mirs6ns

6th International workshop on opportunities and challenges in mid-infrared laser-based gas sensing

September 9 - 11, 2025

Würzburg, Germany

book of abstracts

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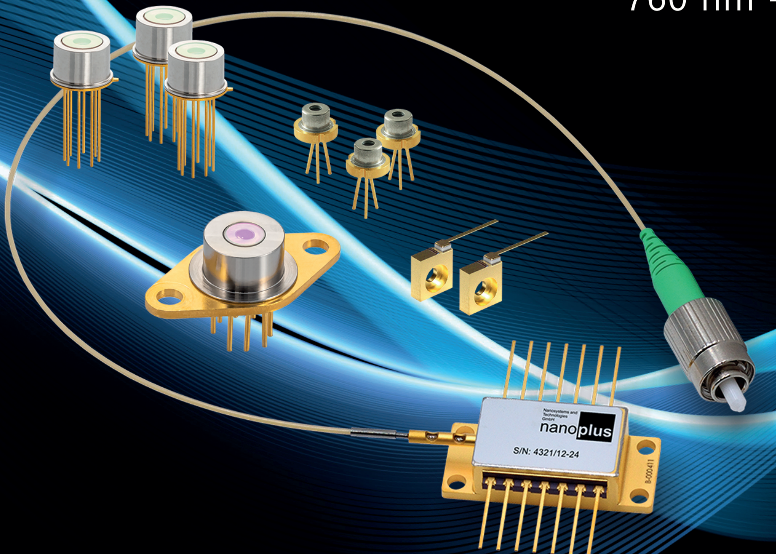
Mid-Infrared LED (MIR LED)
1750 nm - 6500 nm

Superluminescent Diodes (SLD)
760 nm - 3000 nm



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mirs6ns program

Monday, 8.09.2025

18:30 **Registration**

19:00 – 21:00 **Welcome reception at Hotel Rebstock**

Tuesday, 9.09.2025

8:30 – 9:00 **Registration and welcome coffee**

9:00 – 9:10 **Opening**

9:10 – 9:50 **Laurent Cerutti**
University of Montpellier, France
Growth and Study of Sb-based Interband Cascade Laser on GaSb, GaAs and Si Substrates

9:50 – 10:10 **Nicolas Schäfer**
nanoplus, Germany
Spectral Engineering of Interband Cascade LEDs for Sensing Applications in the MIR Spectral Range

10:10 – 10:30 **Andreas Windischhofer**
Vienna University of Technology, Austria
Efficient Simulation of ICLs via Self-Consistent Transport Modeling

10:30 – 10:50 **Anagha Kamath**
University of Würzburg, Germany
Mid-Infrared Photodetection at a 5.31 µm Cutoff Wavelength Using Ga-free InAs/InAsSb Superlattice Absorbers

10:50 – 11:10 **Coffee break**

11:10 – 11:50 **Paweł Kluczyński**
Airoptic, Poland
Mid-Infrared Tunable Laser Analyzers for Industrial Process Control and Continuous Emission Monitoring Applications

11:50 – 12:10 **Adam Polak**
Fraunhofer Centre for Applied Photonics, United Kingdom
Miniaturised Photoacustic Sensor Platform for Real-Time Detection of Environmental Tracers

12:10 – 12:30 **Matthias Bonarens**
Technical University of Darmstadt, Germany
Spatially and Temporally Resolved Emission Measurements on a Hydrogen-Fuelled Annular Combustion Chamber Test Bench

12:30 – 13:30 **Lunch**

13:30 – 14:10 **Michał Nikodem**
Wrocław University of Science and Technology, Poland
Gas Sensing Inside Hollow-Core Fibers: the Good, the Bad, and the Potential

14:10 – 14:30 **Piotr Perehiniec**
Wrocław University of Science and Technology, Poland
Anti-Resonant Hollow Core Fiber – a Useful Tool in Gas Sensing

14:30 – 14:50 **Sebastian Gryska**
Yokogawa Detuschland, Germany
A Practical Guide to Reliable Evaluation of Mid-Infrared Laser Sources for Gas Sensing

14:50 – 15:10 **Takuma Sato**
nextnano, Germany
& Technical University of Munich, Germany
Non-Equiliibrium Green's Function Modeling of Quantum Transport in Sb-based Lasers and Detectors

15:10 – 15:30 **Coffee Break**

15:30 – 16:10 **Peter Geiser**
NEO Monitors, Norway
Hydrogen TDLAS for Industrial Process Control and Safety Applications

16:10 – 16:30 **Suhita Tawade**
Uniphos Envirotronic Pvt, India
Low-Cost Embedded WMS-TDLAS Platform for Ammonia Sensing Using Ambient Water Vapor as Internal Reference

19:00 **Conference dinner at Staatlicher Hofkeller Würzburg**

Wednesday, 10.09.2025

10:00 – 10:40 **Robert Weih**
nanoplus, Germany
Interband Cascade Based Lasers and LEDs for Sensing Applications in the MIR

10:40 – 11:00 **Maeva Fagot**
University of Montpellier, France
Sb-based Interband Cascade Lasers Emitting Below 3 µm Grown on GaSb and GaAs Substrates

11:00 – 11:20 **Kamil Pierściński**
Łukasiewicz Research Network – Institute of Microelectronics and Photonics, Poland
Short-Wavelength Quantum Cascade Lasers Emitting at 3.8 µm for Mid-Infrared Detection Systems

11:20 – 11:40 **Fabian Hartmann**
University of Würzburg, Germany
Design Optimization of Resonant Cavity-Enhanced Interband Cascade Infrared Photodetectors

11:40 – 12:00 **Coffee break**

12:00 – 12:40 **Hsiang-Yu Lo**
ABB Research Center, Switzerland
Sensitive SO_2 Detection Using a QCL-based ICOS Laser Analyzer

12:40 – 13:00 **Jacek Olszewski**
VIGO Photonics, Poland & Wrocław University of Science and Technology, Poland
Design of a Mid-Infrared Ge-Suspended Membrane Waveguide Gas Sensor for CO_2 Detection at 4.26 μm

13:00 – 13:20 **Gourab Dutta Banik**
Physikalisch-Technische Bundesanstalt, Germany
Application of OF-CEAS for NH_3 Impurity Measurement in Biomethane

13:20 – 14:20 **Lunch**

14:20 – 15:00 **Vijasekhar Jayaraman**
Praevium Research Inc., USA
Wafer-Bonded Vertical-Cavity Detectors and Emitters in the Mid-Infrared

15:00 – 15:20 **Marcin Motyka**
Wrocław University of Science and Technology, Poland
High Contrast Gratings for Infrared Electrode with Exceptionally High Conductivity and Transmission in Mid-Infrared Photonics

15:20 – 15:40 **Mikołaj Badura**
Wrocław University of Science and Technology, Poland
Plasmon-Enhanced InP DBRs for Next-Generation Mid-Infrared VCSELs

15:40 – 16:00 **Lorenz Schnegg**
Vienna University of Technology, Austria
Linearity and Saturation Behavior of Interband Cascade Infrared Photodetectors (ICIP) with Gallium-Free Absorber

16:00 – 16:20 **Coffee break**

16:20 – 18:00 **Lab tours**

19:00 – 20:00 **Guided city tour with the Würzburg night watchman**

Thursday, 11.09.2025

9:30 – 10:10	**Marek Vlk** UiT the Arctic University of Norway, Norway *Gas Sensing with MIR Waveguides at The Arctic University of Norway*
10:10 – 10:30	**Bartosz Kamiński** Airoptic, Poland & Wrocław University of Science and Technology, Poland *High Pressure Optical Gas Sensing in Industrial Conditions – Machine Learning Approach for Concentration Prediction*
10:30 – 10:50	**Przemysław Chmielowski** Wrocław University of Science and Technology, Poland *Laser-Base Gas Sensing – Simplifying and Speeding Data Analysis Using Neural Networks*
10:50 – 11:10	**Coffee break**
11:10 – 11:50	**Borislav Hinkov** Silicon Austria Labs, Austria *(M)IR Photonic Integrated Circuits for QKD-Based Telecom and On-Chip Sensing Appllications*
11:50 – 12:10	**Ryszard Piramidowicz** VIGO Photonics, Poland & Warsaw University of Technology & LightHouse, Poland *MIRPIC – Mid-IR Photonic Integrated Circuits for Gas Sensing Applications*
12:10 – 12:30	**Stanisław Stopiński** VIGO Photonics, Poland & Warsaw University of Technology & LightHouse, Poland *Development of the MIRPIC Process Design Kit*
12:30 – 12:50	**Tristan Smołka** Wrocław University of Science and Technology, Poland *Tunable Bandgap and Ultrafast Carrier Dynamics in Dilute-Bismide III–V Alloys for Mid-Infrared Photonics*

12:50 – 13:50 **Lunch**

13:50 – 14:30 **Frédéric Grillot**
Laval University, Canada
Advancement in Mid-Infrared Optoelectronics for Free-Space Optical Applications

14:30 – 14:50 **Johannes Fuchsberger**
Vienna University of Technology, Austria
Continously and Widely Tunable Ring Array Lasers Based on QCL and ICL Material

14:50 – 15:10 **Andreas Bader**
nanoplus, Germany
GaInAsSb and Type-II Superlattice Based Photodetectors for Sensing Applications in the eSWIR and MIR Spectral Range

15:10 – 15:20 **Closing remarks**

15:20 – 17:00 **Lab tours**

the abstracts

Growth and Study of Sb-based Interband Cascade Laser on GaSb, GaAs and Si Substrates

M. Fagot,[1,] D. A. Diaz-Thomas,[1] J. Goutorbe,[1] Y. Rouillard,[1] J.-B. Rodriguez,[1] E. Tournié[1,2] and L. Cerutti[1,*]

[1]*IES, University of Montpellier, CNRS, F-34000 Montpellier, France*
[2]*Institut Universitaire de France (IUF), F-75005 Paris, France*

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Type-II quantum well (QW) interband cascade lasers (ICLs) have emerged as the most efficient laser sources in the mid-infrared (MIR) spectral range, especially between 3 and 6 µm. However, their widespread adoption in commercial applications, such as trace gas detection and industrial process monitoring, is hindered by the use of small, expensive native substrates. A promising solution lies in the growth of ICLs on cost-effective, large-sized mismatched substrates like Si or GaAs. This approach could significantly reduce production costs while enabling the integration of high-performance MIR lasers and photonic sensors with silicon-based photonic integrated circuits (PICs).

We have successfully demonstrated the fabrication of ICLs emitting in the 3 - 5 µm range, grown on both GaAs and Si substrates. Despite the presence of high threading dislocation densities, all devices exhibited performance comparable to those grown on native substrates and showed long device lifetimes. These results suggest that the active region designs based on type-II QWs may possess an inherent tolerance to dislocations, an important advantage for developing low-cost ICLs and enabling the fabrication of optical gas sensors on Si PICs.

This work was partially funded by France 2030 program (EquipEx EXTRA (ANR-11-EQPX-0016), and HYBAT (ANR-21-ESRE-0026)), the French Occitanie Region (LASIDO project), the French Agency for Defense and Innovation (AID-DGA), the Banque Publique d'Investissement (Hyquality Project DOS0188007/00) and the Air Force Office of Scientific Research under award number FA8655-24-1-7038.

Spectral Engineering of Interband Cascade LEDs for sensing applications in the MIR spectral range

N. Schäfer [1], **R. Weih** [1], **J. Koeth** [1] **and S. Höfling** [2]

[1] *nanoplus Advanced Photonics Gerbrunn GmbH, 97218 Gerbrunn, Germany*
[2] *Julius-Maximilians-Universität Würzburg, Physikalisches Institut, Lehrstuhl für Technische Physik, 97074 Würzburg, Germany*

Interband cascade light-emitting diodes (ICLEDs) offer versatile mid-infrared emission with significant potential for spectroscopic applications. We present advanced strategies to precisely engineer their emission spectra, achieving both spectral narrowing and broadening, alongside dual-wavelength operation for enhanced application-specific customization.

Spectral narrowing was realized by converting ICLEDs into resonant-cavity LEDs (RCLEDs) through the integration of a metal mirror on the top surface and a distributed Bragg reflector (DBR) beneath the active region. The active region is thus embedded within a resonant cavity, enhancing spectral selectivity. Flip-chip mounting provides mechanical stability and supports high output power. Spectral tuning towards longer wavelengths was further enabled by depositing a refractive index-matched layer, such as silicon, prior to mirror deposition. By selectively coating half of a split mesa device, dual-wavelength RCLEDs were fabricated, enabling one emission line to serve as a stable reference channel for spectroscopic measurements.

For spectral broadening, molecular beam epitaxy (MBE) was used to engineer active regions comprising quantum wells (QWs) with systematically varied thicknesses. Since the emission wavelength scales with QW thickness, stacking wells with staggered emission energies produced broad or multi-peaked spectra.

Collectively, these advancements position ICLEDs as highly adaptable mid-infrared sources for gas and liquid spectroscopy, paving the way for compact, efficient, and tunable systems suitable for practical analytical uses.

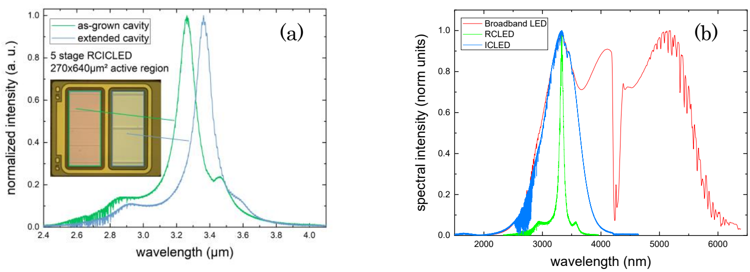


Fig. 1. Two spectrally separated and narrow peaks of a dual-wavelength RCICLED (a). Spectral emission of an ICLED, RCICLED and broadband ICLED demonstrating the customizability of these MIR light sources (b).

Efficient Simulation of ICLs via Self-Consistent Transport Modeling

Andreas Windischhofer, **Nikola Opačak**, **Benedikt Schwarz**

Institute of Solid State Electronics, TU Wien, Gußhausstraße 25a, 1040, Vienna, Austria

Interband cascade lasers (ICLs) are mid-infrared semiconductor lasers that utilize interband transitions to achieve efficient lasing with low threshold currents. Significant performance improvements have been achieved in recent years. These improvements have been driven by technological advances and design refinements informed by experimental and phenomenological observations.

To further optimise ICLs, we have developed a modelling framework dedicated to accurately simulating carrier transport in both the conduction and valence bands. This provides detailed insights into internal device mechanics and supports predictive performance analysis.

Our approach builds on established modelling strategies from quantum cascade lasers (QCLs) [1], aiming at a balance between computational efficiency and physical accuracy. The outcome is a self-consistent, k-space-resolved density matrix rate equation model, as depicted in Figure 1 [2]. This tool is fast enough for practical device optimisation, yet still captures key transport phenomena in ICLs.

A crucial element of ICLs that is absent from QCLs is the semi-metallic interface. Therefore, special focus was required during development. While a first order model has proven to give reasonable results in QCLs, it does not hold in ICLs due to the opposing curvature of the subbands. To circumvent the problems arising from the momentum-conservative approach of the first order, we implemented an effective first-order model that uses an energy-conserving rate. However, we conducted further investigations to gain a more complete and accurate understanding of tunnelling. We will present the challenges of accurately modelling the SMIF in the tight-binding framework and its impact on the correct carrier transport characteristics of ICLs. Building on our newly gained understanding, we will present design suggestions for an improved onset voltage. This could lead to a new generation high-power ICLs.

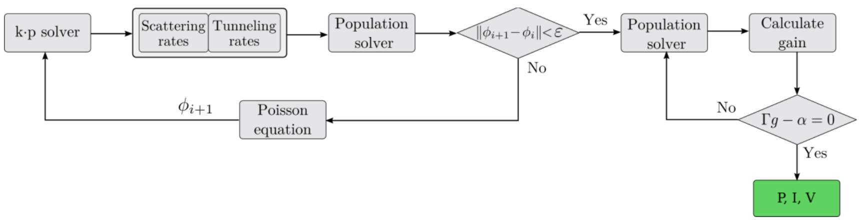


Figure 1: The flowchart of the simulation framework used in the presented work. After [2].

[1] R. Terazzi, J. Faist, New J. Phys. **12**, 033045 (2010).
[2] A. Windischhofer, N. Opačak, B.Schwarz, Laser Photonics Rev **19**, 2400866 (2025).

Mid-infrared photodetection at a 5.31 μm cutoff wavelength using Ga-free InAs/InAsSb superlattice absorbers

A. Kamath[1*], B. Petrović[1], A. Bader[2], S. Krüger[1], R. Weih[2], S. Höfling[1], and F. Hartmann[1]

[1] *Julius-Maximilians-Universität Würzburg, Lehrstuhl für Technische Physik, Am Hubland 97074 Würzburg, Germany*

[2] *nanoplus Advanced Photonics Gerbrunn GmbH, Oberer Kirschberg 4, Gerbrunn, Germany*

The performance of InAs/GaSb type-II superlattice (SL) based mid-infrared photodetectors is often limited by Ga-related point defects in conventional absorbers, which act as Shockley-Read-Hall recombination centers and degrade device efficiency[1]. To address this, we explore Ga-free InAs/$InAs_{1-x}Sb_x$ SL absorbers, enabling reduced defect densities, longer diffusion lengths, and improved transport properties for next-generation infrared detection[2].

These SLs offer great flexibility in tuning the bandgap energy for targeted mid-infrared applications. Simulations performed using nextnano3 software reveal that the cutoff wavelength of strain-compensated InAs/$InAs_{1-x}Sb_x$ SLs strongly depends on both Sb composition and SL period, as shown in Fig. 1[3]. For gas-sensing applications, such as detecting carbon monoxide (CO) with an absorption feature near 4.482 µm, a cutoff wavelength of 5.3–5.5 µm is desirable. The simulations show that $InAs_{0.75}Sb_{0.25}$ with a period of 5-6 nm meets this requirement.

Based on these parameters, three samples with different SL periods were grown on n-GaSb substrates using molecular-beam epitaxy, at a substrate temperature of 450 °C. High-resolution X-ray diffraction measurements verified the designed periodicity and confirmed successful strain compensation. Figure 2 shows room-temperature photoluminescence (RT-PL) for the samples with 4.86, 5.45, and 6.00 nm SL periods. All the samples demonstrate photoluminescence emission near 5.31 µm, consistent with simulations and suitable for gas-sensing. The RT- PL indicates efficient radiative recombination, highlighting the good optical quality of the grown SLs.

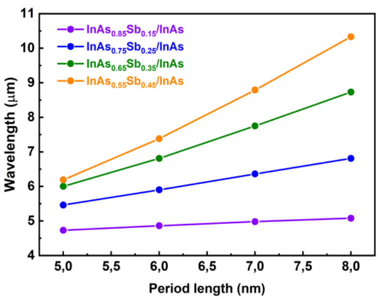


Figure 1: Nextnano simulation showing cutoff wavelengths for different compositions, and period of InAs/$InAs_{1-x}Sb_x$ superlattices.

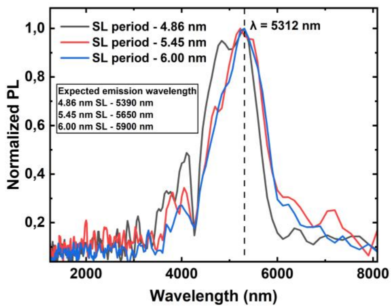


Figure 2: RT-PL showing emission near 5.31 µm for different SL periods.

[1] Klein, B., et al, J. Vac. Sci.Technol. B 32, 02C101 (2014).
[2] Bader, A., et al, Applied Physics Letters 121.4 (2022).
[3] Trellakis, A. et al, Journ. Comput. Electron. 5(4), 285–289 (2006)

Tunable laser analyzers for sulfur recovery applications

Pawel Kluczynski

Airoptic Sp. z o.o., ul. Rubiez 46B, 61-612 Poznan, Poland

Since introduction of the multi-laser in-situ tunable laser analyzer in 2018, the analyzers have been proven in various industrial applications with cumulative operating hours reaching several million. The analyzer was designed for continuous operation in harsh industrial environment to withstand high dust, high temperature conditions, with the capability of incorporating different laser sources from bandgap lasers in near infrared region to interband cascade lasers in mid infrared region.

Tunable laser analyzer gas analyzers have been successfully proven in many demanding process control applications [1],[2]. In this paper we present two types of tunable laser analyzers for sulfur recovery unit (SRU) applications. First type is an in-situ GasEye air demand analyzer with one second response time and immunity to atomic sulfur interferences thanks to application of mid-IR technology. It has been deployed at a refinery in Sweden and operates in a closed loop for process control. Comparison with existing UV analyzer has been performed. It is a first to our knowledge report of an in-situ laser analyzer for this application. The second analyzer presented here is a tunable laser SRU CEM hot wet extractive analyzer for monitoring of NO/NO2/SO2 and O2 in a SRU stack. The system has been deployed at a refinery in the Middle East in 2022. Results of the test are presented.

Both analyzers operate in a continuous mode and thanks to built-in autocalibration feature the analyzers require very little maintenance.

REFERENCES

[1] Krzysztof Siembab, Jakub Kaczmarek and Pawel Kluczynski "Multi-laser tunable laser analyzer for trace level determination of impurities in complex hydrocarbon backgrounds and hydrogen" CEM India 2024, New Delhi (2024)

[2] Pawel Kluczynski "In-situ multi-laser total solution analyzers prove to reduce customer TCO by integrating advanced technique", ATC, Galveston, USA (2022)

Miniaturised Photoacoustic Sensor Platform for Real-Time Detection of Environmental Tracers

A. Polak, J. Feehan, J. Leck and D. Stothard

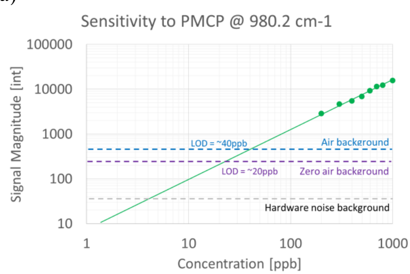
Fraunhofer Centre for Applied Photonics, 99 George Street, G1 1RD Glasgow, UK

We present a miniaturised prototype platform for an ultra-sensitive, point-sample "sniffing" technology designed for the real-time detection of environmental tracer gases. The detection method is based on photoacoustic spectroscopy (PAS), in which modulated mid-infrared light is absorbed by gas molecules, producing periodic pressure variations that are detected acoustically. A broadly tunable external-cavity quantum cascade laser (EC-QCL) serves as the excitation source, enabling access to a spectral range of approximately 200 cm^{-1} and allowing the interrogation of multiple gases with a single instrument.

To enhance sensitivity, a multipass optical cell was integrated within an acoustic resonator, forming an enhanced detection module. This configuration increases both the optical interaction length and acoustic signal strength while maintaining low optical losses. The system achieved detection limits of 20 ppb for perfluoromethylcyclopentane (PMCP - Fig 1(a)) and 20 ppb for perfluoromethylcyclohexane (PMCH).

A semi-ruggedized, handheld demonstrator (7.7 kg, <12.8 dm^3) was built (Fig 1(b)), highlighting the feasibility of deploying this technology in portable field applications. The results underscore the potential of PAS enhanced by optical-acoustic co-design in compact and selective gas sensing.

a)



b)

Fig 1. (a) Sensitivity characteristic to PMCP on 980.2cm^{-1} line; (b) photograph of the final prototype

Acknowledgments: The authors acknowledge financial support from UK Defence Science and Technology Laboratory.

Spatially and temporally resolved emission measurements on a hydrogen-fuelled annular combustion chamber test bench

L. Schuhmann[1], M. Bonarens[1], A. Fischer [2], M. Staufer[2], A. Dreizler[1], and S. Wagner[1]

[1] *Technical University of Darmstadt, Department of Mechanical Engineering, Reactive Flows and Diagnostics, Darmstadt, Germany*
[2] *Rolls-Royce Deutschland Ltd & Co KG, Blankenfelde-Mahlow, Germany*

The transition from carbon-based fuels to hydrogen significantly influences key design parameters of gas turbine combustion chambers. In particular, the reduction of pollutant emissions in the exhaust gases requires optimized design and robust control of the process, especially during transient operation. For these purposes, reliable experimental data on NOx emissions are indispensable. Established chemiluminescence-based measurement systems require regular calibration and are demanding in terms of operation and maintenance. A robust, flexible and calibration-free alternative is tunable diode laser absorption spectroscopy (TDLAS).

In this presentation, results from spatially resolved, extractive TDLAS measurements of NO and NO_2 concentrations in exhaust gases from a hydrogen-fueled full-ring combustion chamber are presented. A compact white-cell, customized for measurements under harsh conditions [1], is used for the measurements. NO transitions at 5184 nm and NO_2 transitions at 3425 nm are probed utilizing nanoplus lasers. The acquired transmission spectra are evaluated using spectroscopic fits, including a comprehensive uncertainty estimation [2]. The results are compared with those of the conventional instrumentation at the test rig (EcoPhysics nCLD 822Mhr).

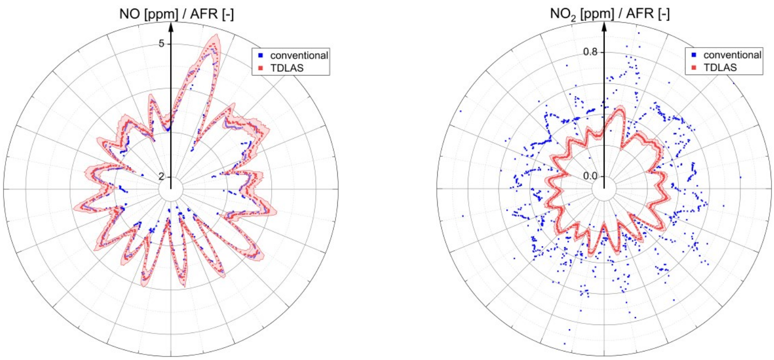


Fig. 1: Results of extractive measurements of NO and NO_2 mole fractions. Samples were taken using a circumferentially traversable probe to measure the gas composition downstream of the 16 injectors.

[1] Schuhmann, L., et al. "Robust optical measurement cell for sensitive in-situ characterization of reactive gas flows." Applied Optics 64.13 (2025): 3447-3455.

[2] Bonarens, M. et al. "A Bayesian framework for incorporating line data uncertainties into the evaluation of TDLAS traces using spectroscopic fits." Journal of Quantitative Spectroscopy and Radiative Transfer (2025).

Gas Sensing inside Hollow-Core Fibers: the Good, the Bad, and the Potential

Michał Nikodem[1], **Piotr Perehiniec**[1], **Patrycja Gronowicz**[1], **Ryszard Buczyński**[2],

[1] *Wrocław University of Science and Technology, Wrocław, Poland*
[2] *Institute of Microelectronics and Photonics, Warsaw and University of Warsaw, Poland*

Laser-based spectroscopy in the infrared spectral region is a useful tool for chemical detection and trace-gas sensing. Although various techniques have been proposed over the past few decades, tunable diode laser absorption spectroscopy (TDLAS) and its derivative, wavelength modulation spectroscopy (WMS), remain the most widely used methods for environmental monitoring and industrial process control. A conventional way to enhance sensitivity in TDLAS or WMS is to increase the optical path length, typically achieved by incorporating multi-pass gas cells into the sensing setup. While this approach is effective, multi-pass cells tend to be bulky, alignment-sensitive, and susceptible to mechanical drift.

Hollow-core fibers (HCFs) can be used as an alternative to multi-pass cells. When coiled, HCFs can serve as compact, low-volume gas cells that maintain long interaction lengths between light and gas. Among the various types, antiresonant hollow-core fibers (ARHCFs) have attracted growing interest in spectroscopic applications [1]. Their broad transmission windows (extending into the mid-infrared even with silica-based materials) along with large core diameters and strong suppression of higher-order modes make them particularly well-suited for laser-based sensing.

In this presentation, we will explore the good, the bad, and the potential of gas sensing inside hollow-core fibers. We will highlight the advantages ARHCFs offer in terms of miniaturization, broad spectral coverage, and fiber integration [2, 3]. We will also address key challenges such as gas filling dynamics, optical losses, and coupling efficiency. Finally, we will present recent experimental results that showcase the unique capabilities of ARHCFs that could enable new classes of compact, high-performance gas sensors not easily achievable with traditional approaches [4, 5].

[1] M. Nikodem, "Laser-Based trace gas detection inside hollow-core fibers: A review," Materials 13, 3983 (2020).
[2] M. Nikodem, G. Gomółka, M. Klimczak, D. Pysz, and R. Buczyński, "Demonstration of mid-infrared gas sensing using an anti-resonant hollow core fiber and a quantum cascade laser," Optics Express 27, 36350-36357 (2019).
[3] G. Gomółka, G. Stępniewski, D. Pysz, R. Buczyński, M. Klimczak, and M. Nikodem, "Highly sensitive methane detection using a mid-infrared interband cascade laser and an anti-resonant hollow-core fiber," Optics Express 31, 3685-3697 (2023).
[4] G. Gomółka, D. Pysz, R. Buczyński, and M. Nikodem, "Dual-Pass Hollow-Core Fiber Gas Spectroscopy Using a Reflective Configuration With Heterodyne-Based Signal Detection," Journal of Lightwave Technology 41, 6094-6101 (2023).
[5] P. Gronowicz, G. Gomolka, D. Pysz, R. Buczynski, and M. Nikodem, "Demonstration of a compact reflective gas sensing probe based on negative-curvature hollow-core fiber," Applied Optics 64, 5624-5631 (2025).

Acknowledgements: this work was is supported by the Ministry of Science end Education, Poland: 'Doktorat Wdrozeniowy' DWD/6/0556/2022.

Anti-resonant hollow core fiber – a useful tool in gas sensing

Piotr Perehiniec[1], Patrycja Gronowicz[1], Ryszard Buczyński[2], Michał Nikodem[1]

[1] *Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Institute of Microelectronics and Photonics, Warsaw and University of Warsaw, Poland*

In recent years, ARHCFs (Anti-Resonant Hollow Core Fibers) have attracted significant interest. While primary potential application of ARHCFs is optical telecommunication, they also have been demonstrated to be useful in optical sensing, particularly gas sensing via laser absorption spectroscopy. In such systems, light passes through a region containing molecules of unknown concentration. As the light reaches the detector, an absorption spectrum is recorded, from which the molecular concentration can be determined using Beer–Lambert's law. The basic setup typically includes a light source, a gas cell, and a detector. Traditionally, the gas cell is a bulky glass chamber, often equipped with internal mirrors to form a multi-pass cell that increases the effective sensing path length. Recently, ARHCFs have been proposed as a compact alternative to conventional gas cells [1].

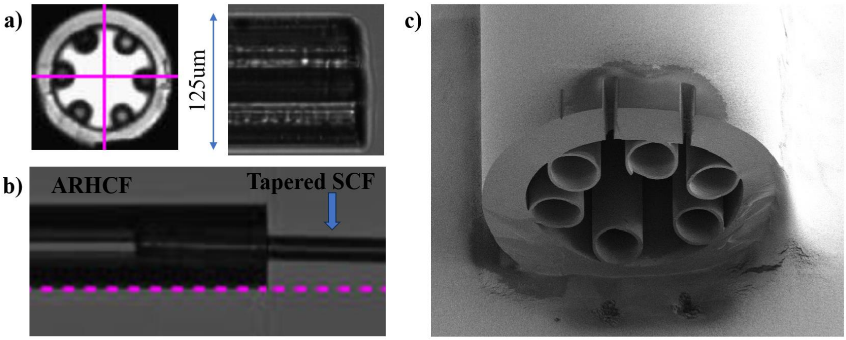


Fig. 1 (a) pictures of the ARHCF taken with a microscope (front and side view); (b) picture of the ARHCF with a tapered solid-core fiber (SCF) that is inserted into the hollow core to serve as a mirror; (c) SEM picture of the ARHCF with side holes drilled using focused ion beam (FIB).

During the conference we will present how ARHCFs can be used in laser-based gas detection, using near- or mid-infrared source. We will demonstrate how sensing setup may benefit from adding modifications to the optical fibers. This includes microdrilling that enables gas flow through side hole in the ARHCF or modifying the ARHCF end to construct a reflective sensing probe, similar to demonstrated in [2].

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A Practical Guide to Reliable Evaluation of Mid-Infrared Laser Sources for Gas Sensing

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Precise characterization of mid-infrared (MIR) laser sources is essential for advancing gas sensing technologies. This presentation outlines a practical workflow addressing the differing evaluation requirements for broadband and narrowband sources and guides the selection of suitable measurement methods - highlighting the trade-offs between optical spectrum analyzers and interferometer-based systems. Common measurement challenges are discussed, including limited dynamic range, artefacts such as ghosting and straylight, and the influence of ambient gases and water vapor. Special emphasis is placed on pulsed laser sources, where timing alignment and detector bandwidth critically impact measurement accuracy. Based on extensive hands-on experience, we present best practices for optimizing test setups, mitigating measurement artefacts, and interpreting results to achieve reliable, reproducible, and application-relevant MIR laser characterization.

Non-Equilibrium Green's Function Modeling of Quantum Transport in Sbbased lasers and detectors

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Several design guidelines for the recombination region of interband cascade lasers (ICLs) have been proposed by 8-band **k·p** Schrödinger-Poisson modeling and confirmed experimentally [1]. This equilibrium modeling, however, does not allow for a quantitative suggestion as to the doping profile and the number of wells in the carrier injector regions in pursuit of reducing threshold current and efficiency droops for further ICL optimization. This will be possible by non-equilibrium carrier transport simulations beyond the Fermi-Dirac carrier statistics. Windischhofer et al. [2] proposed an incoherent rate-equation approach combined with tunneling rates calculated by the density-matrix method. While being numerically efficient, it has not successfully reproduced the threshold currents for varying doping concentration in the electron injector, despite the adjustment of phenomenological simulation input parameters.

The non-equilibrium Green's function (NEGF) formalism allows us to solve quantum tunneling transport in the presence of scattering. Unlike semiclassical methods, it monitors not only the evolution of the state occupation but also the coherence among those states from first principles. We have extended the nextnano.NEGF software, a NEGF quantum transport simulator [3], for interband devices. Specifically, we developed a scheme to construct a modespace NEGF basis [4] from selected solution of an 8-band **k·p** Hamiltonian. Smaller matrices speed up the Dyson-Keldysh iteration in comparison to the formalism with atom-scale real space resolution [5,6]. The optical gain spectrum is calculated by Fermi's golden rule using the NEGF level occupations and multiband momentum operator generalized for arbitrary light polarizations.

First, assuming a quasi-equilibrium (i.e., Fermi-Dirac) distribution of carriers, we apply our interband NEGF model to calculate the threshold carrier densities for various ICL injector designs [7]. Here, the quasi-Fermi levels are assumed constant within the electron and hole injectors, and their splitting is set equal to the potential drop per period. Second, we lift the quasi-equilibrium assumption and simulate non-equilibrium tunneling transport in type-II superlattices under illumination as well as ICLs up to the lasing threshold.

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Hydrogen TDLAS for Industrial Process Control and Safety Applications

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NEO Monitors AS, Skedsmokorset, Norway

Governments around the world are setting increasingly ambitious decarbonization targets to combat the adverse effects of climate change. Achieving these goals requires a multifaceted approach: improving energy efficiency, adopting carbon-free fuels, reducing fugitive greenhouse gas emissions, and significantly expanding electrification through renewable energy sources such as wind, solar, and hydropower.

Hydrogen has played a long-standing role in industrial processes – including petrochemical hydrogenation, ammonia production, and semiconductor manufacturing. In recent years, its potential as a clean, carbon-free energy carrier has generated renewed global interest. This shift is accelerating efforts to reduce reliance on fossil fuels and transition to more sustainable, renewable energy systems.

As renewable energy adoption and carbon-neutral industrial practices gain momentum, existing production processes will need to be upgraded or replaced. In this context, sensitive and accurate gas analyzers are becoming increasingly important. They support process optimization, emissions control, and operational safety in modern, energy-intensive industries.

Among these technologies, Tunable Diode Laser Absorption Spectroscopy (TDLAS) has emerged as a particularly valuable solution, offering rapid response times, high selectivity and sensitivity, and robust long-term reliability.

TDLAS technology delivers several critical benefits: enabling real-time process control that reduces fuel consumption, minimizing fugitive emissions through accurate leak detection and quantification, and ensuring safety by continuously monitoring hazardous conditions. Thanks to its versatility and performance, TDLAS is well-positioned to play a central role in advancing industrial decarbonization efforts while maintaining high safety and efficiency standards.

We will showcase state-of-the-art TDLAS applications for hydrogen measurement in support of the rapidly growing hydrogen economy. This includes solutions for safety monitoring, hydrogen blending with natural gas to lower carbon intensity, and the detection of impurities in hydrogen streams to ensure quality and compliance.

Low-Cost Embedded WMS-TDLAS Platform for Ammonia Sensing Using Ambient Water Vapor as Internal Reference

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Ammonia (NH_3) monitoring plays a crucial role in industrial emission control and environmental safety. In this work, we present a compact, low-cost wavelength Modulation Spectroscopy-based Tunable Diode Laser Absorption Spectroscopy (WMS-TDLAS) platform targeting NH_3 detection near 1512 nm, with sensitivity down to 1 ppm. The system leverages a commercially available 1512 nm DFB laser, a custom-designed 2-meter multi-pass absorption cell, and a InGaAs photodetector. Signal demodulation is performed using a lockin amplifier implemented entirely on an STM32H7 microcontroller, eliminating the need for external processing hardware.

A key innovation of this system is the use of ambient water vapor as an internal wavelength reference, thereby removing the need for a dedicated gas reference cell. The laser is line-locked by calculating the difference between the location of NH_3 line and a nearby H_2O absorption line, which remains invariant under stable environmental conditions. This embedded locking mechanism ensures long-term wavelength stability while simplifying the optical layout.

The system was evaluated using NH_3 gas samples, achieving a minimum detection limit of 1 ppm with high signal-to-noise ratio and baseline stability. While this implementation operates in the near-infrared (NIR) region, the system architecture is wavelength-agnostic and can be readily adapted to mid-infrared (MIR) sensing by substituting suitable laser and detector components, offering a scalable pathway to low-cost, highperformance gas analyzers.

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Interband Cascade based Lasers and LEDs for Sensing Applications in the MIR

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The 6.1 Å semiconductor family represented by the binaries GaSb, InAs and AlSb forms a versatile platform for band structure engineering within the mid infrared (MIR) spectral region. Alloys made of these compositions can cover a wide range of bandgaps and still have a very similar lattice constant. Additionally, the broken bandgap alignment between GaSb and InAs allows electron and hole generation at a so-called semi-metal interface which is utilized for cascading of active quantum wells in interband cascade lasers (ICLs) and interband cascade light emitting diodes (ICLEDs). The ICL concept was first proposed in 1995 [1] and room temperature cw operation for ICLs was first achieved in 2008 [2]. In the following year several design optimizations like the carrier rebalancing concept [3] and the mitigation of intervalence band absorption [4] have led to significant improvements in performance and meanwhile the wavelength range between 2.7 and 6.2µm is accessible with RT cw performance and DFB lasers have been realized in this entire wavelength range. Implementing all these design improvements enabled us to achieve a record low electrical threshold power of less than 10mW with a 3 stage ICL design. At a driving current of 50 mA the laser is still emitting more than 4mW as can be seen in the LIV curve in Figure 1. For most spectroscopic applications this output power level is sufficient, and battery driven devices will benefit from low power dissipation levels.

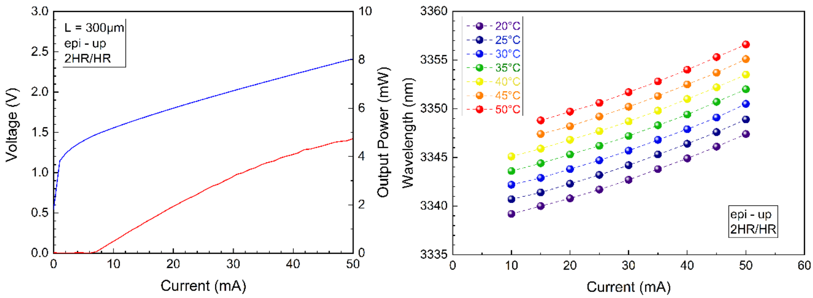

Figure 1 (left) cw light-current-voltage curves of epi-up mounted 300µm long DFB ICL at 3.35µm and an operation temperature of 20°C. (right) Emission wavelength tuning of DFB ICL with heatsink temperature and driving current.

The emission wavelength lies in the fingerprint region of many hydrocarbons around 3345nm. Due to its small active volume the emission wavelength can be tuned over more than 15nm by changing the operation temperature and the driving current of the laser. Tuning rates of 0.30 nm/°C and 0.21 nm/mA were extracted. The corresponding tuning diagram is shown in Figure 1. Based on the same band structure ICLEDs are versatile mid-infrared light sources with significant potential for spectroscopic applications. Within the talk advanced techniques to engineer their emission spectrum, achieving both spectral narrowing and broadening will be discussed. To narrow the spectral emission, ICLEDs were transformed into resonant-cavity LEDs (RCLEDs). This was accomplished by integrating a metal mirror on the top side and a distributed Bragg reflector (DBR) on the bottom, with the active region sandwiched in between.

For spectral broadening, active regions with quantum wells (QWs) of varying thicknesses were designed and grown using molecular beam epitaxy (MBE). The emission wavelength of each QW is dictated by its thickness, enabling precise control of the spectral output. By arranging QWs with overlapping or distinct emission points, devices with broad or multi-peak spectra were realized.

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Sb-based Interband cascade lasers emitting below 3 µm grown on GaSb and GaAs substrates

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Type-II interband cascade lasers (ICLs) are the leading laser sources in the 3–6 µm spectral range, while type-I diode lasers dominate below 3 µm. However, beyond 2.5 µm, diode lasers (DLs) suffer from increased internal losses and Auger recombination, drastically increasing threshold current density [1]. Although GaSb-based DLs grown on Si have shown promising threshold currents [2], their reliability remains limited. In contrast, ICLs are tolerant to dislocations within their operating range [3,4] and offer extrapolated mean time to failure (MTTF) exceeding 35 years. While most efforts have targeted longer wavelengths [5], the potential of ICLs below 3 µm remains largely unexplored. Extending operation into this range could close the performance gap between 2.5 and 3 µm and enhance mid-IR laser technology.

This work presents recent results on type-II ICLs emitting at 2.7 µm, grown by molecular beam epitaxy (MBE) on both GaSb and GaAs substrates. Growth was first performed on GaSb to evaluate device performance, then transferred to GaAs for comparison. The structure includes a five-stage active region, enclosed by 350-nm-thick separate confinement heterostructures and AlSb/InAs superlattice claddings. Lasers with ridge dimensions of 8 µm x 2 mm were fabricated using standard photolithography, with uncoated facets. Figure 1a shows the light-current-voltage (L-I-V) characteristics under pulsed operation (1% DC, 10 kHz) at 20°C. The device on GaAs exhibits a slightly higher threshold current (100 mA vs 80 mA for GaSb), similar slope efficiency (~ 130 mW/A), and higher series resistance (5.9 Ω vs 2.7 Ω for GaSb). Both structures emit between 2.7 and 2.8 µm. Aging tests (Figure 1b) indicate gradual degradation over time, with an extrapolated MTTF of 34 months – about 80 times longer than GaSb DLs on Si. A type-I ICL design is also under investigation to study the impact of quantum well type.

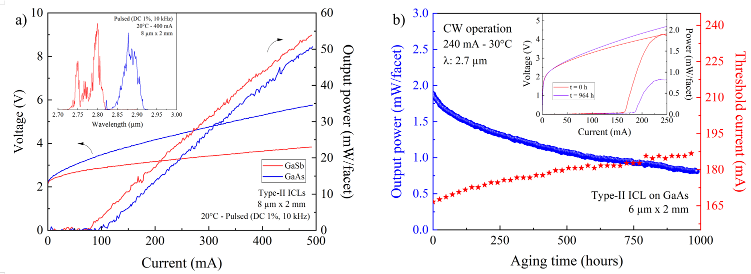

Figure 1 : a) L-I-V curves in pulsed operation at 20°C for ICLs on GaSb (red) and GaAs (blue). b) Aging of the ICL on GaAs, tested in CW operation under an injection current of 240 mA at 30°C.

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This work was partially funded by France 2030 program (EquipEx EXTRA (ANR-11-EQPX-0016), and HYBAT (ANR-21-ESRE-0026)), the French Occitanie Region (LASIDO project), the French Agency for Defense and Innovation (AID-DGA), the Banque Publique d'Investissement (Hyquality Project DOS0188007/00) and the Air Force Office of Scientific Research under award number FA8655-24-1-7038.

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Short-Wavelength Quantum Cascade Lasers Emitting at 3.8 µm for Mid-Infrared Detection Systems

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Łukasiewicz Research Network – Institute of Microelectronics and Photonics, Al. Lotników 32/46, 02-668 Warsaw

This work presents the development and characterization of short-wavelength quantum cascade lasers (QCLs) emitting in the 3.8 µm spectral range, intended for use as light sources in mid-infrared (MIR) spectroscopic detection systems. QCLs offer significant advantages for sensing applications, including high optical power, narrow linewidth, and precise wavelength tunability, making them ideal for detecting trace gases and molecular species through their characteristic absorption features.

The devices were fabricated on InP substrates using strain-compensated InGaAs/InAlAs quantum wells and barriers. To reach the target emission wavelength below 4 µm, the quantum wells were designed with a high indium content (70%) in the active region. The epitaxial structures were grown by molecular beam epitaxy and processed into ridge waveguide lasers. Comprehensive characterization included light–current–voltage (L–I–V) measurements, electroluminescence spectra, and high-resolution X-ray diffraction (HRXRD). The lasers exhibited peak pulsed output powers exceeding 800 mW and continuous-wave (CW) output powers up to 0.5 W at room temperature, confirming their suitability as robust and efficient MIR sources.

Emission around 3.8 µm coincides with strong fundamental absorption bands of several hydrocarbon species, including ethylene (C_2H_4), acetylene (C_2H_2), and other light alkenes. These molecules are of high relevance in environmental monitoring, combustion diagnostics, and industrial process control. The wavelength range also aligns well with atmospheric transmission windows and available high-detectivity photodetectors.

HRXRD results confirm the high crystalline quality of the grown structures, with no evidence of dislocation formation despite the considerable strain from the high indium content. The devices were also evaluated under various electrical driving conditions, including direct modulation, to support advanced detection techniques such as wavelength modulation spectroscopy (WMS) or time-resolved sensing.

The demonstrated CW operation at high power levels and targeted spectral performance establish these QCLs as promising sources for compact and selective MIR detection systems operating in the 3.8–3.9 µm range.

Design optimization of resonant cavity-enhanced interband cascade infrared photodetectors

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Resonant cavity-enhanced interband cascade infrared-photodetectors (RCE-ICIPs) are mid-infrared wavelength detectors suitable for e.g. optical gas-sensing applications. RCE-ICIPs are promising due to their high quantum efficiency, wavelength selectivity, and low dark current density.[1] To realize resonant cavity-enhanced ICIPs for a resonance wavelength of λ = 4.482 µm, where CO exhibits high absorbance, one needs to design the photonic cavity mode (quality factor, cavity length etc.) via optimization of the distributed Bragg reflectors (DBRs) and to optimally position the interband cascade infrared-photodetectors. The absorber region consists of type II superlattice, specifically Ga-free type II superlattice (SL), which will then be placed corresponding to the electric field in the resonator.

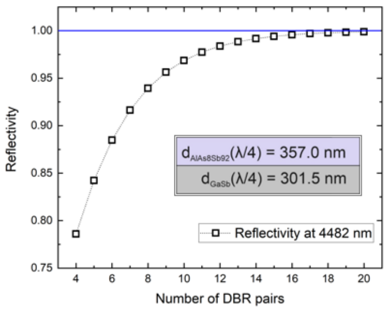

Fig. 1. *Reflectivity of DBR as a function of GaSb/AlAsSb pairs with (thicknesses provided in the inset)*

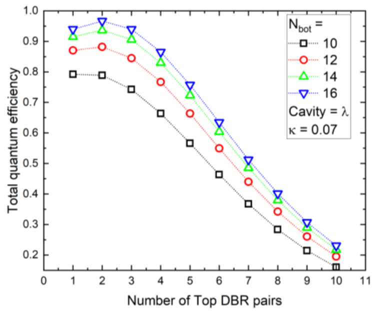

Fig. 2. *Calculated total quantum efficiency for N Botttom DBR pairs and different number of Top DBR pairs.*

Figure 1 shows the simulated reflectance for different numbers of DBR pairs composed of lattice-matched GaSb and $AlAs_{0.08}Sb_{0.92}$ layers, with calculated thicknesses of 301.5 nm for GaSb and 357.0 nm for $AlAs_{0.08}Sb_{0.92}$ to satisfy the quarter-wave condition. Reflectance exceeds 99.99% for 14 pairs and above and reaches above 95% for 10 DBR pairs.

Figure 2 presents the calculated total quantum efficiency of a resonant-enhance ICIP with different number of bottom DBR pairs and varying numbers of top DBR pairs for a cavity length of λ and an absorption coefficient of $\kappa = 0.07$ ($\alpha = 2000$ cm^{-1}) of the type II Ga-free superlattice. For 16 bottom DBR pairs and 2 top DBR pairs, the total quantum efficiency reaches values above 95% thus showing the prospect to reach almost unity in the total quantum efficiency at and intermediate absorption coefficients, i.e. $\kappa = 0.04$ the total quantum efficiency reaches 0.77 at resonance wavelength of $\lambda = 4.482$ µm.

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Sensitive SO_2 detection using a QCL-based ICOS laser analyzer

Hsiang-Yu Lo

ABB Research Center, Switzerland

Sulfur dioxide (SO_2) is a significant airborne molecular contaminant in semiconductor manufacturing, affecting product yield and performance. High-precision sensing and monitoring of SO_2 in cleanroom environments is highly demanded by the semiconductor industry. In this talk, I will introduce the state-of-the-art SO_2 detection technologies and report on the work of setting up a quantum-cascade-laser (QCL)-based trace-gas analyzer using off-axis integrated cavity output spectroscopy technology. We demonstrate that the table-top system is capable of measuring and detecting SO_2 concentration in the ambient air with a precision of 0.15 ppb level at 1 second measurement time. Given the high-power QCL as main cost driver, we investigate what the minimum laser power is required to fulfill the defined technical requirements. This work should facilitate the future product development with lower QCL costs.

Design of a Mid-Infrared Ge-Suspended Membrane Waveguide Gas Sensor for CO_2 Detection at 4.26 μm

Jacek Olszewski [1,2], **Adrian Ślipek** [1,3], **Tadeusz Martynkien** [1,2], **Krzysztof Anders** [1,3], **Stanisław Stopiński** [1,3] **and Ryszard Piramidowicz** [1,3]

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In this contribution, we present a new design for a mid-infrared (MIR) integrated photonic gas sensor based on a suspended-Ge membrane waveguide architecture [1], monolithically integrated with input/output grating couplers for efficient coupling to fiber-optic or free-space optical setups [2] (Fig. 1). The platform targets CO_2 detection at 4.26 μm, a key absorption line in the MIR "fingerprint" region, relevant for environmental sensing and industrial processes monitoring.

Suspended membrane waveguides offer a compelling approach to maximize the light-analyte interaction by allowing a significant fraction of the guided mode, i.e., evanescent field to overlap with the surrounding gaseous medium, thereby enhancing sensitivity. This substantial overlap, combined with the low group velocity of the lowest order TM-like mode TM_0 offered by suspended-Ge membrane rib waveguide architecture, results in a level of interaction with the analyte even higher than in the case of free-space propagation.

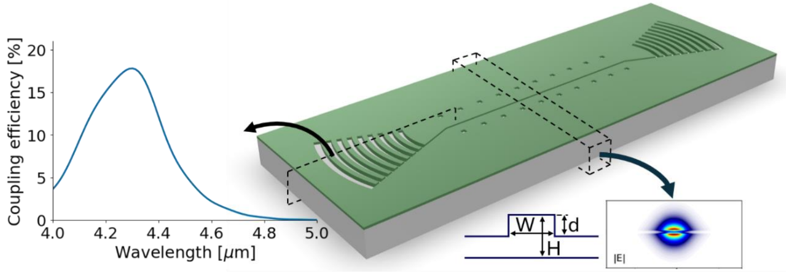

Figure 1. Schematic representation of Ge-suspended membrane waveguide gas sensor architecture. Inset plots show coupling efficiency vs. wavelength (left) and electric field norm profile of the transverse-magnetic fundamental mode TM_0 (right) calculated for H = 468 nm, W = 2.98 μm, d = 50 nm and wavelength 4.26 μm.

According to our numerical simulations, the efficiency of the fully-etched, 3.7 μm-period grating coupler to fiber is around 17% for TM polarization mode with a 1 dB bandwidth of 197 nm. The confinement factor and propagation loss for H = 468 nm equal around 140% and < 1 dB/cm, respectively. This approach provides substantial advantages over conventional SOI-based MIR photonics, which are limited by SiO_2 absorption above ~3.7 μm, and over bulk solutions, offering features of compact size, reduced power requirements, and enhanced interaction per unit length.

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The work was funded by National Center for Research and Development under the European Funds for Smart Economy, project "HyperPIC - Photonic Integrated Circuits for Mid-Infrared Applications" (agreement no. FENG.02.10-IP.01-0005/23-00).

Application of OF-CEAS for NH_3 impurity measurement in biomethane

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Among many impurities present in biomethane, ammonia is a prominent one and needs to be carefully monitored for quality control before injection into the gas grid [1]. In this abstract, we present the capabilities of optical feedback cavity enhance absorption spectroscopy-based analyser for absolute NH_3 amount fraction measurements in biomethane, a primary step towards the use of the instrument as an Optical Gas Standard (OGS) for NH_3 measurement in biomethane. An OGS is a laser spectrometer that can deliver gas species amount fraction results that are directly traceable to the international system of units (SI), i.e. without any prior calibration [2].

The schematic diagram of the OF-CEAS analyser is shown in Figure 1(a). For spectroscopic measurement, a primary reference gas sample of about 19.7± 0.55 µmol/mol NH_3 in CH_4, was used. Figure 1(b) shows typical fitted spectra of ammonia in methane matrix. The presence of

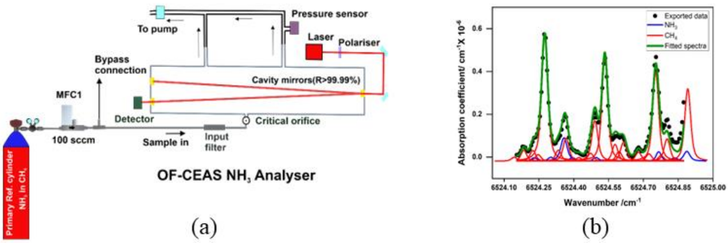

Figure 1: a) Schematic diagram of the OF-CEAS analyzer. b) Measured NH_3 in CH_4

neighboring interfering ammonia and methane lines resulted in an overall complex spectrum as shown in Figure 1(b). Thus, a careful fitting procedure developed at PTB was used to accurately fit the measured spectra to derive accurate and reliable NH_3 amount fractions in methane matrix. From the data in Figure 1(b), an amount fraction of 19.62 ± 0.98 µmol/mol ammonia in methane was derived with a relative uncertainty of 5% (k=1). The spectroscopic results are in excellent agreement with the value (19.70 ± 0.55) provided for the primary reference gas. An optimal precision of 70 nmol/mol (detection limit) has been achieved for the instrument at a time resolution of 290 second. The agreement of the results as well as this high precision demonstrates the capability of the instrument for precise NH_3 impurity measurements in methane/ biomethane and to be operated as an optical gas standard.

Acknowledgements: The project 21NRM04 BiometCAP has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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Wafer-bonded vertical cavity detectors and emitters in the mid-infrared

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In this paper, we overview key results achieved with wafer-bonded vertical cavity detectors and emitters in the mid-infrared. The combination of GaAs-based mirrors and antimonide based (GaSb) active regions has proven to be a high performance and commercially viable approach to realizing vertical cavity devices in the 3-5um range. The thick (>10um) mirror structures are epitaxially grown in the commercially mature GaAs material system, while the thinner (1-2um) active regions are grown in the less mature GaSb material system. This approach has resulted in state-of-the-art vertical cavity surface-emitting lasers (VCSELs), resonant cavity infrared detectors (RCIDs), and resonant cavity interband cascade light emitting diodes (RCICLEDs.

Figures 1A and B show examples of record performance VCSELs[1] and RCIDs[2], respectively, realized using this wafer bonded approach. Figure 1A shows spectra from room-temperature continuous wave (RTCW) optically pumped VCSELs in the 3.3um methane sensing range, showing 4nm tuning as a function of optical pump power. These and additional electrically pumped and MEMS-tunable results achieved in the last 5 years represent, to the best of our knowledge, the only reported RTCW VCSELs at any wavelength longer than 3um. Figure 1B shows absorption spectra as a function of temperature for a wafer-bonded 4.6um RCID using one bonded GaAs/AlGaAs mirror. The combination of high quantum efficiency (60-70%) over 125K-300K and high background suppression represent a state-of-the-art result for non-HgCdTe detectors in this wavelength range.

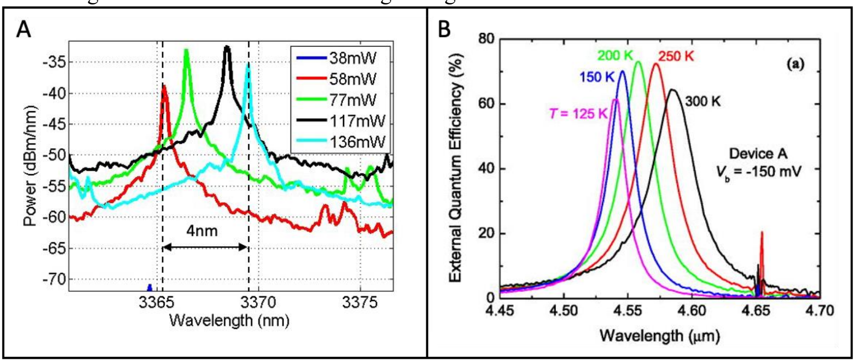

Figure 1.A. RTCW 3.3um VCSELs. **B.** 4.6um RCIDs with >60% EQE and high background suppression.

This talk will present additional details of design, fabrication, and results achieved for emitters and detectors in the 3-5um range using GaAs-based wafer-bonded mirrors, including RCICLEDs, electrically pumped VCSELs, and tunable devices.

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High Contrast Gratings for Infrared Electrode with Exceptionally High Conductivity and Transmission in Mid-Infrared Photonics

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The design of transparent conductive electrodes (TCEs) for optoelectronic devices involves a fundamental trade-off between high electrical conductivity and optical transmittance, which limits their overall efficiency. This work presents a breakthrough in TCE technology by introducing a novel fabrication approach that significantly mitigates this trade-off: a monolithic high-contrast grating integrated with metal, referred to as metalMHCG (see Fig. 1). The metalMHCG structure delivers superior electrical conductivity compared to existing TCEs, while simultaneously offering excellent optical transparency and antireflective characteristics. This study specifically targets TCEs operating in the infrared (IR) spectrum—a challenging domain due to pronounced free-carrier absorption, yet critical for applications such as sensing, thermal imaging, and automotive technologies. The proposed metalMHCG achieves a record 75% absolute transmittance of unpolarized IR light, corresponding to 108% relative transmittance compared to a plain GaAs substrate (designed wavelength for 10µm). Importantly, despite this unprecedented optical performance, the metalMHCG also exhibits record-low sheet resistance, ranging from 0.5 to 1 Ω/sq, several times lower than any previously reported TCE [1]. Additionally, second design structure, composed of gold stripes embedded in a GaAs grating, achieves 94% transmission at 7 µm wavelength and a record-high relative transmittance of 135%, while maintaining a low sheet resistance of 2.8 Ω/sq [2]. The metalMHCG combines outstanding optical and electrical properties, establishing a new performance benchmark among M-FIR TCEs and offering a promising platform for high-power optoelectronic devices such as quantum cascade lasers, infrared detectors, and transparent heaters

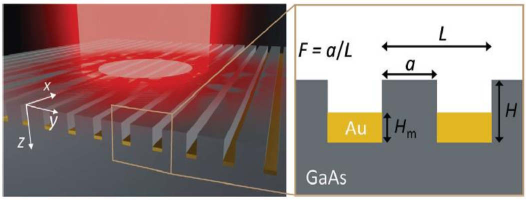

Figure 1. Schematics of the metalMHCG in TE configuration composed of 1D grating on a GaAs wafer with gold stripes implemented in the grooves between the semiconductor stripes [1].

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Plasmon-Enhanced InP DBRs for Next-Generation Mid-Infrared VCSELs

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Mid-infrared optoelectronic devices play a vital role in a wide range of applications, such as gas detection, thermal imaging, and free-space optical communication. These systems commonly utilize interband and quantum cascade active regions operating in the 4–10 µm wavelength range. To achieve surface emission with low beam divergence and ease of integration, highly reflective distributed Bragg reflectors (DBRs) are essential.

This study investigates the underlying principles of a novel class of semiconductor lasers known as quantum-cascade vertical-cavity surface-emitting lasers (QC-VCSELs) [1]. These devices aim to combine the strengths of vertical-cavity surface-emitting lasers (VCSELs) and unipolar quantum-cascade lasers (QCLs). Like VCSELs, QC-VCSELs are expected to emit narrow, low-divergence beams in a single longitudinal mode, free from astigmatism. An added advantage is the ability to evaluate device quality before processing. Furthermore, QC-VCSELs offer flexible wavelength tuning by modifying quantum well parameters, eliminating the need for specific bandgap materials in the active region.

The proposed approach features a monolithic high-index-contrast grating as the top mirror, which serves both as an optical coupler and a region where a vertical electric field component is generated, enabling stimulated emission from the quantum cascade structure.

Conventional DBRs used as bottom mirrors often face material-related challenges, particularly with AlGaAs and AlGaSb, due to lattice mismatch and poor electrical conductivity. To address this, we propose a novel monolithic InP-based structure with doping modulation that circumvents these issues. While traditional DBRs become impractically thick at mid-infrared wavelengths, our design leverages plasmon-induced refractive index changes through doping modulation. This allows high reflectivity without being constrained by lattice matching.

In conclusion, this design offers a promising alternative for mid-infrared optoelectronic devices, addressing existing limitations and enhancing performance and integration potential across various applications.

This work was co-financed by: the Polish National Science Centre under the project OPUS-17 No. 2019/33/B/ST7/02591; the Polish National Agency for Academic Exchange under the contract BPN/BSK/2023/1/00040 and SK-PL-23-0046 as well as Wroclaw University of Science and Technology subsidy.

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Linearity and Saturation behavior of Interband Cascade Infrared Photodetectors (ICIP) with Gallium-free absorber

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Interband cascade infrared photodetectors (ICIPs) show great potential for high-speed applications in the mid infrared range at room temperature. Exemplary applications are high-precision frequency comb spectroscopy, free-space optical communication [1] and lidar [2]. This study is focused on the comparison of the saturation behavior and linearity of ICIPs under high-power conditions of absorber structures which include Gallium in the absorber section and structures which are Gallium-free. The bandsturcture of both are shown in Fig. 1.

It is expected that the modification of the material composition of the absorber section has a significant impact on the saturation behavior and the range over which a linear response can be achieved. First measurements indicate that Gallium-free ICIPs exhibit higher saturation and therewith a broader range with a linear response than the ICIPs containing Gallium.

Preliminary results on the high-speed performance of these ICIPs indicate great potential for more complex applications such as semiconductor frequency combs in the mid infrared. Additionally, the increased spectral coverage of Gallium-free follows the push from interband cascade lasers towards longer wavelengths. The versatile characteristics of these detectors make them also appealing for sensing applications in the mid infrared, such as gas spectroscopy.

Even though the current Gallium-free design exhibits improvements of the saturation and linearity characteristics, we believe that we can further enhance their capabitlities. Therefore, we propose novel structures with a Gallium-free design.

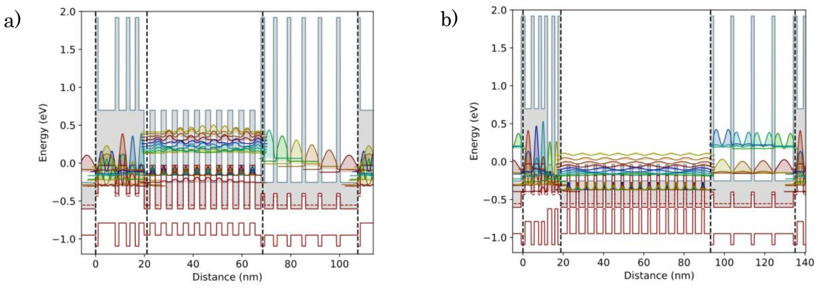

Figure 1. Simulated band structure of a a) Gallium and b) Gallium-free ICIP

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Gas sensing with MIR waveguides at The Arctic University of Norway

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Gas sensing is imperative to advancing our understanding of the global carbon cycle through developing sensor networks, providing ground truth for daily torrents of environmental satellite data, and thorough control of industrial processes among others. Currently available instrumentation can reach detection limits down to units of parts per trillion (ppt). This is often far beyond what is required. E.g. the background methane concentration of 2 parts per million is a million times higher than those detection limits. Besides, it is costly, large, heavy, limited in portability, and its free space optics makes it delicate and thus prone to misalignment causing it to fail in many real-world applications. To this end, we have been developing optical waveguides to facilitate spectroscopic gas detection through the waveguide evanescent field and to enable ruggedized integrated device filling the important gap between performance and requirements.

In this talk, we summarize the progress on the optical waveguides, which yielded detection limits of 20 ppb (parts per billion) for CO_2 [1] and 300 ppb for CH_4 [2] at 4345 nm and 3270.4 nm respectively. We will further report on the progress towards integrating these waveguides with a custom microfluidic gas cell and lens-less edge coupling of a laser. The gas cell only requires few microliters of the gas, which is flown through using modular membrane micropumps.

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High pressure optical gas sensing in industrial conditions – machine learning approach for concentration prediction

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Many applications related to the control of industrial processes under high pressures conditions require fast and precise measurements of gas concentration. However, proper quantitative analysis is demanding due to naturally broadened molecular absorption lines and their overlap, becoming even more difficult when the optical response of several coexisting gasses occurs in the same spectral range. The main limitation of the current laser detection methods is the maximum operating gas pressure (up to approx. 2 bar) due to the mentioned lines broadening, which prevents accurate and selective measurement using spectroscopic data analysis. Most commonly used method for optical gas sensing is wavelength-modulation spectroscopy (WMS). Current solutions are based on a purely analytical approach [1,2], which focuses on fitting the analytical curve to the absorption line spectra. As the industry needs fast and constant feedback solutions, analytical approaches are usually simplified to achieve such requirements. This makes them unfeasible for extreme applications.

In this work, an alternative solution will be presented, employing the partial least squares regression (PLS) method to determine oxygen concentration [3]. One of the advantages of PLS is the ability to make a reliable prediction with the use of dataset containing more predictors then observations. This enables to keep the data gathering (calibration) process short. Therefore, the prediction time can be significantly shorter than in case of currently used analytical solutions. In addition, the PLS models are also fairly quick to build. In order to optimize the PLS model and select the most effective algorithm, a decent analysis was carried out in a broad range of parameters, including spectral ranges, laser parameters and the complexity of databases used to build the model. Initial studies and analyzes were carried out using computer simulations for the data taken from the HITRAN database. Using the obtained conclusions, experimental tests of the developed algorithms were carried out. The machine learning approach was then further optimized and confronted with experimental obstacles.

The obtained results constitute the basis for the development of a practical solution that will allow for maintenance-free monitoring of gas concentration in high pressure conditions, including applications requiring operation in the range from under pressure up to 40 bar.

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Laser-base gas sensing – simplifying and speeding data analysis using neural networks

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Optical spectroscopy is a powerful tool in gas sensing applications. Laser-based spectroscopy offers high sensitivity and selectivity. Additional advantages include fast response time, compact design, and no need for sample preparation. Furthermore, some optical gas sensors can operate continuously in real-world, non-laboratory conditions with only minimal maintenance.

In principle, optical gas sensing is relatively straightforward: a tunable laser source and a detector are used to record an optical spectrum. Molecular concentration information can then be extracted by analyzing the resulting absorption lines (as illustrated in Fig. 1). In practice, however, the analysis is often complicated by the presence of additional signal components. These may include fluctuating and nonlinear baselines, as well as interference fringes that are superimposed on the absorption features. Advanced algorithms employing full-spectrum fitting – including background signal modeling – are typically required to accurately retrieve molecular concentrations. However, these methods can take several seconds, or even tens of seconds for complex spectra, to process a single measurement. Such delays are impractical in scenarios requiring high-speed data acquisition.

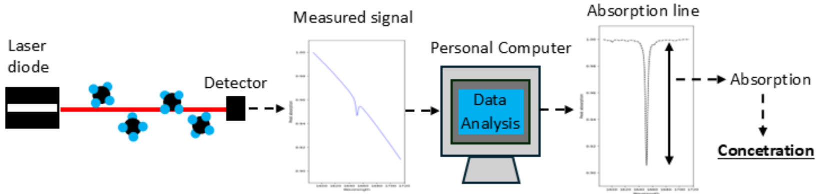

Fig. 1. Schematical diagram of a tunable diode laser absorption spectrometer: laser diode and detector are used to record optical spectrum; recorded signal is analyzed in order to remove unwanted signals (such as baseline or optical fringes) and retrieve information about molecular concentration.

In our work, we investigate whether neural network (NN)-based algorithms can be used for rapid spectral analysis. Our initial experiments are focused on using NN to remove fluctuating baseline from absorption spectra recorded with tunable diode laser absorption spectroscopy (TDLAS). Preliminary results show that while NNs are significantly faster than traditional fitting methods, they can also introduce unexpected errors. During the conference we will highlight critical aspects of NN training that significantly affect the final performance of this approach.

(M)IR PICs for QKD-based telecom and on-chip sensing applications

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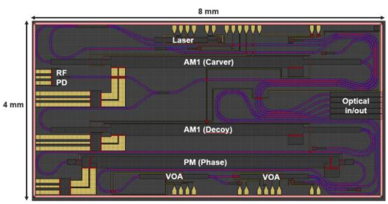
The visible and near-infrared (NIR) spectral ranges have for a long time dominated developments in photonics research for real-world applications including establishing and implementation of photonic integrated circuits (PICs) for sensing and telecom applications. Nowadays, the mid-infrared (MIR) range and in particular MIR PICs also move into focus, showing first demonstrations of fully monolithic integrated and functional devices. They uniquely enable applications for probing the fundamental molecule absorptions in, e.g. bio-chemical liquid sensing experiments [1] or free-space data-transmission in the MIR transparency windows of the atmosphere [2]. For this InP plays a crucial role as a mature material system for advanced optoelectronic devices and PICs, both in the MIR and NIR.
In this presentation we want to discuss the state-of-the-art in terms of PIC developments in both spectral domains. In the NIR, InP has reached a level of commercial PIC availability which can be used to realize novel quantum PIC transmitters for QKD at 1550 nm [3,4]. Their design and operational principle will be the first part of this presentation. In the MIR instead, typical quantum cascade (QC) devices do also benefit from the maturity of the InP material system, but similar multi-element and functional PICs have not yet been demonstrated. This mainly originates from the complex QC quantum structure and difficult epitaxial growth as well as PIC fabrication process, together with the limitations from suitable and readily implemented MIR waveguide materials for on-chip beam-guiding. We will demonstrate how this can be overcome by integrating active QC devices with (passive) plasmonic waveguides and novel on-chip integrated micro-optics. The resulting fully monolithic MIR PICs cover simple linear "lab-on-chips" for in-situ reaction monitoring experiments [1] and more complex MIR beam combiner PICs [5]. In the final part, we want to elaborate, what future MIR PIC developments can learn from the more mature field of NIR PICs.



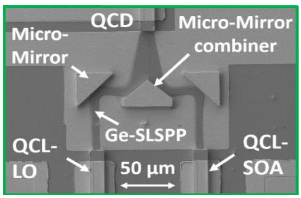


Fig. 1 (left) NIR InP single-photon transmitter PIC for QKD [3]. (right) MIR InP beam combiner PIC [5].

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MIRPIC – mid-IR photonic integrated circuits for gas sensing applications

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Modern photonic integrated circuit (PIC) technologies enable addressing several contemporary scientific and technological megatrends, including high-speed communications, quantum communication and computing, and artificial intelligence, to name a few. In recent years, these fields have undergone a paradigm shift marked by the transition from discrete components to fully integrated photonic solutions. However, there remain areas in which conventional PIC platforms, based on InP, SOI and SiN, cannot be efficiently implemented, primarily due to a limited spectral range of operation. One such area is mid-infrared sensing. In this work, we present and discuss a novel photonic integration platform, MIRPIC, with capabilities that enable the development of highly compact and efficient multi-species gas and liquid sensors.

The MIRPIC integration platform is based on germanium-on-silicon (Ge-on-Si) technology, offering optical transparency from 1.7 μm to 8.0 μm. The current library of developed building blocks includes strip and rib waveguides, multi-mode interference (MMI) splitters/couplers, arrayed waveguide grating (AWG) wavelength multiplexers, and grating couplers. Quantum cascade lasers (QCL) are used as light sources, while type-II superlattice InAs/InAsSb structures serve as photodetectors. Both the laser and detector design and technologies have been optimized for compatibility with the passive photonic circuits and integration in a hybrid process.

Multi-species gas sensing using the MIRPIC platform can be realized through different approaches. The first approach, currently under investigation, is a hybrid sensor in which the photonic integrated circuit serves as a multi-channel transmitter comprising a matrix of QCL lasers coupled to a single output waveguide via either MMI couplers or AWG multiplexers. The output signal is directed into an external gas cell and detected by a discrete mid-IR photodetector. Alternatively, the platform also enables the implementation of a fully integrated sensor, in which the external gas cell is replaced by a highly efficient sensing waveguide. In this configuration, the optical mode is weakly confined, enabling strong interaction of the evanescent field with the surrounding gas. Both approaches will be discussed and compared.

This work received support from the National Center for Research and Development through projects MIRPIC (TECHMATSTRATEG-III/0026/2019-00) and HyperPIC (FENG.02.10-IP.01-0005/23, IPCEI ME/CT). This work has received funding from the European Union’s Horizon Europe under Grant Agreement #101213727, Chips Joint Undertaking (Chips JU).

Development of the MIRPIC Process Design Kit

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The successful market implementation of cutting-edge products and solutions based on InP, SOI, and SiN photonic integrated circuits, observed over the last decade mainly in the telecom and datacom sectors, has been significantly accelerated by the development of dedicated, customized photonic CAD tools that strongly support task automation. This approach draws on the experience of the microelectronics industry, where process design kits (PDKs) have been successfully used both in R&D and fully commercial activities. Despite much higher complexity than their microelectronics counterparts, PDKs for mature photonic technologies operating in the near-infrared, are also commercially available nowadays.

New generic platforms that use non-standard material layer stacks and hybrid or heterogeneous processes tailored for operation in other spectral ranges (VIS and MIR) can benefit from a PDK-oriented approach from the very beginning of the development cycle. The PDK-oriented workflow ensures a seamless process flow from the design through manufacturing, testing, and characterization. R&D activities are accelerated by enabling faster design and simulation of both basic and complex photonic building blocks, e.g., waveguides, couplers, filters, and multiplexers, thus supporting semi-automated mask layout preparation and facilitating design rule checking. Characterization results can be efficiently incorporated into numerical models and subsequently used for component optimization. The interaction between designers and technology development teams is also simplified through the use of a standardized software environment. Finally, commercialization and uptake of the technology are facilitated by the early adoption of industrial standards.

In this work, we present a process design kit developed for MIRPIC - a novel integrated photonic platform based on germanium-on-silicon (Ge-on-Si) technology. The platform combines optical transparency from 1.7 µm to 8.0 µm, CMOS compatibility, offering low propagation losses (< 2.5 dB/cm) and simplified fabrication. Despite these advantages, epitaxial mismatch, surface roughness, and modest refractive index contrast require careful design to ensure low-loss, robust performance. We address these challenges with a validated library of photonic building blocks, including waveguides (straight, bent, tapered), multi-mode interference (MMI) couplers/splitters, edge/grating couplers, Bragg gratings, and arrayed waveguide gratings (AWGs). The MIRPIC PDK supports schematic-driven, layout-based design, simulation-assisted optimization, and mask layout export.

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Tunable Bandgap and Ultrafast Carrier Dynamics in Dilute-Bismide III–V Alloys for Mid-Infrared Photonics

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Dilute bismide III–V compounds offer a powerful route to mid-infrared (mid-IR) optoelectronics, simultaneously lowering the fundamental bandgap and amplifying spin–orbit interactions. We report a comparative optical study of molecular-beam-grown GaSbBi and In(As)SbBi epilayers that maps the coupled evolution of band-edge energies, spin–orbit splitting, and carrier relaxation pathways as a function of Bi (and, in In-alloys, As) content.

Steady-state photoluminescence and photoreflectance confirm that adding 1–8 % Bi drives a red-shift of up to ≈ 200 meV and increases ΔSO beyond the bandgap, suppressing Augerrelated losses crucial for mid-IR lasers. Time-resolved PL and pump-probe transientabsorption spectroscopy reveal that Bi-induced clustering governs nonequilibrium dynamics: characteristic carrier lifetimes stretch from ~30 ps in low-Bi GaSbBi to >150 ps in In(As)SbBi with combined Bi–As incorporation. The longer lifetimes arise from competing defect-assisted trapping and Bi-cluster quantum confinement, a balance that can be tuned through growth temperature and group-V flux ratios.

The ability to engineer [1] bandgap positions across 2.3–3.5 µm, [2] spin–orbit splitting that exceeds Eg, and [3] picosecond-to-hundreds-of-picoseconds carrier decay times provides a versatile design toolkit for next-generation mid-IR lasers, LEDs, photodetectors, and ultrafast modulators. Our results establish GaSbBi and In(As)SbBi as flexible platforms in which optical wavelength, intervalence-band suppression, and recombination speed can be cooptimized through targeted Bi and As incorporation.

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Advancements in Mid-Infrared Optoelectronics for Free-Space Optical Applications

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Free-space optical (FSO) communication enables high-capacity wireless data transfer by transmitting optical signals through the atmosphere, offering a vital alternative to fiber-optic links in terrestrial, airborne, and satellite scenarios [1]. Near-infrared (NIR) systems, particularly those operating around 1.55 µm, have achieved impressive terabit-per-second transmission rates by leveraging coherent modulation, optical amplification, and polarization multiplexing. Nevertheless, their performance is fundamentally constrained by atmospheric impairments, including Mie scattering due to fog, scintillation from turbulence, and molecular absorption.
In contrast, the mid-wave infrared (MWIR, 3–5 µm) and long-wave infrared (LWIR, 8– 14 µm) spectral bands present compelling advantages under such adverse conditions. These include reduced turbulence-induced fluctuations, lower beam divergence, and enhanced spectral discretion—characteristics that are particularly beneficial for secure and resilient communication links [2]. In this context, the choice of light source is a critical factor. For LWIR systems, quantum cascade lasers (QCLs) currently represent the only mature solution. In the MWIR region, both QCLs and interband cascade lasers (ICLs) are viable candidates, with the optimal choice depending on application-specific requirements such as power efficiency, output power, modulation bandwidth, and thermal constraints. QCLs generally offer higher optical power and broader optical bandwidths, making them well suited for high-power FSO applications, albeit at the cost of increased thermal management needs. In contrast, ICLs are more energy-efficient and compact, making them ideal for high-speed energy efficient communications and integrated photonics [2].
This presentation will present the current landscape of MWIR and LWIR photonic platforms, emphasizing their growing potential for high-speed and chaos-based FSO communication systems, encrypted data links, and light detection and ranging (LiDAR) applications in degraded environments [3]. We will show that MIR FSO technologies are no longer confined to laboratory research but are rapidly emerging as practical solutions with far-reaching implications in secure communications, environmental sensing, and defense systems. Finally, we will outline key challenges ahead, including scaling data rates, extending modulation bandwidths, and ensuring robust performance in real-world atmospheric conditions, while highlighting the need for further research to transition from controlled indoor experiments to fully deployable, field-tested systems.

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Continuously and Widely Tunable Ring Array Lasers based on QCL and ICL material

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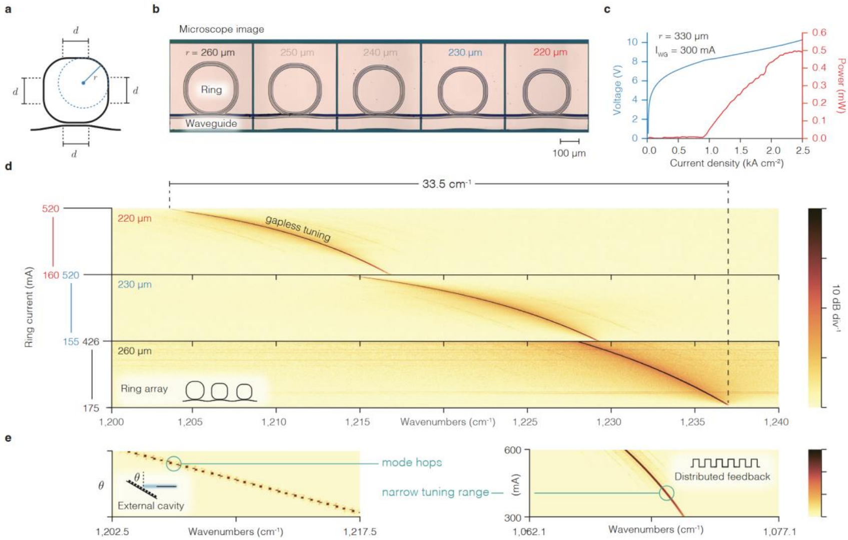
Tunable semiconductor lasers are indispensable for applications ranging from spectroscopy to telecommunications, yet achieving continuous, mode-hop-free tuning across broad frequency ranges in a compact, robust device remains challenging. We present a novel ring array laser platform that combines the single-mode, smooth tuning of distributed feedback (DFB) lasers with an extended tuning range while keeping a compact footprint. The ring array laser comprises multiple small, independently addressable ring lasers which are coupled into a shared bus waveguide. All the rings have slightly different radii, resulting in distinct lasing frequencies. This configuration enables multi-ring spectral sweeps with stable emission facilitated by unidirectional lasing. In contrast to traditional tunable lasers, our device achieves mode-hop-free tuning over broad bandwidths, is resilient under high levels of optical feedback, and supports beam combining for broadband spectral coverage resulting in a combined tuning range of 33 cm^{-1} from three different rings. This versatile platform offers a new pathway for scalable, compact spectroscopic sources, with potential applications across the mid-infrared and beyond. This platform, initially demonstrated using QCL material [1], is expected to be compatible with other semiconductor laser materials, such as ICLs. Extending the approach to different material systems enables access to new wavelength regimes with a single-mode, tunable source. In particular, the use of ICLs—with their low threshold current densities—could pave the way for compact, hand-held, tunable mid-infrared sources.



The ring-array laser. a shows the geometry of a single ring laser element. The laser consists of four straight sections of length d, connected by four quarter circles of radius r. Here, d = 50 µm and r spans from 260 µm to 220 µm, for this particular chip. b shows a microscope image of an example ring-array laser. Each ring is connected together through a bus waveguide. The bus waveguide is separated by an air gap of 1µm along the straight section of the ring lasers. c shows a light-current-voltage (LIV) curve for an example ring with an output power exceeding 0.5 mW. d Three ring QCLs from a single array span over 1 THz of optical bandwidth without mode hops around a center wavelength of 8 µm. Each ring (r = 260, 230, 220µm) is tuned by increasing its bias current as shown by each y axis. This tuning is compared with that of a commercial external cavity QCL (only a small subset of the tuning range is shown) and a commercial distributed feedback (DFB) QCL in e, both of which emit on the order of 100 mW in continuous-wave operation at room temperature. The ring-array laser displays mode-hop free tuning over three times the spectral bandwidth of the DFB QCL. Small side modes present in the spectral sweeps are a result of artifacts in the FTIR.

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GaInAsSb and type-II superlattice based photodetectors for sensing applications in the eSWIR and MIR spectral range

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Detection of radiation in the extended short wavelength infrared (eSWIR, 1.7 – 3.0 µm) and mid infrared (MIR, 3.0 – 8.0 µm) spectral band provides a wide range of applications from gas sensing to IR imaging. The eSWIR is predominantly covered by photodetectors based on strained InGaAs. Due to the high strain, however, the performance and yield of these detectors is greatly reduced. GaInAsSb lattice matched to GaSb-substrates provides a promising alternative capable of covering wavelengths from around 1.7 µm to 5.0 µm. For longer wavelength applications, type-II superlattices (T2SL) photodetectors based on InAs/GaSb or InAs/InAsSb have emerged as a viable alternative to prevalent HgCdTe due to great flexibility in band engineering. The effective bandgap of the T2SLs can be tailored to specific applications and dark current channels like e.g. Auger-recombination can be greatly suppressed [1].
We present an overview of the detector development at nanoplus and highlight improvements in dark current reduction in GaInAsSb-based photodetectors with cut-off wavelengths of 2.5 µm. Dark current densities as low as $4 \cdot 10^{-4}$ A/cm² at room temperature were achieved at a turn-on bias of -100 mV which compares well with published results [2]. At zero bias, a detectivity of $D^* = 4 \cdot 10^{10}$ Jones was achieved at a wavelength of 2330 nm in a single-pass configuration.
Furthermore, we present results on different detector architectures employing T2SL absorbers for sensing applications at wavelengths up to 8 µm. For operation at high temperatures, where the charge carrier diffusion length presents a limitation in detector performance, interband cascade infrared photodetectors (ICIPs) based on InAs/InAsSb and InAs/GaSb T2SL are presented. For applications at lower temperatures, where the carrier diffusion length exceeds the absorption depth, we present results on T2SL based complementary barrier infrared photodetectors (CBIRD).

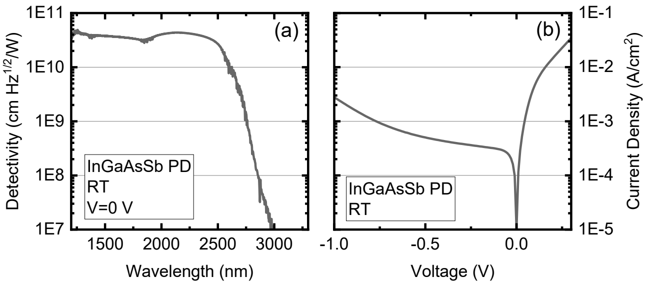

Figure 1 (a) Spectral detectivity and (b) dark current density of GaInAsSb photodetectors at room temperature

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