

# A modular sensing platform on silicon for the mid-infrared

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**Abstract**—Photonics-based sensing in the mid-IR has been proven to be the key technology for in a plethora of applications ranging from environmental monitoring to industrial process control, medical diagnostics, water quality, medical and more. Compared to other sensing approaches, mid-IR spectroscopy-based sensing enables fast, reliable, and consumables-free operation for the detection of trace amounts to high concentration of the targeted analytes. The interest in the technology has been significantly increased due to the maturing of the Quantum Cascade Lasers (QCLs). QCLs offer an up to 2-orders of magnitude enhancement in the signal-to-noise ratio while enabling the direct access to the characteristic molecular fingerprint region of the targeted analytes. The Horizon Europe project M3NIR develops a modular sensing platform for the mid-IR, to significantly boost the technology in terms of performance (low limit of detection, multiple-species detection), footprint (co-integrating of lasers and components) reduction of energy consumption and cost. M3NIR will demonstrate its novel approaches for the monitoring of GHG and ships emission, detection of phosphates and nitrates in water and the breath analysis for health and well-being related applications.

**Keywords**—mid infrared; quantum cascade lasers; PIC, flip-chip integration; microfluidics, sensors.

## I. INTRODUCTION

M3NIR revolutionizes the mid-IR-based detection technology by developing and demonstrating a modular platform for the realization of advanced mid-IR sensing. The high-level concept of the M3NIR modular platform is depicted in Figure 1. The developments per module are presented in the following sections.

## II. MODULARITY OF THE M3NIR PLATFORM

### A. Quantum Cascade Lasers on Ge-on-SOI PICs

In the first layer of modules, M3NIR develops QCLs tailored for integration on a Ge-on-SOI PIC platform. Ge-on-SOI is widely transparent in the mid-infrared (2-8.5  $\mu\text{m}$  band), the high refractive index allows for dense integration, and Ge-on-SOI allows for realizing efficient heaters. The aim is to combine the Ge-on-SOI waveguides with QCL gain chips to make high quality tunable lasers for the mid-infrared with a high yield. Moreover, multiple wavelength bands can be targeted, required for practical applications.

Flip-chip bonding technology was selected to co-integrate QCL sources onto the Ge-on-SOI waveguide circuit. The assembly solution is based on etching a recess in the Ge-on-SOI waveguide substrate, which allows for butt-coupling the laser chip with respect to the Ge-on-SOI waveguide facet. Pedestals sticking out of the recess act as mechanical stoppers providing a sub-micron alignment precision in the vertical direction. The in-plane accuracy is provided using state-of-the-art flip-chip bonding tools.

Efficient optical coupling between the QC gain or laser chip and the Ge-on-SOI waveguide assumes that the modes are matched, which requires adjusting the Ge waveguide width. Proper designs have been established for a wide range of QCL wavelengths. In addition, the impact of longitudinal alignment

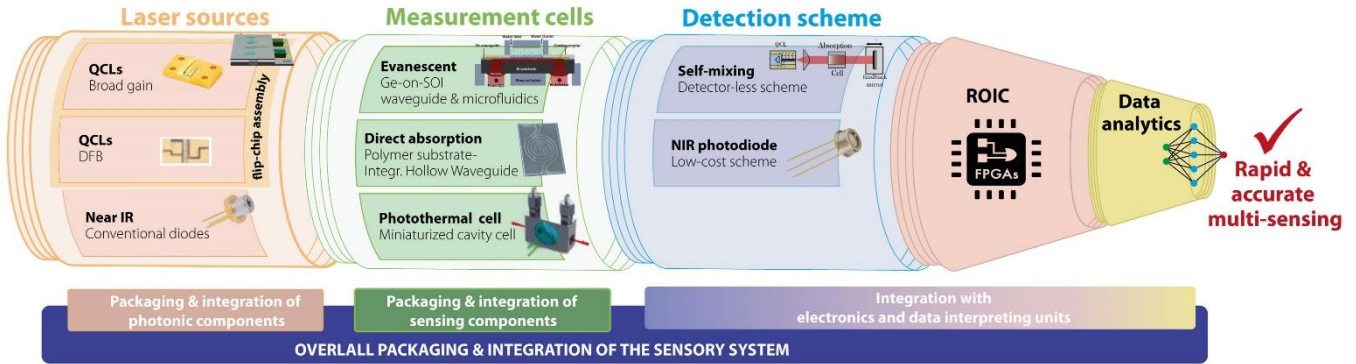


Figure 1 Depiction of the M3NIR modular mid-IR multi-sensing platform.

accuracy is well-understood. The use of solder as a bonding material between the QC chip and the PIC facilitates a very effective heatsinking.

### B. Measurement cell

In the second layer three kinds of measurement cells are integrated. Two cells regard gas measurements, and one regards targeted analytes in liquids.

In the photothermal detection cell, the gas sample with the target analytes is present inside the air-spaced cavity of a Fabry-Perot interferometer. The sensor operates on the principle that selective absorption of mid-IR radiation by the target molecules causes an excitation of their internal energy levels, leading to sample heating by energy transfer due to collisional relaxation. This in turn leads to a change in gas density and thus in its refractive index. This photoinduced change in the refractive index of a sample within the interferometer is detected with high sensitivity by monitoring the phase shift of a probe laser passing through the device.

A second approach for the miniaturization of gas sensing cells is based on the use of substrate-integrated hollow waveguides, whereby mid-infrared radiation is guided via an integrated meandered light channel fabricated into a solid-state substrate material.

The third cell is an evanescent waveguide sensor cell, enabling the interaction of the evanescent field with the liquid medium to be analyzed. The sensing scheme combines the benefits of mid-IR sensing (direct information on the molecular fingerprint of the analytes) and waveguide enabled sensing, i.e., confining the measurement within a specific region where a sensing coating can be applied, as well as robustness of the sensor. The Ge-waveguide chips are equipped with novel optical coupling structures based on downward-coupling gratings and monolithic microlenses integrated in the silicon substrate, allowing free-space, alignment tolerant, through substrate optical interfacing. A solution for integrating the PIC together with a microfluidic cartridge is under development.

### C. Detection scheme

M3NIR employs 2 different detection schemes, that can be used in the platform. In addition to the photothermal sensing scheme described above, M3NIR is developing a self-mixing scheme, which enables detector-free sensors, thus significantly reducing the cost, footprint and energy consumption of the final device.

### D. Electronics

In this layer advanced electronics (laser drivers and readout electronics) are co-integrated inside the advanced sensory system to achieve performance boosting.

### E. Data analytics

Finally, data analytics and intelligence approaches are implemented with the aim to interpret a wide swath of complex data.

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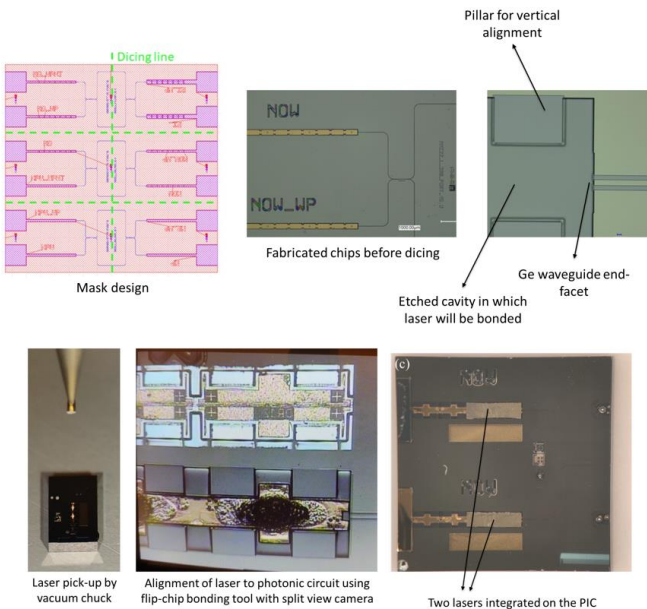


Figure 2 Different steps while integrating QCL chips on the Ge waveguide based PIC.