IPC – Technology Harmonisation Advisory Group (THAG)
European Space Technology Harmonisation Dossier

PHOTONICS

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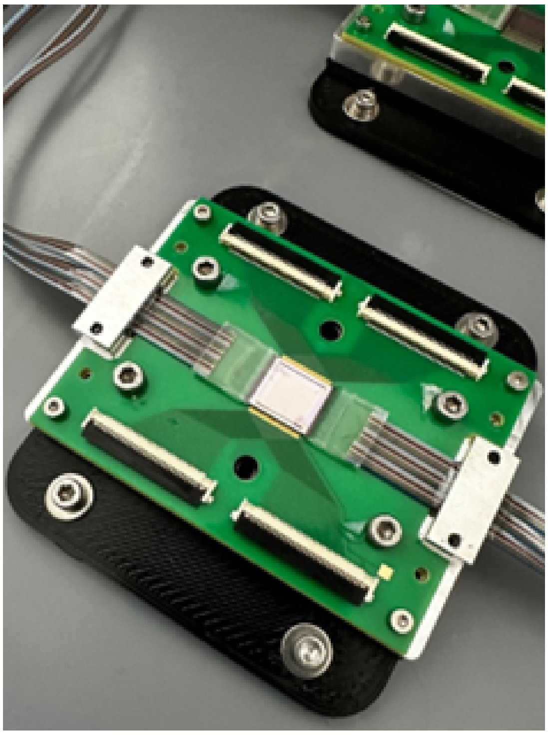

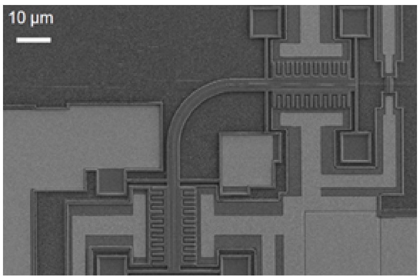

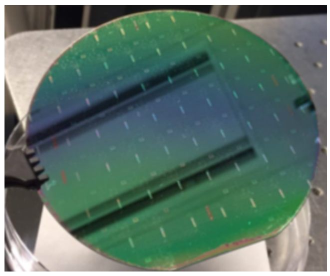

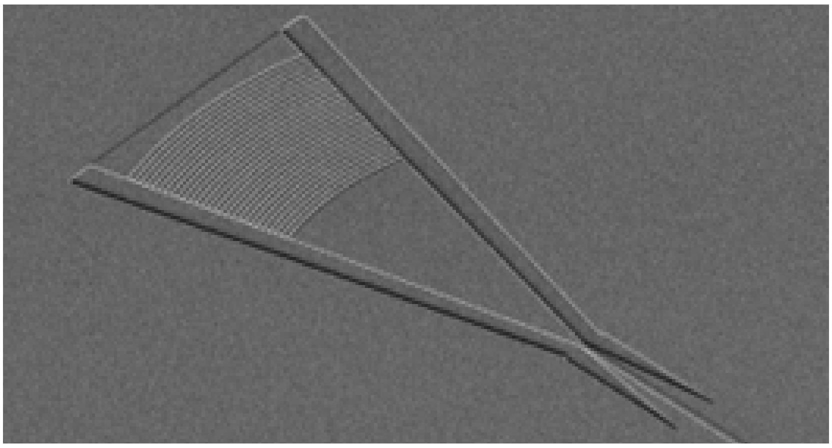

PHOTOMIX Project (EPFL, Switzerland)

IPC

TECHNOLOGY HARMONISATION ADVISORY GROUP

EUROPEAN SPACE TECHNOLOGY HARMONISATION

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PHOTONICS

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1 EXECUTIVE SUMMARY

Photonics is a very broad field which involves the generation, detection, and manipulation of light. This topic covers aspects of waveguided optics, in particular fibre optics and integrated optics for space applications, as well as wireless optics for intra-satellite links. Fiber optics have intrinsic characteristics that make them a prime technology candidate for compact systems such as spacecraft payloads: they are dielectric, low loss, low mass, low volume, mechanically flexible, and offer galvanic isolation and electromagnetic compatibility advantages in terms of emissivity and susceptibility. As such, they are used as building blocks in many satellite subsystems. At component level photonics can be found in lasers for digital and analogue transmission, frequency combs, modulators, photodiodes for digital and analogue communications, opto-couplers, and passives. At equipment level photonic technologies are used, for example, in frequency generation units and converters, routers, RF filters, beam forming networks, fibre sensing and opto-pyrotechnics.

Since 2000 ESA has established a comprehensive programme to investigate the application of Photonics in the space domain, and to develop appropriate technologies. The spectrum of applications spans all types of satellite payloads and platforms, as well as launchers. Regarding payloads, developments have been mainly driven by requirements of digital payloads for high-throughput telecommunication satellites, that have seen a move from copper to fiber optic interconnects. Next generation payloads are under development with data rates at 28 Gbps. The need to reduce energy consumption per bit is pushing the technology to data rates of 56-112 Gbps, and to the adoption of the Near-Packaged Optics (NPO) and Co-Packaged Optics (CPO) with the functional ASIC/FPGAs. In the case of Earth Observation and Science payloads, these are normally investigated on a case-by-case basis.

Regarding launchers, opto-pyrotechnics may enhance mission safety. Opto-pyrotechnics are baselined for use in Ariane 6, making this the first launcher to use fiber optic based pyrotechnic technology for critical functions such as ignition, separation, passivation and neutralisation. The technology is at the moment at industrialisation phase with key building blocks under qualification for the maiden flight. Fiber sensors are also considered for health monitoring for both launchers and spacecraft, encompassing environments from cryogenics to high-temperature re-entry. Fiber Optic Gyroscopes are the only type of fiber optic sensors which has achieved commercial success, with now over 20 years of flight heritage. For ground applications, Photonics are currently investigated for use in Beam Forming Networks in mobile ground terminals or airplanes, and Optical Wireless technologies are investigated for support in AIT activities.

While most of the current applications mainly make use of fiber optics and discrete photonic devices, new applications such as frequency converters or beam forming networks will require a shift to microphotonic integration in the form of Photonic Integrated Circuits (PICs). This is seen as a disruptive technology that will contribute to lower mass, volume, and power consumption, and enable closer integration with control and sensing electronics. Key challenges for integrated photonics are the reduction of optical coupling losses, and the development of several building blocks that remain unavailable, such as isolators and power amplification beyond 100mW.

Europe has a predominant role on Photonics thanks to the pivotal role of ESA in this domain since 2000. Currently, European and Canadian companies are the preferred suppliers of Photonic solutions (end-to-end links and equipment) for digital and analog communication satellite payloads, and are at the forefront to becoming the preferred suppliers for Science payloads as well as on-board data handling and fibre optic structural and thermal monitoring systems. At present, 3 Photonic technologies have been adopted by the commercial space market as standard recurrent products: Fiber Optic Gyroscope (for satellite buses), Fiber Optic Digital Interconnects (for satellite communication digital payloads), and Opto-pyrotechnics (considered for Ariane 6 launcher). The main competitors are located mostly in the US and a few in Japan.

To sustain the leadership and to ensure the sovereignty of Europe in the Photonics domain, the supplier eco-system at component level needs to be sustained. To support this, the Photonics Harmonisation topic also provides a link to activities of the Photonics Components Working Group, including efforts to introduce new standards and best practices for successful introduction of photonics technologies in future payloads and platforms.

The overall goal of the new Photonics Roadmap is to expand the applications of Photonics beyond the existing commercial products. The proposed Roadmap for the next 3 years targets the following 7 Aims:

- **Aim A:** Satellite communication payloads – photonically linked.
- **Aim B:** Satellite communication payloads – microwave photonic equipment (MRO/LO generators, frequency converters, switches, RF filters, beam formers).
- **Aim C:** Scientific payloads (adapt photonic digital and analog links of satellite communication to science payloads, use of microphotonics for science instrumentation).
- **Aim D:** Platforms (space qualified SpaceFiber, stable fiber optic sensors).
- **Aim E:** Launchers (opto-pyro for Ariane and Vega, fiber optic sensors for health monitoring, links for OBDH).
- **Aim F:** Ground segment and aeronautics (optical wireless in AIT, microphotonic beam-forming networks for airplanes).
- **Aim G:** Special measures for photonic integrated circuits and packaging.

The Roadmap requests a budget of 27.9 M€ for 30 new activities that should start within the next 3 years. Out of this total, about 46 % (13.5 M€) is requested for 10 activities deemed to have high criticality.

2 INTRODUCTION

2.1 Document evolution

This document is the Technology Harmonisation Dossier of *Photonics* addressed by Harmonisation in *the 2nd Cycle 2023.* This Technology Harmonisation Dossier is issue number 2 and represents the 2nd visit to this technology subject for Harmonisation.

This document is produced incrementally through the Harmonisation process. The revisions of the document will follow the lifecycle as explained below and summarised in Table 2-1.

Revision Index:

Revision 0	First release of the document. The document is issued for the preparation of the Mapping Meeting. The chapter 8 ***Roadmap*** contains only an indication of proposed future developments.
Revision 1	Released for the preparation of the Roadmap Meeting. The document is revised, taking into account the outcome of the Mapping Meeting. Intermediate draft versions, if needed, shall be named Draft A, Draft B etc. as appropriate.
Revision 2 Draft A, B…	A Draft revision 2 document, called Draft A is released after the Roadmap Meeting. If the Dossier is subject to iterations with THAG, the Drafts shall be named Draft B, Draft C, etc. as appropriate. The chapter ***Roadmap*** is added, reflecting the comments received from Industry and from the THAG at the relevant Meetings dedicated to the Roadmap. The ***Executive Summary*** and ***Conclusions*** are added to the document. After endorsement by IPC-THAG, the Executive Summary and the Conclusions are presented to IPC for endorsement.
Revision 2	Official release after the IPC endorsement of the proposed Roadmap.

Table 2-1: Technology Harmonisation Dossier Lifecycle.

Contents of the Technology Harmonisation Dossier	Rev. 0	Rev. 1	Rev. 2 Draft	Rev. 2 Final
1. Executive Summary				●
2. Introduction	●	●	●	●
3. Harmonisation process and THAG	●	●	●	●
4. Technology status overview	●	●	●	●
5. Mission needs and market perspectives	●	●	●	●
6. Implementation of previous activities	●	●	●	●
7. Summary of the Mapping Meeting		●	●	●
8. Roadmap	§ 8.1	●	●	●
9. Conclusions				●

2.2 Acronym List

ADHA	Advanced Data Handing Architecture
ADK	Assembly Design Kit
AIT	Assembly Integration and Test
AOCS	Attitude and Orbit Control System
ARTA	Ariane-5 Research and Technology Accompaniment program
ARTES	ESA's Telecom Funding Program
ARTES AT	Advanced Technology Funding Program in ARTES
ARTES-C&G	Competitiveness and Growth Funding Program in ARTES
ASIC	Application Specific Integrated Circuit
AWG	Arrayed Waveguide Grating
BFN	Beam Forming Network
CFRP	Composite Fiber Reinforced Plastic
CNES	Centre National d' Etudes Spatiales - French Space Agency
COMSAT	Communication Satellites
COTS	Commercial of The Shelf
CW	Continuous Wave
DAS	Distributed Acoustic Sensing

DEMUX	De-Multiplexer
DFB	Distributed Feedback Laser Diode
DGA	French Government Defence Procurement and Technology Agency
DLR	Deutschen Zentrums für Luft- und Raumfahrt - German Aerospace Centre
DSBSC	Double Side-Band Suppressed Carrier
DTS	Distributed Temperature Sensing
DWDM	Dense Wavelength Division Multiplexing
EAM	Electro-Absorption Modulator
ECM	Entity Capability Mapping
EDFA	Erbium Doped Fiber Amplifier
EOM	Electro-Optical Modulator
EPFC	Electro-photonic Frequency Converter
Er	Erbium
ESA	European Space Agency
ESCC	European Space Component Coordination
FBG	Fiber Bragg Grating
FC	Frequency Converter
FGU	Frequency Generation Unit
FIT	Failure in Time
FLPP	Future Launcher Preparatory Program
FP	Fabry–Pérot
FTB	Fused Biconical Taper
Gbps	Giga bits per second
HDMS	Harmonisation Document Management System
HTS	Harmonisation Tracking System
ICSO	International Conference on Space Optics
IoD	In-orbit Demonstration
IPC	Industrial Policy Committee

ISRF	Instrument Spectral Response Function
ISS	International Space Station
ITAR	International Traffic in Arms Regulation
LIDAR	Light Detection and Ranging
LIOS	Laser Initiated Ordinance System
LO	Local Oscillator
MLL	Mode Locked Laser
MRO	Master Reference Oscillator
MUX	Multiplexer
MZI	Mach-Zehnder Interferometer
ND	Non disclosed
OSB	Optical Safety Barrier
OW	Optical Wireless
P/L	Payload
PDK	Process Design Kit
PIN	Photodiode with an intrinsic layer in the p-n junction.
PLC	Planar Lightwave Circuit
PWG	Photonics Working Group
QKD	Quantum Key Distribution
RD	Reference Document
RF	Radio Frequency
RIN	Relative Intensity Noise
RM	Roadmap
ROM	Rough Order of Magnitude
ROSA	Receiver Optical Sub-Assembly
ROTEX	Rocket Technology Experiment
RTU	Remote Terminal Unit
RX	Receiver

S/C	Spacecraft
SEFI	Single Event Functional Interrupt
SET	Single Event Transient
SMOS	Soil Moisture Ocean Salinity (ESA satellite)
SOA	Semiconductor Optical Amplifier
TAS-F	Thales Alenia Space - France
THD	Technology Harmonisation Dossier
THAG	Technology Harmonisation Advisory Group
TID	Total Ionising Dose
TOSA	Transmitter Optical Sub-Assembly
TRL	Technology Readiness Level
TRP	Technology Research Program
TRT	Technology Readiness Target
TX	Transmitter
VCSEL	Vertical Cavity Surface Emitting Laser
VHTS	Very High Throughput Satellites
WDM	Wavelength Division Multiplexing
Yb	Ytterbium

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3 HARMONISATION PROCESS AND THAG

The process of harmonising and elaborating a future strategy for European space technology was initiated in 2000 in response to the adoption of a Resolution titled “Shaping the Future of Europe in Space” adopted at the ESA Ministerial Council in May 1999. The Technology Harmonisation initiative has subsequently been developed to achieve better-coordinated research and development (R&D) activities among all actors of European space sector and to establish a strong technology base as a key to the worldwide competitiveness of European Industry and to the success of future space missions. It involves establishing a harmonised European Space Technology Roadmap and preparing a European Space Technology Master Plan, through a process of concertation, coordination, harmonisation and agreement between ESA’s member states, the European Commission, European Industry and ESA itself.

The main objectives of the Technology Harmonisation initiative are to:

- “Fill strategic gaps” and “Minimise unnecessary duplications”
- Consolidate European Strategic capabilities
- Achieve a coordinated and committed European Space Technology Policy
- Contribute to continuity and coherence between Technology and Industrial Policies.

It is a voluntary and transparent ESA-led process, based on the principle of shared information, consultation and coordination between participants. The continuous support from all participants (ESA directorates, national delegations, research institutions and industry) is therefore a necessity. Moreover, its success relies heavily on stakeholders’ openness to exchange information on results of on-going developments and on future plans on their interest and willingness to discuss and agree on a common and concerted approach and on their readiness to follow the agreed recommendations and Roadmaps.

The Technology Harmonisation Advisory Group (THAG) is an ESA delegate body, setup in 2006 to advise the ESA Industrial Policy Committee (IPC) on Technology Harmonisation matters. It is composed of a maximum of two delegates for each ESA Member State and Canada, who may be accompanied by experts for some specific issues. The THAG may advise the IPC, at its request, on technology related matters, such as technology strategy, technology plans, technology non-dependence and worldwide technology watch. The THAG is part of the Harmonisation process and participates in producing the Harmonisation documents, including this document.

The purpose of this Technology Harmonisation Dossier is to present, at the end of the Harmonisation process, a consensus on:

- The picture of the Technology as it currently is (Mapping):
  - A description of the topic state of the art, why it has been selected for Harmonisation and which is the exact scope of the Harmonisation
  - The list of main European players and their products
  - The main players outside of Europe and a comparison between European products and non- European ones

    - The mission needs, market perspective, technology trends and possibility of spin-in/spin-out
- A proposed way to advance the Technology at European level (Roadmap)
    - The Roadmap itself, which presents on-going and future activities, based upon data received during the Mapping Meeting, including:
        - Description of the activity (e.g. beginning and end TRL, contribution to Non-Dependence, Building Block)
        - Status (running, funded but not running, new proposal)
        - Planned budget and schedule
        - Priorities (for new proposal only)
        - Best Fit possible ESA or National programmes for new proposals or actual programme (ESA or not) in other cases
        - Link between proposed activities and technology requirements
    - A summary of the budget requested in the Roadmap in various breakdown (e.g. time wise, per priority, per program)
- A summary of the main points and issues raised during the Harmonisation cycle.

It is important to take note that the roadmap agreed through the Harmonisation process is a recommendation which is used as one input when preparing ESA and National work plans but does not constitute a work plan by itself. It does not guarantee that the recommended budget will be available nor that proposed activities will be started in the program they are proposed or even at all. Its purpose is to present the consensus on the best way forward as can be foreseen when the Harmonisation cycle is run; it is not binding on either ESA or National Delegations. However, these recommendations are endorsed by ESA Industrial Policy Committee (IPC) when it endorses the Conclusions document (which covers all the topics in a given year).

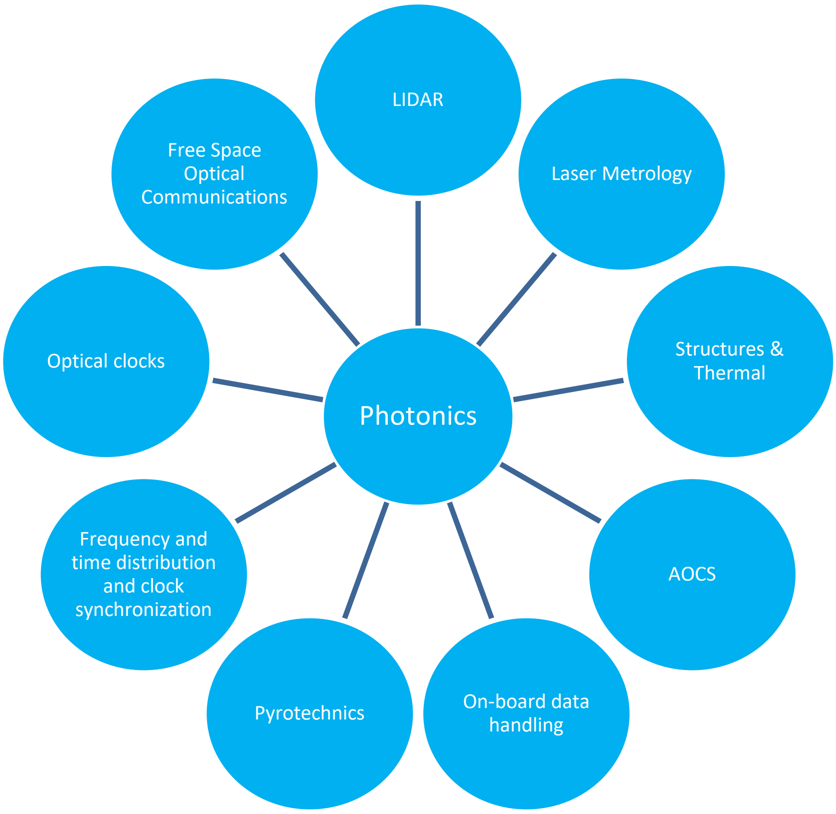
This document, as well as all Harmonisation documentation (for all cycles), is available on the Harmonisation Document Management System (https://tec-polaris.esa.int/eclipse/i-layout!view.action).

More details on this process can be requested by sending an email to harmo@esa.int.

4 TECHNOLOGY STATUS OVERVIEW

4.1 Technology Description

‘Photonics’ is a general term that covers a very broad field which includes the **generation**, **detection** and **manipulation** of **light**. This technology topic shall be restricted to cover only waveguided optics, in particular fiber optics and planar waveguides with the only exception to this being Optical Wireless for intra-S/C communications. Since these generic photonic building blocks are common to a number of different fields, the harmonisation field will further restrict itself to cover at system level only photonic applications that have not been already harmonised in other topics, such as *LIDAR Critical Subsystems*, *Optical Communications from Space*, and *Frequency and Time Generation and Distribution* Dossiers. The focus of this topic shall therefore be on the use of fiber optics and microphotonics (i.e Photonic Integrated Circuits) in spacecraft payloads and platforms, and launchers.



Fiber optics is a new technology in Spacecraft Engineering. The incorporation of fiber optic links in the ISS since 2000 and the dual launch of SMOS (carrying over 700m optical communication links for its payload, the biggest in the world at the time) and PROBA II (carrying the first fibre optic sensor subsystem in the world) in November 2009 were the first demonstrations of the technology [RD-SMOS, RD-PROBA].

The starting point for the **commercial use** of Photonics **as a standard recurrent product** in Space Missions can be traced in the adoption of the ASTRIX Fibre Optic Gyroscope as a standard equipment in **S/C Platforms** [RD-GYRO]. For Satellite Platforms, fibre optics are under investigation for use as the thermal monitoring subsystem and structural management through the measurement of stresses and strains. PROBA 2 has successfully demonstrated thermal and pressure monitoring system for satellites over more than 10 years of operational life in orbit. On the communication cabling linking the various instruments to the On Board Processor or Mass Memory the “Space-Fiber” has been established and it is now going through ECSS standardisation. As required data rates continue to increase, the fiber-based “Space-Fibre” is expected to eventually become the preferred standard and medium for the communications links.

In **Payloads**, the developments were driven mainly by the requirements of the Digital Payloads for High Throughput Telecommunication Satellites; photonic technologies have emerged as an enabling technology. The launch of SES-17 in October 2021 represents a turning point in the adoption of the technology since the Digital Payload of this satellite relies on hundreds of fiber optic interconnects running at 11.5 Gbps [RD-SES-17]. This represents a significant technology inflection point as we move from copper interconnections to optical ones in telecom digital payloads. Next generation payloads are already under development with data rates at 28 Gbps, and the need to reduce energy consumption per bit of these payloads is pushing the technology to 56 Gbps (and even to 112 Gbps) and the adoption of the Near-Packaged Optics (NPO) and Co-Packaged Optics (CPO) with the functional ASIC/FPGAs. The developments on “Digital Photonics” are followed by investigations in applications of “Analog Photonics” conveying microwave signals up to Q/V and even W- and D-band. This refers primarily to linking the Phased Array Antenna to the Digital Processor by fiber optic links. Furthermore, it refers to functions like frequency generation and distribution, frequency conversion, RF filtering, and RF signal beamforming.

In **Earth or Space Science mission Payloads**, Photonics are investigated on a case by case and have been adopted in the JUICE mission’s scalar magnetometer launched in April 2023 [RD-JUICE]. The JUICE scalar magnetometer (MAGSCA) objective is to characterise the Jovian magnetic field, its interaction with the internal magnetic field of Ganymede, and to study the subsurface oceans of Ganymede, Callisto, and Europa. MAGSCA uses rubidium atoms laser-excited into a decoupled dark state to measure the scalar magnetic field. The critical photonic components include: VCSEL source, PIN photodiodes and a fibre optic harness to transmit the modulated laser signal to the gas cell located at the end of a 10m long boom. The challenge of qualification of this payload was characterised by a very challenging thermal and radiation environment which included the combination of cold thermal environment and very high total ionising dose and high radiation dose rate.

In 2013, ESA selected ‘The Gravitational Universe’ as the theme for the third large-class mission, L3, to be developed under ESA’s Cosmic Vision science planning cycle, with launch scheduled for the early 2030s. On 20 June 2017, ESA’s Science Programme Committee chose LISA as the L3 mission. LISA has since entered a more detailed phase of study and will be proposed for ‘adoption’ early 2024 before the implementation phase begins. Today ESA is engaged in assessing the reliability of COTS photonic components baselined for use in the LISA laser system together with Tyndall National Institute (IE) and LusoSpace (PT). Currently the focus is on the constructional analysis of a range of photonic components (pump laser diodes, EOMs, photodiodes, switches, couplers, combiners, mode strippers, optical isolators). In addition, some specific de-risk testing will be carried out. The lack of a high-power optical switch with technical specifications matching the application has led to the development of a custom device.

The European Commission is preparing a Quantum Space Gravimetry (QSG) pathfinder mission for space gravimetry to be launched by 2030. In preparation for the mission, in 2022 the European Commission has funded via the Horizon Europe programme the space project CARIOQA-PMP (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry – Pathfinder Mission Preparation). The project led by CNES is working on enhancing the TRL of critical components, such as the physics package, Bose Einstein condensate (BEC) generation and rotation compensation systems. The quantum accelerometer core comprises of a complex laser system based on cold rubidium atom interferometry.

In **Launchers**, opto-pyrotechnics have been baselined for use in ARIANE-6 leading to the first application of this kind [RD-OPTOPYRO]. Fiber Sensors are also considered for health monitoring which can be very important especially in reusable launch vehicles for applications in structural health monitoring. In such a case the optical fibers are embedded in the composite structure parts of the launcher. Communication links in launchers may be served by the Space-Fibre standard especially due to the long link lengths involved. ESA together with industrial partners (DLR, SAL (AT) and APP Ariane Group (NL)) have been studying the use of laser ignition as a means of igniting cryogenic stages. Weight reduction considerations and redundancy considerations have led to an increased interest in laser igniter technologies to replace the conventional pyrotechnical or spark plug igniters in use today. This technology is particularly interesting due to the need for re-ignition that will be required of the upper stage Vinci engine [RD-LASER IGNITION].

Lastly, looking at applications on **Ground** such as the Assembly Integration and Testing (AIT) facilities or at applications in ground satellite terminals it has to be highlighted that Photonics are currently investigated for use as the “photonic core” in Beam Forming Networks in mobile ground terminals or airplanes. Similarly Optical Wireless technologies are investigated for supporting AIT activities within satellite integration facilities.

While most of these applications make use mainly of fiber optics and **discrete photonic devices**, ESA has also initiated a consistent programme of activities to shift the technology towards “**Microphotonic integration**” in the form of Photonic Integrated Circuits (PICs) as a disruptive technology. It is expected that several functions will be implemented by such microphotonic technologies that will contribute to the lower mass, volume, power consumption and the closer integration with control and sense electronics.

With the introduction of photonics at system and equipment level there is a need to constantly support the eco-system at component level to ensure European sovereignty in this domain. This topic provides an overview of basic building blocks at component level and provides the link to the activities of the Photonics Components Working Group and the efforts to introduce new standards and best practice to ensure the successful introduction of photonics into future payloads and platforms.

4.2 Technology Background

Photonic technologies covering both fiber and integrated optics have been a rapidly evolving field with immense impact on the global economy. Extremely low loss optical fibers form the neural network of current telecommunication infrastructure proliferating rapidly from the backbone network to the access network. Modern telecommunications and the internet would simply not have been possible without optical fibers and integrated optics.

Being dielectric, low loss, low mass, low volume, mechanically flexible and offering galvanic isolation and EMC advantages in terms of both emissivity and susceptibility, fiber optics are a prime candidate technology for a minimalistic system like a spacecraft payload. From this point of view it was natural that as soon as fiber optics established themselves as a technology for ground telecommunications, an investigation for possible applications on board satellites was initiated. Fiber optics were baselined and built for the International Space Station and a thorough investigation of applications in COMSATs P/Ls was performed by labs in both Europe and the USA. By the mid 1990's almost all the applications had been investigated covering simple analog and digital links as well as the standard functions of a COMSAT P/L: frequency generation, frequency conversion, switching, beam forming, photonic RF filtering [RD-PAUL, RD -BAISTER]. The use of integrated optics to perform several of these functions was critical. It was then mainly a question of maturing the technologies and giving flight opportunities for the Photonic technologies to be adopted by S/C and P/L engineers.

Since 2000 ESA established a comprehensive programme to investigate the applicability of Photonics in spacecraft engineering and in turn to develop the appropriate technologies [RD-ESA-TRP]. The spectrum of applications spanned all types of satellite payloads and platforms as well as launchers. The programme of activities was supported by a significant amount of funding, it is on-going, and uses each flight opportunity to demonstrate the technology. In parallel to this, ESA together with CNES and industrial partners Airbus and Exail (formerly iXblue) have taken Fibre Optic Gyro (FOG) technology and qualified it for space flight, ensuring European sovereignty over this critical technology. Airbus and Exail have developed a family of FOGs that have been essential in ensuring the success of a large number of European satellite missions covering Telecom, Science and Earth Observation missions [see Figure 4-2, RD-FOG-ASTRIX]. ESA has now accumulated well over 2 decades of inflight experience which continues to improve our understanding of the various photonic elements that are integral parts of the FOG equipment and supports the push of photonic technologies into further satellite applications.

Figure 4-2: Astrix 200 FOG from Exail.

The first satellite to extensively use fiber optics for its main P/L was ESA's SMOS satellite launched in November 2009 (optical harness was integrated by ADS Spain, see Figure 4-3). Within the same launch ESA's PROBA II technology demonstration satellite carried the first fiber optic sensor system, instrumenting the S/C's propulsion subsystem. Both operated flawlessly for over 9 years demonstrating the usefulness and robustness of the technology and serve as a baseline example for more advanced use of photonics in the S/C and P/L.

In parallel, and as the data capacity handling requirements of modern COMSAT P/Ls has increased, it was clear that fiber optics will need to be employed to overcome the interconnect bottleneck. Hence in 2016 TAS was the first Prime to baseline fiber optics for its DTP-5 P/L with its maiden space flight eventually launched in October 2021 on board the SES-17 satellite. Fiber optics are now expected to be the baseline technology for all COMSAT Digital P/Ls in the future with the required data rate per link to increase from 11.5 Gbps to 28 Gbps, to 56 Gbps to 112 Gbps.

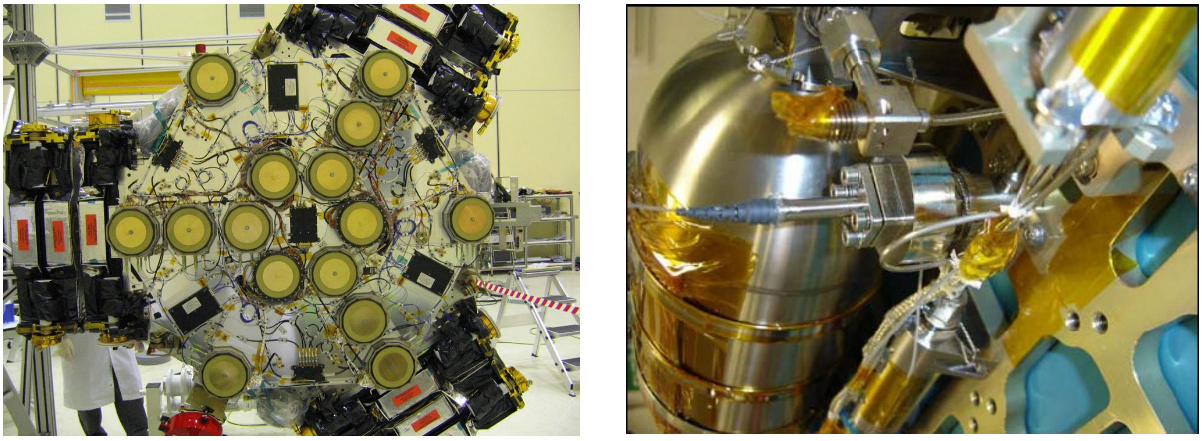


Figure 4-3: SMOS and PROBA II were launched together in a dual launch in November 2009.

Europe has a predominant role on Photonics due to the pivotal role of the comprehensive programme of work initiated by ESA since 2000 and supported by the various national delegations. Currently European/Canadian companies are the preferred suppliers of "Photonic Solutions" (end-to-end links and/or equipment) for Digital and Analog COMSAT P/Ls and are in the forefront, becoming the preferred suppliers for links for Scientific P/Ls as well as of links for S/C OBDH and fibre optic structural and thermal monitoring systems. They are supported by a group of European/Canadian companies that are suppliers of photonic component necessary to compose the various links and equipment. At present, 3 Photonic technologies have been adopted by the commercial space market as standard recurrent products:

- Fiber Optic Gyroscope (for satellite buses)
- Fiber Optic Digital Interconnects (for COMSAT Digital PLs)
- Opto-pyrotechnics (considered for ARIANE 6 launcher)

Over the next 3-5 years covered by this Roadmap the target is to expand the applicability of Photonics beyond the above 3 products, developing the photonic components and equipment to TRL-8 by using all possible funding avenues and where possible to TRL-9 with In Orbit Demonstrations.

4.3 Areas Covered by this Dossier

This technology topic covers all aspects of waveguided optics including fiber and integrated optics. It also includes all the applications of photonics for both payloads and platforms. This topic does not cover the hybrid devices and equipment used in Laser Communication Terminals, LIDARs, RF & Optical Metrology, QKD and Optical Clocks which are covered in other harmonisation topics. While not covering the previously mentioned areas at equipment/system level, the following technical dossiers:

- **AOCS Sensors and Actuators** (Optical Gyro Technology). Last harmonised in 2020 Cycle 1.
- **LIDAR Critical Subsystems**. Last harmonised in 2022 Cycle 1.
- **Micro and Nano Technologies** (focused mainly on MOEMS – optical switch, optical attenuators). Last harmonised in 2020 Cycle 1.
- **Optical Communications for Space** (QKD, Optical Terminals). Last harmonised in 2022 Cycle 2.
- **Pyrotechnic Devices** (Opto-pyro for launchers). Last harmonised in 2020 Cycle 2.
- Frequency and Time Generation and Distribution Space and Ground. Harmonised in 2023 Cycle 2.
- **On-Board Computers, Data Handling Systems and Microelectronics** (Space-Fiber). Last harmonised in 2021 Cycle 1.
- **Array antennas and Periodic Structures**. Last harmonised in 2022 Cycle 1.
- **PCB and Electronic Assembly Technologies**. Last harmonised in 2022 Cycle 1. Contains Photonic PCB.
- **Actuator Building Blocks for Mechanisms** (covering encoders). Last harmonised in 2021 Cycle 2.

The one exception to the waveguided definition of the technology is the application of optical wireless. Optical wireless by definition is not a guided solution but has been included in this photonics topic as it relates to intra-satellite optical communications which are fully covered by the present Photonic topic.

The areas to be covered are presented in terms of **Technology building blocks** while the Roadmap to future activities is structured in terms of **Applications.**

With reference to the ESA Technology Tree 4.1 (LINK), this topic covers the following domains.

Table 4-1 Technology Tree domains covered by the topic.

Technology Domain		Technology Sub-Domain		Technology-Group		Coverage (Partial/Total)	Comments
ID	**Name**	**ID**	**Name**	**ID**	**Name**		
1	Onboard Data Subsystems	A	Payload Data Processing	II	Hardware Technologies for Payload Data Processing	Partial	Only the Photonic part
1	Onboard Data Subsystems	B	Onboard Data Management	IV	On-board Networks and Control/Monitoring	Partial	Only the Photonic part
1	Onboard Data Subsystems	C	Microelectronics for Digital and Analogue Applications	II	Digital and Analogue Devices and Technologies	Partial	Only the Photonic part
4	Space Systems Environments and Effects	A	Space Environments	II	In-flight Environments Monitoring	Partial	Personal Dosimeter flown on ISS
6	RF Subsystems, Payloads and Technologies	D	RF Payloads	II	Telecommunication Payloads	Partial	Only the Photonic part
6	RF Subsystems, Payloads and Technologies	D	RF Payloads	III	Remote Sensing Instruments	Partial	Only the Photonic part
7	Electromagnetic Technologies and Techniques	A	Antennas	III	Array Antennas and Standalone Radiators	Partial	Only the Photonic part
15	Mechanisms	H	Pyrotechnic Technologies	IV	Optical Ignition Technologies	Total	Opto-pyrotechnics for launchers
16	Optics	B	Optical Components Technology and Materials	II	Micro-Optics Components, MOEMS, Optical Fibres and Passive Integrated Optics	Partial	
16	Optics	C	Optical Equipment and Instrument Technology	I	Spectrometers, Imaging Spectrometers, Radiometers	Partial	
17	Optoelectronics	C	Photonics	I	RF Photonics	Total	
17	Optoelectronics	C	Photonics	II	Micro- & Nano-Photonics	Total	

Technology Domain		Technology Sub-Domain		Technology-Group		Coverage (Partial/Total)	Comments
17	Optoelectronics	C	Photonics	III	Fibre-Optic Sensors	Total	
17	Optoelectronics	E	Quantum Technologies	II	Quantum Communication	Partial	
17	Optoelectronics	E	Quantum Technologies	III	Quantum Information Processing and Simulations	Partial	
19	Propulsion	A	Chemical Propulsion Technologies	I	Liquid Propulsion Subsystems	Partial	Only the Photonic part
19	Propulsion	B	Electric Propulsion Technologies	I	Electrostatic Propulsion Subsystems	Partial	Only the Photonic part
20	Structures	F	Damage Tolerance and Health Monitoring	II	Structural Health Monitoring Sensor Technologies	Partial	Only the Photonic part
20	Structures	G	Launchers, Reentry Vehicles, Planetary Vehicles	I	Technologies for Design and Verification of Advanced Primary Structures	Partial	Only the Photonic part
20	Structures	G	Launchers, Re-entry Vehicles, Planetary Vehicles	II	Advanced Tank Design and Verification Technologies	Partial	Only the Photonic part
21	Thermal	C	Thermal Protection	II	Reusable Subsystems	Partial	No sub-domain dedicated to sensors, applicable across multiple sub domains
23	EEE Components and Quality	B	EEE Component Technologies	IV	Optoelectronic Active and Passive Components	Total	
23	EEE Components and Quality	B	EEE Component Technologies	V	Hybrids and Micropackaging	Partial	

Within ESA, this technology falls within Competence Domain 1 (EEE Components, Photonic, MEMS), as indicated in the Harmonisation Workplan 2023 document (ESA/IPC(2022)87).

4.4 Rationale for Harmonisation of the Technology

As the commercial space market for Photonic technologies is now emerging and Europe is the pioneer in supplying Photonic solutions for satellites, it is important that the efforts of various entities and nations are harmonised in order to:

- Ensure the best possible utilisation of funding resources;
- Promote the best coordination of efforts among companies aiming to become suppliers of photonics for space;
- Enabling the development and protecting the European supply chain of critical components and elements on which future photonic payloads will rely to ensure the competitiveness of European space industry on the world stage;
- Stimulating appropriate research and developments enabling spin in from terrestrial applications;
- Fostering the synergies between our European funding partners such as EC and national bodies to enable developments to be transferred seamlessly across our space programmes;
- Support the spin-in of terrestrial applications identifying where and how COTS products can be used;
- Enabling early adoption of the technologies developed in Europe by supporting IODs;
- Providing support to the European space industry to keep pace with the fast evolving photonic technologies;
- Enabling Europe to take advantage of new opportunities provided by photonics;
- Ensure that the key issues are identified in order to establish the right technology developments in the right time frame;
- Provide an overview of European photonic capabilities, strategy and supporting resources to help direct industry and support the introduction and evolution of photonics into spacecraft applications.

This is the second time that such an effort takes place following the release of the first edition of the THD on Photonics in 2018 following a year of deliberations.

As a conclusion of this harmonisation effort will be a comprehensive roadmap where funding agencies will know the fields to be funded and potential suppliers will have a clear understanding of this upcoming market.

International Conference on Space Optics (ICSO)

A main resource that provides information on the various developments on Photonic Technologies and Equipment for Space is the ESA/CNES International Conference on Space Optics, held biannually since 1991 [RD-ICSO]. Since its 2006 edition there has been systematically a stream of sessions on Photonics where almost all the work undertaken in Europe and Canada is presented. ICSO is perceived by the Photonics community as the biannual meeting point for reporting all advancements in the field of Space Photonics and in general of Space Optics.

Photonics Components Working Group

The **Photonics Working Group** (PWG) is a subsidiary of the Components Technology Board (CTB) and is supported by Space Agencies and industry [RD-CTB]. The Group is responsible for overviewing at component level the availability of critical elements covering all space applications (Optical Communications, LIDAR, metrology, sensing). The main purpose of this working group is to track the status of photonic components with respect to:

- Sharing evaluation and qualification experience
- Tracking the latest developments in the field of photonics relevant to future missions
- Working towards standardisation across testing and qualification
- Maintaining a components development roadmap
- Ensuring European non-dependence in this technology domain

The Photonics Working Group produces a continuously updated component development roadmap which is available to CTB members. When drafting the present THD and roadmap, the recommendations of the PWG have been considered.

The Photonics Working Group has also been instrumental in developing guidelines which can be used by industry in the evaluation and qualification of key photonic components. Currently in progress is the development of an ESCC Basic Specification for radiation testing of optical fibers, and a set of ESCC Basic Specifications addressing Lithium Niobate based Electro-optical modulators [RD-ESCC]. Furthermore, there is a guideline produced by ISROS for reliability assurance of digital optical transceivers [RD ISROS].

4.5 Key Issues

The experience of the first 3 Photonic products that have been adopted by the space market revealed that the main challenges to overcome are:

- Focus on developing the technologies to offer a distinct advantage for the targeted application. Identifying such an advantage is key for any decision to change technology for a specific application. For example, in introducing Photonic Analog Links in COMSAT P/Ls the key issue is to reduce the power consumption through uncooled transmitters and to increase the density of transmitters/receivers by use of PICs.
- Identify the “entry” (first) customer in the commercial market.
- Meet the cost/price targets set by the customer.
- Proceed with the Qualification of parts which in many cases requires redesign or accommodation of performance issues at system level. This can be the case of

qualifying COTS which in certain cases may suffer from radiation effects and/or inadequate packaging.

Notice that the 2018 edition advocated that it is important to perform In Orbit Demonstrations where possible and appropriate. However, experience from the 3 Photonic products adopted by the space market has proved that having an IoD is not critical for decision making. Hence, the cost/benefit for an IoD should be assessed on a case by case basis for any Photonic product considered for commercial use.

In addition to the above, other challenges to be considered include:

- Work on a standardised qualification approach for each family of parts including packaging redesigns. Where possible issue such standards or guidelines. Examples include guidelines for laser diodes (ESCC23201 and ESCC23202 for Evaluation and Qualification respectively, see RD-ESCC), and the ISROS guidelines for qualification testing of photonic digital interconnects [RD-ISROS].
- Where possible, identify a stable doubled-sourced supply chain for HIREL parts.

Currently the efforts are targeting the following:

On optical digital links for Digital P/Ls

Create a robust European supply chain for the key photonic technologies to unleash the full potential of deep sub-micron digital processing:

- Providing radiation hardened driving electronics for optical transceiver technology;
- Suitable high density optical harness solutions to interconnect the optical transceivers;
- Ensuring that current packaging solutions are suitable for the use in vacuum and full range of space thermal and mechanical environments;
- Ensuring the extended lifetimes (up to 18 years) required in space applications;
- Enabling reduction of transceivers power consumption (targeting 5pJ/bit).

On analog links for COMSAT P/Ls

- Providing cooler-less transmitters with power link power consumption of 0.1W.
- Providing high density packaging of the transmitters and receivers and use of ribbon fibers so as to reduce the complexity and time/effort dedicated on harness management.
- Provide a radiation tolerant and thermally qualified transceivers.

On-board Equipment for Microwave photonic functions

- Develop PICs that provide the required functional performance.
- Develop PICs that are of very low power.
- Develop overall equipment design that makes use of PICs and appropriate interfaces in a minimalistic size.
- Meet the cost targets requested by the targeted applications.

On sensors for thermal, mechanical and shape monitoring

- Reducing the cost and complexity of the transducer element and associated harness. To demonstrate extended operational lifetimes for the sensors.
- Investigate the use of microphotonics to reduce cost and improve the reliability of the interrogator.
- Look to distributed sensing and novel optical fibre designs to maximise multiplexing capacity and allow new functions such as shape sensing.
- Development of new optical fibres to facilitate the introduction of high spatial resolution and high dynamic rate distributed sensors suitable for temperature and structural health monitoring.
- Development of algorithms to support data reduction in distributed sensing, and the use of data to support the development digital twins with ever increasing data processing.

On Launchers

- Develop a robust European fiber optic harness solution suitable for the launcher environment able to cope with a very wide thermal environment and adapted for high power handling.
- Continue to investigate new test means to ensure reliable test coverage of the optical harness to provide high spatial resolution Fault Detection Isolation and Recovery solutions. Further investigation of the latest techniques would be valuable to demonstrate how reliability of the harness can be ensured through the use of these optical techniques.
- For future reusable launch vehicles investigate the use of fiber optic structural health monitoring solutions to enable the fast turnaround of these vehicles. In particular the use of distributed sensing could permit better sensor coverage of critical structures.

Some overall comments on:

IoDs:

Although proven to be non-essential for decision making, **In Orbit Demonstrations** and the preparation towards one expedites the efforts of technology suppliers for a full product qualification and increases the level of confidence for both the Primes and the Operators. At present, European Photonic Equipment is carried in IoDs on board 3 MAXAR's satellites [RD-DAS]. Any Photonic Equipment Supplier and any Photonic Payload Supplier will need to consider how critical a concrete IoD plan is prior to the commercial offers to the RFQs by PL Primes and Operators.

Micro photonics:

The experience of the past 5 years has highlighted that the effort for identifying key advantages for each targeted application has led to a **shift from discrete Photonics to Integrated Photonics.** In almost applications identified where Photonics are applicable there is a requirement to develop Microphotonic versions that can offer significant advantages in reducing mass-power-volume-footprint. Actually, in some applications it is this critical step in miniaturisation that enables a positive trade-off of photonics compared to electronics and in turn a switch of technologies. Key issues towards minimisation of Photonics and shift towards Microphotonic Equipment are:

- Hybrid integration of active with passive parts (lasers and detectors with waveguides);
- Improve the frequency response of lasers/modulators/detectors;
- Improve the gain of the amplification stages;
- Integration of microphotonics and electronics required in many applications;
- Packaging and thermal management suitable for the space environment;
- Qualification and reliability.

Although Space funding cannot support the work of basic developments in microphotonics it can support developments in identifying the applicability into space applications and solve all the problems that are more engineering challenges rather than fundamental material issues. ESA has a comprehensive programme of work initiated in 2001 where the 5 main equipment in Telecom Payloads and the Interrogation Unit in Platform thermal monitoring units are considered for implementation in Micro-photonic platforms. As a side note to spaceborne photonics it has to be highlighted that during the period since the first edition there have been two industry-initiated efforts to employ such PIC technology for beam forming networks as the “Photonic Core” of satellite antennas on board aircraft and mobile platforms on earth. Both efforts are funded by ESA’s ARTES programme.

The key challenge remains for integrated photonics to reduce optical coupling losses, and to develop several building blocks which remain unavailable on the majority of integrated photonics circuits designed today, namely:

- Isolators;
- Power amplification beyond 100mW;
- Co-integration of electronics with photonic building blocks.

While many research efforts continue to address these short comings, it is clear that photonic integration can have a very positive impact on the cost of manufacturing complex photonic systems, and in the case of the space the subsequent qualification effort. In addition, the evaluation and qualification effort for application in space can be simplified overall since the optical circuit can be treated as a single ‘hybrid’ component as opposed to a series of independent discrete elements; although the procurement and testing will require careful tailoring and becomes even more challenging to standardise. Where a complex optical circuit can be treated as a single component as opposed to the testing that would be required of discrete photonic components.

The European Commission has invested strategically in photonic integrated photonic packaging solutions and has established a gateway to support industry find suitable European packaging solutions for PICs called PIXAPP. PIXAPP Photonics Packaging Pilot Line uses its extensive packaging capabilities across its European partner network to provide services and guidelines to support European industry. The processes used are based on PIXAPP's open access packaging design rules and Assembly Design Kit (ADK). Phix (NL) provides an assembly and packaging service for photonic integrated circuits (PICs) and has published some useful PIC packaging design guidelines to support best practices in PIC packaging [RD-Phix_PIC].

Photonic Packaging:

It is well understood that photonic packaging accounts for the larger part of the total cost of manufacturing photonic components, and therefore efforts to reduce this significant cost is a key challenge to be managed in the development of photonic components. This can be particularly relevant for space components as they must not only work in the space radiation environment but must also survive launch and work sometimes for 20 years in a vacuum environment. The operation of photonics in the space environment leads to significant challenges, such as:

- The use of hermetic packaging which has traditionally been used to protect high reliability components, which is being increasingly questioned as new space demands lower cost components.
- Shock and vibration levels which typically exceed the levels required in most terrestrial applications.
- Thermal management in vacuum environments.
- Lifetimes that exceed most terrestrial expectations, which impose severe reliability requirements on the components.
- Increasingly complex and customized packaging solutions required for the co-integration of photonics and electronics.
- As photonics are introduced into increasingly complex system in package solutions the need to perform testing at various levels of the integration and packaging process to improve the yield becomes a critical consideration.

COTS and modified COTS:

With new commercial driving forces impacting the space market, there is an increasing interest to make use of COTS components to manage the cost of space technology. This is not new for the field of photonics that has typically adopted this strategy as few photonic technologies have been formally qualified or can be found on a qualified parts list. However, as COTS technologies are increasingly being adopted, cost effect means of evaluating and managing these components needs to be found. This will be a particular challenge as the photonic market evolves very quickly pushed mainly by the forces in the terrestrial telecom market.

Qualification of Photonics

Photonic components fall within the umbrella of EEE components and therefore the relevant product assurance processes apply (see [RD-ECSS-Q-ST-60]). However, when it comes to the photonic components to be applied within a space project, there are very few specifications existing within European Cooperation for Space Standardisation [RD ESCC] which are directly applicable for the procurement process and to define the evaluation and qualification test programs. Typically, the standards for EEE parts are also applied to photonic components with significant adaptation. There are some ongoing efforts to develop new ESCC standards addressing some generic photonics technologies. However, due to the rapid evolution in this technology domain, the broad application range, and the relatively low quantities, it is unlikely to reach the same level of coverage as for the main EEE domains. This is further exacerbated by the reliance on COTS. In certain applications where there is overlap with terrestrial domains (such as telecom, data-centres or automotive) it may be possible to have HiRel COTS parts, but for many applications with specific performances this will not be the case.

Therefore, having a consistent approach to the reliability assurance of photonics for space applications will remain a significant challenge.

4.6 Technology State of the Art in Europe

Figure 4-4 displays, per country, the number of European entities with confirmed capabilities in the scope of this technology harmonisation. The data is collected from the esa-star entity capability mapping (ECM) module. The total number of confirmed entities is 126. The full list of entities per country and their ECM status is to be provided in Annex A at the end of the cycle.

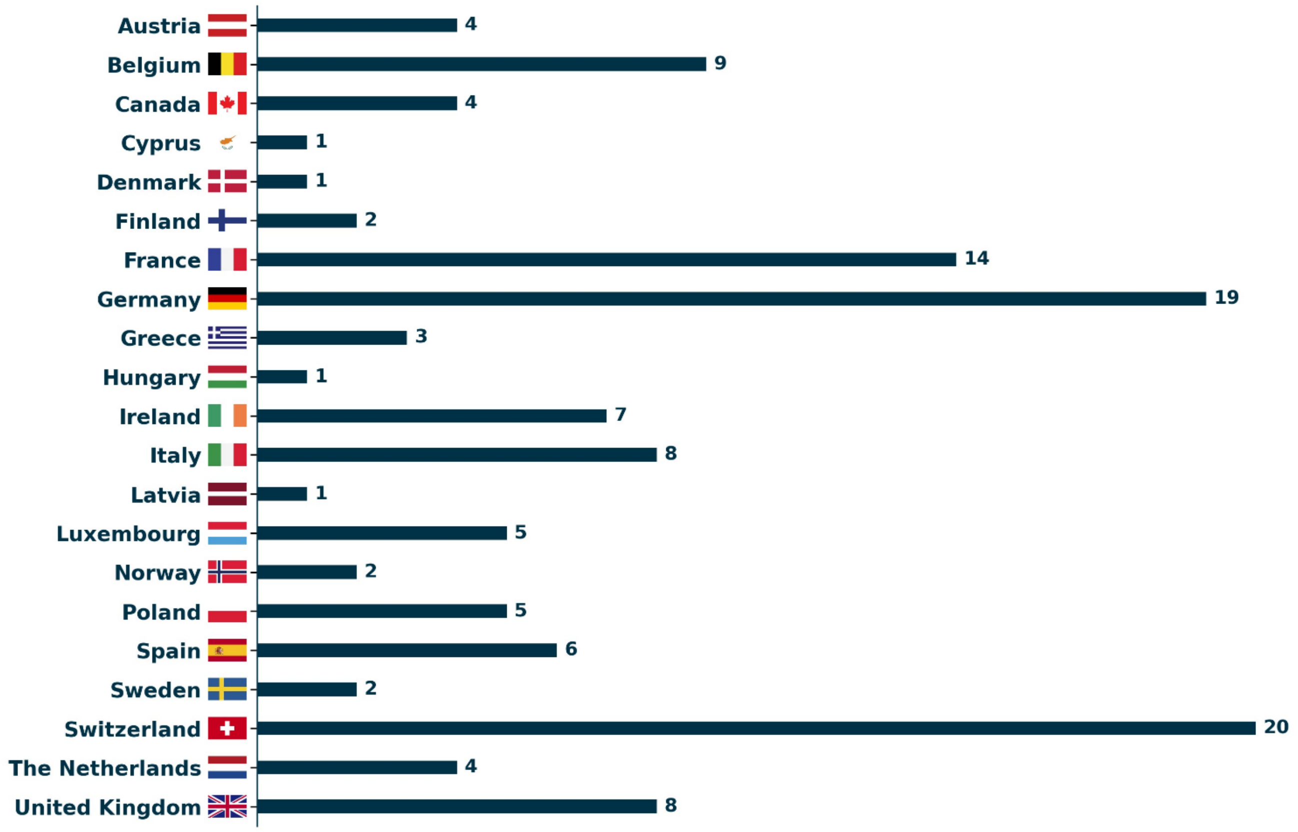


Figure 4-4: Number of European entities with confirmed capabilities in the Harmonisation topic Photonics per country, as tracked in esa-star ECM and as of January 2024.

The application of Photonics (fiber and integrated optics) in Space is distinguished in the ones applied to the **Payload** and the ones applied to the **Platform**. Europe is in the forefront of developments of Photonics in Space with a total investment in the order several tens of Meuro tunnelled through ESA, the EU and the national Space-supporting Agencies to industry. As a result, European and Canadian companies are currently the main suppliers of this technology. Photonics in Space can also be distinguished according to their position in the value chain role for the various applications as:

- **Discrete and Hybrid Components** (e.g lasers, modulators, photodiodes, passives, transceivers etc)
- **Sub-systems** (optical amplifier)

- **End-to-end links** (digital and analog)
- **Equipment** (such as Frequency Generator Unit, Frequency Converter, Router, Filter, Beam Former, Thermal Monitoring Unit, Pyrotechnics)
- Entire **Payload** architecture using a number of Photonic Equipment

They are presented in the next subsections following this categorisation.

The following subsections present in more detail the current status of the various photonic components and hybrid devices that constitute building blocks of the Photonic in all the applications outlined in Section 4.3

4.6.1 Components

4.6.1.1 Lasers and Drivers for Digital transmission

Today the predominant lasers used in digital intra-satellite links are the 850 nm GaAs Vertical Cavity Surface Emitting Laser (VCSEL). These are currently the preferred solution on the basis of maturity of the technology for terrestrial applications, ease of coupling to optical to multi-mode fibers, radiation tolerance, and suitability to operation over a wide thermal range. VCSELs are available covering bandwidth beyond 25 Gbps, and are available as single VCSEL chips to VCSEL arrays with up to 16 parallel channels, compatible with fiber ribbon technology. The main European suppliers of this technology are trumpf (D), VI Systems (D) and Coherent (F/US, CH). Coherent announced the capability of VCSELs to support 100 Gbps transmission using PAM-4 [RD-COHERENT]. US suppliers like Broadcom and Lumentum are key competitor suppliers from the US.

State of the art Failure in Time (FIT) values for 850 nm VCSELs are in single figures, which means that over 35 years (i.e far more than required for space missions) of operation can be guaranteed for these devices even at elevated temperatures of 85°C. Main challenge remains that VCSEL technology is fast evolving and therefore obsolescence is considered to be a threat for the space market.

(a) (b)

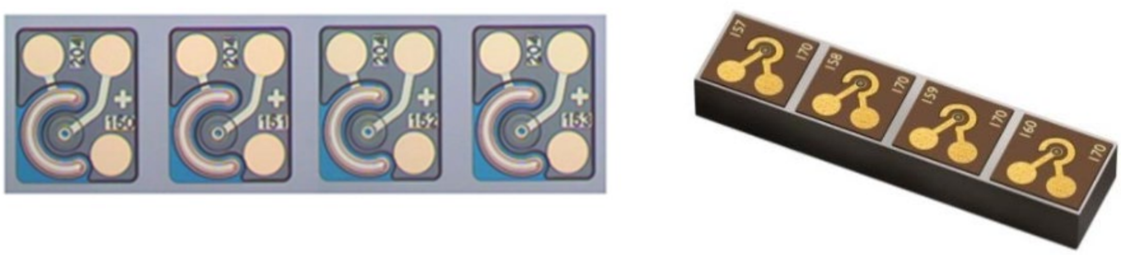


Figure 4-5: VCSEL arrays from a) COHERENT (ex II-VI Laser Enterprise), and b) TRUMPF.

Much of the current research effort is directed towards increasing the speed and reducing the power consumption of VCSELs. Chalmers University of Technology is one of the world leaders in this field and has demonstrated over 71 Gbps data transfer, while IBM has demonstrated a record 1pJ/bit [RD-CHALMERS].

However, the availability of such high speed VCSEL-based transmitters in space depends on the radiation tolerance of the drivers. Radiation hard drivers are today unavailable in Europe for VCSELs. LEO Space Photonics currently develops 25/32 Gbps (NRZ) VCSEL drivers specifically for Space. Similarly, TETRA Semiconductors develops drivers for the 28/56 Gbps transmission.

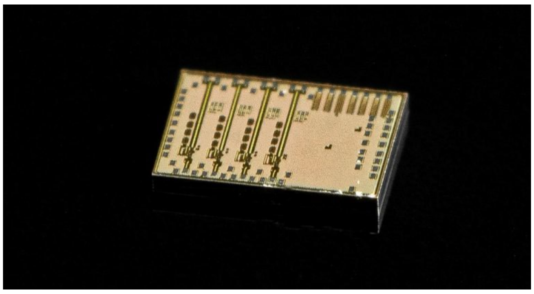


Figure 4-6: LEO Space Photonics.

Moving to even higher data rates in the range of 112 Gbps and beyond there is an inflection point for technology shift from VCSEL based transmitters to ones based on PICs with the option among using InP, SiPh and SiN platforms or any combination of these. Currently mBryonics and IMEC pursue such a development of PIC-based transceivers reaching 56 Gbps with NRZ modulation. Similarly, companies like RANOVUS and POET Photonics offer such solutions to reach in excess of 100 Gbps with PAM4 modulation and high density fiber connections allowing chiplets that can exceed 1 Tbps in aggregate. They use micro-ring resonators as the modulators and specially designed interposers. However, such PIC-based transceiver products have not been qualified for space yet and their qualification will be one of the main targets in the coming years. IBM (CA) has also developed co-packaged solutions aimed at their High Performance Computing applications. These solutions take benefit of both their VCSEL and packaging expertise, resulting in optical interconnections with below 5pJ/bit performance.

It is important that the ASIC/FPGA industrial community adopts and drives the integration of high speed optical interconnects into their products. It is expected that such ASIC/FPGAs will be supplied to payload manufacturers with integrated optical interconnects. There will be challenges especially in the packaging and thermal management as distances between the data source and the optical engine have to be kept minimum in order to achieve the desired power reduction. The main challenge may come from the fact that thermal management for space products will, by necessity, have to be different to accommodate operation in a vacuum environment. Additionally, the lifetime requirements of the space products may need to exceed those for ground operations where there is a quicker evolution. Moreover, many of the high-density CPO and NPO solutions require an external multi-wavelength (WDM CW) laser source, which will need to be thermally controlled to maintain fix separation between WDM optical tones (e.g. Sivers Photonics (UK)).

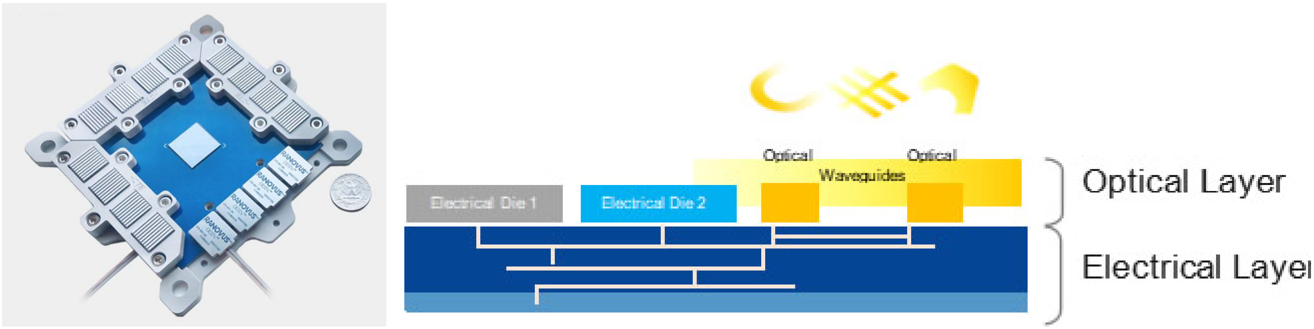


Figure 4-7: Transceiver Chiplets by RANOVUS and Interposer concept by POET technologies for >100 Gbps transmission.

4.6.1.2 Lasers and Modulators for Analog Transmission

Until recently the main type of laser used for analog transmission was the **DFB with external modulators (like Mach-Zenhder type)** and with main requirements the low RIN and frequency/amplitude stability over time and temperature. Current European suppliers of such DFB lasers include 3SP Technologies, and Toptica Eagleyard Photonics. Gooch and Houseg is a US based supplier that has developed products for the space market which have been used in European space projects. Several other COTS suppliers such as EMCORE and AOI exist that offer competitive products that have lower TEC power consumption. In addition, several Japanese laser diode companies such as Fitel offer high reliability laser diodes in the telecom wavelengths from 1300-1600 nm which have been used in space flight hardware. As the Thermo-electric cooler used in such lasers consumes significant amount of power, finding ways to reduce this power consumption is a very important line of development and may lead to technology change. Latest studies have highlighted the use of un-cooled structures combining **Lasers integrated with EAM type of modulators** as the most suitable for Photonic Analog Links. These are the EAM-Laser-Modules (ELM). Coherent (in US and Europe in CH) is the main supplier of these devices. It is expected that the move towards Integrated Microwave Photonics will open the path to very low power consumption of a fraction of a Watt per microwave photonic link up to Q/V band and very high-density transmitter arrays which in turn will lead to the commercial adoption of such Photonic Analog Links by the COMSAT P/L Primes in the same manner that was followed for the Digital Photonic Links.

DFB laser diodes at wavelengths outside the telecom window are also used in a number of applications for distance measurements within instruments. For instance, in GAIA an 852 nm DFB from Toptica Eagleyard photonics (DE) is used to measure the line-of-site angle between the two telescopes. In Earth Observation FTIR instruments, such as MTG-IRS, IASI-NG, and FORUM, DFBs are used to measure positions or distances within the interferometer.

Increasingly DFBs are also being sought at custom wavelengths to address the needs of sensing and quantum experiments. VCSEL lasers at these wavelengths are also of interest, and have been used not only for micro atomic clocks but also for sources to control atomic magnetometers, such as those employed in the JUICE's scalar magnetometer. In Europe, companies such as Sivers Semiconductors (UK) and VIGO Photonics (PL) are companies that are able to offer custom laser source components as they offer the complete front-end and back-end production line for semiconductor components.

Mode Locked lasers and Optical Frequency Combs

Such lasers are considered in equipment like the Frequency Converters and ADCs where they provide the sampling clock (see EPFC later in this Section). The critical performance characteristic is the need for extremely low jitter. NKT Photonics (formerly One-Five) manufactures MLLs and has supplied such a device for use as the optical clock input in a Photonic Sampler equipment for space developed by DAS Photonics as part of an Electro-Photonic ADC. A similar work is performed by the University of Ghent and Antwerp Space as the optical sampling clock input for an Electro-Photonic Frequency Converter-EPFC using **microphotonic technologies** which makes the whole fabrication more challenging. Another company is Menhir Photonics (CH) which has developed a monolithic oscillator femtosecond laser at 1550 nm with pulse repetition frequencies between 250 MHz and 2.5 GHz with extremely low phase noise and exceptional timing jitter less than 1 fs and very good prospects with respect to space environment (radiation, thermo-mechanical). One good example of where this technology is finding an application is ESTRACK. This major development project with Cycle Gmbh (DE) is aimed at developing a frequency and timing distribution system for ESA's satellite tracking network using the low noise laser from Menhir Photonics.

If Europe is to pioneer the use of EPFCs and EPADCs then European companies must be able to deliver the critically important Opto-Electronic Oscillators and the MLL needed to drive them.

Frequency Combs

The optical frequency comb is a disruptive technology expected to impact many applications including the generation of low noise microwave signals. Optical frequencies are on the order of 50,000 times higher than the best microwave references, but are too fast to be counted directly as microwave signals can, which is why a frequency comb is required to divide the frequency down to lower frequencies that can be directly detected using standard electronics.

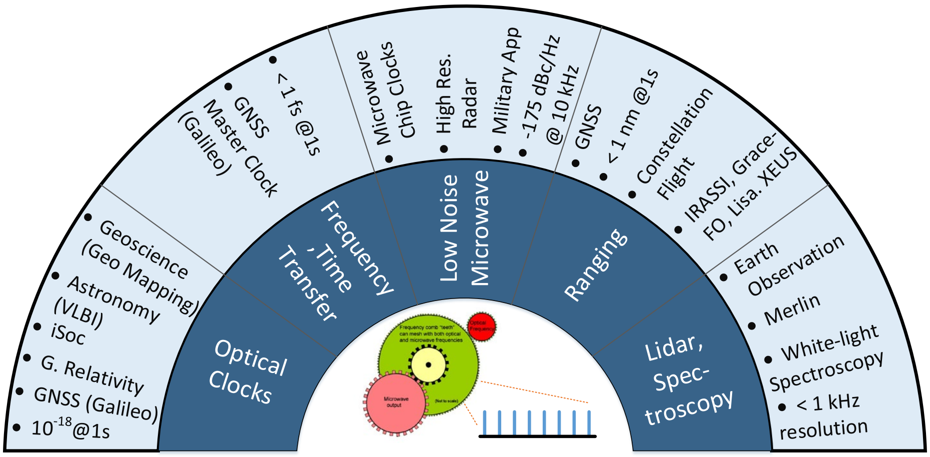


Figure 4-8: Frequency comb space applications.

Highly accurate measurements of frequency are not only relevant to atomic clocks but also important in other fields such as detection of biological agents, synchronization of advanced telecommunication systems to range and velocity measurements of remote targets. Several European players are active in the field of frequency combs including Menlo Systems, OHB and CSEM (CH) for high performance optical clocks. The main application of these devices is in optical clocks and frequency dissemination, a more detailed description of these applications is covered in the *Frequency and Time Generation and Distribution Harmonisation Dossier*.

Menlo Systems together with Exail (former iXblue) have developed new radiation hard fiber amplifier technology to improve the robustness of stabilised fiber based frequency combs, demonstrating the technology to be suitable for MEO missions. CSEM MLL technology demonstrated very good preliminary radiation hardness in addition to very low noise performances. Micro frequency combs currently cannot compete in performance but steps are being made to improve the performance including by companies such as Ligentec in Switzerland and PILOT Photonics in Ireland.

Sources for the Characterisation of Spectrometer Instruments

An important element of many Earth Observation missions are the tools required for the on-ground and in-orbit calibration of spectrometers and spectrographs. This is especially true of the ultra and hyper-spectral instruments essential to the Copernicus programme and beyond where a more accurate knowledge of the Instrument Spectral Response Function (ISRF) is key to more performant future generations of instruments. The current calibration approaches rely on an extensive and challenging on-ground calibration campaign, driving both cost and schedule, as well as the need for mechanically stable instrument designs. The instrument stability requirement induces design constraints, with impacts on mass and complexity, that may be totally or partially lifted if in-orbit ISRF characterisation is possible. These on-ground calibration techniques rely on very expensive test campaigns performed in vacuum conditions. The means that performing accurate in-orbit calibration of the ISRF is expected to reduce cost and delivery time of future space-borne imaging spectrometers, as well as improve their performance stability by periodically re-calibrating the ISRF in-orbit.

A second type of calibration often required to monitor instrument properties is radiometric calibration, often also relying on on-board sources but in this case necessarily broadband, such as lamps, LEDs, SLEDs or combinations thereof.

The key challenge to address for both ISRF and radiometric calibration, is that each solution is unique and the wavelengths of the emitters are usually not falling in ranges which can be spun-in from terrestrial applications; with the spectral range from the UV up to, and including, the SWIR2 regions (350 nm-2.5 μm).

Current Space solutions for ISRF calibration often rely on COTS parts, with the emission properties (wavelength and its stability) being the critical aspects, and less emphasis on the longevity in operation since the sources may only have a cumulative operation in the entire mission lifetime of <100 hours. The devices may be in TO packages, or for more complex hybrid solutions a butterfly package. Some custom solutions specific for space are available, for instance from Toptica Eagleyard photonics (DE) and Nanoplus (DE).

Although each mission tends to have an individual solution, a promising future direction could be to develop broadband sources which could provide a more generic solution. A recent study by TNO has found that microphotonic frequency combs could lead to very interesting solutions in terms of sources for the on-board calibration of Earth observation payloads. The challenge remains to develop comb sources covering the complete UV-SWIR range of optical frequencies (350 nm-2.5 μm). A study from Airbus in the framework of CarbonSat and an ITI primed with Ligentec (CH) highlighted furthermore the advantages and demonstrated TRL3 for the micro frequency comb technology. Airbus also partnered with Iloomina for highly efficient conversion microcombs and with KIT for photonics wire bonding, both technologies being required for on-board ISRF measurements.

Building on the development of an on-board calibration source developed through the ESA funded micro-spectrometer (μSpec) programme [RD-COS-2021], LioniX (NL) in collaboration with University Twente (NL) have developed a tuneable laser source suitable for supporting both sensing (780 nm, 850 nm) and communications (1550 nm) applications. The laser is based on the hybrid integration of an external tuning element based on SiN butt coupled to an InP gain chip. These lasers have been commercialised through the spin-off company Chilas (NL), and have been evaluated for space compatibility (vibration and radiation) [RD-LXI-EPP, RD-CEM-Per]. The current laser baseline uses thermal tuning elements, but work is ongoing to demonstrate the reliability of PZT tuning elements which can bring improvements in both performance as well as reduce power consumption. PZT actuator technology is currently under investigation for its sensitivity to radiation under an OSIP COTS campaign activity in collaboration between LioniX, Chilas and coordinated by Airbus France [RD-ADS-2022].

4.6.1.3 Pump Lasers for Optical Amplifiers

Pump lasers are used in optical amplifiers at different levels of output optical power. It is the main power consuming source in the optical amplifiers and as such the one that needs thermal management and attention for the reliability figures. Pump lasers that are considered (without being “qualified” yet) for space are produced by Lumentum (CA), 3SP Technologies and Coherent. Competition from the US and even China is present. It is pivotal that these products remain competitive as Optical Amplifiers are critical devices not only in Photonic P/Ls (intra-satellite links) but also in optical inter-satellite links and satellite-ground links with the emergence of many constellation networks.

4.6.1.4 Pump Lasers for Optical Cooling

Optical cooling is a disruptive cooling technology based on Anti-Stokes fluorescence in fluoride crystals. This is currently developed in the frame of *Cryogenics and Focal Plane Cooling* THD. The link with this present THD is that a pump laser source is needed to provide optical power to the cooling crystal. The main challenge for the development is the overall cooling efficiency. After the cooling crystal the laser source is the second main contributor to the efficiency. Depending on the dopant, Ytterbium or Holmium, the pump wavelength is either 1020 nm or 2070 nm. Laser diodes with 20 W at 1020 nm or 2070 nm are currently not available. In this view, the development of a laser diode to replace the current fibre lasers would represent a significant increase of Wall Plug Efficiency.

4.6.1.5 Photodetectors for digital communications

GaAs PIN diode is the work horse for this application, due to maturity of the product for ground applications, and having a good compromise between sensitivity and power consumption making it suitable for low power transceiver designs. The main European suppliers of these devices are Trumpf, Coherent (ex II-VI), VI Systems and ALBIS Technologies (CH). Standard PIN diode products are available with large apertures, good responsivity and with bandwidths in excess of 25 GHz. Recently several companies have demonstrated data throughput of over 100 Gbps. The main challenge will be to find ways of reducing the power consumption of the receiver chain, which consumes the largest portion of the power in a digital optical link.

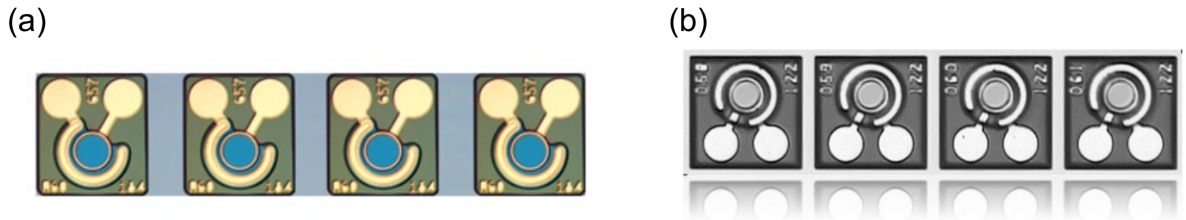


Figure 4-9: PIN diode arrays from a) Coherent, and b) Trumpf.

4.6.1.6 Photodetectors/photoreceivers for analog communications

In analog (microwave) link it is critical that the photodetector can have high dynamic range and high power handling capability combined with a large frequency bandwidth. Having both a large bandwidth and high power handling capability proves to be a big challenge. Uni-Travelling Carrier photodiode (UTC-PD) is a candidate technology due to their large frequency bandwidth. Currently Thales Research and Technology, ALBIS Technologies, and Coherent work on this field providing photodetectors for analog links with bandwidths exceeding 50 GHz and power handling greater than 20 dBm.

Designing such a receiver requires the above photodetectors and delicate design and manufacturing of the post-photodetection electronics especially with reference to the frequency response and amplification. DAS Photonics, VECTRAWAVE, Antwerp Space and Microwave Photoncis GmbH work on microwave receivers for space applications. The EU Horizon 2020 project SIPhoDiAS, led by LEO Space Photonics, is developing a Ka- and Q-band analogue photodetectors that will be assembled in compact packages and will host InP photodetector chips with monolithically integrated lenses assembled with RF matching circuits. Similar suppliers of such microwave photonic receivers for space are to be expected also from the US or even other countries. Increasing the efficiency, bandwidth and saturation power level of these detectors continues to be the main focus in order to improve the overall efficiency of optical microwave photonic links.

4.6.1.7 Optocouplers

An optocoupler is a component that transfers signals between two electrical circuits by means of an optical signal in order to provide galvanic isolation. In space, opto-couplers are widely used to safely isolate low power, delicate, and expensive electronic components from high power circuits, or to provide a means of interfacing circuits with high ground potential differences, protecting circuits from large common mode voltages, and eliminating noise and interference due to undesirable ground loop currents.

In Europe we currently have no suppliers offering qualified space-grade radiation tolerant opto-couplers for the satellite market. Through a series of ECI and GSTP funded activities starting from 2011, OPTOI (IT) has developed LCC4 and LCC6 package optocoupler variants which have passed a space evaluation, and currently have a TRL-5. Isocom (UK) is a European based company offering COTS optocouplers and optoswitches, and have done some evaluation towards space application of their products.

A further emerging application for optocouplers is within electric propulsion platforms, which are increasingly used across telecom, navigation, Earth observation and science applications. Compared to the usual applications for optocouplers, the key difference is the bus voltage. For electric propulsion platforms it is preferred to have a bus voltage closer to the propulsion system operating voltage (e.g. 300V), whereas typical platforms have 24 V, or maybe 50 V. Correspondingly, the optocouplers are required to have higher than typical voltage output.

Although the need is rapidly increasing, the market availability is very limited, and only non-hermetic parts are available off-the-shelf. Suitability for such parts in space is not yet clear.

4.6.1.8 Passive Fiber Optics Couplers/Splitters

The optical coupler or splitter is a key building block of an optical system used for power splitting in a fiber system. Typically in fiber there are two different approaches commonly used, the fused biconical taper-FBT splitter and the planar lightwave circuit splitter. The fused coupler is based on process involving the fusion and tapering of two or more fibers together. The tapered fibers are then encapsulated to protect them from the environment. The planar lightwave circuit-PLC is a newer technology that relies on lithographic approaches to design waveguides in a glass layer deposited on a silicon wafer.

FBTs have been used in several ESA missions, with the SMOS mission in 2009 using a cascade of them to create a clock distribution network. The couplers used on SMOS were developed by the UK company Gooch and Housego.

PLC offers an advantage for space missions where a reliable higher degree of splitting is required (up to 1x64) or where more accurate control of the splitting ratio is required. The splitting ratio in a PLC design is also less sensitive to the input wavelength. It is also more compact than FBT, especially for higher splitting numbers, and is more suitable for extreme thermal environments. FBT however is a more mature product with flight heritage, and is less expensive for low splitting numbers (1x4 or less).

Most of the large PLC manufacturers are located either in Asia or the US and are supplying the terrestrial telecom market. SQS Vlaknova optika a.s located in the Czech Republic offer a range of PLC splitters and polarisation beam splitters for harsh environments.

4.6.1.9 MUX/DEMUX

Optical multiplexer and demultiplexers are passive fiber optic coupled components that either combine or split optical signals based on the wavelength of the incoming signal. These are important building blocks in an optical payload as they allow with low loss to combine or split optical signals based on the incoming wavelength. These devices are widely used in the terrestrial network and are based typically of one of two technologies; thin film filter technology or Arrayed Waveguide Gratings (AWGs) which is a planar waveguide technology. Thin film filter technology is generally appropriate where the number of multiplexed channels is relatively low, as the loss increases with the number of channels, as it is typically based on either cascade of single channel splitters, or multiple reflections in a slab waveguide coated with a filter array. Mux/demux are standard telecom components and are available from a wide selection of companies like KYLIA (FR).

AWGs on the other hand are a technology based on wafer scale integration of waveguides on a silicon (glass on Silicon, SOI, SiN) or InP wafer. Today the maturity of PLC AWGs is very high as they are widely used for DWDM in terrestrial telecom networks. Temperature compensated designs are available that have relatively small sensitivity to temperature. As this technology is based mainly on PLC the majority of the suppliers are either based in the US or Asia with relatively few manufacturers in Europe. Senko (JP) is one of the Asian suppliers offering high quality athermal AWG products.

AWGs can also be made in other material systems other than silica on silicon (InP, SOI, SiN). Many of the European integrated photonic foundries (IMEC (BE), Cornerstone (UK), VTT (FI), HHI (DE), Smart Photonics (NL), Ligentec (CH), etc.) are able to offer AWG designs as a basic building block supported in their PDK libraries. Other companies such as VLC Photonics (ES) and Bright Photonics (NL) are integrated photonic design houses that can support industry with the design of custom AWGs according to specific needs.

4.6.1.10 Isolators

Isolators may be used in several photonic architectures where back reflections may impair the performance or damaging in particular the laser sources. One needs to distinguish between bulk and fiber coupled isolators as they address different application with different requirements in terms e.g of power and polarization. So far there has not been dedicated development of isolators for Space and different Device/Equipment manufacturers have different experience when testing isolators. Frequently such products are procured from Asian companies. It will be important to have a European/Canadian company willing to work towards a space-qualified isolator and to develop appropriate ESCC standards. The emergence of satellite constellations and the consequent substantial market of optical amplifiers means that there can be a substantial market also for space-qualified isolators. In Europe, SpaceTech GmbH produces a bulk optical isolator for space. Micro-isolators are needed in laser diode packages and are required over a range of different wavelengths from the VIS through to NIR. Today there are relatively few European suppliers of isolators with most being located in China or the US. SpaceTech GmbH develops a micro-optic isolator in the visible wavelength range (780nm centre wavelength). Today the magneto-optical crystals (CdMnTe) are unavailable in Europe and have to be sourced from a single supplier in the US.

4.6.1.11 Optical Fibers

Optical fibers are one of the key building blocks of any photonic network. Typically they are split into a number of different categories depending on their geometry and function. The majority of space applications rely on one of the following types of fiber; single mode, multi-mode or polarization maintaining fiber. These come in cables of single fibers or multi-fibers (ribbon). Beyond this there are some specialty fiber types such as polarizing fiber, micro structured fiber, and fibers that will support the transmission of wavelengths beyond the UV-VIS-NIR range (200nm-2200nm) supported by typical fused silica fibers.

Single Fibers

Optical fibers have flown on several missions, the first satellite to fly optical fibers extensively was SMOS in 2009. The fiber used in the SMOS mission was a standard single mode fiber from Corning (SMF 28). Beyond this application optical fibers have been used in a variety of specific applications from LIDAR, Altimeters, interferometers and laser communication terminals, each of these applications has required a unique fiber so there has been little opportunity for standardization. This however could change in the coming years as there appears to be a growing market for intra-satellite optical communications. In particular, the on-board digital telecom processors and the SpaceFibre. The SpaceFibre standard specifies the use of a standard 50 micron core OM3 fiber (ISO/IEC 11801 standard), which is a commonly used telecom standard which defines the bandwidth distance product that can be sustained by the optical fiber (2000MHz*km). Given the short lengths of fiber used in satellite applications this is expected to be adequate for future needs. In space a key parameter to consider is the insensitivity of the optical fiber to radiation darkening. This phenomenon has been studied for many years, and is extremely complex given that it is dependent on the glass composition, the manufacturing process, the thermal and mechanical environment, wavelength, radiation flux and even the operational scenario (photo bleaching). The literature contains many references to testing performed over the years and CNES is maintaining a database of results which is available to the space community for reference.

Today the main European companies offering a wide range of optical fibers including in some cases ‘radhard’ optical fibers, include Draka, Fibrecore, J-Fiber, IXFiber, and in the US the fiber by OFS proved to be rad-hard. In addition there are a number of specialty fiber manufacturers such as Fibrecore, InPhoTech, AcreoFiberlab and IXFiber who have the capability to make custom optical fibers. Europe also has some state of the art capability in the manufacture of microstructured optical fibers in companies such as InPhoTech, PERFOS and NKT Photonics. Microstructured fibers allow new optical properties such as photonic bandgap structures, multicore structures (active and passive applications), suspended core, airclad, ultra-high nonlinearity to support frequency combs or ultra-broadband sources or dedicated to enhanced or custom sensing applications. One example of this technology is the use of a Kagome hollow core fiber for the frequency stabilisation of a diode laser for use in future space-based differential lidar for monitoring the atmosphere at 2 microns [RD-HCF]. Hollow core fibers including anti-resonant structures developed by the ORC Southampton University are demonstrating low loss performance close to that of solid core which is opening up applications which can benefit from the unique properties of the air core namely extremely low non-linear effects, increased speed of transmission and low thermal sensitivity. These new applications include; high power signals as required in free space optical communications, time and frequency transfer over fiber and communication signals where latency is critical.

Active fiber (e.g. fiber doped with rare earths such as Erbium) development and production is critical to the space market as the technology is a key component in the development of laser and amplifier products used in many space applications, e.g. optical communications terminals, fiber optic gyros, and LIDARs. Exail and Fibercore are two companies in Europe specialising in these types of active optical fibers for the space environment. For amplification in the MIR region from 2-5nm, exotic glasses have to be used to extend the transmission window. ZBLAN is one such glass that can be used to make optical fiber amplifiers and lasers in the MIR. Le Verre Fluoré is a global leader in the manufacturing of doped ZBLAN glass fibers for use in amplifiers and lasers.

Thanks to precise glass processing it is possible to extract more from optical fibers and optical fiber components. Glass processing includes splicing, polishing, tapering, shaping and applying coatings. These added value steps are critical in the design of custom optical fibre systems; efficient splicing of optical fibers with different mode size or structure; tapering in the custom design of couplers, splitters and light collectors; application of novel coatings (metal e.g. copper, silver, nickel, gold) to enable the optical fiber to survive in challenging environments. A wide range of optical fiber postprocessing technologies are offered by companies such as InPhoTech, Fibrecore and AlphaNov. Northlab Photonics AB (SE) is a European company specialising in the distribution and development of tools and technologies for optical fiber preparation, fusion splicing, processing and related applications.

Multi-mode - Multiple Fibers -Ribbon fibers

In Digital and Analog links in COMSAT PLs it is pivotal to have a **high-density packaging of transmitters/receivers that can be integrated with the various equipme**nt i.e., the DSP and the Antenna LNAs as well as the mid-boards inside the DSP. Such links are served by multi-fiber cables hosting 4,8,12 and up to 72 fibers in a single ferule to match with the high-density MT connector interfaces which have become the standard for high density fiber optic solutions both in the terrestrial telecom network as well as for space applications. The fiber themselves have been multi-mode for the current Digital Links as the short distances are not expected to cause dispersion issues and in addition they are less sensitive to misalignment and suffer less from insertion loss due to end face contamination. However, as payloads look to increase interconnect density and bandwidth there is a trend in the terrestrial telecom to move towards single mode fiber solutions which enable wavelength division multiplexing and suffer less from dispersion.

Fiber Cable Assemblies and Connectors

For the purposes of this document an optical fiber cable assembly is essentially an optical fiber inside a cable construction with a connector on each end. The key elements in this assembly are the optical fiber (discussed in the previous section), cable (this is an external jacket put around the optical fiber to offer further protection against the mechanical environment) and the connector set (placed on the end of the fiber to allow connection of two sections of fiber). Today there are many different cable constructions possible, each offering its own unique advantages. These can broadly be classed into the following three categories, **tight buffer, semi-loose tube** and **loose tube**. There are a wide variety of possible materials which are used with many of them suitable for space where low outgassing is a key concern. The most popular designs are semi-loose tube because of the wide temperature range that it can support.

The first extensive use of fiber optic cables in space was the digital communication harness onboard the ISS (Figure 4-10). The cable used here was the OC1640 from Brand Rex (UK), which has since been discontinued. The OC1640 was designed for a temperature range of -100 °C to +125 °C based on a loose tube design, and was terminated with Amphenol Mil Std. 38999 connectors to make a very rugged cable assembly.

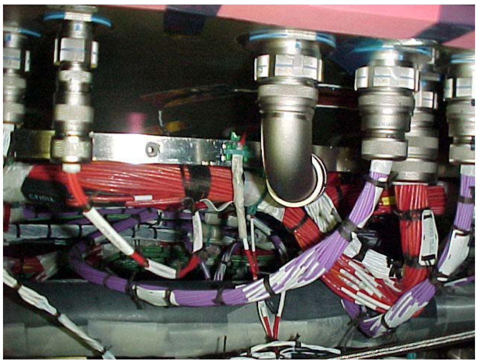


Figure 4-10: Optical fibers on the ISS (purple colour).

Since its deployment on the Space Shuttle, the GSC-13-84639-07 fiber optic cable from W.L. Gore has become the de facto standard for space applications. This semi loose tube design has been used in many space missions including SMOS where it was terminated with Diamond AVIM connectors.

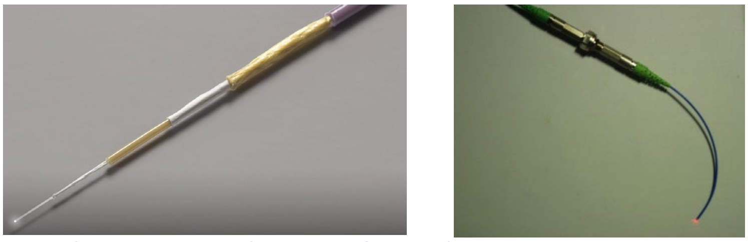


Figure 4-11: GSC-13-84639-07 fiber optic cable from W.L. Gore (left), terminated with a Diamond AVIM connector as in the SMOS mission (right).

As mentioned above the cable assembly consists also of connectors on each end of the cable. To this point several different connectors have been used in space from the large Mil Std 38999 connectors on the ISS to the smaller single ferrule AVIM connectors used on SMOS. Over the last 5 years, as the market for space qualified cable assemblies matures especially with the imminent use of these in future payloads ESA has been investing in the development of ESCC standards to cover these. As a result a basic specification for fiber cable assemblies (ESCC 2263420), has been published. Based on this a ESCC Generic Specification has been elaborated for optical fiber cable assemblies with single fiber ferrules (ESCC Generic

Specification 3420). This has given Diamond (CH) the opportunity to qualify a cable assembly based on their mini-AVIM connector with a peek loose tube cable. **As a result the mini-AVIM is the first fiber optic component to be added to the European QPL**. ESCC standards covering multifiber cable assemblies are now also in development and it is hoped that a basic specification will soon be available.

With the first wide spread use of fiber optics transceivers on board the SES-17 VHTS a high density harness solution has been qualified for space by Thales Alenia Space together with their industrial partners. This technology was based on a combination of a ruggedised low outgassing multifiber (12 fibers) cable with aerospace heritage, Q-MTitan connetors with MT contacts and specially modified HDQX connector housings based on the aerospace ARINC standard, illustrated in Figure 4-12. The solution was specially adapted to meet stringent EMI performance specifications [RD-Harness].

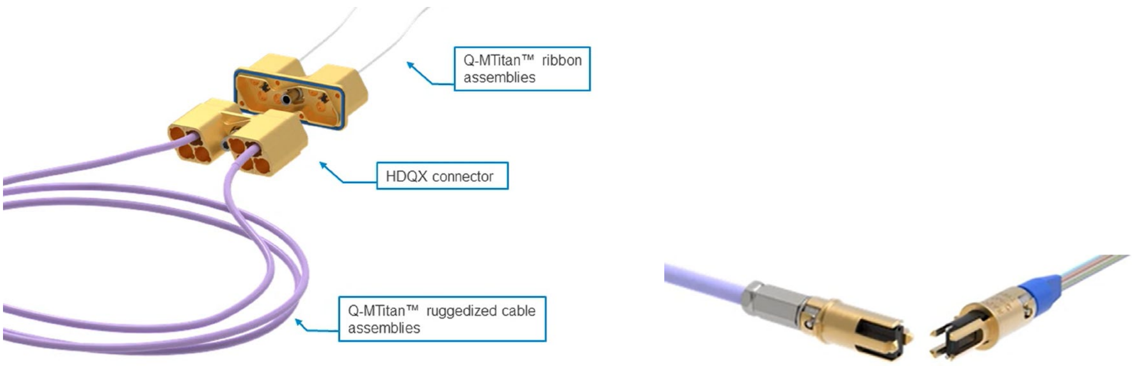


Figure 4-12: Radiall's harness assembly developed for SES-17.

For launcher application cable assemblies have been extensively evaluated for the optopyro application. These have largely focused on products with previous launcher heritage, namely the Mil Std. 38999 connector housing which has heritage from applications such as the ISS and space shuttle. Smaller more compact connectors however may be suitable for future applications where the solution is not required to have this level of robustness. Evaluation of other connectors such as the LC and the mini-AVIM have already shown that these more compact designs should be adequate even for launcher mechanical loads. The optical harness for the optopyro application is a specific development requiring extremely robust solution using a single family of connectors. Here, the Souriau family of 38999 Mil Standard connectors together with the Helio inserts are baselined. Special back shells have been designed for this application to make the solution suitable for the launcher environment. Duetsch have also developed a cable assembly for this application that has been tested in the launcher environment. Special requirements for the launcher application include pull strength of 500N, lanyard release connectors, and a family of connectors going from 24 way down to 1 channel connectors.

Figure 4-13: Souriou Mil Std 38999 connector family with Elio contacts (left) and cable assembly (right)

Suppliers in Europe able to offer a complete fiber optic harness solution include Radiall, GlenAir-UK, TE-Connectivity, Amphenol, Axon Cables and Souriau. Several companies in Europe offer cable manufacturing capability including Leoni, Prysmian Group and Nexans. Finally there are a few companies such as AVOptics and T&G Elektro who specialise in the manufacturing of custom harness solutions for harsh environments.

Optical Interconnection Planes for Fiber Harness Management solutions

As the number of fiber optic links is increased to levels of several tens or even hundreds (a VHTS Digital Processor may employ more than 2000 fibers in ribbon cables) there is an emerging need to manage them. Manual management would be very time consuming work increasing the overall cost of AIT. Fiber harness also needs some sort of physical/mechanical protection against all types of mishandling. The approach adopted is this of the properly laminated Fiber Optics Interconnection Plane with several names like Fiber Optic Flexible Routing Assembly (FOFRA) or “Optical Backplane”. TE Connectivity is main supplier of such Optical Backplanes and T&G Elektro works also towards the qualification of their FOFRA technology [RD-FOFRA – see Figure 4-14].

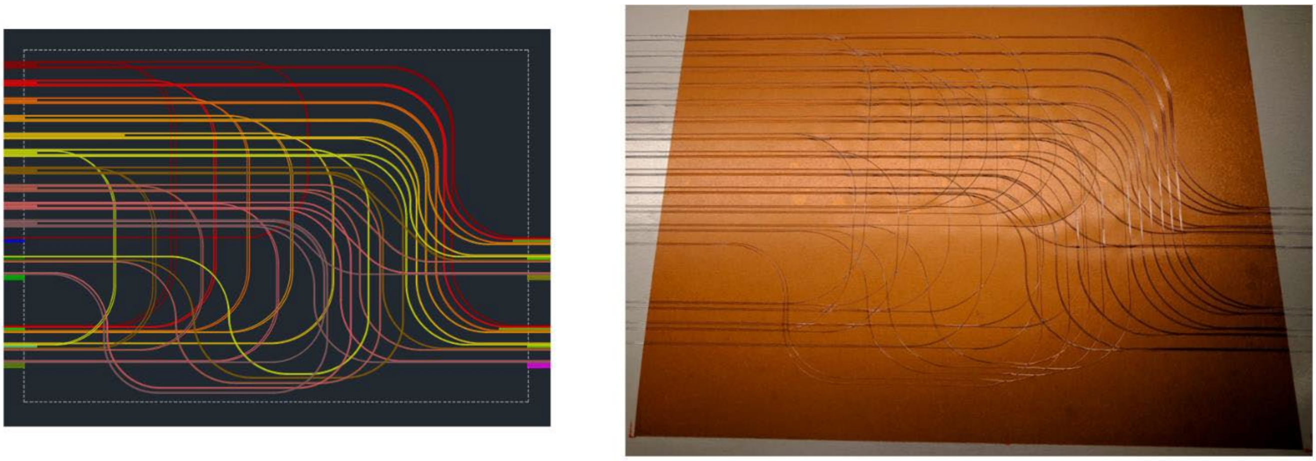


Figure 4-14: Fiber Optic Routing Assembly [RD-FOFRA].

4.6.1.12 Optical Amplifiers

Space-borne Optical Amplifiers at 1550 nm are used both for intra-satellite applications as well as for inter-satellite links (the latter reach power levels of tens of atts and are covered by the Optical Communications THD). Currently MPB, Gooch and Housego, CILAS and Lumibird work towards supplying a full family of space qualified amplifiers with some of them already in advanced TRL. Since the 2018 edition of this THD the power levels requirements have increased markedly whereas the power efficiency remains at the levels of 10-15% revealing that the thermal management of such devices in the vacuum conditions of Space is probably the biggest challenge. Glenair (US) has claimed wall plug efficiency of 20% which is considered the higher reported so far [RD-GLENAIR]. Fuelled by the big demand for such amplifiers for the constellations inter-satellite links these companies have been working consistently developing products to serve the customer needs. This has brought European/Canadian amplifier suppliers to the forefront in the market. Competition is expected from current US suppliers that are expected to supply constellations like the Space-X with tens of thousands of amplifiers creating economies of scale that can allow them to compete on cost. Therefore, it is pivotal that the European/Canadian suppliers quickly advance the maturity of a family of products to TRL-8 and are ready to respond to the RFQs by Primes. Main challenges are the increase of the Wall Plug Efficiency to >20% while maintaining the smallest possible footprint.

A similar development takes place at the 1064nm exclusively targeting the free-space link. For this reason, the 1064 nm optical amplifiers are covered in the “OPTICAL SPACE COMMUNICATIONS” THD.

A development is currently running to assess the impact of cryogenic environment on semiconductor optical amplifier (SOA). So far, a dramatic increase of performances has been reported by Air Liquide: +15dB on the gain up to 52dB, the Noise Figure decreasing down to theoretical limit of 3dB and efficiency raising up to 41% [RD-ALAT-SOA]. The challenges include assessment of the best configuration where the gain in Wall Plug Efficiency becomes relevant for a space application, and the assessment of other photonics device behaviour in cryogenic environments.

4.6.1.13 Optical Modulators

Optical Modulators are a critical building block for the Analog Links and several Equipment in Photonic Payloads. Similarly, they are used in intersatellite links. The requirements in terms of frequency response reaches the 50 GHz and the figure of merit includes the $V\pi$ voltage as well as the insertion losses. It is known from the current activities that the main challenge is the stability of the bias point over time and temperature (in vacuum). It is of paramount importance that the Optical Modulators provide the reliability and credibility required in order to enable the realization of the Photonic PL concepts. The technology to be used probably will depend on the application with Mach_Zehnder modulators and EAMs being the main technologies to compete. In Europe/Canada Exail (MZI on LiNbO3), Versics in CH (MZI on lithium niobate on insulator), and AXENIC (MZI on GaAs) are players that are expected to be suppliers of MZI-based modulators. Coherent supplies EAMs integrated with DFB lasers in an EML package. Integration of a large number of modulators in a high-density package is critical for applications like the analog links from multi-element antenna to DSP and back. Significant competition exists from the US suppliers some of which promote their products for Space.

4.6.2 End-to-end links

4.6.2.1 Digital Multi-fiber (ribbon) Links

The one application that has emerged since the 2018 edition of this THD is the **intra-Processor digital links** using VCSEL and multi-fiber (4 and 12) ribbon cables [RD-TAS-OIs, RD-SES-17]. Using transceivers with 4, 8 and 12 channels offers extremely high bandwidths which are required in present payloads and are only to be increased in future ones. As multi-channel transceivers are now widespread terrestrial applications from Aircraft avionics to data centres where SWAP figures of merit are of critical concern Space can leverage on all relevant developments. There is a clear path on the evolution of such links:

- 10 Gbps, VCSEL, NRZ
- 28 Gbps, VCSEL, NRZ
- 56 Gbps, VCSEL, PAM-4 or SiPh NRZ
- 112 Gbps, SiPh, PAM-4, co-packaged with ASIC/FPGAs or VCSEL

Today the market is dominated by a single supplier for 10 and 28 Gbps.(Smiths Interconnect) [RD-SES-17]. RADIALL (FR) has also developed optical transceiver products for the space market under funding from CNES and ESA. This device is currently based on their existing Aerospace market products. ALTER-UK is a new company on the field developing 28 and 56 Gbps VCSEL based links. Similarly, mBryonics is developing 56Gbps optical interconnects co-packaged with functional IC under an ESA TDE contract. Competition from the US include Glenair (however operations are interrupted in 2023) and Ultracomm. ESA and DLR are currently evaluating COTS transceiver products from Amphenol (DE) and APITech (UK) to understand how these non-hermetic components could perform in the space environment. Looking longer term, upcoming players using advanced Silicon Photonic technology include RANOVUS (CND & DE), IBM (CND), Sicoya (DE) and POET Technology (CND). These companies are designing Near or Co-packaged optical solutions targeting the high density - high bandwidth requirements coming from data centres, AI factories and high performance computing.

(a) (b)

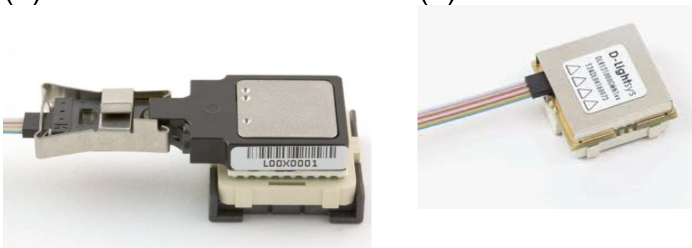


Figure 4-15: Parallel transceiver packages from a) Smiths interconnect, b) RADIALL (ex D-lightsys).

Advanced Data Handling Architecture (ADHA)

ADHA is an effort by ESA and its major industrial partners to establish a modular avionic solution to meet future spacecraft needs. Its objective is to establish a versatile, compact, modular and scalable Data Handling System architecture using standardised building blocks on interface, module and unit level. The standardisation of such an interface allows interchangeable and interoperable electronic modules on a standard versatile backplane ensuring modules from different manufacturers can be combined into one or several ADHA units reducing development time and cost. Other benefits of this higher integration of units will lead to harness and mass reduction. ADHA is considered to be a potential accelerator for the adoption of new technologies such as optical backplanes, which have already been adopted in the latest generation of VHTS digital payloads. [RD - ADHA].

ADHA matches well with standard communication protocol such as PCI and SpaceFibre (ECSS-E-ST-50-11C) which in turn can be addressed at the physical layer by fiber optic transceiver technology which can easily facilitate data rates from 1-25 Gbps in a fully scalable protocol agnostic solution. ESA has been funding development in the field of SpaceFiber for over 20 years. Up to this point most of the developments have focused on data bandwidths below 2.5Gbps which can be handled by copper SpaceFibre solutions, but as the data rates continue to increase there is an interest to look at adopting optical fiber solutions to address the area of modular avionics. Multichannel transceivers could be ideal for addressing the needs of ADHA Units particularly when the data rates are above 10Gbps; Figure 4-16 illustrates a generic implementation of a two ADHA unit avionic implementation.

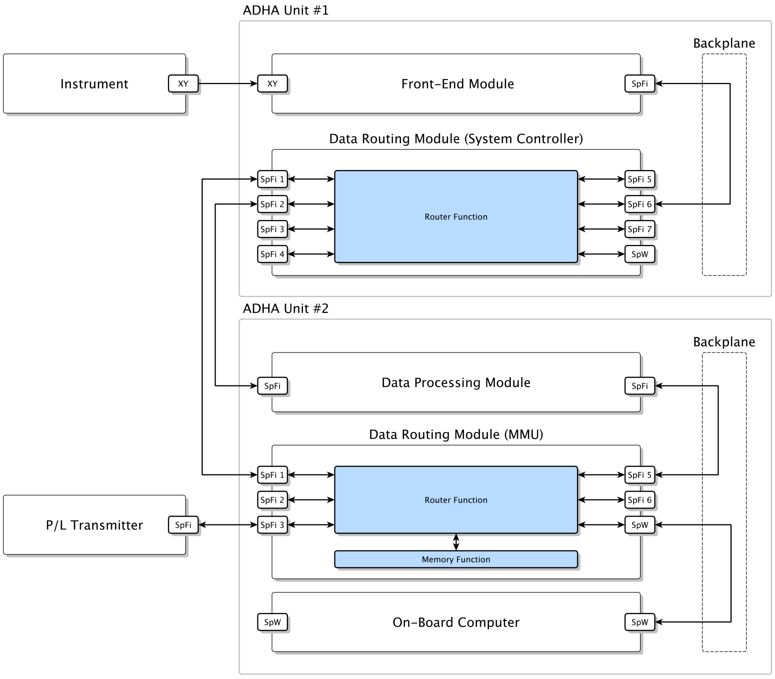


Figure 4-16: Two ADHA unit implementation of a satellite avionic architecture.

In such an architecture the 4 lane bi-directional optical transceivers at 12.5Gbps could be a good baseline solution. What is still lacking is a standardised approach to the optical harness which could match with the protocol agnostic transceivers. Internal research and development at ESA have already demonstrated the feasibility of SpaceFibre implementation at 10Gbps, as illustrated in Figure 4-17 an 8 port SpaceFibre implementation on a Xilinx KU60 FPGA running over Smiths Interconnect LightAble transceivers.

SpaceFibre working group members include the following: ADS Germany & France, OHB (DE), TAS (F), Beyond Gravity (SE), Star Dundee (UK), Frontgrade Gaisler (SE), IngeniArs (IT). SpaceFibre IP cores are available from European manufacturers (Star Dundee, Gaisler, IngeniArs).

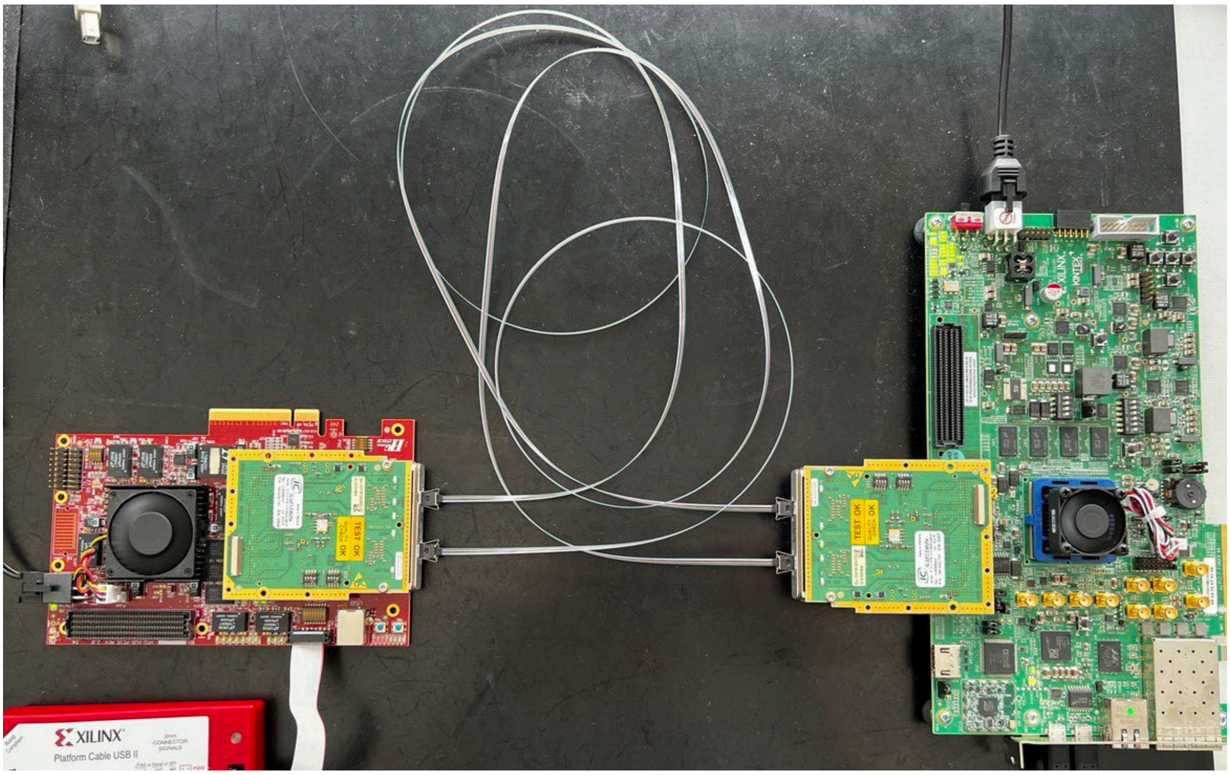


Figure 4-17: An 8 port SpaceFibre demonstrator implementation on a Xilinx FPGA over fiber optic transceivers.

Active Optical Cable for SpaceWire and SpaceFibre

An active optical cable or media convertor is an optical fiber link assembly where the optoelectronics are embedded in the cable itself and that has only an electrical interface externally. Such links have been designed for several terrestrial applications (data centres, high performance computing), mainly to ensure the link is robust to EMI and can handle very high data bandwidth (>10Gbps over several meters of cable), and that the contamination sensitive optical interfaces are protected inside the cable construction**. The SpaceFibre standard has included an active optical cable as one optical implementation for the future** as it is considered an interesting approach to make use of the more mature electrical interface (connector design) without having to really consider the constraints of managing the open optical interface**.** DAS Photonics (ES) with support from ESA has developed a prototype of a SpaceWire active optical cable, see Figure 4-18. The transceiver based on hermetic VSCEL TOSA and hermetic PIN diode ROSA operating at 100Mbps suitable for SpaceWire are embedded in the back-shell of a 9pin D-type connector.

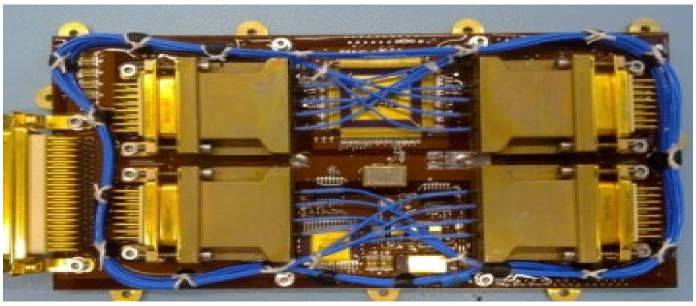


Figure 4-18: IOD on AlphaSat of the DAS Photonic Active Optical Cable

This design has been flown on AlphaSat (Technology Demonstration Payload 8) and PROBA V Satellite – Hermod. Hermod was a demonstration of not only the active optical cable from DAS Photonics but was also a technology demonstration of high density connector cable assemblies from T&G Elektro, see Figure 4-19.

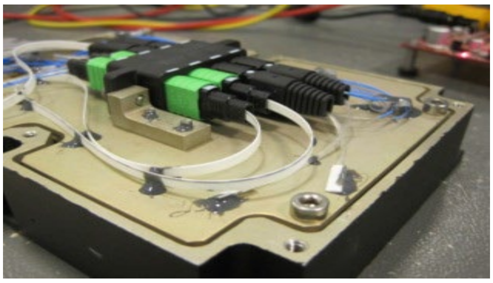


Figure 4-19: Hermod IOD on board PROBA V.

Commercial active cable solutions from the US have also appeared from companies such as Glenair and Airborn, which are actively addressing the space market segment.

4.6.2.2 Analog Links

The analog links used massively **in COMSAT PLs linking the Rx antenna LNAs to the DSP and the DSP to the Tx antenna HPAs**. The number is typically several hundreds of such links per PL. They key to such links are:

- The high density that will allow the integration to the antennas and the use of ribbon fibers. This will have a significant impact on the harness management and the required time and effort during AIT.
- The very low power considering the very high number of links. It has to be underlined that the fiber optic links are “active” requiring power which, when considered in aggregate, results in several hundreds of Watts. They are called to replace passive coaxial cables that require zero power. So, the power penalty to be paid has to be kept to minimum for Photonic Analog Links to be adopted in commercial PLs just like the Digital ones.

Another application of Photonics for Analog Links is for the **distribution of the LO signal from the Master Reference Oscillator to the Frequency Converters.** There have been several demonstrations of this idea and even an IoD [RD-DAS]. The key requirement is the RF signal performance since this is the case of transferring a high-Q LO reference.

Potential suppliers of such links include Microwave Photonics GmbH, DAS Photonics and Antwerp Space in Europe. These links will likely be the first Analog Photonic technology to be adopted by PL designers and hence the suppliers landscape is still open to any entry that can fulfil the 2 main requirements outlined above. The first company to fulfil these requirements and get the first commercial offer will have a significant advantage over competing suppliers.

4.6.3 Equipment

Beyond serving links, Photonics are considered for performing the 5 main functions in typical COMSAT PLs i.e.: Frequency Generation in the Master Reference Oscillator and Local Oscillator (integrated with the frequency converter), Frequency Conversion, Switching, RF filtering and Beam Forming. Both big primes TAS and ADS have demonstrated architectures involving such equipment. DAS Photonics is the only supplier of such equipment worldwide with a clear record of IoDs in MAXAR's built satellites for European Operators. It seems however that the introduction of Photonic RF Equipment will have to follow first the introduction of low power consumption Photonic Analog link and adaptation of PICs to build confidence in the technology. Specifically on these 5 equipment:

4.6.3.1 FGU – photonic generation of a microwave (Master Reference or Local) Oscillator

Photonic FGU refers to the optical generation of a high Q microwave carrier. Usually this is achieved by means of DSBSC modulation and heterodyning on a photodetector. TAS-F and DAS Photonics are the 2 European companies that worked to supply such an Equipment whereas ADS integrated such a payload in a demonstrator. The main challenge in achieving the high Q microwave carrier is the frequency stability which is linked to stability of both the laser source and the optical modulator used for the modulation. The technology status and the competitive environment on these components are described in the relevant paragraphs above. There is no information of companies outside Europe supplying space qualified Photonic FGUs. DAS Photonics has flown such an equipment in IoDs with MAXAR [RD-DAS].

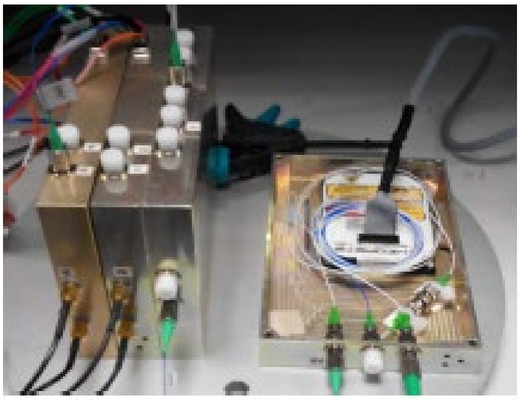


Figure 4-20: Photonic generation of dual frequency optical LO.

On the same topic, **Microphotonic FGU** for use in satellite PLs has also been pursued by EPFL(CH)/CSEM and the challenge here is to be able to achieve the performance of the various distinct Photonics components in their microphotonic version while also integrating them in the same fabric and package. Although similar approaches are investigated in R&D centers internationally, there is no company that claims to be a supplier of such a product for Space.

An alternative approach to develop FGU equipment was demonstrated by LioniX International together with UC3M and Dublin City University, where a **microphotonic integrated hybrid circuit** of Indium Phosphide reflective SOAs (RSOA), InP Photo Detectors (POD) and a silicon nitride PIC, forming the external cavity, phase locked, dual-laser source was fabricated [RD-UC3M-Gon]. A similar LO was utilized by SENER, UC3M and LioniX International for an integrated reconfigurable filter [RD-UC3M-Zar].

MLL used for frequency combs, like the NKT Photonics and Menhir Photonics technologies, can also be used as FGU as originally demonstrated by CSEM with Albis high-power handling photodiodes [RD-CSEM].

4.6.3.2 Frequency Converter

The Frequency Converter converts an input microwave signal from one frequency to another. There are different scenarios depending on how the LO reference is delivered.

a. In a first case the LO is delivered in the form of a photonic DSBSC reference from the Master Reference Oscillator and then mixes with the incoming signal from the antenna and various RF products are generated when beating takes place in the photodetector. With appropriate filtering the desired down/up converted signal is selected. This kind of approach is open to Multi-FC when the MRO is a WDM one with replica of the MPR signal over many wavelengths. TAS-F and DAS Photonics are the 2 European companies that worked to develop such an Equipment [RD-TAS-PhFC]. The core component of a Frequency Converter is an optical modulator that functions as a mixer. The stability over time and temperature of the performance of the modulator is critical. This is described in the relevant paragraph on modulators. There is no information of companies outside Europe supplying space qualified Photonic FGUs. DAS Photonics has flown such an equipment in IoDs with MAXAR [RD-DAS].

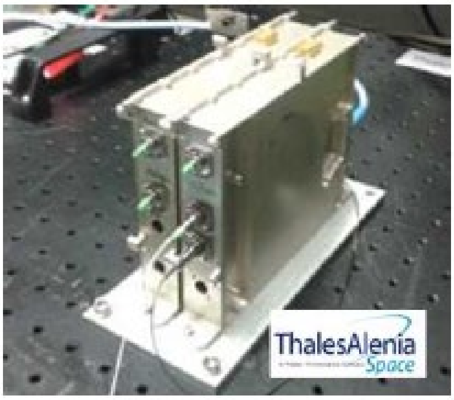


Figure 4-21: Photonic Frequency Converter

A variant of the Frequency Converter is the **Electro-Photonic Frequency Sampler** a product aiming at converting any high frequency to almost baseband in a in a single step rather in two or more frequency conversion steps. It can be applicable especially to future Digital PLs if accompanied with the appropriate ADCs. DAS Photonics has developed such a sampler based on discrete Photonic components while Antwerp Space with the University of Ghent pursued the same in microphotonic format. The key challenges are with the MLL (see relevant section on MLL) which have to be of low jitter. Especially in the microphotonic version the fabrication challenges are significant however such integration is an enabler for broader use of this device integrated with mixers in every channel chain as opposed to the case where the LO is delivered by a centralized MRO and distributed to the mixers which are in every channel chain. This type of Equipment may be proved a key in future Digital PLs and Europe should establish a leadership. So far no other company outside Europe claims to be a supplier of such a type of Equipment. The H2020 EU project PhLEXSAT with MDA and DAS Photonics is developing Photonic sampler, Ultra-low jitter photonic clock for precise sampling and Photonic-assisted ADC and DAC for digital channelizers for Q/V-band operation together with the On-board digital processing firmware. Miniaturization will be achieved by fabricating and integrating a modulator photonic integrated circuit (PIC) and high-linear photodiode PIC with electronics in the photonic ADC and DAC components. The project is aiming at TRL of 5.

4.6.3.3 Router-Wavelength Selective Switch

A Photonic Router routes an optical signal from one input port to one output port. The core of a Router is an NxN Optical Crossconnect Switch. Such a Switch may be accompanied with WDM DEMUX at the entrance and WDM MUX at the output so it functions as a Wavelength Selective Switch. In Europe, SODERN worked on space qualifying the Optical Switch of

POLATIS (Huber+Suhner now) and TAS-F used the Optical Switches (low and high port number) of SERCALO (CH) in a Photonic PL demonstrator [RD-TAS-PhPL, RD-ADS-OPTIMA]. However, this work is at present on a stand still as the market demand by such switches by GEO PLs that existed when the 2018 edition of this THD was released has not continued and the companies discontinued their effort. A renewed application can be found in Optical Routing of WDM signals in WDM-ISL connected satellite networks like the LASERLIGHT and ESA's HYDRON demonstration mission.

Figure 4-22: Photonic Router/Wavelength Selective Switch

ESA supported the development of microphotonic switch technology based on silicon photonics. Low port count switches are being developed based on MZI implementations with both PIN and thermal actuation designs have been elaborated with packaging concepts as shown in Figure 4-23. Also, EPFL in collaboration with Thales Alenia Space (CH) have developed a breadboard of 72x72 port switch based on MEMS waveguide based silicon photonic switch, pictured in Figure 4-24. The objective to breadboard a fully packaged, optically and electrically interfaced photonic integrated circuit latching switch, providing dynamic reconfiguration capability for on-board Photonic Payloads that can switch with sub millisecond speed.

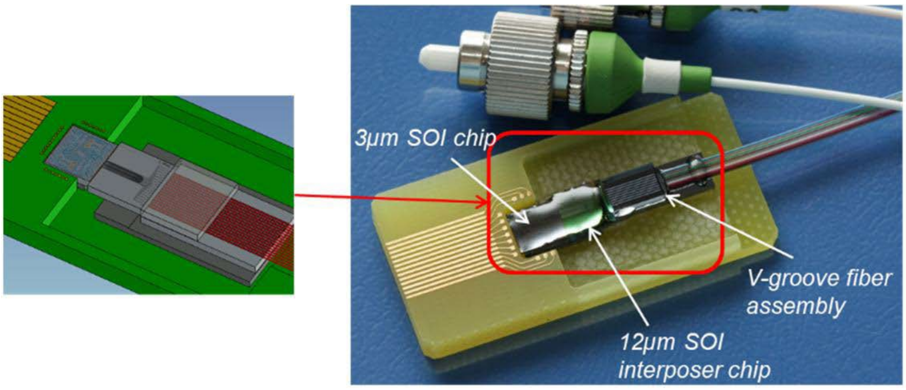


Figure 4-23: VTT Standard SMF to SOI PIC package design.

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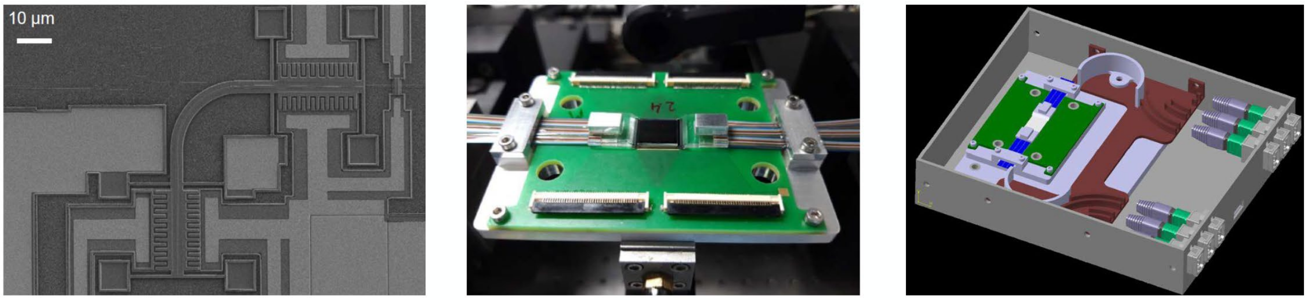


Figure 4-24: EPFL optical switch, silicon design, packaged PIC and equipment design.

Today circuit switches are considered interesting for use on constellations of satellites, giving added flexibility on-board for the routing of data. In the future the desire will be to have faster switching allowing burst mode switching which could be used to route packets or frames of data.

4.6.3.4 RF Filter

The main driver behind the implementation of a Photonic RF Filter is the possibility to offer:

- tunability of the central frequency
- adjustability of the pass-band

properties that cannot be offered by current technologies on a single equipment and rather require a bank of individual ones. DAS Photonics and LioniX International are the two European companies working on providing the “Photonic Core” for such an Equipment for Space using discrete photonics and microphotonics respectively. SENER uses the Photonic Core of LIONIX to produce such an RF equipment whereas DAS Photonics integrates itself the equipment. An integrated microwave photonic channel selector filter with FSR equal to 10.6668 GHz, capable of demultiplexing independently RF payloads in the whole Ka-, Q- and V-band, including optical injection locking (OIL), has been developed by SENER, UC3M and LioniX International. The filter consists of 2 stages of filtering: The 1st stage of filtering is based on a CROW filter and serves as channel BW regulator. The second stage of filtering consists of AMZI-lattice filters and serves as FSR extender [RD-LXI-MIT].

The development is still in TRL-3 so the next step is to improve the maturity.

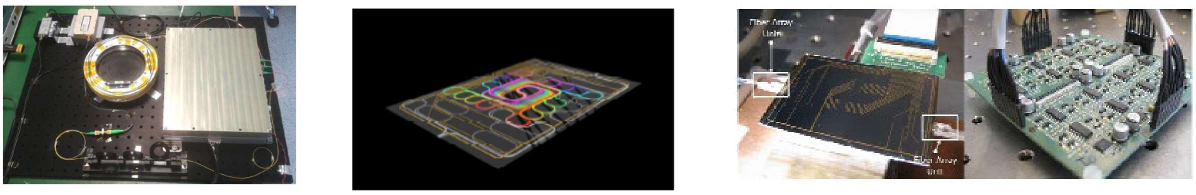
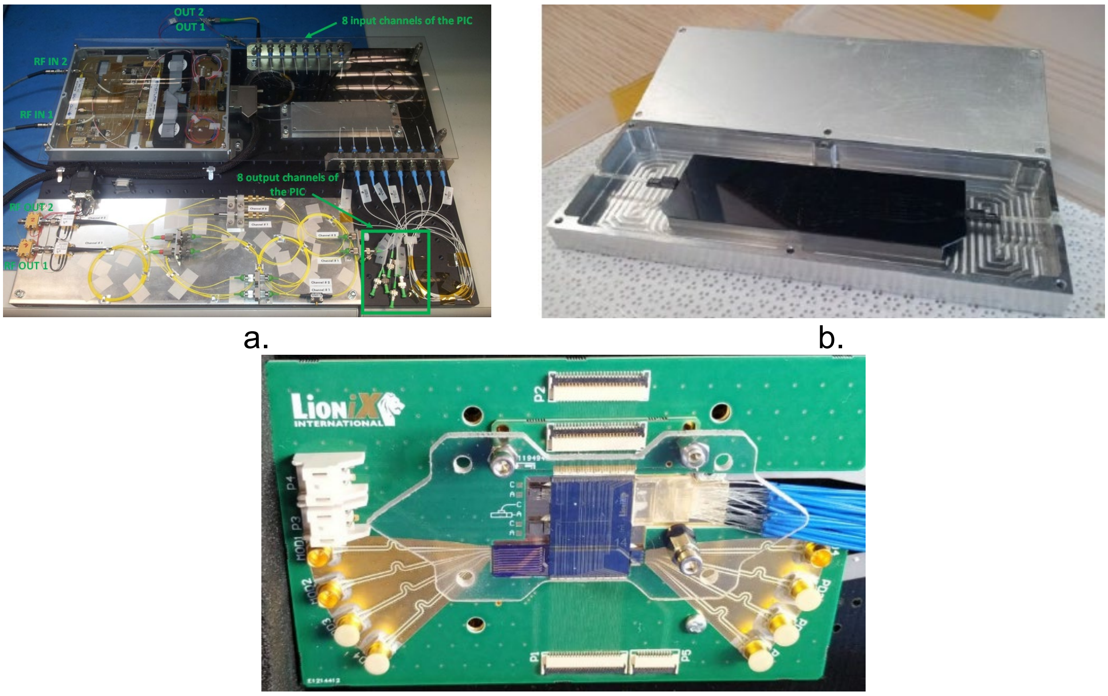


Figure 4-25: Photonic RF filter demonstrator by DAS Photonics (left) and LIONIX (middle and right) [RD-LXI-TAD].

4.6.3.5 Beam Forming Network

The photonic Beam Forming Network (BFN) arrangements are considered both for the transmit and the receive side and refer to scenarios of multi-radiating element and usually multi-beam antennas. Current designs rely on **microphotonic circuits** as the "photonic core" of such a BFN equipment and the main effort is to reduce the power consumption and minimize the mass and volume. DAS Photonics and LIONIX have demonstrated such microphotonic BFN solutions for Space and TAS and ADS consider the application of BFN in their PLs. Although there is significant effort in BFNs worldwide it is not known whether any company foresees to supply space-qualified versions yet. Interestingly, VIASAT and SINUTA work on using such Photonic Cores from LIONIX and PIC Advanced (with IT Aveiro) to produce BFN equipment for satellite antennas on board airplanes and mobile vehicles in ground. Cost is pivotal for such applications. If successful, it may be the first application of Photonic BFN.

Furthermore, LIONIX has implemented integrated coherent and incoherent (multibeam) BFNs under national, and EU programs for X-Band (LEO-SAR) [RD-H2020-SPACE]. As part of the H2020 project SPACEBEAM, the consortium led by Scuola Superiore Santa Anna is developing an innovative radar receiver based on optical beamforming network realised as a PIC. The work aims to enable the concept of reconfigurable multi-beam Scan-on-Receive (SCORE) Synthetic Aperture Radar (SAR) for Earth observation applications.



a. b.

c.

Figure 4-26: Microphotonic integrated Optical BFN fully assembled. Figures a) and b) show a passive Silicon based Butler matrix type BFN made by DAS Photonics. Figure c) shows a BFN based on a hybrid InP active part combined with a passive Silicon Nitride made by LIONIX.

4.6.3.6 Microphotonic Instrumentation [Science Payloads]

ESA continues to exploit the developments in the field of lab on a chip in order to further its aim to develop technologies suitable for human and robotic exploration which is expected to expand over the coming years as it unveils an ambitious exploration program targeting a return to the moon and further exploration of Mars and beyond. Under ESA's TDE contract for the IDOS (Integrated label-free Detection in Optofluidics Systems for Sample Analysis) activity [RD-KAY-2021], Surfix, LioniX International and Kayser Italia developed a fully hybridly integrated interferometric biosensor breadboard comprising a (1) 850 nm tunable VCSEL, (2) photo detectors and (3) microfluidic rotary valve in an aMZI photonic chip for fluidic control in particular to detect nucleic acids (DNA), hydrocarbons (B(a)P), and proteins (C-Rreactive Proteine, Human Serum Albumin) in MARS soil. The achieved sensitivity of the integrated breadboard was at least 4x10-7 (RIU).

4.6.3.7 Optical Wireless

In Optical Wireless, Europe has the initiative due to 15 years of work primarily by INTA including several IoDs during the period 1998-2012 [RD-INTA]. Since the 2018 edition of the THD Scuola Superiore Santa Anna has engaged together with TAS-I to assess how the technology has evolved. At the moment no product is available commercially at a space grade level and the next step will be to establish a company that desires to function as supplier. Main technical challenges are the minimization and optimisation of the "optical antenna" and the cost. No companies outside Europe are known to provide Optical Wireless for Satellites. OLEDCOMM (F) is a start-up company claiming the use of optical wireless for applications in satellites and launchers. It has to be mentioned that such Optical Wireless technologies can also find applications in AIT Halls to expedite the AIT process.

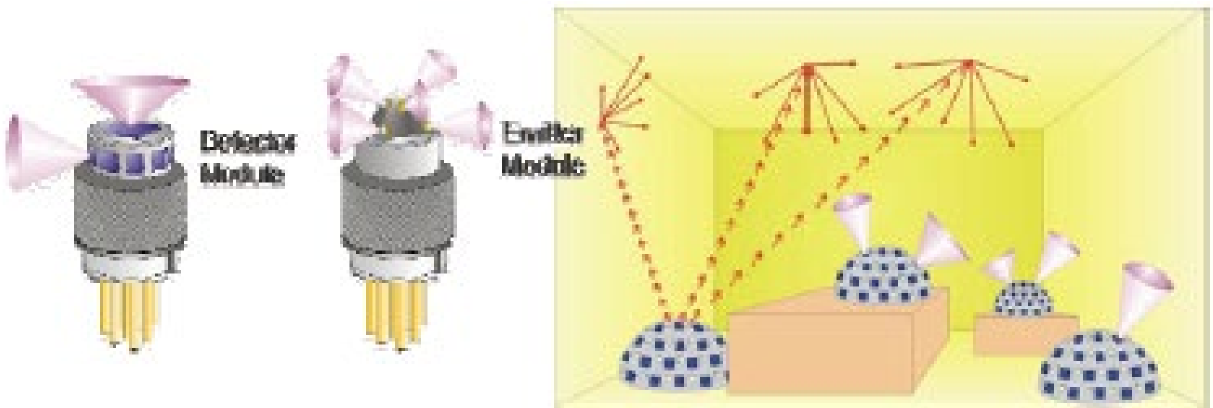


Figure 4-27: Optical Antennas for diffused infrared transmission.

4.6.3.8 Fiber Sensing

For over two decades the European Space Agency has investigated the possibility of using fiber optic sensors in spacecraft engineering as tools to advance the monitoring and control of spacecraft. The applications have been diverse covering both launcher and satellite applications and encompassing environments from cryogenic to high temperature re-entry applications.

Fiber Optic Gyroscopes (FOG)

The FOG is the only fiber optic sensor which has achieved commercial success, and which today has over 20 years of flight heritage. ESA in collaboration with CNES and our industrial partners (Exail and Airbus) have developed a complete family of sensors that cover the full range of spacecraft applications. This technology is not covered in this technology harmonisation dossier as it is already covered in the *AOCS Sensors and Actuators technology harmonisation dossier*, last harmonised in 2020 Cycle 1.

Developments in both laser and fiber technology are leading to interesting new sensing possibilities. One such example is the development of ultra low loss hollow core fiber by groups such as the Optical Research Centre of Southampton University. These could potentially have an impact on future FOG technology. ESA continues to investigate the integration of photonic sensing technologies on integrated platforms as a means of improving the SWAP of critical technologies required in inertial measurement (rotation and acceleration measurement). The challenge is to improve on the performance of MEMS technology while maintaining the SWAP advantage.

Exail and Airbus, together with ETH Zurich and DLR, are since 2020 working as part of the Horizon 2020 EURISA consortium for the development of a cost-effective, high performance IMU (Inertial Measurement Unit) based on fiber-optic gyroscopes and MEMS quartz accelerometers for future space missions. The engineering model will undergo environmental testing and it is design to be used in applications such as space navigation, entry descent and landing and planetary operations. The project is targeting TRL 6.

Fiber Sensors for Monitoring of Thermal Protection Systems during re-entry

MPB (CA) and EMXYS (ES) have both demonstrated the stable operation of fiber optic sensors to monitor temperatures above 1000 degrees C over 100s of hours using special regenerative FBGs. MPB in collaboration with DLR has developed a FBG sensing platform to monitor these high temperature gratings during re-entry. The demonstrator was flown on the ROTEX rocket in 2016. Regenerative gratings stable at operating temperatures above 1000 degrees C are available from both MPB (Canada) and UPV (Spain).

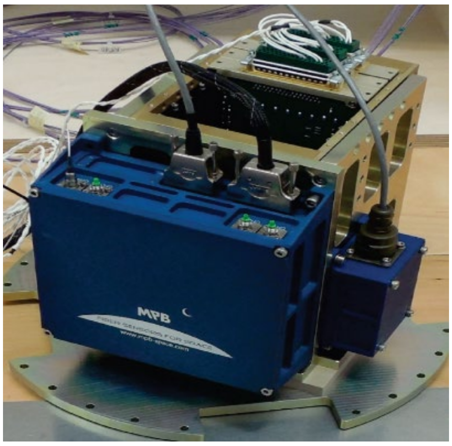


Figure 4-28: Right -. High temperature experiment on ROTEX. Left - High temperature fiber optic pressure sensor from Oxsensis after Thermal testing.

High temperature dynamic and static pressure measurements are of interest in space applications particularly in the field of lunch vehicle thrusters. Today the temperature limits of this technology are at around 800 degrees C. Optical fiber sensors based on sapphire FP cavity have demonstrated a capability to operate up to 1200 degree C. Oxensis (UK) have demonstrated their specially packaged fiber optic solutions can measure dynamic pressure up to 1200 degree C. These sensors are adapted from technology used in monitoring turbines. The fundamental upper limit of this technology in terms of temperature is probably around 1700 degrees C, however some research into new packaging materials would be required. The above sensors can be pivotally important in the new era of reusable launchers soon to include markets like space tourism which in the 2018 edition of this THD were foreseen but were not present at the time. Any investment on this technology has to be linked to potential for IoDs with such vehicles.

Structural Health Monitoring using Fiber Optic Sensors

For over two decades the European Space Agency has investigated the possibility of using fiber optic sensors in spacecraft engineering as tools to advance the monitoring and control of spacecraft. The applications have been diverse covering both launcher and satellite applications and encompassing environments from cryogenic to high temperature re-entry applications. Several demonstrations of structural health monitoring of space structures have been performed from thin antenna structures to the monitoring of optical telescope structures [Ref-FOS1]. The concepts have either targeted the monitoring of damage in these structures by monitoring the changing strain fields or using the strain field to allow adaptation of the structure to compensate for thermal deformations of the structure or the damping of vibrations by active feedback. The optical fiber sensor network in these cases brings advantages as it offers an light weight harness solution. Today FBG accelerometers are not sufficiently compact to be interesting for satellites, however the deduction of accelerations from distributed strain fields in a structure has been demonstrated.

Spacecraft propellent tanks represent a particular problem where structural monitoring is of great interest especially when thin overwrap composites are used to make light weight tank structures. These types of tanks are prone to degradation phenomena such as barely visible impact damage which insitu distributed sensing could help in identifying. Measurement of the fluid within the tanks is also of prime interest especially when in zero gravity conditions where it is difficult to predict the position of fluid in the tank. Finally the measurement of remaining fluid in a tank at end of life is also a critically important task. All these aspects of tank monitoring make for an interesting need for advanced sensor solutions with high coverage of sensors. ESA has several activities in both GSTP and the ARTES program looking at the use of fiber optics in composite tanks. Companies like Com & Sens (BE) have built up a strong expertise in the monitoring of composite structures using fibre optics. The main challenge of embedding fibre optic composites remains the ingress and egress of the optical fibers. Com & Sens have developed new approaches to address this problem including the use of self-writing waveguides. Inphotech (PL) have also investigated the use of distributed fiber sensors based on OFDR techniques to monitor spacecraft panels. Demonstrating the use of this technology to monitor the structural integrity of panels.

As stated in the previous paragraph this technology can be very important for reusable launchers and an opportunity to demonstrate them in an IoD will be pivotal and getting the sensors adopted by the launchers manufacturers.

Pre-Fabricated Photonically-wired Panels

OHB(DE) together with HPS (PO) have designed and tested a Satellite panel with integrated optical fibers for strain, temperature measurement and for optical communication. The demonstrator successfully illustrated that this approach could result in substantial harness mass savings and could have a positive impact on AIT procedures. The main challenge remains the sensor network design and mounting approaches which remain at a lower TRL.

Figure 4-29: HPS built photonically wired panel undergoing vibration testing.

Micro-photonics impact on fiber optic sensing

Current fiber optic interrogators are based on an assembly of several photonic components in order to generate the broadband light or tunable light source, wavelength calibration elements, and detectors and all the control electronics to control the sources and process the received signals. Such a system for several fiber sensor channels results in quite a complex optical board which relies on a number of photonic COTS elements combined with a number of fusion splices. The use of integrated photonics is seen as a promising way to dramatically reduce the number of passive components required in such and interrogator and to either integrate even the active components through hybrid or monolithic integration further reducing the size and weight of the device. Photon First (NL) and IMEC (BE) have both demonstrated integrated FBG based interrogators with suitable performances for space applications.

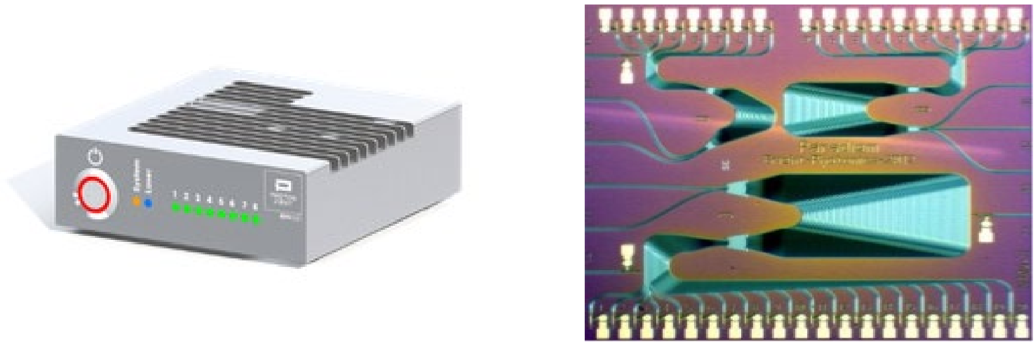


Figure 4-30: Photon First (NL) Microphotonic FBG Interrogator based on InP Photonic Integrated Chip.

Distributed Optical Fiber Sensors based on the scattering mechanisms in glass

To date most of the effort at ESA has been directed to investigating FBG sensors. This emphasis is changing as new distributed sensing approaches start to emerge that offer very high spatial resolution strain and temperature measurement possibilities [R-FOS2]. Effectively turning a piece of optical fiber into a sensor with 1000s of measurement points with <cm spatial resolution. High spatial resolution DTS is available leading to cm spatial resolution temperature measurements using Raman scattering which is independent of strain, making the fiber into an elegant temperature sensor suitable for many applications onboard a satellite. European companies such as Luciol (CH) offer commercial terrestrial solutions capable of cm resolution and 1.5 degreeC temperature accuracy.

Inphotech (PL) have demonstrated the potential of distributed optical fiber sensors for the monitoring of the material autoclave curing process during the manufacturing of CFRP composites. Using an OFDR (Optical Frequency Domain Reflectometer) measurement technique provides a detailed insight into the development of the strains induced in the curing process, as illustrated in Figure 4-31. Such techniques provide a unique means of monitoring the complete life of the structure from manufacturing right through to end of life.

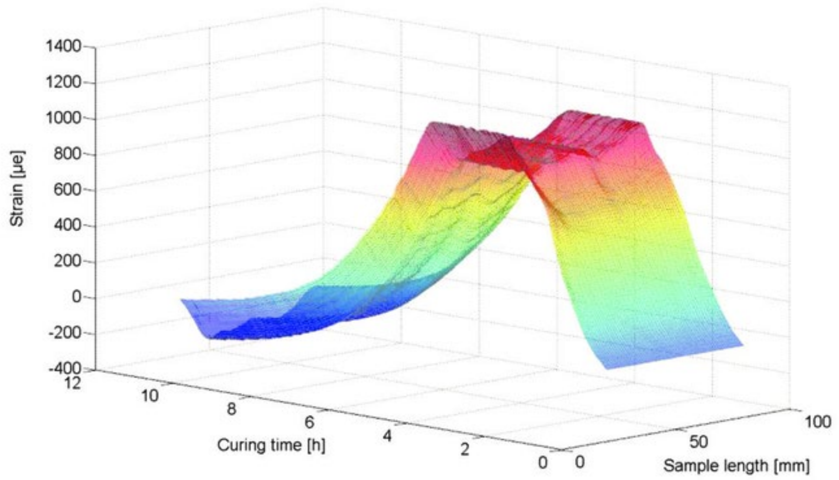


Figure 4-31: Strain distribution in a composite panel measured using an embedded optical fiber.

Fiber Optic Sensors for Human and Robotic Exploration

With the release of bold exploration roadmaps for space tourism and lunar exploitation it is clear that there will be many important measurement challenges to be addressed. NASA has been actively looking at the use of fibre optic sensor for the monitoring inflatable space structures. By weaving optical fibers into the Kevlar strength bands used in the inflatable structure, an OFDR interrogator from Luna Technologies (US) was able to monitor the distributed strain in the structure, and was able to monitor structural health as damage was intentionally introduced to the strength bands.

Lunar exploration may also benefit from distributed sensing in particular distributed acoustic sensors (DAS). Several physics packages have been proposed for lunar seismic exploration where DAS systems are proposed to be used to measure lunar quakes and impacts which can give scientists an insight into the composition and structure of the moon. Clearly there would be many challenges associated to this including coupling effectively the acoustic waves to the fiber optic cable, and the processing of the large amounts of data that would be generated.

Fiber Sensors for Ground Segment - 3-Axis accelerometer based on photonically interrogated MEMS structures.

The measurement of low frequency micro vibrations continues to be a challenge for conventional accelerometers, especially when compact form factors with low mass harness are of interest for monitoring space structures. Photonically interrogated 3 axis MEMS accelerometers promise to address these limitations. Optics 11 offer a FP interferometer based system which is currently under investigation.

Figure 4-32: Optics 1 optical sensor interrogator (left) and 3-axis accelerometer prototype (right).

4.6.3.9 Optopyrotechnics

Optopyrotechnics technology has been baselined for the Ariane 6 launcher where it will be used to perform some of the key pyro functions. The technology has entered the industrialization phase and the key building blocks are under qualification for the maiden launch; Power Firing Unit (which includes the Laser Firing Unit, Optical Safety Barrier, Optical Harness and Laser Initiated Devices. In addition to these main building blocks end to end test means such as OTDR (optical time domain reflectometers) have been developed by IDQ(CH) using Superconducting Nanowire Single Photon Detector technology to enable high spatial resolution loss measurement.

A detailed discussion of this technology will not be covered in this dossier as it is proposed to be covered in future updates of the Pyrotechnics Harmonisation Dossier. The supply chain of components and equipment for optopyro include the following European entities:

- Laser Diodes: Eagleyard (DE), II-VI Lasers (CH),
- Cable Harness: Souriau (FR)
- Laser Firing Unit: Airbus CRISA (ES), Thales (BE), AlphaNOV (FR), KDA (NO)
- Optical Safety Barrier: KDA (NO), Souriau (FR), AlphaNOV (FR)
- Laser Initiated Detonator: Nexter (FR), ISL (FR)
- OTDR: IQD (CH), Luciol (CH)

4.6.3.10 Micro photonics in Europe/Canada

Microphotonics is the integration of photonic components in the form of Photonic Integrated Circuits (PICs) through wafer scale integration techniques allowing complete photonic systems on a chip. Today thanks to concerted National and European funding over the last 20 years Europe has succeeded in building a strong ecosystem of researchers, chip designers, foundries, and software developers to scale up microphotonic technology and take advantage of the disruptive nature of this technology. Not only is the integration of photonics and electronics expected to solve the bandwidth problem that we face with our insatiable demand for data, but it is expected to have other far-reaching applications from medical point of care sensors to industrial and transportation applications. The integration of photonics, electronics and MEMS technologies will certainly have many applications given it can dramatically impact the cost of these systems, just as microelectronics and ASICs have had on the field of electronics and computing. Thanks to European Commission funding, and the collaborative effort across microphotonic ecosystem, the cost to access manufacturing a photonic integrated chips has dropped dramatically making this technology available to almost any company. This has largely been possible through the introduction of **user friendly design software**, process design kits (PDKs) combined with sponsored training schemes aimed at helping individuals master the design of PICs and the **Multi Project Wafer runs** addressing the need to share the cost of production. The attractive nature of this technology is that with volume production the cost of these photonic chips could drop to 10s of Euros and make it available for many consumer devices.

Due to the extensive National and European funding of microphotonics, Europe has to a large extent being leading this field and has a well developed eco system covering all the elements needed to successfully transfer an idea into a production pilot line.

Microphotonics in both digital and microwave domains are very much relevant to space applications and companies that wish to be suppliers of this technology are expected to make extensive use of the European Microphotonic Fabrication Ecosystem as highlighted below:

- **Software**

  Lumerical (Ansys now), Photon Design, Luceda Photonics, , VPIphotonics, Synopsis, Mentor Graphics, Optiwave, Cadence, Keysight, Nazca Design

- **Design**

  VLC Photonics, Bright Photonics, Luceda, XiO Photonics, Sicoya, Rockley Photonics, University of Cyprus, PICAdvanced, Carlos III University of Madrid, IDLabs-IMEC, CSEM

- **Foundry**

  SMART Photonics, Ligentec, Fraunhofer HHI, IMEC, LETI, IHP, ST Microelectronics, LioniX International, VTT, Sivers Photonics (former CST), Canadian Photonics Fabrication Centre, AMO, IMB-CNM, Cornerstone Southampton, Inphotec, CSEM, Lumentum, TU/e

- **Characterization/Test Service**
  VLC Photonics, Fraunhofer HHI, CSEM

- **Packaging Service**
  Phix, Photon First, IPPS, ALTER-UK, Aifotec, XiO Photonics, Ficontec, IBM (CND), Tyndall, Bay Photonics, CEA-Leti

- **PIC Photonic Pilot Lines**
  PIXAPP, JePPIX, MIRPHAB, PIX4life, PHABULOμS, MedPhab

4.6.3.11 Photonic Packaging in Europe/Canada

To date space photonics relies largely on the COTS products developed for the terrestrial Telecom market. In this market, packaging is of key importance as it drives the cost of optoelectronic components and accounts for a significant part of the overall cost of the product. Packaging of optoelectronics is a complex multifaceted process which includes optical, mechanical, thermal and electrical design. It is the optical alignment and tolerancing, which make optoelectronic components expensive and difficult to package as compared with traditional electronic devices. In space, we must consider several additional challenges, namely a very specific environment which includes vacuum and radiation which can have considerable impact on packaging. One of the key challenges that is faced by the space community is how to manage the reliability of COTS parts for space applications, where space is not the primary customer. Reliability figures are mainly driven by packaging issues. Today most Telecom components are mass-produced in Asia where little control is possible over the manufacturing process. This means that the space industry must find a way of managing the packaging needs for space by identifying and fostering European and international capabilities that support our needs.

Some innovations in photonic packaging include wafer level chip scale packaging offered by SCHOTT Primoceler Oy [FIN] is just one technology innovation that's setting new standards, offering hermetic laser bonding of two or more glass wafers without heat or added materials. Additive manufacturing using two photon polymerisation allows the printing of optical microstructures directly onto photonic integrated chips to create lenses, optical wires and other free form optical components. European companies such as Nanoscribe offer 3D printers capable of manufacturing these innovative structures directly onto various chip substrates, such as InP, SOI and Si3N4.

Today several European companies have specialized in offering capabilities for packaging for space including, LioniX International (NL) for Si3N4, Phix (NL), Photon First (NL), Inphotec (IT), mBryonics (IRL), VTT (FIN) for SiPhotonics, HHI (DE) for InP, ALTER (UK), Gooch & Housego (UK), 3S Photonics (FR), Eagleyard (DE). Tyndall's Photonic Packaging and Integration Group offers packaging services which can be used to take research concepts to commercialization. FiconTEC GmbH (DE) and Aifotec (DE) also offer prototyping, engineering design and product industrialization services targeting photonic packaging for the aerospace, military and automotive markets.

Packaging is further complicated by the need to address the system in package design space where increasingly packages need to incorporate multiple different technologies in a single package, such as is required in co-packed optics. To address these new technologies new packaging concepts will be required to deal with higher density of electrical interconnects, the higher frequency bandwidth of the transmitted signals combined with the need to manage increasingly higher thermal loads. This will require innovations not only in thermal management techniques such as micro heat pipes, but also the introduction of new heat spreader materials and substrates able to manage the density of interconnects while providing high frequency electrical performance.

PIXAPP is a European Commission funded Pilot Line that has been established to support European companies in the task of packaging photonic integrated chips. PIXAPP supports companies by matching industries need with the European capabilities in packaging. In addition to this they are driving packaging standards to enable lower cost packaging. This is achieved by designing a set of packaging building blocks that are standardised, much like the foundries have established PDKs, PIXAPP have been adding what they call Assembly Design Kits (ADK) that can be matched to the PDKs coming from the foundries covering fiber attach, laser attach, micro optics, flip chip of electronics and wire bond standards. The ADKs are software designed in the same way as PDKs are for the integrated design and are already available in software tools such as those available from companies such as Synopsis. The need in packaging is to move to lower cost standardised solutions where wafer level testing and assembly becomes possible, helping to substantially reduce costs.

4.7 Competitiveness and Benchmarking

At present, at **Payload** level although it is known that US Primes have some internal program on Photonics, it is TAS and AIRBUS that have openly presented their versions of Analog Photonic Payloads. These companies are also the first Prime to use parallel multigigabit fiber optic digital links in a commercial order for a Digital Payload. It is also known that MAXAR, investigates the applicability of microwave Photonic links and equipment and has several IoDs of equipment built by DAS Photonics [RD-DAS]. As far as **Photonic Equipment** for Photonic Payload and Fiber Sensor based Thermal monitoring Systems for Platform are concerned only European/Canadian companies have presented publicly their work and commitment to become suppliers of such Equipment. From this point of view European companies appear to lead the supply market ahead of possible competition.

On the other hand it is known that US **Launchers** procure already opto-pyrotechnics by US suppliers which means that on that application the US is ahead of Europe/Canada. ARIANE 6 will be the first launcher to employ opto-pyrotechnics,

At **Device/Component** level although there are several European/Canadian companies active in supplying space-qualified products there are also suppliers primarily from the US that promote such similar space-qualified products that are competitive to the European/Canadian ones. In certain cases US products exhibit performance that cannot be matched yet by European/Canadian suppliers. As an example, on high speed digital interconnects the critical VCSEL electronic drivers as well as VCSEL and Photodiodes, US companies are the prime source. The European and Canadian offerings based on COTS VCSEL drivers and TIA have demonstrated that while they do not suffer from Latch-up or functional interrupts (SEFIs) they will suffer from SETs which will result in a loss of bits during the SET event, something to be accounted and counteracted when used in Space. Similarly, until recently European Photonic Equipment suppliers procured Optical Modulators from US suppliers (due to the better stability over time and temperature offered by their products) as well as laser sources due to their lower power consumption and photodetectors due to their power handling capability. These are all areas where Europe/Canada needs to invest and already several activities are underway aiming as a first target to provide power-efficient, high density, Photonic Analog Links.

The following Table 4-2 includes a list of the US-based companies offering competing products in the market of Space Photonics.

Table 4-2: Non-European Industry involved in Space Photonics.

Company/Institution – Nationality	Type of Product	Remarks
RENESAS – USA	VCSEL Drivers for Digital Interconnects at 28 Gbps	Rad-hard drivers, power consumption
RENESAS – USA	TIAs for Digital Interconnects at 28/56 Gbps	Rad-hard TIAs, power consumption
BROADCOM – USA	VCSEL for digital links at 28/56 Gbps - 100Gbps (PAM4)	Extended temperature and Radiation tested, current consumption, numerical aperture
COHERENT - USA	VCSEL for digital links at 100 Gbps (PAM4)	
BROADCOM – USA	Photodiodes for digital links at 28 Gbps – 100 Gbps (PAM4)	Extended temperature, responsivity, aperture diameter
COHERENT - USA	Photodiodes for digital links at 100 Gbps (PAM4)	
EMCORE – USA	Lasers (for microwave transmission)	Low TEC consumption
HAMAMATSU – JAPAN	DFB laser sources	Maturity at TRL-9
EOSPACE – USA	Optical Modulators	Stable operation
XL Photonics – USA	Photodetectors	Large Surface-High power
HAMAMATSU – JAPAN	FIber coupled photoreceiver	Maturity at TRL-9
OSI Optoelectronics - USA	Fiber coupled photoreceiver	Maturity at TRL- 9
Micron Optics – USA	FBG Interrogator for ground testing ‘Hyperion”	Large BW offers High degree of multiplexing in a single channel

A further outline of the non-European entities companies offering competitive products (benchmarks) a to current European suppliers is depicted in Table 4-3.

Table 4-3: Competitiveness of selected European products.

Name of the Product	Technical Characteristics of benchmark product	Technical Characteristics of European product	Maturity Status (TRL) of Non European product
Laser Drivers for Digital Interconnects	Rad-hard, very low power consumption drivers at 28/56 Gbps – 100 Gbps (PAM-4)	The development is in low TRL	TRL-8
VCSELs or other lasers for digital transmission	Extended Temperature operation at 28/56 Gbps operation, current consumption numerical aperture	Slightly higher power consumption	?
Photodiodes for digital reception	Extended Temperature operation at 28/56 Gbps, responsivity, aperture diameter	Competitive and almost similar to the US one	?
TIAs for digital reception	Rad hard, very low power consumption TIAs operating in 28/56 Gbps	The development is in low TRL	
Lasers for Analog Transmission	Uncooled operation	High TEC consumption	TRL-6
Modulators for Analog transmission		In the process of qualifying – not yet stable	TRL-8
Photodetectors for analog reception	Large surface-higher power handling capability, up to 50 GHz	Small surface-lower power handling capability	
Fiber Coupled Photoreceivers	Maturity on TRL-9	Less mature	5-6
FBG Interrogators for ground testing			
Optical Delay Trimmers	Existing	Non-existing	N/A

4.8 Technology Trends and Technology Synergies and Transfer Opportunities

4.8.1 Keywords for Spin-in technologies/sectors

KEYWORDS: Integrated optics, Microphotonics, Green Internet, Distributed Fiber Sensons, Photonics in Nuclear enviroments

Photonics are evolving rapidly in ground applications and Space cannot be a real driver especially for the lower TRL developments. However, it is important to monitor continuously these developments and at the right time to invest the right amount of funding in order to spin in to Space specific technologies that will be identified as being of interest. There are a few particular directions of developments that are of interest:

- **Power Efficient discrete photonic components**: the continuous improvements of functional performance, power consumption reduction (driven by the need for “Green Internet”) and mass and volume reduction of Photonics is of immediate interest in space applications. Examples are the increased wall-plug efficiency Optical Amplifiers, laser sources with very low thermal dissipation and no need for TEC, high frequency optical modulators with very low $V\pi$ and low insertion losses, high frequency-high dynamic range optical receivers. All these components and hybrid devices play a key role in a number of spaceborne applications and in the minimalistic conditions of a S/C every improvement in efficiency is important and should be exploited.
- **Digital Microphotonics:** The development of massive data centres is driving many new innovations in the field of transceiver design, in particular low cost microphotonic fabrication with reduced power dissipation is a critical enabler for this application. Silicon Electronic/Photonic ICs are pursued. Such micro Electro-Photonic solutions are already under consideration in ESA. Especially in digital Payloads the idea of ASICs/FPGAs with optical I/O interconnects has emerged as the next step that can enable high throughput communications with ease of thermal management.
- **Analog Micrphotonics:** There are several developments of microwave integrated optics inground for applications like BFN for the 5G//6G applications that can be directly related to similar applications in Space. This includes the integration of active and passive components operating with the appropriate RF performance at the frequency bands reserved for satellite communications up to W-band The use of integrated optics Optical Frequency Combs is another technology that can be used in Frequency Conversion units. The development of such microphotonic solutions is of great interest in Space as currently microphotonic versions of all COMSAT Payload Equipment are under development. Hybrid integration has the higher chances of being implemented whereas monolithic integration remains a holy grail for the photonic integration community.

- As opposed to FBGs and FP sensors which offer quasi distributed sensing, a new generation of fiber optic senors are emerging, such **as distributed acoustic sensing** (DAS) and distributed temperature sensing (DTS). These distributed fiber optic sensors are based on one or more of the inherent scattering mechanisms inherent to the glass material of the optical fiber (Raman, Brillouin or Rayleigh scattering). Changes in the properties of these scattering mechanisms (either wavelength or amplitude) are used to extract information concerning the strain or temperature field experience by the fiber, and by combining this with radar approaches the strain and or temperature field along the fiber can be extracted. On ground the use of truly distributed fiber optic sensing is finding a wide variety applications including the monitoring of tunnels, embankments, pipelines, railway lines and electrical cables. The challenge today is extracting this information with a high spatial and temporal fidelity suitable for space structures, where the interest is to measure strain or temperature with sub-centimetre resolution. The application of this would be very disruptive as it promises the capacity to capture 1000s of sensing points along a short strand of fiber . The combination of these developments with novel multi-core fibers will open the door to many interesting capabilities such as shape monitoring of large and flexible space structures. This combined with the increased capabilities of digital processing should allow real time monitoring of shape.

Both the EU and National Institutional funding agencies are funding the development of photonic technologies for non-space applications, which however can have a direct impact on advancing the TRL of photonic technologies/products for use in space. The tables below depict a non-exhaustive list of spin-in activities provided by the EU and the National Space Agencies which conclude after 2023.

4.8.2 Keywords for Spin-Off technologies/sectors

KEYWORDS/PHRASES: Radiation-Hard Photonics, rad-hard active fibers for optical amplifiers, microwave photonics, digital photonics, photonic payloads

As ESA qualifies components and equipment for operation under the unique characteristics of the space environment i.e. the vacuum and the radiation spin off can be envisaged in similar environments e.g. nuclear reactors and facilities like hospitals and research centres using radiation. Development of high power lasers in the visible and in the IR range that could be used in extra-satellite communications and in optopyrotechnics for example would also benefit the industrial field (manufacturing, medical, etc…).

5 MISSION NEEDS AND MARKET PERSPECTIVES

5.1 Application to Missions and Market Perspectives

5.1.1 Application to Missions

Photonics are considered primarily for COMSAT Payloads and Buses. Scientific Payloads shall also make extensive use of fiber optic links, and custom solutions for calibration and instrument metrology. Finally, ARIANE-6 has specified opto-pyrotechnics as the baseline technology.

Table 5-1: Missions relevant to Space Optics and projected investment

Mission / Mission Type	Technology Development Need	TRL Target	ROM Cost
COMSAT PAYLOADS	Rad-hard VCSEL drivers and TIAs for Digital Links inside the DSP	TRL-8	5 Meuro
	Co-packaged/near-packaged optical solutions for next generation processors	TRL-6	5 Meuro
	Cooler-less lasers for analog links antenna-DSP-antenna	TRL-8	5 Meuro
	High density, temperature stable modulators for analog links	TRL-8	1 Meuro
	High density, high frequency, high dynamic range photodetectors	TRL-8	1 Meuro
	Efficient and stable frequency generation and frequency conversion units	TRL-6	1 Meuro
	Qualified Photonic Switches	TRL-6	5 Meuro
	Qualified Photonic BFN	TRL-6	6 Meuro
	Qualified Photonic RF Filters and (DE)MUXs	TRL-6	3Meuro
SCIENCE PAYLOADS	Photonic Digital Links for all high data rate instruments	TRL-8	1 Meuro
	Photonic Analog Links for SAR	TRL-6	1 Meuro
	Laser sources for science payloads	TRL-8	1 Meuro
	Micrphotonic Instrumentation	TRL-6	1 Meuro
ALL TYPES S/C PLATFORMS	ADHA and standardisation of Space-Fiber links for OBDH	TRL-8	2 Meuro
	Optical Wireless	TRL-8	2 Meuro
	Optical Temperature Sensors	TRL-8	1 Meuro
LAUNCHERS	Opto-pyrotechnics	TRL-8	2 Meuro
	Qualified Fiber Optic Sensors	TRL-8	1 Meuro
	Laser ignition for future launchers	TRL-6	2 Meuro

Mission / Mission Type	Technology Development Need	TRL Target	ROM Cost
GROUND SEGMENT	Optical Wireless	TRL-6	1Meuro
	Fiber optic sensors for ground segment	TRL-9	1 Meuro

5.1.2 Market Perspectives

Euroconsult has performed a market study to quantify the market for Photonics that would be addressable by European suppliers over the next decade (2022-2031). The estimate of the addressable market is based on Euroconsult's most recent satellite and ground segment forecast released end of 2022 for all types of satellites (any size, any operator, any country, any application). The satellite market that is addressable by European suppliers is a subset of that total market, considering commercial and technical addressability by European suppliers. provides a summary and overview of the main take aways of the market assessment and forecast of the addressable market for European Photonics.

The detailed report on the market assessment is attached in Annex B.

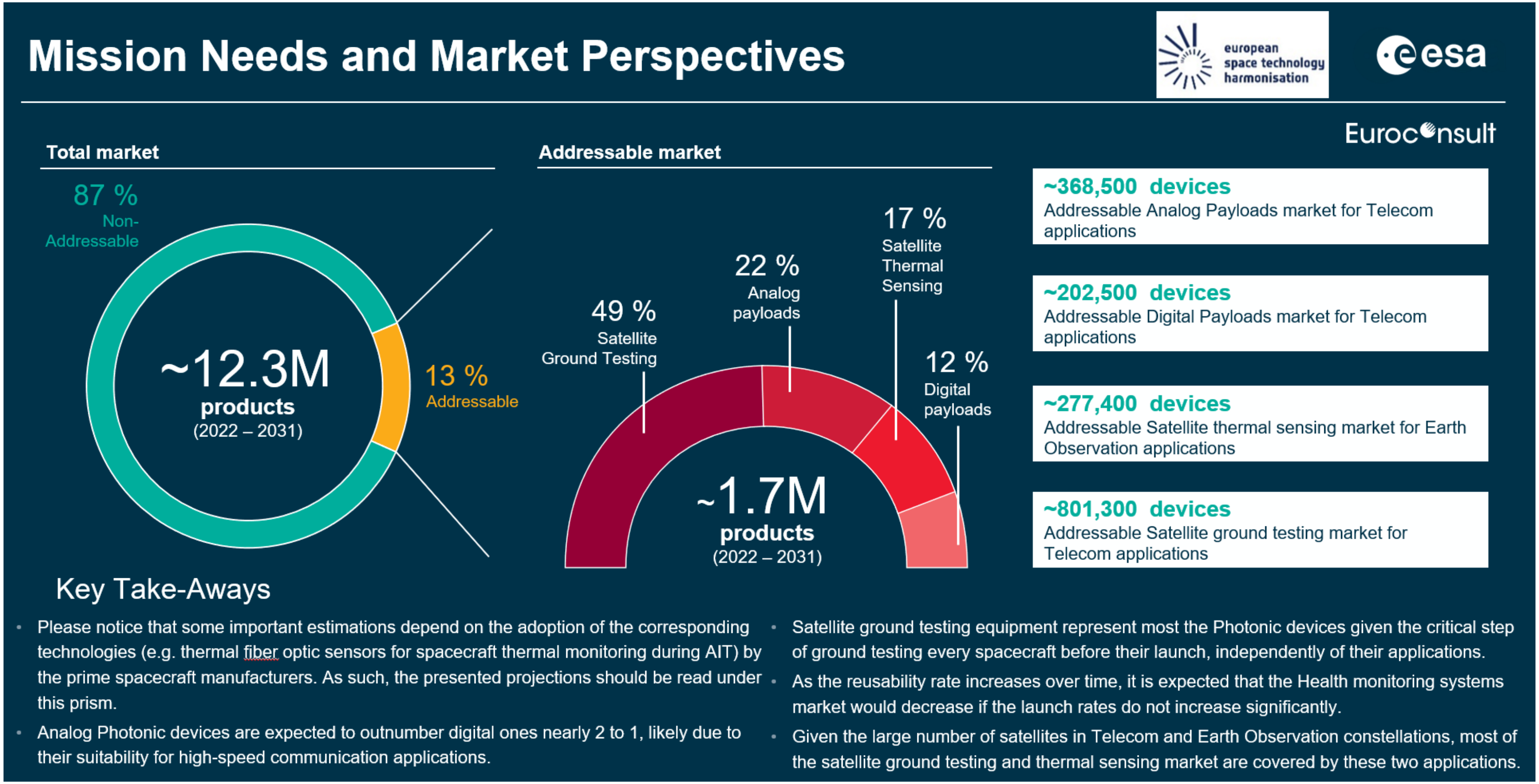


Figure 5-1: Market Assessment key take-aways.

Since the release of the first edition of this THD and the introduction of the Photonic Digital Interconnects at commercial COMSAT PLs along the FOG and the Opto-pyrotechnics the market potentials for Photonics has been better clarified. By now it is understood that every HTS PLs embarking a DSP will require hundreds of **photonic digital links** (2000 as a conservative rule of thumb). When **photonic analog links** will be baselined a number of such links that equals twice the number of radiating elements (antenna to DSP and DSP to antenna) will be required. This again as a rule of thumb will be in the order to 500 per satellite having as a basis scenario an antenna with 250 radiating elements. This number may even increase to 1000 per satellite if one considers that each antennae element produces a Horizontal and a Vertical polarised signal. The above numbers when accounted for the total number of GEO satellites ordered per year provide a good basis for any potential supplier of Digital and/or Analog links to estimate the total volume of the market. Further adoption of these links by the NGSO satellites may lead to a remarkable further increase of the market size.

In the market assessment attempted by this THD the main uncertainty comes from the potential market size of Microwave Photonic Equipment like the FGU for MRO/LO and the Frequency Converters who have already been demonstrated in 3 IoDs by DAS Photonics. Although both big Primes in Europe, ADS and TAS, have demonstrated such payload designs in the laboratory there has not been any further work since 2020 when the EU OPTIMA project was concluded [RD-ADS-OPTIMA]. This is despite the fact that both companies had run studies showing the benefits of introducing Photonics in GEO PLs primarily offering flexibility in resource allocations. The emerging market of NGSO constellations is of importance due to the extremely high number of satellites and despite their small S/C-P/L size. One of the conclusions of previous studies was that if one constellation employs Photonics, for example as Frequency Converters, it will pay back immediately for all the investment made by the company in this technology. The cost of Photonic Equipment in such hybrid “Microwave-Photonic Payload” designs is in the order of several Meuros which is to be defined for each design and RFQ offer.

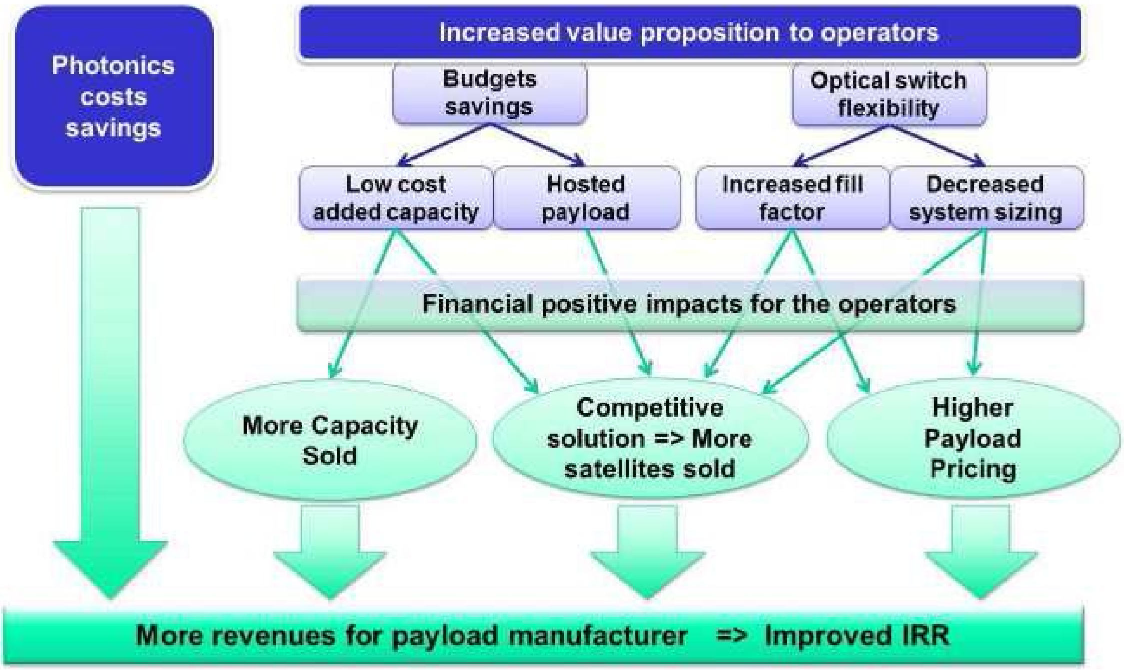


Figure 5-2: Value proposition of Photonics in Analog COMSAT PLs assessed by TAS in [RD-TAS-RDMP].

Spin off applications of the technologies developed under for Telecom payloads are expected to the EO and Space Science payloads. These first candidate technologies are the Digital and Analog links (for e.g. SAR) linking instruments to On Board Processor or Mass Memory. The SpaceFiber product is expected to be employed in all sorts of **Scientific Payloads** as well in all type of **Platforms** as a technology for OBDH links. It is reasonable to assume that most of the high-bit rate instruments would use a SpaceFiber. An estimation of the respective market can then be made on the basis of the calculated number of such instruments expected to fly over the coming few years.

The market **for fiber optic sensing systems** is difficult to calculate as it includes both ground and flight instrumentation and needs to consider both the interrogator and sensor arrays. Both the HSB and the MRTU engineering models consider telecom satellites with a large number of temperature sensors (such as the E3000 and NGP platforms) as their primary target application. The expected volumes of large Telecom satellites is expected to be around 10-15 per year, and the cost of a thermal monitoring system for such a large platform including sensors can be around 600k€. In addition the supply of sensors and interrogators for ground test facilities could add considerably to this value. Added value propositions such as the photonically wired panels, heater tapes or mechanical structures with integrated fiber optic sensors are also seen as a means to bring new functionality to space equipment. The market estimations depicted in Figure 5.1 are based on the assumption of adoption of fiber sensors and a baseline thermal monitoring technology in AIT. However, this is still debatable and further advances need to be accomplished before fiber sensors are introduced in AIT. Figure 5.1 must be seen under this prism.

The market for the **Opto-pyrotechnics in Launchers** is easier to be defined as the technology has been baselined for the Ariane 6 launcher, the first flight of which is planned for 2023. Here after Ariane Group plan to launch between 9 -12 flights per year. Today the industrial landscape has taken shape and with the optopyro system being split between in different parts supplied by different companies. The total cost of the pyro system is unknown at this time, but it is safe to assume that this represents some 10s of MEuro of business over the first 35 Ariane 6 flights, planned by 2030.

In the **Ground AIT** the market is obviously limited to the number of AIT halls. The number of Optical Wireless or Fiber Optic Sensors systems to be procured will be linked to the number of AIT Halls. The value of each such system is in the order of some tens or hundreds of keuros Nevertheless the importance of this market is that introduces the S/C engineers in these new technologies opening the way of introducing the same solution in flight.

5.2 European Strategic Interest

Europe has invested significantly in Photonics for Space since 2001 and a family of companies that have the aspiration to be the preferred suppliers of photonic components, devices equipment and payloads has been formed. 3 Photonic products have by now been adopted by the space market creating also the “first to enter the market” suppliers. To a large extend this influences the supplier’s potential for the next decade since the first selected supplier would be in position to claim space heritage for upcoming RFQs. Europe/Canada must ensure that their companies are the selected ones in order to maintain the current dynamic fuelled by tens of Meuros of investment. If this does not happen then the danger is that US competitors will appear to harvest the fruits of more than 20 years of European/Canadian efforts to establish Photonics as a standard technology in satellites. Due to the increasing importance of Photonics in many applications it has to be ensured that a sustained and sufficient level of funding is quickly made available in Europe to keep the leadership position by sustaining a viable supply chain.

6 IMPLEMENTATION OF PREVIOUS ACTIVITIES

6.1 Previous Roadmap and Recommendations Implementation Status

This section shows statistics on the previous Roadmap generated by the Harmonisation Tracking System (HTS). More details can be found in the HTS Report updated and distributed once a year and accessible on the HDMS (https://tec-polaris.esa.int/).

The following figure shows general statistics about the 2018 Roadmap agreed in Fall 2022 and the situation at the moment of its agreement.

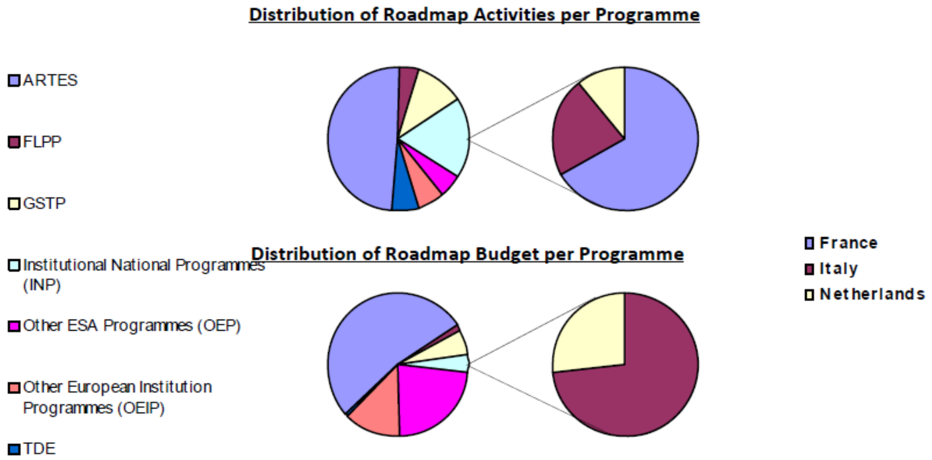
General Roadmap Statistics

**planned budget, excluding confidential or not provided*

The Roadmap has 52 activities, for a total of 69633 k€* including 6 activities for which there is no budget estimate.

- ***Roadmap Activities Distribution per Programme***

  - ESA: 40 activities for a budget of 58083 k€*
  - National: 9 activities for a budget of 2750 k€*



- ***Roadmap Activities Status when this Roadmap was Approved***

  Out of the 52 activities for the total Roadmap budget of 69633 k€*:
  - 26 Roadmap Activities for a budget of 36533 k€* had been already approved before Harmonisation.
  - 26 Roadmap Activities for a budget of 33100 k€* had not been approved before Harmonisation or no funding status defined.

- ***Roadmap ESA Activities Status when this Roadmap was Approved***

  Out of the 40 Roadmap ESA activities for the total Roadmap budget of 58083 k€*:
  - 15 Roadmap Activities for a budget of 27983 k€* had been already approved before Harmonisation.
  - 25 Roadmap Activities for a budget of 30100 k€* had not been approved before Harmonisation or no funding status defined.

Figure 6-1 Harmonisation topic Photonics Roadmap as agreed in 2018.

The following figures show the level of implementation of that 2018 Roadmap assessed during the Fall 2022:

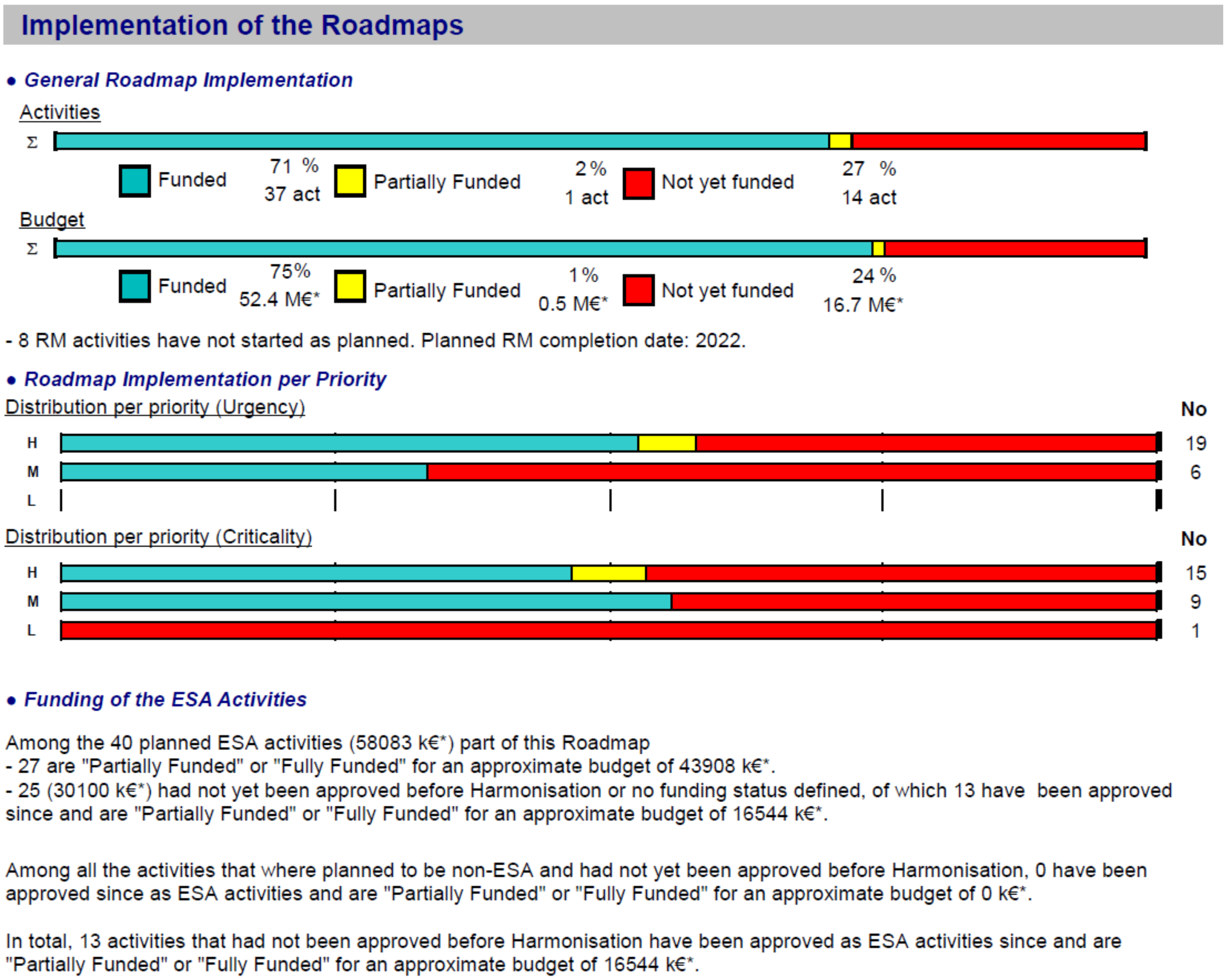
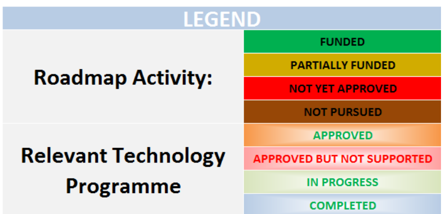


Figure 6-2 Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status

Based on the figure above, 13 ESA activities of the 2018 Roadmap have been approved since then and are “Partially Funded” or “Fully Funded” for a budget of about 16.5 M€ (16,544 k€).

The following Gantt Chart shows the detailed 2022 implementation status of the previous Roadmap agreed in 2018.



The Gantt Chart shows two types of horizontal bars:

- solid fill bars represent the Roadmap activities;
- gradient fill bars represent relevant activities from Technology Plans.

Other relevant information shown on the Gantt Chart includes the current status (colour code as detailed in the legend), the planned programme, start/end dates and TRL (start and target). The absence of a solid bar for a Roadmap activity means that no start/end date is defined in the Roadmap for that specific activity.

			Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	Supplier		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
AIM A:		COM digital payloads																			
AIM A	A01	Space qualified digital interconnects	H	H	2000								ARTES			TRL 7					
		28 Gbps Transceivers for Space			*535*	*5f.011 SL9010*	*'eflex Photonics*						*TRL 4*	*ARTES ScyLight*					*TRL 8*		
	A02	Electro-photonic ADC	M	L	2000								TRL 3	ARTES			TRL 5				
	A03	ASICS with optical inputs / outputs	H	M	2500									ARTES				TRL 6			
		nectivity solutions based on advanced microphotonics for future Digital Telecommunications Payloads			*500*	*T506-605MM*	*mbryonics*							*TRL 2*	*TDE*				*TRL 3*		
	A04	Fiber Optic Flexible Routing Assembly (FOFRA)			225	5D.032				TRL 5	ARTES				TRL 7						
		Fiber optical flexible routing assembly (FOFRA)			*225*	*5D.032*	*T & G ELEKTRO*			*TRL 5*	*ARTES CG*								*TRL 7*		

Figure 6-3: Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status vs planned (1/5)

		Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	Supplier		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
AIM B:	**COM analog payloads**																			
B01	**Optical polarization modulator**				5C.366						TRL 4	ARTES				TRL 7				
	Optical polarization modulator				*5C.366 - 4000123240*	*Optelian Access*					*TRL 4*	*ARTES CG*			*TRL 7*					
B02	**Space qualified photonic routers**	H	H	2000									ARTES			TRL 7				
	LEO / GEO Optical Switch Matrix 25x25			*3000*	*5F.022*											*TRL 3*	*ARTES ScyLight*			*TRL 5*
B03	**SODAH**			3000							TRL 3	OEIP			TRL 6					
	SODaH: Software Defined Space Optical Data Highway			*3106*							*TRL 3*	*H2020*			*TRL 6*					
B04	**Space qualified MUX/DEMUX**	H	H	2000									ARTES			TRL 7				
	Wavelength division multiplexer (WDM) and de-multiplexer at 1550 nm for space applications			*500*	*5G.027*											*TRL 3*	*ARTES ScyLight*			*TRL 5*
B05	**Photonic RF filters**	H	M	2000								ARTES				TRL 7				
	Photonic RF tuneable Demultiplexer for Broadband Satellites			*500*	*T517-701MM*	*NER Aeroespac*								*TRL 2*	*TDE*			*TRL 3*		
B06	**Photonic beam forming network**	H	M	2000							TRL 3	ARTES					TRL 7			
B07	**Microphonic frequency converters**	H	H									ARTES					TRL 7			
	Development of photonic building blocks for communications satellite payloads					*Antwerp Space*						*TRL 3*	*ARTES CG*				*TRL 6*			
B08	**Large Scale Integrated Photonic Switch Matrix for Dynamic Reconfiguration of Optical Payloads**			850	5C.364						TRL 3	ARTES			TRL 5					
	Large scale integrated photonic switch matrix			*850*	*5C.364*	*le Poly. Lausan*						*TRL 3*	*ARTES AT*				*TRL 5*			
B09	**Optical Switches based on Si Photonics**			175	B02017157						TRL 3	TDE		TRL 5						
	Optical Switches based on Si Photonics			*175*	*B02017157*	*VTT*					*TRL 3*	*Discovery*					*TRL 5*			
B10	**Single String Photonic Payload (SSPP) and Multi String Photonic Payload (MSPP)**				contract 4000122614					TRL 5	ARTES			TRL 7						
	Single String Photonic Payload (SSPP) and Multi String Photonic Payload (MSPP)				*4000122614*					*TRL 5*	*ARTES CG*			*TRL 7*						
B11	**Lasers for analogue transmission**	H	H	500									ARTES		TRL 8					
	Development of photonic interconnections for the next generation on-board digital processor			*900*	*4000129688 - SL9006*									*TRL 4*	*ARTES ScyLight*			*TRL 6*		
B12	**Space Qualified Pump Laser Module**	H	H	500								ARTES			TRL 8					
	High power pump laser modules for Erbium-Ytterbium doped fibre amplifiers			*900*	*5F.040*											*TRL 3*	*ARTES ScyLight*			*TRL 6*
B13	**High Power High Dynamic Range Photo Receiver for COMSAT Payloads**			392	5C.237				TRL 3	ARTES				TRL 5						
	High Power Photoreceivers for High Dynamic Range - High Frequency Photonic RF Links (CCN incl)			*392*	*5C.237*	*OPTOELECTRO*			*TRL 2*	*ARTES AT*					*TRL 4*					
B14	**Space Qualified High Power High Dynamic Range PD**	H	H	600									ARTES		TRL 8					
	Bandpass RF O/E Converter (BAROC)			*762*	*5F.027*	*is Optoelectron*								*TRL 4*	*ARTES ScyLight*			*TRL 7*		

AIM B

Figure 6-4: Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status vs planned (2/5)

		Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	Supplier		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
AIM B:	COM analog payloads																			
B15	Pigtailed InGaAs photodiode @ 1550nm	H	M	350									GSTP		TRL 7					
	Pigtailed InGaAs photodiode @ 1550 nm, Evaluation and space qualification			*350*						*TRL 4*	*CNES*			*TRL 7*						
B16	Fibre coupled optical isolators	H	H	500								TRL 4	ARTES		TRL 6					
B17	Pump Combiner High Reliability	M	M	300								TRL 3	TDE			TRL 6				
B18	Space qualified FGU	H	H	2000								TRL 5	ARTES			TRL 7				
B19	Space qualified Frequency Converter Unit	H	H	2000								TRL 5	ARTES			TRL 7				
B20	Space qualified photonic equipment	H	H	2000								TRL 5	ARTES			TRL 7				
B21	Space qualified photonic payload	H	H	500								TRL 6	ARTES			TRL 8				
B22	Packaging of Integrated Optic Technologies	M	H	1600								GSTP			TRL 4					
	ged integrated photonics-based RF/optical hybrid transceiver for sensing and communication (PIOTS)			*1197*	*GT27-001MM*	*ola Sup Sant Ar*					*TRL 5*	*GSTP*						*TRL 7*		
	Packaging of photonics for laser communication terminals			*800*	*5F.029*											*TRL 3*	*ARTES ScyLight*			*TRL 5*
B23	OPTIMA			2800					TRL n/a	OEIP			TRL n/a							
B24	Ka band Photoreceiver			0					TRL 3	INP [FR]			TRL 4							
B25	Dual Drive LiNbO3 modulator			0					TRL 2	INP [FR]			TRL 3							
B26	Transport of multiplexed RF signal over fiber			0							TRL 3	INP [FR]		TRL 5						
B27	CUSCO			0							TRL 3	INP [FR]		TRL 5						
B28	WDM component evaluation			0							TRL 3	INP [FR]			TRL 5					
B29	Design, fabrication, evaluation in representative environment			0					TRL 3	INP [FR]				TRL 5						
B30	Monolitic integration of modulator/driver electronic-photonic for satellite lasercom (OISLs)			3000							TRL 3	OEIP				TRL 5				
B31	27-33 DBM optical fiber amplifiers for space applications			280	5C.284					TRL 3	ARTES			TRL 5						
	27-33 optical fiber amplifiers for space applications			*280*	*5C.284*	*MPB*		*TRL 3*	*ARTES 5.2*						*TRL 8*					
	High-Power radiation hard optical fibre amplifiers for satellite communication			*247*	*5A.048*	*G&H*		*TRL 3*	*ARTES 5.2*				*TRL 5*							

Figure 6-5: Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status vs planned (3/5)

		Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	Supplier	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
AIM C:	**Payloads in Earth Observation and Space Science Payloads**																	
C01	Space fiber optical harness	H	H	200							TRL 5	GSTP			TRL 6			
C02	Space fiber optical transceiver	H	H	1000							TRL 4	GSTP			TRL 6			
C03	Polarising Optical Fibre	M	M	250							TRL 3	TDE		TRL 5				
C04	Optical Harness for future L-Band radiometer			300	MME-EOP-2017				TRL 3	OEP			TRL 5					
	Optical Harness for future L-Band radiometer			*300*	*MME-EOP-2017*	*AS PHOTONICS*			*TRL 3*	*EOPP*				*TRL 5*				
C06	RF/Optical transceiver for communications in space			1000	2017-33-H.0				TRL 2	INP [IT]			TRL 4					
	RF/Optical transceiver for communications in space			*1000*	*2017-33-H.0*				*TRL 2*	*INP*				*TRL 4*				
C07	Photonics-based frequency-agile RF transceiver for satellite systems			1000	2017-34-H.0				TRL 2	INP [IT]			TRL 4					
	Photonics-based frequency-agile RF transceiver for satellite systems			*1000*	*2017-34-H.0*				*TRL 2*	*INP*				*TRL 4*				
C08	Optical Space Instrumentation Network			750	NSO KNW.2017.003					TRL 3	INP [NL]			TRL 4				
	Optical Space Instrumentation Network			*750*	*NSO KNW.2017.003*					*TRL 3*	*INP*			*TRL 4*				
AIM D:	**S/C platforms**																	
D01	Optical wireless in platforms			700	4G.023					TRL 4	ARTES			TRL 5				
	Optical wireless in platforms			*700*	*4G.023*					*TRL 4*	*ARTES AT*					*TRL 5*		
D02	Distributed thermal and strain sensing			450	4D. 051						ARTES			TRL 4				
D03	Shape sensing of large deployable structures using multicore optical fibers	M	M	500								ARTES			TRL 4			
	In-orbit Optical Shape Sensing Measurements			*600*	*4E.075*	*INRM*							*TRL 3*	*ARTES AT*			*TRL 5*	
D04	Development of hermetic optocouplers for space applications			200	G617-222QT				TRL 4	GSTP			TRL 6					
	Development of hermetic optocouplers for space applications			*200*	*G617-222QT*	*TOELETTRONI*			*TRL 4*	*GSTP*			*TRL 5*					

Figure 6-6: Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status vs planned (4/5)

			Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	Supplier		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
AIM E:		Launchers																			
AIM E	E01	Space qualified optopyrotechnics for Ariane			#####					TRL 5	OEP							TRL 8			
		Space qualified optopyrotechnics for Ariane			*####*					*TRL 5*	*ARIANE-6*							*TRL 8*			
	E02	Space qualified optopyrotechnics for VEGA	H	M	300								OEP		TRL 8						
		Second Generation Optopyro Systems for Launchers (contract 1)			*2000*	*4000129011*										*TRL 3*	*FLPP*		*TRL 5*		
		Second Generation Optopyro Systems for Launchers (contract 2)			*2000*	*4000138035*										*TRL 3*	*FLPP*		*TRL 5*		
	E03	Structural Health Monitoring of Composites Using Fibre Optics	M	M	500								TRL 3	FLPP			TRL 5				
		Integrated Optical Fibres in Launcher and Spacecraft Composite Structures			*500*	*G61A-005MS*	*INPHOTECH*					*TRL 3*	*GSTP*					*TRL 5*			
	E04	Reliable Sensor Network (IR Wireless)			300			TRL 5	FLPP						TRL 6						
		Reliable Sensor Network (IR Wireless)			*300*	*4000110733*		*TRL 5*	*FLPP*						*TRL 6*						
	E05	Integrated Optical Fibers in Launchers and Spacecraft Composite Structures			500	G61A-005MS						TRL 3	GSTP		TRL 4						
		Integrated Optical Fibres in Launcher and Spacecraft Composite Structures			*500*	*G61A-005MS*	*INPHOTECH*					*TRL 3*	*GSTP*					*TRL 5*			
AIM F:		Aeronautics																			
AIM F	F01	Innovative Ground Segment Components for VIASAT-3 SATCOM System			4000	17.3TT.13					TRL 3	ARTES						TRL 4			
		Innovative Ground Segment Components for VIASAT-3 SATCOM System			*4000*	*17.3TT.13*					*TRL 3*	*ARTES*						*TRL 4*			

Figure 6-7: Harmonisation topic Photonics 2018 Roadmap: 2022 implementation status vs planned (5/5)

6.2 Additional Activities

The following table provides a list of activities in the **Photonics** domain that were not included in the 2018 roadmap but were approved and started/completed between 2018 and 2023.

Table 6-1 Summary of additional activities (ESA only) not included in previous roadmap.

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
MICOR: MICrowave Optical oscilatoR	200	GSTP De-risk	G617-241TAabh	Ongoing	n/a	n/a	2022	2023
Black Silicon induced junction photodiode applied to scintillator-based detectors for hard X-ray and Gamma ray detectors	350	GSTP	GT12-400MM	Ongoing	5	6	2022	2023
IDOS: Integrated label-free detection in optofluidics systems for sample analysis	350	TDE	T314-603MM	Complete			2020	2023
In orbit Metrology of Large Deployable Reflectors	500	TDE	T120-601MS	Complete	2	4	2020	2023

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
WDM High-Power Optical Amplifier at 1550nm		ARTES		Ongoing	4	5	2023	2026
Laser Transmitters for smallsats and cubesats		ARTES		Complete	4	5	2018	2022
RETINA: Four-quadrant InGaAS avalanche photodiodes for LEO direct-to-Earth optical ground station	472	ARTES ScyLight	6C.016	ongoing	3	6	2023	2025
Digital and analog optical interconnects for the next generation on-board processors		ARTES ScyLight		ongoing	4	8	2020	2024
56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads	ND	ARTES ScyLight	5F.015	Ongoing	3	6	2023	2025
ASIC/FPGA with 112 Gbps Optical I/Os	ND	ARTES ScyLight	5C.480	Funded	3	4	2024	2026

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
Reliable Lithium Niobate Modulators (RELINO)	ND	ARTES C&G	6B.124 4000141266	Ongoing	4	6	2023	2025
Lithium Niobate Photonic integrated circuit based high speed, low voltage modulators for microwave photonics	350	NAVISP Phase 3 E1	E/0365-70	Ongoing	3	5	2023	2025
High density Lithium Niobate integrated photonic circuits for high-speed low-voltage modulators	175	Discovery	4000141010	Ongoing	2	3	2023	2024
Photonic RF tuneable Demultiplexer for Broadband Satellites	500	TDE	T517-701MM	Ongoing	2	3	2021	2023
Large scale integrated photonic switch matrix	800	ARTES A&T	5C.364	Ongoing	3	5	2019	2023
High-power fibre-coupled optical switch for space applications	500	TDE	T217-074NA	Ongoing	3	4	2023	2025
Optical Switches based on Silicon Photonics	175	Discovery	4000123859	Ongoing	3	4	2019	2023

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
Microwave Photonic Satellite PL based on Tunable Optical Comb Generators	250	PECS	CY2_16	Ongoing	2	3	2019	2023
V-band FGU implemented with Integrated Photonics	250	PECS	CY3_02	Funded	3	4	2024	2026
Integrated Photonics Frequency Generation Unit for High Throughput Satellites	65	Discovery	4000138240	Ongoing	2	3	2021	2024
Photonic generation of sub-thz signals using optoelectronic oscillator	100	PECS	CY4_01	Ongoing	2	3	2023	2024
Integrated microwave photonic technology for wide-frequency tuning signal generation	100	Discovery	4000135351	Ongoing	2	3	2021	2024
Photonic Signal Processing to remove all 5G/6G band signal from the water signal	50	Discovery	4000137231	Ongoing	2	3	2022	2025
Packaged integrated photonics-based RF/optical hybrid transceiver for sensing and communication	1200	GSTP	GT27-001MM	Ongoing	3	5	2020	2024
High power optical termination	250	TDE	T723-801ED	Funded	3	4	2024	2026

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
Photonic Components analysis in support of the LISA laser system development	600	CTP	C217-084FT	Ongoing	n/a	n/a	2019	2023
Cold Photonics	175	Discovery	4000135867	Ongoing	2	4	2022	2023
Optical Vector Magnetometer Based on The Hanle Effect	750	CTP	T207-068MM	Funded	2	3	2023	2025
Laser Wireless Power Transfer	1000	E3P	E2CX-048	Funded	3	5	2023	2024
High-speed integrated electro-optic modulation and up-conversion for cold atom experiment in the visible range	175	Discovery	4000137426	Funded	2	3	2023	2024
High performance space-grade frequency-combs	100	Discovery	4000137426	Funded	2	3	2023	2024
Narrow linewidth frequency agile integrated photonic lasers for space	175	Discovery	4000137426	Funded	2	3	2023	2024
Autonomous and viable processes to manufacture complex structures in space	130	ESA StarTiger	AO/2-1823/22/NL/AS	Ongoing	4	4	2023	2023

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
Optical Wireless On-Board Data Transmission "Light Fidelity" (LiFi) for Telecom Spacecraft	800	ARTES AT	4000125458/19/UK/NR	Ongoing	3	4	2021	2024
Optical Fibre Cable for Space Applications	500	GSTP	GT17-301ED	Funded	4	6	2023	2025
Optical Fiber Micro-Kelvin Temperature Sensor Network	400	CTP	4000135481	Ongoing	3	4	2021	2023
Improving satellite propellant gauging accuracy with high accuracy optical pressure sensors	175	Discovery	4000138372	Ongoing	3	4	2022	2024
Simple Fiber-Optic Strain sensor for monitoring preload in critical bolted joints.	175	TDE	4000138375	Ongoing	3	4	2022	2024
Photonically Assisted Multibeam Phased Array Antenna		ARTES C&G	6C.030	Ongoing			2022	2024
AIDAN - Innovative Ground Segment Components for Satcom Systems		ARTES 33	40000121956/17/NL/CLP	Ongoing	4	9	2017	2024
Evaluation of radiation sensitivity of Photonics Integrated Circuits technology	175	Discovery	4000136428	Ongoing	4	5	2022	2023

Title	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
					Start	End	Start	End
Towards a high performance space-grade frequency-combs	103	Discovery	4000138841	Ongoing	2	4	2022	2024
AutoMAIT Co-Packaged Optics for Space		ARTES ScyLight	5F.035	Ongoing	4	5	2022	2024
Erbium-doped photonic integrated circuit-based amplifier	175	Discovery	4000141527	Ongoing	2	3	2023	2024
Thormux- Tuneable Photonic RF Demultiplexer for Broadband Satellites	500	TDE	T517-701MM	Ongoing	3	4	2021	2024

The cumulative ESA budget approved for these 45 additional activities is 12.7 M€ (12,745 k€), excluding confidential budgets.

Table 6-2 Summary of additional activities (non-ESA) not included in previous roadmap.

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
Power solution in vacuum PS (6W)	AVIM™ Family	ND	Internal funding (CH)			4		2022	
Power solution in vacuum PS+ (16W)	AVIM™ Family	ND	Internal funding (CH)			4		2022	
Compact multichannel for cryogenics and in-vacuum application	New connector	ND	Internal funding (CH)			6		2022	

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
µSpec BreadBoarding activity	On-board calibration stimulus Instrument Cluster: LXI is subcontractor to Cosine	525	Instrument Cluster (NL)	3190032	completed	4	6	2021	2022
Broadband Spectral Shaper on-a-chip	Flattening laser frequency comb spectra with a high dynamic range, broadband spectral shaper on-a-chip	100	CALTECH / JPL / NASA (NL)		completed	3	4	2020	2022
PhotonDelta Flagship	Building a Dutch Ecosystem for Integrated Photonics Modules in Space	3119	Stichting PhotonDelta (NL)	1903020	Ongoing	3	7	2020	2024
NextGen HighTech	develops a new generation of high-tech equipment within six application domains: laser satellite communication, biomedical production technology, semiconductors, composites, energy and agri-food.	1,200,000	Nationaal Groeifonds (tweede ronde) (NL)		Ongoing	4	7	2023	2028
PhotonDelta	Brings the Dutch Ecosysteem for integrated Photonics to European Top Level.	1,100,000	Nationaal Groeifonds (tweede ronde) (NL)		Ongoing	4	7	2023	2028
FREE	Superhighway for digital data; Optical Wireless Superhighways: Free photons (at home and in space): FREE	4,100	NWO Perspectief Research Program 2020 (NL)	TTW P19-13	Ongoing	3	5	2021	2025

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
Technology Development LiDAR imager	Space LiDAR Feasibility and Preliminary Design Study	600	PPP Project	100 348 613	Ongoing	3	5	2023	2024
Phlexsat	Photonic COMSAT PL employing Photonic ADCs	3,000	EC H2020		ongoing	3	4	2021	2024
MINIBOT	Transceivers for VHTS DTP 32 Gbos	3,000			ongoing	3	5	2023	2025
EURISA	FOG based IMU	3,280	EC H2020		ongoing	3	5	2021	2024
SIPHODIAS	Opto-electronic (O/E) modules for communication SIPHODIAS invests in state-of-the-art SiGe BiCMOS, GaAs and InP manufacturing technologies as well as innovative assembly and module packaging to deliver high-speed digital optical transceivers, high-bandwidth electro-optic modulator arrays and miniaturized analogue photodetectors. The optical transceivers are designed to deliver >100 Gb/s optical interconnects within the payload digital processor whereas modulators and photodetectors will enable operating frequencies in the Q and V-band respectively. SIPhoDiAS developments are targeting the sustained	3,000	EC H202		complete	2	4	2019	2023

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
	entry of photonics into the state of the art communication satellites.								
SPACEBEAM	Photonic beamforming SPACE SAR system with integrated photonic BEAMforming The SPACEBEAM receiver will be based on an optical beamforming network realized as a photonic integrated circuit (PIC). The PIC will implement a precise and continuous beamforming of wideband signals, also realizing a frequency-agnostic photonic down-conversion of signals in the range from 5 to 40 GHz. In order to push the maturity of the SPACEBEAM technology to TRL 6, the project will also develop and test a Space-compliant package for the PIC.	3,000	EC H2020		ongoing	2	4	2021	2024
Thin Film Lithium Niobate (TFLN) modulator development	The objective of this action is to design, to fabricate and to carry out a preliminary evaluation of a low drive voltage electro-optical modulator based on the TFLN technology. Target performance - Wavelength : 1550 nm ; EO bandwidth : 25 GHz; Return Loss : -15	70	CNES R&T (FR)		ongoing	3	5	2022	2024

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
	dB ; Vpi RF : 3 V ; Vpi DC : 4.5 V								
Development and preliminary evaluation of multichannel connector for PM and SM fibers with APC termini	The goal of this study is to carry out the design, the prototype manufacturing, the performance characterization and a preliminary evaluation of a new connector	50	CNES R&T (FR)		Ongoing	2	4	2023	2025
Development and preliminary evaluation of monochannel connector for PM and SM fibers with APC termini	The goal of this study is to carry out the design, the prototype manufacturing, the performance characterization and a preliminary evaluation of a new connector	50	CNES R&T (FR)		Ongoing	2	4	2022	2024
Laser module 1.55 µm in BTF package for space application	Development of a 1.55 µm DFB laser module in BTF package for transmission with coherent modulation. Demonstration of the module ability to withstand geostationary space conditions. Target performance: Low noise (-160 dBc/Hz) narrow linewidth laser (<500 kHz) single frequency DFB laser	744	COOP - French Plan de Relance, under the coordination of CNES (FR)		Ongoing	4	7	2021	2024
Preliminary evaluation of fiber optical cables for space applications	The goal of this study is to perform a procurement, preliminary evaluation and testing of optical cables assessing a list of potential candidates for space applications. Target performance:	80	COOP - French Plan de Relance, under the coordination of		Ongoing	2	4	2023	2025

Title	Description	Budget (k€)	Prog.	Ref.	Status	TRL level		Date (year)	
						Start	End	Start	End
	SM, PM and MM fibers robustness evaluation		CNES (FR)						

6.3 Reference for Prioritisation

6.3.1 Yearly Reference Budget

The yearly reference budget is used as input to determine the priorities of new activities proposed in the new roadmap. It is based on the budget of ESA activities newly approved since the previous Roadmap was adopted.

- According to the implementation of the previous roadmap mentioned in Sect. 6.1, 13 ESA activities of the 2018 Roadmap have been approved since then and are “Partially Funded” or “Fully Funded” for a budget of about 16.5 M€ (16,544 k€).
- For what concerns the additional ESA activities described in Sect. 6.2, 45 ESA activities not part of the 2018 Roadmap have been approved for a budget of about 12.7 M€ (12,745 k€).

Therefore a total of 58 ESA activities were approved since 2018 for a budget of 29.3 M€ (29,289 k€).

The yearly reference is equal to the sum of the budget of all relevant activities approved since the previous Roadmap divided by the number of years since then (6 years; 2018-2023 including 2023):

Yearly Reference Budget: 4.9 M€

6.3.2 Overall Reference Budget

The overall reference budget is equal to the yearly reference budget multiplied by the number of years until the latest activity start date of the new roadmap (3 years, 2024-2026):

Overall Reference Budget: 14.5 M€

7 SUMMARY OF THE MAPPING MEETING

The key points covered at the Mapping Meeting can be summarised as follows:

- The photonic dossier continues to be relevant, even as the technology reaches higher maturity which leads to its adoption into a variety of other harmonisation roadmaps. The dossier remains a means to catch technologies that do not fit into other more focused topics, and also critical photonic components which span across many technology domains, and which are managed by the Photonics Component Working Group.
- Uncertainty on market size and opportunities for some photonics devices was brought up in several interventions. Market opportunities such as satellite constellations and missions carrying magnetometers that are difficult to calibrate in orbit (e.g. Jupiter space environment) were mentioned.
- It was apparent that photonic scientific instrumentation is underrepresented in the current dossier, which will be addressed in the update.
- The potential of PICS (in particular related to SWaP advantages) calls for further addressing development efforts vs commercial viability. In particular, ESA experts commented that the electronic-photonic integration will be a key element in the development towards making photonics competitive to present electronic solutions.
- ESA experts noted that photonic technologies have numerous applications and their presence in other Harmonisation dossiers is growing (e.g. Lidar Critical Subsystems, Optical Communications for Space, Pyrotechnic Devices, Frequency and Time Generation and Distribution).
- ESA experts also noted that the electronic driver circuits in digital interconnects are important components that are not covered in other dossiers and could be considered within the Photonics dossier even if these are not purely photonics components.
- Photonics technologies for space applications can greatly benefit from developments in non-space sectors. Stakeholders recommend following the European technology platform Photonics21 and their activities to identify spin-in opportunities.
- Finally, ESA experts remarked that photonics devices are in competition with other traditional technologies (e.g. photonic temperature sensors vs thermocouples), and there is a strong need for LSIs to derive figures of merit to better compare the performances of each.
- Quite a number of the suggested changes concerned technologies covered in other technology dossiers. This was particularly the case for technologies relevant to the optical communication dossier.

- The large funding committed by the Netherlands to the commercialisation of photonics was noted, with the need to elaborate on how much of this could find its way into the space sector.

8 ROADMAP

8.1 General Development Approach

The main objectives to be reached by this Roadmap are to:

- To identify the next Photonic technologies to be adopted by Space Applications due to a clearly define advantage
- To identify the critical steps

The work to meet these objectives is distinguished in 6 aims covered by the foreseen Roadmap and each aim includes several areas for development. The aims are structured according to Applications and are depicted in the table below:

Table 8-1 Aims of the technology roadmap

Ref.	Title	Description
AIM A	COMSAT PLs – Photonically linked	• Develop space qualified electronics for the Tx/Rx of digital link at 56Gbps, 112 Gbps and even higher. • Develop ASICS with optical I/Os • Develop cooler-less, very low power consumption and very high-density Photonic Analog Links
AIM B	COMSAT PLs – Microwave Photonic Equipment	• Develop microphotonic MRO/LO generators • Develop microphotonic Frequency Converters • Develop microphotonic Switches • Develop microphotonic RF filters • Develop microphotonic Beam Former
AIM C	SCIENTIFIC PLs	• Adapt Photonic Digital and Analog links of COMSAT PLs to Scientific PLs • Investigate the use of microphotonics for scientific instrumentation
AIM D	PLATFORMS	• Develop Space qualified SpaceFiber products • Develop stable fiber optic sensors
AIM E	LAUNCHERS	• Qualify the Opto-pyro in time for the ARIANE-6 launch • Transfer the Opto-pyro for ARIANE-6 know-how to VEGA • Consider fiber optic sensors for health monitoring • Consider fiber optic links for OBDH

Ref.	Title	Description
AIM F	GROUND SEGMENT and AERONAUTICS	• Use of Optical Wireless in AIT • Develop qualified and cost effective microphotonic BFN for airplanes
AIM G	Special measures for Photonic ICs and Packaging	• Evaluate radiation hardening of existing PICs • Advanced the integration of Electronics with Photonics ICs with automated processes • Provide reliable packaging solutions

8.2 Detailed Development Approach

A detailed description of the associated Roadmap activities (running = green, funded=orange and new/proposed=red) within each Aim is given below.

Note that the Roadmap presented is a recommendation only and that proposals must follow relevant procedures (ESA or European or National) as applicable.

Table 8-2 Detailed description of Roadmap activities

Ref.	Title	Description	Remark
AIM A	COMSAT PLs - Photonically linked		
A01	28 Gbps Transceivers for Space	The objective of this activity is to develop 28Gbps per lane optical transceivers for space.	Programme: Scylight COFUNDED - Budget, country confidential
A02	Very high-throughput inter-connectivity solutions based on advanced microphotonics for future Digital Telecommunications Payloads	The objective of the activity is to assess the suitability and demonstrate the benefits of advanced microphotonic solutions for the implementation of very high-throughput inter-connections and routing for future digital communication satellites payloads.	[FROM PREVIOUS RM 2018] Supplier: mbryonics
A03	56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads	The objective is to develop optical transceivers at 28/56 Gbps per lane	Programme: Scylight COFUNDED - Budget, country confidential
A04	56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads	The objective is to develop optical transceivers at 56 Gbps per lane	To be solicited by industry in a co-funded proposal following a current co-funded contract under ARTES C&G, as well as a TDE contract.

Ref.	Title	Description	Remark
A05	ASIC/FPGA with 112 Gbps Optical I/Os	The objective of this activity is to develop the technology step needed to enable the use of optical interconnects at speeds of up to 112 Gbps. This should be demonstrated through testing of an integrated digital signal functions (ASIC and FPGAs) with the developed electro-optic transceiver photonic integrated circuits that form the optical I/Os to replace traditional electrical I/O.	Programme: ARTES ScyLight - Work Plan 2023. It follows a similar TDE activity on 56Gbps with mBryonics as the contractor
A06	ASIC/FPGA with 112 Gbps Optical I/Os	The objective of this activity is to develop the technology step needed to enable the use of optical interconnects at speeds of up to 112 Gbps. This should be demonstrated through testing of an integrated digital signal functions (ASIC and FPGAs) with the developed electro-optic transceiver photonic integrated circuits that form the optical I/Os to replace traditional electrical I/O.	To follow the above ARTES activity. Given the relevance to the ASIC/FPGA development any further work on higher TRL needs to be coordinated and probably driven by the corresponding industry/esa section and harmonisation dossier
A07	Development of photonic interconnections for the next generation on-board digital processor	The project aims to develop the required photonic interconnections to enable the next generation processors that are critical for "VHTS satellites" and "Space Wide Web" and Next Generation Constellations	Programme: Scylight COFUNDED - Budget, country confidential. Related to A01 - 28 Gbps Transceivers for space
A08	Power efficient onboard analog photonic interconnects for high throughput satellites	To develop very low power analog photonic interconnects for linking antennas to the on-board digital processor in high throughput satellites, also in view of an all optical satellite implementation	Programme: ARTES ScyLight - Work Plan 2024. It follows the development of a current co-funded activity in an elaborated way.
A09	Power efficient onboard analog photonic interconnects for high throughput satellites	To develop very low power analog photonic interconnects for linking antennas to the on-board digital processor in high throughput satellites, also in view of an all optical satellite implementation	Programme: ARTES ScyLight. It will follow the development of a currently proposed activity. To be solicited by industry in a co-funded proposal following a current co-funded contract
A10	Bandpass RF OE Converter (BAROC)		Programme: Scylight COFUNDED - Budget, country confidential

Ref.	Title	Description	Remark
A11	Fiber Optic Flexi Routing Assembly - FOFRA	To qualify the FOFRA for space	Follow up of a current ARTES 5.2 activity. To be solicited by industry in a cofunded proposal
A12	High density optical fibre cable assemblies for photonic interconnections	To develop multi-fiber assemblies including fiber links and connectors for telecom payload applications	Programme: ARTES ScyLight - 2024 Work Plan - On request (reserved budget)
A13	Reliable Lithium Niobate Modulators (RELINO)	To develop and qualify thin films Lithium Niobate Modulators	Programme: ARTES C&G COFUNDED - Budget, country confidential
A14	Lithium Niobate Photonic integrated circuit based high speed, low voltage modulators for microwave photonics	To develop a suite of high-speed devices, IQ (quadrature) modulators, Mach-Zehnder modulators (MZM), splitters and delay lines based on $LiNbO_3$ hybrid integrated photonics based on the use of a dedicated PDK	This is a similar activity to A13
A15	High density Lithium Niobate integrated photonic circuits for high-speed low-voltage modulators	This project aims to develop key building blocks in thin film lithium niobate specifically for high-speed low voltage modulators.	Programme: Discovery & Preparation (OSIP). Supplier: Luxintellicence
A16	Electro-optical iQ modulator	Develop and assess an iQ modulator for 1550nm	Programme: ScyLight or C&G Also proposed by the Photonics WG of the Component Technology Board - PH020
A17	Thin Film Lithium Niobate (TFLN) modulator development	The objective of this action is to design, to fabricate and to carry out a preliminary evaluation of a low drive voltage electro-optical modulator based on the TFLN technology. Target performance - Wavelength : 1550 nm ; EO bandwidth : 25 GHz; Return Loss : -15 dB ; Vpi RF : 3 V ; Vpi DC : 4.5 V	Programme: CNES R&T Supplier: Exail
A18	Development and preliminary evaluation of multichannel connector for PM and SM fibers with APC termini	The goal of this study is to carry out the design, the prototype manufacturing, the performance characterization and a preliminary evaluation of a new connector	Programme: CNES R&T Supplier: Souriau

Ref.	Title	Description	Remark
A19	Development and preliminary evaluation of monochannel connector for PM and SM fibers with APC termini	The goal of this study is to carry out the design, the prototype manufacturing, the performance characterization and a preliminary evaluation of a new connector	Programme: CNES R&T Supplier: SEDI-ATI
AIM B	COMSAT PLs - Microwave Photonic Equipment		
B01	Photonic RF tuneable Demultiplexer for Broadband Satellites	The objective of the activity is to design, manufacture and verify a novel photonic RF (de)multiplexer performing flexible allocation of pass-band bandwidth (125 MHz-1000 MHz) and central frequency (over 2 GHz in Ka/Q/V bands).	Supplier: SENER Aeroespacial, S.A.
B02	Photonic RF tuneable Demultiplexer for Broadband Satellites	The objective of the activity is to dedevelop a novel photonic RF (de)multiplexer performing flexible allocation of pass-band bandwidth (125 MHz-1000 MHz) and central frequency (over 2 GHz in Ka/Q/V bands).	Continuation of a TDE activity
B03	Large scale integrated photonic switch matrix	To develop a PIC based breadboard of a switch with high number of ports (72x72)	Programme: ARTES A &T Supplier: ECOLE POLYTECHNIQUE FEDEDALE DE LAU
B04	High-power fibre-coupled optical switch for space applications	To support the LISA Mission with 1x2 switch for high power laser beam switch	Supplier:CSEM SA. Centre Suisse dElectronique
B05	Optical Switches based on Silicon Photonics	The objective was to package and evaluate silico photonic switches for space applications.	Programme: Discovery & Preparation (OSIP) Supplier: VTT
B06	Low-port count switch for Space	To develop and qualify a low-port count switch for Earth Observation instrumentation	
B07	Photonic switch for Space Applications	The objective of this activity is to qualify a photonic ROAMD for use in optically interlinked satellite networks	Programme: Scylight To be solicited by industry in a co-funded proposal
B08	Microwave Photonic Satellite PL based on Tunable Optical Comb Generators	The objective is to reproduce a photonic frequency generation unit (FGU) for payloads based on the optical frequency comb generator (OFCG) concept. A demonstrator will be developed to prove the feasibility of simultaneous multi-band local oscillator generation.	Programme: PECS Supplier: University of Cyprus, Electronics, Microwaves, Photonics and Sensors Research Centre (EMPHASIS)

Ref.	Title	Description	Remark
B09	V-band FGU implemented with Integrated Photonics	The objective of this activity is to design, fabricate and test photonic integrated circuits, to demonstrate the concept of generating a microwave signal around 48 GHz using photonic integrated technology. The activity aims to support technology advances targeted at payload hardware for High Throughput Satellites (HTS) with V-band feeder links.	Programme: PECS Supplier: University of Cyprus, Electronics, Microwaves, Photonics and Sensors Research Centre (EMPHASIS)
B10	Integrated Photonics Frequency Generation Unit for High Throughput Satellites	This project will demonstrate a tunable MW frequency generation unit for the K, Ka, Q/V, and W bands using the heterodyning of optical carriers obtained from a photonic integrated optical frequency comb (OFC) source.	Programme: Discovery & Preparation (OSIP) partner research programme, Dublin University
B11	Photonic generation of sub-thz signals using optoelectronic oscillator	The objective of the activity is to demonstrate a 100GHz OptoElectronic Oscillator (OEO) in a laboratory environment to show that down conversion of a signal at frequencies above 200 Ghz is feasible in a front-end receiver for earth observation instruments	Programme: PECS Supplier: University of Cyprus, Electronics, Microwaves, Photonics and Sensors Research Centre (EMPHASIS)
B12	Photonic generation of sub-thz signals using optoelectronic oscillator	The objective of the activity is to demonstrate a 100GHz OptoElectronic Oscillator (OEO) in a laboratory environment to show that down conversion of a signal at frequencies above 200 Ghz is feasible in a front-end receiver for earth observation instruments	Programme: PECS
B13	Integrated microwave photonic technology for wide-frequency tuning signal generation	Three year research activity to investigate the generation of low phase noise signals using integrated photonics.	Programme: Discovery & Preparation (OSIP) partner research programme, Carlos III Madrid University
B14	Wavelength division multiplexer (WDM) and de-multiplexer at 1550 nm for space applications	To develop WDM MUX/DEMUX for use in WDM extra-satellite and intra-satellite applications	[FROM PREVIOUS RM 2018] Programme: ARTES ScyLight
B15	High power pump laser modules for Erbium-Ytterbium doped fibre amplifiers	To develop pump lasers for Er/Yb optical amplifiers for extra-satellite and intra-satellite links	[FROM PREVIOUS RM 2018] Programme: ARTES ScyLight

Ref.	Title	Description	Remark
B16	Single mode pump laser module for Erbium-Ytterbium doped fibre amplifiers	The objective is to evaluate existing devices and assess suitability for space of laser diode modules having >650mW output power single mode, pigtailed package, butterfly or mini-dil type. Operating temperature -40 to 70degC. Application is a preamplifier stage of optical amplifiers, ASE sources, source for gyroscope and fibre lasers.	Programme: ARTES ScyLight Also proposed by the Photonics WG of the Components Technology Board - PH017
B17	Advanced pump schemes for high WPE Optical Amplifiers	Develop advanced optical engines and pump shceme to increase the WPE from 10-15% to >20%.	Programme: ARTES ScyLight
B18	Photonic Signal Processing to remove all 5G/6G band signal from the water signal	The research will concentrate on the removal of these 5G signals using microwave photonic filtering techniques recently being developed at Royal Holloway for UK defence company Leonardo Ltd. The research will also develop a method to correct the small effect of removing the 5G signal from the water signal.	Programme: Discovery & Preparation (OSIP)
B19	Spaceborne Photonic BFN	To develop a spaceborne Photonic BFN for UHTS	Programme: ARTES ScyLight
B20	Packaged integrated photonics-based RF/optical hybrid transceiver for sensing and communication	develop a single multipurpose space-grade packaged optical circuit suitable for sensors and communication applications.	Supplier: Inphotec (SSSA)
B21	High power optical termination	To develop a high power optical termination for polarisation maintaining fibers, for optical outputs in the range 10 to 100W.	TDE Workplan for 2023-2024 Also proposed by the Photonics WG of the Component Technology Board - PH025
B22	Fibre coupled optical isolators	Development of a optical isolator suitable for use in a high power 1550nm fibre amplifier systems. The objective is to establish a European supply chain for these components. Applications in optical communications, LIDAR, and cold-atom handling systems.	Also proposed by the Photonics WG of the Component Technology Board - PH080

Ref.	Title	Description	Remark
B23	Laser module 1.55 µm in BTF package for space application	Development of a 1.55 µm DFB laser module in BTF package for transmission with coherent modulation. Demonstration of the module ability to withstand geostationary space conditions. Target performance: Low noise (-160 dBc/Hz) narrow linewidth laser (<500 kHz) single frequency DFB laser	Programme: COOP - funded in the scope of French Plan de Relance, under the coordination of CNES Supplier: Lumibird
AIM C	SCIENTIFIC Payloads		
C01	Photonic Components analysis in support of the LISA laser system development	The objective is to perform an in depth analysis on the photonic components baselined in the LISA laser system development activities	CCN (C217-092FI) to C217-084FT funded through Industrial Policy Task Force with Ireland Supplier: Tyndall
C02	Microphotonic Scientific Instrumentation	The objective is to study the application of microphotonic technologies in scientific instrumentation	
C03	Cold Photonics	Study the impact of cryogenic environments on the performance of SOA, to see if these can be used as an alternative to fiber pre-amplifiers	Programme: Discovery & Preparation (OSIP) Supplier: Air Liquide Advanced Technologies
C04	Test facility for Cold Photonics	To develop a test facilities to test photonic in temperature down to 4K	
C05	Optical Vector Magnetometer Based on The Hanle Effect	To build and characterise a breadboard of a low field optical vector magnetometer for future space missions.	In the planning DN with Supplier: Austrian Academy of Sciences
C06	Laser Wireless Power Transfer	Design and test a breadboard of an end to end system for the transfer of power over a free space link for applications in lunar exploration.	
C07	Narrow Linewidth Single-Frequency CW 1550nm Laser	Narrow Linewidth Single-Frequency CW Laser seed source for amplifiers. This laser could be used in optical instruments based on amplifiers such as LIDAR (and Laser Communication Terminals).	Also proposed by the Photonics WG of the Component Technology Board - PH101
C08	Fiber optic rotary joint	The objective is to develop a rotary joint for rotating structures like solar panels and rotating scientific instruments that use fiber optic for signal transfer to the S/C platform.	Also proposed by the Photonics WG of the Component Technology Board - PH109

Ref.	Title	Description	Remark
C09	Laser development for atomic sensors based on Rubidium vapors	This activity is to develop 795nm single mode lasers (e.g. VCSELs) suitable for atomic sensors to be used in space. Such lasers have been used in miniaturized timing source for navigation, as well as a scalar magnetomer for Juice. However there is no longer a suitable European supplier for such a component.	Also proposed by the Photonics WG of the Component Technology Board - PH107
C10	High-speed integrated electro-optic modulation and up-conversion for cold atom experiment in the visible range	Design a lithium niobate-on-insulator (LNOI) platform to integrate an electro-optic modulator (EOM) with a periodically poled lithium niobate (PPLN) building block on the same photonic chip.	Programme: Discovery & Preparation (OSIP). Supplier: ETHZ
C11	High performance space-grade frequency-combs	Development of a integrated f-to-2f stabilization tool based on integrated photonics	Programme: Discovery & Preparation (OSIP). Supplier: Menhir Photonics
C12	Narrow linewidth frequency agile integrated photonic lasers for space	Design, fabrication and test of a ultra-compact narrow linewidth (sub-kHz) with frequency agility from 400-2700nm suitable for applications from FMCW LIDAR to sensing and communication.	Programme: Discovery & Preparation (OSIP). Supplier: DeepLight
AIM D	S/C PLATFORMS		
D01	In-orbit Optical Shape Sensing Measurements	Develop an optical metrology for measuring the shape of antenna reflectors in space	[FROM PREVIOUS RM 2018] Programme: ARTES AT Supplier: INST NAZIONALE DI RICERCA METROLOGI
D02	Distributed, High Resolution Fiber Optic Thermal and Structural Monitoring for Telecom Platforms	To develop temperature/strain fiber optic sensors for Telecom S/C	Under consideration by ARTES AT/SCYLIGHT
D03	Optical Wireless On-Board Data Transmission "Light Fidelity" (LiFi) for Telecom Spacecraft	Develop OW solutions for intra-satellite applications and AIT	Programme: ARTES AT Supplier: SSSA
D04	Optical Wireless Intra-S/C Comms	Qualify OW	Programme: Scylight To follow a current ARTES activity by an industry-initiated co-funded proposal

Ref.	Title	Description	Remark
D05	End-to-end on-board data handling architecture based on optical high-speed links	Develop next-generation of products for end-to-end payload data handling architecture based on optical high-speed link	Part of the GSTP Element 1 Develop Compendium 2022 (Generic Technologies) - on request
D06	Optical Fibre Cable for Space Applications	To develop/evaluate a fiber optic cable for space	GSTP Element 1 Develop Work Plan 2022
D07	Optical Fiber Micro-Kelvin Temperature Sensor Network	Investigate the use of fiber optic sensors to enable the development of a network of temperature sensors for the LISA mission	Prime Supplier: IEEC
D08	Improving satellite propellant gauging accuracy with high accuracy optical pressure sensors	Breadboard design and testing of a fibre laser based optical sensor for measuring pressure in propellent tanks.	Programme: Discovery & Preparation (OSIP). Supplier: Optech
D09	Simple Fiber-Optic Strain sensor for monitoring preload in critical bolted joints.	Develop and evaluate a fiber optic sensor for measurement of preloads in bolts.	Supplier: Xpanse
D10	Preliminary evaluation of fiber optical cables for space applications	The goal of this study is to perform a procurement, preliminary evaluation and testing of optical cables assessing a list of potential candidates for space applications. Target performance: SM, PM and MM fibers robustness evaluation	Programme: CNES R&T Supplier: Adveotec
AIM E	LAUNCHERS		
E01	Optopyrotechnic Technology Demonstration	The Second Generation optopyro system proposed builds on this optopyro heritage, but introduces additional concepts to the First Generation by further improving competitiveness by reducing mass, cost and optical power need. It will include: - Assessment of requirements - Investigation of architecture (including laser firing unit, optical switch, laser initiated devices) - Preliminary design - Demonstrator and test plan to reach TRL 5	[FROM PREVIOUS RM 2018] E/0279-01 FLPP Demonstrators Advanced Techno Core Supplier: Kongsberg Defence & Aerospace
E02	Photonic Health Monitoring System	To develop a photonic health monitoring system for reusable launchers	

Ref.	Title	Description	Remark
E03	Optical Harness for launchers	To develop an optical harness solution adapted to the launcher environment.	Based on experience from the development of E01
E04	Laser ignition system	To develop a laser ignition architecture for launchers with fiber optic distribution of laser ignition signals	Based on experience from the development of E02
E05	Distributed Fiber Optic sensing for Launch Pad activities	To investigate the use of distributed fiber optic sensing during launch pad preparatory activities and launch.	
AIM F	GROUND SEGMENT, AERONAUTICS, ROVERS		
F01	Photonically Assisted Multibeam Phased Array Antenna	The objective is to develop a photonic BFN for Aeornautic and ground mobile vehicles satellite antennas	Programme: ARTES C&G COFUNDED - Budget, country and supplier confidential
F02	Innovative Ground Segment Components for Satcom Systems	The objective is to develop a photonic BFN for Aeornautic satellite antennas	Programme: ARTES 33 COFUNDED - Budget, country and supplier confidential
F03	Antenna Remoting and use in AIT at Q/V/W bands	To develop fiber optic links for use in Q/V/W bands in AIT and antenna remoting	ARTES Scylight
F04	Optical Read-Out for MEMS sensors	To develop and optical read-out solution for AOCS MEMS sensors in satellites and rovers	
AIM G	Special measures for Photonic ICs and Packaging		
G01	Evaluation of radiation sensitivity of Photonics Integrated Circuits technology	Radiation assessment of a tunable laser PIC source and variable coupler with PZT actuator under a TID radiation environment.	Programme: Discovery & Preparation (OSIP) Suppliers: Airbus DS, LioniX
G02	AutoMAIT Co-Packaged Optics for Space	Integrated photonic packaging using microoptics inside the package.	Programme: Scylight COFUNDED - Budget, country confidential
G03	Space Photonic Packaging	Develop a packaging process for PICs based on a set of qualified processes	Programme: Scylight COFUNDED - Budget, country confidential
G04	Development of a standardised process for photonic integrated circuits (PICs) and electronics integration technology	Development of a optimised process for photonic integrated circuits and electronics integration technology that can be used as guidelines PIC designers	Programme: ARTES ScyLight 2023 - on Request

Ref.	Title	Description	Remark
G05	PIC building blocks Assessment for Space	Assessment of essential functions for PICs, such as isolators and amplifiers that would enable higher degree of integration for fibre sensing, LIDAR and communication applications	Also proposed by the Photonics WG of the Component Technology Board - PH096
G06	Erbium-doped photonic integrated circuit-based amplifier	Develop an integrated Er doped waveguide amplifier on PIC platform for satellite communication applications.	Programme: Discovery & Preparation (OSIP). Supplier: Luxintellicence

8.3 Roadmap Planning and Budget Statistics

A representation of the schedule corresponding to the proposed roadmap is presented below.

			Urg.	Crit.	Budget (k€)	Act. Prog. Ref.		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	
AIM A:		COMSAT PLs - Photonically linked																		
AIM A	A01	28 Gbps Transceivers for Space			0	SL.9010				TRL 4	ARTES				TRL 8					
AIM A	A02	Very high-throughput inter-connectivity solutions based on advanced microphotonics for future Dig			500	T506-605MM				TRL 2	TDE				TRL 3					
AIM A	A03	56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads			0	5F.015							TRL 3	ARTES			TRL 6			
AIM A	A04	56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads	M	H	1000									A03 ->	TRL 6	ARTES			TRL 8	
AIM A	A05	ASIC/FPGA with 112 Gbps Optical I/Os			1500	5C.480							A02 ->	TRL 3	ARTES			TRL 4		
AIM A	A06	ASIC/FPGA with 112 Gbps Optical I/Os	M	H	5000										A05 ->	TRL 5	ARTES			TRL 8
AIM A	A07	Development of photonic interconnections for the next generation on-board digital processor			0	SL.9006				TRL 4	ARTES					TRL 6				
AIM A	A08	Power efficient onboard analog photonic interconnects for high throughput satellites			2500								A07 ->	TRL 4	ARTES			TRL 6		
AIM A	A09	Power efficient onboard analog photonic interconnects for high throughput satellites	M	H	2000										A08 ->	TRL 6	ARTES			TRL 8
AIM A	A10	Bandpass RF OE Converter (BAROC)			0	5F.027					5C.237 ->	TRL 4	ARTES			TRL 6				
AIM A	A11	Fiber Optic Flexi Routing Assembly - FOFRA	H	H	300								5D.032 ->	TRL 6	ARTES		TRL 8			
AIM A	A12	High density optical fibre cable assemblies for photonic interconnections	H	H	600	5F.039							TRL 3	ARTES			TRL 6			
AIM A	A13	Reliable Lithium Niobate Modulators (RELINO)			0	.124 40001412							TRL 4	ARTES			TRL 6			
AIM A	A14	Lithium Niobate Photonic integrated circuit based high speed, low voltage modulators for microwav			350	- NAVISP I							TRL 3	NAVISP			TRL 5			
AIM A	A15	High density Lithium Niobate integrated photonic circuits for high-speed low-voltage modulators			175	4000141010							TRL 2	OEP		TRL 3				
AIM A	A16	Electro-optical iQ modulator	H	H	500									TRL 4	ARTES			TRL 5		
AIM A	A17	Thin Film Lithium Niobate (TFLN) modulator development			70							TRL 3	INP [FR]			TRL 5				
AIM A	A18	Development and preliminary evaluation of multichannel connector for PM and SM fibers with APC			50								TRL 2	INP [FR]			TRL 4			
AIM A	A19	Development and preliminary evaluation of monochannel connector for PM and SM fibers with AP(			50							TRL 2	INP [FR]			TRL 4				

Figure 8-1: Roadmap Planning and Budget Statistics (1/4)

		Urg.	Crit.	Budget (k€)	Act. Prog. Ref.		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	
AIM B:	COMSAT PLs - Microwave Photonic Equipment																		
B01	Photonic RF tuneable Demultiplexer for Broadband Satellites			500	T517-701MM					TRL 2	TDE			TRL 3					
B02	Photonic RF tuneable Demultiplexer for Broadband Satellites	M	M	1000										TRL 4	ARTES			TRL 6	
B03	Large scale integrated photonic switch matrix			800	5C.364			TRL 3	ARTES					TRL 5					
B04	High-power fibre-coupled optical switch for space applications			500	T217-074NA							TRL 3	TDE			TRL 4			
B05	Optical Switches based on Silicon Photonics			175	4000123859			TRL 3	OEP					TRL 4					
B06	Low-port count switch for Space	M	M	1000											FutureEO			TRL 8	
B07	Photonic switch for Space Applications	H	H	2000									TRL 5	ARTES			TRL 8		
B08	Microwave Photonic Satellite PL based on Tunable Optical Comb Generators			250	CY2_16			TRL 2	OEP					TRL 3					
B09	V-band FGU implemented with Integrated Photonics			250	CY3_02							B08 ->	TRL 3	OEP			TRL 4		
B10	Integrated Photonics Frequency Generation Unit for High Throughput Satellites			65	4000138240					TRL 2	OEP				TRL 3				
B11	Photonic generation of sub-thz signals using optoelectronic oscillator			100	CY4_01							TRL 2	OEP		TRL 3				
B12	Photonic generation of sub-thz signals using optoelectronic oscillator	M	M	250										TRL 3	OEP		TRL 4		
B13	Integrated microwave photonic technology for wide-frequency tuning signal generation			100	4000135351					TRL 2	OEP				TRL 3				
B14	Wavelength division multiplexer (WDM) and de-multiplexer at 1550 nm for space applications			500	5G.027							TRL 3	ARTES			TRL 5			
B15	High power pump laser modules for Erbium-Ytterbium doped fibre amplifiers			500	5F.040							TRL 4	ARTES			TRL 5			
B16	Single mode pump laser module for Erbium-Ytterbium doped fibre amplifiers	M	M	400										TRL 5	ARTES			TRL 6	
B17	Advanced pump schemes for high WPE Optical Amplifiers	M	M	500										TRL 3	ARTES			TRL 5	
B18	Photonic Signal Processing to remove all 5G/6G band signal from the water signal			50	4000137231						TRL 2	OEP				TRL 3			
B19	Spaceborne Photonic BFN	M	M	2000										TRL 3	ARTES				TRL 5
B20	Packaged integrated photonics-based RF/optical hybrid transceiver for sensing and communication			1200	GT27-001MM				TRL 3	GSTP					TRL 5				
B21	High power optical termination			250	T723-801ED								TRL 3	TDE			TRL 4		
B22	Fibre coupled optical isolators	M	M	300										TRL 3	GSTP			TRL 5	
B23	Laser module 1.55 µm in BTF package for space application			744						TRL 4	INP [FR]				TRL 7				

Figure 8-2: Roadmap Planning and Budget Statistics (2/4)

	ID	Title	Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
AIM C:		SCIENTIFIC Payloads																
AIM C	C01	Photonic Components analysis in support of the LISA laser system development			600	C217-084ET		TRL n/a	CTP					TRL n/a				
AIM C	C02	Microphotonic Scientific Instrumenattion	M	M	300									TRL 2	TDE		TRL 3	
AIM C	C03	Cold Photonics			175	4000135867					TRL 2	OEP		TRL 4				
AIM C	C04	Test facility for Cold Photonics	M	M	400								TRL n/a	GSTP			TRL n/a	
AIM C	C05	Optical Vector Magnetometer Based on The Hanle Effect			750	T207-068MM						TRL 2	CTP			TRL 3		
AIM C	C06	Laser Wireless Power Transfer			1000	E2CX-048						TRL 3	E3P		TRL 5			
AIM C	C07	Narrow Linewidth Single-Frequency CW 1550nm Laser	M	M	500								TRL 2	GSTP			TRL 4	
AIM C	C08	Fiber optic rotary joint	L	L	300											FutureEO		TRL 4
AIM C	C09	Laser development for atomic sensors based on Rubidium vapors	M	M	300									TRL 3	TDE			TRL 4
AIM C	C10	High-speed integrated electro-optic modulation and up-conversion for cold atom experiment in the			175	4000137426						TRL 2	OEP		TRL 3			
AIM C	C11	High performance space-grade frequency-combs			100	4000137426						TRL 2	OEP		TRL 3			
AIM C	C12	Narrow linewidth frequency agile integrated photonic lasers for space			175	4000137426						TRL 2	OEP		TRL 3			
AIM D:		S/C PLATFORMS																
AIM D	D01	In-orbit Optical Shape Sensing Measurements			600	4E.075				TRL 3	ARTES			TRL 5				
AIM D	D02	Distributed, High Resolution Fiber Optic Thermal and Structural Monitoring for Telecom Platforms	M	H	750									TRL 3	ARTES			TRL 5
AIM D	D03	Optical Wireless On-Board Data Transmission "Light Fidelity" (LiFi) for Telecom Spacecraft			800	125458/19/UI				TRL 3	ARTES				TRL 4			
AIM D	D04	Optical Wireless Intra-S/C Comms	M	M	1000								D03 ->	TRL 5	ARTES		TRL 8	
AIM D	D05	End-to-end on-board data handling architecture based on optical high-speed links	H	M	1200	GT17-619ED							TRL 3	GSTP			TRL 6	
AIM D	D06	Optical Fibre Cable for Space Applications			500	GT17-301ED						TRL 4	GSTP			TRL 6		
AIM D	D07	Optical Fiber Micro-Kelvin Temperature Sensor Network			400	4000135481				TRL 3	CTP			TRL 4				
AIM D	D08	Improving satellite propellant gauging accuracy with high accuracy optical pressure sensors			175	4000138372					TRL 3	OEP			TRL 4			
AIM D	D09	Simple Fiber-Optic Strain sensor for monitoring preload in critical bolted joints.			175	4000138375					TRL 3	TDE			TRL 4			
AIM D	D10	Preliminary evaluation of fiber optical cables for space applications			80							TRL 2	INP [FR]			TRL 4		

Figure 8-3: Roadmap Planning and Budget Statistics (3/4)

			Urg.	Crit.	Budget (k€)	Act. Prog. Ref.	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
AIM E:		LAUNCHERS																
AIM E	E01	Optopyrotechnic Technology Demonstration			2000						TRL 3	FLPP			TRL 5			
AIM E	E02	Photonic Health Monitoting System	M	M	1000									TRL 3	FLPP			TRL 5
AIM E	E03	Optical Harness for launchers	H	H	500								TRL 4	FLPP			TRL 6	
AIM E	E04	Laser ignition system	M	M	800									TRL 3	FLPP		TRL 5	
AIM E	E05	Distributed Fiber Optic sensing for Launch Pad activities	M	M	500									TRL 4	FLPP			TRL 6
AIM F:		GROUND SEGMENT, AERONAUTICS, ROVERS																
AIM F	F01	Photonically Assisted Multibeam Phased Array Antenna			0	6C.030						ARTES						
AIM F	F02	Innovative Ground Segment Components for Satcom Systems			0	/CCN-photonic,	ARTES											
AIM F	F03	Antenna Remoting and use in AIT at Q/V/W bands	M	M	800									TRL 4	ARTES		TRL 6	
AIM F	F04	Optical Read-Out fo MEMS sensors	M	M	1000								TRL 3	GSTP			TRL 5	
AIM G:		Special measures for Photonic ICs and Packaging																
AIM G	G01	Evaluation of radiation sensitivity of Photonics Integrated Circuits technology			175	4000136428					TRL 4	OEP		TRL 5				
AIM G	G02	AutoMAIT Co-Packaged Optics for Space			0	5F.035					TRL 4	ARTES			TRL 5			
AIM G	G03	Space Photonic Packaging			0							TRL 3	ARTES			TRL 5		
AIM G	G04	Development of a standardised process for photonic integrated circuits (PICs) and electronics integr	H	H	900	5F.042						TRL 3	ARTES	TRL 5				
AIM G	G05	PIC building blocks Assessment for Space	M	M	800								TRL 3	GSTP			TRL 5	
AIM G	G06	Erbium-doped photonic integrated circuit-based amplifier			175	4000141527						TRL 2	OEP		TRL 3			

Figure 8-4: Roadmap Planning and Budget Statistics (4/4)

9 CONCLUSIONS

Photonic technologies are used as building blocks in many satellite subsystems, spanning a wide range of applications across payloads, platforms, and launchers. Iin this context, the topic Photonics covers aspects of waveguided optics, in particular fibre optics and integrated optics for space application, as well as wireless optics for intra-satellite links.

Since ESA initiated a comprehensive R&D programme in 2000 on photonic technologies for the space domain, 3 products have been adopted by the space industry: Fiber Optic Gyroscopes, Optical Digital Interconnects and Opto-pyrotechnics (considered now for Ariane 6). New applications may include optical analog interconnects, and equipment such as frequency generation units, frequency converters, switches and beam forming networks. For these applications to succeed, a change in technology from discrete photonics to photonic integrated circuits (PICs) is the chosen path to reduce mass, volume and, if also possible, power consumption.

Experience has shown that to successfully introduce a photonics product in the market it is crucial to identify a compelling competitive advantage and a first adopter of the technology. Although an In-orbit-Demonstration was deemed not to be critical in such cases, it is still useful to assess an IOD against cost and schedule on a case by case basis. Currently, Europe and Canada maintain a leading position on the supply of photonic devices and equipment. However a number of components such as the electronic circuits for optical digital interconnects are still procured from the US. It is essential that measures are taken to replace the source of such components by European and Canadian suppliers.

A stable flux of funding has to be maintained over the next years to foster the developments of products to ensure availability of suppliers locally, and to cover new applications. In particular, special measures have to be taken to mature the photonics ICs and packaging technologies.

The overall goal of the new Photonics Roadmap is to expand the applications of Photonics beyond the existing commercial products. The proposed Roadmap for the next 3 years targets the following 7 Aims:

- **Aim A:** Satellite communication payloads – photonically linked.
- **Aim B:** Satellite communication payloads – microwave photonic equipment (MRO/LO generators, frequency converters, switches, RF filters, beam formers).
- **Aim C:** Scientific payloads (adapt photonic digital and analog links of satellite communication to science payloads, use of microphotonics for science instrumentation).
- **Aim D:** Platforms (space qualified SpaceFiber, stable fiber optic sensors).
- **Aim E:** Launchers (opto-pyro for Ariane and Vega, fiber optic sensors for health monitoring, links for OBDH).
- **Aim F:** Ground segment and aeronautics (optical wireless in AIT, microphotonic beam-forming networks for airplanes).
- **Aim G:** Special measures for photonic integrated circuits and packaging.

The breakdown of the proposed overall budget per programme, as well as the budget distribution per Aim, and other statistics are provided in the following table and graphs, respectively.

Breakdown per programme	Appr. (k€)	Prop. (k€)
TDE	1,925	600
GSTP	1,700	4,200
ARTES	7,200	18,750
CTP	1,750	0
FutureEO	0	1,300
Discovery	0	0
E3P	1,000	0
FLPP	2,000	2,800
S2P	0	0
EGEP	0	0
ETP	0	0
NAVISP	350	0
Other ESA Programmes (OEP)	2,315	250
TOTAL ESA Programmes	18,240	27,900
Institutional National Programmes (INP)	994	0
Commercial Programmes (CP)	0	0
Other European Institution Programmes (OEIP)	0	0
Other National Programmes (ONP)	0	0
TOTAL NON-ESA Programmes	994	0
Programme Not Identified (PNI)	0	0
Other	0	0
TOTAL	**19,234**	**27,900**
	47,134	

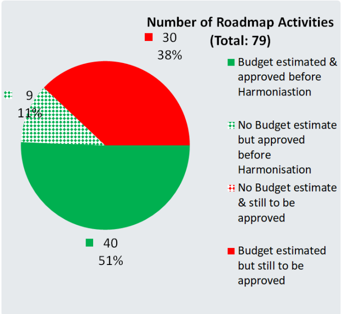
Harmonisation Roadmap: Photonics

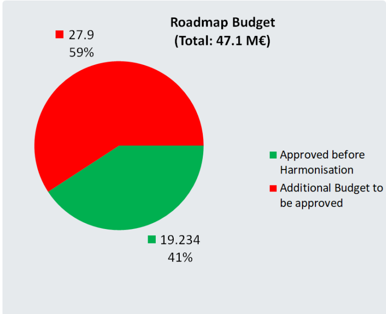
Competence Domain(s): 1,5

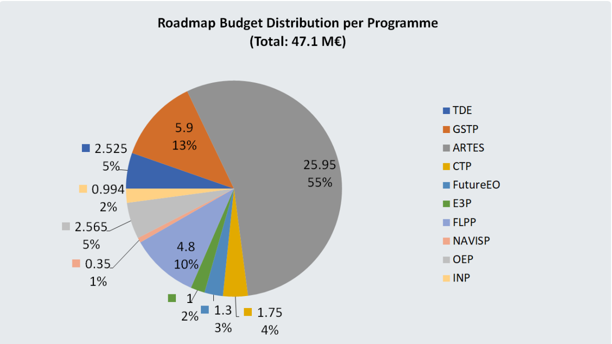
Technology Domain(s): 17-C,1-A,6-D

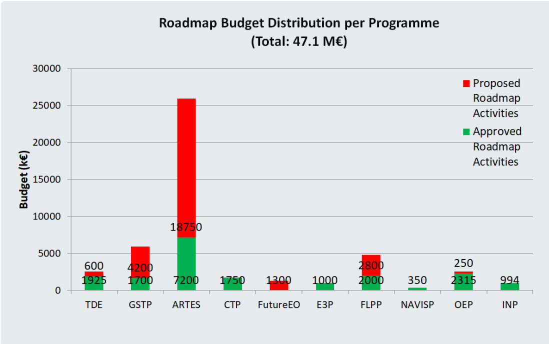
Issue: 2 | **Revision: 2**

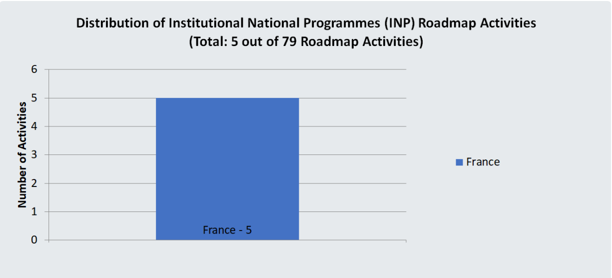
Cycle: 2023.2

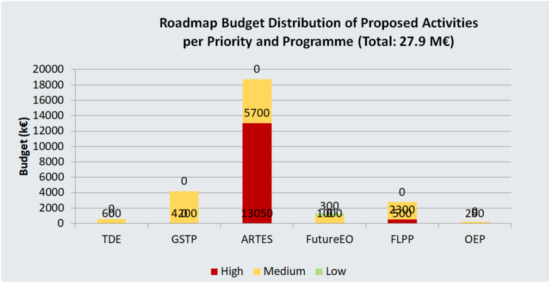


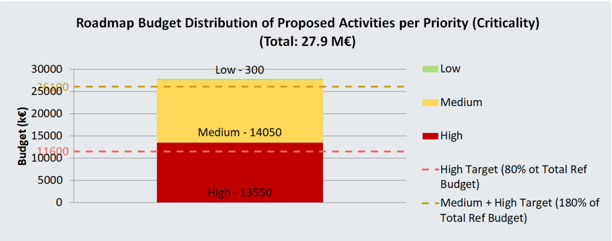


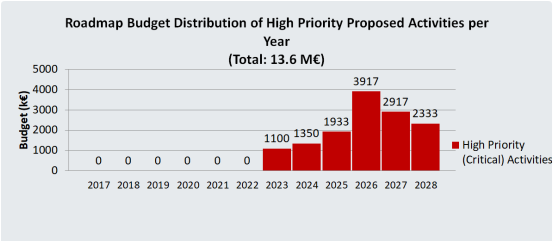


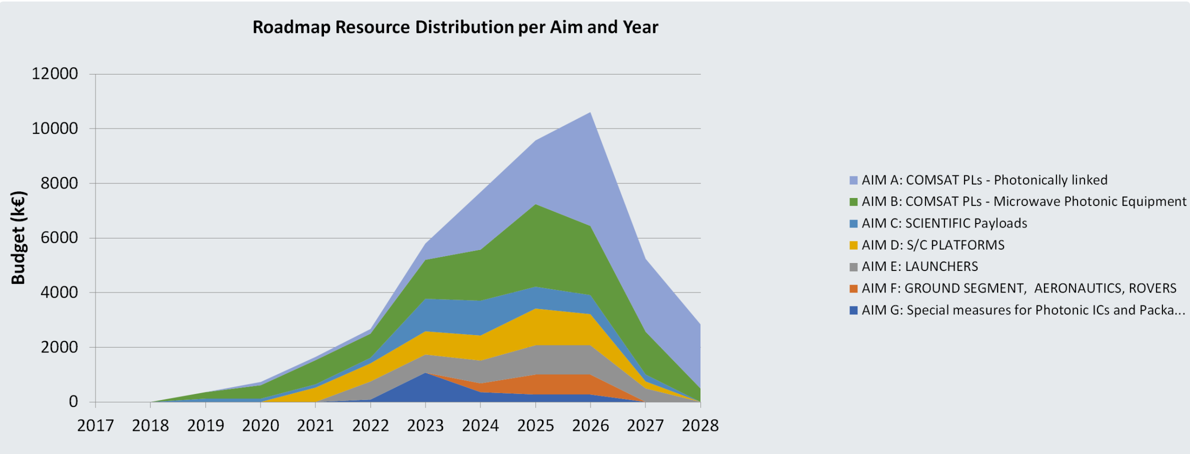












The Roadmap requests a budget of 27.9 M€ for 30 new activities that should start within the next 3 years. Out of this total, about 46 % (13.5 M€) is requested for 10 activities deemed to have high criticality.

- A04 - 56 Gb/s per channel Optical Transceiver Module for Telecommunication Satellite Digital Payloads
- A06 - ASIC/FPGA with 112 Gbps Optical I/Os
- A09 - Power efficient onboard analog photonic interconnects for high throughput satellites
- A11 - Fiber Optic Flexi Routing Assembly – FOFRA
- A12 - High density optical fibre cable assemblies for photonic interconnects
- A16 - Electro-optical iQ modulator
- B07 - Photonic switch for Space Applications
- D02 - Distributed, High Resolution Fiber Optic Thermal and Structural Monitoring for Telecom Platforms
- E03 - Optical Harness for launchers
- G04 - Development of a standardised process for photonic integrated circuits (PICs) and electronics integration technology

ANNEX

A. List of European Entities

Table 9-1 displays a list of European entities involved in Photonics, that have been identified during the harmonisation of the 2nd cycle 2023. The list is an extract of the esa-star Entity Capability Mapping (ECM) module, where stakeholders contributing to the Harmonisation process can provide their feedback on the capabilities of European Entities relevant to this THD.

Note that the last column of the table displays the ECM status as follows:

- Confirmed – The capabilities of the entity have been verified within the scope of this technology topic and within the current harmonisation cycle, by an ESA expert or the corresponding THAG national delegation.
- Not Assessed – The capabilities of the entity have been reviewed but it was not possible to confirm them during the Harmonisation cycle. The entity is maintained in the list of entities in scope with the Harmonisation topic for assessment in future revisits.
- Not in esa-star – The entity was identified as relevant but not registered in the esa-star platform within the current harmonisation cycle.

The table, compiled in January 2024, is provided as an attachment in this Annex.

2023.2_Photonics_ECM list

Note that this list is dynamic in esa-star. As more Entities start working on space photonics, the names will be included in the list. Similarly, if an Entity is not in the list and wishes to be there, please contact the Harmonisation team at harmo@esa.int.

B. Market Assessment Report for *Photonics*

Euroconsult, under an ESA contract for the support of the European Space Technology Harmonisation, has carried out a market study and estimated forecast spanning the next 8 years (up to 2030) specifically targeted at the technologies and products of the topic Photonics.

The market assessment is provided as an attachment. To ensure access to the attachment, Adobe Acrobat reader is recommended.

2023.2_Photonics_
Market Assessment_

Please notice that some important estimations depend on the adoption of the corresponding technologies (e.g. thermal fiber optic sensors for spacecraft thermal monitoring during AIT) by the prime spacecraft manufacturers. As such, the presented projections should be read under this prism.

ESA Member States:
Austria
Belgium
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Luxembourg
Netherlands
Norway
Poland
Portugal
Romania
Spain
Sweden
Switzerland
United Kingdom

Long-standing Cooperating State:
Canada

Cooperating States in Europe:
Bulgaria
Croatia
Cyprus
Malta

Associate Members:
Latvia
Lithuania
Slovakia
Slovenia

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