the inner cladding in Si is a great geometry to have a maximum mixing effect, resulting in an optimum pump signal absorption by the active core of the fiber. ■



The beam is guided through the single mode doped core (Si with Er/Yb) of the fiber. The octagonal cladding around is pure glass (Si) as well as the outer circular clad, but with some fluorine doping (SiF) to lower its index. They are finally covered with a high temperature dual acrylate coating with high index.

* A Triple Clad fiber is also available. Compared with the Er-Yb All Glass Double Clad structure, it contains a low index inner coating, with guiding properties of the outer silica cladding. It makes the fiber easier to use with classical combiners when specific high power pumping combiners are required with the All Glass Double Clad fibers.

Double Clad All-Glass Er/Yb Fibers

IXF-2CF-AG-EY-O-5-105-125-HTC & IXF-2CF-AG-EY-O-9-105-125-HTC

Part number	IXF-2CF-AG-EY-O-5-105-125-HTC	IXF-2CF-AG-EY-O-9-105-125-HTC
Core diameter	5 ± 0.5 µm	8.5 ± 0.5 µm
Inner clad diameter (flat-flat)	105 ± 3 µm	105 ± 3 µm
Inner clad shape	octagonal	octagonal
Clad diameter	125 ± 3 µm	125 ± 3 µm
Outer clad shape	circular	circular
Core-clad offset	< 1.0 µm	< 1.0 µm
Coating diameter	215 ± 15 µm	215 ± 15 µm
Coating Material	High temperature acrylate coatings (long term temperature up to 125°C) High Index coatings	High temperature acrylate coatings (long term temperature up to 125°C) High Index coatings
Core NA	0.19 ± 0.02	0.14 ± 0.015
Inner clad NA	≥ 0.22	≥ 0.22
MFD @1550nm	6.3 µm	9.3 µm
Clad absorption @915nm	1.1 ± 0.15 dB/m	2.8 ± 0.5 dB/m
Clad absorption @976nm*	3.7 ± 0.5 dB/m	10.0 ± 2.0 dB/m
Core absorption @1536nm	75 ± 15 dB/m	75 ± 10 dB/m
Multimode background losses	< 50 dB/km	< 50 dB/km
Proof test level	100 kpsi	100 kpsi
Power Conversion Efficiency (PCE)**	> 40 %	> 40 %

* Calculated from 915 nm absorption value
** Following XFS/080301ARL procedure
Specifications are subject to change without notice

TURN-KEY FREQUENCY-STABILIZED LASER SYSTEMS

iXblue Quantum Sensors division (formerly Muquans) specializes in very high performance instrumentation and is the first company in the world to exploit laser-cooled quantum manipulation techniques on an industrial scale. The company provides a complete range of solutions based on this breakthrough technology, including a quantum gravimeter, an atomic clock, or frequency transfer systems over fiber. iXblue developed very high performance laser systems, the ILS, in order to operate these commercial quantum solutions.

Turn-key laser systems for Quantum Technologies and laser-cooled atoms

iXblue presents a new generation of compact and agile intelligent laser systems (ILS) offering a precise control of the laser 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 wavelength for other species can be addressed and a wide variety of configurations are available.

The laser architecture is based on the utilization of slave lasers, frequency-locked to a master laser whose frequency is stabilized on an atomic transition using saturated absorption spectroscopy. The laser systems are equipped with dedicated electronics, 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.

Easy-to-use, flexible and reliable laser system, with state-of-the-art optical performance

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 iXblue feature state-of-the-art optical performances that meet the stringent demand 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 the ILS systems, the performances of quantum physics labs can be accessible to a much broader spectrum of users. 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 allow 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.

According to the customer requirements, each module of the ILS systems can be customized, while ensuring long-term stability:

- **The seed module:** it can include a DFB laser diode or an ECDL as a seed laser. Dedicated ultra low-noise electronics are developed to achieve outstanding spectral features.
- **The amplification module:** specific EDFA architecture developed with strong R&D efforts to optimize several key parameters (Amplified Spontaneous Emission - ASE, wall-plug efficiency, polarization characteristics, and power stability).
- **The frequency doubling module:** second harmonic generation obtained with a PPLN waveguide crystal qualified for high power operation. It offers a very high conversion efficiency which loosens constraints on power requirements and management of thermal effects.
- **The frequency-stabilization module:** stabilization on an atomic transition thanks to an optimized saturated absorption spectroscopy technique. Our design is based on a heated and magnetically shielded gas cell and includes specific ultra low-noise frequency-lock electronics. This allows to keep the laser frequency locked on the atomic transition over several months. In addition, the locking of the laser frequency is automated and does not require any optimization from the user.

The ILS systems is already used in promising quantum computing applications, proving its reliability and performance for such complex tasks. The spatialization of the seed module is in progress and will open perspectives for the ILS systems in the space market, together with other iXblue solutions (fiber-optics, modulators, free-space optic components), for ground base station of satellites constellation for example. ■

Read p. 54 to discover how the ILS series can serve the field deployment of the Absolute Quantum Gravimeter on Mount Etna volcano.

Frequency-controlled laser systems

DEDICATED TO ATOM COOLING AND TRAPPING

A WIDE VARIETY OF CONFIGURATIONS ARE 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 1>3 or 1>6 output fibers per laser head, with independent power control.

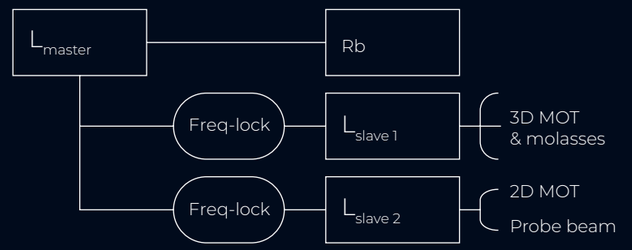
OPTICAL CHARACTERISTICS

Operating wavelength	780.23 nm (D2 line of 87Rb and 85Rb)
Output power	> 300 mW per laser head (direct use for atom manipulation)
Linewidth	< 60 kHz
Tunability range	up to 1GHz
Sweeping rate	> 250 MHz/ms typ.
Polarization	30 dB typ.
Beam quality	TEM∞ 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 14U, depending on the laser configuration
Supply voltage	100-240 VAC, 50-60 Hz
Electrical power consumption	<250 W typical, depending on the laser configuration
Air-cooling	

EXAMPLE OF CONFIGURATION DEVELOPED FOR BOSE-EINSTEIN CONDENSATION EXPERIMENT:



OPTICAL HYBRIDS IN FREE-SPACE

DESIGN, FOR THE EXTRACTION OF PHASE, AMPLITUDE, AND POLARIZATION

The Telecom industry has long been in an active search for innovative technologies enabling ever higher transmission rate. iXblue Photonics Solutions division (formerly Kylia) has an extensive experience in developing such innovation for fiber-optic telecommunications, in particular devices that can demodulate optical signals with very complex modulation.

iXblue demodulation solution: a ground-breaking approach based on telecom technologies

Telecommunications have historically been based on the coding of information in binary mode (series of 0 and 1). With the use of optic fibers, the binary coding was applied through the amplitude modulation of laser light, driver of the information. This “on-off keying” modulation implies a “bit time” rate relative to the frequency of modulation per second. A bit time of 1 ns means a transmission rate of 1 Gbit/s. A modulation solution is needed for the emission laser, and a demodulation solution is needed at the receiver side to convert the amplitude modulation in an electrical signal with data usable by a computer.

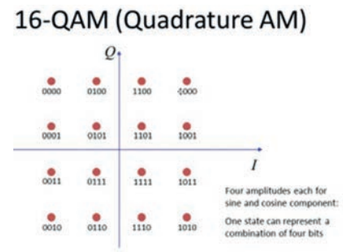
When the need for transmission rate higher than Gbit/s came, new up-to-date modulation and demodulation technologies had to be developed. iXblue has been able to offer various products for such complex demodulation, based on free-space design and a long-term expertise in telecom technology. A series of products (iXblue MICS series) is dedicated to the multiplexing and demultiplexing, meaning the capability to transfer in a unique optic fiber many laser beams of different wavelengths (i.e 40 laser beams at 40 different wavelengths – 1528 to 1560 nm, the C-band - in a typical telecom fiber). Another series of products (iXblue MINT series) uses another property of light for the demodulation, the phase of the electro-magnetic wave. The modulation is easier and faster with the phase (0 or π) than with the amplitude. The optical DPSK (Differential Phase Shift Keying) demodulation is made possible with the MINT product, and it applies to transmission rate around 10 times higher (10 Gbit/s).

iXblue COH 90° optical hybrids solution

Then came the generation of “QAM” technologies, a modulation technique using both phase and amplitude of the electro-magnetic wave. On top of the previous advantages, this solution allows the use of intermediate values (between 0 and 1, between 0 and π) for the modulation. It gives much more possibilities to code the information. The QAM16 and QAM64 technology can for example deal with 4 to 6 bits in a single bit time.

The demodulation of the signal is complex and made possible by iXblue COH 90° optical hybrids solution. The phase, the

iXblue 90° Optical Hybrid



”THE COH 90° OPTICAL HYBRIDS, OUR MOST ADVANCED DEMODULATION SOLUTION, IS VERY FLEXIBLE. IT CAN BE APPLIED TO SIMPLE MODULATION, AND THEN TO MORE COMPLEX MODULATION WITHOUT ANY UPDATE.”

- AURÉLIEN BOUTIN, TECHNICAL HEAD OF IXBLUE PHOTONICS SOLUTIONS DIVISION

amplitude and even the polarization are extracted by performing four 90° phase stepped interferences between the signal and a reference, a local oscillator at a specific frequency. If the signal processing is not mastered by iXblue, its core competencies rely in the design and the assembly of a free-space optical solution adapted to any kind of modulation. The COH 90° optical hybrids, the most advanced iXblue demodulation solution, is very flexible. It can be applied to simple modulation, and then to more complex modulation without any update.

From telecom to space applications

If the telecom market was the first addressed by these modulation solutions, a large range of new applications find it useful today. Being able to demodulate the phase of a signal, in particular, is very powerful for example in metrology, for instance as an optic sensors measuring a tiny physical parameter that interacts with the phase of the electro-magnetic wave. In the medical field as well, it has some application: the Optical Coherent Tomography (OCT) uses it to image under-skin tissues by the demodulation of reflected signal. iXblue COH 90° optical hybrids is also qualified for space applications, such as laser communications or satellites constellation. Many other devices exist in the Telecom wavelength band, the “C-band” (i.e silicon chip), but iXblue free-space solution is the only one able to address both the C-band and the L-band (wavelength from 1570 to 1630 nm). It is also better in the C-band than the silicon solution, thanks to the better performance of the free-space solution optics for the demodulation of polarization (reaching 25 to 30 dB of extinction rate), as well as better balanced uniformities (0,2 dB) and 90° phase shift accuracy (phase shift is may be tunable as an option). Today, perspectives are even promising for iXblue demodulation solution towards all Telecom bands with a single device working from O- to L-band (from 1260 nm to 1620 nm). ■

iXblue 90° Optical Hybrid

THE MOST ADVANCED IXBLUE DEMODULATION SOLUTION

		COH90SP (Single Polarization)	COH90DP (Dual Polarization)	
Parameter		**Specification**		**Remarks/Conditions**
Operating Wavelength range (OWR)	COH	1520nm to 1570nm		
	COH - X Option	1520nm to 1625nm		
IL uniformity [1,2] (ΔIL)	COH	1dB typ. (Max value 2dB)		Without connectors
	COH - X Option	0,5dB typ. (Max value 1dB)		
IL dual uniformity [1,2] (Δdual)	COH	0,5dB typ. (Max value 1dB)		Between balanced outputs Without connectors
	COH - X Option	0,2dB typ. (Max value 0,5dB)		
Packaging size	COH	70 x 52 x 10		Excluding fiber boots
	COH - X Option	180 x 32 x 19.5		
Insertion Losses from Signal[1] (IL→S)		7.0 typ. (Max value 8,5dB)		Including natural losses
Phase shift between I and Q[1] (φ)		90° (+/- 5°)		
Skew		0.5ps typ. (Max Value 1ps)		Measured at connectors end - For all outputs
Optical return loss (ORL)		35dB		
Output fiber Type	SM	SMF-28		With 900µm loose tube
	PM	Panda PM		
Fiber Pigtail Length		1.0m (+/-0.1m)		
Maximal optical input power (OpIn)		300mW		
Insertion Losses from LO1 (IL→LO)		7.0 typ. (Max value 8,5dB)	10.0 typ. (Max value 11,5dB)	Including natural losses
Polarization splitting ratio (PSR)		Not available	20dB	
Polarization Extinction Ratio (PER)		20dB	20dB	
Input fiber Type	SM	Not available	SMF28	With 900µm loose tube
	PM	PM Panda	Option PM Panda	
Options		Only available for X Option		
Phase shift tunability (Δφ)		+/- 20deg		For applying 3V
Max Input Voltage (U)		+4		

1 measured over OTR and OWR for all states of polarization
2 from Signal or LO

02

APPLICATION CASES

LULI2000 FACILITY POWERED BY IXBLUE MODBOX FRONT-END

LULI2000 experimental room
© Ecole polytechnique - J.Barande

"SURELY, LULI2000 IS EQUIPPED WITH ONE OF THE BEST MODBOX SOLUTION AVAILABLE TODAY, AND IT IS EVEN TOTALLY UNIQUE REGARDING THE NUMBER OF VARIOUS LASER BEAMS AVAILABLE SIMULTANEOUSLY."

- LOÏC MEIGNIEN, LULI2000 FACILITY MANAGER

LULI2000 is a high-power laser system dedicated to scientific research. It is hosted since the early 2000's in Paris-Saclay, in France, at the Laboratory for the Users of Intense Lasers (LULI), a joint research unit of Ecole Polytechnique, CNRS, CEA and Sorbonne Université. The facility delivers 4 chains of high-energy laser beams obtained after focusing onto tiny focal spots (up to 200 µm in diameter). The interaction with small targets produces very hot plasmas, up to many hundred million degrees, high densities and high pressures. Depending on the laser and target parameters, these laser-generated plasmas may be compared to stars or planet interiors.

The main research topics concern laser inertial fusion and all its physical components, fundamental physics of hot and dense plasmas and its applications in astrophysics and geophysics, or the physics and processing of materials. LULI2000 also helps to prepare at best the experimental campaigns on very large facilities (like Laser MegaJoule in France, and XFEL in Germany), by validating concepts, testing diagnostics, training the technical staff, etc.

In 2010, the LULI2000 facility was totally modernized and gained a lot in capability and reliability, at the instigation of Loïc Meignien, new facility manager. He impelled the modernization of the whole pilot room of the facility and the installation of new fiber laser oscillators on the 3 main laser beams enabling different pulse profile shaping. He initiated the collaboration with iXblue around the development of the ModBox solution, leading to a versatile facility, where the temporal shaping and timing could be changed and programmed in advance. "It generated an increase of scientific outputs, in astrophysics for example." according to Loïc Meignien.

"Since the first prototype of the ModBox that we have developed 10 years ago with iXblue, we have had a very fruitful partnership. We have continously exchanged together to obtain the best solution for our facility. It was eventually supplied by iXblue to other French and European high-energy laser facilities. Today we have reached the 4th generation of ModBox installed at LULI2000".

He points out another advantage: "iXblue ModBox solutions are based on the most up-to-date telecom components, when other large high-energy laser facilities still use technologies from the late 90's. Surely, LULI2000 is equipped with one of the best ModBox solution available today, and it is even totally unique regarding the number of various laser beams available simultaneously."

iXblue Optical Pulse Shaper & Laser Front End

Based on its unique in-house technologies, iXblue has developed the ModBox-FrontEnd, a turnkey system ideal for optical pulse shaping. iXblue has built up a strong experience in such systems and successfully installed them in many research laboratories over the world, and in industrial companies. With these ModBoxes, iXblue offers the most comprehensive portfolio of versatile sub-nanosecond resolution laser pulse shaping based on $LiNbO_3$ modulator design, company flagship expertise.

The ModBox-FrontEnd is challenging the state of the art of temporal pulse shaping performance, as Alexandre Soujaeff, ModBox Business Engineer 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"

Laser Nuclear Fusion

Last year, the NIF laboratory announced a breakthrough in nuclear fusion with a record generation of energy in a laser induced nuclear fusion reaction. More than a GigaWatt of fusion power was generated for 100 ps in a hot-spot the size of a human hair. In parallel, there are a couple of startups offering to develop power plants based on innovative concepts using laser as a driver for nuclear fusion (not to be confused with inertial fusion technology like the ITER

High Energy and High Peak Power Lasers

PULSE CHARACTERISTICS FOR HIGH ENERGY EXPERIMENTAL STUDIES

Stable and adjustable energy level

Adjustable optical pulse shape

Adjustable pulse duration

Adjustable pulse repetition frequency

Low jitter

High pulse contrast

The ability to temporally shape the pulse of a laser beam is of critical importance for some applications, such as large high-power lasers infrastructures like LULI2000. iXblue ModBox FE is able to generate laser pulses with any kind of temporal shape.

THE ACCURATE TEMPORAL CONTROL ALLOWED BY THE MODBOX GUARANTEES A HIGH PEAK POWER AT THE OUTPUT OF THE L4 ATON LASER SYSTEM.

project that uses a Tokamak technology). In both cases, the goal is to use the intensity of several laser beam pulses converging on a tiny nuclear fuel target.

For nuclear fusion with lasers, the temporal pulse shaping is crucial as the energy involved is huge, and thus any deviation in the laser pulse shape and contrast can have a disastrous impact on the experiment. iXblue ModBox is a solution totally suited to this field thanks to its ability to control the temporal profile and timing of all the laser beams focused on target toward the fusion ignition.

Laser and particle beams for "Big Science"

Another field of application are the lasers used in research to explore interactions of photons with beam of particles, or to control or generate beams of fundamental particles like electrons/protons or X-ray radiation. For this field of fundamental science, a ModBox is convenient as it can also create tailored optical pulse burst on demand. "For example, impulsion from few tens of picoseconds to hundreds of ns of a specific shape can be generated at a repetition rate up to 100 kHz, with a very high precision and flexibility. This kind of "burst mode" is convenient for linear particles accelerator which are set with a specific tempo." points out Alexandre S.

Pumping laser for very powerful laser

An example of very powerful laser facility is the L4 ATON laser system at ELI Beamlines infrastructure located near Prague in Czech Republic. It is designed to reach an exceptional multi-petawatt laser peak power of 10 PW. It will allow the production of particle beams and radiation with unique parameters, allowing the exploration of new research's fields from relativistic physics to vacuum physics.

To achieve these results, the L4 laser is based on mixed glass and OPCPA (Optical Parametric Chrip Pulse Amplification) technologies, including iXblue ModBox. The temporal shaping is mandatory in this application to offer flexibility and precision in the manipulation of the laser optical spectrum. The accurate temporal control allowed by the ModBox guarantees a high peak power at the output of the L4 laser.

Shot peening in industry

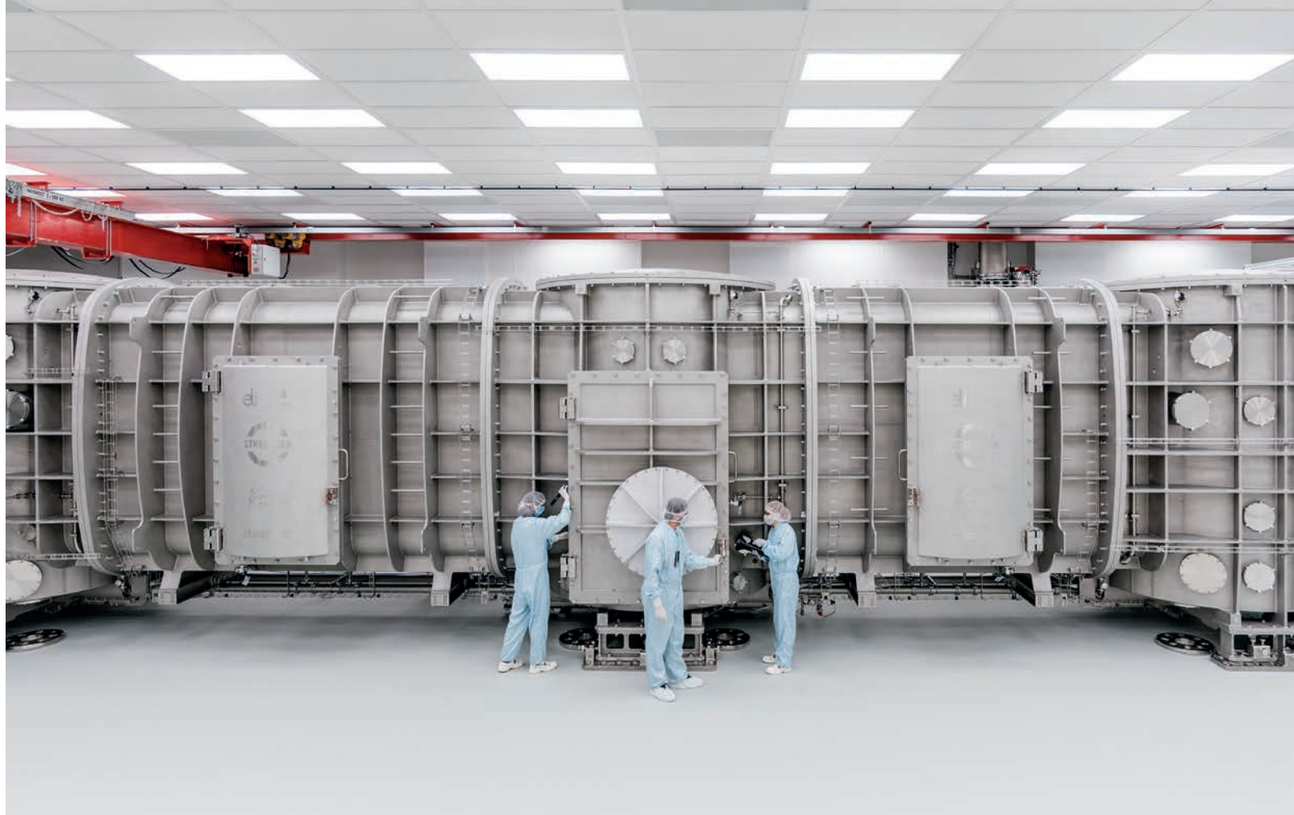
High-power lasers with advanced pulse shaping are used in an industrial application: the shot peening, also known as shot blasting. It is a process used to strengthen metallic parts of complex structures used in harsh environment (i.e. in aeronautics), to prevent fatigue, stress and corrosion failures for a longer product lifetime.

For this type of industrial application, iXblue ModBox solutions offer a very controlled and repeatable solution to shape the laser beam. iXblue is already supplying the leading companies of this high-end industrial market.

From components to the last version of iXblue ModBox-FrontEnd

Today, the ModBox-FrontEnd offers the ultimate performance for the end user by integrating screened and selected components that are controlled by a dedicated software interface for intuitive (and gradual) control to provide reliable and stable operation. Continuous product development is central to the company's activities. This focus on innovation has enabled the company to establish and maintain a leading position in the strategic laser market.

iXblue masters the 3 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 iXblue expertise, leading to the most recent products currently in the company portfolio. In the ModBox Front-End market for optical pulse shaping, iXblue really offers the unique solution currently available. Each ModBox can be customized to the customer needs, thanks to our standardized building blocks. ■



L4 Aton laser system / Copyright: ELI Beamlines

> IN THE MODBOX FRONT-END MARKET FOR OPTICAL PULSE SHAPING, IXBLUE REALLY OFFERS THE UNIQUE SOLUTION CURRENTLY AVAILABLE.
>
> - ALEXANDRE SOUJAEFF, MODBOX BUSINESS ENGINEER

IXBLUE EXTENSIVE COMPONENTS PORTFOLIO FOR 2µM FIBER LASERS APPLICATIONS

The optical fiber doped with rare-earth elements - the active gain medium - and Bragg gratings - the mirrors of the laser cavity - are key components mastered by iXblue for many years, especially in the 1 and 1,5 µm range. They are being incorporated in a growing number of laser applications such as lidars, laser markers, laser cutters, plastic welding, defense lasers and a new sector: lasers for medical purposes. Today, new applications are rising for fiber lasers in the 2 µm range, which has driven recent innovation in specialty fiber technology.

Even though they are still more expensive than the 1 or 1,5 µm lasers, the 2 µm lasers address "niche" markets but with strong added value. If one of the main advantages of the 2 µm laser is its power, it also has a considerable asset for many applications as it is "eye-safe". Indeed our eye is sensitive to its beam and instinctively closes itself when touched. That is not the case with thinner laser beam that can reach deep inside our eye and damage it irreversibly.

The 2 µm laser for LIDAR with applications in defense and environment

The generic term of LIDAR for LIght Detection And Ranging finds its use nowadays in many different systems and applications, from the scanning of surroundings to create a 3-D digital map of obstacles (for instance in autonomous driving applications) to atmospheric Lidars that detect gases or aerosol particules (for instance in environmental applications). Another well spread application is the detection of atmospheric turbulences to secure wind-turbines operation or airports. All these systems have different requirements in terms of wavelength, power and pulse profiles.

iXblue offers a wide range of specialty fibers and Electro-Optic Modulators (EOMs) that can answer the various challenges of Lidar applications. Fiber laser sources emitting around 1.5 µm have already shown key advantages in the fields of wind farms and aircraft safety: versatility, modularity, and robustness of alignments to vibrations. The applications opened today for 2µm fiber lasers in defense and atmospheric science represent appealing future markets for iXblue.

The French-German Research Saint-Louis Institute (ISL), at the occasion of a research program with the DGA (French Government Defence procurement and technology agency), has obtained and presented in 2021 some interesting results using an iXblue optic fiber: a monolithic laser source with thulium-holmium co-doped fiber in single oscillator emitting 195 W at 2090 nm in continuous mode.

The 2 µm laser for urology

An interest is rising among medical laser manufacturers for thulium-doped fiber. Laser technologies are used in flexible ureteroscopy, for ureteric and kidney stone management. The goal is to be minimally invasive without breaking the skin barrier. The thulium fiber laser has several advantages over the Holmium YAG laser, traditionally used in urology. With a wavelength of 1940 nm, the absorption coefficient of thulium fiber laser is four times greater in water (1940 nm matches the near-infrared absorption peak of liquid water at room temperature), and it enables much smaller spot sizes to be created with less powerful pulses but at a much higher rate. It has average and peak powers of 100 W and it does not burst tissues, providing clean and precise cutting. It allows for pulse prolongation up to 12 ms, with regular pulses. Therefore, the power produced by the laser has a constant peak, called the super pulse creation. It is perfect for surgical applications, providing even greater precision and less collateral damage.

iXblue has developed a fiber laser cavity (a thulium doped fiber and fiber Bragg gratings - FBG), for this innovative laser technology that may become an important milestone for kidney stone treatment.

iXblue portfolio for 2 µm fiber lasers and FBGs

With its extensive experience and its large fibers and FBG Laser mirrors portfolio, iXblue can support the emergence of innovations in 2 µm fiber lasers. iXblue solutions to reach high-power (higher than 50 W) lasers but also power scaling in lasers will draw the attention of experts as they are based on proven-and-tested manufacturing processes.

Any small irregularities contained in an optic fiber architecture (especially at the junctions of fibers) can heat rapidly and damage the fiber. Each step of the fabrication process of a FBG must be carefully controlled to avoid these irregularities. iXblue know-how on special optic fibers is key on this aspect. It led to the development of a specific "HP" process for high-power applications, on top of the already existing expertise in term of excellent matching of (passive/active) optic fibers and in term of packaging for optimal thermal dissipation. The resistance towards heat is increased by a factor 10 with iXblue FBGs compared to the competitors' solutions.

The doped fibers in iXblue portfolio especially address the range of 1900 to 2090 nm (i.e 1940 nm for urology, 2036 nm for LIDAR, etc.), with different absorption wavelengths available for the FBGs that can be incorporated to any kind of fiber. Most importantly, iXblue can produce custom fibers based on core co-doped with Thulium (Tm), Holmium (Ho), or both (Tm/Ho), with on demand customization: any core size (4 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).

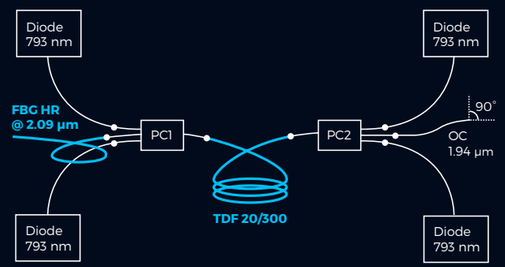
iXblue provides splicing services for specialty fibers (high power, large diameter, etc.) with adapted recoating and packaging solutions. The resulting sub-assemblies will be validated with a test report for final qualification (efficiency, temperature, ...). From its on-the-shelve products up to the most recent generation innovative products, iXblue can answer its customer needs, even the most exotic ones, with the same quality and reliability: from very short series (several components) to larger volumes (tens to hundreds of components), but always with specific customizations. Parameters that can be adjusted are the wavelength of the filter (between 600 and 2000 nm), the bandwidth of the reflected beam, the level of reflectivity of the FBG, and the spectral shape of the FBG. iXblue can create prototypes that can be industrialized very quickly. ■

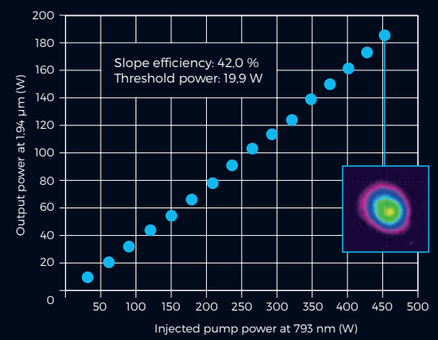
iXblue portfolio for 2µm fiber lasers applications

Doping Materials	
Thulium	Single Clad 4 and 5 µm core, PM and non-PM Double Clad 6 to 25 µm core, PM and non-PM
Thulium-Holmium	Double Clad 6 to 25 µm core, PM and non-PM Triple Clad 18µm core
Holmium	Single Clad 8µm core, PM and non-PM Single Clad 20 µm core, PM Triple Clad 20 µm core
	Matching passive fibers available Custom versions available

Fiber Type	Typical available Wavelengths – High Power process
4 to 25µm core Single Clad, Double Clad and Triple Clad PM and non-PM Double C	1908 – 1940- 1950 -2036-2050- 2090- 2120
	Custom versions available

Other components available at iXblue for 2µm:
Lithium Niobate Modulators, Variable Optical Delay Lines, beam splitters, beam combiners





200W Laser cavity with iXblue Thulium double clad Fiber (courtesy of French-German Institut of Saint Louis - ISL)

TOWARDS WATT-LEVEL DEEP-UV AND BLUE LASERS BASED ON NOVEL ND-DOPED FIBERS

For more than 10 years, iXblue is engaged in a fruitfull 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 on ions, materials, and photonics. It aims at developing new sources of laser based on optical fibers doped with Neodymium (Nd) for blue/deep-UV wavelength laser emission.

Nd-doped fiber laser sources can emit at high power near 900 nm (more than 80 W) which is useful in many scientific or technological applications requiring accuracy as much as strict power. They can be used as femtoseconds pulsed lasers in the 920 nm regime in medical imaging for the "two-photon microscopy" technique (i.e cellular tissues), as continuous-wave single-frequency lasers in the blue domain (frequency doubled) to cooldown strontium atoms for quantum applications. But they can also serve as lasers emitting in the Deep-UV (frequency quadrupled) 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).

The lasers commonly used today to reach the near-IR spectral domain is the titanium-sapphire (Ti:Sapphire) laser. It is a quite voluminous solid laser that requires an additional pumping laser, and that needs regular and important maintenance checks, making it quite expensive. All-fiber based lasers are much easier to install and maintain.

The lasers based on ytterbium doped optical fibers are quite common today, but they emit at a unique long wavelength at 1µm. From all silica-based fibers only lasers based on neodymium doped optical fibers can directly reach such short wavelength as 900 nm. 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 wavelength (in deep-UV around 225 nm).

But the development of Nd-doped fiber lasers faced some challenges. One of them comes from the 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.

On small 5 µm core fibers, a "W-profile" shaping with controlled leak of the 1 µm wavelength was first designed by iXblue. A few watts could be obtained from this PM fibers. For higher power, it was possible to achieve even higher output powers thanks to the use of LMA fibers provided by iXblue. It would have been impossible to deal with the non-linear effect with normal geometry of fiber and "W profiles" are inefficient on larger core size. In order to keep as low as possible the 1060 nm emission, the design had to be optimized for a better core/clad ratio, also by playing on the absorption rate, doping levels and the length of the fiber, while maintaining the polarization and a low NA. They were challenging technological moves successfully overcome by iXblue.

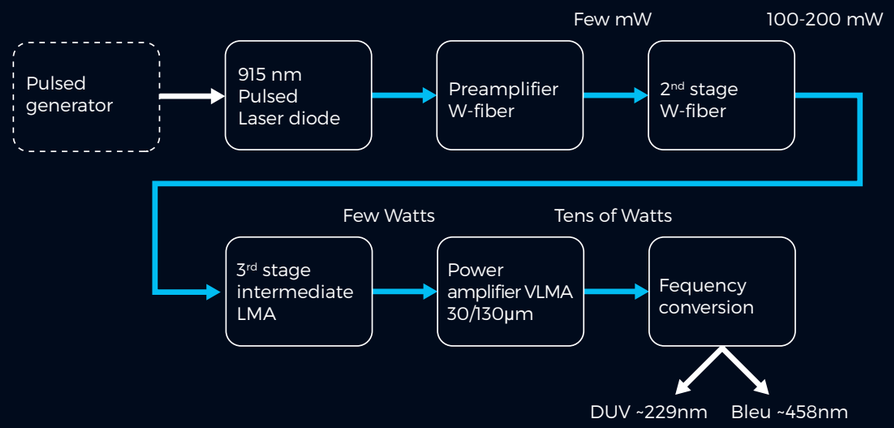
iXblue saw a rising interest from its customers for this type of fiber laser source (i.e fiber lasers for the 2-photon microscopy) and the opportunity to industrialize them. It is a direct result of the collaboration with the CIMAP lab.

The joint research program "NEODUV" is in progress until end-2023. Funded by the French National Research Agency (ANR), it involves CIMAP (Caen) and LP2N (Bordeaux) academic laboratories and their industrial partners iXblue and Oxxius (Lannion). The plan is to significantly increase the performances of laser sources based on neodymium doped alumino-phospho-silicate fibers (SiO_2-Al_2O_3-P_2O_5-Nd_2O_3) in single-frequency and short-pulse regimes. The first step is to develop a fiber with iXblue, then a laser source in pulsed regime at CIMAP Caen, the continuous-wave single-frequency in blue wavelength to cool down strontium atoms with LP2N, and the frequency conversion stages with Oxxius. The consortium combines unique competencies at the worldwide scale for those developments.

The collaboration with the CIMAP lab is expected to bring more outcomes in the near future in term of technological developments such as new combiners that do not exist yet. Some mode adaptors are also expected as they cannot be manufactured in a research lab for such applications in the 900 nm regime. The next perspectives for the CIMAP research team, still in collaboration with iXblue R&D teams, is the generation of high-energy ultra-short pulses (femtosecond). It will require the testing of several iXblue optical fibers to choose the best match for the amplification level within a MOPA architecture. ■

IXBLUE SAW A RISING INTEREST FROM ITS CUSTOMERS FOR THIS TYPE OF FIBER LASER SOURCE AND THE OPPORTUNITY TO INDUSTRIALIZE THEM. IT IS A DIRECT RESULT OF THE COLLABORATION WITH THE CIMAP LAB.

Schematic of MOPA configuration



Latest update from Photonics West 2022

Kilian Le Corre, a joint PhD student at iXblue and CIMAP lab, presented during the last Photonics West event in January 2022 the development of ultra-low numerical aperture NA large mode area neodymium doped alumino-phospho-silica fibers with different clad-to-core ratios for high power laser emission around 910nm. It showed that the 30/130µm (core/cladding) fiber was the most efficient, with a record output power of 83W at 910nm, yielding a 44% slope efficiency and a good beam quality (M^2~1.5). Parasitic power at 1060nm was kept lower than 1W and no sign of roll-off was observed at maximum pump power.

The experiment was made in an academic environment for demonstration and testing, however integration in small modules, similar to those of Ytterbium doped fiber lasers, should be quite straightforward. No cooling system was necessary as the heating of the fiber stayed very reasonable.

A YEAR-LONG FIELD CAMPAIGN ON MOUNT ETNA TO PROVE THE ABSOLUTE QUANTUM GRAVIMETER VALUE FOR VOLCANOLOGY

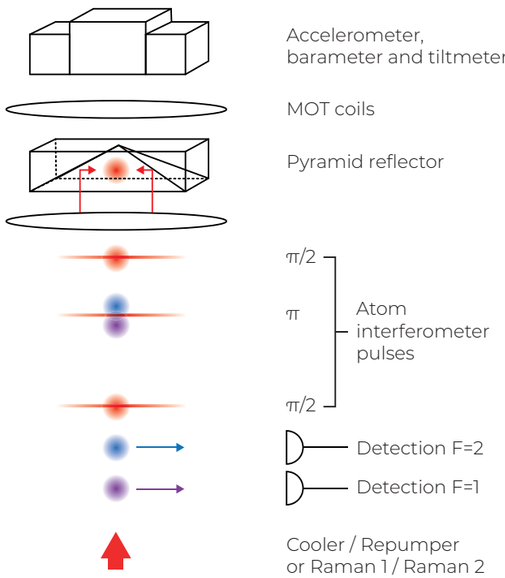
High-precision gravity measurements using Quantum Technologies and laser-cooled atoms

WITH ITS ABSOLUTE QUANTUM GRAVIMETER, IXBLUE OFFERS AN OUTSTANDING PRECISION FOR THE GRAVITY MEASUREMENT.

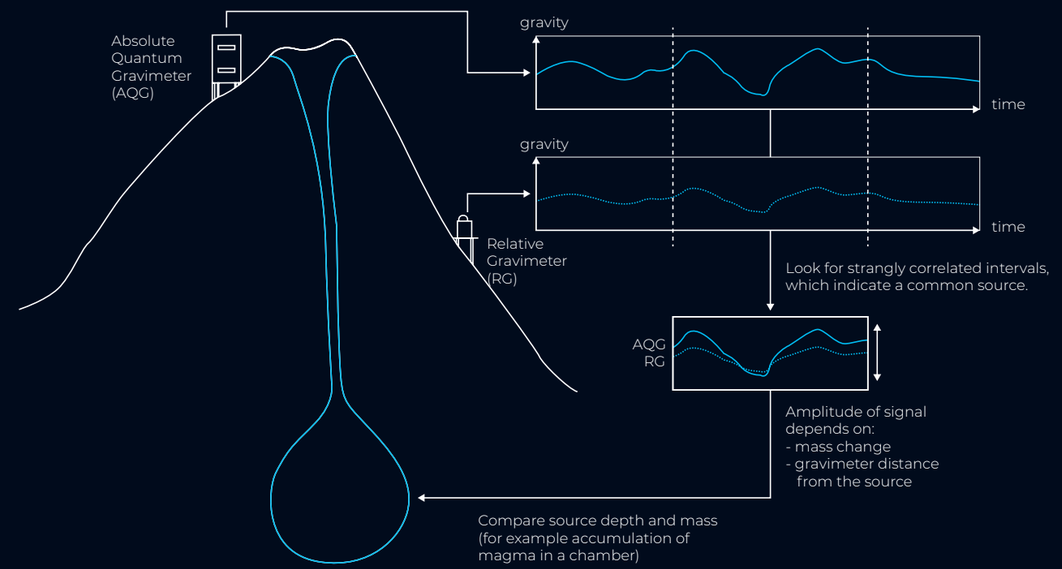
A gravimeter is a device that can measure the gravity field on Earth. Gravity is an acceleration, characterizing the free fall of a given object in meters per second square ($m.s^{-2}$). At a given location, its value depends on the distribution of nearby masses, and sub-surface density inhomogeneities give rise to small variations of the local gravity value in space or in time. The ability to measure these fluctuations with high precision finds applications in geophysics, reservoir monitoring, geodesy, metrology and sub-surface imaging for civil engineering. With its Absolute Quantum Gravimeter, iXblue offers an outstanding precision for the gravity measurement (at the level of 10^{-8} $m.s^{-2}$, which corresponds to approximately one part in 109 of the standard Earth gravity g=9.8 $m.s^{-2}$).

Absolute gravity meters measure the acceleration undergone by a free-falling test-mass. The most common technology relies on optical interferometry, where the position of a mirror in free-fall is tracked optically. However, these instruments are not well suited for continuous measurements in field conditions, in particular because of the presence of moving mechanical parts under vacuum that make them quite fragile, and because they are complex to operate.

iXblue Absolute Quantum Gravimeter (AQG) uses an ensemble of laser-cooled rubidium atoms as a test mass. Taking advantage of the wave-particle duality, quantum matter-wave interferences are used to measure the acceleration of the atoms as they fall and to track variations of the value of gravity over time. This technique is one of the ballistic free-fall methods proclaimed by the International Bureau of Weights and Measures (BIPM) as an official primary method for the measurement of gravity.



iXblue quantum sensors for volcanology



Data collected by the Absolute Quantum Gravimeter and the MEMS gravimeter will be analyzed and combined with models and other sensors. Because gravimeters are sensitive to deep mass changes, they are seen as promising candidates to detect early signs of eruptions, when the magma is still far from the surface.

A turn-key transportable and easy-to-operate quantum sensor on top of Mount Etna

QUANTUM GRAVITY SENSORS LIKE THE AQG CAN BE USED FOR ANY APPLICATIONS WHERE MAPPING THE UNDERGROUND MASS DISTRIBUTION IS RELEVANT.

The goal of the European project NEWTON-g, led by the Italian National Institute of and funded by the European Commission, is to place a network of gravity sensors on Etna Mount, in Italy and provide high-quality data. It serves as a high-performance reference, while the rest of the network will be composed of many small, less accurate but also less consuming gravimeters based on MEMS. Each gravimeter will offer the equivalent of a pixel for a mesh coverage of the volcano's depths. Measuring the variations of the gravity in such a way will allow to resolve density and provide real-time images of gravity changes.

Using the data from the array of gravimeters, geophysicists will be able to constrain volcanological models and get a better understanding of processes leading to eruptions. With respect to other technologies, the AQG has proven its ability to provide high resolution measurements in the challenging environment of an active volcano. It is in particular highly robust against seismic noise coming from the volcano and can provide continuous absolute gravity measurements while being remotely operated. This proves to be of high importance given the difficult access conditions on Mt Etna. The AQG is a turn-key solution for geophysicists, allowing a high level of performance with no need to recalibrate the system. Being able to collect data without interruptions on timescales ranging from months to years is very important for understanding complex geophysical systems. At this stage, iXblue solution has no existing commercial industry-grade competitor able to provide all these features in a single instrument.

The technical results of the AQG within the NEWTON-g project on Mount Etna are currently under evaluation for scientific publication. They conclude on the true advantage of the AQG solution for such a long-term field mission. Recent data has also shown the robustness of the AQG during eruptive events on the volcano. iXblue photonics solutions are at the heart of this success. The AQG embarks sub-components developed by iXblue, like the Intelligent Laser Systems (ILS - read p.30), the iMOB series (read p.66) and soon the specialty fiber optics. The ILS system relies on the use of lasers operating at 1560 nm. This approach therefore gives access to a wide variety of high performance fibered optical components, originally developed for high-bit-rate optical communication systems.

Quantum gravity sensors like the AQG can be used for any applications where mapping the underground mass distribution is relevant. This applies to hydrology and seismology, as well as civil engineering projects to detect voids, sink holes, tunnels and cavities. iXblue quantum gravimeters are already being used in other fields than geophysics – for example, with the French Ministry of Defence to supply shipborne quantum gravimeters in the frame of a joint project with ONERA, the French national aerospace research center. ■

iXblue Absolute Quantum Gravimeter on top of Mount Etna

RÉFIMEVE+

THE FRENCH NATIONAL METROLOGICAL FIBER NETWORK WITH EUROPEAN VOCATION

> THE TECHNOLOGY OF OPTICAL FREQUENCY TRANSFER PROVIDED BY IXBLUE ENABLES TO OVERCOME THE CHIEF LIMITATIONS AND ENSURES A FREQUENCY TRANSFER AT THE LEVEL OF 10^{-19} OVER LONG DISTANCES AS LONG AS THOUSANDS OF KM.
>
> - VINCENT MENORET, HEAD OF QUANTUM GRAVIMETRY AND FREQUENCY TRANSFER AT IXBLUE

Transferring an ultra-stable optical frequency on Internet over long-distances

The best clocks available today are optical clocks, a technology that allows a more precise measurement of frequency compared to the former best technology (but still widely used): microwave clocks. Optical clocks are often the size of a lab room, and their ability to measure with an extreme precision is not necessary for many practical applications. On the other hand, they are the most precise absolute reference for any other type of clock, which is today critical for fundamental research (i.e optical frequency metrology, spectroscopy, radioastronomy). Moreover, the rise of optical clocks now enables to anticipate a redefinition of the SI unit of time, the second. In this context, optical clocks will become the primary standard to build global (UTC) times. It is necessary to compare clock signals to ensure such a consistent time definition.

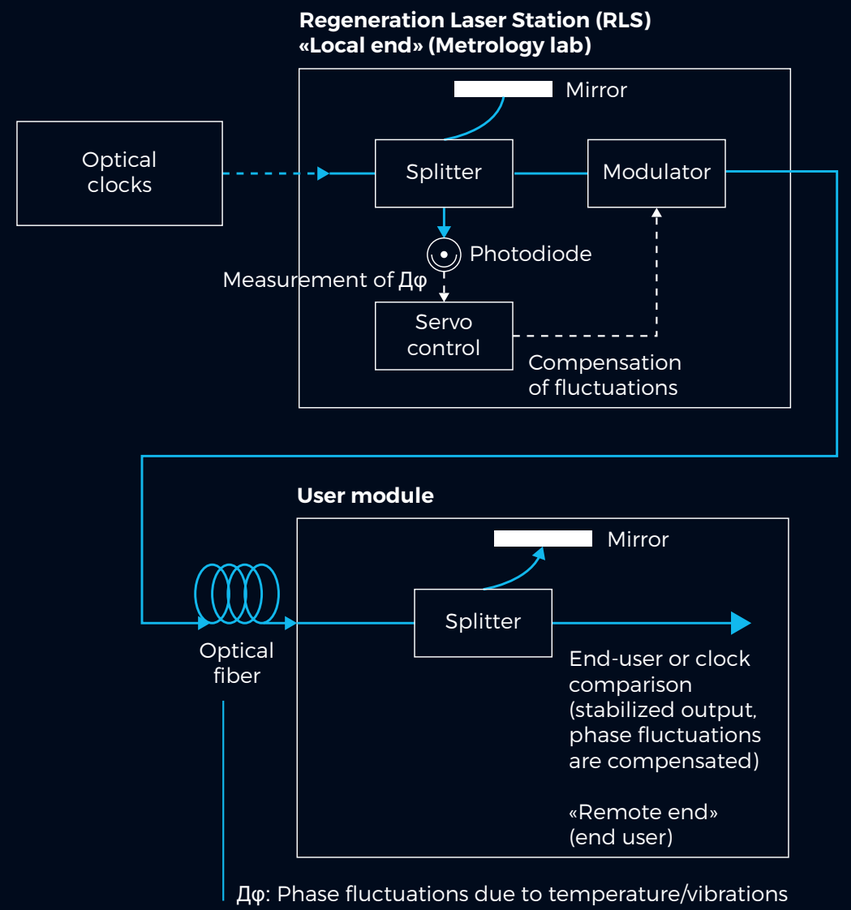
Currently, the transfer of ultra-precise frequencies over long distances for clock comparisons or dissemination to end-users faces the difficulty of transporting information without degradation when clocks are separated by hundreds or even thousands of kilometers. This can be achieved if one of the clocks is transportable, but this solution is mostly not flexible and hard to organize. Another possibility is to use one or more GNSS or telecommunication satellites. Despite their high level of maturity, performances of such comparisons are currently limited to a 10^{-16} level in relative terms. While those performances are sufficient to compare the best micro-wave atomic standards, they are simply insufficient to compare the best optical clocks, whose relative frequency stabilities stand at the level of 10^{-18}. The technology of optical frequency transfer provided by iXblue enables to overcome these chief limitations and ensures a frequency transfer at the level of 10^{-19} over long distances as long as thousands of km.

This is the context in which the French REFIMEVE+ (Metrological Fiber Network with European Vocation+) project started. It is based on the ability to transfer an ultra-stable optical frequency on Internet over long-distances without any traffic disruption. The transfer is done via optical fibers, the same that are used for the Telecom network (in C-band, at wavelengths around 1550 nm). Initiated in 2012 by a consortium of French research labs, the LPL (a CNRS/Université Sorbonne Paris Nord lab) and the SYRTE (a CNRS/LNE/Observatoire de Paris lab), in partnership with RENATER (network operator for the French higher education and research), the project was extended in 2020. It is connected to other European countries, such as UK, Germany, and Italy.

The ultra-stable laser of an optical clock generates a laser oscillation with a frequency stable at the level of 10^{-18}, which is the reference signal to be disseminated. The use of a frequency comb allows to transfer this reference signal to a particular wavelength in the telecom C-band, that will be injected in existing telecom networks. In the REFIMEVE+ network, the initial optical frequency reference is given by the LNE-SYRTE laboratory at the Observatoire de Paris,

iXblue regeneration laser station (rls) in REFIMEVE+ network

TRANSFER OF INDUSTRIAL-GRADE OPTICAL FREQUENCY OVER 5000 KM



the national metrological institute for time and frequency that provides the Coordinated Universal Time (UTC) of France and a long-term partner of iXblue

Metrology system turned into certified industry-grade turnkey devices

iXblue is the industrial company in charge of providing the hardware dedicated to ultra-stable optical frequency transfer over optical fibers. As a supervisor, to ensure a high quality of service and maintain the security of the host telecom network, the company deploys its compact Regeneration Laser Station (RLS) so that the laser oscillation can be electronically "re-shaped" around every 500 km in a dedicated hub (i.e Paris <> Lyon). The regeneration of the reference optical signal in the RLS stations is achieved thanks to the heterodyne optical phase-locking of an integrated ultra low-noise laser diode on the reference signal. The regeneration station actively compensates for the phase noise accumulated due to thermal and mechanical fluctuations during propagation along the fiber. As a result, it is an equipment of choice for state-of-the-art optical clock remote comparisons.

The REFIMEVE+ network uses the shelters covering the telecom network to re-amplify periodically the optical frequency (around every 80-100 km). iXblue is also in charge of deploying all the hardware and to ensure the quality of the transferred signals using a dedicated remote supervision tool, to which all the equipments are connected and provide data in real time. More than 5000 km of fiber are already connected to the REFIMEVE+ network, connecting 4 new links to the two initial hubs in Paris (LNE-SYRTE and LPL labs). In total, iXblue has deployed around 20 RLS stations, and 30 more will be installed soon.

This network is now a national French research infrastructure playing a role in the optical frequency metrology field, to help different research labs to compare "their own reference", but it also provides an absolute frequency reference to various scientific experiments and end-users (research centers, space agencies, etc.). REFIMEVE+ is gaining in popularity in France neighbors' countries, and iXblue solution for the regeneration of the metrological signal appears very stable and robust compared with the usually "home-made" existing solutions. Most importantly, it is an industry-grade solution that is certified, robust and enables remarkable uptime. iXblue solution for optical frequency transfer can be deployed within a few days and has shown to provide uptimes as high as 99 % over a week.

The true and deep understanding of iXblue teams for the fundamental physics behind its technology explains the absolute quality of its time & frequency reference products. The competencies gained in the development of the absolute quantum gravimeter are re-injected in every product of the company and became its expertise. Most of the sub-components are also produced in-house with the same level of demand. ■

> THE TRUE AND DEEP UNDERSTANDING OF IXBLUE TEAMS FOR THE FUNDAMENTAL PHYSICS BEHIND ITS TECHNOLOGY EXPLAINS THE ABSOLUTE QUALITY OF ITS TIME & FREQUENCY REFERENCE PRODUCTS.

The REFIMEVE+ project (2012-2024)

A NATIONAL-SCALE FREQUENCY TRANSFER NETWORK WITH EUROPEAN VOCATION

FREE-SPACE MICRO-OPTICS

FOR THE MONITORING OF SUBMARINES POWER CABLES

Focus inside an iMOB bench produced for the Quantum Computing market

FEBUS Optics is an Electro-Optic Modulators (EOMs) supplier and turnkey solution provider bringing a new generation of optical fiber-based sensor systems to the market using Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS) and Distributed Strain Sensing (DSS). Its solution can be used in particular for the maintenance and monitoring of infrastructures, such as submarine power cables for Marine Renewable Energy. The company has been a customer of iXblue since 2017, using its micro-optic components, with an important level of customization.

"Our distributed sensing systems have been taken to a next level of performance, among the best available in the market today, thanks to the free-space micro-optics solutions provided by iXblue. Its components are today compulsory in our own systems." Vincent LANTICQ, CTO of FEBUS Optics. He adds: "We are fully satisfied with iXblue solution. There was never any problem with the products we have received until now, which is quite rare. Another factor of trust for us as a customer is the very direct and transparent communication with iXblue. It makes iXblue one of the top rated FEBUS Optics' suppliers. We also know we can rely on a great and quick technical support from the team. The company controls its full production chain, and the technical documentation attached to the product is very clear and appreciated by our R&D team."

iXblue large portfolio opens perspectives for the developments of future FEBUS Optics products: "We know that iXblue offers a wide range of solutions that could apply to our different systems. We are looking forward to work with iXblue on the development of new products, customized to address our specific future needs. We know we can count on iXblue ability to perform free-space dynamic assembling to provide compact solutions for our future challenges. Maybe in the future, free-space micro-optics can be used more deeply in our design, enabling to obtain very compact systems."

iXblue expertise in the ultra-precise assembly of optical elements on glass breadboards

iXblue (formerly Kylia) has long aimed at differentiating its offer in term of high performance and high degree of customization, leading to strong added value for its customers. In addition to its catalogue of products, the free-space micro-optics assembling offers today a technological solution in line with the expectation of many different markets. It opens perspectives towards new innovations that will address tomorrow the technical challenges of new customers.

The LIDAR industry for environmental science (wind measurement) is already addressed by custom free-space optical setups, but also the telecom market via some big players and the laser tracker systems market via a well established industry leader of the field. Quantum technology is another market successfully addressed by iXblue free-space.

Customed Integrated Micro-Optics Benches (iMOB) for Quantum Technology

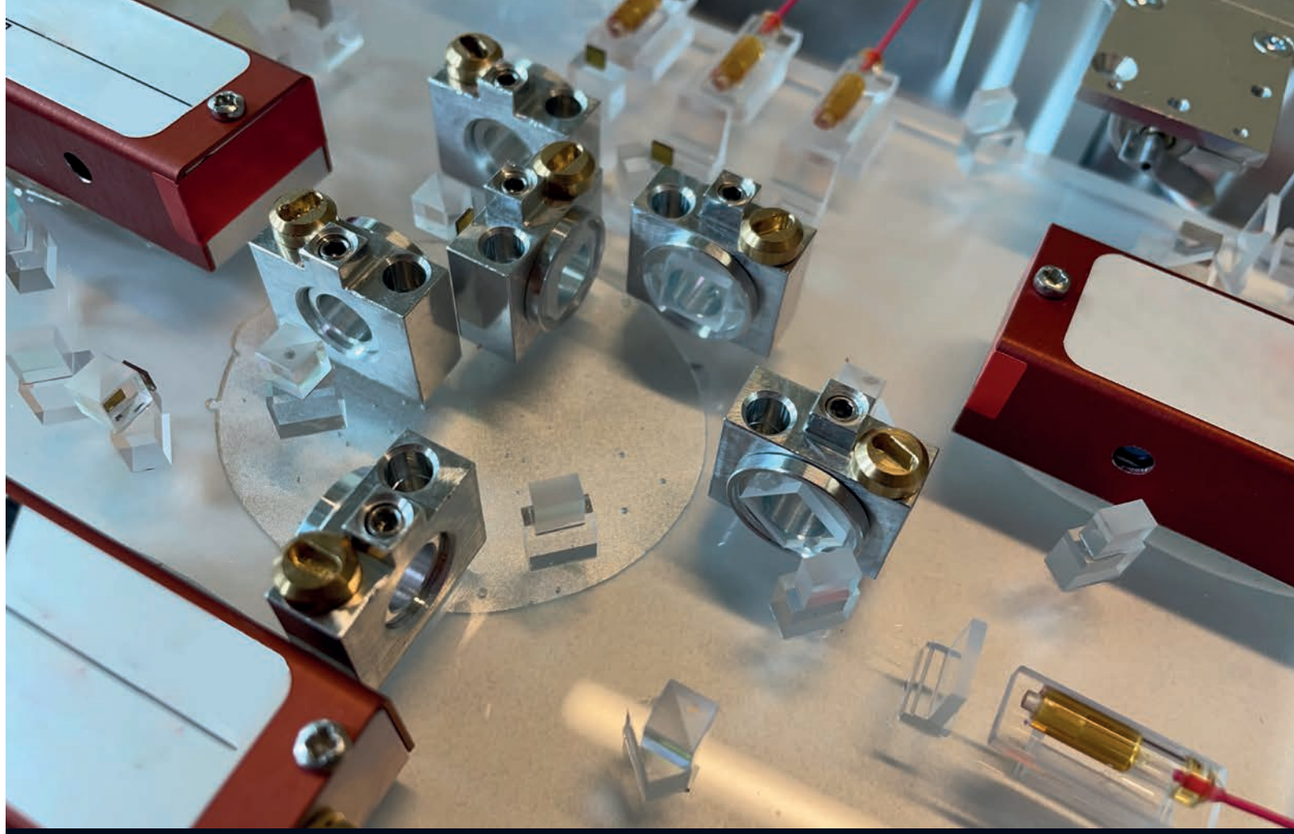
The iMOB series is a new generation of fibered optical benches integrating within a compact and ultra-stable package a wide variety of optical functions such as power splitters, combiners, optical switches, frequency shifters, etc. As a result, free-space optics set-ups are transformed into turn-key ultra-stable integrated sub-systems. Exploiting micro-optics technologies, the optical architecture relies on a classical design based on the utilization of polarizers, manually adjustable wave-plates and polarizing beam splitters (PBS). Thanks to a fully integrated architecture and assembling processes developed for optical fiber telecommunications, these modules feature an exceptional alignment stability over an extended operating temperature range. It also removes any constraint of optical alignment or optics cleaning.

The iMOB benches are produced for iXblue Quantum Sensing division (formerly Muquans), for integration in complex architectures, with multiple lasers beams and multiple parameters. A device is manufactured according to given specifications, in one to tens of samples, and always composed of the 20-30 same building blocks, with an optical fiber in input and output. But the design is always specific. In total, around 200 different types of iMOB have already been produced.

A particular need of the quantum sensing market is addressed by the iMOB: the Polarization Exctintion Ratio (PER). It quantifies the ratio between the expected polarization state and the one which is not expected. 25 to 35 dB are easily reached with iMOB, thanks to the free-space assembling. It can even compensate the polarization defaults related to the matching with fiber optic. ■

"WE KNOW WE CAN COUNT ON THE ABILITY OF IXBLUE TO PERFORM FREE-SPACE DYNAMIC ASSEMBLING TO PROVIDE COMPACT SOLUTIONS FOR OUR FUTURE CHALLENGES."

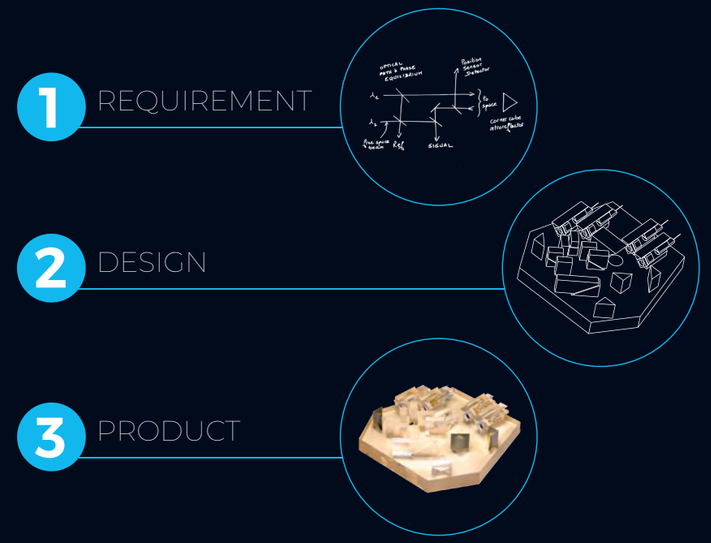
- VINCENT LANTICQ, CTO OF FEBUS OPTICS



iXblue ground-breaking approach to design, develop and integrate optical setups with industry-grade optical building blocks

Starting from customer's specifications (simple drawing or detailed specifications), iXblue develops industrial optical products dedicated to be used as EOM's subsystems. iXblue expertise lies on the ultra-accurate assembly of optical elements on glass breadboards, using 6D positioning. Thanks to its know-how in assembly epoxies, initially developed for the telecom industry, it can provide stable and robust devices, built to be used in extreme environment.

iXblue can lead or be part in all the product development steps: design, prototype assembly and product manufacturing.



LATEST SCIENTIFIC PUBLICATIONS

iXblue 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.

SPACE MODULATORS & TRANSCEIVERS

Laser Communication Technologies for Space Applications
IEEE Photonics Conferences (USA). Special Symposium on Space Photonics – September 2019
Co-presented with Airbus Defence & Space

Assessment of the performance of DPSK and OOK modulations at 25 Gb/s for satellite-based optical communications
IEEE International Conference on Space Optical Systems and Applications (ICSOS), USA – October 2019
Co-presented with Airbus Defence & Space

Optical Fibers and $LiNbO_3$ Modulators for Space Applications
Presented at the Paris Space Week – February 2020

From photonic components to transceivers
Presented at EPIC Meeting on New Space at ESA ESTEC – September 2020

2 µM FIBER LASERS

Gain-controlled Broadband Tuneability in Self-Mode-locked Tm-doped Fibre Laser Through Variable Feedback
Under review
Co-written with Leibniz Institute of Photonic Technology and Novosibirsk State University

Unravelling Saturable Absorption of Tm-doped Fibres for New Level of Integrated Femtosecond Pulse Generation
Under review
Co-written with Leibniz Institute of Photonic Technology

Free-running and imposed-wavelength cavities for high power continuous-wave Tm^{3+}, Ho^{3+} codoped single-oscillator fiber laser
Presented at the Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC 2021) – June 2021
Co-written with French-German research Institute of Saint-Louis (ISL) and CELIA lab (CNRS/CEA/Bordeaux Univ.)

Diffraction limited 195-W continuous wave laser emission at 2.09 µm from a Tm^{3+}, Ho^{3+}-codoped single-oscillator monolithic fiber laser
Optics Express Vol. 29, Issue 5, pp. 6599-6607 (2021)
Co-written with ISL and CELIA lab

Multi-watt broadband wavelength tunable polarization maintaining Tm-doped fiber laser module
SPIE LASE 2021 - Proceedings Vol. 11665, Fiber Lasers XVIII: Technology and Systems; 1166524
Co-written with Cybel LLC (USA) and Ecole Polytechnique Orléans Univ.

High performance +23 dBm miniature PM Ho-doped fiber amplifier at 2100 nm
SPIE LASE 2021 - Proceedings Vol. 11665, Fiber Lasers XVIII: Technology and Systems; 1166529
Co-written with Cybel LLC (USA)

2090 nm 200 W Peak Power 50 ns Pulsed PM Ho-Doped Fiber Amplifier Pumped at 1860 nm
IEEE Journal of Lightwave Technology - Volume: 39 Issue: 15 – August 2021
Co-written with Cybel LLC and Thales TRT

2-µm Narrow Linewidth All-Fiber DFB Fiber Bragg Grating Lasers for Ho- and Tm-Doped Fiber-Amplifier Applications
IEEE Journal of Lightwave Technology - Volume: 39 Issue: 15 – August 2021
Co-written with Cybel LLC and ENSSAT Lannion

2051 nm narrow linewidth all-fibre dfb laser for holmium-doped fibre-amplifier applications
Presented at the 46th European Conference on Optical Communication (ECOC 2020) – December 2020
Co-written with Cybel LLC and ENSSAT Lannion

BLUE/DEEP-UV LASERS BASED ON NOVEL ND-DOPED FIBERS

Efficient pulsed Nd-doped fiber laser at 905 nm and frequency conversion to 452nm and 226nm
SPIE LASE 2021 - Proceedings Vol. 11665, Fiber Lasers XVIII: Technology and Systems; 116651M
Co-written with CIMAP lab (CNRS/CEA/ENSICAEN/Normandie Univ.) and LP2N lab (CNRS/IOGS/Bordeaux Univ.)

RADIATION-HARDENED FIBERS

Recent Advances in Radiation-Hardened Fiber-Optic Amplifiers for Space-based Laser Communications
Presented at the OSA Advanced Photonics Congress 2021, Photonic Networks and Devices – July 2021
Co-written with Hubert Curien Lab. (Saint-Etienne Univ./CNRS/IOGS), CNES and Politecnico di Bari.

Radiation tolerant frequency comb fiber laser for space applications
SPIE OPTO 2022 - Proceedings Vol. 11997, Optical Components and Materials XIX; 119970G
Co-written with Menlo Systems GmbH and Fraunhofer INT

QUANTUM GRAVIMETER

Gravity measurements below 10^{-9} g with a transportable absolute quantum gravimeter
Nature Scientific Reports – Vol 8, Art. 12300 (2018)
Co-written with LP2N, LNE-SYRTE, Montpellier Univ. and Toulouse Univ.

Compact differential gravimeter at the quantum projection-noise limit
Physical Review A – Vol. 105, 022801 (2022)
Co-written with LNE-SYRTE

METROLOGICAL FIBER NETWORK

First industrial-grade coherent fiber link for optical frequency standard dissemination
Applied Optics - Vol. 57, Issue 25, pp. 7203-7210 (2018)
Co-written with LPL, LNE-SYRTE, LP2N, RENATER and Syrlinks

COMPACT AND AUTONOMOUS FIBER LASER SYSTEM

A fibered laser system for the MIGA large scale atom interferometer
Nature Scientific Reports – Vol. 10, Art. 3268 (2020)
Co-written with LP2N, LNE-SYRTE and Univ. di Bologna

A french consortium (led by CNES) is in charge of assembly-integration and ground tests of the payload of the LISA space mission (Laser Interferometer Space Antenna). This activity uses - among other features - an iodine frequency-stabilized telecom laser (1596.7 nm), after a frequency tripling process, both of them being developed jointly by SYRTE lab and iXblue:

Toward industrial and fibered non-linear sum frequency generation devices
Presented at the CLEO EUROPE – June 2021

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