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Integrated, Modular, Multisensing, Mid- and Near- IR sensing platform

M3NIR - Deliverable report

D2.1 - Report on the designing aspects and guidelines of the M3NIR modules

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About M3NIR

M3NIR plans to boost photonics-based sensing technology in terms of performance, reduction of footprint, energy consumption and costs. The value chain to be implemented by the M3NIR project includes the optimization of the manufacturing approaches of mid-infrared photonic devices, the development of relevant electronics and the high-level integration of other components like microfluidics for the realization of high-performance sensors. With the extra focus towards miniaturized configuration, robustness, maintenance-free operation, low power consumption and cost-effective sensing, M3NIR aims to create a modular, highly adaptable and efficient multi-sensing platform, which will be validated in the domains of environmental monitoring and healthcare. The project makes use of novel schemes for component integration and packaging, enabling both scientific and industrial breakthroughs.

M3NIR consortium members

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Lead Author	Bart Kuyken (IMEC)
Co-Author(s)	Geert Van Steenberge (IMEC)

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Publishable summary

Deliverable “D2.1 Report on the designing aspects and guidelines of the M3NIR modules” is part of work package “WP2: Specifications & overall architecture of the sensory systems and application use cases”. The report consolidates all codesign aspects of the several modules and sub-circuits. The generated guidelines are essentials for the main development phase of the project to follow.

Contents

List of acronyms, abbreviations and definitions

Abbreviation	Definitions
QCL	Quantum Cascade laser
DFB	Distributed Feedback
FP	Fabry-Perot
Ge-on-SOI	Germanium on Silicon on Insulator
EC	External Cavity
PIC	Photonic Integrated Circuit
ICAPS	Interferometric cavity-assisted photothermal spectroscopy
LOD	Limit-of-detection
iHWG	Substrate-integrated hollow waveguide

1. Introduction

Deliverable "D2.1 Report on the designing aspects and guidelines of the M3NIR modules" is part of "WP2: Specifications & overall architecture of the sensory systems and application use cases". The report consolidates all codesign aspects of the mid-IR PIC modules and sub-circuits. Other modules required for the final sensing demonstrators are being specified within the "WP3: Development of modular mid-IR laser components for reduced energy consumption sensing" and "WP4: Development of key structural modules of the M3NIR platform", and include electronics, microfluidics, hollow waveguides, and benchtop set-ups in which all novel devices are to be integrated throughout the project lifetime (upon novel device availability).

The deliverable 2.1 is aligned with deliverable 2.2. However, within deliverable 2.1 we start from the sensors and go in more depth on how the specifications are translated in actual design aspects for the various mid-IR PIC modules and sub-circuits.

As outlined within deliverable 2.2, M3NIR focuses on three different use cases for which we will define the mid-IR PIC modules, the sub-circuits and the codesign aspects. The measurement techniques and the corresponding benchtop set-ups in which the novel mid-IR PIC modules and sub-circuits are to be integrated are:

1) Interferometric cavity-assisted photothermal spectroscopy (ICAPS), in which an optical cavity is utilized as a transducer for highly sensitive gas detection with the application of photothermal spectroscopy, providing an ultra-low absorption volume within a rugged sensing element. A quantum cascade laser serves as mid-IR excitation source to induce refractive index changes in the sample, and a near-IR laser serves as probe source to monitor the photo-induced variations. Multi-wavelength QCL sources integrated on a single Ge-on-SOI photonic integrated circuit (PIC) will enable the target miniaturization. A novel implementation of balanced detection will be implemented, eliminating the influence of external noise.
2) Evanescent field spectroscopy for liquid analysis, relying on the traveling of mid-IR radiation through a Ge waveguide, enabling the interaction of the evanescent field with the liquid medium to be analysed, resulting in the absorption spectrum of the medium carrying the targeted analytes. The Ge-on-SOI PICs will be equipped with novel optical coupling structures, allowing for an alignment-tolerant free-space coupling interface, enabling ease of use, and providing an elegant integration of the PIC with the microfluidic cartridge. A low limit-of-detection (LOD) will be achieved through the integration of a hydrophobic mesoporous enrichment layer. Broadly tuneable PIC-based sources will replace bulkier external-cavity quantum cascade laser (EC-QCL) sources to allow for reduction in size and cost.
3) Lastly, a gas analyser for biomedical applications will be developed, enabling breath analysis. Miniaturization of gas absorption cells is provided by the "substrate-integrated hollow waveguide" (iHWG) devices, which are to be efficiently coupled with the multi-wavelength QCL sources integrated on the Ge-on-SOI PIC. By exploiting the potential of self-mixing interferometry, the QCL itself will acts as a high speed and highly sensitive detector, avoiding the use of more expensive cooled mid-IR detectors.

Table 1: Overview of deliverable D2.1.

Deliverable Number	Short deliverable name	Lead beneficiary	Type	Dissemination level	Due date
D2.1	Report on the designing aspects and guidelines of the M3NIR modules	IMEC	R	PU	M5

2. Ge-on-SOI PIC platform with integrated QCLs

An analysis of the analytes to be detected and their corresponding mid-IR fingerprints is presented in detail in deliverable 2.2. As the analytes for the three different use cases cover a very broad mid-IR wavelength range, we have split-up the analytes in two groups, corresponding to two versions of the Ge-on-SOI PIC platform with integrated QCL sources. The first generation will focus on shorter wavelengths, while the second version will target longer wavelengths, as shown in Table 2.

Table 2: Two versions of the Ge-on-SOI PIC platform with integrated QCL sources.

Use Case #	Mid-IR active platform version 1	Mid-IR active platform version 2
1	NO 1,900.08 cm-1 (5.26 µm) CO 2,179.77 cm-1 (4.58 µm) N_2O 2,180.42 cm-1 (4.59 µm)	NO_2 1,602.75 cm^{-1} (6.17 µm) SO_2 1,380.93 cm^{-1} (7.24 µm) CH_4 1,297 - 1,299 cm^{-1} (7.71 - 7.70 µm)
2	not applicable (using commercial EC-QCL source in benchtop set-up)	Ammonium $[NH_4]^+$ 1550 - 1250 cm^{-1} (6.45 - 8.00 µm) Nitrate $[NO_3]^-$ 1500 - 1250 cm^{-1} (6.66 - 8.00 µm)
3	$^{12}CO_2$ 2,310.0 cm^{-1} (4.33 µm) $^{13}CO_2$ 2,270.3 cm^{-1} (4.40 µm)	$^{13}CO_2/^{12}CO_2$ 2,400 - 2,200 cm^{-1} (4.15 - 4.55 µm)

2.1. Mid-IR active platform version 1

2.1.1. Ge-on-SOI waveguide platform

In a first step the Ge-on-SOI PIC platform will focus on a wavelength region between 4.2 and 5.3 micron, being able to detect NO, CO, N_2O, $^{12}CO_2$ and $^{13}CO_2$. For this first version of the PIC platform, the thickness of the Germanium is 2 µm, the top Si layer is 3.2 µm, and buried oxide is 2 µm, and the handle wafer has a thickness of 750 µm. The dimensions of the waveguide will be designed to be such that the waveguides are single mode (typical waveguide width of 3-10 µm). Both fully etched (100%) & partly etched (50%) waveguides will be considered. Target waveguide loss is 3-5 dB/cm. Waveguide facets should have a loss below 1%.

Table 3: Ge-on-SOI waveguide platform specifications.

Mid-IR active platform version 1	
Ge-on-SOI layer thicknesses	Ge: 2 µm; Si: 3.2 µm; SiO_2: 2 µm; Si substrate: 750 µm
Single mode waveguides	over wavelength range from 4.2 till 5.3 micron
waveguide loss	3-5 dB/cm
waveguide facet reflection loss	below 1%

2.1.2. Quantum Cascade gain chips

For the first version of the Ge-on-SOI platform, we will integrate quantum cascade gain chips covering wavenumbers from 2400 cm^{-1} to 1900 cm^{-1}. These first QC gain chips will be selected from the current stock within ALPES, to enable integration early in the project. Depending on the availability of devices within the ALPES stock, both DFB lasers, narrowband and broadband QC gain chips will be considered, as long as compatibility with the target analytes listed in Table 2 (in terms of wavelength) is provided. Optical power should be at least 50 mW. Different concepts for integration of the QC gain chip and the Ge-on-SOI PIC platform will be developed. In a first phase, a hybrid integration strategy will be followed, allowing for using active alignment between a QC gain chip and the Ge-on-SOI PIC, resulting in a low-loss coupling. In a second phase, flip-chip integration will be used to enable a more industrially scalable integration concept compatible with the target volumes of the M3NIR devices. The target coupling loss between the Germanium-on-SOI and QC chip is below 3 dB. The QC gain chip will work at room temperature, stabilised using a thermoelectric cooling (TEC) element.

Table 4: QC gain chip specifications.

Mid-IR active platform version 1	
QC gain chip	covering wavenumbers from 2400 cm^{-1} to 1900 cm^{-1}
optical power	>50 mW
selection from ALPES stock	DFB lasers, narrowband and broadband FP QC gain chip
integration strategy	hybrid integration (using active alignment) and flip-chip integration
target coupling loss	below 3 dB between Germanium-on-SOI and QC chip
operating temperature	room temperature

2.1.3. Distributed Bragg Reflector Laser

The QCLs integrated on the PIC will work at room temperature, and the target wavelengths to correspond to the use cases described above include: 1,900.08 cm^{-1} (5.26 µm); 2,179.77 cm^{-1} (4.58 µm); 2,180.42 cm^{-1} (4.59 µm); 2,310.0 cm^{-1} (4.33 µm); 2,270.3 cm^{-1} (4.40 µm). The wavelengths will be defined through the integration of custom designed distributed Bragg reflectors in the Ge-on-SOI PIC platform. The gratings themselves are targeted to have a reflectivity of at least 50% to enable lasing. Their FWHM reflection band should be less than 50 GHz to enable single mode operation.

Table 5: DBR specifications.

Mid-IR active platform version 1	
DBR wavelengths	1,900.08 cm^{-1} (5.26 µm); 2,179.77 cm^{-1} (4.58 µm); 2,180.42 cm^{-1} (4.59 µm); 2,361.5 cm^{-1} (4.23 µm); 2,270.3 cm^{-1} (4.40 µm)
reflectivity	at least 50%
FWHM reflection band	less than 50 GHz

2.1.4. Passive components and filters

Within M3NIR, we will develop multiplexers which combine multiple (2 or 3) channels with an insertion loss below 5 dB and crosstalk of less than –15 dB. Thermo-optic wavelength tuning elements will be integrated on the Ge-on-SOI PIC platform, to allow for a tuning range of 0.1% of the central wavelength. Wavelength tuning is to be performed at a rate above 500 Hz.

Table 6: Passive components and filter specifications.

Mid-IR active platform version 1	
multiplexer # channels	2 or 3 channels

insertion loss	below 5 dB
crosstalk	less than –15 dB
thermo optic wavelength tuning	at least 0.1% of the central wavelength
wavelength tuning rate	above 500 Hz

2.2. Mid-IR active platform version 2

2.2.1. Ge-on-SOI waveguide platform

In a second step the Ge-on-SOI PIC platform will focus on a wavelength region between 6 and 8 microns, being able to detect NO_2, SO_2, CH_4, Ammonium $[NH_4]^+$ and Nitrate $[NO_3]^-$. Ideally, we will use the same Ge-on-SOI epi-stack, unless the optical simulations suggest the use of more optimum layer thicknesses. Similar as for the first version of the platform, the dimensions of the waveguides are to be optimized for single mode. Again, the target waveguide propagation loss is 3-5 dB/cm, although for the longer wavelengths this certainly brings an additional risk. Facets should have a loss below 1%.

Table 7: Ge-on-SOI waveguide platform specifications.

Mid-IR active platform version 2	
Ge-on-SOI layer thicknesses	ideally identical to version 1 to enable compatibility
Single mode waveguides	over wavelength range from 6 till 8 microns
waveguide loss	3-5 dB/cm
waveguide facet reflection loss	below 1%

2.2.2. Quantum Cascade gain chips

For the second version of the Ge-on-SOI platform, we will integrate quantum cascade gain chips covering wavenumbers from 1600 cm^{-1} to 1250 cm^{-1}. These second version QC gain chips will result from the dedicated design and processing by ALPES. Both narrowband and broadband QC gain chips will be included (as required for the use cases mentioned in Table 2), and similar as for the first version the optical power should be at least 50 mW. The integration concept for this second version will be based on self-aligned flip-chip integration, providing high coupling efficiency as well as an industrially scalable approach. The target coupling loss between the Germanium-on-SOI and QC chip is below 3 dB. The QC gain chip will work at room temperature, stabilised using a thermoelectric cooling (TEC) element.

Table 8: QC gain chip specifications.

Mid-IR active platform version 2	
QC gain chip	covering wavenumbers from 1600 cm^{-1} to 1250 cm^{-1}
optical power	>50 mW
novel design and processing	narrowband and broadband FP QC gain chip
integration strategy	self-aligned flip-chip integration
target coupling loss	below 3 dB between Germanium-on-SOI and QC chip
operating temperature	room temperature

2.2.3. Distributed Bragg Reflector Laser

The QCLs integrated on the PIC will work at room temperature, and the target wavelengths to correspond to the use case 1 described above include: 1,602.75 cm^{-1} (6.17 µm); 1,380.93 cm^{-1} (7.24 µm); 1,297 - 1,299 cm^{-1} (7.71 - 7.70 µm). The wavelengths will be defined through the integration of custom designed distributed Bragg reflectors in the Ge-on-SOI PIC platform. The gratings themselves are targeted to have a reflectivity of at least 50% to enable lasing. Their FWHM reflection band should be less than 50 GHz to enable single mode operation.

Table 9: DBR filter specifications.

Mid-IR active platform version 2	
DBR wavelengths	1,602.75 cm^{-1} (6.17 µm); 1,380.93 cm^{-1} (7.24 µm); 1,297 - 1,299 cm^{-1} (7.71 - 7.70 µm)
reflectivity	at least 50%
FWHM reflection band	less than 50 GHz

2.2.4. Broadly tunable Laser

The broadly tuneable laser will work at room temperature and cover the wavelength range of 1,500 - 1,250 cm^{-1} (6.66 - 8.00 µm), as defined for use case 2. To enable this, we will develop a broadly tuneable Vernier reflector with a target reflection of more than >30%, and a FWHM of the filter below 50 GHz. In addition to this broadly tuneable laser for use case 2, we will also target a broadly tuneable laser for use case 3, over the wavelength range of interest (2,400 - 2,200 cm^{-1} (4.15 - 4.55 µm)).

Thermo-optic wavelength tuning allows for a tuning range of 0.1% of the central wavelength for DBR, and for a tuning range of 5% of the central wavelength for the broadly tuneable laser.

Table 10: Vernier filter specifications.

Mid-IR active platform version 2	
Tuneable Vernier filter	1,500 - 1,250 cm^{-1} (6.66 - 8.00 µm) 2,400 - 2,200 cm^{-1} (4.15 - 4.55 µm)
reflectivity	at least 30%
FWHM reflection band	less than 50 GHz

3. Passive Ge-on-SOI waveguide circuit

In addition to the active mid-IR platform, a passive platform will be developed, targeting the use case 2 (in combination with a commercially available external cavity QCL source). Many of the above listed building blocks part of the active platform will obviously also be integrated on the passive platform. In addition, the use case 2 requires the use of broadband grating couplers, for the external misalignment tolerant coupling to the PIC. Target is to develop a grating coupler with an incidence angle below 5 degrees, and a coupling loss of less than 5 dB. The 3-dB bandwidth will be 5% of the central wavelength. Parallel channels will be combined to reach the full wavelength range defined by use case 2. In addition, micro-lenses will be integrated monolithically in the Si substrate, collimating the beam with a target beam diameter above 100 µm and providing a 1-dB misalignment tolerance of 25 µm.

Table 11: Passive platform specifications.

Mid-IR passive platform (components not listed in the active platform)	
grating coupler incidence angle	below 5 degrees
grating coupler coupling loss	less than 5 dB
grating coupler 3-dB bandwidth	5% of the central wavelength
micro-lens beam diameter	above 100 µm
micro-lens beam misalignment tolerance	1-dB misalignment tolerance of 25 µm

4. Conclusions

This document summarizes the essential specifications of the PIC-platform components of the M3NIR sensor platforms. In a first iteration, we will target the shorter wavelengths and only narrow tuneable lasers, while in a second iteration we will include the longer wavelengths and broadly tuneable lasers. The document describes for both these bands the specifications of the sub components. In addition, the passive PIC platform for liquid sensing is specified.

[i] **Deliverable Type**
Please indicate the type of the deliverable using one of the following codes:
R Document, report
DEM Demonstrator, pilot, prototype

[ii] **Dissemination level**
Please indicate the dissemination level using one of the following codes:
PU Public
SEN Sensitive, only for members of the consortium (including the Commission Services)