Photonics21 Strategic Research and Innovation Agenda (SRIA) –

4. Photonics Research and Innovation Challenges

4.5 Safety, Security, Defense and Space

➢ Main socio-economic challenges addressed

Sovereignty is a growing issue for the EU. A key aspect in maintaining or increasing EU sovereignty in critical sectors is securing the resources required for intra-EU production of key photonic components and systems. This includes both tangible and intangible assets, as well as human resources.
The EU is dependent on external sources for its photonics components such as lasers as well as numerous photonics-based services and active functions. Global players control material resources, e. g. mines for the industrial base of crystal growth. EU Research into alternative materials will drive a level of independence, building of objects whose surface/bulk properties are equivalent.
Lastly, photonics components completed with active electronic processing which could lead to the same photonics function.
Initial urgent action is to improve and upscale the means to grow crystals in Europe (Gallium Antimonide GaSb, Silicon Carbide SiC, Gallium Phosphide GaP, Sapphire, …) in order to decrease EU dependence on Russia, China and the United States.
Several key optic and electronic components used by the industry (e.g. lenses, PCB components, housings, etc.) come from extra-EU supply chains. This further amplifies risks in business continuity and resilience of production facilities. In applications related to EU security, this becomes critical.
Gaining sovereignty does not happen lacking workforces, trained people, education of European engineers and technicians. These actions are of utmost importance to maintain and develop the European way of doing things.
In this context, the role of safety, security, defense, and space is to mitigate negative effects that might arise from EU's actions and to protect the European population from harm of other state and non-state actors. New and unexpected threats emerged in recent years, from terrorist attacks on European territory to war near the EU borders. As a result, the theater is expanded from peer-on-peer conflicts to include a multi-domain "conflict continuum" from cooperation through competition to crisis and conflict with no clear front line[1]. Emerging technologies on the consumer market such as small drones or 3D printing devices also exacerbate the threat on European life-sustaining infrastructure and population, especially in smart cities. NATO addresses parts of this problem, through the "NATO Policy for the Protection of Civilians" adopted at the Warsaw Summit in 2016[2]. Photonics plays a major role to improve security while maintaining the safety of the population. The variety of optical techniques is large, ranging from means to identify people interacting in social media to supporting policing functions through directed optical interactions.
The importance of photonics for current and future development of the defence sector is illustrated by the Defence Advanced Research Projects Agency (DARPA): more than 20% of the current DARPA's

[1] D. Kilcullen, G. Pendleton, „Future urban conflict, technology, and the protection of civilians," The Stimson Centre, 2021
[2] https://www.nato.int/cps/en/natohq/official_texts_133945.htm

Microsystems Technology Office (MTO) projects (10 out of) are based on photonics and optical sensing.[3]

The pressure on energy supply is expected to continue to increase over the next few decades, as fossil fuel resources dwindle and the need to reduce the amount of greenhouse gases (carbon, methane) released into the atmosphere is an urgent issue. In parallel to the reduction of energy consumption, the protection of power plants, energy fields and other critical gridded infrastructure becomes increasingly vital.

In addition, the "New Space" which leads to large increases of the number of satellites orbiting around earth requires new approaches to identify/remove waste /debris in space.

Key applications and domains addressed by photonics, related to EU sovereignty and security include:

- Networking: This includes telecom technologies (free-space telecom for space sat to ground, sat to sat, and terrestrial links, secure and high bitrate telecom), space technologies (telecom constellations, sensor for positioning, navigation and timing (PNT) in constellation, deorbiting capabilities based on photonics for sensing and laser for action) and security based on quantum technologies (QKD, quantum sensor, quantum secured encryption with photonics, Sensor protection against laser radiations), Information presentation (screens, Augmented or Virtual Reality)
- Sensing: Sensors for situational awareness, surveillance and reconnaissance, environment monitoring at long range, CBRN detection
- Security: Energy deposition (Anti-drone systems, new threat countermeasures)

European defence is an important economic factor throughout the continent: in 2014, the industry had a turnover of €97.3b, with 500,000 people employed directly, with 1.2 million jobs as an indirect result[4].
In comparison, the European Space industry is much smaller with sales of €8.8b, and direct employment of approximately 43,000 FTEs[5]. The public Safety & Security market in Europe represent $100b with a projected world robust CAGR of 9.4%.[6]
Photonics technologies will provide a crucial advantage to the defence, space, security and safety sectors: photonics offers essential enabling technology solutions to all tasks related to the acquisition, transmission, handling, storing, processing and displaying of data, allowing people and organisations to utilise their resources to full effect. This is particularly true once photonics-enabled quantum-computing technology will become a practical reality.

➢ Major photonics research & innovation challenges

Optics and photonics are becoming omnipresent in defense systems, even when the system is not optically based. Modern defense systems are migrating toward optically based imaging, remote sensing, communications, and effectors. Optical sensing technology provides the ability to communicate information at high bandwidths from mobile platforms and can also identify chemical, biological, and nuclear threats, an ability fundamental for security and safety. Photonics is expected to make an impact in future spacecraft engineering by replacing or enhancing conventional electrical approaches in the fields of digital and RF telecom payloads, sensors, micro LIDAR and spectrometers.

When it comes to space, aviation and defense equipment, size, weight and power (SWaP-C) are all important. This holds true when considering unmanned vehicles limited payloads (drones/robots) or man-

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[3] https://www.darpa.mil/about-us/offices/mto#OfficeProgramsList
[4] "Defence Industry – Fact Sheet on the European Union", - 2022 - www.europarl.europa.eu/factsheets/en
[5] Space Market, How to facilitate access and create an open and competitive market? Policy Department for Economic, Scientific and Quality of Life Policies, PE 695.483 - November 2021.
[6] Public Safety & Security Market Size, Share & Forecast -2032 (futuremarketinsights.com),
https://www.futuremarketinsights.com/reports/public-safety-and-security-market

portable equipment. Proposed technologies to be developed must have the foundation/potential for cost reduction when scaled.

Photonic integrated circuits (PICs) are in this respect the preferred option to address SWAP-C issues. As these chips increase in complexity and functionality they are finding new applications; miniaturized spectrometers, integrated solid state gyro, laser beam steering, complex optical modulation/demodulation, optical switching, optical beam forming. Beside the targeted SWAP-C advantage, PICs also offers a potential cost reduction (manufacturing, assembly and qualification).

Currently, Indium Phosphide InP and Silicon Si are the two mainstream photonic integration platforms. Heterogenious integration, although now maturing, may limit the optical power needed for some microwave photonics applications or induce too much loss for quantum communications stringent requirements (QKD), and the development of monolithic integration of III-V on Si remains a challenge. Other possible platforms having specific properties (e.g. Silicon Nitride SiNx for low loss, Silicon Germanium SiGe for wider spectral compatibility, Lithium Niobate LiNbO3 or GaP for nonlinearity, polymers for flexibility) allow operation in the MWIR to visible range, which is important for atomic clocks, communications, CBRN detection, quantum and bio-sensors. Furthermore SiC or Aluminum Nitride AlN wide band-gap platforms will allow to reach the UV for new bio-sensors.

Hybrid/heterogenous and monolithic integration of various materials and components on these platforms represents a long term challenge to be taken up, but the interconnection of devices produced on different platforms will in the meantime permit cost-effective small-medium production of devices for specific applications (for example chiplets).

The assembly of different technology building blocks by 3D integration, on optical/electrical interposer, co-packaged or connected by passive waveguides or fiber routing systems must be considered, as well as the 3D stacking of sensors and AI chips. Micro-optical technologies (including meta, diffractive, micro-lenses), eventually at the wafer level, must be developed for optical sensors relevant to small-satellites and drone-based monitoring. 3D optic miniaturization would notably enable quantum sensors based on cold atoms to fit into these limited payloads vehicles.

In parallel with the integration efforts, progress on discrete components is necessary. This is particularly the case for the performance of laser sources. An increase in power spectral density in a wide spectral range (visible to MWIR, or even THz) is required for many applications (long range 3D imaging, chemical sensing, quantum sensing, aerospace-grade component quality control, …), with additional demanding specifications in terms of noise, linewidth, jitter, tuneability or modulation bandwidth. The technologies considered include semiconductor, solid-state and fiber lasers/amplifiers. High stability lasers are necessary for all pillars of quantum technologies. High tuneability is required for sensing applications. High-speed modulation is required for telecommunications applications.

High power amplifier coherently combined systems in the kW range will also be needed at 1.5 μm telecom wavelengths for ground-base to satellite feeder links and PICs can be used to split, phase-lock the amplifier channels, and steer the output beam far-field. PIC-based coherent combining is also useful at the receiver end to mitigate atmospheric effects.

An increase in the range of active sensors generally implies a large increase in the laser power required, but some architectures may be more advantageous than others from this point of view. This is for example the case of coherent detection continuous lidars (FMCW) compared to pulsed time-of-flight systems, which also provide speed information. The significant efforts made for the development of autonomous vehicles should be leveraged for long-range applications.

Regarding spectroscopic configurations, higher sensitivity, i.e. via compact cells with long path-length or novel sensing modalities (e.g. dual frequency comb spectroscopy, photothermal sensing), could increase signal-to-noise ratio, thus reducing the need for optical power.

Increasing the sensitivity of photodetectors is also a key point that will limit the need for optical power. The development of efficient, high-bandwidth, low-noise single-photon detectors in the near- and mid-infrared range is critical for secure fiber or free-space communications networks, while the availability of 2D arrays of single-photon avalanche detectors (SPADs) would enable 3D imaging without scanners for situation awareness in defense and security applications, and pave the way for quantum imaging.

Reducing the pixel's size of focal plane arrays (FPAs) down to the optical diffraction limit or slightly below will help to improve resolution or to reduce the optic's size. Image processing algorithms based on AI or more traditionally designed will also lead to higher imaging performance while the integration of spectral filters and polarizers can bring additional benefits in terms of discrimination of objects (decamouflage) or laser wavelengths. Among the other non-exclusive techniques to improve the performance of Detection, Reconnaissance, Identification and Tracking of imaging systems, one can find: improved signal-to-noise ratio through High Dynamic Range capabilities thanks to increased charge handling capacity through 3D integration or digital pixels, increased sensitivity for laser pulse detection through Asynchronous Laser Pulse Detection in the pixel readout circuit or other even more advanced design in multifunction pixels.

Advances in optical technologies are driven by the requirements on size, weight, resolution, and cost of imaging optics and by the architectures of sub-systems to point, track, and stabilize the line-of-sight of laser beam directors. High optical resolution in imaging systems and low divergence laser beams correlate with the effective diameter of the photon collecting resp. beam forming aperture. Large aperture optics are in general heavy, costly, and induce unwanted optical aberrations. A way to tackle these problems is the use of segmented optics and electronic feedback loops to control and manipulate the wavefront across the aperture. Coherently coupled multi-aperture laser beam directors are required for long-range optical data links and directed energy applications. New feedback strategies like target-in-the loop algorithms need to be devised to control the phase settings on the sub-apertures and to shape the irradiance on the receiver/target.

Incorporating digital image processing functions as part of the optical system opens up new dimensions in the optical design space. Replacing lenses by digital processing functions in combination with point-spread function engineering could reduce the number of lenses required for aberration compensation and may improve the performance of the digital image processor. Additionally, freeform and meta-optics are expected to greatly simplify optical systems required for long-range surveillance and reconnaissance operations as well as in small-sized optics for miniaturized mobile platforms.

UAVs are omnipresent in today's conflicts and the threat of drone attacks in large public events or on critical infrastructures must be seriously taken into account. There is 2 ways to deny the mission of UAVs or other mobile threats like missiles, either dazzling with low power laser or the sensor-agnostic destruction with high power lasers.

Very high power lasers are needed to neutralize such targets but eye-safety is mandatory. The current defense initiatives build on existing kW-level 1 μm fiber laser technology and spectral or coherent beam combining (SBC & CBC) to reach the required power, but eye-safe 2 μm technology based of fibers, laser crystals or semiconductors would be better suited against drones in urban scenarios. Another approach is based on targeting the absorption bands of organic material (i.e. by attacking carbon bonds in resins and polymers via MWIR laser sources) comprising the UAVs, thus achieving more efficient energy deposition, with less power (<100W).

Innovative concepts for monolithic semiconductor laser/amplifier 2D phase-arrays are required for SWAP-C issues. Progress in CBC lasers will also benefits manufacturing applications.

Assuring that production of basic materials (i.e. III-V compound semiconductors such as GaSb, GaP, InAs, InSb) for making the devices is being secured and developed in Europe, by helping existing research centres/companies to develop the technologies to a higher levels, bigger diametres, higher production scale, new materials.

➢ Cooperation needs with Horizon Europe Missions or partnerships

Photonics provides a framework for securing Europe's technological sovereignty across the five Horizon Europe Missions:

- Climate resilient Europe for at least 150 EU regions by 2030
- 100 climate neutral and smart cities by 2030
- Restore our ocean and waters by 2030
- A soil deal for Europe
- The European Beating Cancer Plan.

The Photonics 21 stakeholders will address innovative photonics solutions related to safety, security, space, and defence to achieve the following objectives related to the Horizon Europe Missions:

(1) Enhance the collaboration between the techno-scientific community and European industry through innovative, attractive, and concrete research projects assuring Europe's transformation into a green, healthy, and resilient continent;
(2) develop photonics hardware, software and system solutions that facilitates safe and secure execution of Europe Horizon Missions and defend the transformation process against any adversary;
(3) build low rate initial production (LRIP) lines for security and defence products whose lifecycles are dominated by characteristics very different from mass markets products for daily use.

Through the implementation of the roadmap, the challenges posed by the Horizon Europe Missions will be addressed by a coordinated effort linking the necessary resources via clearly defined, targeted, and measurable activities across different photonics disciplines and stakeholders in research institutions and industry.

EDA CapTech Optronics: the European Defense Agency (EDA) currently organises its R&T priorities in 11 Capability Technology (CapTech) groups, which are networking fora for experts from government, industry, SMEs and academia, moderated by EDA[7]. Close collaboration with the EDA CapTech Optronics (also called EOST – Electro-Optical Sensors Technologies) would be highly beneficial given the importance placed on dual-use technologies by this CapTech. A major task of this CapTech is to elaborate SRA documents, including "…forecasting future civilian technology development in electro-optics relevant to military users, identifying areas where civilian technology development will not be sufficient for the needs of the military user…". The joint elaboration of SRAs involving dual-use optical technologies is therefore highly beneficial.

EDF: the European Commission establish a dedicated fund with the EU budget, the European Defence Fund (EDF)[8], to support collaborative research and development of key products and technologies for the security and defence of Europe and its citizens. The multi-annual budget of the fund is about €8b for the framework 2021-2027, with 1/3 for research actions. As concluded from a review of DARPA activities, photonic technologies will play a major role in many areas of EDF. Consequentially, the joint elaboration of dual-use optical technologies for Safety, Security, Space and Defence applications will be beneficial, reducing the duplication of efforts and maximising the synergistic effects of joint planning (and possibly execution) of advanced dual-use photonic technologies.

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[7] https://eda.europa.eu/what-we-do/all-activities/activities-search/captech-optronics
[8] https://defence-industry-space.ec.europa.eu/eu-defence-industry/european-defence-fund-edf_en

➢ **Roadmap for 2025 – 2030**

	2025-2027	**2028-2030**
Photonics Research (R) Challenges, TRL up to 5	• Sub-systems based on emerging PIC platforms with hybrid and heterogeneous integration of various materials and components, allowing operation in the MWIR to UV range, for applications in atomic clocks, communications, CBRN detection, quantum and bio-sensors. • Development of efficient, high-bandwidth, low-noise single-photon detectors in the near- and mid-infrared range. • Low-noise lasers for quantum technologies • 2D arrays of single-photon avalanche detectors (SPADs). • New approaches incorporating digital processing functions as part of the optical design space for imaging systems / laser beam directors.	• Sub-systems based on PIC platforms with monolithic and heterogeneous integration of materials and components • Quantum tolerant PIC chips (QPIC) • 2D SPAD arrays with embedded processing • High power 2D phase-array semi-conductor lasers
Photonics Innovation (I) Challenges, TRL starting from 5	• Assembly of different technology photonic building blocks by 3D integration, on optical/electrical interposer, co-packaged or connected by passive waveguides or fiber routing systems. • Micro-optical technologies (including meta, diffractive, micro-lenses), eventually at the wafer level. • Photonic technologies for satellite constellations: space tolerant sensors for positioning, navigation and timing (PNT), inter-satellite distance measurements • Free-space telecom systems for the Quantum Secured Network (QSN), based on novel photonic components • SWAP-C innovative sensors for long range situational awareness, ISR[9], 3D imaging and chemical sensing (CBRN) • High power eye-safe laser developments for emerging threat countermeasures, including dazzling, jamming and neutralizing capabilities. • Sensors protection against laser radiations • Growth of crucial III-V and oxide materials for photonics and exploration of advanced processing techniques	• Demonstration of fused optics/electronics imaging systems • 3D stacking of sensors and photonics AI chips. • Miniaturized PNT sensors including quantum-based sensors for Quantum Information Network (QIN). • Miniaturized long range sensors exploiting quantum technologies • SWAP-C eye-safe high power laser effector systems • Large size III-V substrates and epitaxial wafers
Joint actions required with other Horizon Europe Missions or partnerships		

[9] ISR: Intelligence, surveillance, and reconnaissance, i. e. monitoring an assigned area consistently over a given period of time to build up operational knowledge