PREIN

Photonics Finland OPD2024
28 - 30 May 2024, Helsinki, Finland

FLAGSHIP FOR PHOTONICS RESEARCH AND INNOVATION (PREIN)

Optics and Photonics Days 2024
May 28, Helsinki

FLAGSHIP PROGRAMME

Tampere University
UNIVERSITY OF EASTERN FINLAND
Aalto University
VTT

Program

15:00-15:30 **PREIN summary of 2023 activities**

15:30-16:15 **Pitch sessions of PREIN internal research projects**

16:15-16:30 **Research highlights: PREIN Research Council of Finland Proof of Concept projects**

16:30-17:15 **Innovative ecosystem for doctoral education in Photonics (I-DEEP)**

17:15-18:00 **Panel discussion**

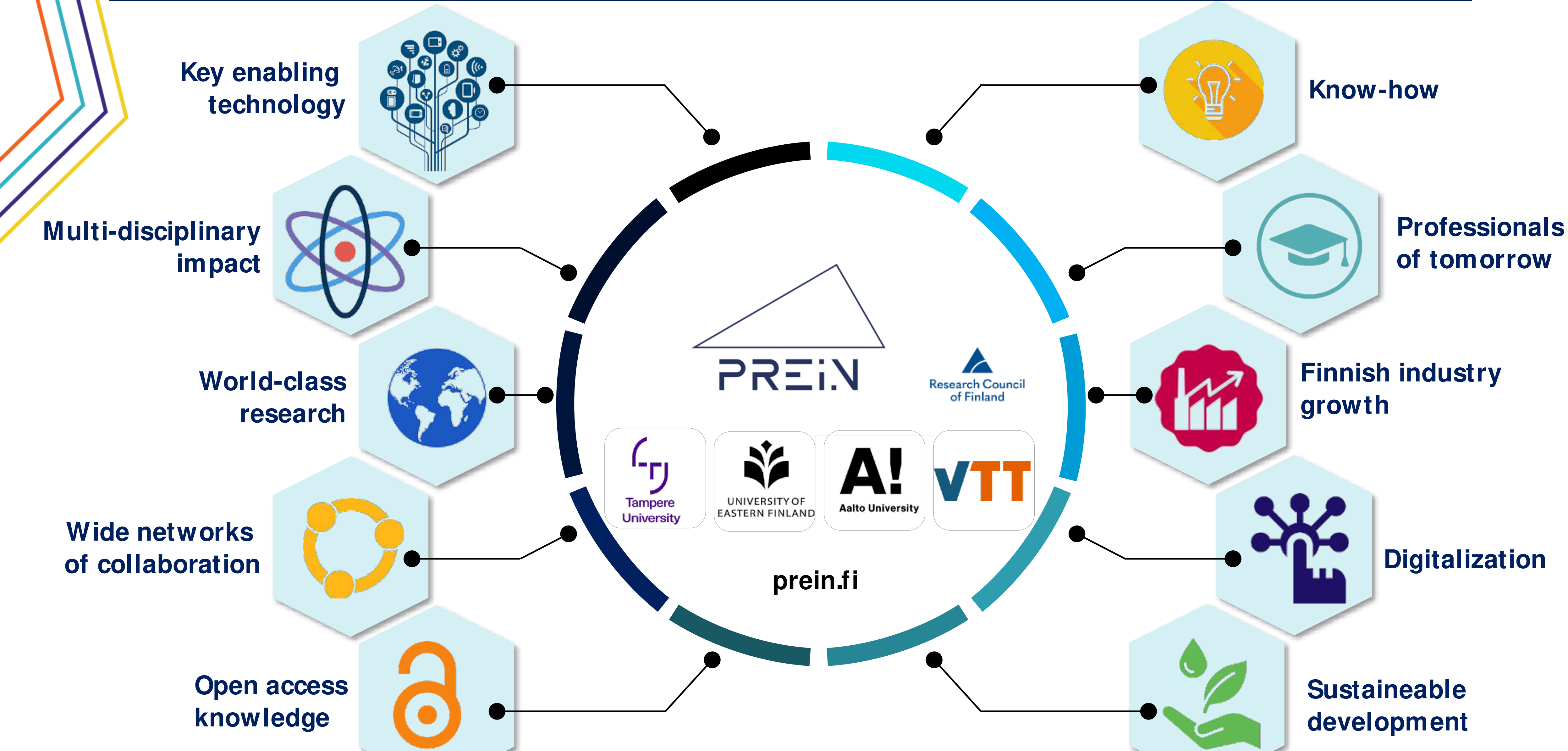
In the past 10 years Finland has established an extensive ecosystem for Photonics RDI

RESEARCH NETWORK ▶ **Flaghsip for Photonics Research and Innovation (PREIN)**
Research excellence
PREIN

INFRA. NETWORK ▶ **Finnish National Infrastructure for Light-Based Technologies (FINNLIGHT)**
Open-access infrastructure covering full innovation chain
FinnLight

INDUSTRY NETWORK ▶ **Photonics Finland**
National networking platform for business & industry
Photonics Finland

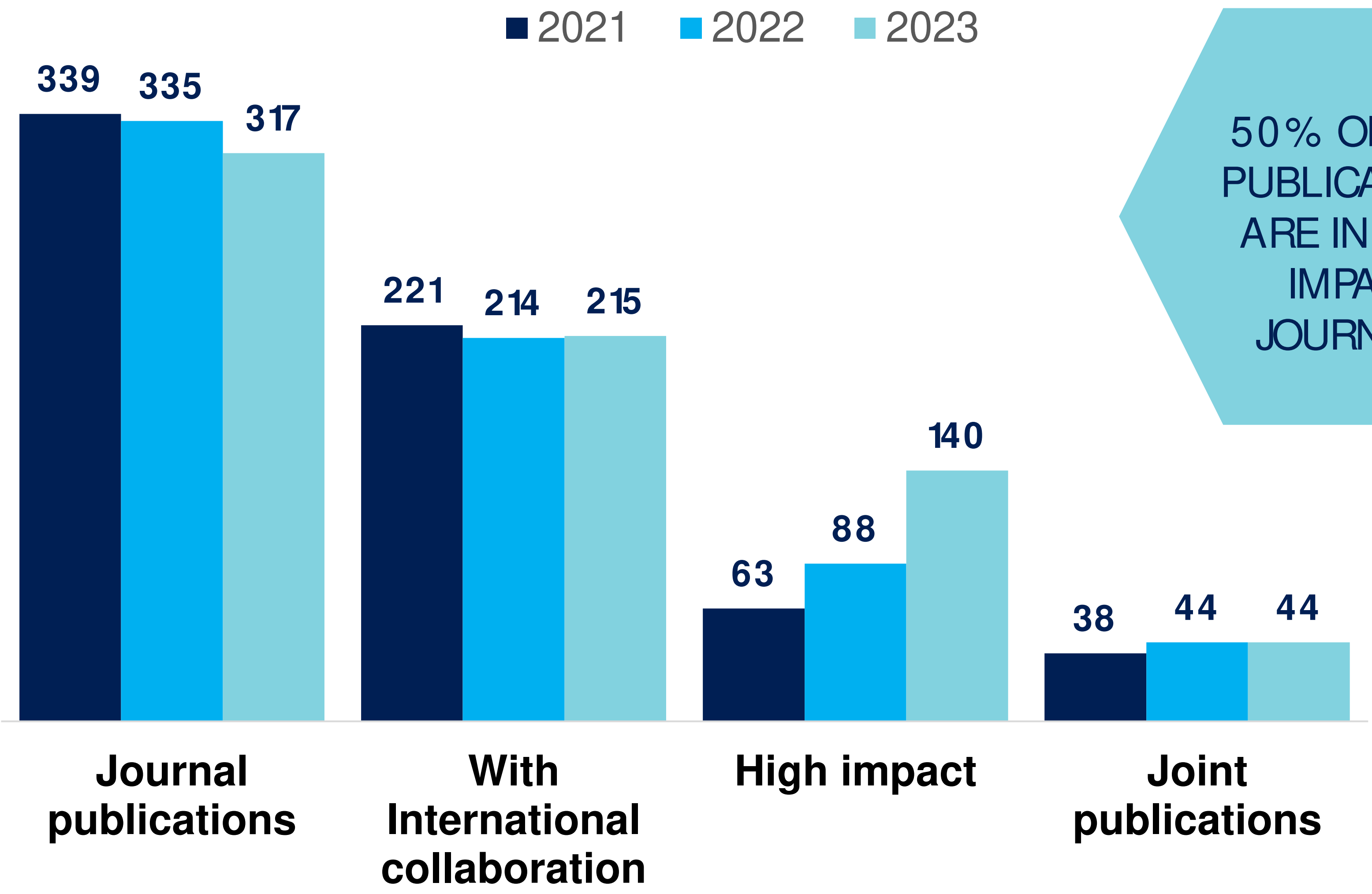
EDUCATION NETWORK ▶ **Innovative Doctoral Education Ecosystem for Photonics (I-DEEP)**
Doctoral pilot program to support business & industry
I- DEEP



RESEARCH FOR GLOBAL IMPACT

- LIFE SCIENCE & HEALTCARE
- ENVRIONMENTAL MONITORING
- QUANTUM TECHNOLOGIES
- PHOTOVOLTAIC & CLEAN ENERGY

PREIN Ecosystem Strengthens Research Quality



50% OF OUR PUBLICATIONS ARE IN HIGH IMPACT JOURNALS

80% OF OUR PUBLICATIONS ARE OPEN ACCESS

PREIN Ecosystem Strengthens Research Quality

STAFF

+50%
(500+)

DIVERSITY

29% FEMALE
46% FOREIGNERS

EDUCATION

315 MSc and 118 PhD PRODUCED

NETWORKING

2 NETWORKING EVENTS PER MONTH

STARTUPS

7 NEW STARTUPS

PATENTS

62 PATENT APPLICATIONS

Collaboration & Dissemination

PREIN workshop

- Thematic events
- Internal events for researchers and students
- Outreach events

Students visit to Aalto

Light for families

Collaboration & Dissemination

- Public people
- Media
- Arts

Valon voimalla - Fotoniikka on puhdasta energiaa!

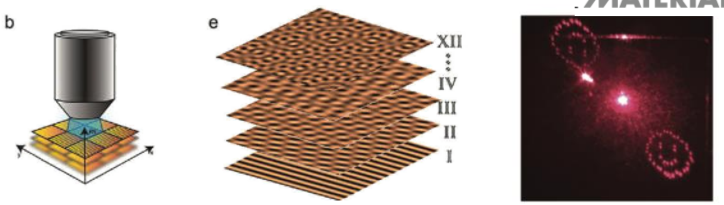
Arts

Media

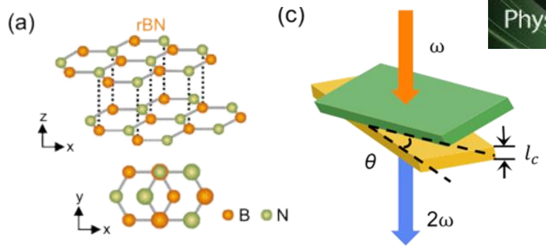
Scientific Highlights

Material Science

Complex Fourier Surfaces by Superposition of Multiple Gratings on Azobenzene Thin Films ADVANCED OPTICAL MATERIALS

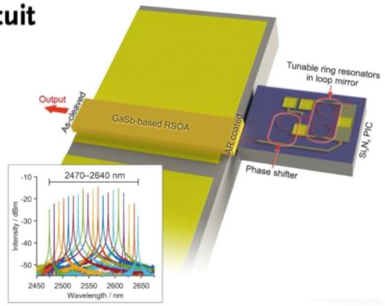


Twist Phase Matching in Two-Dimensional Materials Physical Review Letters

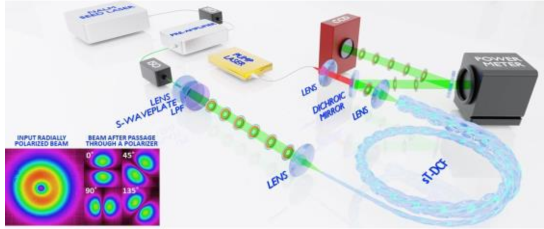


Light Sources

Widely Tunable (2.47–2.64 μm) Hybrid Laser Based on GaSb/GaInAsSb Quantum-Wells and a Low-Loss Si_3N_4 Photonic Integrated Circuit LASER & PHOTONICS REVIEWS

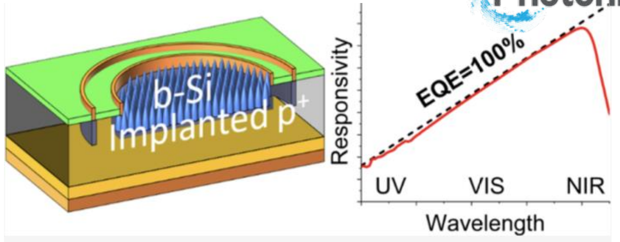


Double-clad ytterbium-doped tapered fiber with circular birefringence as a gain medium for structured light Optics Letters

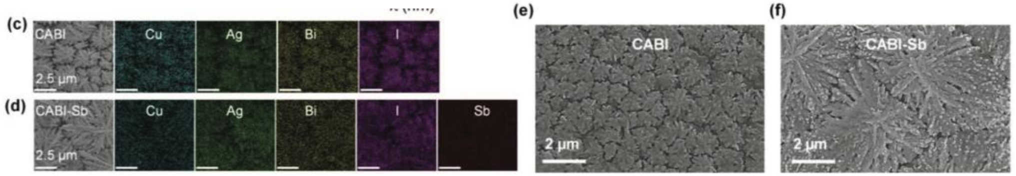


Solar Energy

Boron-Implanted Black Silicon Photodiode with Close-to-Ideal Responsivity from 200 to 1000 nm ACS Photonics



Antimony-Bismuth Alloying: The Key to a Major Boost in the Efficiency of Lead-Free Perovskite-Inspired Photovoltaics NANO · MICRO small



Increasing the Impact of Our Research

COLLABORATION

Joint projects coordinated by postdocs in each partner institution

3 projects funded on solar cells, environmental sensing, and quantum photonics

PROOF-OF-CONCEPT

Demonstrating the feasibility of ideas and utilise research results

3 projects funded on integrated laser sources,nanolasers, and detection of black plastics

DOCTORAL TRAINING

Innovative approaches to accelerate graduation time without compromising quality

New national innovative doctoral education ecosystem for Photonics

ROADMAP

Long-term vision of our research and target areas where we envision our technology can have an impact

New roadmap for 2024-2027+ with technologies in sensing, imaging, light generation & solar energy

PREIN 2020-2024 Roadmap

	Smart sensors		Integrated Photonics		Light sources			Photovoltaic		
					Mid-IR sources					
	Biosensors	Gas sensing	Components	LIDAR	Supercontinuum	Tunable photonic integrated circuit lasers	Nanoscale	III-V solar cells	Perovskites	c-Si
2020–2021	Printable microfluidistic platform for bioaffinity assays	Broadband photoacoustic gas analyser for 2.5 – 3.5 um using super continuum source	Hybrid III-V-on-silicon-on-insulator lasers	Large waveguide arrays and printed 3D lenses for >10m working distance	Watt-level sub nanosecond seed laser beyond 2.3 um	GaSb-based gain for 2.7 um	III-V QDs for 1.5 µm and 2D materials um	Compact concentrator photovoltaic proto panel 28% eff. and highly eff. 4J SCs	Design and synthesis of non-toxic lead-free perovskites	Passivated Emitter and Rear Cell and/or Tunnel Oxide Passivated Contact b-Si solar cells
2021–2022	Fluorescence readout with single photon Fluorescence readout with single photon detectors (SPAD)	Miniaturized interferometer for portable photoacoustic broadband gas sensor	100 GHz on-chip optical modulators	Tunable light source based on hybrid III-V integration on 3 um silicon-on-insulator	Fiber or waveguide integrated architecture	Low-loss silicon photonics echelle gratings and ring-resonators at 2–3 um	High-speed few-photons plasmonic nanolasers at cryogenic temperature	New 5J and 6J solar cells for ~50%ww eff.	Earth-abundant photovoltaic components and green-solvent processing	Extending to possible tandem cell technology
2022–2023	Integration of printable microfluidistic sensor platform with Fluorescence readout with single photon detector -based readout for ultra-sensitive and selective biosensing	Utilizing of tunable photonic integrated circuit lasers for broadband gas sensing	100 nm bandwidth on-chip circulator for photonic integrated circuits	Waveguide gratings and phase modulators for fast power-efficient 3D scanning	Machine-learning control	Hybrid integration of gain chips and tuning silicon photonics elements	Single particle excitation based on plasmonic cavity with broad tuning	Compact concentrator photovoltaic panels with >40% eff.	Environmental and mechanical stability of green photovoltaic components	Upscaling the selected b-Si solar cell technology (possibly with external partners)
2023–2024	Time-gated Fluorescence readout with single photon detector array for Raman sensing on the microfluidistic platform	Miniaturized gas sensor based on a tunable photonic integrated circuit laser at 2-3 um wavelength	10 Tbps hybrid transceiver	Integrated LIDAR module on a single chip	Compact on demand supercontinuum in 2–8 um	Wavelength programable integrated laser in 2–3 um	Efficient single particle excitation and high-speed nanolasers with ultra-low energy/bit	Compact panels integrated with dense matrix micro-concentrator photovoltaic III–V chips	Device engineering to maximize the performance of green perovskite photovoltaics	Panel fabrication and outdoor testing in collaboration with industry

Life science | **ICT** | **Autonomous vehicles and mobile devices** | **Environmental monitoring and healthcare** | **Quantum cryptography and superconducting logic** | **Compact efficient photovoltaic panels and clean energy**

ABOUT 75% OF OBJECTIVES REACHED

NEW RDI OBJECTIVES FOR NEXT 4 YEARS

TARGETS IN APPLICATION AREAS RATHER THAN COMPOENNT LEVEL

Year	Sensing			Imaging			Light Generation & Manipulation			Solar Energy		
	Biosensing	Environmental Sensing	Industrial Sensing	Advanced Microscopy	LIDAR	Hyperspectral Imaging	Quantum Light	Tunable Active Devices	Ultrafast Lasers	New Materials & Concepts	Perovskites	Crystalline Silicon
2024	New plasmonic substrates enabling digital	Soil-carbon analysis	Mineral micro-spectroscopy and mineral mapping	THz super-resolution microscopy	FMCW Lidar chip with integrated 1D OPA	THz & IR hyperspectral imagers	QD material for telecom C-L band	PIC laser for 3 um	Pulsed plasmonic nanolasers	Lead-free perovskite PV active layers in flexible modules at 50% FF & 2% PCE	Integrated flexible perovskite PV modules	Utilize up-conversion in PERC solar cells
2025	High-Q metasurfaces Vis-NIR Spectrometry in wearable devices	Microplastics from open water	Bioprocess control using sensor fusion	High-transmission extra-long field-of-view microscope	FMCW Lidar chip with 2D beam steering	On-chip hyperspectral imager	Deterministic telecom wavelength single & entangled photon sources	On-chip isolators & circulators On-chip polarization management	Fully-integrated on-chip laser with 1 W av. power	Advanced integrated PV for low power applications (PCE>20%)	Fully solution processed perovskite PV with over 10% PCE	Surface passivation & charge transfer for photo-electro-chemical cells
2026	Record-high SERS Quantum biosensing of temperature, pH, ROS in living cells	Few-ppb atmospheric gas sensors	In-line microplastics monitoring	Novel fluorophores & markers	Sub-wavelength-pitch waveguide arrays using HOM	Advanced post-processing using AI & ML	High-Q cavities based on metamaterials	1D/2D materials-based lasers	Fiber-based 350-800 nm structured light Fiber-based optical computing	PV module made from biodegradable materials	Device engineering to reach 5% PCE for green perovskite PVs	Tandem perovskite solar cells with nanostructure to reduce reflective losses
2027	Single molecule detection with plasmonic substrates			Quantum super-resolution fluorescence microscope	On-chip 3D LIDAR		Chip-based quantum operation using photon pairs	On-chip laser with 100+ nm tuning range	GHz pulsed PIC laser for triggering quantum emission	Perovskite-inspired materials for self-powered photodetectors	R2R processed flexible perovskite PV	

Enviromental monitoring and healthcare · Life science · Autonomous vehicles and mobile devices · Safety & Security · Quantum technologies · ICT · Clean energy & sustainability

Comprehensive Summary in our 2023 Annual Report

CONTENTS

Advanced Infrastructure Supporting RDI in Light-based Technologies

- Entire photonics value chain: design, fabrication, integration, characterization
- Open to external researchers and companies

FinnLight

Finnlight.fi

National Roadmap Infrastructure

Research Council of Finland

Advanced Infrastructure Supporting RDI in Light-based Technologies

National roadmap status: 2021-2024

Applied to renew status for 2025-2029

Successfull in 2023 funding call (3.8 M€) to expand our capabilities

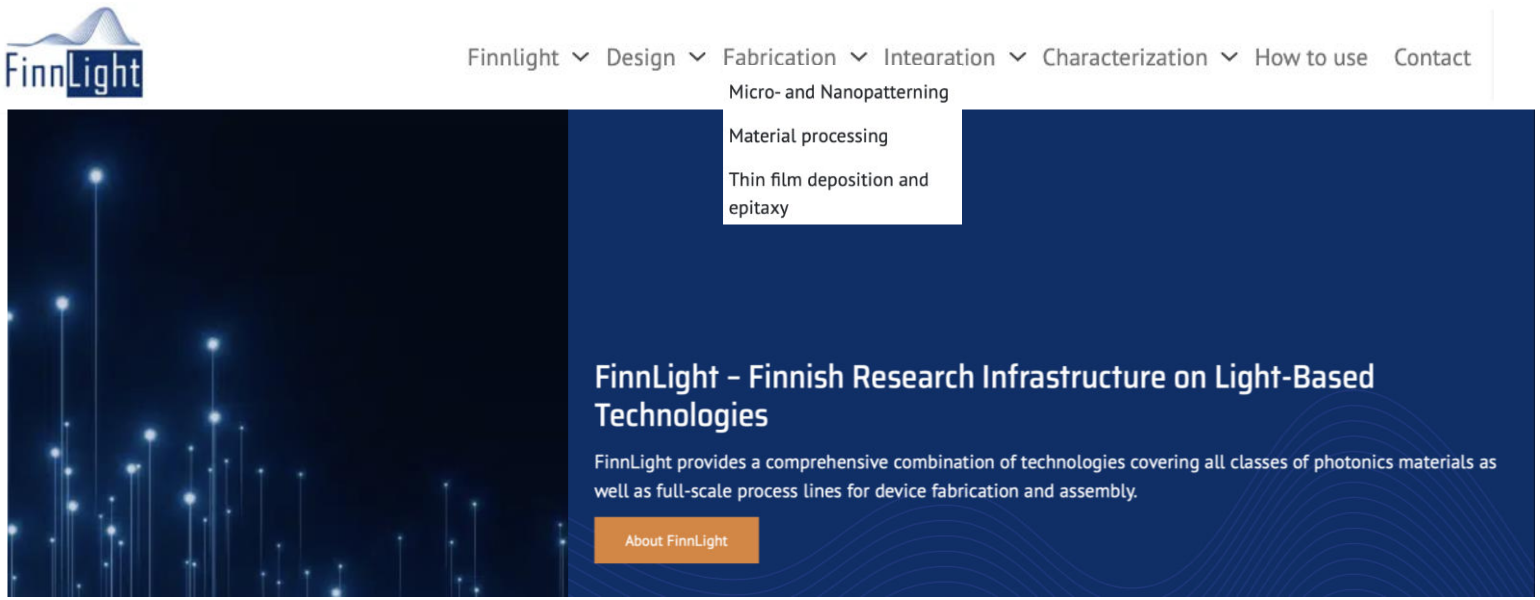
FinnLight

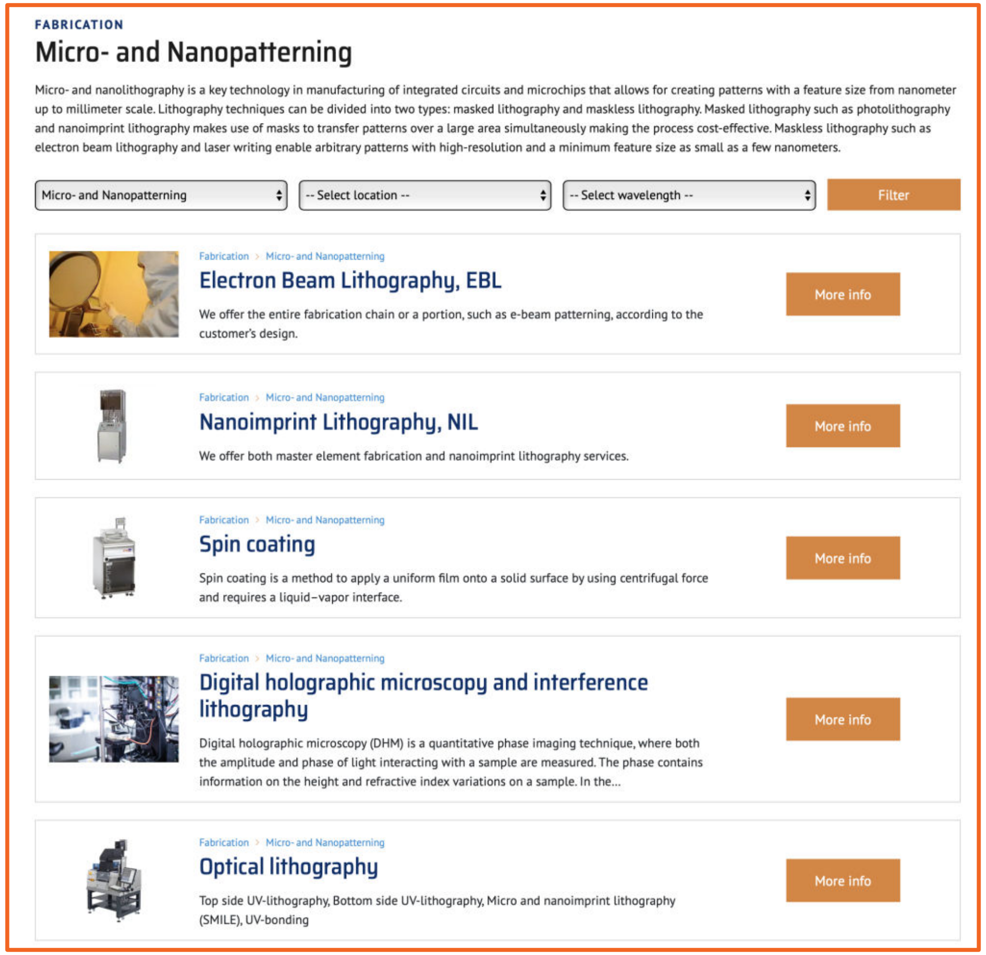
Finnlight.fi

National Roadmap Infrastructure

Research Council of Finland

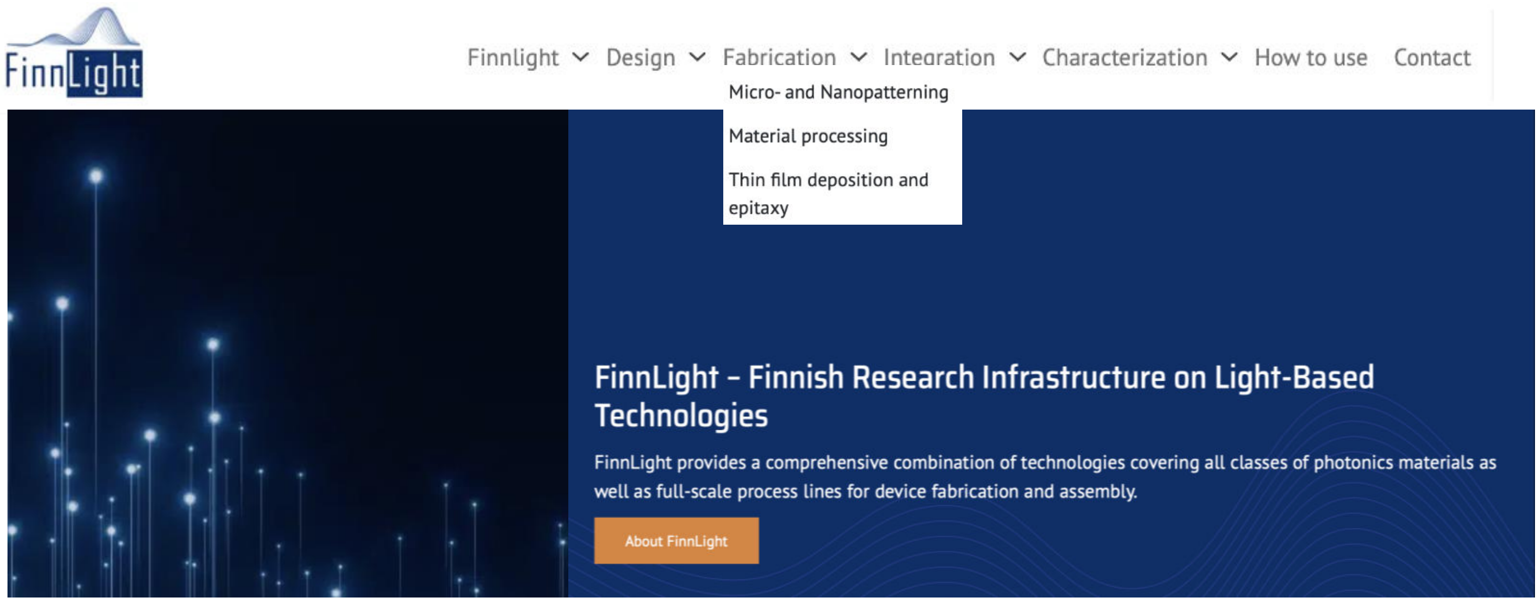
How to Use our Infrastructure Network?

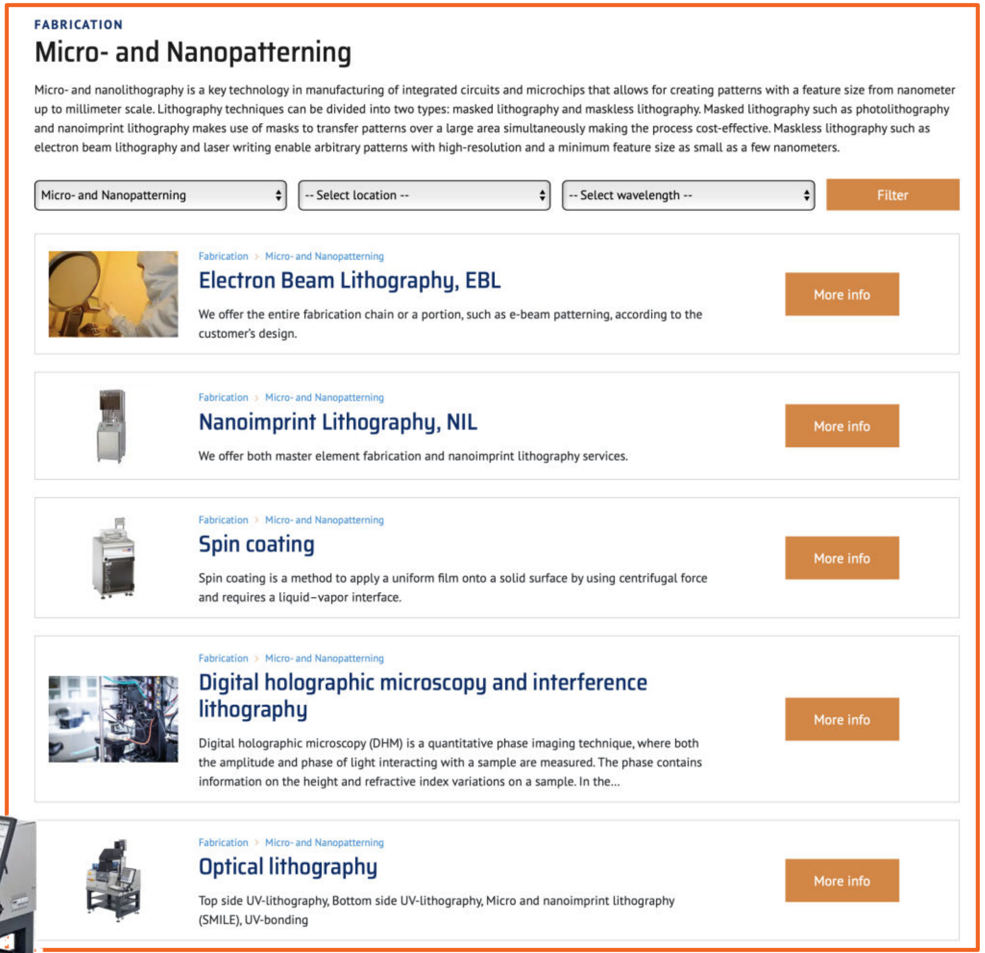


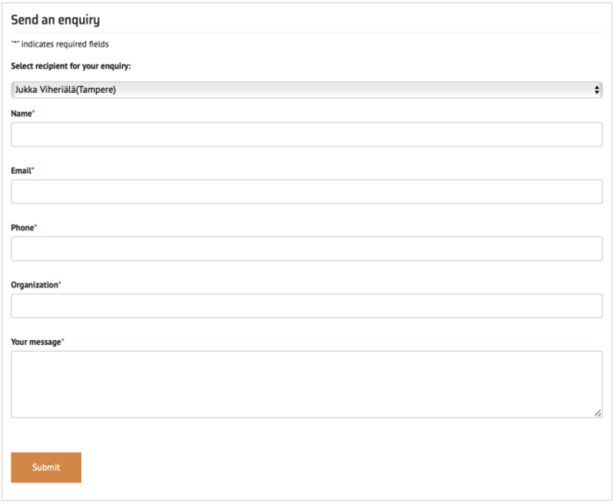


finnlight.fi

How to Use our Infrastructure Network?

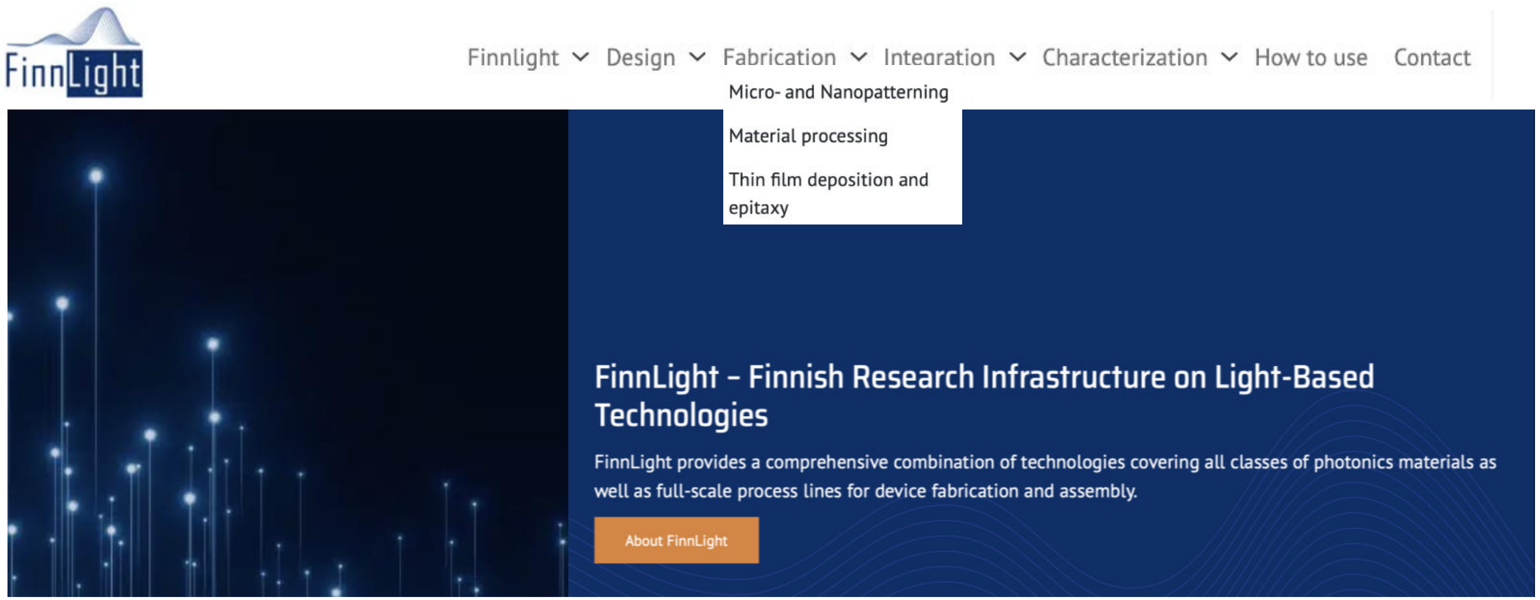


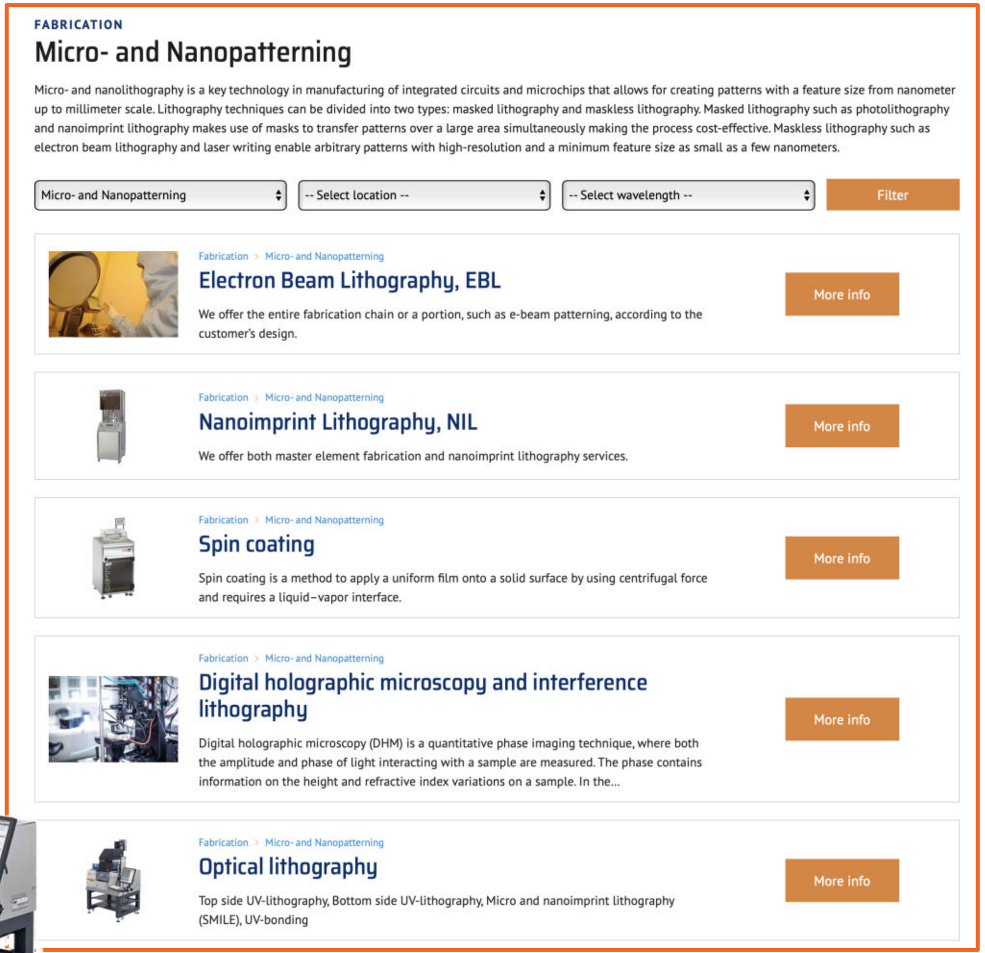




Find the service you need & click to contact form

How to Use our Infrastructure Network?



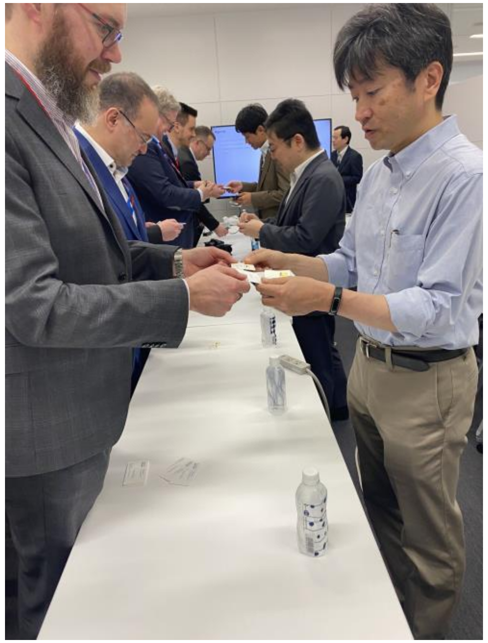


Manager position open next week (located at Tampere University)

Find the service you need & click to contact form

Company collaboration

- Exhibitions
- PREIN meets X
- Business delegations
- Investments



Business Finland’s photonics business delegation in Japan

Investing in Photonics and Microelectronics

Finland Pavillion at Photonics West

Education Campaign: Photonics Explorer Kit

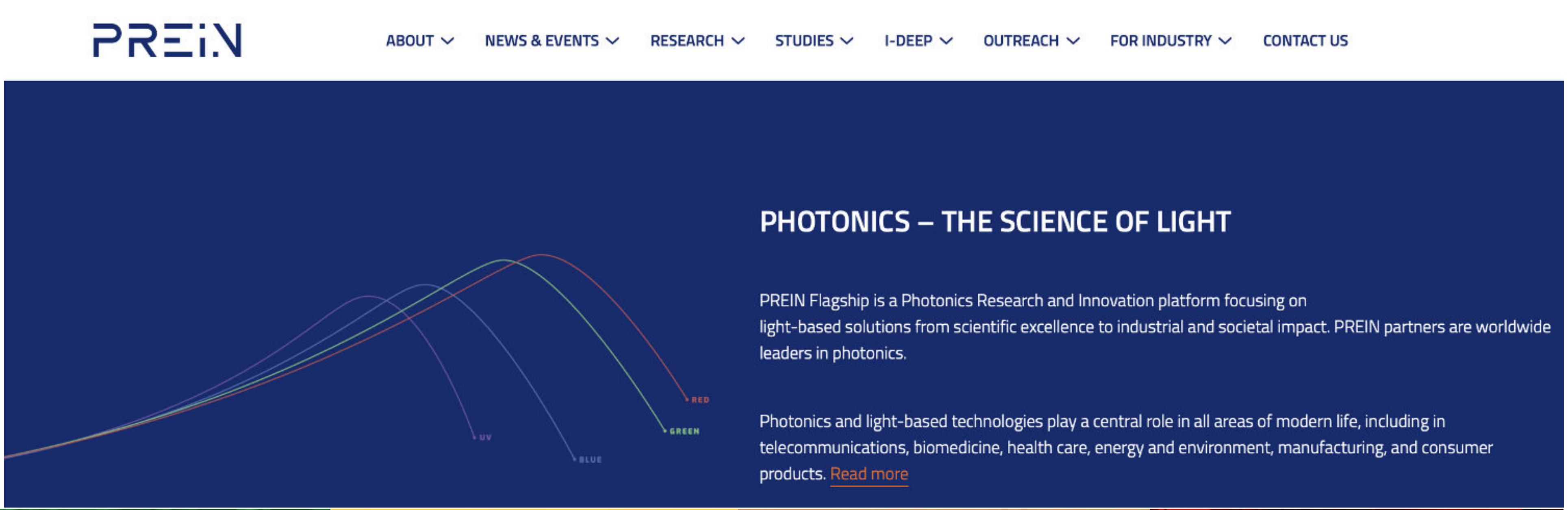
- Donate 1 Kit to a school, **PREIN/Photonics Finland will donate 2 more!**
- Over 100 optical components
- Recreational activity to interest children in science

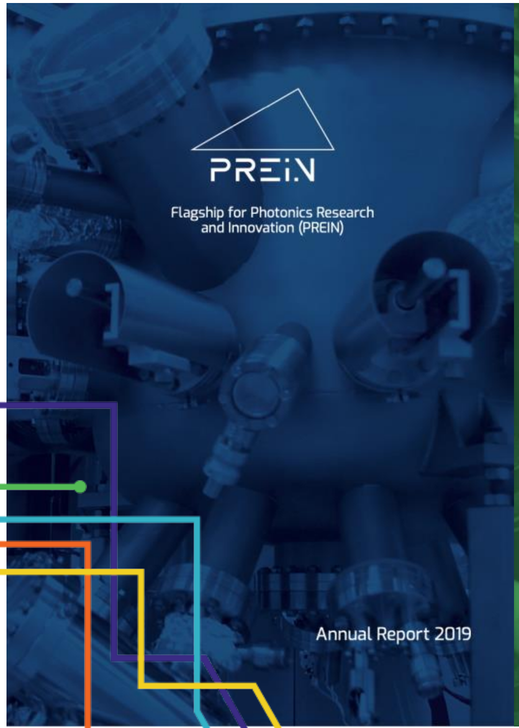
Photonics Finland

PREIN
Photonics Research and Innovation

Useful Resources

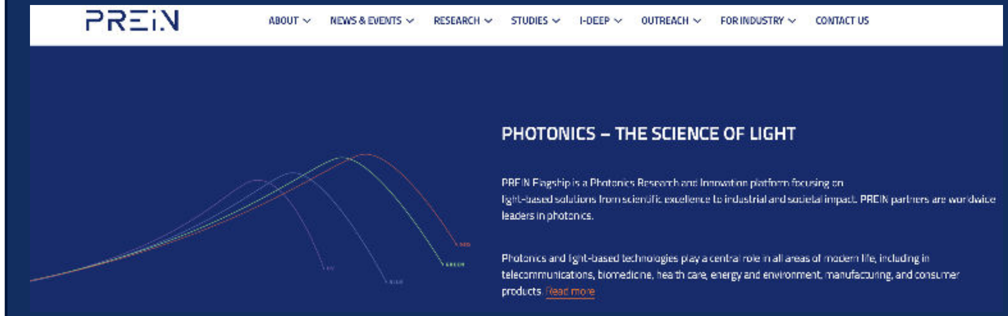
prein.fi





Websites

Prein.fi



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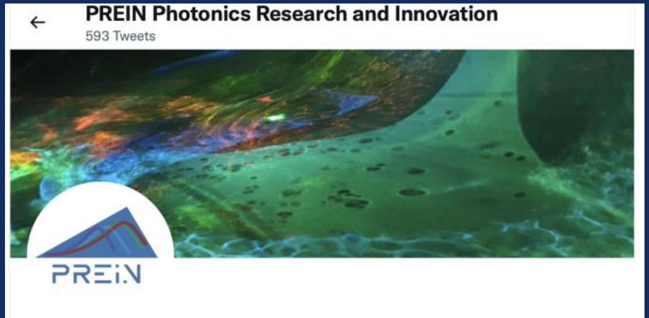
Channels

LinkedIn

X/Twitter



Newsletter

PREIN Team

Goëry Genty
Director

Jyrki Saarinen
Vice-director

Tea Vellamo
Admin. coordinator

Juha Purmonen
Impact manager

Kristiina Pispala
Communication specialist

Raili Termälä
Impact specialist

Program

15:00-15:30 PREIN summary of 2023 activities

Goëry Genty, PREIN Director, Tampere University

15:30-16:15 Pitch sessions of PREIN internal research projects

Thomas Kraft (VTT), Perovskite-inspired indoor photovoltaics for sustainable Internet-of-Things
Juha Toivonen (TAU), Multi-sensory environmental sensing for enhanced sensitivity and selectivity
George Thomas (VTT), and Vladimir Kornienko (Aalto), Structured Quantum Photonics with Geometric Phases
and Integrated Circuits

16:15-16:30 Research highlights: PREIN Research Council of Finland Proof of Concept projects

Mircea Guina (TAU), Integrated pulsed lasers driving industrial scaling of quantum technologies (IntegrateQT)
Eduardo Maia Paiva (VTT), Broadband active hyperspectral sensing for black plastic

16:30-17:15 Innovative ecosystem for doctoral education in Photonics (I-DEEP)

Sari Multala, Opening words (video)
Goëry Genty, presentation of I-DEEP
Heikki Holmberg, Industry vision

17:15-18:00 Panel discussion

Jyrki Saarinen, PREIN/UEF
Suvi-Tuuli Akkanen, PhD researcher Aalto University
Leena Pöntynen, Technology Industries
Heikki Holmberg, Research and Development Director, Okmetic Oy
Jyri Hämäläinen, Vice President of Research, Aalto University

Perovskite-inspired **I**ndoor Photovoltaics for Sustainable Inter**n**et-of-**T**hings

PINT

Thomas Kraft, PhD
Senior Scientist, Project Manager
VTT

 thomas.kraft@vtt.fi

Perovskite-inspired indoor photovoltaics for sustainable Internet-of-Things

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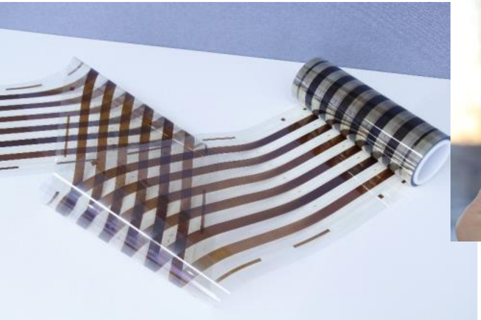
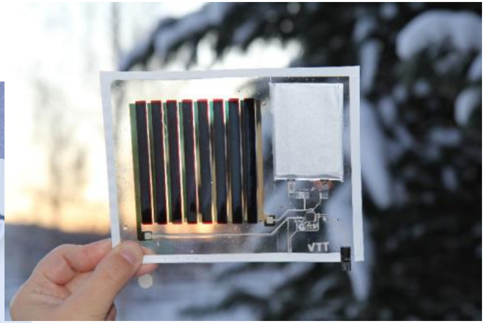
Photonics Research and Innovation

VTT

- Powering the internet-of-things:
  - Perovskite solar cells are efficient photovoltaic technology that can solve this issue leading to self-powered and wireless devices.

→ The aim is to develop lead-free perovskite-inspired materials (**PIMs**) for indoor photovoltaic (**IPV**) applications.





UNIVERSITY OF EASTERN FINLAND

Molecular Modeling
Mikko Linnolahti

Hybrid Solar Cells
Paola Vivo

Tampere University

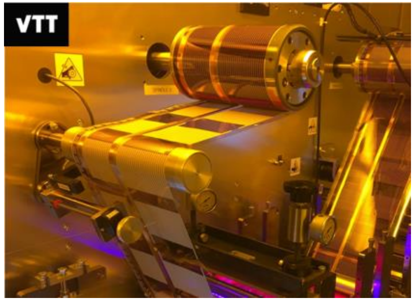
Aalto University

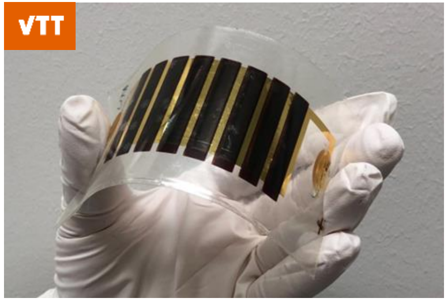
Multifunctional Materials Design
Jaana Vapaavuori

VTT

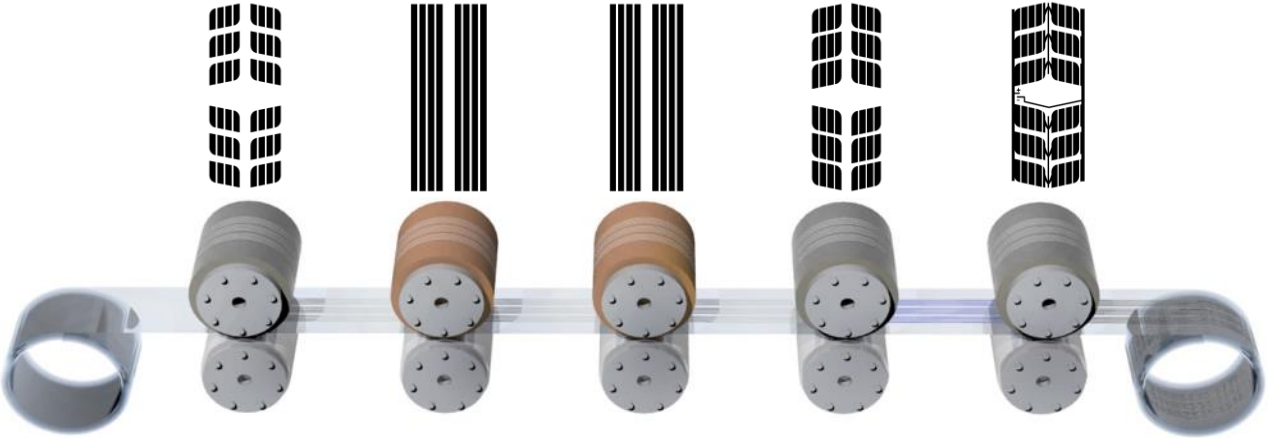
Printed Materials Systems
Thomas Kraft

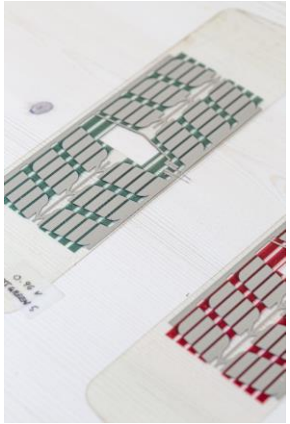
Device Manufacturing





Multilayer processing



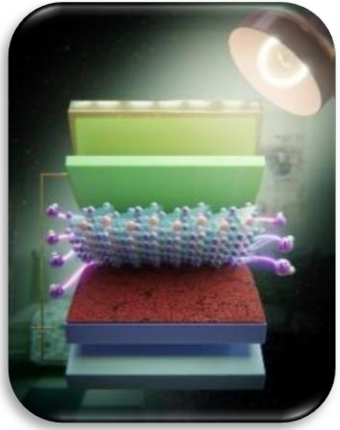


Spin, slot die, blade, bar coating. Gravure, flexo, screen printing. Encapsulation, lamination

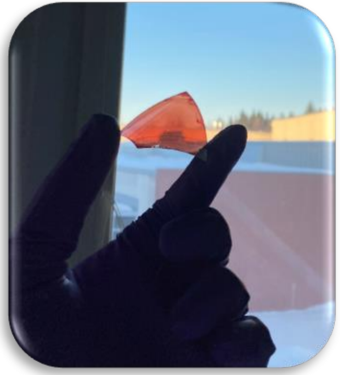
PINT Project

PREIN Photonics Research and Innovation

VTT



Indoor PIM for PV
-lead-free-



Develop a new family of lead-free PIMs

Tampere University

UNIVERSITY OF EASTERN FINLAND

VTT

Establish an ad-hoc processing method

Tampere University

VTT

Sustainable low-cost manufacturing of flexible PIM-based indoor PVs

Aalto University

VTT

Investigate stability of indoor PVs

Aalto University

PINT Project

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UNIVERSITY OF EASTERN FINLAND
Tampere University

- ✓ Developing a new family of lead-free PIMs for indoor photovoltaics
  - ✓ **Molecular modeling** aims to aid in developing a new family of lead-free perovskite-inspired materials
  - ✓ Initiated by assessing the effects of polymorphism on the **predicted electronic structure and stability of perovskites**
- ✓ Material (structural, spectroscopic) characterization
- ✓ Device performance assessment, including operational stability

A new Bismuth perovskite-inspired material for IPVs

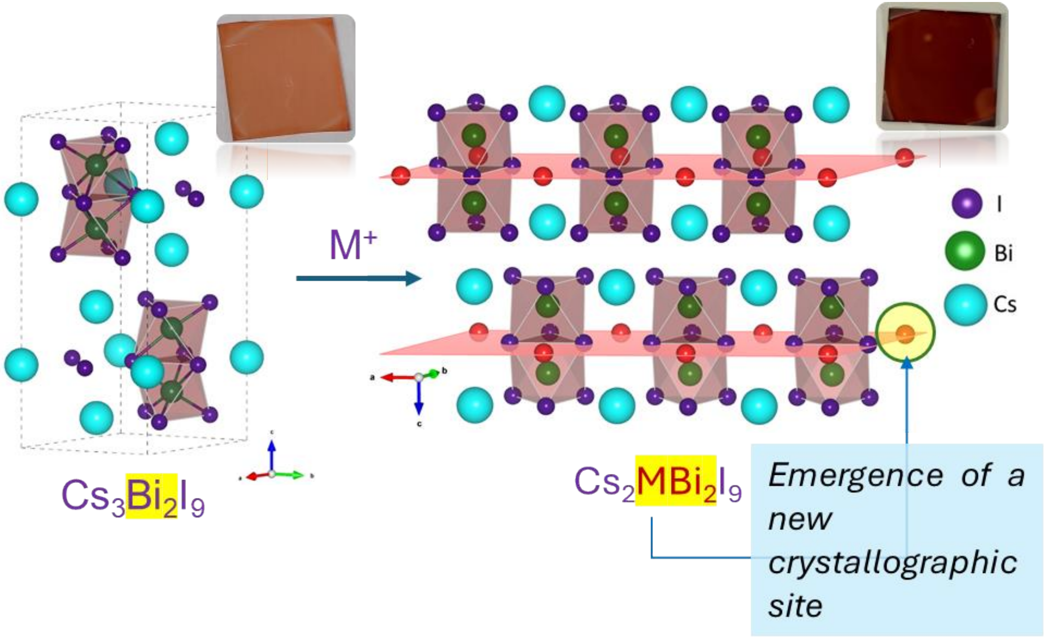
PREIN Photonics Research and Innovation

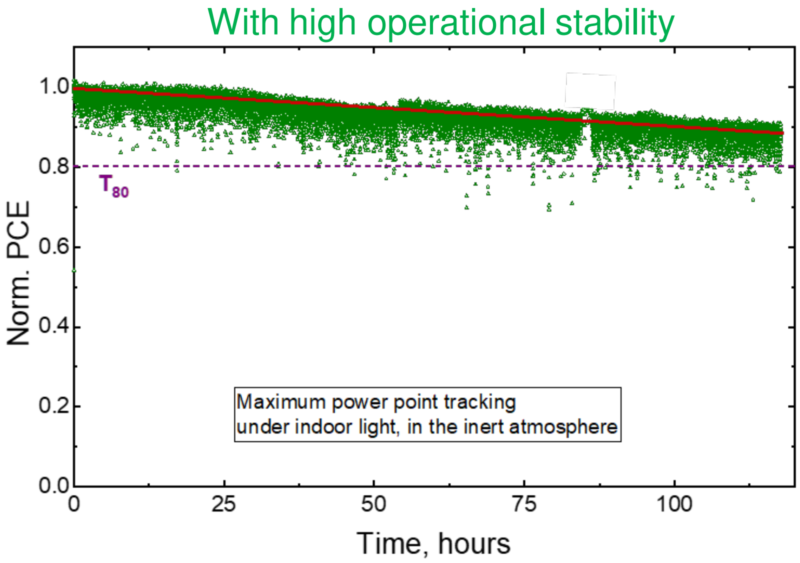
Tampere University

0D→2D: A-site cation engineering facilitate the electronic dimensionality **tuning for improved carrier transfer**.

Bandgap reduction: A-site cation engineering **lowers the bandgap** for enhanced indoor light absorption.

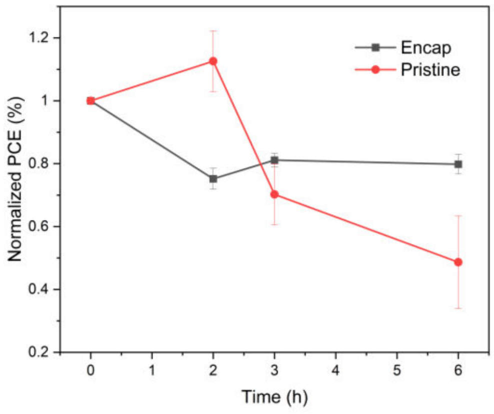
Promising IPV performance: **IPV efficiency of ~5%** has been achieved for $Cs_2MBi_2I_9$.



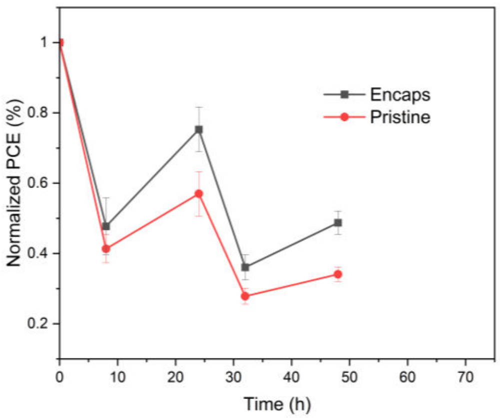


Understanding of CABI solar cell's durability to environmental factors (Cu_2AgBiI_6)

- CABI less sensitive to moisture compared to lead-based perovskite solar cells
- Photo stability is a challenge; light management has potential to improve this



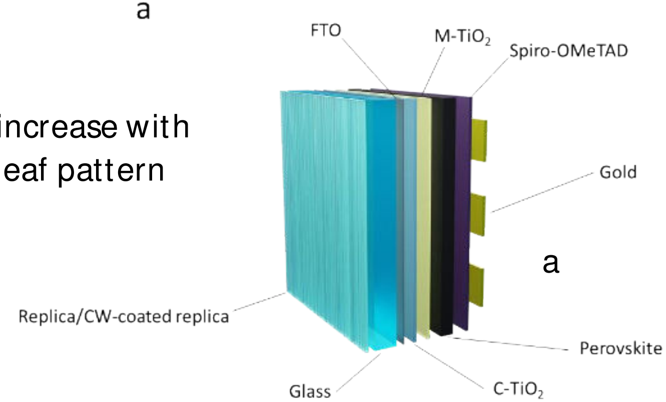
Encapsulated and pristine devices exposed to 90% RH

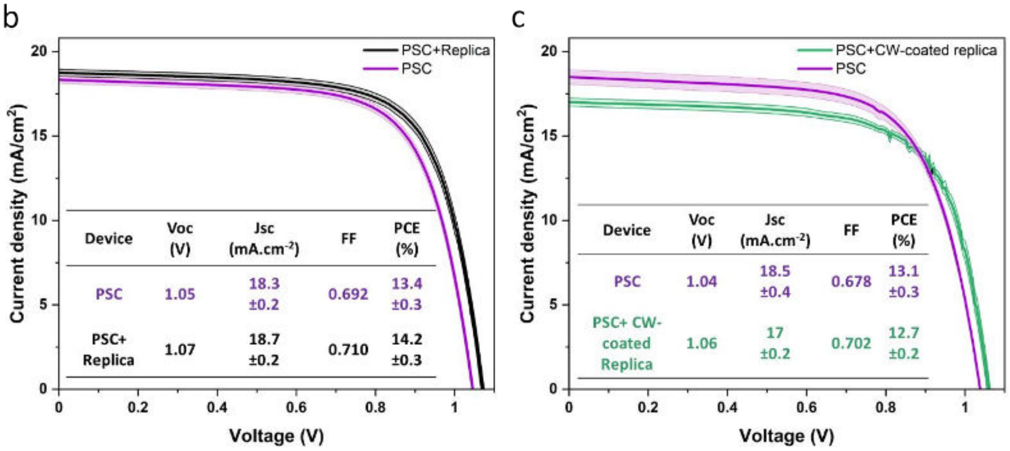


Encapsulated and pristine devices under cycles of 8 hours under 1 sun and 16 hours resting in the dark in the ambient condition

In-situ encapsulation and surface patterning

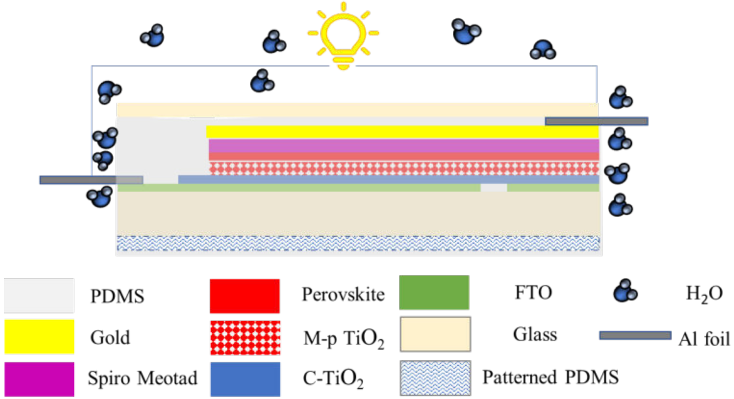
8% PCE increase with surface leaf pattern



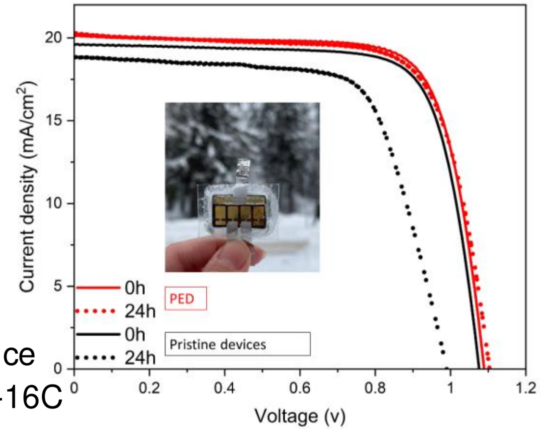


Device	Voc (V)	Jsc (mA.cm⁻²)	FF	PCE (%)
PSC	1.05	18.3 ±0.2	0.692	13.4 ±0.3
PSC+ Replica	1.07	18.7 ±0.2	0.710	14.2 ±0.3

Device	Voc (V)	Jsc (mA.cm⁻²)	FF	PCE (%)
PSC	1.04	18.5 ±0.4	0.678	13.1 ±0.3
PSC+ CW-coated Replica	1.06	17 ±0.2	0.702	12.7 ±0.2



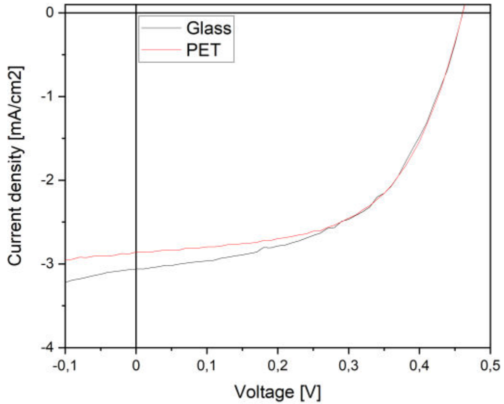
Performance testing at -16C

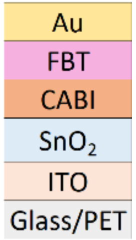


Upscaling

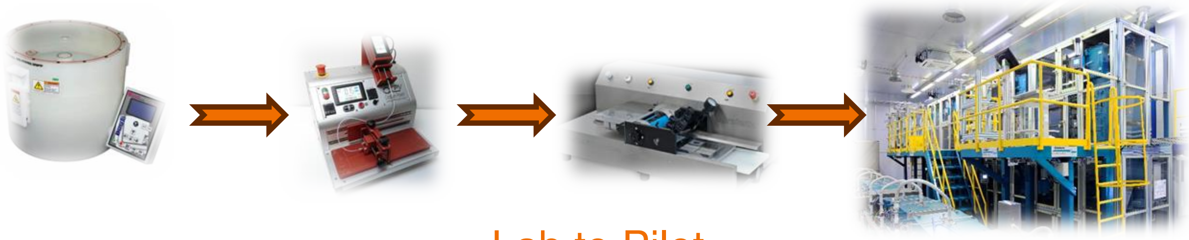
- **Motivation**
  - Volume deposition methods for lead-free perovskite-inspired material (Cu_2AgBiI_6) → Aiming for roll-to-roll applicable techniques

- **Key Results**
  - Ambient solution processing of lead-free perovskite-inspired material (Cu_2AgBiI_6) on flexible substrate (*manuscript under preparation*)
  - Investigation performance and thin-film morphology



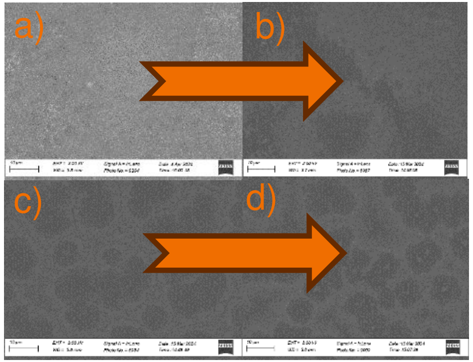


IV-figures from the devices made on glass and PET.



Lab to Pilot

Similar performance going to flexible substrates



glass to PET

coating to printing

Scanning electron microscope images from Cu_2AgBiI_6 films processed via spin coating on glass (a) and PET (b), and slot-die coating on PET (c), and gravure printing on PET (d).

PINT outcome

- New class of lead-free perovskite inspired materials used in IPV
- Sustainable encapsulation and light management approaches
- Volume compatible upscaling options on flexible materials

ACADEMY OF FINLAND FLAGSHIP PROGRAMME Tampere University Aalto University UNIVERSITY OF EASTERN FINLAND VTT

Technology Partnerships with VTT

- Printed & Hybrid Electronics Infrastructure
- Prototyping & Process development
- Machine Sourcing & Ramp-Up
- Technology Consultation

VTT

Facilities video:
https://www.youtube.com/watch?v=sh62l9fFXgI

Thank you to my colleagues at VTT and all partners!

Contact

thomas.kraft@vtt.fi
+358 20 722 2070

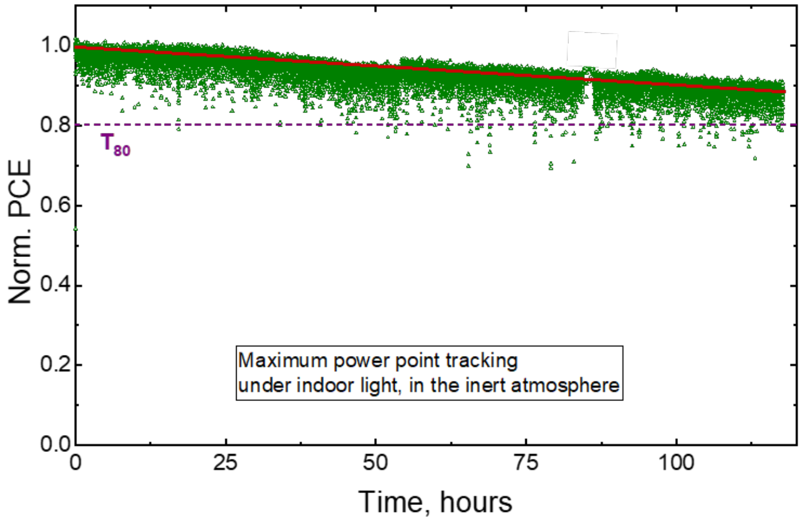
VTT Technical Research Centre of Finland Ltd
Kaitoväylä 1 (street address)
P.O. Box 1100
90571 Oulu
Finland

www.vttprintedintelligence.fi
www.printocent.net

- Molecular modeling aims to aid in developing a new family of lead-free perovskite-inspired materials
- Mid-term goal is to assess software capabilities and demonstrate how input structure impacts material properties of interest
- Initiated by assessing the effects of polymorphism on the predicted electronic structure and stability of perovskites
- Perovskites are chosen due to abundant experimental data and readily available tools for building different polymorph structures

Convex Hull Analysis: Online databases allow reliable determination of thermodynamic stability for a given composition
Polymorph Stability: Assessing polymorph stability accurately requires employing higher-level theories
Energy-Band Gap Correlation: An inverse correlation between total energy and band gap has been observed between polymorphs with same composition
Spin-Orbit Coupling: Exclude spin-orbit coupling for more accurate electronic structure calculations
Pnma Polymorphs: Using Pnma space group polymorphs appears to improve band gap accuracy over the ideal cub
perovskite structure

Project-II: A mixed-metal chalcogenide-halide material for stable IPV performance



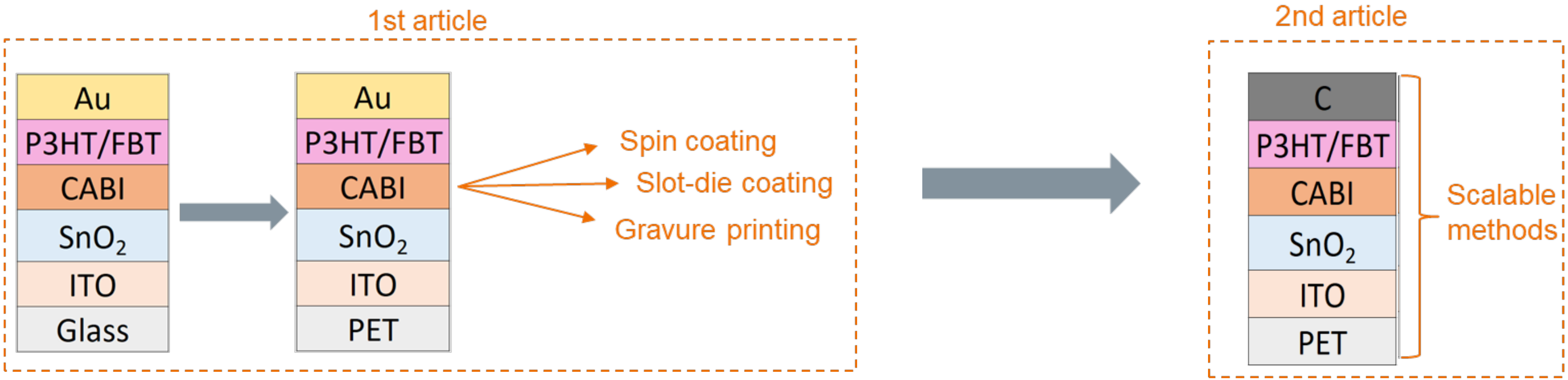
A pnictogen-based perovskite-inspired material that contains both chalcogenide (for stability) and halide (for defect tolerance) ions has been synthesized. $Cs_2MBi_2I_9$

Defect tolerance: A low Urbach energy of ~ 35 meV suggests a good defect tolerance.

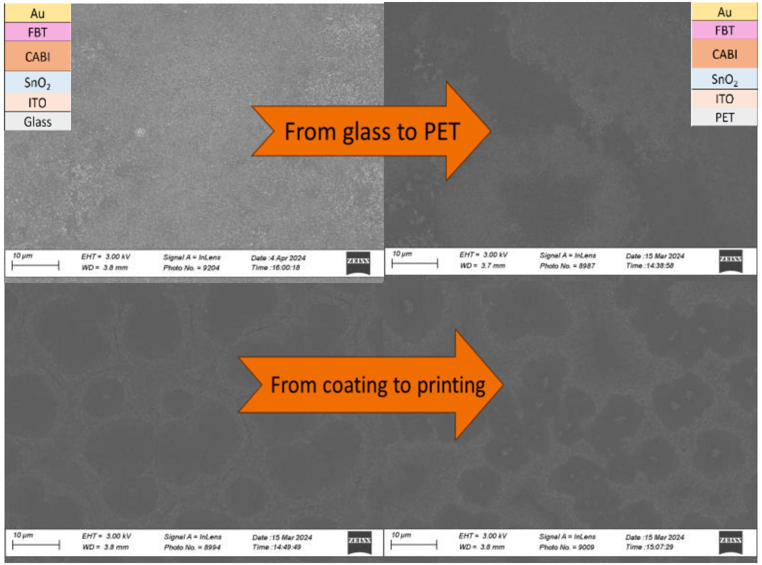
High IPV operational stability: A stable performance for more than 100 hours has been achieved.

Target

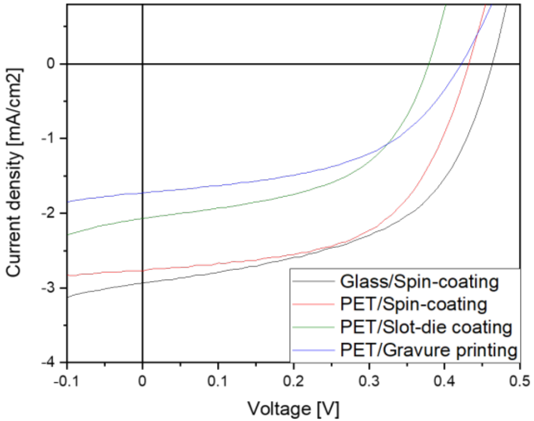
- World record on glass / controlled atmosphere: ~2.5%
  - Tampere University ~1.0%
  - VTT: 0.77% / glass and 0.76% / flex
- No article on flexible Cu_2AgBiI_6 (CABI) devices



Results



Champion cells	PCE [%]	Voc [V]	Jsc [mA/cm2]	FF [%]
Glass / Spin	0.77	0.46	3.06	54.30
Flex / Spin	0.76	0.46	2.86	57.66
Flex / Slot-die coating	0.41	0.38	2.07	51.81
Flex / Gravure printing	0.36	0.42	1.73	49.46



Results

- SEM analysis reveals distinct morphological features influenced by deposition methods.
- Differences observed in uniformity, surface coverage, and roughness, and crystal orientation.
- Device fabrication on flexible substrate proved to yield similar performance as to the device fabricated on glass.

Tampere University

Multi-sensory environmental sensing for enhanced sensitivity and selectivity

Juha Toivonen, Tampere University

Tampere University UNIVERSITY OF EASTERN FINLAND Aalto University VTT

Tampere University

Sample preparation

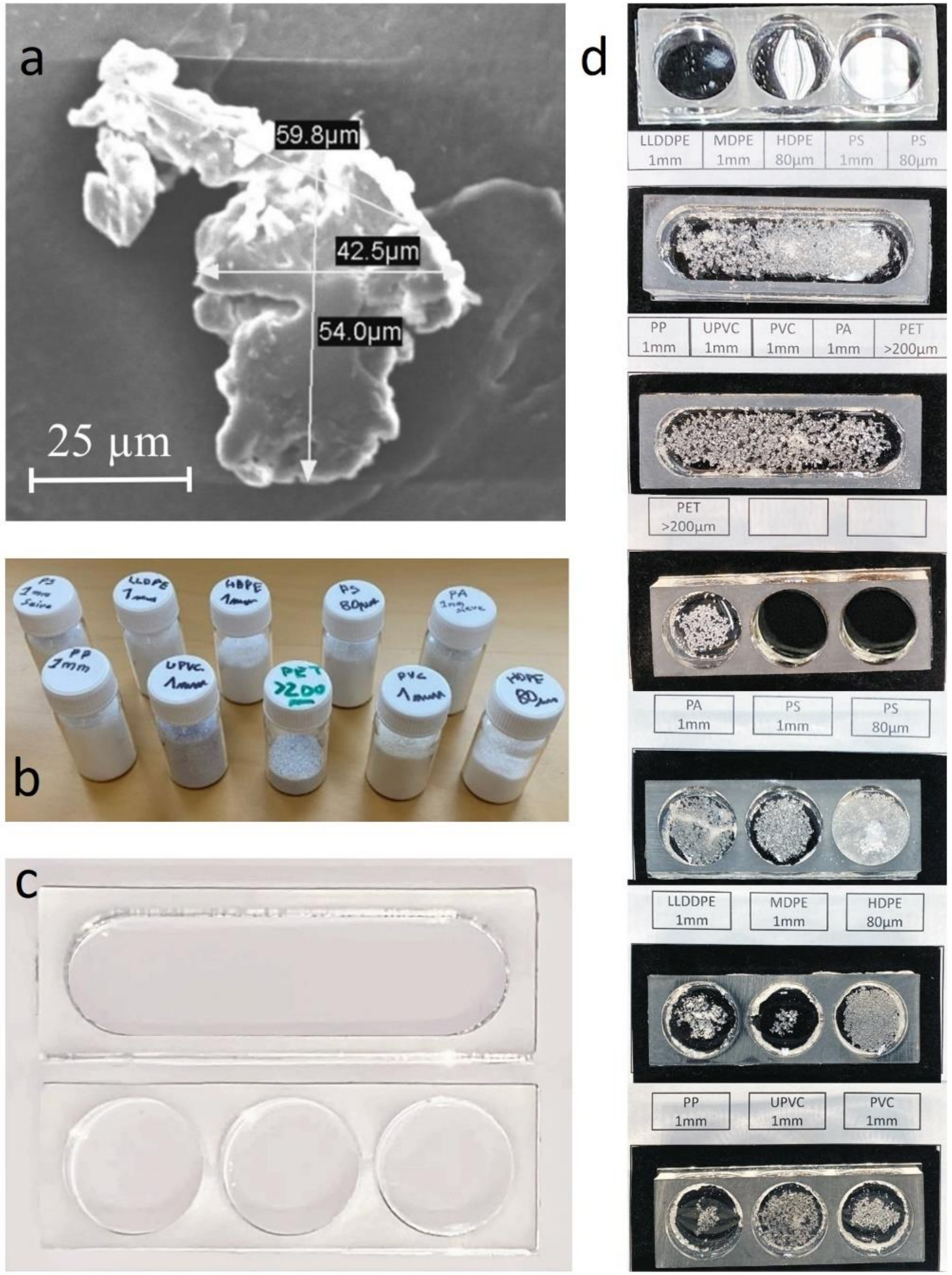
We prepare MPs of different types using milling of commercial plastic sheets [1].

a) Scanning electron microscopic picture of a polypropylene microplastic fabricated by milling.

b) Photograph of the ten grinded microplastic samples.

c) Photograph of the elongated and circular cuvettes.

d) Arrangement of the cuvettes and sample holders on the measurement table.



[1] B. Hrovat, E. Uurasjärvi, A. Koistinen, K. Peiponen, M. Roussey, M. Viitala, "Preparation of Synthetic Micro- and Nanoplastics for Method Validation Studies," *Science of The Total Environment* **925**, 17182 (2024)

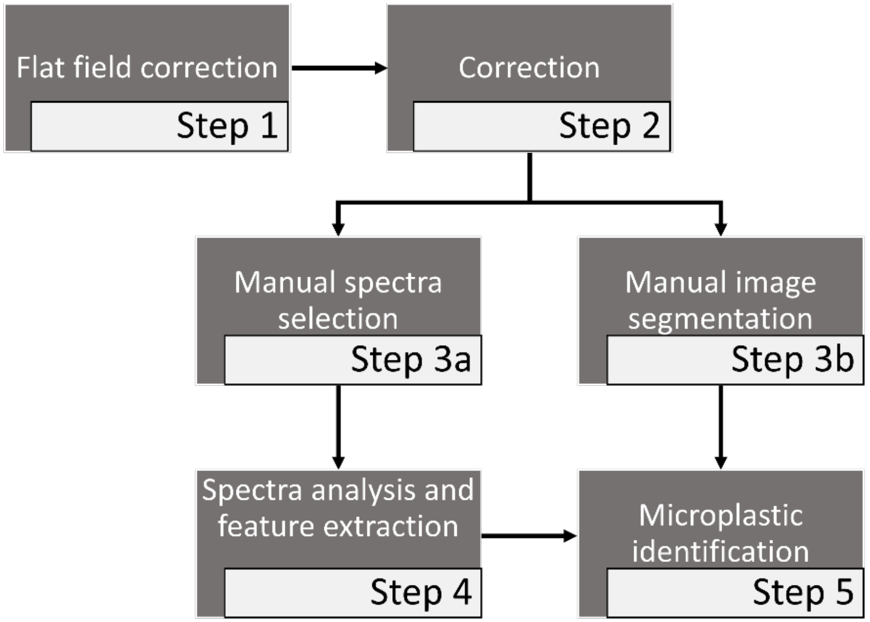
Tampere University

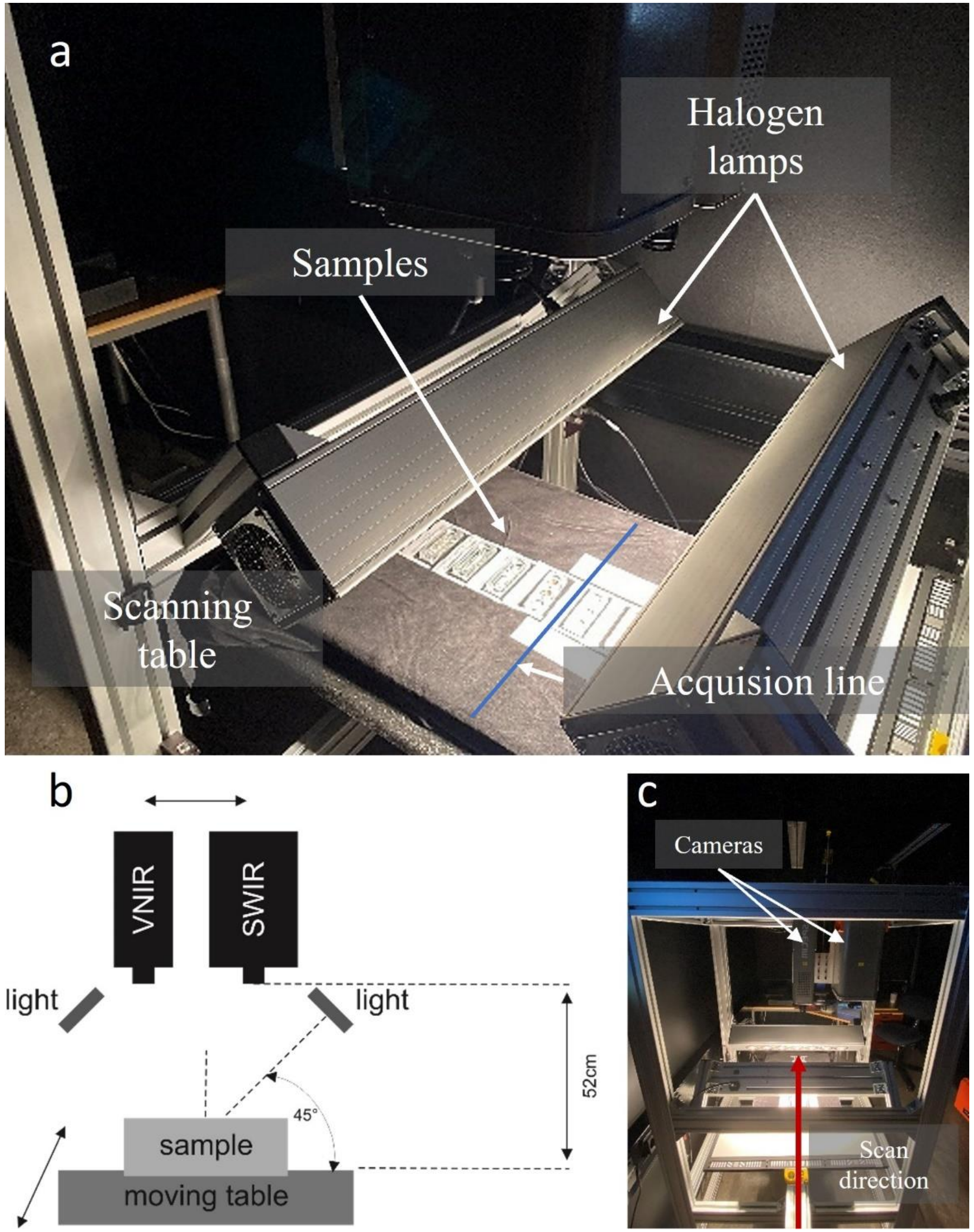
Hyperspectral imaging

Microplastics are mixed with tap water.

a) Schematics of the setup.

b) and c) Photographs of the experimental setup.





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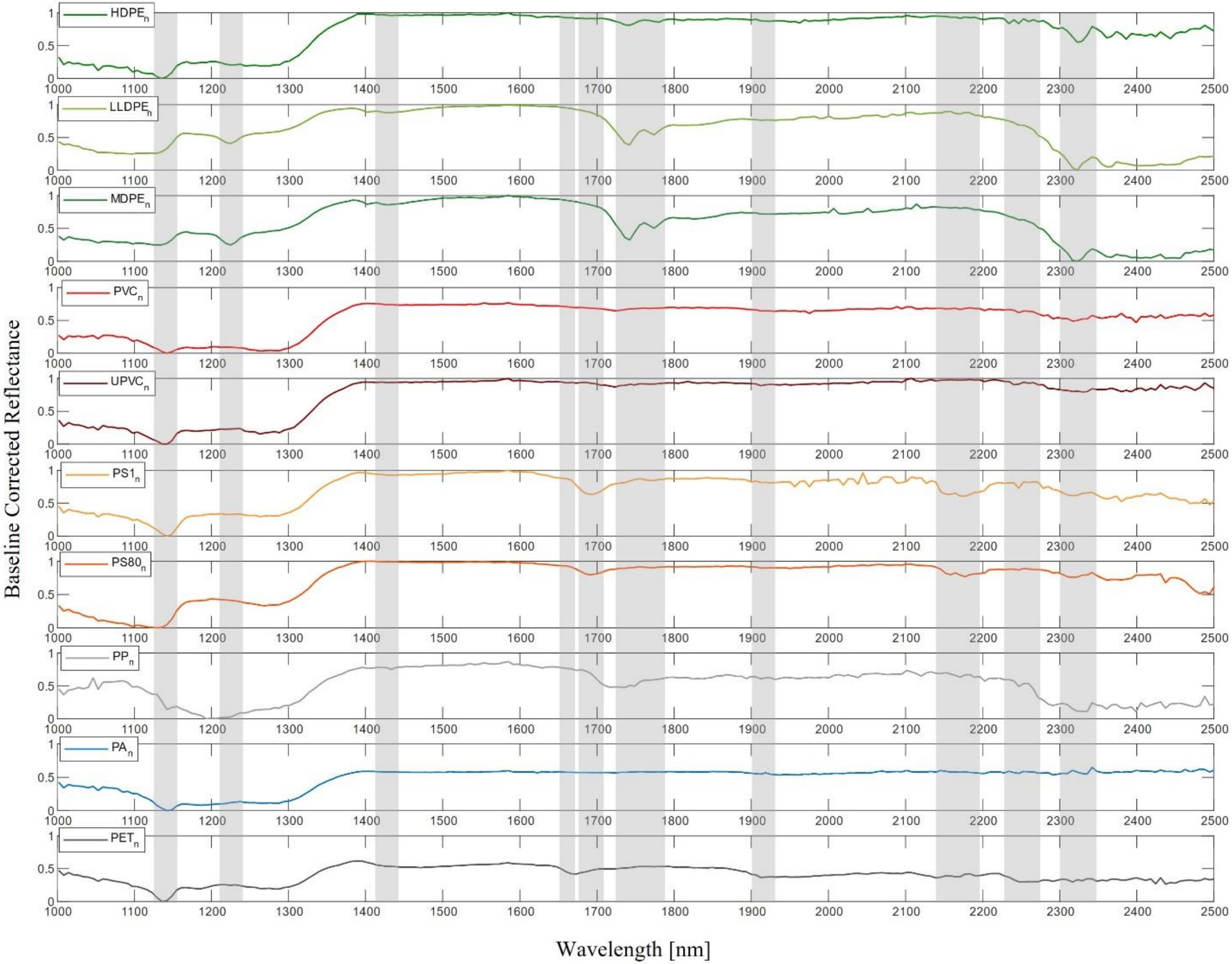
Spectra

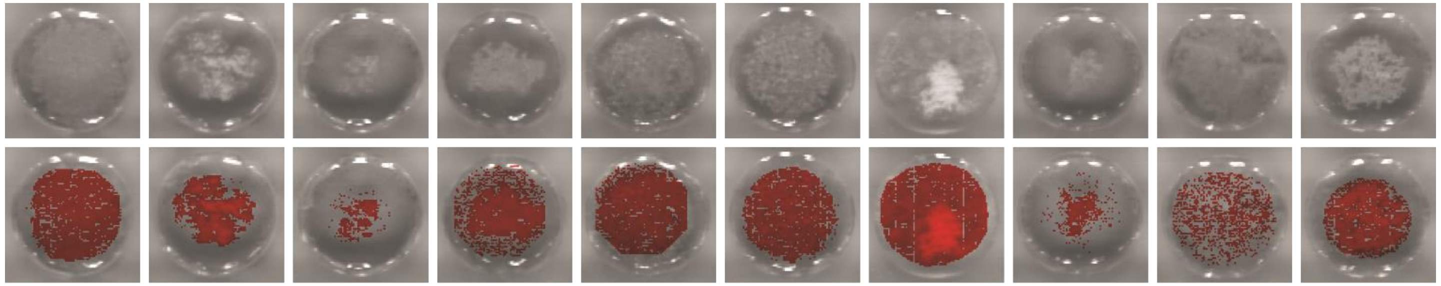
- Subtraction of water spectrum
- Correction with 1550 nm
- Gray stripes mark the main spectral features.



Analysis and identification

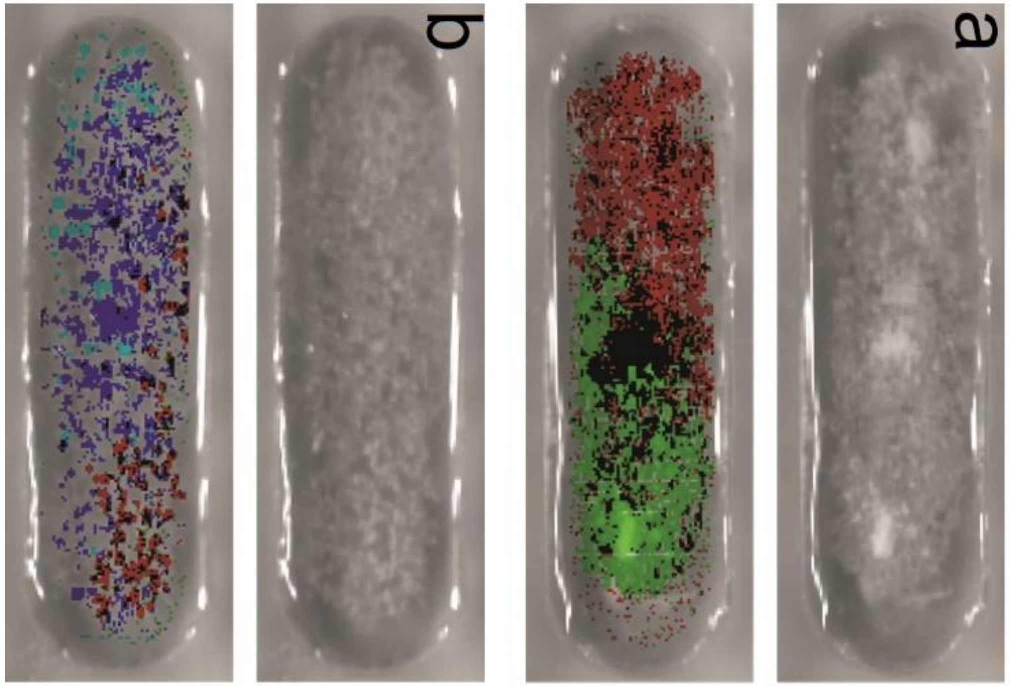
- Using derivative of the spectra to build a decision table

MP type	Spectral Features (nm)													
	1130	1661	1680	1698	1717	1736	1768	1906	2146	2171	2241	2266	2317	2355
HDPE						1	1						1	1
LLDPE						1	1						1	1
MDPE						1	1						1	1
PVC					1	1								
UPVC					1	1								
PS1			1						1	1				
PS80			1						1	1				
PP				1								1		
PA	1					1				1				
PET		1						1			1			


HDPE LLDPE MDPE PVC UPVC PS 1 PS 80 PP PA PET

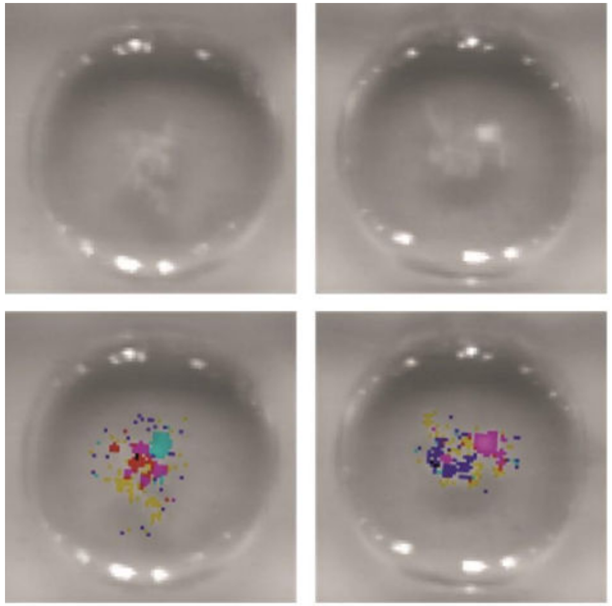
- Individual MP identification test
- Overlayed with the microplastics identification mask

Identification of microplastic mixtures



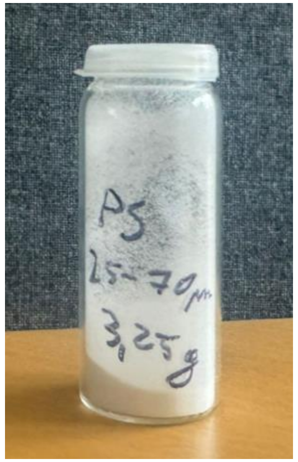
- PP
- UPVC/PVC
- PA
- PET
- unclassified

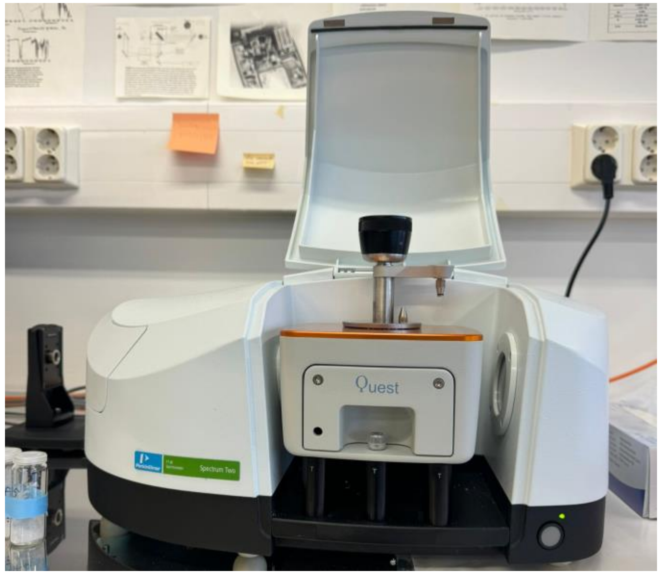
- PS 1/PS 80
- HDPE/LLDPE/MDPE
- unclassified

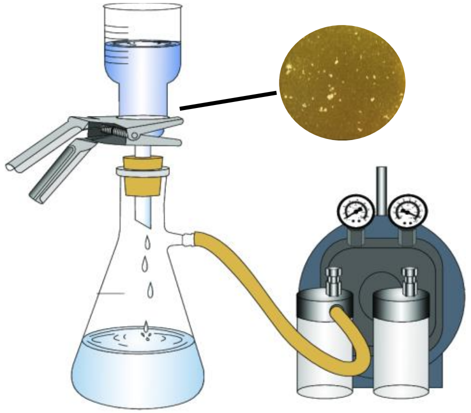


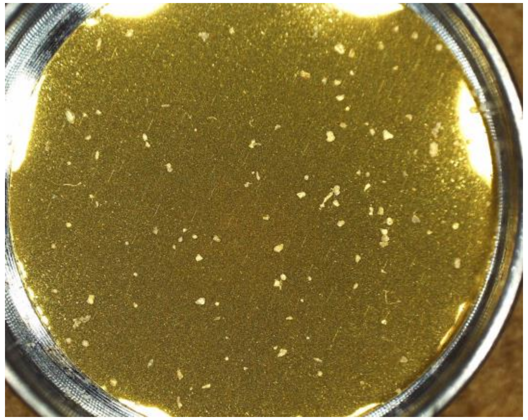
- PP
- UPVC/PVC
- PA
- PET
- HDPE/MDPE/LLDPE
- PS 1/PS 80
- unclassified

FTIR and photoacoustic spectroscopy

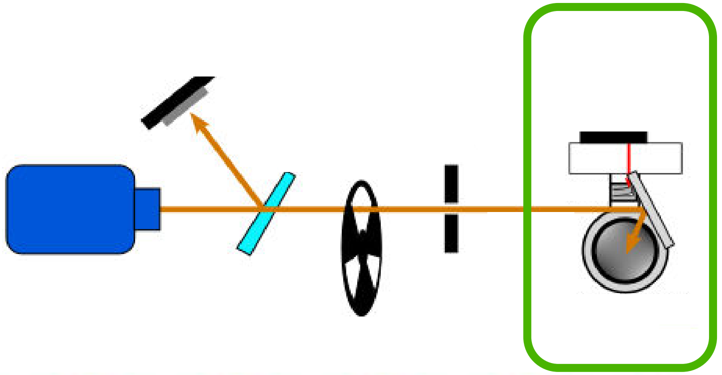


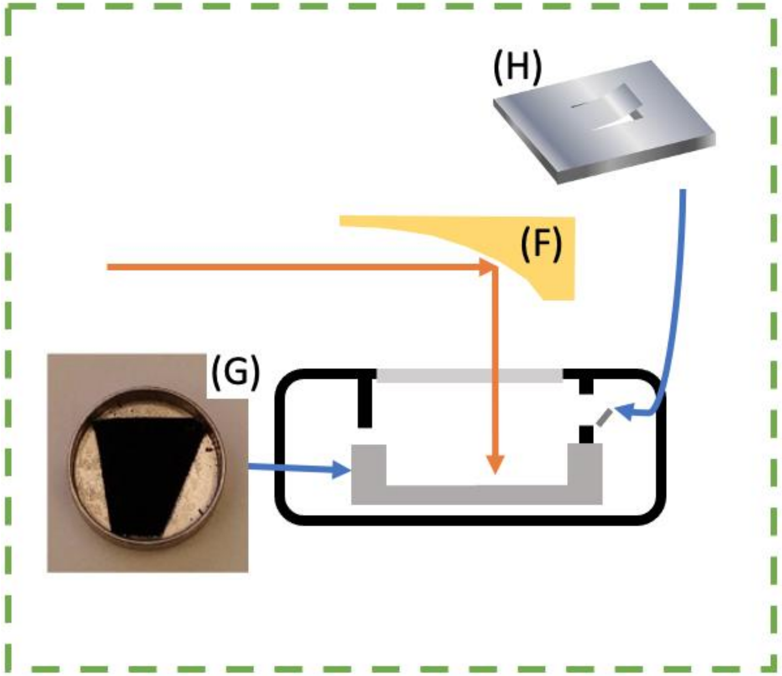




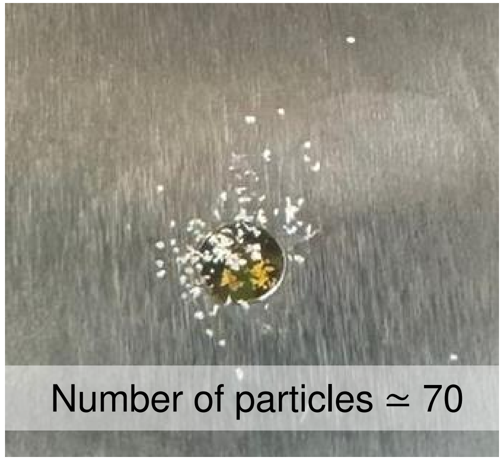


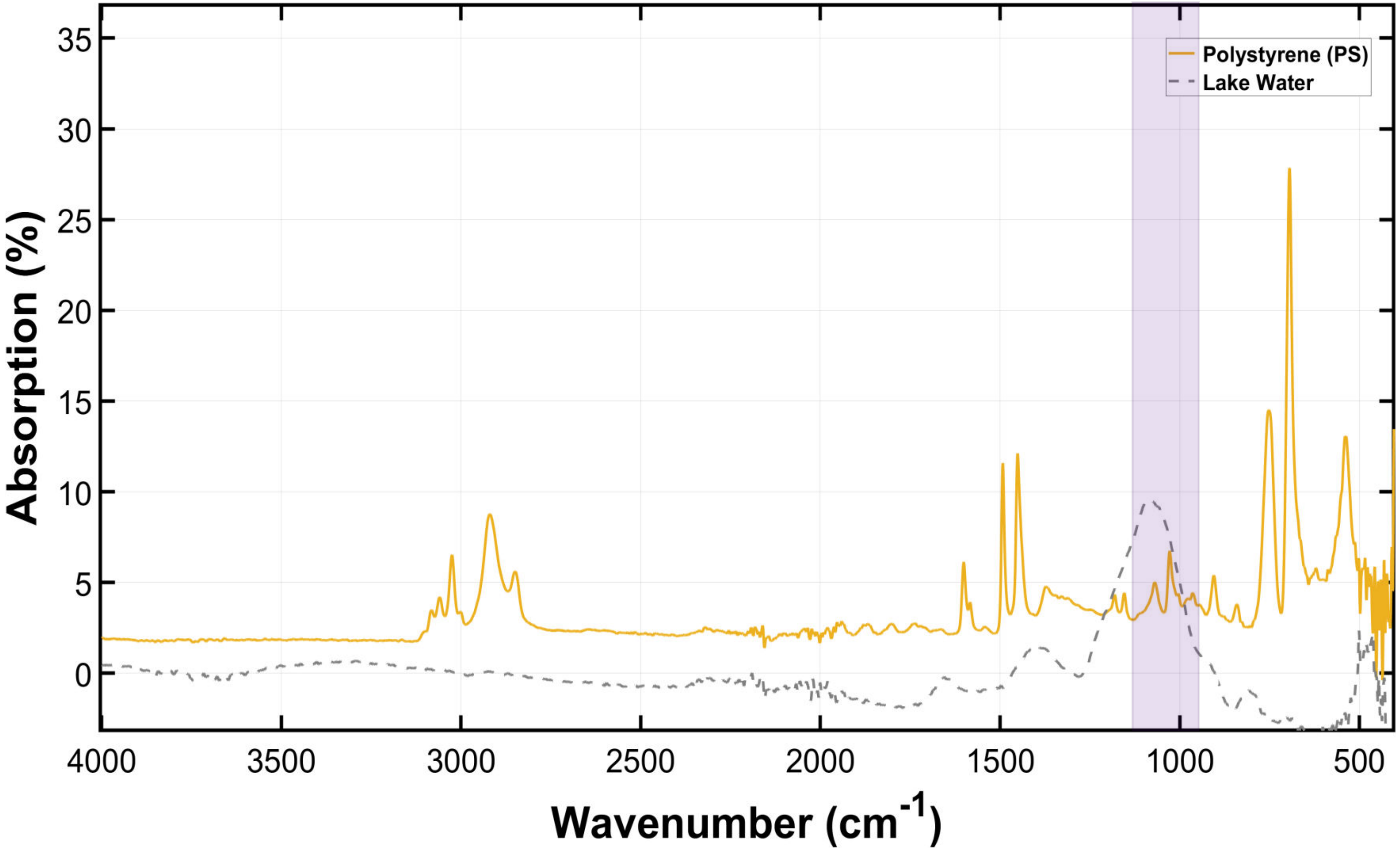
9 mm



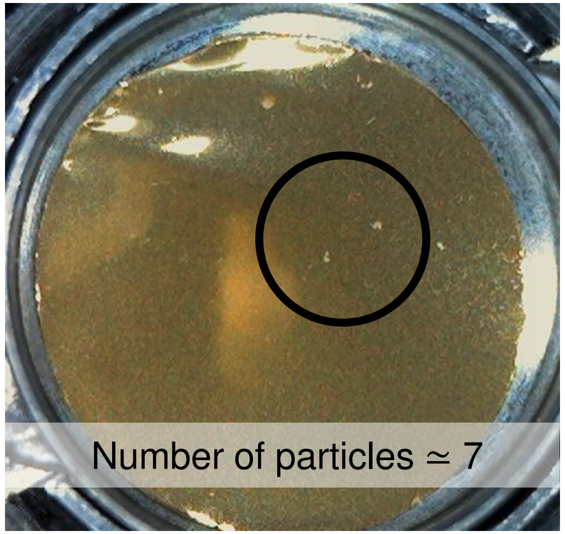


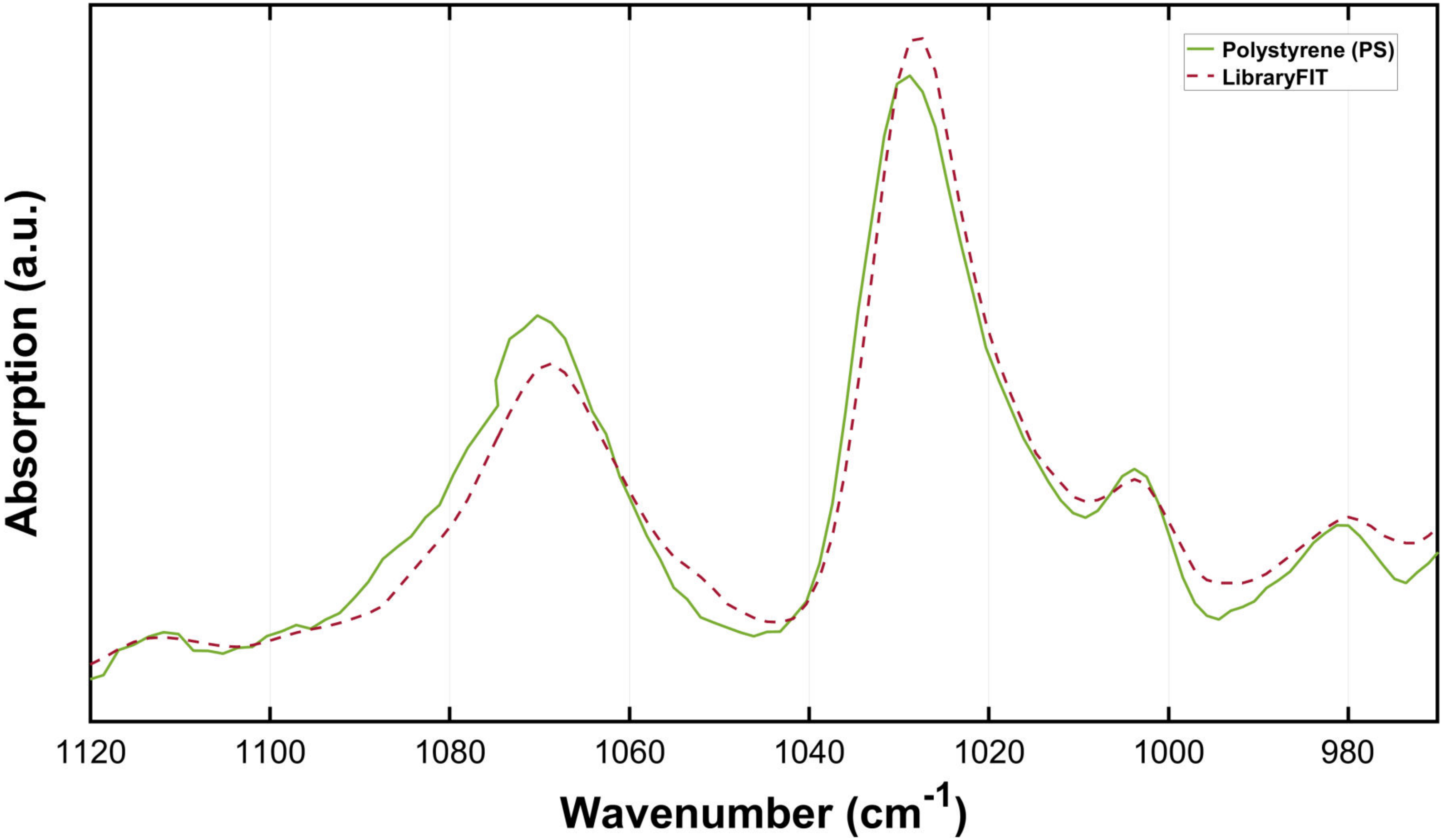
FTIR using large number of particles



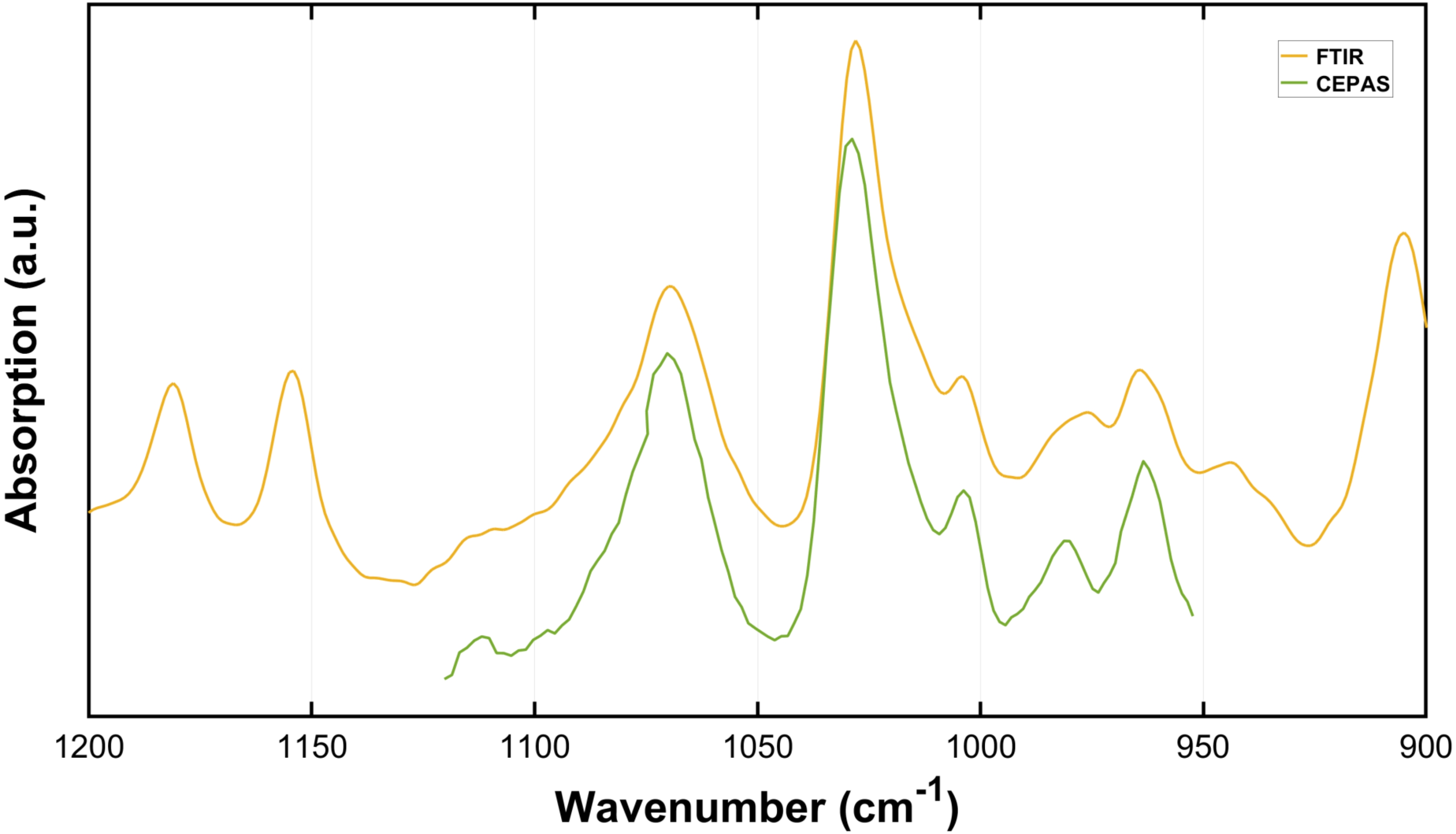


Photoacoustic sensing with less particles



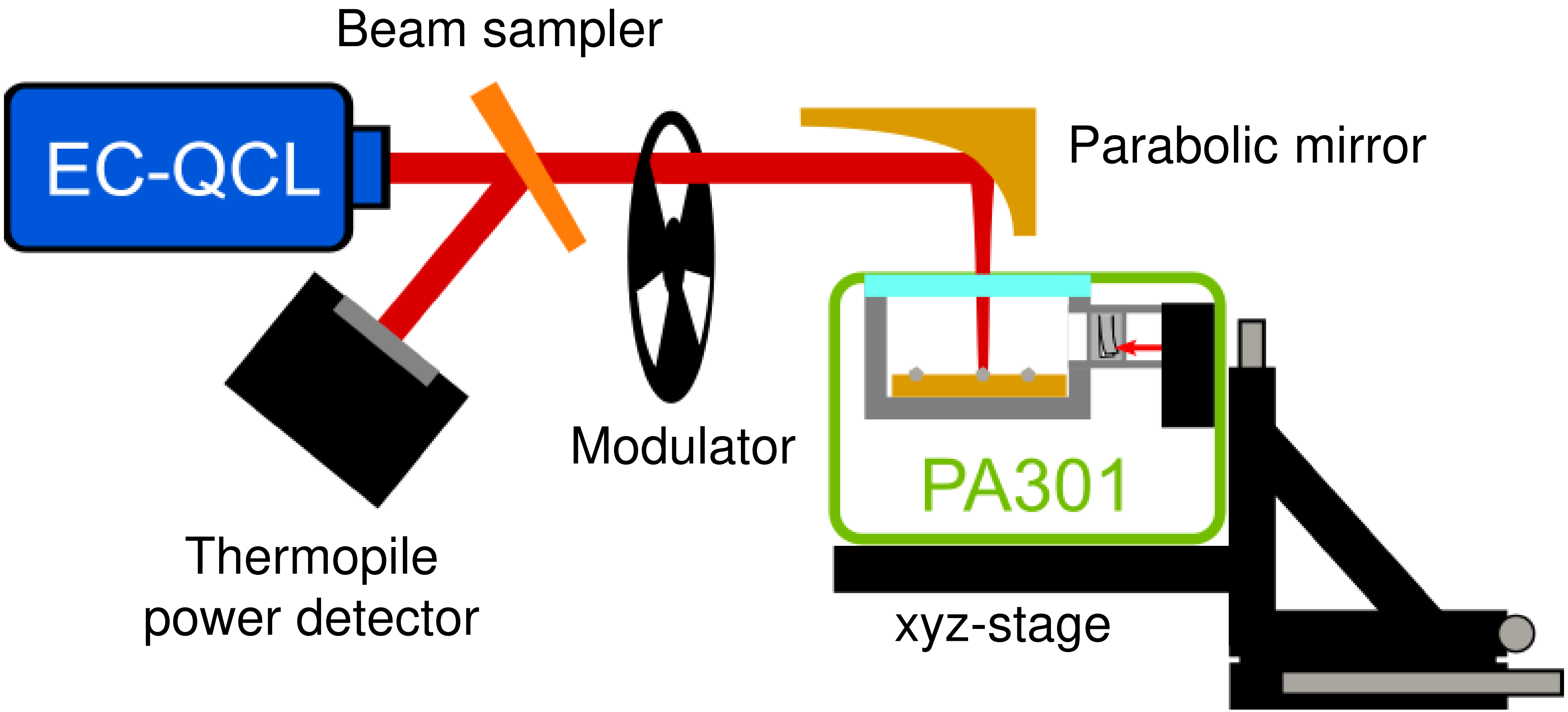


Comparison of FTIR and photoacoustic



Setup

- Wavelength range 8.5-10.5 µm
- Beam size ~300 µm at sample



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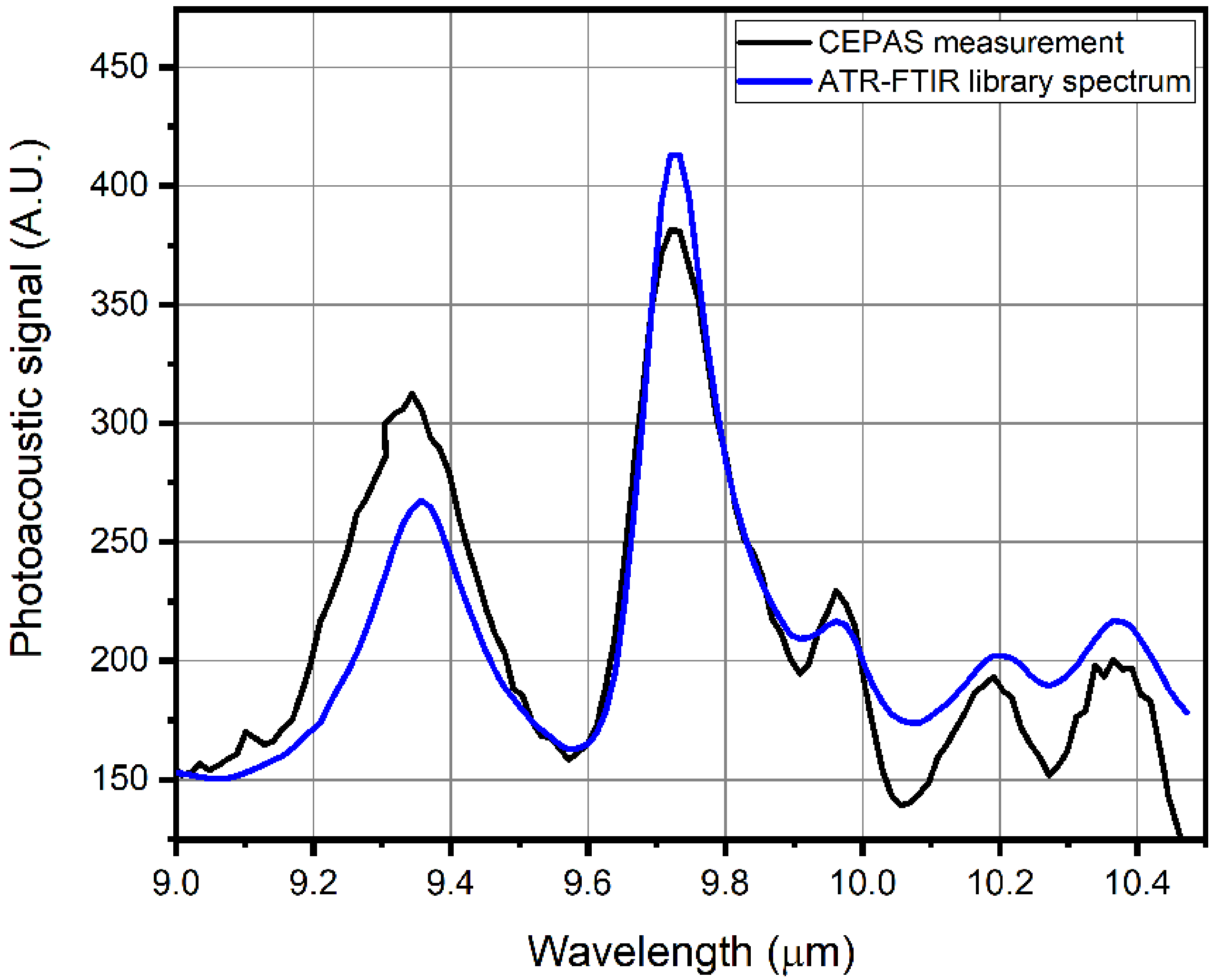
Example spectrum



- Single particle polystyrene spectrum
- Particle size: 25-70 um

Conclusion

- Own microplastic particle production for testing
- Hyperspectral imaging
- Fourier-transform spectroscopy
- Photoacoustic spectroscopy with tunable laser
- Sensitivity down to single particle level

Structured Quantum Photonics with Geometric Phases and Integrated Circuits

PREIN Annual Event, OPD 2024

28th May 2024, Helsinki

George Thomas, Vladimir Kornienko

Aalto-yliopisto

Tampere University

UNIVERSITY OF EASTERN FINLAND

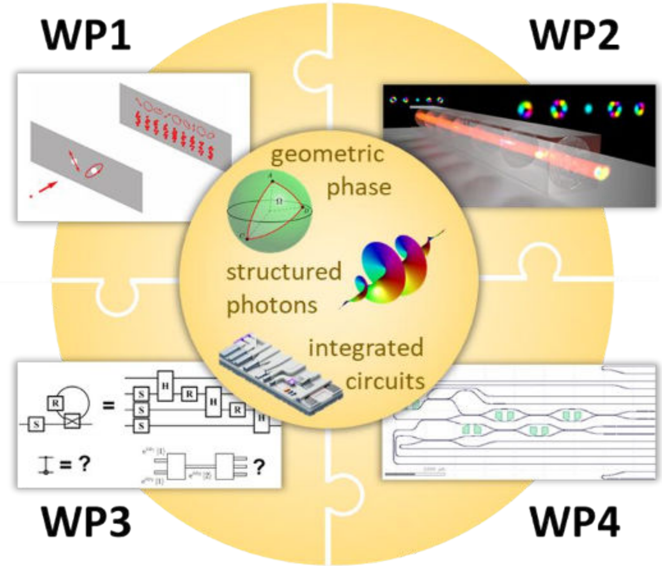
VTT

Introduction

- Project aims the combination of Quantum Optics, Structured Light, and Integrated Optics.
- Fundamental theoretical aspects of the geometric phase in quantum optics.
- Experimental implementations with structured free-space optics and photonic integrated circuits.

Geometrical phase and its relation with wave-particle duality: UEF

Structured light: TAU



Geometric phase related to multiphotons, photonic quantum computing: AALTO

Photonic integrated circuits: VTT

Introduction

Phases in Quantum dynamics

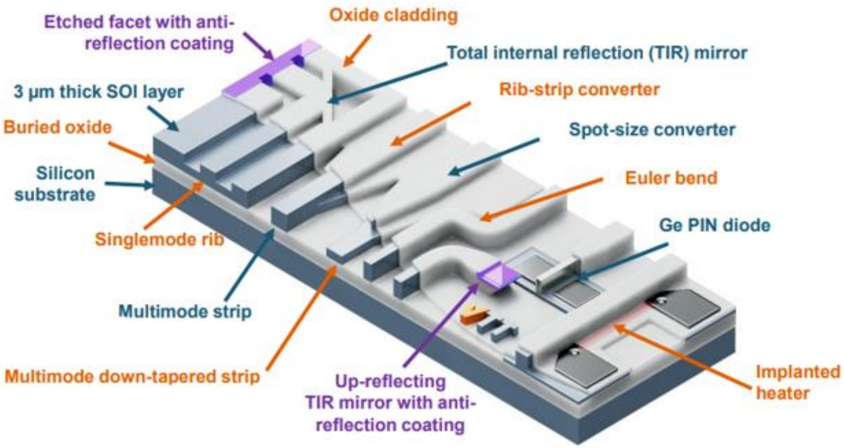
Geometric phase (Pancharatnam–Berry phase): Phase accumulated during the evolution of the system due to the geometrical properties of Hamiltonian's parameter space and usually observed in cyclic evolution [1,2].

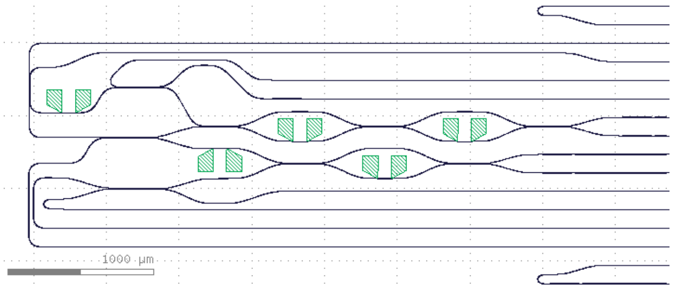
Dynamical phase: Phase accumulated due to the energy of the quantum system during the evolution.

Structured photons: Higher dimensional systems of light with arbitrary coherent superposition of polarizations and spatial modes [3,4].

[1] S. Pancharatnam Proc. Indian Acad. Sci. A. **44** 247 (1956).
[2] M. V Berry, Proceedings of the Royal Society A. **392** 45 (1954).
[3] E. Nagali et al, Phys. Rev. A **81**, 052317 (2010).
[4] A. Sit et al, Optica **4** 1006 (2017).

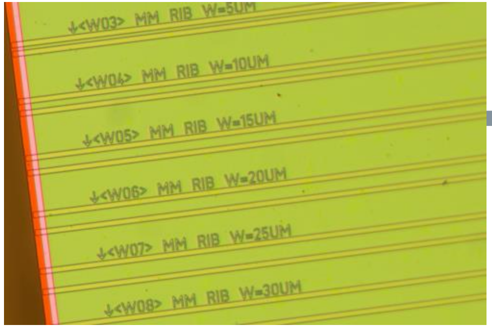
Photonic integrated circuits





Photonic CNOT gate on thick SOI platform (Aalto/VTT)

VTT's 3µm thick SOI platform is a useful candidate for the quantum technologies [Ref: Advanced Photonics Nexus 2, 024002 (2023).]



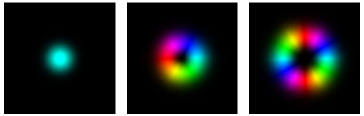
Chip with multimode waveguides are fabricated in thick SOI platform for coupling structured light modes to waveguide modes (TAU/VTT)

High-dimensional interface for structured light

<u>Idea:</u>
using multiplane light conversion (MPLC) technique to implement high-dimensional interface between free-space and on-chip multi-mode light fields

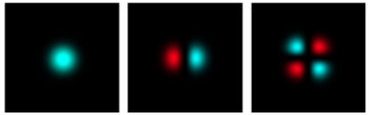
free space modes:

- Laguerre Gauss modes $LG_{p,l}$

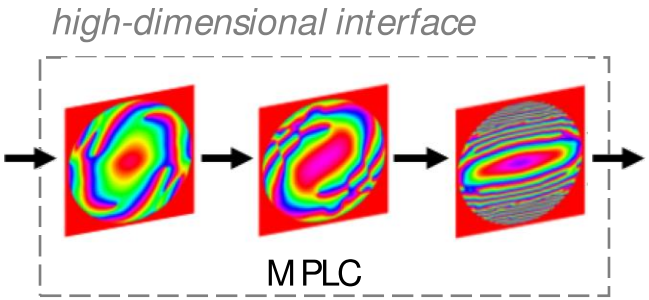


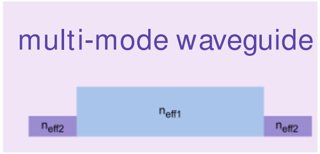
$LG_{0,0}$ $LG_{0,1}$ $LG_{0,2}$

- Hermite Gauss modes $HG_{n,m}$

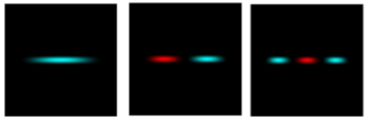


$HG_{0,1}$ $HG_{0,1}$ $HG_{1,1}$



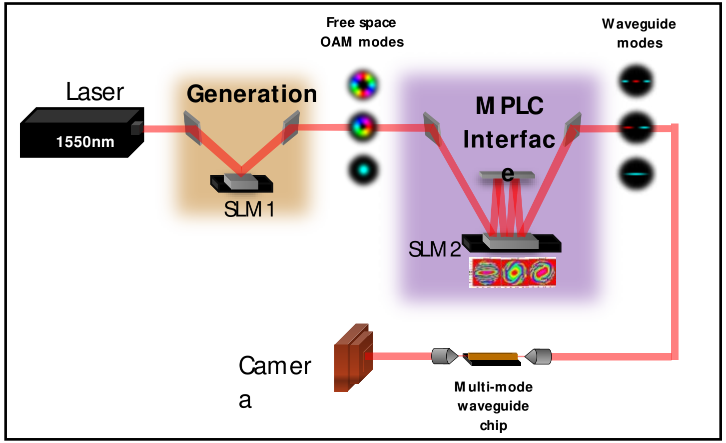


waveguide modes:



High-dimensional interface for structured light

Experimental implementation

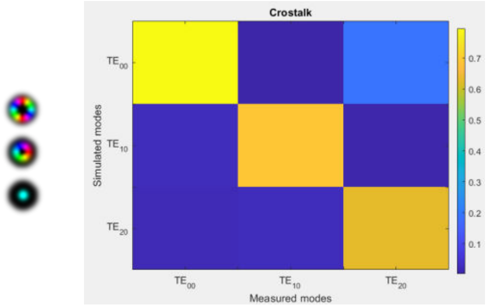


Simplified drawing of the experimental set-up

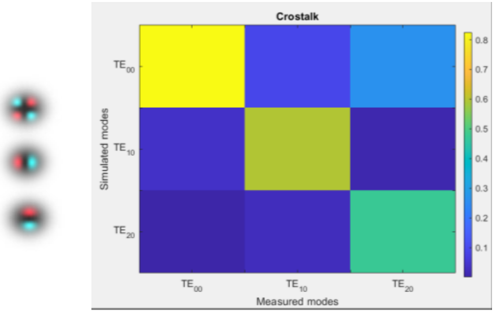
Measured cross talks

Preliminary results

Laguerre-Gauss

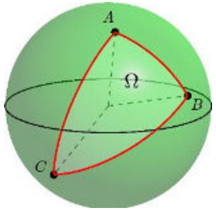


Hermite-Gauss

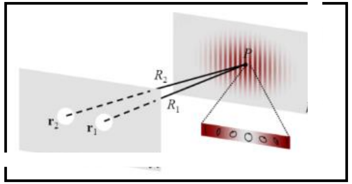


Geometric phase and wave–particle duality

- Pancharatnam–Berry phase [1]: $|\Phi_G| = \Omega/2$
  - geometric phase that vectorial light gains as its polarization state undergoes a cyclic evolution
  - occurs even if the dynamical phase is absent
  - fundamental (wave) property of the photon [2]



Observed in two-slit interference with classical light fields [3,4]



- Photon in double-slit setup [5]: $|\Phi'_G| + \Upsilon \leq 1$ ⟸ $\Phi'_G = \Phi_G/\pi$ (wave aspect), $\Upsilon = D_0/D_S$ (particle aspect)
  - $0 \leq |\Phi'_G| \leq 1$ and $0 \leq \Upsilon \leq 1$
- In cyclic polarization evolution: $|\Phi'_G| + \Upsilon = 1$ ⟸ Strong complementarity!

[1] E. Cohen et al., *Nat. Rev. Phys.* **1**, 437 (2019).
[2] P. G. Kwiat & R. Y. Chiao, *Phys. Rev. Lett.* **66**, 588 (1991).
[3] A. Hannonen, H. Partanen, A. Leinonen, J. Heikkinen, T. K. Hakala, A. T. Friberg & T. Setälä, *Optica* **7**, 1435 (2020).
[4] A. Leinonen, A. Hannonen, H. Partanen, J. Heikkinen, T. Setälä, A. T. Friberg & T. K. Hakala, *Commun. Phys.* **6**, 132 (2023).
[5] E. Pillinen, A. Halder, A. T. Friberg, T. Setälä & A. Norrman, *arXiv:2310.20273* (2023).

Geometric phase with NOON states

- Four-mode NOON state at the slit plane $\mathcal{A}$:

$$|\psi\rangle = c_{1x}|N,0,0,0\rangle + c_{1y}|0,N,0,0\rangle + c_{2x}|0,0,N,0\rangle + c_{2y}|0,0,0,N\rangle$$

- Four Stokes operators ($j = 0,1,2,3$):

$$\hat{S}_j^{(N)}(\mathbf{r}_1,\mathbf{r}_2) = |C|^{2N}\left[\hat{a}_{1x}^{\dagger N}\,\hat{a}_{1y}^{\dagger N}\right]\boldsymbol{\sigma}_j\left[\hat{a}_{2x}^{N}\,\hat{a}_{2y}^{N}\right]^{\mathrm{T}}$$

- Polarization modulation at the screen $\mathcal{B}$:

$$S_j^{(N)}(\mathbf{r}) = \frac{|K|^{2N}}{r^{2N}}\left[S_j^{(N)}(\mathbf{r}_1) + S_j^{(N)}(\mathbf{r}_2) + 2\left|S_j^{(N)}(\mathbf{r}_1,\mathbf{r}_2)\right|\cos\left(Nk\Delta r + \theta_j(\mathbf{r}_1,\mathbf{r}_2)\right)\right],\quad \Delta r = r_2 - r_1$$

- Poincaré-type sphere for the NOON state:

$$\left[S_0^{(N)}(\mathbf{r})\right]^2 = \left[S_1^{(N)}(\mathbf{r})\right]^2 + \left[S_2^{(N)}(\mathbf{r})\right]^2 + \left[S_3^{(N)}(\mathbf{r})\right]^2$$

N times faster polarization evolution and geometric-phase accumulation!

- Geometric phase in one cycle: $\Phi_{\mathrm{G}}^{(N)} = \pm\pi\left(1 - \Upsilon^{(N)}\right)$

WPI ratio: $\Upsilon^{(N)} = D_0^{(N)} / D_S^{(N)}$

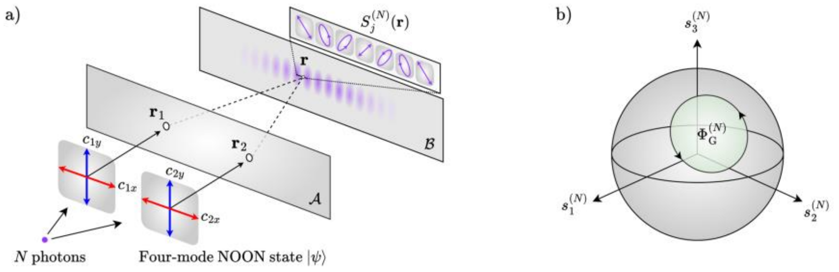
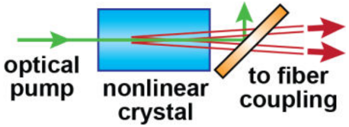


Fig 1. NOON-state polarization modulation a) in double-slit interference and b) on a Poincaré-type sphere.

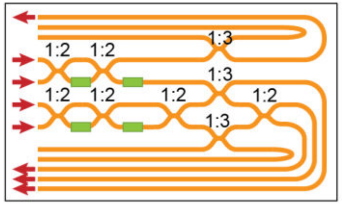
Photonic integrated circuits – control and photon source optimization



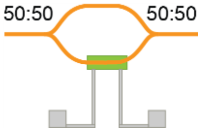
Photon source schematic

power splitters

Y-branches



Non-deterministic CNOT gate

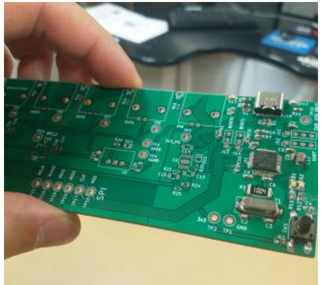


Mach-Zehnder interferometers

- Design a source of heralded single photons and biphotons @ infrared range (> 1.3 um).
- Test the performance of photonic integrated circuits (PICs) at the single-photon level.
- Reconstruct the transfer matrix **M** matrix of a PIC device.

A lossless linear optical multiport device can be characterized by the transfer matrix **M**:

$$\begin{pmatrix} \hat{a}_1^{\text{out}\,\dagger} \\ \hat{a}_2^{\text{out}\,\dagger} \\ \dots \end{pmatrix} = \mathbf{M} \begin{pmatrix} \hat{a}_1^{\text{in}\,\dagger} \\ \hat{a}_2^{\text{in}\,\dagger} \\ \dots \end{pmatrix}$$



An optical multiport with an arbitrary number of inputs and outputs can be characterized with a source of biphoton pairs via the Hong-Ou-Mandel (HOM) interference.

HOM interference visibility:

$$V_{ijkl} = (C_{ij}^{kl} - Q_{ij}^{kl})/C_{ij}^{kl}$$

(≈ boson sampling, reversed.)

Indistinguishable photons:

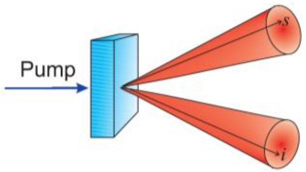
$$Q_{ij}^{kl} = \frac{1}{1+\delta_{ij}} |M_{ik}M_{jl} + M_{il}M_{jk}|^2$$

Controller for thermo-optical phase shifters (PCB stage):
ARM microcontroller + voltage output DAQs, 7 channels. kHz rate.

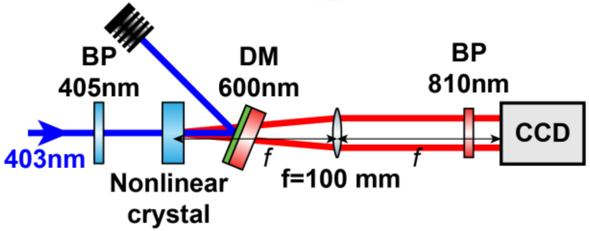
Distinguishable photons:

$$C_{ij}^{kl} = |M_{ik}M_{jl}|^2 + |M_{il}M_{jk}|^2$$

Photonic integrated circuits – control and photon source optimization



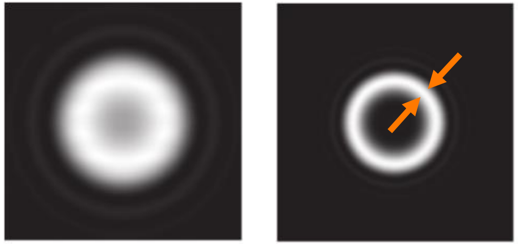
$$\begin{cases} \omega_p = \omega_\mathrm{A} + \omega_\mathrm{B} \\ \hat{\mathbf{k}}_p = \hat{\mathbf{k}}_\mathrm{A} + \hat{\mathbf{k}}_\mathrm{B} \end{cases}$$



- Lack of accessible infrared detectors: visible light characterization + dispersion-based computations
- Spontaneous parametric down-conversion (SPDC) as a probing tool: zero-field vacuum fluctuations span the whole frequency range and have uniform brightness.
- Use the biphoton amplitude to compute the correlation moments.

A biphoton field amplitude $\Psi(\mathbf{k}_1,\mathbf{k}_2)$ can be computed using the formalism of macroscopic nonlinear optics.

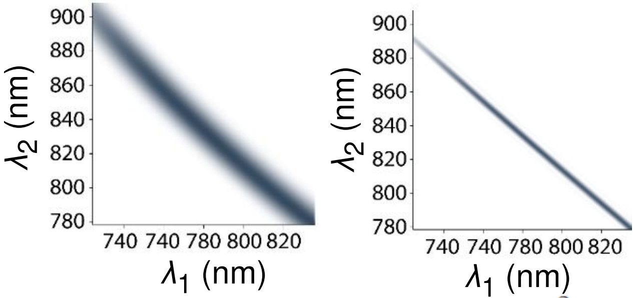
Unconditional photon detection probability (single counts):



L=1 mm L=3 mm

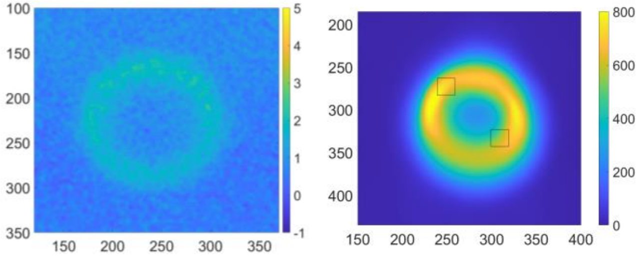
$$\frac{dw^{uncond}}{dk_{1\perp x}} = \int dk_{2\perp x} \left|\Psi(k_{1\perp x}, k_{2\perp x})\right|^2$$

Conditional photon detection probability (coincidences):



$$\frac{dw^{cond}}{dx_1} = \left.\frac{\left|\Psi(k_{1\perp x}, k_{2\perp})\right|^2}{\int dk_{1\perp x} \left|\Psi(k_{1\perp x}, k_{2\perp x})\right|^2}\right|_{k_{2\perp x}}$$

Measurements at $\lambda_P = 403$ nm:



type-I BiBO 0.25 mm, type-I BBO 10.0 mm
Optical pump: 403 nm, continuous wave, 10 mW
CCD camera: no gain, 0.1-1s exposure times

Thank You!!

Main contacts:
Prof. Ilkka Tittonen (AALTO)
Dr. Robert Fickler (TAU)
Dr. Andreas Norrman (UEF)
Dr. George Thomas (VTT)

PREIN

Aalto-yliopisto
Tampere University
UNIVERSITY OF EASTERN FINLAND
VTT

Tampereen yliopisto
Tampere University

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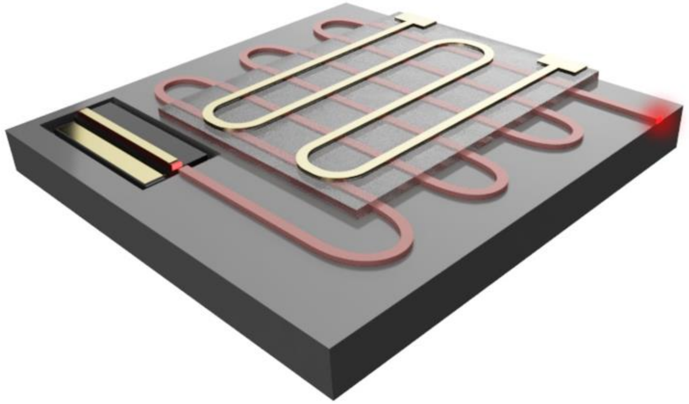
Photonics Finland
OPD2024

Integrated pulsed laser driving industrial scaling of quantum technology – IntegrateQT –

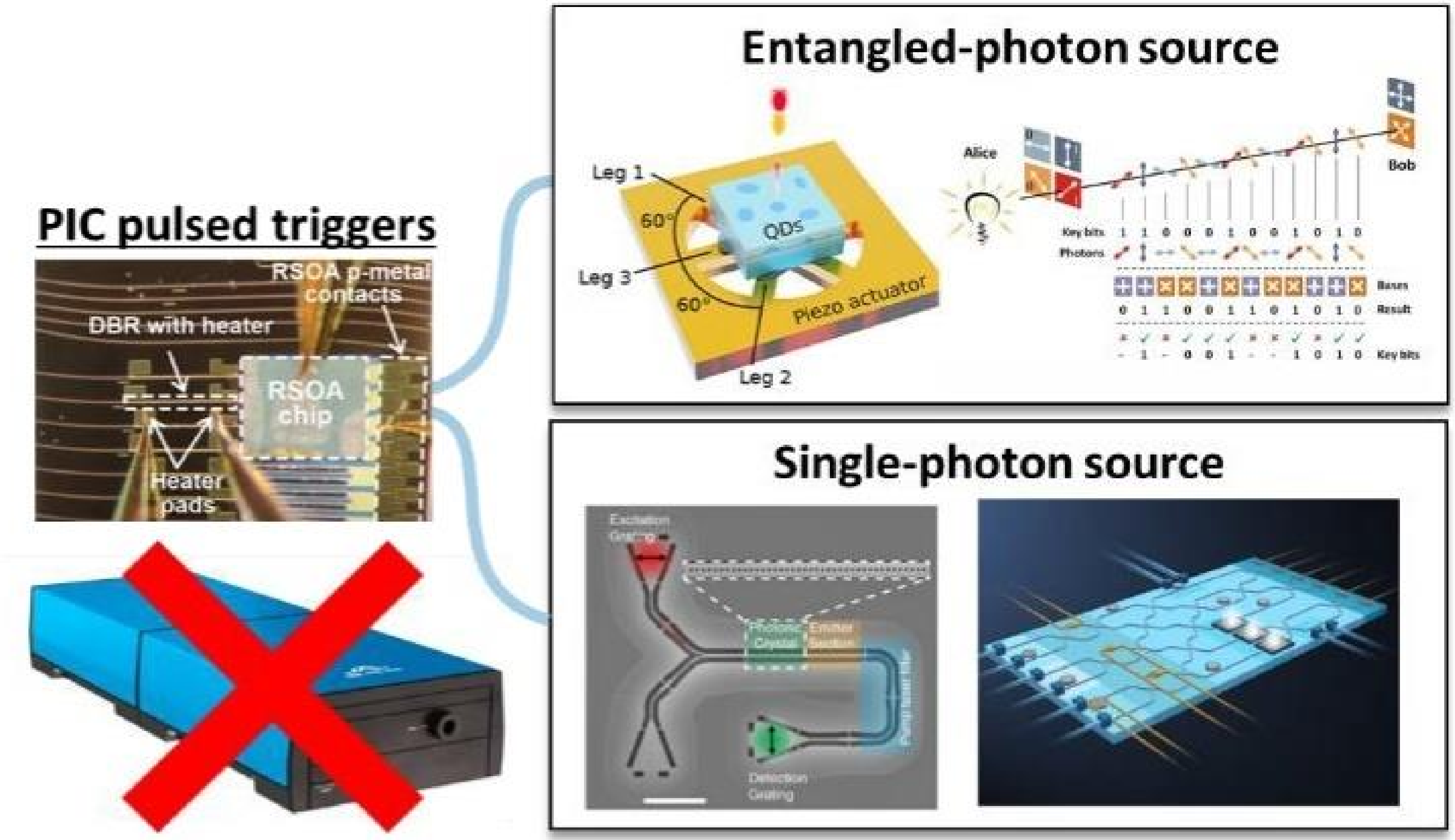
Mircea Guina, Prof.
Optoelectronics Research Centre, Photonics / Physics Unit
Faculty of Engineering and Natural Sciences,
Tampere University

www.research.tuni.fi/orc
www.tuni.fi/photonics
www.prein.fi
https://www.linkedin.com/in/mircea-guina/
mircea.guina@tuni.fi

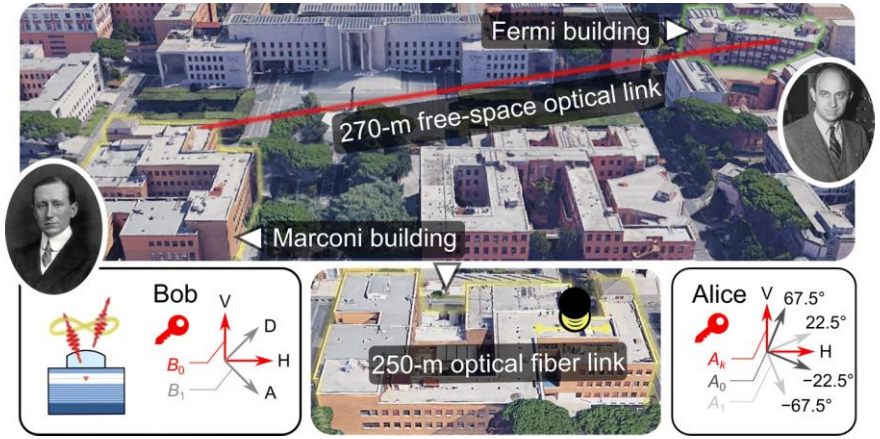
ORC



Project in a nutshell



HAN-SEN ZHONG et al. Science 370, 1460 (2020)

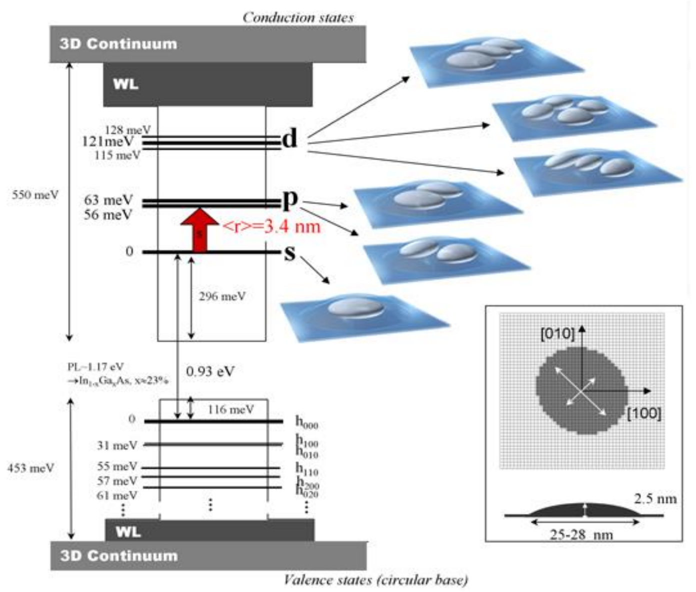


F. B. Basset et al. Sci. Adv. 7, 6379 (2021)

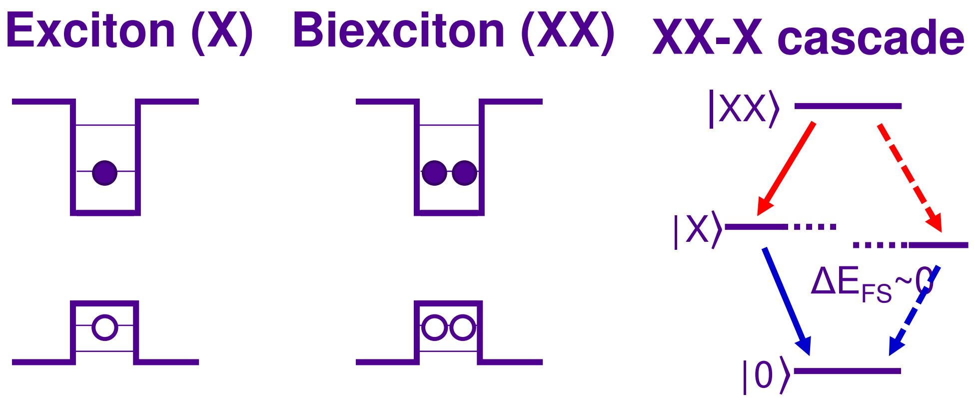
General goal: development of PIC-based mode-locked lasers and demonstrate their applicability for single and entangle-photon generation with QDs @780 nm, @940nm, and @1.5 µm wavelengths.

Benefits of semiconductor Quantum Dots

- **Artificial atoms** with tailorable emission wavelength
- **Compatibility** for integration with semiconductor electronic, optoelectronic and integrated photonic platforms
  - Photonic integration
  - Semiconductor DBR mirrors and vertical cavities
  - P-I-N junctions for applying gate voltage
- **Single-photon emission** from exciton recombination
  - Fast spontaneous lifetime
- **Polarization entangled-photon** emission from biexciton-exciton cascade (if small FSS)



- **An ideal single-photon source:**
  - Triggered photons on-demand
  - High repetition rate
  - All photons are identical – indistinguishability
  - 100% fidelity of entanglement



QDs vs. Spontaneous Parametric Down-Conversion

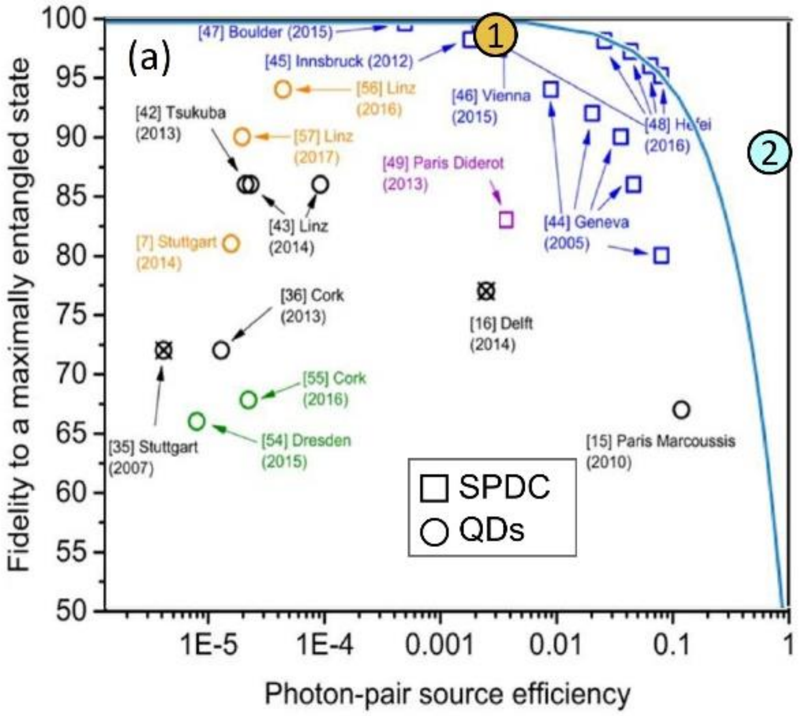
QDs are single-atom-like <u>deterministic emitters</u>

→ Possibility to achieve **high photon rate** and **high fidelity of entanglement** simultaneously

SPDC is a probabilistic process

→ Increase of photon rate increases the number of multiphoton events

→ Degradation of entanglement and single photon quality

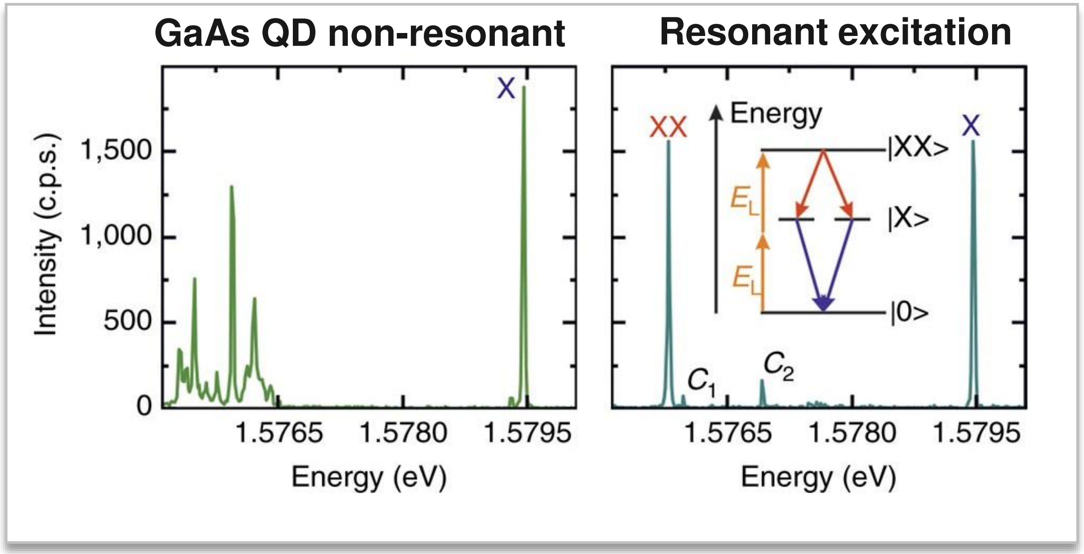


[1] D. Huber et al. (A. Rastelli) Phys. Rev. Lett. **121**, 033902 (2018)

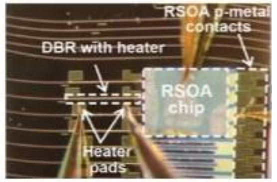
[2] Jin Liu et al. (A. Rastelli) Nature Nanotechnology **14**, 586 (2019)

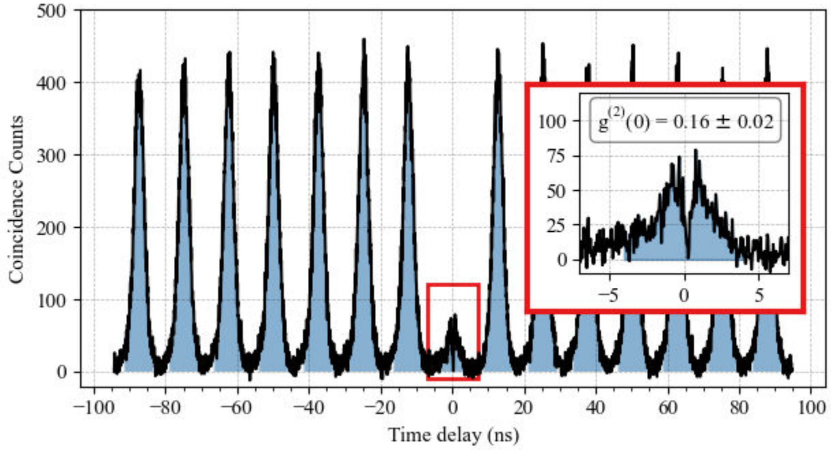
The scalability issue

- **Use of complex and expensive excitation lasers (TiSa, OPO)**
  - Tuned in resonance with the QD emission to avoid charge accumulation outside QDs



D. Huber et al. Nature Communications 8, 15506 (2017).

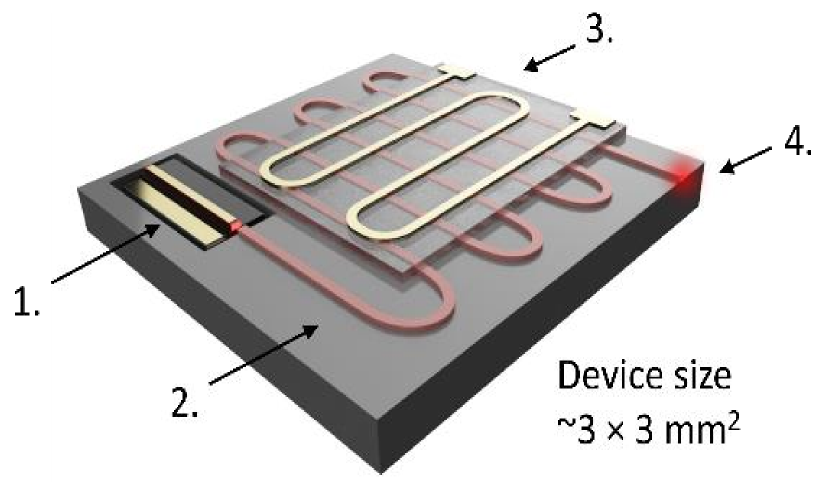




- **Need: a fully-integrated chip-based excitation source for resonant excitation**

Specific goals

- **Wavelength range:**
  - → 780+/-1nm for GaAs/AlGaAs QDs
  - → 940+/-1nm for InGaAs/GaAs QDs
  - →1500+/-2nm GaSb/AlGaSb QDs
- **Average power:** a few mW
- **Pulse duration:** <30 ps is sufficient for the PoC; SoA <10ps (sets the upper limit for the fidelity entanglement)
- Spectral width of < 0.5 nm
- **Repetition rate:** 0.5 – 2 GHz. Limited by the spontaneous lifetime of the QD material (~200ps for GaAs QDs and ~700ps for InGaAs QDs). Use an optical cavity to enhance the spontaneous rate of the QD (x10).



(1) Optoelectronic gain chip with saturable absorber section; (2) A SiN PIC chip forming an extended waveguide cavity; (3) a heating element for wavelength tuning; and (4) an output port for fibre coupling to QIPC.

- **<u>Main challenge</u>: coupling losses and spurious reflections at Gain Chip / PIC interface.**

Links to PREIN WPs (WP3 & WP4)

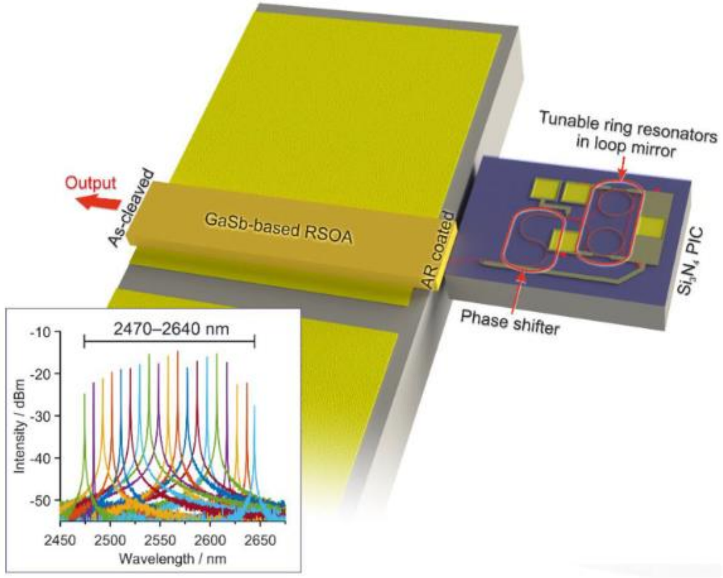
LASER
& PHOTONICS
REVIEWS

Research Article | Open Access

Widely Tunable (2.47–2.64 μm) Hybrid Laser Based on GaSb/GaInAsSb Quantum-Wells and a Low-Loss Si_3N_4 Photonic Integrated Circuit

Samu-Pekka Ojanen, Jukka Viheriälä, Nouman Zia, Eero Koivusalo, Joonas Hilska, Heidi Tuorila, Mircea Guina

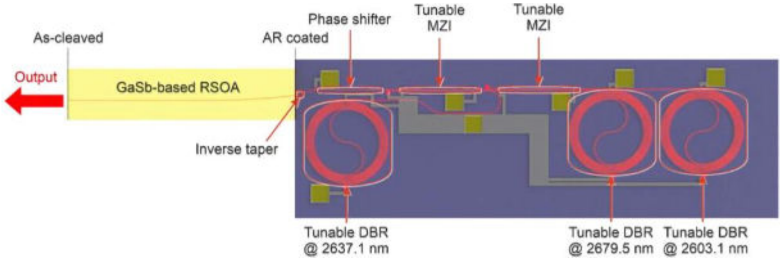
First published: 14 April 2023 | https://doi.org/10.1002/lpor.202201028 | Citations: 1

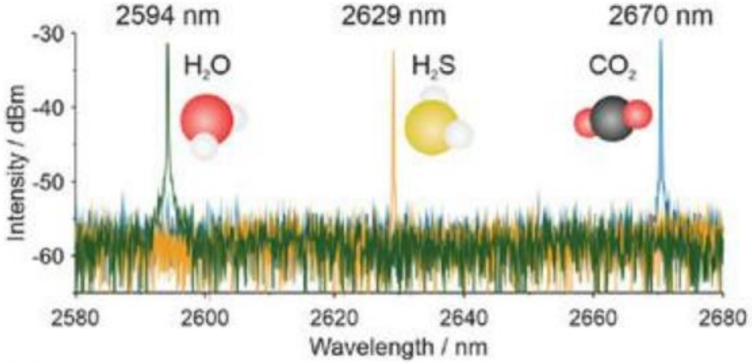


Discretely Tunable (2594, 2629, 2670 nm) GaSb/Si_3N_4 Hybrid Laser for Multiwavelength Spectroscopy

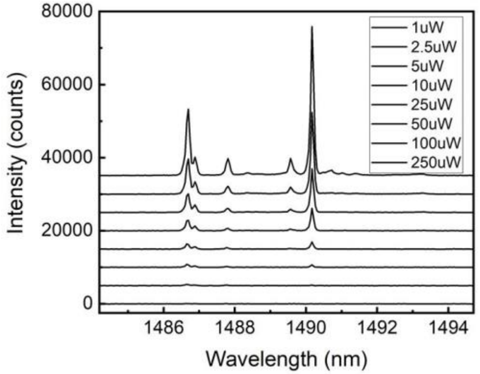
Samu-Pekka Ojanen, Jukka Viheriälä, Nouman Zia, Eero Koivusalo, Joonas Hilska, Heidi Tuorila, Mircea Guina

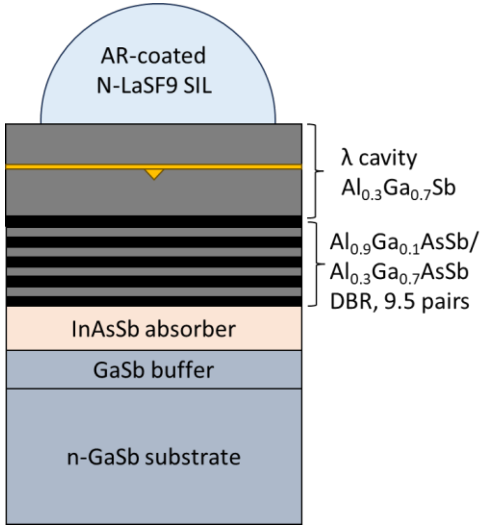
First published: 15 September 2023 | https://doi.org/10.1002/lpor.202300492





GaSb QD system @ 1.5 μm





Teemu Hakkarainen et al.

Current status (month 5/24)

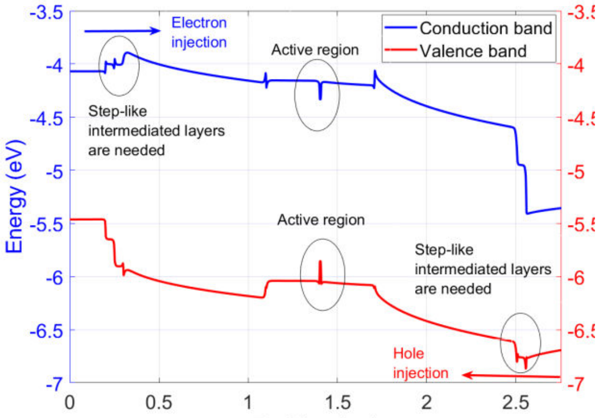
➢ Epi-structure

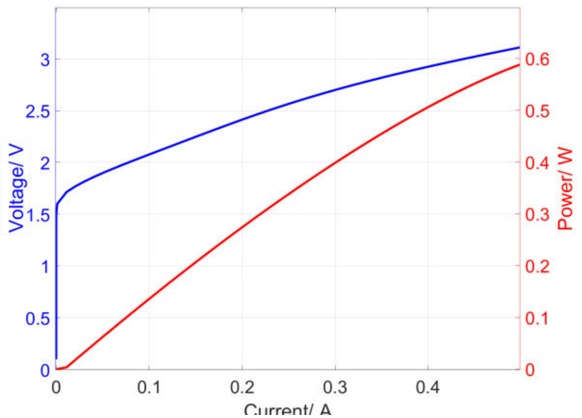
- Design ready for 780nm, 940nm
  → Selection of layer compositions for high modal gain and low loss, optimization of electrical characteristics
- 940 nm Epi to be grown early June

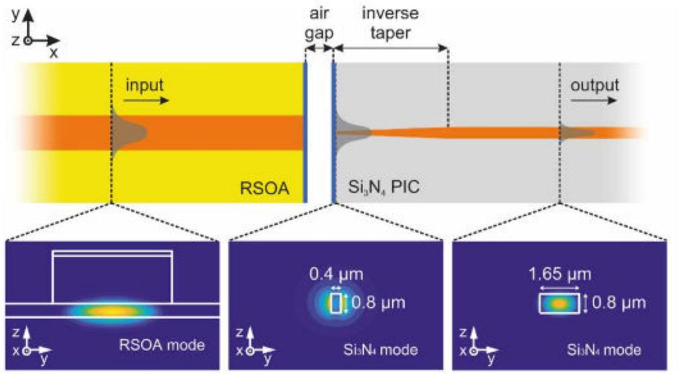
➢ PIC

- PIC/III-V interface design started
  →PIC platform selected
  → Selection of III-V WG and PIC-interface Circuit layouts to be started
- Plan to submit design to MPW run in Q4/2024

Simulation of 780 nm structure



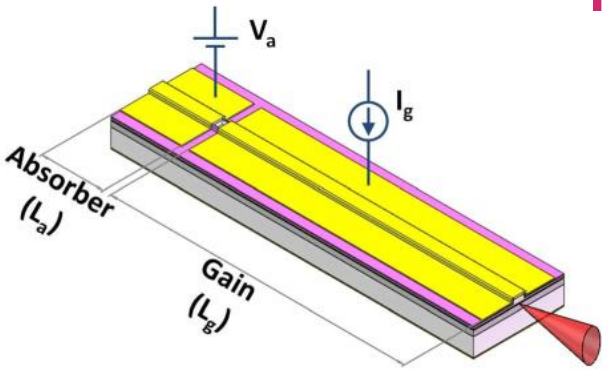


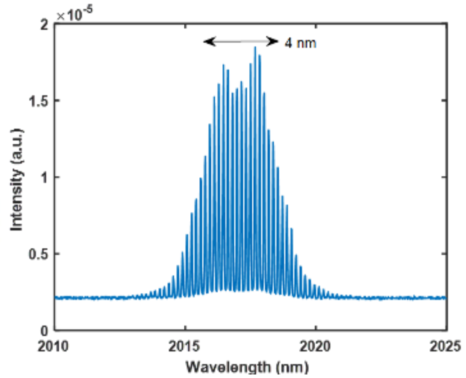


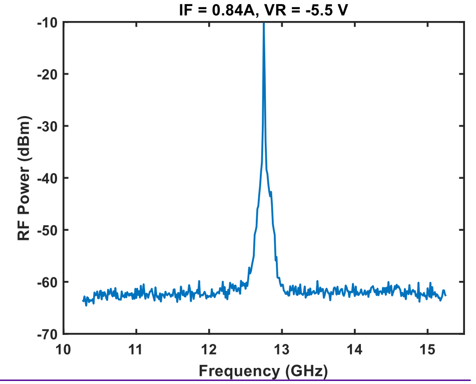
Connected activity: 2µm GaSb MLLD status

See presentation by Ajwaad Quashef

- **Mode locking achieved using monolithic geometry**
- **Designs offering high isolation and reliability exhibits poor mode lockir**
- **Now AR coated chips are used in extended cavity configuration**
  - With gold mirror in free space
  - With PIC delay line



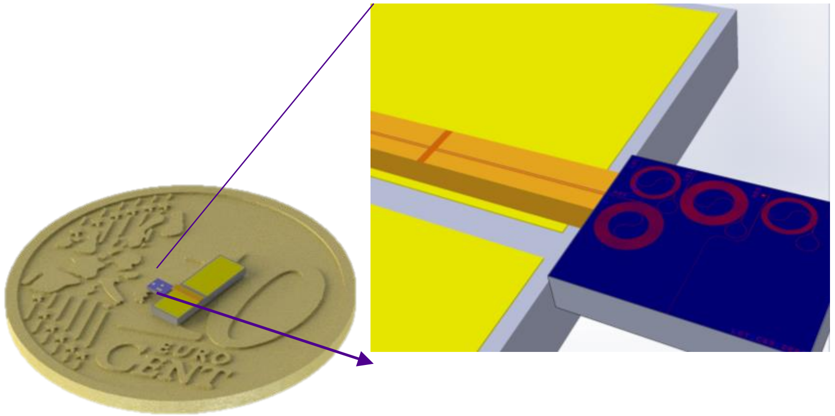




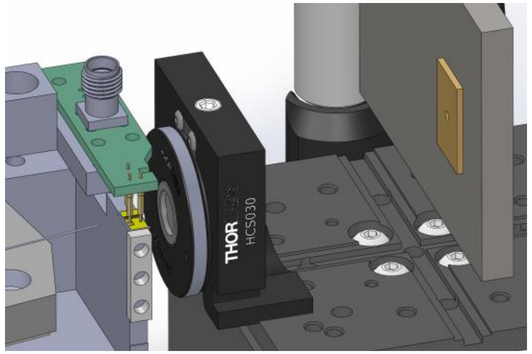
Monolithic

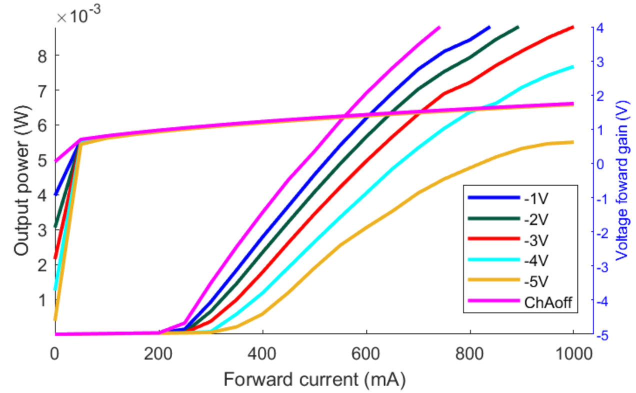
Extended cavity

PIC based



Free space





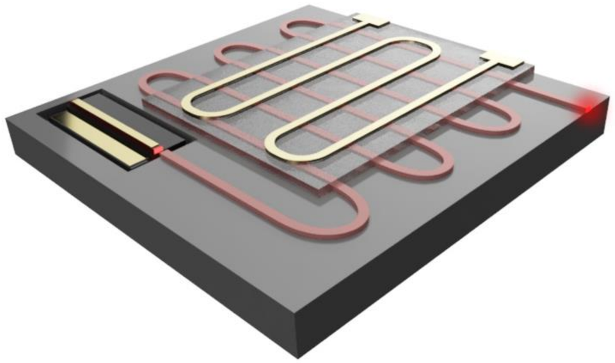
Roadmap to applications with GaSb QDs

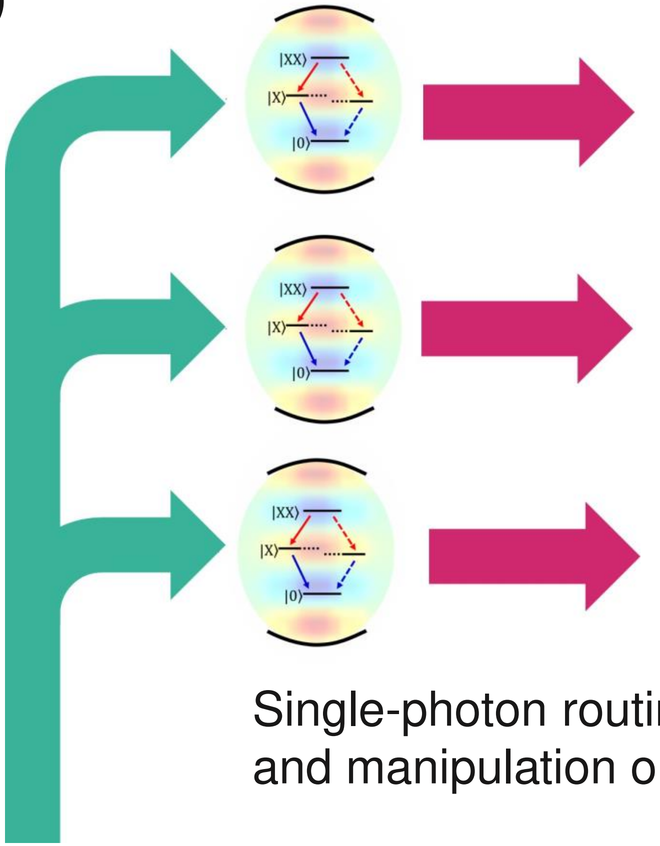
Photonic integration on Si-on-insulator (SOI)

Arrays of QDs

On-chip routing of trigger laser

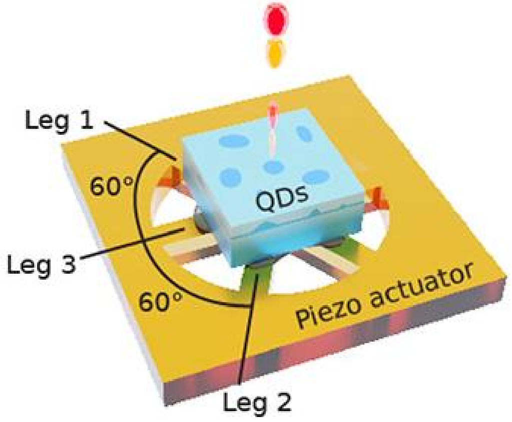
Integrated chip-based GHz pulsed trigger laser with wavelength tuning





Single-photon routing and manipulation on SOI

Entangled-photon sources at telecom wavelength



- **P-I-N gate** – charge stabilization
- **Piezo** – FSS elimination
- **Cavity** – emission enhancement and extraction efficiency

Collaborators

Prof. Peter Lodahl
Niels Bohr Institute

JOHANNES KEPLER UNIVERSITÄT LINZ

Prof. Armando Rasteli
Niels Bohr Institute

Research team

Dr. Teemu Hakkarainen
Dr. Jukka Viheriälä
Joonas Hilska
Patrik Rajala
Samu-Pekka Ojanen
Heidi Tuorila
Helmer Piirilä
Ajawaad Quashef

Funding

PREIN

ACADEMY OF FINLAND

BUSINESS FINLAND

Tampere Univ. Institute of Advanced Study

IntegrateQT
QuantSi
CryoLight

QuTI

Tampere University

Thank you!

NEXT-GEN PACKAGING: EUROPEAN CHIPS ACT AND ADVANCES IN MICROELECTRONICS & PHOTONICS

Time: 11.6.2024 at 14:00-17:30 (Finnish time)
Evening program 18:00-21:00 (Finnish time)

Place: Congress Centre Puistotorni, Hämeenpuisto 28, Tampere

IMAPS Nordic 2024 Conference and Exhibition on Microelectronics and Packaging

11th – 13th June 2024, #NordPac24

Register here

Dr. Martin Letz, Schott AG, Germany

Semiconductor packaging using structured glass panels as platform

Executive Director Twan Korthorst, Synopsys Photonic IC Solutions

Scalable foundry enablement for electronic and photonic co-design

Dr. How Yuan Hwang, Tyndall National Institute

Photonic Components Integration – the common ground with microelectronic packaging.

BUSINESS FINLAND BUSINESS TAMPERE iMAPS NORDIC NORDPAC

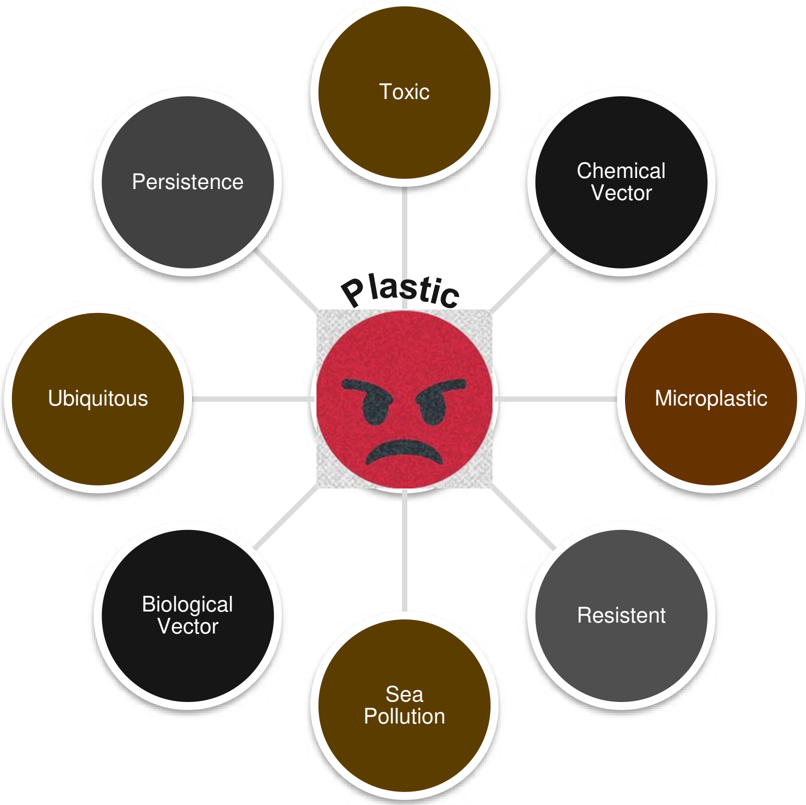
Workshop at NordPac:
Photonics-electronics integration and co-packaging.
From technology to applications.

Broadband active hyperspectral sensing for black plastic

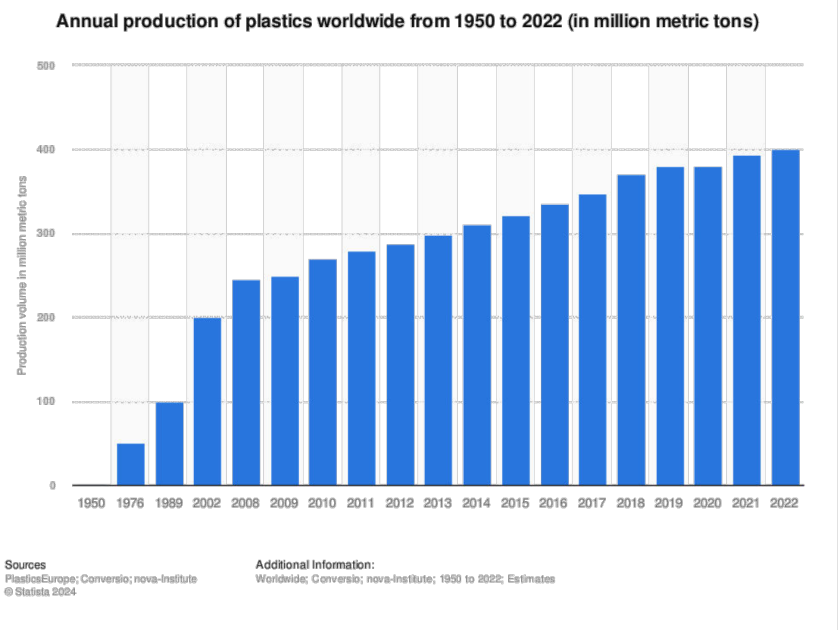
Eduardo Maia Paiva

7.6.2024 VTT – beyond the obvious

Plastic is a wonderful material! Is it?



Plastic Management



How much plastic is recycled today?

Recycling rates vary by location, plastic type and application. Scientists estimate that only around 9 percent of all the plastic waste generated globally is recycled. Most of our plastic waste – a whopping 79 percent – ends up in landfills or in nature. Some 12 percent is incinerated.

Source: https://stories.undp.org/why-arent-we-recycling-more-plastic#:~:text=Scientists%20estimate%20that%20only%20around,Some%2012%20percent%20is%20incinerated.

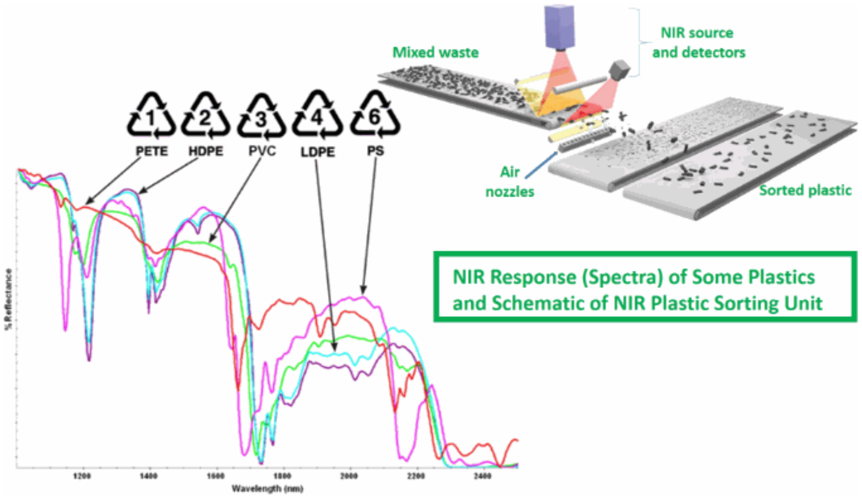
Plastic recycling: A big challenge!

- Plastics are several hundred different kinds of material that can be sorted by:
  - colours
  - shapes
  - chemical structure or a blend class
  - physical-chemical properties
  - commercial value
  - …

- HIPS and ABS black plastic wastes:
  - are 55% of the Waste of Electric and Electrical Equipment (WEEE) stream.
  - Commercial interest
- Plastic sorting optical technologies
  - Near Infrared spectroscopy

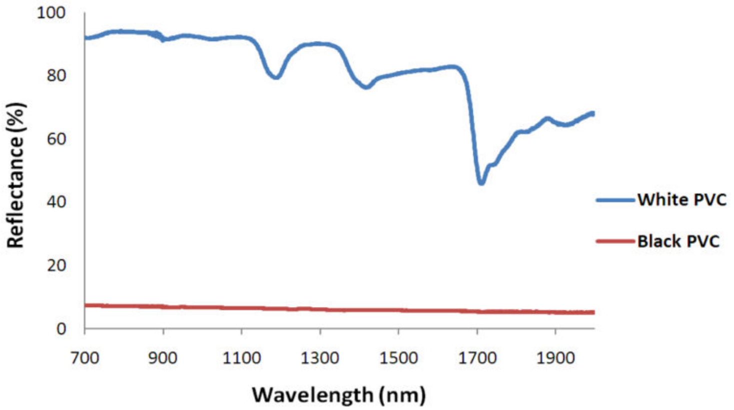
Plastic sorting optical technologies

- Near Infrared hyperspectral imaging
  - Chemical identification and/or quantification
  - Fast, versatile, and adapted
  - Non-destructive
  - Relatively cheap



https://www.oceaninsight.com/blog/spectroscopy-for-plastics-recycling/

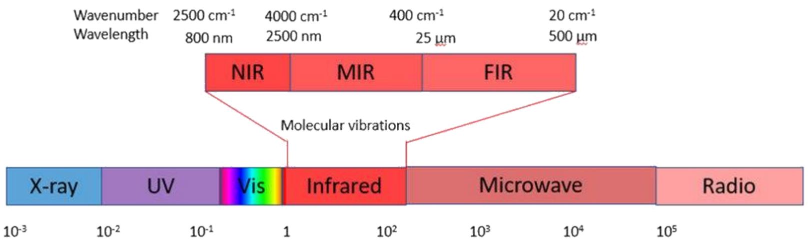
- However, it can not sort black plastic.
  - Carbon black absorbs all NIR light



World Academy of Science, Engineering and Technology International Journal of Mechanical and Mechatronics Engineering Vol:6, No:5, 2012

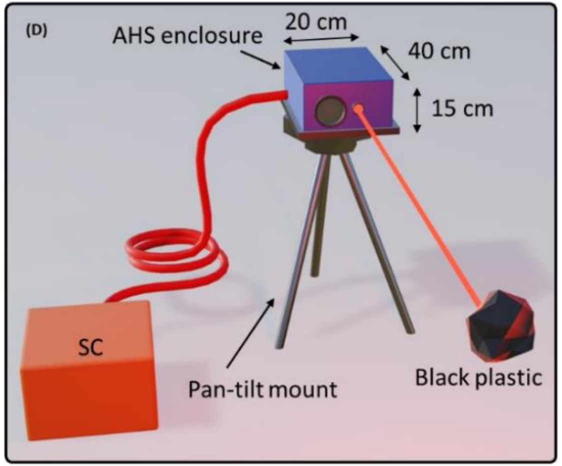
Plastic sorting optical technologies

- Mid-Infrared spectroscopy
  - It has the ability to sense black plastic

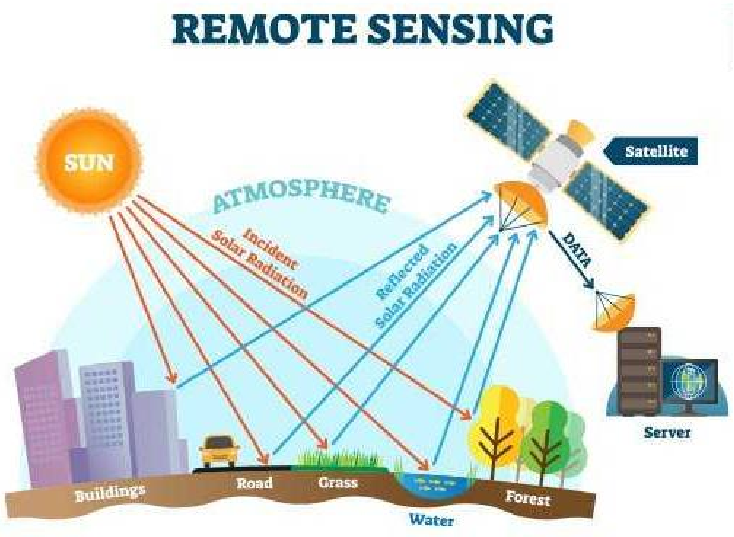


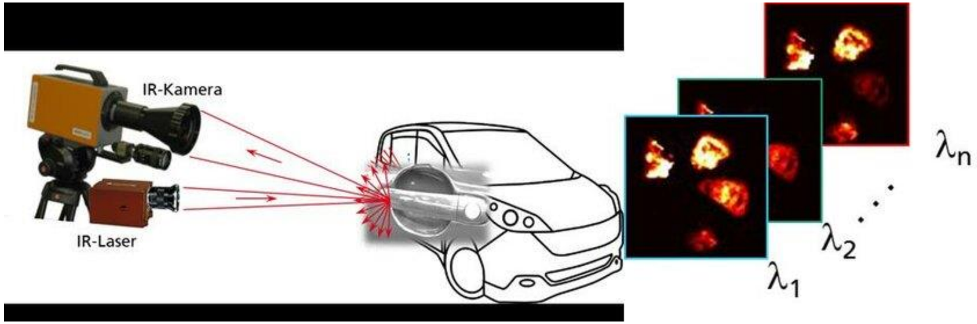
- However:
  - The traditional MIR spectroscopy (DRIFT and ATR) is limited by spectral acquisition rates.

- Solution:
  - Combining a broadband MIR light source with the VTT expertise in Active HyperSpectral (AHS) imaging technology.



Active Hyperspectral – AHS

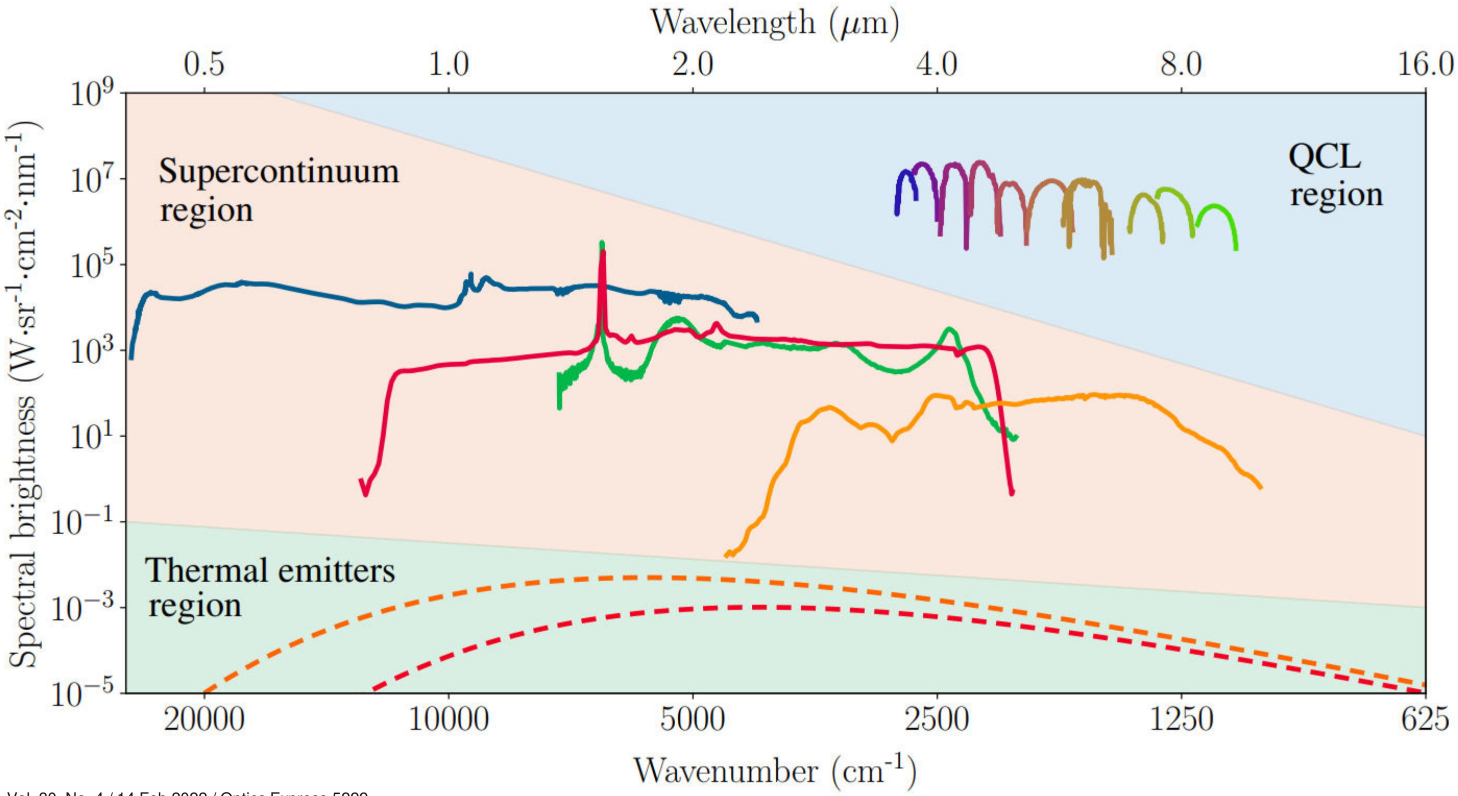




Supercontinuum Active Hyperspectral – SC-AHS

VTT

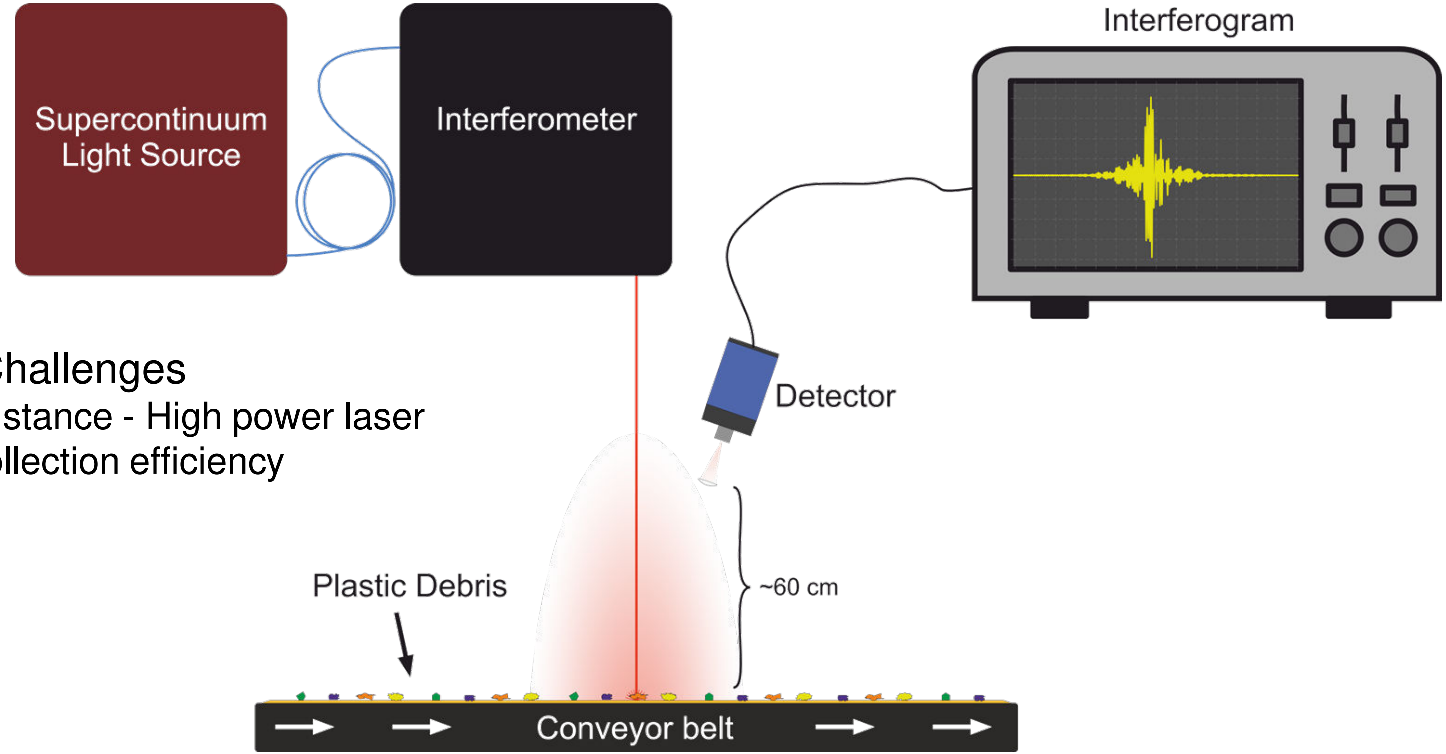
- The first challenge is to have a high-power broadband MIR light source.



Vol. 30, No. 4 / 14 Feb 2022 / Optics Express 5222

Prototype - SC-AHS

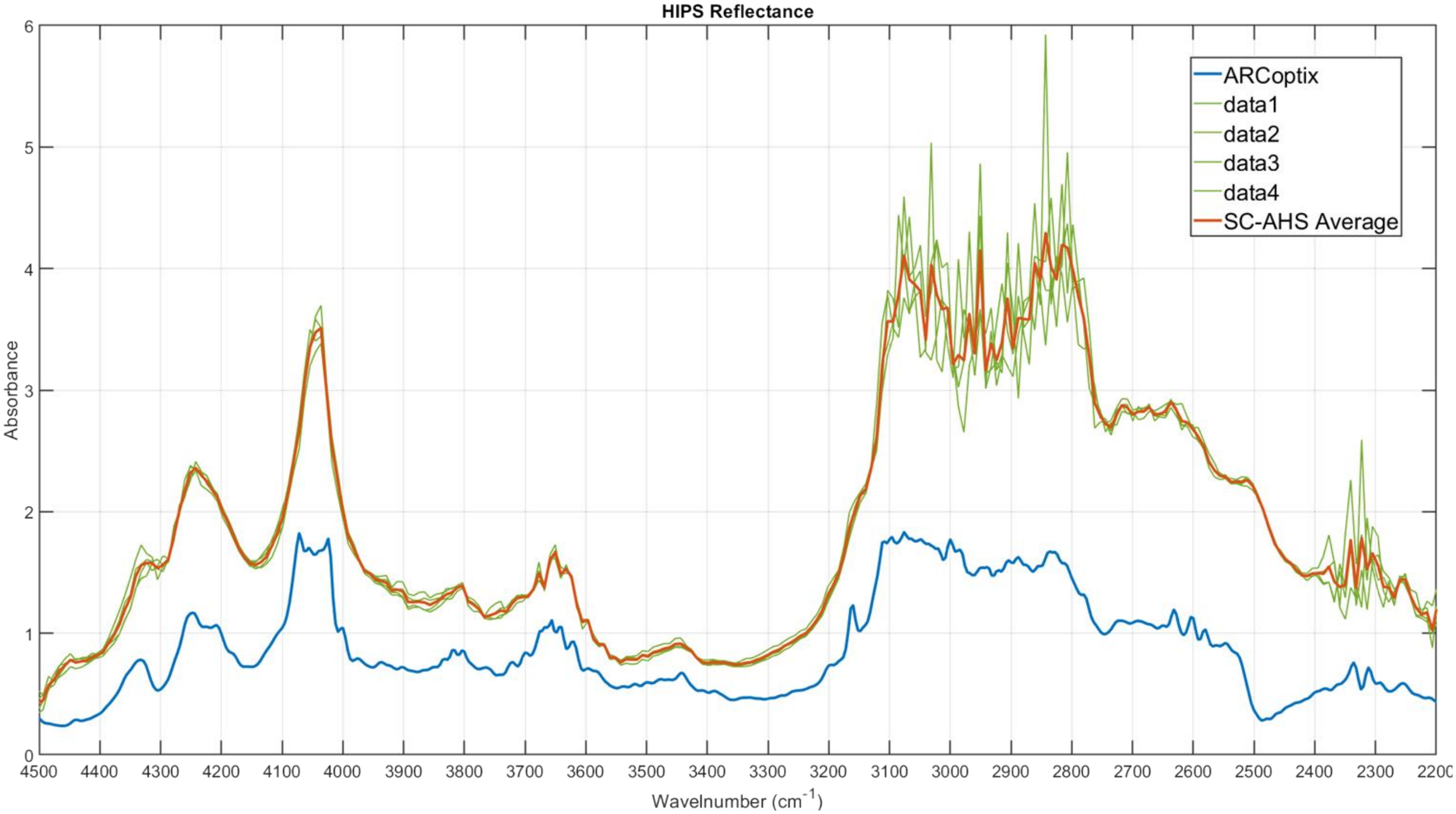
- The imaging is be made by scanning laterally while conveyor belt rolling.



- Critical points - Challenges
  - Measuring at a distance - High power laser
  - Maximize light collection efficiency
  - Fast scanning

Preliminary Results

VTT



Project Schedule

Project tasks & planned events		2024												2025											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Research tasks																									
T1	Development of benchtop system																								
T2	Evaluation of the bencthtop system																								
T3	Modification of the setup for standoff detection																								
T4	Data collection - reference samples																								
T5	Data collection - waste samples																								
T6	Classification models for polymer identification																								
T7	Demonstration																					D			
	Reporting and publications																								
Cooperation events																									
	Workshop			WS																					
	Visit											V													
	Final seminar																						S		
Dissemination																									
	Conferences									C1									C2						

Implementation of interaction and impact

- EU Horizon projects – NONTOX - finalized
  - The NONTOX project successfully deployed an AHS prototype in a pilot recycling plant with SWERIM AB, sorting WEEE plastics by brominated flame-retardant content.
  - 1.95-2.45 µm spectral range
- EU Horizon projects – PRIMUS - ongoing
  - The EU PRIMUS project aims to develop and validate a method for assessing degradation in WEEE plastics using recycled plastic from CoolR
- Current project
  - Cover the gap in black plastic sorting in recycling plants.
  - Release an AHS prototype able to be tested at VTT’s Polymer Pilot facility using a conveyor belt.

Implementation of interaction and impact

VTT

Societal and Environmental Impact:

- VTT focuses on improving recycled material quality and product value.
- Black plastics make up 15% of household plastic waste.
- Recycling challenges include hazardous substances like flame retardants.
- Current disposal methods mainly involve incineration.
- Recycling potential could reduce greenhouse gas emissions.
- Project technology aims to increase recycling rates by addressing sorting issues.
- Long-term impact expected upon implementation in recycling plants.
- Key performance indicator: Increase in recycled black plastic.

Economic Impact:

- Project outcomes focus on intellectual property rights and commercial potential.

beyond the obvious

Dr. Eduardo Maia Paiva

eduardo.maiapaiva@vtt.fi

https://www.vttresearch.com/en/ourservices/optical-spectroscopy