Flagship for Photonics Research and Innovation (PREIN)

Annual Report 2021

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SUMMARY 2021

We have some wonderful news! The Flagship for Photonics Research and Innovation has secured funding for another term and will continue its operation during the period 2023–2026. This successful extension follows up from the thorough mid-term evaluation of the Flagship program conducted by the Academy of Finland last fall.

Assessing in detail our research and impact achievements, key indicators, and future plans, the international evaluation panel appointed by the Academy has highly praised PREIN in its report, stating that "the scientific excellence and economic impact of the PREIN Flagship can be considered as outstanding." We are very grateful to the PREIN community members for their enthusiasm and efforts to accomplish world-class science, achieve major economic impact, and support high-level education. These have paid off! As highlighted by the panel of experts, "the strengths of the PREIN Flagship are closely connected to scientific excellence, the realized ecosystem with, alongside the scientific expertise in the three leading Finnish universities, active participation of VTT, the links with industrial partners and education and schools." Of course, building on the past years, we can, and should, still aim at improving our operation, efficiency, and visibility. This does not mean we should perform better, but it should be seen as a sign of a healthy functioning and developing community.

The pandemic unfortunately continued in 2021, but in the following pages you will see that PREIN has actively continued and even expanded some of its activities. Research visibility and impact have kept growing with a significant increase in the number of publications, joint work, and high impact publications. As a part of the re-application process, we have therefore planned some changes in the structural organization to increase our operation efficiency and to give our researchers the opportunity to focus even more on their research. Following our roadmap from last year, new research thematic will also be initiated including for example quantum technologies, metasurfaces, or artificial intelligence photonics. Photonics industry in Finland has continued its strong growth despite of the many challenges in the global economy. Start-ups and growth companies in photonics have been successful in raising funding and commercializing their world-leading innovations. There are more open job positions than candidates! Fortunately, studying and working in photonics in Finland is attracting foreigners from all over the world and this is also why we should put some extra effort towards developing our educational programs to ensure we can provide enough talents to the industry. Together with Photonics Finland, we have continued to organize joint thematic events. Some of these were also organized together with other Flagships. In the spring, we have launched two national recruitment channels for photonics industry and companies: Job Board under Photonics Finland web site and Photonics Job-board Finland LinkedIn group. We have also initiated a series of innovation events at the University of Eastern Finland and Tampere University, a series that will continue in 2022 at other partners.

PREIN outreach activities recovered well in 2021 and we started organizing again various kinds of events to general public and companies. Although some activities still need to wait for the society and business to be completely open again, the pandemic also taught us new ways for communication – a digital leap. In May, PREIN participated in the International Day of Light and even extended it to the International Week of Light with a full week of events. In education, the Photonics Explorer Kit outreach campaign continued, and we launched a national competition "Valon mahdollisuudet" for schools with light-related thematic. Last summer, the field of Photonics gained publicity, when "Valoa huomiseen" was selected for panel discussion in Suomi Areena broadcasted by MTV3. Among the panelist there were, e.g., Minister of Environment and Member of the European Parliament.

We wish to sincerely acknowledge all PREIN members for facing challenges with strength, and determination, which is fully reflected in the success of PREIN. We hope you will enjoy reading the following pages that summarize yet another year of PREIN activities.

Goëry Genty & Jyrki Saarinen

IN BRIEF

PREIN – The Flagship for Photonics Research and Innovation

PREIN – The Flagship for Photonics Research and Innovation is one ten in the Academy of Finland flagship program. PREIN was selected among the six flagships in 2019, and four additional flagships were nominated in 2020 to complete the flagship program. The Academy of Finland flagship program supports high-quality research, creates future know-how for significant societal and economic impact.

PREIN is a research and innovation platform focusing on light-based solutions covering the entire innovation value chain from fundamental and applied research to prototype and technology development, industrial collaboration and start-ups. PREIN is committed to develop high-class education and research environments, state-of-the-art open-access infrastructure, as well as promote innovation culture and diversity. PREIN is a national initiative between four partners:

- Tampere University (TAU) - Coordinator
- University of Eastern Finland (UEF)
- Aalto University (Aalto)
- VTT Technical Research Centre of Finland (VTT)

PREIN has set scientific, societal, and educational impact objectives and monitors the achievement of them annually, as well as reports bi-annually results to the Academy of Finland. The six flagships selected in 2019 had their first mid-term reporting in 2021 including an evaluation meeting with the Academy of Finland and an external evaluation panel. Based on the reporting and the evaluation the Flagship scientific achievements and impact was evaluated and the continuation and funding were decided. PREIN reached the set targets of the two-year reporting period and received outstanding results is the mid-term evaluation.

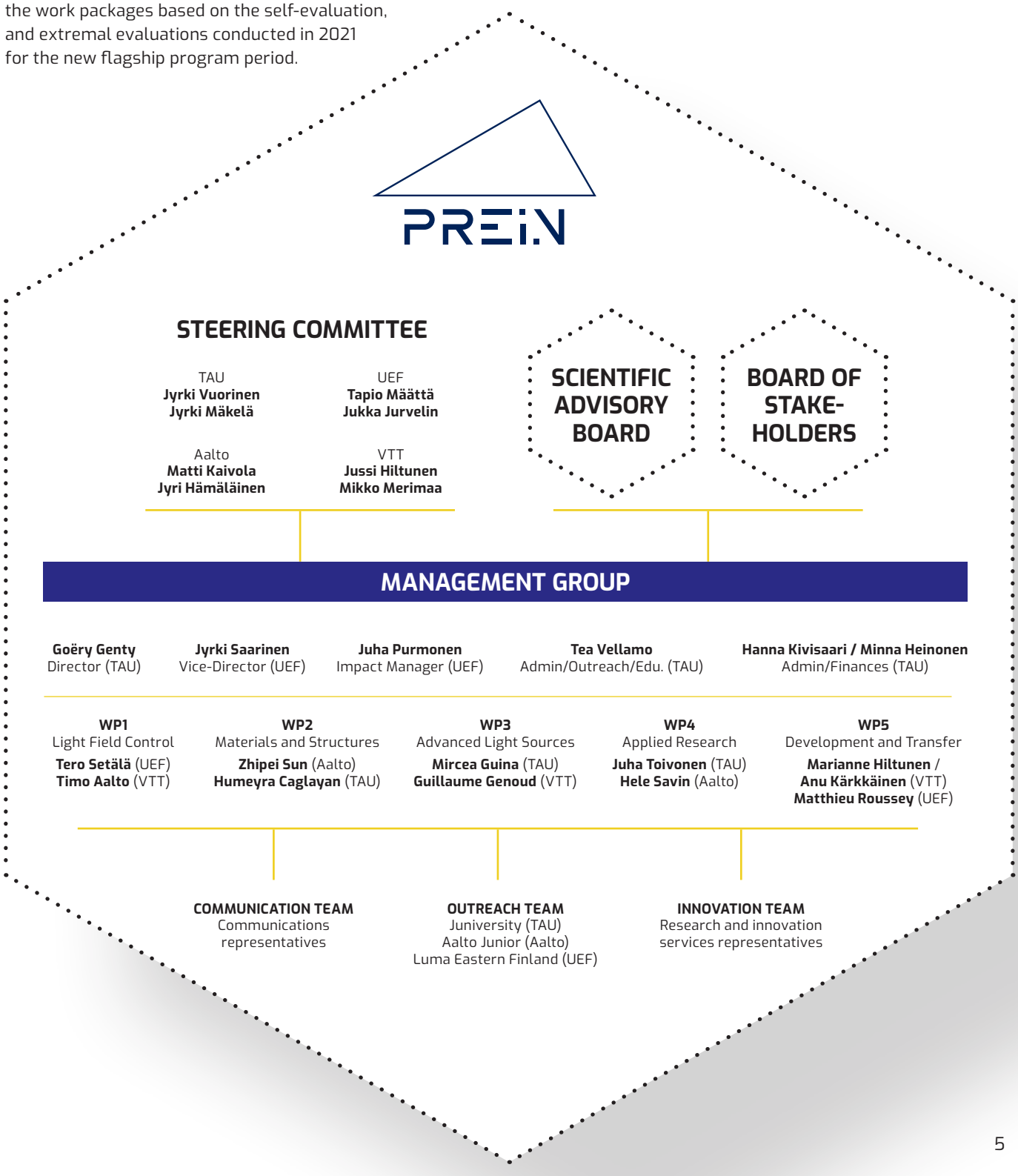
PREIN STRUCTURE 2021

In 2021, the structure of PREIN remained the same as in 2020 with some minor changes in responsible persons. The cooperation and shared themes between the different work packages have been enhanced, while some WP leadership and administrative roles have been transferred during the year due to changes in staff.

There will be a profound structural development of the work packages based on the self-evaluation, and extremal evaluations conducted in 2021 for the new flagship program period.

Changes in the work package leadership and Steering Committee are also foreseen.

Regular meetings of the important bodies, Steering Committee, Management Group and support teams have continued on-line during the year 2021.



ORGANIZATION

The management and leadership structure and key positions in PREIN Flagship have remained the same in 2021. Professor Goëry Genty from Tampere University leads the Flagship as Director of PREIN and is responsible for the overall management. Professor Jyrki Saarinen from the University of Eastern Finland continues as Vice-Director being responsible for the activities related to economic growth and other societal impact.

The original structure of organizing the research continues, with research divided into five work packages (WPs) of which three of them focus on fundamental research and one on applied research. In addition, the fifth WP is dedicated for technology transfer. Each WP is led by a WP leader, supported by a vice-leader who are responsible for the WP management and scientific progress. The WP leadership and responsibilities continued to be the same in 2021, with only one change: The WP5 leader position was transferred from Marianne Hiltunen (VTT) to Anu Kärkkäinen (VTT) keeping the gender balance and the equal division of responsibilities among the partner organizations.

The Management Group has continued as before with the directors, the work package leaders and vice leaders, the administrative coordinators, and the impact persons. The Management Group has the authority to make decisions regarding everyday activities of PREIN such as recruitment and initiating new research topics based on the recommendations of the WP's.

The Steering Committee is continuing its work overseeing the activities of the Flagship and monitoring the progress. In 2021, the mid-term reporting including the key performance indicators were presented to the Steering Committee. The Steering Committee is the link to the institutional level of the partner organizations ensuring resource and infrastructure development and institutional commitment of the organizations. The Steering Committee also validates changes in the Management or the WP structure.

The administrative coordinators facilitate everyday management, acting as the link to the supporting teams. The Communications Team communicates internally about the Flagship in the partner organizations and helps in producing popularized news stories on the PREIN activities to the public.

The Outreach Team focuses on the activities directed at children and young people and produces events and material on photonics directed to these target groups. The Innovation Team monitors the potential of research results and promotes their transfer to the innovation pipeline in collaboration with WP5.

WORK PACKAGES

WP1 LIGHT FIELD CONTROL

- Polarization and coherence control
- Temporal and spectral control
- Nanoscale localization

WP2 MATERIALS AND STRUCTURES

- Advanced optoelectronic alloys
- Nanomaterials, metamaterials and nanostructures
- Photonics integration platforms

WP3 LIGHT SOURCES

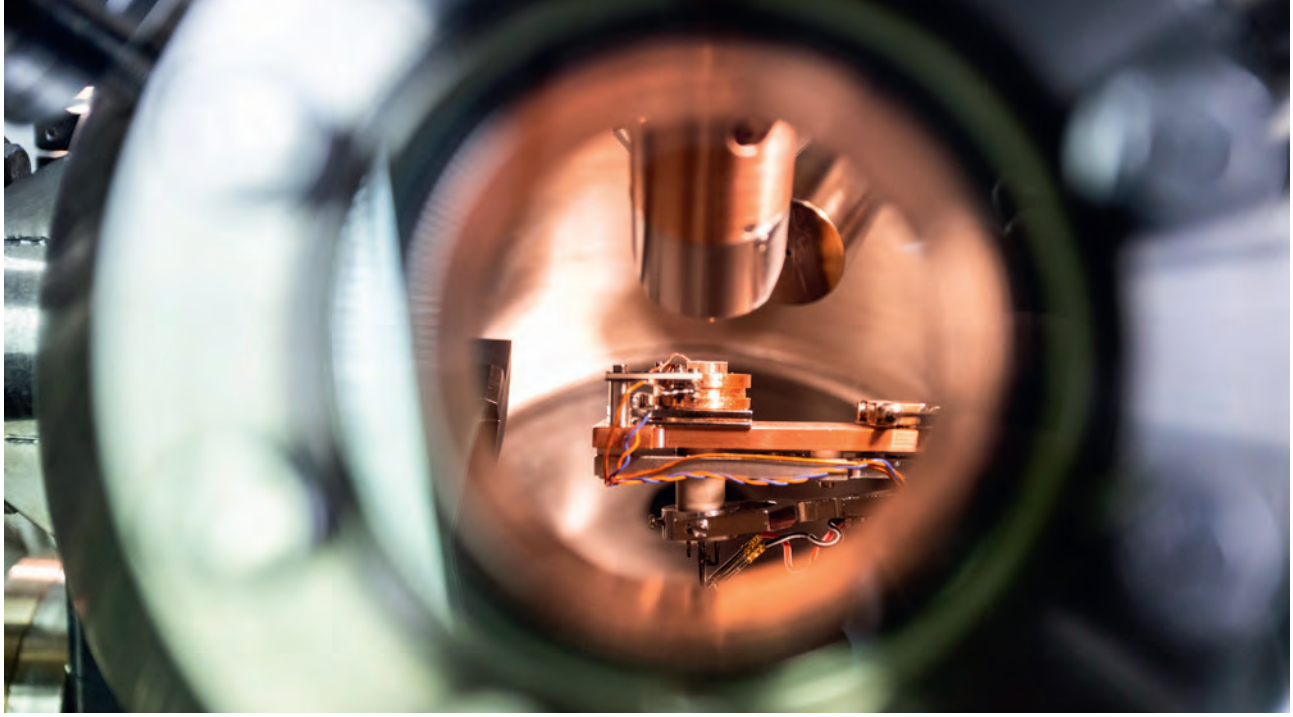
- Mid-infrared laser sources
- Visible laser sources
- High-energy pulsed sources for eye-safe wavelengths
- Single photon sources

WP4 APPLIED RESEARCH

- Portable and disposable sensors
- LIDAR technologies
- Smart photovoltaic modules

WP5 TECHNOLOGY TRANSFER

- Facilitate innovation transfer to companies
- Provide testbeds and prototypes for industry
- Promote photonics-based solutions to industry



ADVISORY BOARDS

PREIN is supported by a Scientific Advisory Board comprising high-level international scientists. Unfortunately, during the year 2021, the Scientific Advisory Board members were unable to visit the Flagship due to COVID-19 pandemic related restrictions. The evaluation of the Flagship scientific activities was carried out through an on-line survey.

The Board of Stakeholders, which includes representatives from national funding agencies, ministries, large corporations, SME's, start-ups, and venture capitalists, links the Flagship to both public and private sectors. This allows PREIN to affect policymaking and receive feedback on industrial needs. The Stakeholders collaborate with the Flagship in thematic events, reports, and annual Board of Stakeholder meetings. The 2021 Board of stakeholders' meeting was held in on-line format in December.

SCIENTIFIC ADVISORY BOARD

Prof. Yasuhiko Arakawa
University of Tokyo, Japan

Prof. Michal Lipson
Columbia University, USA

Prof. Christine Silberhorn
Paderborn University, Germany

Prof. Lluis Torner
Institute of Photonic Sciences, Spain

Prof. Sergei Turitsyn
Aston University, UK

BOARD OF STAKEHOLDERS

Timo Ahopelto, Lifeline Ventures

Jyrki Huttunen, Oplatek

Marko Jalonen, Vaisala

Laura Juvonen, Technology Industries of Finland

Reijo Kangas, Business Finland

Pirjo Kutinlahti, Ministry of Economic Affairs and Employment in Finland

Risto Linturi, Futurist

Eero Salmelin, Huawei

Antti Sunnari, Dispelix

RESEARCH & RESEARCHERS

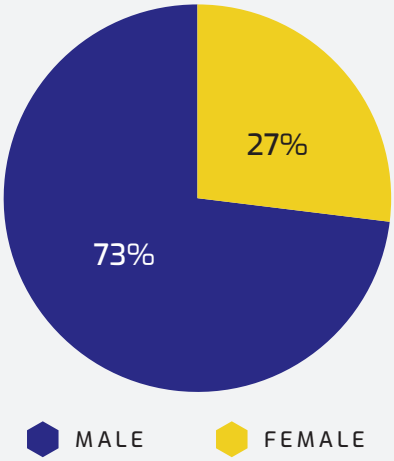
PREIN has identified application areas where the partners' joint expertise is expected to lead to significant breakthroughs which were defined in the research roadmap for 2020–2024. In 2021, PREIN research has continued on the themes defined in the roadmap and there have also been new research groups incorporated in PREIN in the partner organizations, as well as new themes that have developed more rapidly such as quantum photonics which will receive the status of work package in the new flagship program period from 2022 onwards.

The number of researchers involved in PREIN activities has remained on a stable level. There were approximately 350 researchers working in PREIN in 2019 and 380 in 2020, whereas the number of researchers working in PREIN in 2021 was approximately 450 with some changes within the partners due to new recruitments as well as some projects ending.

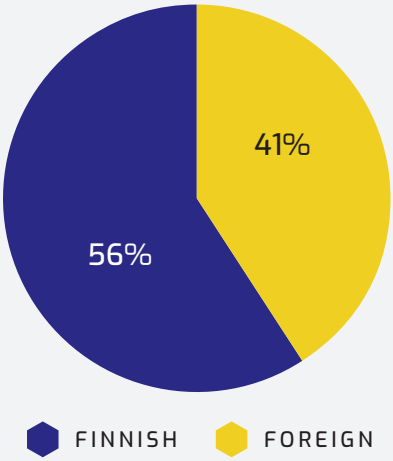
The number of staff involved in the Flagship activities is high in VTT as most of the researchers work for several different projects and thus dedicate only a part of their working hours to PREIN, and therefore the VTT staff numbers are presented in full-time equivalent (FTE). Postdoctoral researchers and PhD students form the largest group in the PREIN staff like in the previous years.

Gender balance and diversity constitute two important key performance indicators in the Flagship program and PREIN has committed to increasing the percentage of female researchers and international researchers. The percentages have grown steadily, with the percentage of female researchers rising to 27% compared to 25% in 2020 and the percentage of foreign research staff reaching 41% compared to 36% in 2020.

GENDER DIVISION OF EMPLOYEES



FOREIGN PERSONNEL



RESEARCH HIGHLIGHTS

WP1: LIGHT FIELD CONTROL

OVERVIEW

WP1 is to develop and study novel concepts for harnessing and manipulating the properties of optical fields including spatial localization and confinement, temporal and spectral characteristics, polarization and coherence. These concepts are then feeding into the design and development of novel structures in WP2 with possible applications in WP3 and WP4.

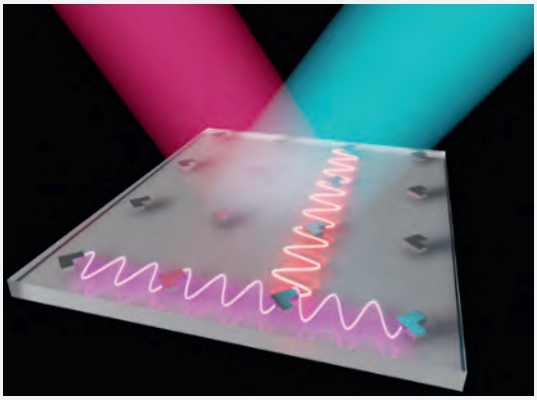
SELECTED 2021 HIGHLIGHTS

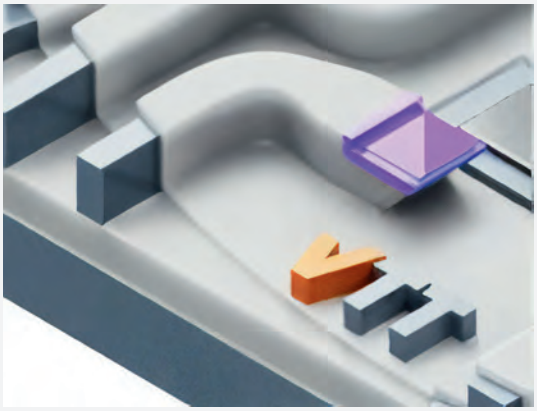
- Coherence and random polarization (UEF/TAU/Aalto): Several results on the nature of coherence and polarization in random electromagnetic beams and nonparaxial light (including plasmon excitations) have been demonstrated. Laser cavities with enhanced epsilon-near-zero (EENZ) mirrors were shown to allow for remarkable coherence control and the source coherence of plasmonic lattice lasers was demonstrated to have a strong effect on their beaming properties. Vector beams have further been shown to provide unique opportunities for spectroscopic measurements and selective mode excitation in nanoparticles.

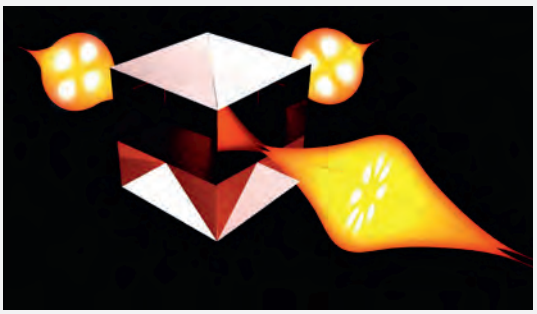
- Polarization splitting and management (VTT/UEF/TAU): Polarization splitting with up to 19 dB extinction ratio was demonstrated using Mach-Zehnder interferometers having total internal reflection mirrors with polarization-dependent phase shifts. Preliminary design concepts for polarization management via metasurfaces integrated in silicon photonics platform via up-reflecting mirrors have been studied. Polarization control of the temporal profile and polarity of the photocurrent pulses generated in the semiconductor-based nanocomposite films by surface photogalvanic and photon drag effects was also demonstrated.

- Metasurface-based nonlinear photonic components (TAU/UEF/Aalto): It was shown against the common belief that also metallic systems can support very narrow resonances (Q>2000), therefore acting as potential materials to realize resonance-based components (filters, sensors etc.). Phasematched stacked metasurface structures were realized and their ability to enhance the nonlinear responses was successfully demonstrated. An experimental technique to characterize the average nonlinear responses of individual nanoparticles was also developed.

- Quantum light research (TAU/UEF): Recently developed methods to perform unitary modulations of multiple spatial modes have been pushed into the quantum domain. Two-photon interferences, one of the most important photonic quantum effects in terms of quantum information, have been observed and studied in different modal configurations.







Top: Plasmonic nanostructure supporting extremely narrow collective responses (orange and violet wave).
Middle: Concept of up-reflecting mirrors integrated into photonics circuit for light polarization control.
Bottom: Twisted NOON-states generated through two-photon bunching for super-resolution angular rotations.

UPCOMING DEVELOPMENTS

- Coherence and random polarization (UEF/TAU/Aalto): Definition of spin for random polychromatic light and novel geometrical visualization of spatial coherence. Generation of pulse trains under various coherence control mechanisms. Realization of dark mode nanoscale lasers.

- Polarization splitting and management (VTT/UEF/TAU): Final design of a metasurface on silicon photonic platform. Demonstration of up-reflecting mirror structure for polarization splitting and rotation over a broad spectral range seeding to the development of an optical isolator with >100 nm bandwidth and <2 dB insertion loss. New structures will be implemented to demonstrate Faraday rotation in silicon waveguides and isolators based on these rotators will be designed.

- Metasurface-based nonlinear photonic components (TAU/UEF/Aalto): Engineering the coupling between nanoparticles by fabricating hybrid waveguide-metasurface devices. Investigation of how nonlinear metasurfaces can be phasematched using a resonant cavity setup under continuous wave excitation and by using a multipass configuration and ultrashort pulses excitation.

- Quantum light research (TAU/UEF): Extending NOON-states to various spatial structures and obtain different super-resolving mechanisms. Integrate quantum optic operations in glass and develop coupling mechanisms to multimode waveguides. Developing novel multi-particle high-dimensional entanglement schemes invoking the spatial mode degree of freedom. Adapting the Path Integral Monte Carlo computational method to simulated photonics materials. Development of the quantum formalism for the description of coherence and polarization in 3D light.

SELECTED 2021 PUBLICATIONS

1. F. Ahmed et al., "Multilayer MoTe2 field-effect transistor at high temperatures", Advanced Material Interfaces **8**, 2100950 (2021)

2. X. Zang et al., "Efficient hybrid-mode excitation in plasmonic nano-antennas by tightly focused higher-order vector beams", Journal of the Optical Society of America B **38**, 521 (2021)

3. M. Koivurova et al., "Coherence switching with metamaterials", Physical Review Letters **127**, 153902 (2021)

4. B. O. Asamoah et al., "Polarization dependent beaming properties of a plasmonic lattice laser", New Journal of Physics **23**, 063037 (2021)

5. M. Al lakki, A. T. Friberg, and T. Setälä, "Complete coherence of random, nonstationary electromagnetic fields", Opt. Lett. **46**, 1756 (2021)

6. M. Saad Bin-Alam et al. "Ultra-high-Q resonances in plasmonic metasurfaces", Nature Communications **12**, 974 (2021)

7. M. Hiekkamäki, F. Bouchard, and R. Fickler, "Photonic angular superresolution using twisted NOON states", Physical Review Letters **127**, 263601 (2021)

8. C. W. Robson, Y. Tamashevich, T. T. Rantala, and M. Ornigotti, "Path integrals: from quantum mechanics to photonics", APL Photonics **6**, 071103 (2021)

9. L. Kopf et al., "Spectral vector beams for high-speed spectroscopic measurements", Optica **8**, 930 (2021)

10. D. Shahwar, M. Cherchi, M. Harjanne, M. Kapulainen, and T. Aalto, "Polarization splitters for micron-scale silicon photonics", Proceedings of SPIE **11691**, Silicon Photonics XVI, 1169104 (2021)

WP2: MATERIALS AND STRUCTURES

OVERVIEW

The objective of WP2 is to design and develop novel classes of materials and structures, study their properties and realize integrated architectures that allow linking the fundamental research performed in WP1 to the devices and applications developed in WP3–WP4. The range of materials and structures studied spans rom advanced optoelectronic alloys and 2D materials to plasmonic and epsilon-near-zero nanostructures up to photonic integrated circuits.

SELECTED 2021 HIGHLIGHTS:

- 3D printed SOI-OPA lens for micro-LIDAR (VTT/UEF): We have developed methods for 3D printing of lenses and printed the 3rd generation free form lenses using Opticlear materials. The lens surface roughness is well below the micrometre scale, and the lens collimation characteristics are comparable to those of commercial lenses.

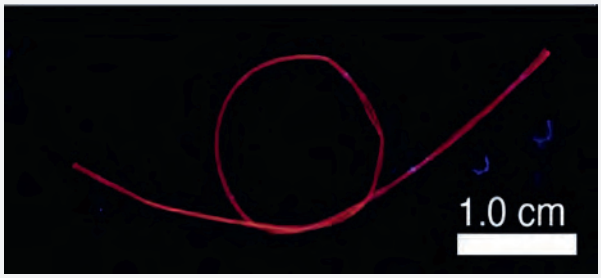
- Cellulose-based optical fibers (TAU/Aalto/VTT): Hybrid optical fibres wet-spun from aqueous methylcellulose dispersions under ambient conditions have been demonstrated. The combination of excellent mechanical properties (Young's modulus and maximum strain values up to 8.4 GPa and 52%, respectively), low attenuation coefficient (propagation loss of <1.47 dB cm^{-1}), and high photostability makes the methylcellulose-based composite fibres excellent candidates for multifunctional optical fibres and sensors.

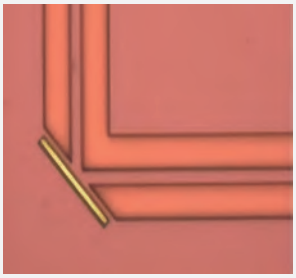
- Novel fabrication and integration methods for 2D materials (Aalto/UEF): High-temperature (up to 673 K) electro-thermal response of MoTe2-based field-effect transistors was studied to provide the thermal endurance limits of 2D materials. Enhancement of nonlinearity in 2D materials has been demonstrated using different approaches (plasmonics, energy transfer, and hybrid silicon waveguides). These results open novel perspectives for photonics and optoelectronic applications of 2D materials, such as integrated light sources, detectors, sensors, and information processing..

- Novel THz components (UEF/Aalto): By combining 3D printing, electroplating and chemical vapor deposition processes, extremely broadband "bubble wrap" polymer nanomembranes covered with multilayered graphene and nearly perfect absorption in the THz range have been fabricated. Patterning of aligned multi-walled carbon nanotubes for tunable THz metasurfaces has also been demonstrated.

- Characterization and simulation of micron-scale silicon waveguides (VTT/Aalto/TAU): Linear and nonlinear losses of micro-scale waveguides were fully studied over a broad spectral range from 1480 to 2270 nm. The study shows that the losses are dominated by the sidewall roughness in good agreement with theoretical predictions. Using a Mach-Zehnder interferometer design, novel polarization splitters with >15 dB extinction ratio for both polarizations and 100 nm operation bandwidth have been developed.

Left: 3D printed lens; **Middle:** Cellulose optical fibre showing high photoluminescence and flexibility; **Right:** Integrated mirror for silicon waveguides





UPCOMING DEVELOPMENTS

- Plasmonics for enhanced detection and fast switching/modulation (VTT/TAU): a noble-metal-free, low loss plasmonic material featuring with ultrafast electrical tuneability will be combined with advanced design and optimization techniques for the development of integrated photodetector and switching/modulator applications. Low-cost high resolution all-optical time-to-frequency converters and optical switches/gates based on plasmon-enhanced ENZ materials will be realized.

- 2D materials for integrated active photonics (VTT/Aalto/UEF): Large-area 2D materials with will be exploited for high-speed optical components integrated on microscopic silicon waveguides. Graphene integration into an experimental pilot line project for the development of 2D materials will be continued with the goal to bring the graphene processes to the level required for the semiconductor industry.

- THz metasurfaces (UEF/Aalto/TAU): Free-standing tunable THz metasurface based on periodic ensemble of graphene-enhanced silicon meta-atoms will be fabricated and tested in the THz range. The concept of metasurface working in the bifurcations and hysteresis regimes as a basis for new THz photonic devices will be investigated.

SELECTED 2021 PUBLICATIONS

1. J. Rossi et al., "Photoacoustic characteristics of carbon-based infrared absorbers," Photoacoustics **23**, 100265 (2021)

2. V. Hynninen et al., "Luminescent gold nanocluster-methylcellulose composite optical fibers with low attenuation coefficient and high photostability," Small **17**, 2005205 (2021)

3. M. Tanabe et al., "Characterization of predictable quantum efficient detector in terms of optical non-linearity in the visible to near-infrared range," Metrologia **58**, 055012 (2021)

4. F. Ahmed et al., "Multilayer $MoTe_2$ field-effect transistor at high temperatures," Advanced Material Interfaces **8**, 2100950 (2021)

5. F. Yao et al., "Complete structural characterization of single carbon nanotubes by Rayleigh scattering circular dichroism," Nature Nanotechnology **16**, 1073-1078 (2021)

6. L. Du et al., "Giant anisotropic photonics in the 1D van der Waals semiconductor fibrous red phosphorus," Nature Communications **12**, 4822 (2021)

7. Y. Dai et al., "Broadband plasmon-enhanced four-wave mixing in monolayer MoS2," Nano Letters **21**, 6321-6327 (2021)

8. H. Hong et al., "Giant enhancement of optical nonlinearity in two-dimensional materials by multiphoton-excitation resonance energy transfer from quantum dots," Nature Photonics **15**, 510-515 (2021)

9. M. Baah et al., "All-Graphene Perfect Broadband THz absorber," Carbon **185**, 709-716 (2021)

10. O. V. Sedelnikova et al., "Laser patterning of aligned carbon nanotubes arrays: morphology, surface structure and interaction with terahertz radiation," Materials **14**, 3275 (2021)

WP3: LIGHT SOURCES

OVERVIEW

This goal is to develops lasers with optimized characteristics for specific applications. The WP is directly connected to WP4 where some of the applications exploits these laser sources. Emphasis is currently on the development of novel-light emitters for quantum technology applications including integration on silicon, light sources operating at cryogenic temperature, hybrid integration track of photonic integrated circuits-based light sources, as well as mid-infrared sources for sensing and imaging applications.

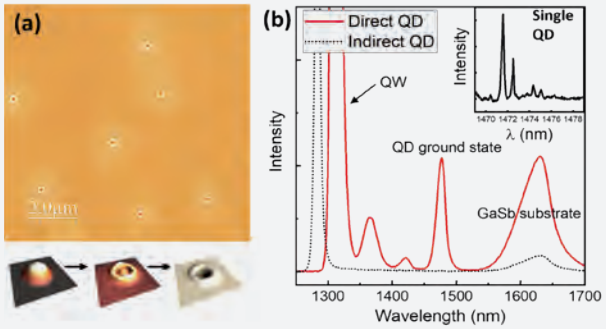
SELECTED 2021 HIGHLIGHTS

- Novel type of emitter based on GaSb/AlGaSb quantum dots (TAU): Using droplet-etched nanoholes filling in AlGaSb, GaSb/AlGaSb quantum dots with type I band alignment and narrow-linewidth excitonic emission at 1.5 µm wavelength was demonstrated. The density of the GaSb QDs can be adjusted by several orders of magnitude down to <1 µm-2 as required for single-QD quantum emitters. Furthermore, we have achieved extremely uniform QDs, with the ensemble PL peak width of just 8 meV. That is less QD-to-QD wavelength variation than in the uniform SoA GaAs/AlGaAs QDs and significantly less than in In(Ga)As/GaAs Stranski-Krastanov QDs. These early results underline the potential of the GaSb/AlGaSb QDs for quantum photonic applications.

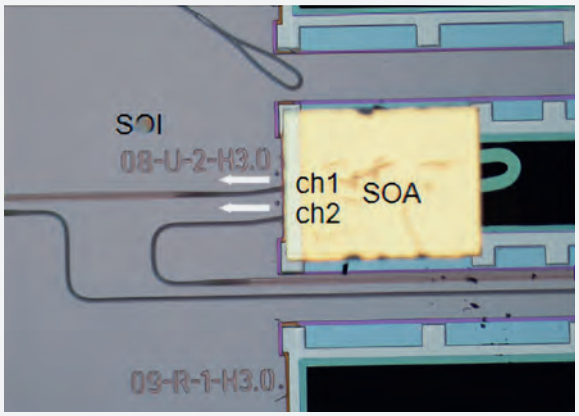
- Photonic integrated circuits-based sources (TAU/VTT): InP-based traveling-wave gain chips containing U-bend geometry have been developed. This particular waveguide architecture allows for placing both input and output on one facet of the device to ease the hybrid integration using flip-chip bonding on silicon platform greatly simplifying the chip alignment. Euler bend geometry was further exploited to achieve low loss U-bends with small footprint. Preliminary tests on integration on silicon-on-insulator platform were also conducted

- Machine learning control of ultrabroadband light sources (TAU): the use of machine learning techniques for controlling and optimizing the characteristics of broadband supercontinuum sources has been explored. Several key results have been achieved including the demonstration of neural network architectures for predicting supercontinuum generation under a wide range of parameters and regimes, and the implementation of a genetic algorithm for supercontinuum spectra tailored to molecular spectroscopy applications.

(a) AFM of droplet-etched nanoholes in AlGaSb surface. (b) Ensemble PL spectra of quantum dots formed by filling the nanoholes with GaSb. The inset shows narrow-linewidth excitonic emission from a single direct-bandgap GaSb quantum dot.

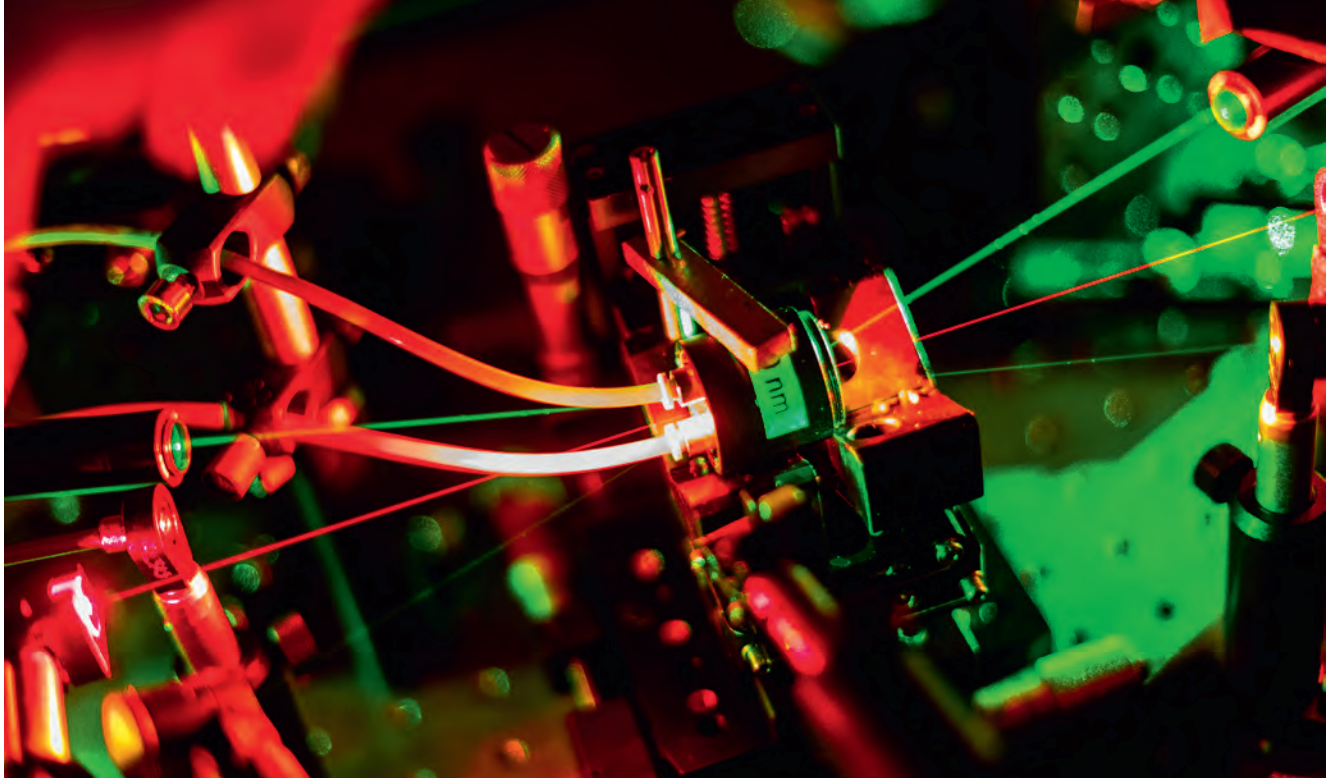


A hybrid photonic integrated circuit-based laser incorporating novel InP gain waveguides with U-bend architecture



NEW PROJECT FUNDING FOR LIGHT SOURCES WITH PREIN PARTNERS

- Project PICAP (2021–2023), Business Finland (TAU & VTT): Photonic Integrated Circuits for Industrial Applications (PICAP) project is a major co-innovation project funded by Business Finland and uniting the key actors contributing to the development of silicon-photonics ecosystem. The total budget including industrial actors is more than 8 M€ covering three years. The overlap with PREIN activities is multi-fold spanning from the development of new device concepts to applications development in sensing and health monitoring, involving both TAU and VTT.



UPCOMING DEVELOPMENTS

- Development of 1.6-2 µm emitters for plastic detections (TAU/UEF): we aim at developing wavelength-locked high-power laser diodes with emission tailored to the optical detection of plastics. Specific wavelengths targeted are 1666 nm (Polyethylene terephthalate absorption), 1684 nm (Polystyrene absorption), 1720 nm (Unplasticised polyvinyl chloride absorption), and 1711 nm (Polypropylene absorption). The customized diodes will be used in connection with photonic integration concepts.

- Hybrid 2.7 µm emitters employing flip-chip integration (TAU/VTT): Building on the successful demonstration of a hybrid GaSb/SOI tunable lasers emitting at around 2.7 µm, we aim at demonstrating continuous wave operation with a tuning band in excess of 100 nm.

- Efficient emitters for high-speed communication at cryogenic temperatures (TAU/VTT): Micron-scale light sources with efficient emission approaching femtojoule per bit at cryogenic temperatures will be targeted. Such light sources are needed for optical transfer of information in superconductivity-based quantum computers where the use of RF cables for communication is limitative due to the associated heat generation.

- Integrated QD emitters on silicon (TAU): Building on our recent demonstration of GaSb quantum dots with direct emission at 1.5 µm wavelength, nonclassical light sources in the same wavelength range and using scalable fabrications compatible with silicon will be developed.

- On-demand ultrabroadband sources (TAU): broadband supercontinuum sources whose spectrum can be tailored on-demand for specific sensing and imaging applications using neural networks will be implemented.

SELECTED 2021 PUBLICATIONS

1. Y. Huang et al., "Room-temperature electron spin polarization exceeding 90% in an opto-spintronic semiconductor nanostructure via remote spin filtering," Nature Photonics **15**, 475-482 (2021)

2. H.-M Phung et al., "Quantum dot membrane external-cavity surface-emitting laser at 1.5 µm," Applied Physics Letters **118**, 231101 (2021)

3. Chellu et al., "GaAs surface passivation for InAs/GaAs quantum dot based nanophotonic devices," Nanotechnology **32**, 130001 (2021)

4. J. Hilska, A. Chellu, and T. Hakkarainen, "Nanohole Etching in AlGaSb with Gallium Droplets," Crystal Growth and Design **21**, 1917-1923 (2021)

5. Chellu, J. Hilska, J.-P. Penttinen, AND T. Hakkarainen, "Highly uniform GaSb quantum dots with indirect–direct bandgap crossover at telecom range," APL Materials **9**, 051116 (2021)

6. L. Salmela et al., "Predicting ultrafast nonlinear dynamics in fibre optics with a recurrent neural network," Nature Machine Intelligence **3**, 344–354 (2021)

7. E. Tagkoudi, C. Amiot, G. Genty, and C.-Sophie Brès, "Extreme polarization-dependent supercontinuum generation in an uncladded silicon nitride waveguide," Optics Express **29**, 21348-21357 (2021)

WP4: APPLIED RESEARCH

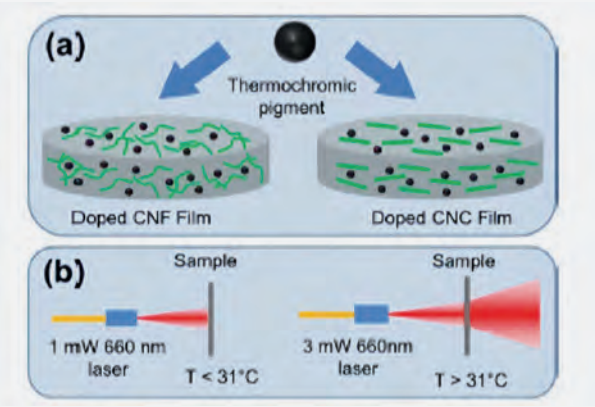
OVERVIEW

Photonics has a wide range of applications and underpins many modern technologies. In this WP we currently focus on three areas where there is a strong synergy between the different partners, including portable and disposable sensors, Lidar technologies, and solar energy.

SELECTED 2021 HIGHLIGHTS

Nanocellulose based optical immunodiagnostic (VTT/Aalto/TAU): A green flexible photonic device exploiting a nanocellulose film doped with a thermochromic pigment has been successfully developed for sensing applications in collaboration with the FinnCeres Flagship. The transparency of the film can be controlled with the power of laser.

Depiction of control of the transparency of the film with the power of laser.

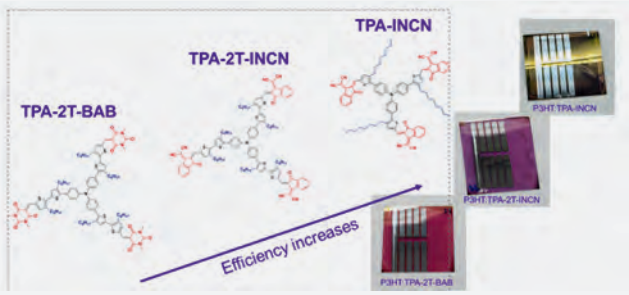


Visualizing hypochlorous acid production by human neutrophils (UEF): We have demonstrated that green fluorescence graphene quantum dots can be employed for revealing the presence of the hypochlorous acid in aqueous solutions and cellular systems. This finding makes graphene quantum dots a biodegradable material and promising sensing agent for for various biomedical applications.

Silicon-on-insulator optical phased array for Lidar (VTT/UEF): A silicon on insulator optical phased array chip was designed using 3 µm thick silicon waveguides allowing for beam collimation both in horizontal and vertical directions.

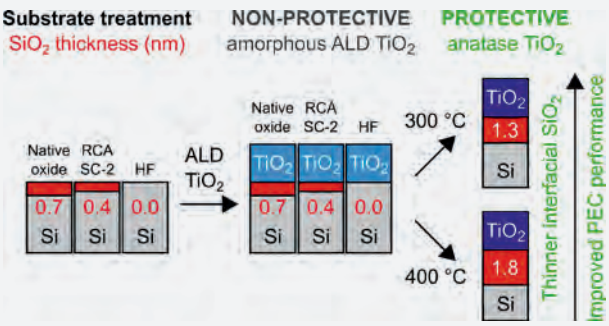
Flexible photovoltaics (VTT/TAU): In flexible solar cell development, high-throughput, high-yield manufacturing of solar cells is the next challenge before they enter the market (i.e. perovskites and polymer active layers). With novel synthesized materials, we have evaluated the use of star-shaped non-fullerene acceptor materials for photovoltaic applications. In addition, flexible perovskite solar cells were fabricated via roll-to-roll methods.

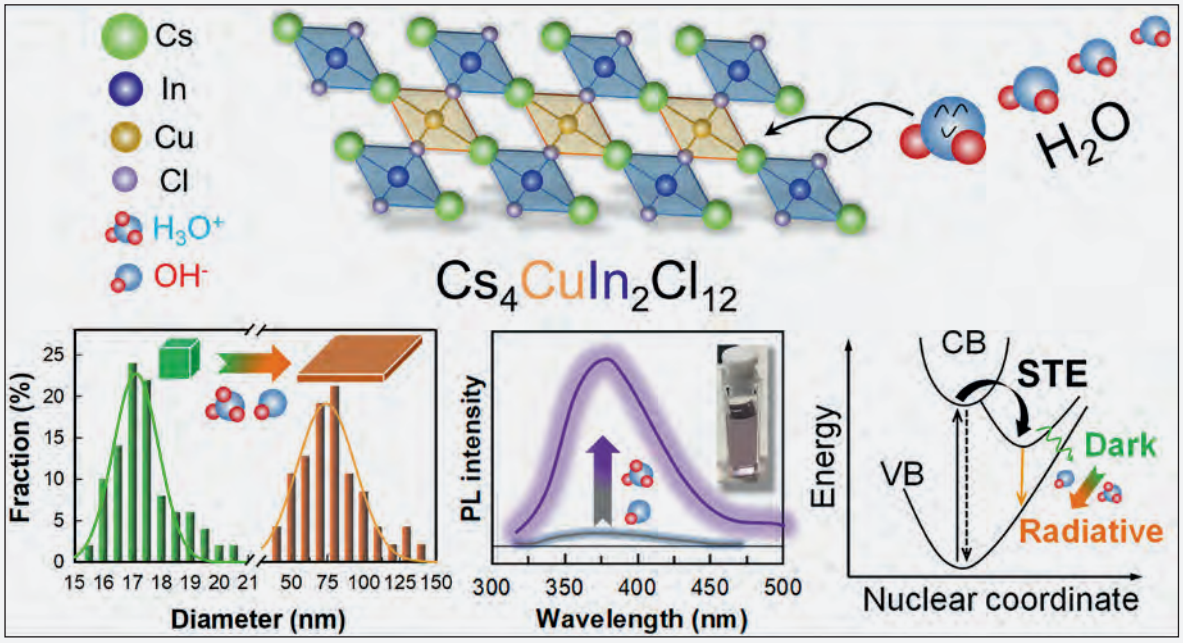
Organic photovoltaics synthesized non-fullerene acceptors.



Interface engineering of atomic layer deposition TiO_2 protective coatings on silicon for solar fuel applications (TAU): The combination of atomic layer deposition TiO_2 process parameters and sequential heat-treatment was shown to determine the performance of TiO_2 photoelectrode coating while silicon wafer cleaning treatments had only little effect. These results allow increasing the lifetime of atomic layer deposition TiO_2 protected semiconductor photoelectrodes in solar fuel cell applications.

Substrate pre-treatment and post-deposition annealing both affect the thickness of interfacial Si oxide layer in ALD TiO_2 protected Si photoelectrodes. Optimization of ALD process temperature allowed the use of lower post-deposition annealing temperature of 300 °C instead of 400 °C improving the photoelectrochemical cell performance.





Structure of lead-free $Cs_4CuIn_2Cl_{12}$ layered double perovskite nanocrystals and its photoluminescence properties, where the presence of water molecules in this structure enhances the photoluminescence quantum yield in the near-UV range.

Light-conversion thin films for photovoltaic applications (Aalto/TAU): Novel upconverting $(Er,Ho)_2O_3$ thin films have been fabricated by atomic layer deposition that can absorb low or high energy photons and emit photons with energies matching the absorption threshold of silicon solar cells. These films were then coupled with a c-Si bifacial solar cell to demonstrate 2.8% enhancement in the short-circuit current density.

Moisture-assisted near-UV emission enhancement of lead-free Perovskite nanocrystals (TAU): Colloidal synthesis of lead-free $Cs_4CuIn_2Cl_{12}$ layered double perovskite nanocrystals via a facile moisture-assisted hot-injection method stemming from relatively nontoxic precursors was demonstrated. The presence of water molecules was shown to enhance the photoluminescence quantum yield (mainly in the near-UV range), induces a morphological transformation from 3D nanocubes to 2D nanoplatelets, and converts the dark transitions to radiative transitions for the observed self-trapped excitons relaxation.

Visible-light absorbing TiO_2:curcumin thin films with ALD/MLD (Aalto): Novel TiO_2:curcumin superlattice structures where monomolecular curcumin layers are embedded within a TiO_2 film have been fabricated using atomic/molecular layer deposition, allowing for extending the light absorption range to the entire visible region. This could pave the way for the use of these films e.g. for light-driven destruction of pathogens.

Compact and lightweight concentrated photovoltaic panels (TAU/UEF): In 2020 the first prototype concentrated photovoltaic -panels have been developed that aim for low weight, compact size and high efficiency. The prototypes showed up to 28% efficiency. To enable even higher efficiencies, a new type of concentrated photovoltaic solar cell materials and advanced high-performance nanostructured antireflection coatings have been developed. These are to be integrated to the prototype platform developed earlier with expected boosted performance.

UPCOMING DEVELOPMENTS

Optical Phased Arrays and Grating Coupler for LIDAR Applications (VTT/UEF): The micro-LiDAR chip will be combined with the 4th generation of 3D printed lenses as well as with a grating out-coupler to enable the non-mechanical beam steering.

Pb-free flexible perovskite solar cells (VTT/TAU): Our target is to develop lead-free perovskite materials leading for scalable and sustainable manufacturing of perovskite solar cells.

Hyperspectral miniature systems for wearable sensors: In order to expand hyperspectral detection in wearable devices, we will introduce hyperspectral units that are applied simultaneously both in body measurement and in sweat analysis.

Solar fuel production using TiO_2 -based photonic crystals (TAU/UEF): Atomic layer deposition of Cu functionalized IO TiO_2 structures with improved photocatalytic activity towards CO_2 reduction have been demonstrated. The optimization of the atomic layer deposition Cu process and post-deposition annealing for improved performance will continue.

Ultra-high quantum efficiency Si-based solar cell for solar fuel production (TAU/Aalto): Atomic layer deposition of TiO_2 protected silicon photocathodes have been achieved. Interfacial photo-carrier dynamics analysis during photoelectrochemical cell operation will be conducted to identify the rate-determining reaction steps that will yield improved efficiency.

Compact and lightweight concentrated photovoltaic panels (TAU/UEF/Aalto): The development of ultrathin optics for sub-centimeter thick concentrated photovoltaic panels using imaging type lenses and solar cell chip miniaturization will continue targeting panels that are more compact, eco-friendly and more efficient.

Luminescent solar concentrators based on Perovskite nanocrystals on silicon solar cells (TAU/Aalto): Current-voltage and optical measurements for luminescent solar concentrator films deposited on glass and attached vertically to solar cells will be performed to characterize the properties of the films and their stability.

SELECTED 2021 PUBLICATIONS

1. F. Bisconti et al., "One-step polymer assisted roll-to-roll gravure-printed perovskite solar cells without using anti-solvent bathing," Cell Reports Physical Science **2**, 100639 (2021)

2. F. Bisconti et al., "Polymer-Assisted Single-Step Slot-Die Coating of Flexible Perovskite Solar Cells at Mild Temperature from Dimethyl Sulfoxide," ChemPlusChem **86**, 1442-1450 (2021)

3. J. Saari et al., "Interface engineering of TiO_2 photoelectrode coatings grown by atomic layer deposition on silicon," ACS Omega **6**, 27501 (2021).

4. A. Ghazy et al., "Luminescent (Er,Ho)2O3 thin films by ALD to enhance the performance of silicon solar cells," Solar Energy Materials & Solar Cells **219**, 110787 (2021)

5. A. Ghazy, M. Safdar, M. Lastusaari, H. Savin, and M. Karppinen, "Advances in upconversion enhanced solar cell performance," Solar Energy Materials & Solar Cells **230**, 111234 (2021)

6. J. Mei, M. Liu, P. Vivo, and V. Pecunia, "Two-Dimensional Antimony-Based Perovskite-Inspired Materials for High-Performance Self-Powered Photodetectors," Advanced Functional Matererials **31**, 2106295 (2021)

7. M. Liu et al., "Manganese Doping Promotes the Synthesis of Bismuth-based Perovskite Nanocrystals While Tuning Their Band Structures," Small **17**, 2100101 (2021)

8. L. Canil et al., "Tuning Halide Perovskite Energy Levels Energy," Environmental Science **14**, 1429 (2021)

9. A. Aho et al., "Wide spectral coverage (0.7–2.2 eV) lattice-matched multijunction solar cells based on AlGaInP, AlGaAs and GaInNAsSb materials," Progress in Photovoltaics: Research and Applications **29**: 869-875 (2021)

10. J. Reuna et al., "Use of nanostructured alumina thin films in multilayer anti-reflective coatings," Nanotechnology **32**, 215602 (2021)

11. J. Isometsä et al., "Achieving surface recombination velocity below 10 cm/s in n-type germanium using ALD Al2O3," APL Materials **9**, 111113 (2021)

12. M. Madadi, J. Heiska, J. Multia, and M. Karppinen, "Atomic and molecular layer deposition of alkali metal based thin films," ACS Applied Materials & Interfaces **13**, 56793 (2021).

13. Philip, R. Ghiyasi, and M. Karppinen, "Visible-light absorbing TiO_2:curcumin thin films with ALD/MLD," ChemNanoMat **7**, 253 (2021).

RESEARCH OUTPUTS AND INTERNATIONAL RESEARCH COLLABORATION 2021

Detailed bibliometric analysis conducted with Scopus/ SciVal shows that PREIN research is highly influential and has improved during the Flagship program period. All the indicators from 2021 exceed results from the previous years. The number of publications has increased significantly with a rise of 37% since 2020, totaling at 339 A-class publications in 2021. This improvement in the scientific productivity of the PREIN researchers is impressive.

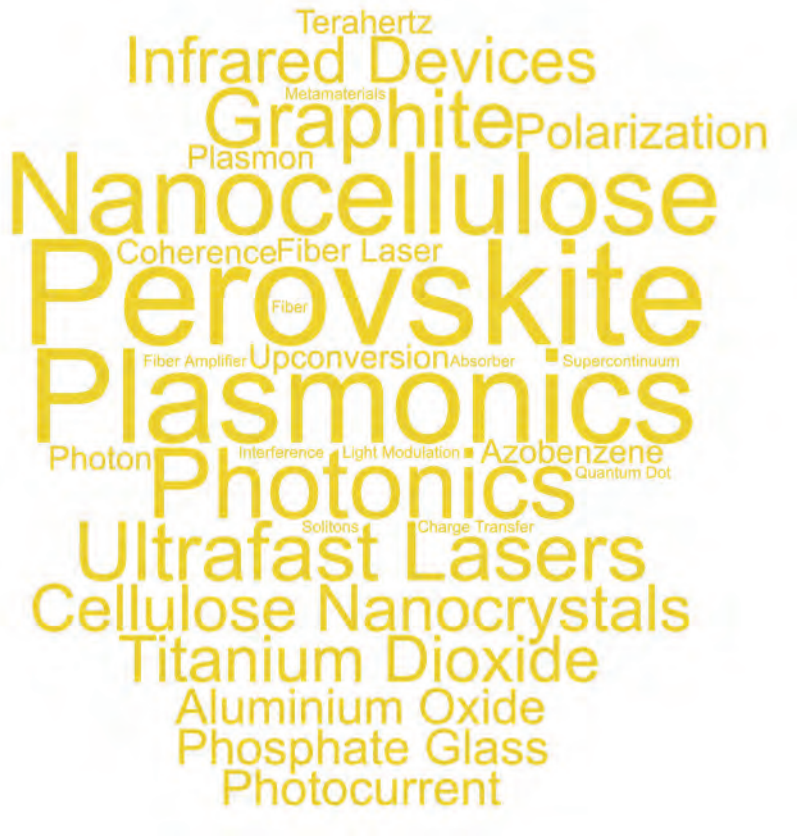
Similarly, the proportion of publications in high-impact journals (IF>7) has increased by 34% reaching 63 publications in 2021. Up to 45% of PREIN-related publications are published in the top 10% journals and 11% of publications in the top 10% most cited publications worldwide. The field-weighted citation Impact for PREIN-affiliated publications is consistently higher than the national average and articles from PREIN researchers are published in high-impact journals much more regularly than the national average.

PREIN has formed significant research collaboration networks with 320 international institutions with whom PREIN researchers have collaborative publications. In 2021, up to 65% of publications include international collaboration. This shows that international collaboration has remained on a steady high level with a wide geographical distribution. New institutions have been added to the collaboration network as the number of institutions PREIN collaborated with rose from 280 in 2020 to 320 in 2021.

Another important aspect is the accessibility of PREIN scientific output which has also improved to a good level of 69% of articles published in open access journals in 2021.The increase here is also significant as the rate of open access was 55% in 2020. Thus, PREIN has been successful in its aim to increase open access publication.

Key phrase analysis showed that a number of very active research areas reflecting well the WP structure of PREIN, but also represent new emerging research areas.

PREIN 2021 publications by journals (only journals with more than 3 publications are shown).



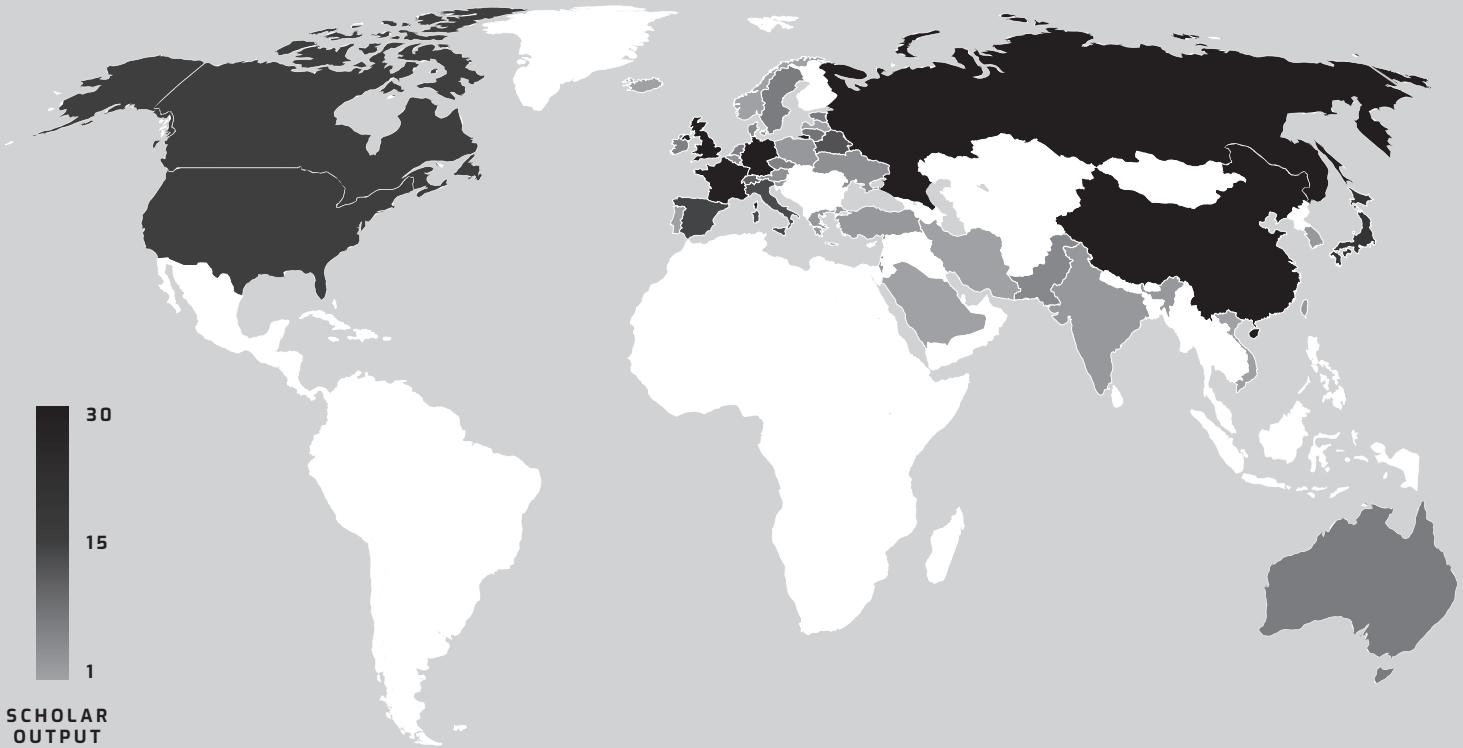
Wordcloud of 2021 research areas.

OF PUBLICATIONS ARE OPEN ACCESS **69%**

PUBLICATIONS IN HIGH-IMPACT (IF>7) JOURNALS **63**

IN TOP 10% JOURNALS **45%**

PREIN international collaboration network.



PREIN Timeline 2021

- NEWSLETTER
- MEETINGS
- EDUCATION EVENTS
- OUTREACH EVENTS
- THEMATIC EVENTS
- PREIN WORKSHOPS
- FAIRS
- OTHER 2021

JAN

- **15 Jan** Innovating in Photonics and Medical Technologies / UEF (on-line)
- **29 Jan** LUMA-representative meeting

FEB

- PREIN newsletter 1/2021
- **9 Feb** Management Group meeting (on-line)
- **17 Feb** LinkedIn Recruiting Webinar for HR
- **22 Feb** Steering Committee meeting (on-line)
- **26 Feb** Innovation in Photonics /TAU (on-line)

MAR

- **19 March** LUMA-representative meeting
- **22 March** Kumppanuudet monimuotoisen tutkimus- ja innovaatioyhteistyön tukena / Academy of Finland
- **25 March** PREIN workshop on Light Sources/ TAU (on-line)
- **31 March** LinkedIn Webinar for Applicants in Photonics

APR

- PREIN newsletter 2/2021
- **7 April** Management Group meeting (on-line)
- **14 Apr** Photonics for all: Optics (on-line)
- **29 April** PREIN workshop on Photonics and Chemistry / TAU (on-line)

MAY

- **5 May** Photonics for Space (on-line)
- **10–12 May** Valon viikko / LUMA UEF, Aalto Junior, Juniversity TAU (on-line)
- **15 May** Winner of Valon mahdollisuudet competition for schools
- **18 May** Photonics for a Sustainable Environment (on-line)
- **20–21 May** International Day of Light conference TAU SPIE (on-line)
- **25 May** Steering Committee meeting (on-line)
- **26 May** Nordic Photonics Forum meeting (on-line)

JUN

- PREIN newsletter 3/2021
- **3 June** MedPhab – Photonics pilot line for medical diagnostics (on-line)
- **4 June** Board of Stakeholder meeting and Management Group meeting (on-line)
- **10 June** Photonics & AI (on-line) with FCAI
- **16 June** Photonics Center 'Lights on' webinar

16 July Suomi Areena (on-line) Valoa huomiseen – Fotoniikka ratkaisemassa globaaleja haasteita -panel discussion

24 Sept Tutkijoiden yö (TAU) – robotics theme

Month of Photonics

22 Nov Forest and Photonics (with FCAI and Unite flagships) Joensuu

JUL · AUG · SEP · OCT · NOV · DEC

16–20 Aug Joensuu Summer School on Optics 2021: Hyperspectral Imaging (on-line)

28 Oct Photonics Application on-line lecture series starts (UEF)

1 Dec PREIN annual event

1–3 Dec Optics and Photonics Days Logomo, Turku

EDUCATION 2021

MASTER'S DEGREE EDUCATION

The COVID-19 pandemic still affected the international master's degree program causing difficulties for the international students. Most of teaching activities, excluding small group laboratory work, continued in on-line mode in 2021. The difficulties in mobilities and on-line teaching arrangements were somewhat reflected in the educational environment. In all, there were 17 persons who obtained a doctoral degree in 2021 from the PREIN partner universities, and 39 persons who graduated from the master's degree program in photonics.

JOINT PILOT COURSE IN OPTICAL DESIGN

The educational collaboration between the PREIN partner universities was strengthened with an Agreement on Joint Education signed in 2020. The first pilot course on Optical Design was implemented in the autumn of 2021. Lectures of the course were organized in on-line format by the University of Eastern Finland, and course-related exercises were organized locally by each partner university. Altogether 20 students participated on the course in the first implementation. The plan is to continue the course collaboration, and to extend it in the future to more courses addressing possible overlaps and the specialization and profiling of the PREIN partner universities.

DOCTORAL EDUCATION

Regular summer schools have been organized as a part of doctoral education activities, with an annual summer school in the University of Eastern Finland and a bi-annual summer school in Tampere. The summer school on 'Optics: Hyperspectral Imaging' was organized by the University of Eastern Finland in on-line format in August 2021, whereas the Tampere summer school is planned to be organized in the following year. The Joensuu Summer School was organized completely remotely with over 150 registered participants around the world.

CONTINUOUS EDUCATION AND COURSES

In the year 2021 the following short-term continuous education courses were offered to a large target group. Both webinars, Photonics Applications and Finnish Fotoniikan perusteet (Basics of Photonics), were offered on-line, free of charge, and were open to anyone interested.

Training is also offered in more specific short-term courses directed at companies and employees in photonics industry. These courses have been planned according to the needs and requirements to further increase photonics skills in related companies.

APPLICATIONS OF PHOTONICS WEBINAR IN OCTOBER-NOVEMBER

The Application of Photonics course is popular among master's students and can be included in some of the degree programs in photonics in the partner universities. The course was organized as a series of hybrid lectures in Joensuu and online with company visits reserved to the photonics master's students only, but the on-line application and company presentations were open to anyone interested. Students were also given an opportunity to attend only on-line presentations which interested them most.

BASICS OF PHOTONICS (FOTONIIKAN PERUSTEET)

Due to the COVID-19 pandemic, Finnish universities decided to offer their open university education in on-line format and also to grant participation on the courses for free. As a part of these free open course offerings, the University of Eastern Finland offered the Basics of Photonics course in 2021. The course is suitable for anyone interested in photonics and light, and who need an understanding of photonics. There were no prerequisite or background knowledge requirements for the participants.

EVENTS 2021

During 2021, the events and meetings continued mostly on-line. There were seven adminstrative meetings, four internal thematic events and fourteen events aimed at external target groups in fields using photonics applications ranging from forestry to medical fields. The main photonics event in 2021 was the the Optics and Photonics Days in December.

PREIN has decided to participate in the largest and most important photonics fairs to promote research activities and offer services and expertise to potential international industrial partners. These include LASER World of Photonics exhibition organized bi-annually as the main European event and Photonics West Fair in the United States. In 2021 both fairs Photonics West and Laser World of Photonics were cancelled, and the next Photonics West fair will be organized in 2022 and Laser World of Photonics in 2023.

INTERNAL EVENTS

The internal events in 2021 included both the PREIN administrative meetings and the workshops organized primarily to increase the collaboration of the PREIN partners in several thematic research areas. Although the workshops were aimed at PREIN members, the on-line events were open to anyone interested upon registration.

The adminstrative PREIN meetings were organized on-line during the whole year 2021 including the meetings of the Management Group, Steering Committee and meetings with the outreach, communications and innovation teams. There were three Steering Committee meetings and three Management Group meetings in 2021.

The Scientific Advisory Board did not have a meeting in 2021 but provided an on-line evaluation on the scientific and related impact activities of PREIN for the mid-term evaluation submitted in February and re-application submitted in June 2021.

The Board of Stakeholders meeting was arranged on-line in June 2021 and gathered the PREIN members and external stakeholders together to discuss the PREIN activities. The focus of this meeting was particularly on the ways popularizing of the scientific research results.

PREIN WORKSHOPS

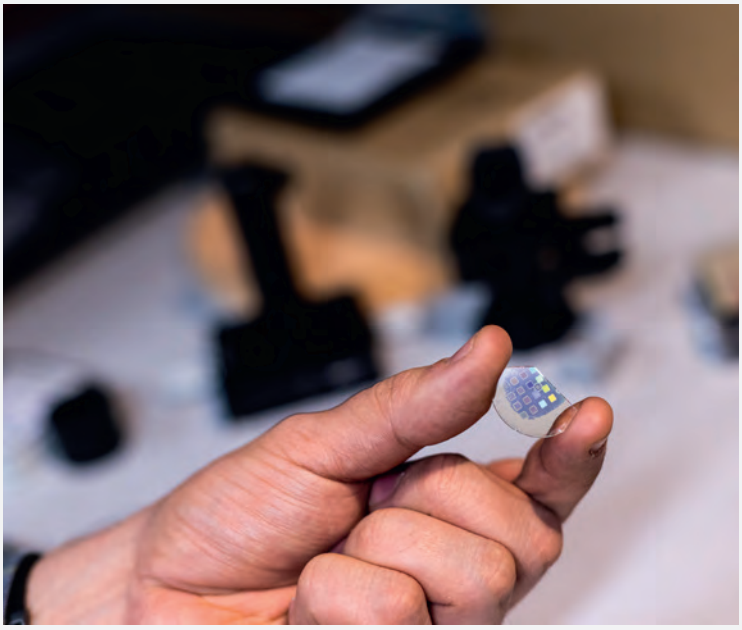
The Internal research cooperation within PREIN partner organizations was enhanced by organizing thematic workshops on cross-cutting themes in the partner organizations.

WORKSHOP ON LIGHT SOURCES IN MARCH

This workshop was organized by Tampere University. The event presented different kinds of light sources including semiconductor-based, fiber-based and hybrid light sources, as well as their applications in quantum technologies, spectroscopy and sensing and different technology platforms. There were 109 participants mostly from the PREIN partner organizations.

WORKSHOP ON PHOTONICS AND CHEMISTRY IN APRIL

The webinar was organized by Tampere University. There were 155 participants altogether with almost half being PREIN partners and half external participants from other research groups based in the University of Helsinki, University of Jyväskylä and University of Turku among others.



EXTERNAL EVENTS

Almost all the external events were organized on-line in 2021. The photonics webinar series "Photonics4", organized together by Photonics Finland and PREIN, was launched in 2020 and continued in 2021, with several thematic webinars targeted at different target groups within field benefitting from photonics applications. There were approximately 800 participants in the events in 2021 from PREIN member organizations, other universities and research institutions from Finland and abroad, people working in photonics industry companies, students and other people interested in the themes.

PHOTONICS EVENTS

There were two important themes in 2021 in the events organized: innovation and recruitment. The events were organized on-line.

To increase innovation activities among the PREIN partner researchers, PREIN launched a series of innovation events to bring together the innovation services and photonics researchers and to showcase successful research activities which have been able to become spin-off or start-up activities.

Recruitment was chosen as a theme to help the photonics and related industry, and students and graduates to meet each other. The event continued recruitment related events and activities that PREIN and Photonics Finland launched in 2020. Two events aimed at different target groups were organized in 2021 and the events will continue in 2022.

INNOVATING IN PHOTONICS AND MEDICAL TECHNOLOGIES IN JANUARY

The webinar on Innovating in Photonics and Medical Technologies was organized by the University of Eastern Finland and the event was mainly targeted at researchers in Eastern Finland. The webinar was co-organized by the Photonics Research and Innovation (PREIN) Flagship and the Experts in Medical Computing (EMC) program, which is organized jointly

by the University of Eastern Finland and Savonia University of Applied Sciences.

INNOVATION IN PHOTONICS IN FEBRUARY

The Innovation event was organized on-line by Tampere University. In addition, to inform on innovation services, there were spin-off company presentations from Optosense and Vexlum. Optosense produces humidity sensors and Vexlum specializes in lasers. There were 22 participants in the webinar.

LINKEDIN RECRUITING WEBINAR FOR HR IN FEBRUARY

Photonics Finland and Photonics Flagship PREIN organized a webinar on LinkedIn recruitment platform to provide practical information for employers on how to use LinkedIn for recruiting. The invited webinar speaker was Tom Laine, an internationally acclaimed LinkedIn expert. The newly launched Photonics Job Board was also promoted. The platform will provide information for all Photonics Jobs available in Finland. The event was organized in Finnish.

LINKEDIN WEBINAR FOR APPLICANTS IN PHOTONICS IN MARCH

PREIN and Photonics Finland organized a LinkedIn-training for photonics student jobseekers in March. The event included a LinkedIn-training for students and jobseekers given by Tom Laine, who presented how to create an appealing profile for job hunting, how to maximize post visibility and how to find Photonics jobs in LinkedIn. In addition, an extension to the Photonics Job Board was introduced, where students and jobseekers will be able to post their LinkedIn-profiles. The event was targeted at potential applicants, students and graduates in photonics and related fields.

APPLICATIONS OF PHOTONICS ON-LINE LECTURE SERIES IN OCTOBER-NOVEMBER

The Applications of Photonics series showcased practical applications of photonics from an industrial point of view. Key professionals from companies gave presentations and introduced their businesses, technologies and applications. A total of 22 companies were invited, each from a distinct sub-field of

photonics. The event offered researchers, student, alumni and company experts, the possibility to network with each other.

PHOTONICS CENTER 'LIGHTS ON' WEBINAR IN JUNE

To celebrate the establishment of the Photonics Center in Joensuu and to present the available services to potential collaborators the webinar showcased the infrastructure which will be available in Joensuu. The service coverage includes equipment, facilities and experts, as well as support to photonics companies in business development, capital acquisition and networking. Start-up companies are offered additional expert and accelerator services.

FOREST AND PHOTONICS IN NOVEMBER

Forest and Photonics is a thematic event organized annually to promote the synergies of photonics applications in forestry. In 2021, the flagships for artificial intelligence, FCAI and the Unite flagship focusing on Forest-Human-Machine Interplay, were invited to participate in the event and to contribute to the cross-cutting themes of digitalization and new technologies revolutionizing forestry and forest industry. The event was organized in Joensuu in November as a face-to-face event, but the presentations were also streamed on-line. Forest and Photonics is an event where researchers, experts and industry representatives can learn from presentations, network, seek collaboration and to discuss with other professionals from forestry and technology fields.

OPTICS AND PHOTONICS DAYS IN DECEMBER

The main event of the year was the Optics and Photonics Days which was organized in the city of Turku in December. Optics and Photonics Days is an annual central event in the fields of optics and photonics in Finland. The event brought together academic and industrial branches of photonics, as well as presented the state of the art of research and development to the community. In 2021, the event gathered around 200 participants on-site. The program was divided between academic sessions, industrial sessions and the exhibition combining around 30 industries working in Photonics in Finland or abroad. The program also included a special session on Women in Optics and Photonics, a large poster session of 60 poster presentations and a Job Fair. Related events to Nordic Photonics meeting, the PREIN annual meeting and Photonics Finland Autumn meeting were held adjacent to the Optics and Photonics Days. The PREIN event consisted of a join session on the recent flagship-level activities and workshops on the work package related themes. There were around 60 participants in the PREIN event.

PHOTONICS4 WEBINARS

The webinar series titled "Photonics4" which was launched in May 2020, continued in 2021 with five events in 2021. The webinar events were organized by Photonics Finland in collaboration with PREIN and other relevant stakeholders depending on the theme of the event. Each event was targeted to a specific field of photonics applications and aimed for both photonics researchers and experts and companies from the particular field of industry.

PHOTONICS FOR ALL: OPTICS IN APRIL

A full day webinar was organized in promoting the expertise in optical design, testing and manufacturing from 3D-printed optics, fiber optics, glass molding, optics film, optics welding and precision engineering. In addition, there was an aim to bring the capabilities to the knowledge of industry. All the PREIN partners presented their expertise in the event, as well as seven companies specializing in optical applications.

PHOTONICS FOR SPACE IN MAY

The on-line event was jointly organized by Photonics Finland, PREIN and the Business Finland space program. The webinar aimed to spur conversation about the New Space Economy and opportunities it opens for photonics and photonics innovation. The potential of photonics in space industry is constantly growing as new applications are found.

PHOTONICS FOR A SUSTAINABLE FUTURE IN MAY

The event was organized by Photonics Finland and PREIN in collaboration with Photonics Austria. The opening words of the event were presented by Krista Mikkonen, Minister of Environment. Speakers included European level experts in research on sustainability, but also companies involved in sustainable applications. The aim of the workshop was to find out how photonics drives sustainability, for example, enabling high-tech solutions which contribute to protecting the environment and preserving resources. From reduced material consumption through to saving energy the impact of photonics is evident. The participants discussed global environmental challenges, the potential of photonics to solve the challenges, and the potential, diversity, and capacity for innovation of photonics as an 'enabler' of sustainability.

NORDIC PHOTONICS FORUM MEETING IN MAY

PREIN participated in the event organized by Photonics Finland where the cooperation opportunities in Nordic photonics were discussed with Photonics Sweden. In addition, the Photonics21 and the EU Commission's new project PhotonHUB Europe activities and synergies were presented. The possibility to increase collaboration with Baltic countries was also addressed through the representative of the Baltic Photonics Cluster active in Lithuania, Latvia and Estonia.

MEDPHAB – PHOTONICS PILOT LINE FOR MEDICAL DIAGNOSTICS IN JUNE

The webinar showcased MedPhab - European Pilot Line for Photonic Medical Devices in which the PREIN partner VTT is involved. MedPhab accelerates the commercialization of diagnostic devices and instruments for treatment based on photonics. The pilot production line focuses on three application areas: hospital environment, home care devices and equipment for chemical diagnostics. The webinar introduced MedPhab technology capabilities and the collaboration possibilities it offers to companies. The PREIN partner VTT represents the Finnish expertise in the international MedPhab community.

PHOTONICS AND ARTIFICIAL INTELLIGENCE IN JUNE

Photonics and Artificial Intelligence webinar organized in June was a collaborative event by Photonics Finland, PREIN and the flagship for Artificial Intelligence, FCAI. Both photonics and artificial intelligence are key enabling technologies essential for almost all industries. For example, autonomous cars, industrial automation, virtual reality, medical imaging, and border control - all rely on photonics and AI technologies. Photonics and AI webinar was organized to find out what can be achieved when these technologies are brought together. In addition to presenting the flagships and their members capabilities, there were also international experts from ITMO University in Russia and key industrial experts from companies applying photonics and artificial intelligence.

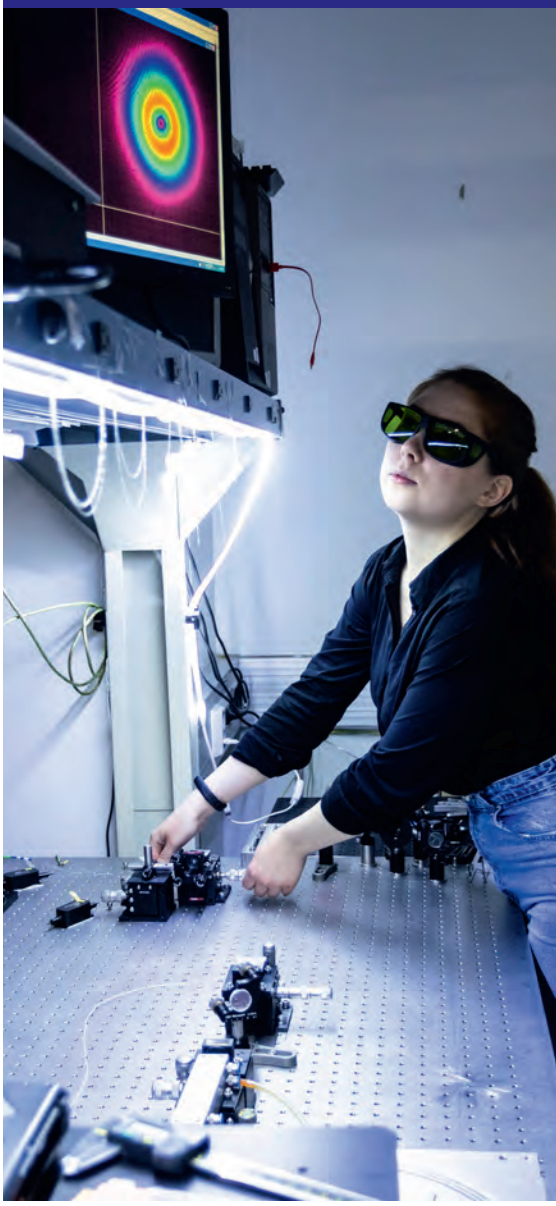
IMPACT

In 2021 many of the impact activities have developed further and more results have been gained in scientific, societal and education impact.

As part of the mid-term evaluation of the Flagship program the Academy of Finland invited an external panel to evaluate the impact of the flagships in 2021. The international experts evaluated the scientific impact, impact on economic growth and impact of society in PREIN Flagship in September 2021. The evaluators praised the scientific impact noting on the increase of publications and significant number of competed funding secured. PREIN Flagship has witnessed a particularly rapid growth of industry partnerships especially through the involvement of VTT. PREIN was also recognized to have a broad scope not just in research and state-of-the-art open-access national infrastructures, but also as a provider of top-level education and reaching out to schools to promote careers in science and technology. According to the evaluation: "Overall, the scientific excellence and economic impact of PREIN Flagship can be considered as outstanding." PREIN received the best overall rating and the highest scores in all the evaluation categories. The external evaluation supports the development of PREIN in the next flagship program period.

INTERNATIONAL FLAGSHIPS EVALUATION PANEL STATED:

"Overall, the scientific excellence and economic impact of PREIN Flagship can be considered as outstanding."



SCIENCE AND INNOVATION

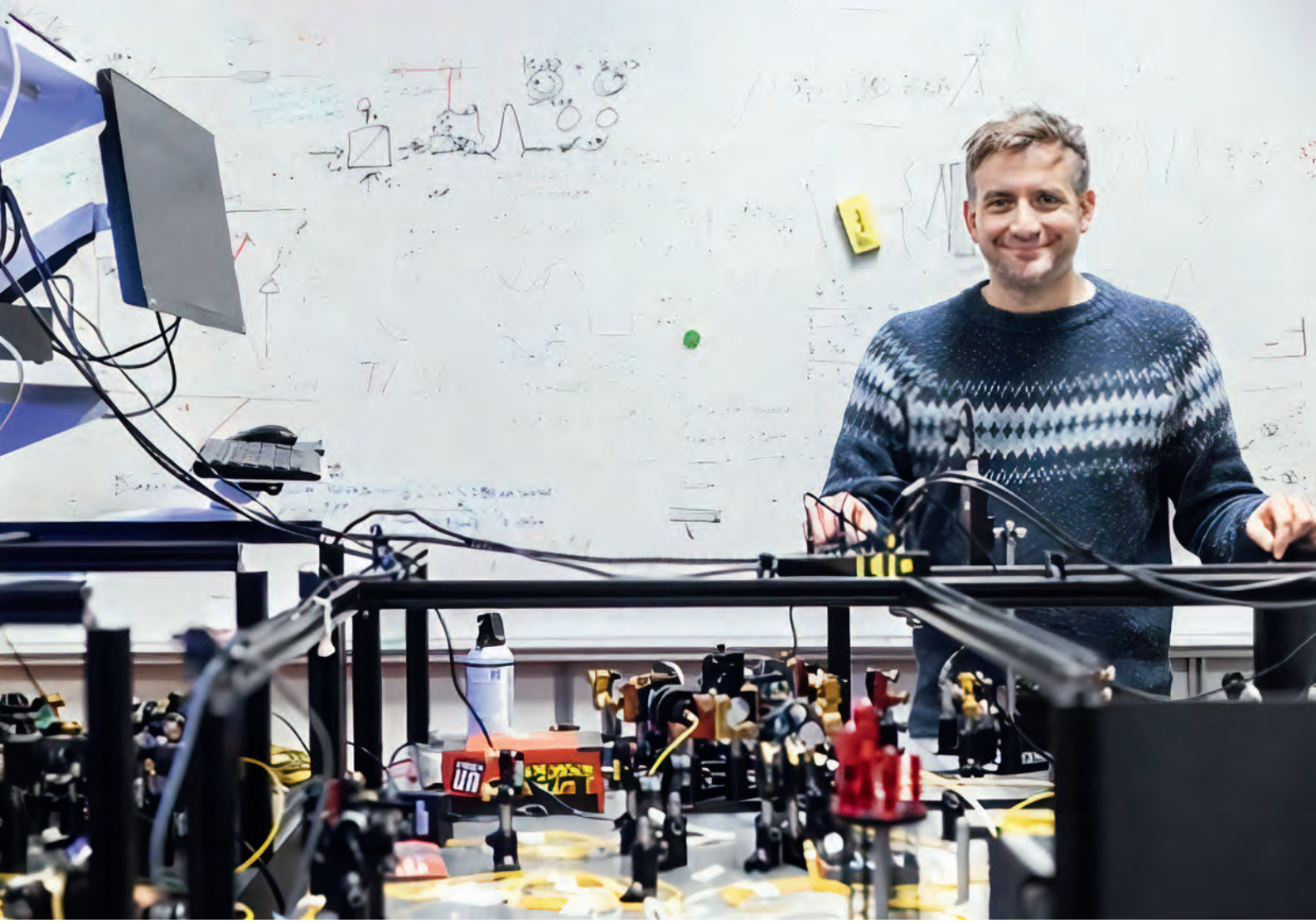
The scientific impact of PREIN is manifested in 2021 also through the prestigious funding received. Photonics research projects were granted significant funding from sources including the Academy of Finland, Business Finland, and European funding agencies also in 2021.

ACADEMY OF FINLAND

In 2021, the Academy of Finland has granted PREIN partners four Academy Project and one Academy Research Fellow funding. Additionally smaller mobility grants were given for mobilities to and from the PREIN partner universities.

The Academy projects that received their funding decision in 2021 included:

Elimination of Contact Losses in Semiconductors through Atomic-scale Interface Research and Engineering (COLO)
A joint project between Aalto University, Associate Professor Hele Savin and University of Turku researchers is funded for the years 2021–2025. The goal of this consortium project is to get a breakthrough in atomic-scale understanding and engineering of metal-semiconductor interfaces which are a limiting part of current devices like transistor and LED and reduce device efficiency. Due to reactivity of surfaces (e.g. silicon surfaces) with processing conditions, the surfaces have different properties from bulk crystals and high densities of material defects which degrade electrical properties. Another problem is how to get intense signal from embedded Si device interfaces with atomic identification. To reach the main objectives: (i) correlations between electrical properties and atomic and electronic structures of interfaces; (ii) controlled ways to decrease contact losses in devices, we bridge in



pioneering way surface-science and semiconductor technology expertise of two groups

Tunable THz Chiral Metamaterials
Professor Yuri Svirko from the University of Eastern Finland received funding for the Academy project Tunable THz Chiral Metamaterials. The project focuses on creating metamaterials examining the ways the limitations imposed by nature can be overcome by replacing bulk materials with composite particles with sizes much smaller than the radiation wavelength. The resulting metamaterial consists of two- or three-dimensional matrices of particles (meta-atoms) of subsurface wavelength. The freedom to design meta-atoms enables a sensitive setting of the electromagnetic properties of the metamaterial. The project develops and studies chiral metamaterials, which interact with right and left circularly polarized electromagnetic waves in different ways and enable control of the entirety of the terahertz electromagnetic waves.

Flying Aero-Robots Based on Light Responsive Materials Assembly (FAIRY)
Hao Zeng from Tampere University received funding for the Academy Project FAIRY for 2021–2026. The project is carried out to create the world's first small-scale flying robot that is built from smart materials and can be driven using light energy. The results will open up new avenues of research in materials science and advance the development of innovative small-scale robotic devices. The main challenge lies in manufacturing aircraft wings that interact with air flow and are powerful enough to propel a robot through the air.

ULTRAFAST PHOTONICS: UPHYPE
Petr Obraztsov from the University of Eastern Finland received Academy Research Fellow funding for the project UPHYPE which studies hybrid inorganic perovskites. These are a new type of semiconductor with great potential for low cost and high-performance solar cell applications. Although intensive studies have been conducted on perovskite solar cells to date, even the basic mechanisms of high energy conversion efficiency are still under discussion. organic-inorganic hybrid materials having a perovskite structure. A combination of advanced ultra-fast time-resolution optical, THz, luminous flux, and photoelectron spectroscopes is used in experimental studies of the dynamic behavior of charge carriers immediately after light excitation. The resulting experimental analyzes and modeling of the results will be used to develop new photonics devices

based on hybrid perovskites, such as THz radiation emitters and detectors, radiation modulators, and impregnable absorbers. The project is funded for the years 2021–2026.

EUROPEAN RESEARCH COMMISSION (ERC) GRANTS

Assistant Professor Robert Fickler from Tampere University was granted an ERC Starting Grant for the project Twisted Ions – A novel tool for quantum science. The project received funding in 2021 for the years 2022–2024. A recently developed field of research investigates techniques and effects of structuring matter-waves, i.e., a wave-like beams of massive particles. At its core is one of the most fundamental principles of quantum physics, the so-called wave-particle dualism. According to the principle, quantum objects can appear as waves and particles, even though in classical physics both concepts are something very different.

Associate Professor Tanja Tarvainen from the University of Eastern Finland was granted the ERC Consolidator Grant for five years starting 2021. Her research aims at developing novel quantitative imaging modalities based on coupled physics. Coupled physics imaging combines the benefits of two physical phenomena, such as light and ultrasound through the photoacoustic effect. The research aims at the development of quantitative tomographic techniques utilising methods of Bayesian inverse problems. The aim is to provide new imaging modalities for biomedical imaging and research..

INNOVATION

There were several projects running for the commercializing of research in 2021. In 2021 there were 32 invention disclosures and 17 patents filed by PREIN partners. There was also a transfer of invention from Tampere University to **Ampliconyx Oy** on the method for stabilization of similariton pulses in mode-locked fiber lasers.

The VTT LaunchPad business incubator project **HyperMine** was founded in 2021. The science-based incubator VTT LaunchPad delivers VTT's strategy to renew industries and society by spinning off companies built on VTT's technologies. In the incubator, we bring VTT researchers and IPR together with the best business minds and investors. HyperMine project investigates active hyperspectral technology which enables early phase ore mapping in underground and surface mines. It helps to get more natural resources for sustainable development with less effort and environmental effects.

BUSINESS FINLAND RESEARCH TO BUSINESS FUNDING

Research to Business (R2B) funding is intended for researchers and research groups in universities and other research organizations who want to build new business based on their research and commercialize their idea. The project must have several commercialization options – the entity who commercializes the idea cannot be known at the start or during the project. The actual product and business development occur after the project either within a new company being established, or as a new business activity in an existing company.

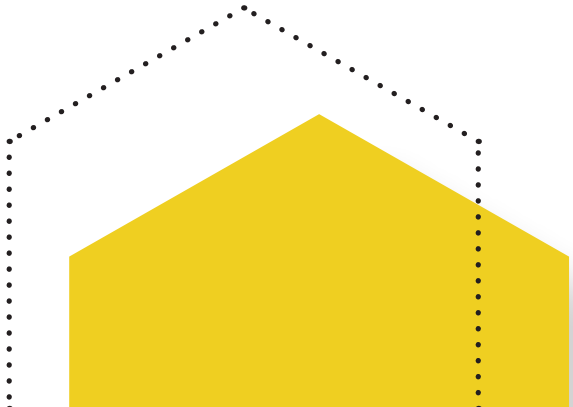
There were two Research to Business (R2B) projects funded in 2021 in which the PREIN members are involved. The following projects at the University of Eastern Finland received R2B funding in 2021:

- Time-domain diffuse optical tomography system based on nanosecond scale pulse illuminations
- Compact X-ray tube with nanocarbon cold cathode

Human Optimized XR
The Human Optimized XR consortium project between several universities and 15 companies received funding as a Business Finland Co-Innovation project linking university research tightly linked and interested in Finnish industry.

BUSINESS FINLAND CO-CREATION AND CO-INNOVATION FUNDING

Research organizations can form a joint Co-Innovation joint action if it is related to the ecosystem of leading companies. Leading companies' roadmaps define the themes, in which the development of new knowledge and expertise focused, and on where a public research is possible. Companies may have different roles: they may have their own R&D project, or they may be co-funding the research project or act as a subcontractor



Thermal Channel Technologies is a start-up from VTT developing cooling technology used in high intensity LED luminaires.

to a project implemented by another company. Companies and research organizations collaborate to develop new knowledge and innovations to serve as a basis for international business activities. Prior the Co-Innovation phase, in a Co-Creation project research organizations and companies work on a new research idea together.

There are two Business Finland Co-Innovation projects funded in 2021 in which the PREIN members are involved:

- HUMan Optimized xR . The involved PREIN partners are Tampere University, Aalto University and University of Eastern Finland
- CEIWA - Circular Economy of water in industrial processes, with VTT as a partner

INDUSTRY COLLABORATION

Economic impact and industrial collaboration are increased through tight collaboration with Photonics Finland mainly as PREIN and Photonics Finland continue to increase and tighten their cooperation.

New Photonics Start-ups
The VTT-based Thermal Channel Technology start-up Thermal Channel Technologies Oy, a VTT spin-off company, has developed a cooling solution that is considerably more efficient than current commercial solutions, used e.g. in the charging stations of electric cars, 5G base stations, smart grids, and high intensity LED luminaires. Thermal Channel Technologies Oy commercializes the CooliBlade technology, which has closed a one-million-euro seed investment round. The CooliBlade project also received VTT LaunchPad funding in 2020.

The Photonics Center venture in Joensuu can also be considered a start-up of the University of Eastern Finland.

Photonics Center – Collaboration for Business and Research, based in Joensuu
One of the major infrastructural investments from the PREIN partner University of Eastern Finland and its regional partners has been the new Photonics Center Oy (a non-profit company) in Joensuu. The parties of the Photonics Center Agreement are the City of Joensuu, Business Joensuu, University of Eastern Finland, Karelia University of Applied Sciences, Riveria Training Consortium, University Properties of Finland, and the Regional Council of North Karelia. The Center will be officially opened in 2022.

SOCIETAL IMPACT

The aims to increase the visibility of photonics and educate the general public about the possibilities light-based technologies can offer are important for PREIN. The visibility of photonics is also increased by stories in popular media. There were 16 news stories on PREIN Flagship, related photonics research or researchers published in the national media. The first Tiede magazine collaboration article on solar power was published in 2021.

OUTREACH 2021

The aims to increase the visibility of photonics and educate the general public about the possibilities light-based technologies can offer are important for PREIN and therefore PREIN participates in events targeted at the general public and arranges activities targeted at children and youngsters. In these activities PREIN partners with the outreach experts in the partner organizations and the photonics industry's umbrella organization Photonics Finland.

Furthermore, the visibility of photonics is increased by stories in popular media. The visibility in media kept constant with 17 news stories on photonics published in national media. The PREIN newsletter reached 190 followers in 2021 and the PREIN Twitter account increased its followers close to 700.

SUOMI AREENA 2021

PREIN and Photonics Finland participated in Suomi Areena, one of the most popular events on politics, society, culture and sports in Finland. The panel discussion was organized on-line and streamed through the MTV3 channels. The topic of the PREIN and Photonics Finland panel discussion in 2021 was Light for Tomorrow - Photonics Solving Global Challenges. The panel discussion focused on the science and technology of light, photonics, the effects of which already extend to the everyday life of us all. Photonics is a light-based technology that provides solutions to most global challenges. For example, solar cells generate green electricity and LED lamps save electricity. Photonics is estimated to reduce CO2 emissions by 3 billion tons by 2030. Photonics applications cover the electronics, pharmaceutical, healthcare and food industries. What would the internet be without an optical fiber connection or a smartphone without a camera and touch screen?

Speakers of the panel discussion organized by PREIN and Photonics Finland included:

Host: Peter Nyman
Panelists: Henna Virkkunen, MEP, Coalition Party,
Antti Vasara, President and CEO, VTT
Jyrki Saarinen, Professor, Vice President of PREIN, Institute of Photonics, University of Eastern Finland (UEF)
Krista Mikkonen, Minister of the Environment and Climate, Vihreät – De Gröna
Risto Linturi, futurist

WEEK OF LIGHT EVENTS

To celebrate the International Day of Light on May 16, PREIN and the LUMA collaboration partners, Juniversity, Aalto Junior and LUMA Center Eastern Finland organized several on-line events during the week between May 10–12. The thematic week called "Valon viikko" was directed at children, young people, schools and teachers. The LUMA partners and PREIN organized on-line workshops directed at different target groups ranging from early education to high schools. The event was a part of the official program of the International Day of Light, IDL 2021 and it was also registered as the year of science 2021 activities to increase the national visibility. All the LUMA partners promoted the activities to their contacts and to local schools.

The workshops reached almost 1 000 participants during the week and some of the material remain

permanently available for independent activities. Although the content was developed for the thematic week, the LUMA actors will incorporate the activities in their regular offering.

Juniversity organized an on-line workshop directed at the primary education level with the target age of five to six years. The workshop titled "Hehkun värikkäät tunteet" (Colorful Feelings of Glow) was structured as a narrative workshop about Hehku character, who expresses his feelings in different colors, but he does not recognize which color means which feeling. By studying the phenomena of light, the children were able to identify the different feelings and name them. The workshop combined photonics and light-related phenomena with storytelling and emotional education. The workshop was planned and implemented for the first time in six supervised workshops during the theme week, and it reached 109 children and 12 primary education teachers. The workshop was then integrated in the regular Juniversity workshop offering and ran an additional 11 times in 2021. All together the workshop was organized 15 times in 2021 reaching around 300 participants in total.

Aalto Junior provided an on-line workshop directed at elementary school levels on building a spectroscope. The workshop explored the spectrum of light and showed the participants how to craft their own spectroscope with accessories found at home. The workshops reached about 500 participants during the thematic week and the material for the workshop is available on the web sites of PREIN and Aalto Junior also for later reference and independent activity.

LUMA Eastern Finland produced a science activity video "Science trick: from a transparent to a reflector." Science Tricks are short, self-paced science sessions that consist of video, work instructions, and research questions. The video was shared in YouTube and also via Instagram. During the theme week the video was viewed 121 times. The activity remains available for further independent use.

PREIN organized a workshop on using the Photonics Explorer Kit reaching almost 90 students in upper secondary levels. The workshop included activities in the following themes: Light meets material (LED lights, different surfaces and printed function instruction), Light diffraction (accessories laser pointers and water glasses), Spectrometer (accessories: diffraction lattice). In addition, there are more video tutorials available for using the Photonics Explorer Kit directed at teachers to help them organize classroom activities by themselves.

PREIN also provided thematic on-line presentations on photonics research themes on an approachable level suitable for potential students and high school

students. The speakers and topics were Jaana Vapaavuori, Aalto University: “From plants to solar cells”; Mikko Huttunen, Tampere University “What can you do with ultra-short laser pulses?” and Petri Karvinen, University of Eastern Finland “Really small things and some X-rays.” There were 45 participants together in the three presentations.

COMPETITION FOR SCHOOLS

PREIN and the LUMA partners organized a light-themed competition directed at upper secondary and high-school levels titled “Valon mahdollisuudet” (Possibilities of Light). The competition was launched in January 2021 with three different challenges and invited student groups to participate and document their solutions and experiments. The challenges were building your own optical measuring equipment, describing and simulating a light phenomenon and the challenge of growing food on Mars. There were 18 groups who delivered their project work by the deadline on April 30th. The winners were declared in May just before the international day of light, and all the participating schools were awarded a Photonics Explorer Kit.

PHOTONICS EXPLORER KIT CAMPAIGN

The Photonics Explorer Kit campaign launched on the International Day of Light in 2020 continued also in 2021 and PREIN and Photonics Finland renewed their commitment of donating one kit each for all the private or company donations made.

Although the Photonics Explorer Kit has focused on the Finnish context, there has been additional impact through the spread of the Photonics Explorer Kit to new regions in the world. The Photonics Explorer Kit campaign has inspired international researchers in PREIN partners to introduce the kit to their home countries. This has led to the Photonics Explorer Kit being launched in Ghana in 2021.

OTHER ACTIVITIES

The SPIE student organization at Tampere University organized an on-line conference to celebrate the International Day of Light in May. The two-day event on May 20–21 hosted international speakers, student presentation, poster sessions and an industrial session. The on-line conference was sponsored by PREIN.

In September Tutkijoiden yö (TAU) – Researchers’ Night featured a podcast by Arri Priimägi with the title “Valolla voi muuttaa ja kontrolloida materiaaleja” (Light can change and control materials).

In the Aalto Junior workshop children could make their own spectroscope and see white light split into a rainbow. The University of Eastern Finland LUMA center showed how a see-through object can become a reflector.

A part of the winning work on describing and simulating a light phenomenon – Heart nebula by the group from Tampere Yhteiskoulun lukio

PRIZES AND ACKNOWLEDGEMENTS

AWARDS FROM OPD21

Photonics Finland presented the Optics and Photonics Days 2021 (OPD21) nominated awards, which were shared in three categories:

- **The Company of The Year 2020**
- **The Best Doctoral Thesis 2019 and 2020**
- **The Best OPD21 poster Awards (3 posters)**

THE COMPANY OF THE YEAR 2020 – VARJO TECHNOLOGIES

The best company of the year 2020 award was received by Varjo Technologies for their innovative work on immersive computing. Varjo Technology has been developing state of the art headset allowing the most immersive mixed reality experience ever constructed when real and virtual elements blend together naturally.

Teemu Tomberg – The best doctoral thesis in 2020.

THE BEST DOCTORAL THESIS AWARDS – PHD TEEMU TOMBERG (2020) AND PHD MATIAS KOIVUROVA (2019)

The best doctoral thesis in 2020 was awarded to **PhD Teemu Tomberg** from the University of Helsinki for his work on "Application of interferometry and cantilever-enhanced photo acoustic spectroscopy to background-free trace gas detection".

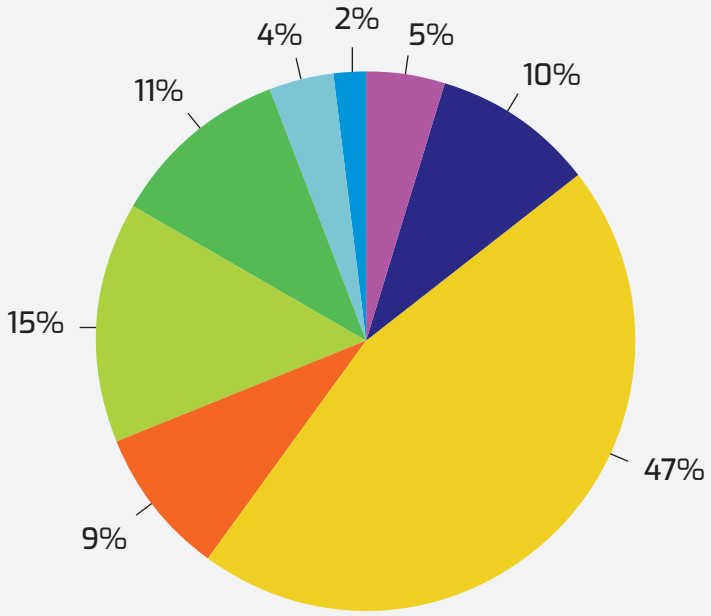
THE BEST OPD21 POSTER AWARDS – MEHR FATIMA, PRABUDEVA RAMU AND LEA KOPF

Mehr Fatima, research scientist at VTT Technical Research Center of Finland, National Institute of Metrology VTT MIKES with her poster on "Radiocarbon dioxide detection using cantilever-enhanced photo acoustic spectroscopy".

Prabudeva Ramu, doctoral researcher in the Optoelectronics Research Center at Tampere University with his poster on "Ultra-thin and flexible solar cells for space applications".

Lea Kopf, doctoral researcher in the Experimental Quantum Optics group at Tampere University with her poster on "Spectral vector beams".

2021 FUNDING SOURCES



- ACADEMY OF FINLAND FLAGSHIP FUNDING
- OTHER ACADEMY OF FINLAND FUNDING
- UNIVERSITY/RESEARCH INSTITUTE'S FUNDING
- BUSINESS FINLAND
- EU
- BUSINESS COMPANIES
- OTHER FINNISH & FOREIGN
- EXTERNAL IN-KIND CONTRIBUTION TO THE FLAGSHIP

FUNDING 2021

The total funding of PREIN in 2021 reached 52.1 million euros in 2021 with 2.5 million of flagship funding and 49.6 million euros from other sources. The Academy of Finland flagship funding, constituting 5 % of the total funding, acts as leverage to increase other sources of funding. The main source of funding for the Flagship is the institutional funding from the partner organizations constituting approximately half of the total funding. The proportion of institutional funding has declined slightly as PREIN has been able to secure more external funding. Overall, the distribution of the funding sources has remained similar compared to previous years with only slight changes. The most significant change is the increase in company funding rising from 9% in 2020 to 11% in 2021.

PREIN

Photonics Research
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FLAGSHIP PROGRAMME

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