VERNIER-EFFECT STRATEGIES FOR EFFICIENT INTEGRATED OPTICAL SENSING

Prof. Vittorio M. N. Passaro

Photonics Research Group, Dipartimento di Ingegneria Elettrica e dell’Informazione
Politecnico di Bari, Via E. Orabona n. 4, 70125 Bari - Italy
vittorio.passaro@poliba.it, WEB page: http://dee.poliba.it/photonicsgroup

Keynote speech

SENSORSDEVICES 2018, Venice, 17th September, 2018
OUTLINE

- **PHOTONIC SENSING APPLICATIONS**

- **PHOTONIC DEVICES FOR SENSING APPLICATIONS**
  - Design of photonic waveguides;
  - Optical sensing principles;
  - Group IV material systems and alloys.

- **PHOTONIC ARCHITECTURES BASED ON VERNIER EFFECT**
  - The Vernier effect for photonic sensing;
  - Vernier sensors based on cascaded microring resonators;
  - Vernier sensors based on cascaded ring resonator and MZI;
  - Vernier sensors based on cascaded ring resonator and MZI with a Sagnac loop.

- **ADVANCED PHOTONIC SENSORS OPERATING IN THE NEAR-IR AND MID-IR**
  - Sensing principles for gas detection in the mid-IR;
  - Photonic sensors based on the Vernier effect for methane and ethane detection;
  - Experimental demonstration of the Vernier effect in integrated Photonics.

- **CONCLUSIONS**
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PHOTONIC SENSING APPLICATIONS

PHOTONIC SENSORS FOR BIOMEDICAL APPLICATIONS:
- Monitoring of protein aggregation processes (e.g., biotin-streptavidin, biotin-avidin, antibody-antigen);
- Real-time monitoring of DNA hybridization;
- *In vitro*-in *vivo* detection of viruses, bacteria, tumor and cancer biomarkers;
- Monitoring of glucose in blood, pH, biological temperature.

PHOTONIC SENSORS FOR SAFETY AND FOOD QUALITY CONTROL:
- Explosive-trace detection (TNT, RDX);
- Measure of angular velocity in gyroscopes (automotive, aerospace);
- Detection of pathogenic microorganisms (bacteria, viruses).

PHOTONIC SENSORS FOR ENVIRONMENTAL MONITORING:
- Detection of harmful gases (CO₂, CH₄, CO, NO, SO₂);
- Monitoring of electromagnetic fields;
- Detection of pollutants in liquids (e.g., pesticides, heavy metals).
PHOTONIC SENSING APPLICATIONS

PHOTONIC INTEGRATED SENSING: (LABEL-FREE) APPLICATIONS

- Monitoring of protein aggregation processes (e.g., biotin-streptavidin, biotin-avidin, antibody-antigen);
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**SUB-MICROMETER OPTICAL WAVEGUIDES IN SOI TECHNOLOGY**

**SILICON-WIRE WAVEGUIDE**

- **Cover Medium**
- **Si**
- **SiO₂**

**RIB WAVEGUIDE**

- **Cover Medium**
- **Si**
- **SiO₂**

**SLOT WAVEGUIDE**

- **Cover Medium**
- **Si**
- **SiO₂**

Finite element method (FEM) simulations
SILICON-ON-INSULATOR PHOTOニック WAVEGUIDES FOR SENSING APPLICATIONS

SILICON-WIRE WAVEGUIDE

MEMBRANE WAVEGUIDE

SLOT WAVEGUIDE

h = 250nm, w = 450nm, λ = 1.55μm, quasi-TM.

h = 250nm, w = 800nm, λ = 1.55μm, quasi-TM.

h = 324nm, w = 180nm, g = 100nm, λ = 1.55μm, quasi-TE.

Finite element method (FEM) simulations

✓ SILICON-ON-INSULATOR (SOI) TECHNOLOGY
  ▪ STANDARD TECHNOLOGICAL PLATFORM (E.G. MICROELECTRONICS).

✓ EVANESCENT FIELD PHOTOニック BIOSENSING
  ▪ HIGH REFRACTIVE INDEX CONTRAST (Δn ≈ 2);
  ▪ HIGH OPTICAL FIELD CONFINEMENT;
  ▪ SUB-MICROMETER PHOTOニック DEVICE DIMENSIONS
  ▪ LOW LOSSES (< 1 dB/cm).

Slot waveguides

Electric field discontinuity

\[ \frac{|E_L|}{E_H} = \left( \frac{n_H}{n_L} \right)^2 \]
PHOTONIC SENSING PRINCIPLES

HOMOGENEOUS SENSING

Applications

<table>
<thead>
<tr>
<th>IR cover</th>
<th>IR Gas/Liquid</th>
<th>Δn_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_{air} = 1</td>
<td>n_{He} = 1.000035</td>
<td>0.0035</td>
</tr>
<tr>
<td>n_{air} = 1</td>
<td>n_{CO2} = 1.000059</td>
<td>0.0059</td>
</tr>
<tr>
<td>n_{air} = 1</td>
<td>n_{Ar} = 1.000278</td>
<td>0.0278</td>
</tr>
<tr>
<td>n_{air} = 1</td>
<td>n_{N2} = 1.000294</td>
<td>0.0294</td>
</tr>
<tr>
<td>n_{air} = 1</td>
<td>n_{C2H2} = 1.000593</td>
<td>0.0593</td>
</tr>
<tr>
<td>n_{water} = 1.33</td>
<td>n_{NaCl} ≈ 1.33</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

Refractive indices @ 1.55μm

S_h = \frac{\partial n_{eff}}{\partial n_c}

SURFACE SENSING

S_s = \frac{\partial n_{eff}}{\partial \rho}

ρ ≈ 2÷10 nm

Optical Absorption

Beer-Lambert law

I = I_0 \exp(-\alpha L); \ \alpha = \varepsilon C

C = analyte concentration
ε = molar absorption coefficient

Absorption spectra of gases and liquid solutions in the mid-IR
GROUP IV MATERIAL SYSTEMS AND ALLOYS

SLOT WAVEGUIDES OPTIMIZED FOR HOMOGENEOUS SENSING @ $\lambda = 3.39 \mu m$ e $\lambda = 2.883 \mu m$

MTS-1: Ge(0.78)Si(0.08)Sn(0.14)/Ge(0.97)C(0.03)/Si – $t = 20$ nm, $w = 390$ nm, $s = 50$ nm, $h = 560$ nm.

MTS-2: Ge(0.78)Si(0.08)Sn(0.14)/Ge(0.91)Sn(0.09)/Si – $t = 20$ nm, $w = 380$ nm, $s = 50$ nm, $h = 520$ nm.

Complex fabrication but ultra-high performance!
**OVERVIEW OF SOI SENSOR PERFORMANCE AND ARCHITECTURES**

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Technology</th>
<th>Performance</th>
<th>Size</th>
<th>Analyte</th>
</tr>
</thead>
<tbody>
<tr>
<td>MZI</td>
<td>SOI</td>
<td>$8.7 \times 10^{-7}$ RIU/ppm</td>
<td>2.1mm-long</td>
<td>BTEX</td>
</tr>
<tr>
<td>MZI</td>
<td>CMOS-compatible</td>
<td>0.3 pg/mm$^2$</td>
<td>1.8mm-long (&lt;9 - array)</td>
<td>IgG, goat, rabbit</td>
</tr>
<tr>
<td>SPR</td>
<td>CMOS-compatible</td>
<td>3022nm/RIU, 70pg/mm$^2$</td>
<td>~ 800μm$^2$</td>
<td>Molecules</td>
</tr>
<tr>
<td>Grating</td>
<td>SOI</td>
<td>~ 120nm, ~ 10$^{-4}$RIU</td>
<td>173μm-long</td>
<td>Biological reactions</td>
</tr>
<tr>
<td>PhC-slot</td>
<td>SOI</td>
<td>100ppm</td>
<td>300μm-long</td>
<td>Methane</td>
</tr>
<tr>
<td>PhC-slot</td>
<td>SOI</td>
<td>510nm/RIU, 1x10$^{-5}$RIU</td>
<td>2μm-cavity length</td>
<td>Gases: N$_2$, He, CO$_2$</td>
</tr>
<tr>
<td>Directional coupler</td>
<td>SOI</td>
<td>0.1 g/L</td>
<td>~ 1mm$^2$ (footprint)</td>
<td>Glucose</td>
</tr>
<tr>
<td>MMI</td>
<td>SOI</td>
<td>+152, -172</td>
<td>1.607μm-long</td>
<td>Glucose, etanole</td>
</tr>
<tr>
<td>Slot-ring resonator</td>
<td>SOI</td>
<td>2000nm/RIU, 3.8x10$^{-3}$RIU</td>
<td>~ 1mm$^2$ (footprint)</td>
<td>Molecules, Gases</td>
</tr>
<tr>
<td>Ring resonator</td>
<td>SOI</td>
<td>60fM</td>
<td>175x500μm$^2$ (x32- array)</td>
<td>DNA</td>
</tr>
<tr>
<td>Cascaded resonators</td>
<td>SOI</td>
<td>2169nm/RIU, 8.3x10$^{-6}$RIU</td>
<td>200x70μm$^2$ (2x- array)</td>
<td>NaCl, molecules</td>
</tr>
</tbody>
</table>

Some examples in SOI technology platform:
- Mach-Zehnder Interferometers (MZI)
- Directional Couplers
- Photonic Crystals (PhC)
- Surface Plasmon Resonance (SPR)
- Integrated Bragg GRATings
- Multi-Mode Interferometers (MMI)
- Ring Resonators
- Cascade-coupled Ring Resonators
- Integrated Waveguides
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THE VERNIER EFFECT FOR PHOTONIC SENSING

Vernier effect achieved by using two frequency scales with different periods $D'$ and $D''$, where one scale slides along the other scale which is fixed.

$D'' = D' \cdot \left(\frac{n-1}{n}\right)$ with $n$ a positive integer number.

$$\frac{FSR''}{FSR'} = \frac{L'}{L''} = \frac{n-1}{n}$$

THE VERNIER EFFECT IN PHOTONIC INTEGRATED CIRCUITS

Schematic of a Vernier architecture based on cascaded integrated ring resonators optimized for sensing purposes.

(a) Qualitative planar ring resonator spectrum; (b) zoom in a resonant peak at the wavelength $\lambda_n$. 

-> loss
Vernier sensors based on cascaded microring resonators

Vernier transmittance: \( T_v = T_{\text{Ring}#1} \cdot T_{\text{Ring}#2} = T_{\text{Filter}} \cdot T_{\text{Sensor}}(n_{\text{cover}}); \)

- The first regime (optical filtering): \( \Delta \text{FSR} > \min(\Delta \lambda_{\text{FWHM}}(\text{Ring}#1, \text{Ring}#2)); \)
- The second regime (optical sensing): \( \Delta \text{FSR} < \min(\Delta \lambda_{\text{FWHM}}(\text{Ring}#1, \text{Ring}#2)). \)

First regime

Sensing performance can be enhanced with respect to a single ring resonator:

Vernier gain: \( G_v = \frac{\text{FSR}_{\text{filter}}}{|\Delta \text{FSR}|}; \)
Wavelength shift induced by sensing: \( \Delta \lambda_v = \Delta \lambda_{\text{res}} \cdot G_v; \)
Wavelength sensitivity: \( S_{\lambda,v} = S_{\lambda} \cdot G_v; \)
Overall Free Spectral Range: \( \text{FSR}_v = \frac{\text{FSR}_{\text{filter}} \cdot \text{FSR}_{\text{sensor}}}{|\Delta \text{FSR}|}; \)

Second regime

Homogeneous sensing refractive index variations:
\( \Delta n_{c,\text{min}} = n_g \frac{\Delta \text{FSR}}{\lambda_{\text{res}}} S_{\lambda}^{-1}; \quad \Delta n_{c,\text{max}} = \frac{\text{FSR}_v}{S_{\lambda,v}}; \)
Surface sensing refractive index variations:
\( \Delta t_{\text{ad, min}} = n_g \frac{\Delta \text{FSR}}{\lambda_{\text{res}}} S_{\lambda}^{-1}; \quad \Delta t_{\text{ad, max}} = \frac{\text{FSR}_v}{S_{\lambda,v}}. \)
MODELING OF ADVANCED PHOTONIC ARCHITECTURES BASED ON RESONANT MICROCAVITIES

Generalized approach

Mason’s rule

Delay line signal processing

Z-Transform domain

Resonant microcavity

IN

\( k_1 \)

OUT

\( k_2 \)

Loss-free directional couplers (\( q_1 = q_2 = 0 \))

Signal Flow Graph

\[ T_f(z) = \frac{Y(z)}{X(z)} = \frac{q_1 q_2 S_1 S_2 \sqrt{\gamma_1} z^{-1}}{1 - q_1 q_2 C_1 C_2 \gamma_1 z^{-1}} \]

\( \gamma = \exp(-\alpha \cdot L) \)

\( z = \exp(-j 2\pi T \nu) \)

\[ T = \frac{L \cdot n_{\text{eff}}}{c} \Rightarrow FSR = \frac{1}{T} = \frac{c}{L \cdot n_{\text{eff}}} \]

Plot

Transmittance

\( \lambda = 3.39 \mu m \)

\( \exp(-\gamma \cdot L) \)

\( \exp(-j 2\pi T \nu) \)

1

2

1
Signal Flow Graph of a Vernier architecture based on cascade-coupled racetrack resonators.

\[ T_v(\tilde{z}) = \frac{S_1 S_2 S_3 S_4 \sqrt{\gamma_1 \gamma_2 \tilde{z}_1^{-1} \tilde{z}_2^{-1}}}{1 - C_1 C_2 \gamma_1 \tilde{z}_1^{-1} - C_3 C_4 \gamma_2 \tilde{z}_2^{-1} + C_1 C_2 C_3 C_4 \gamma_1 \gamma_2 \tilde{z}_1^{-1} \tilde{z}_2^{-1}} \]

Mason’s rule direct formulation.

\[ T_v(\tilde{z}) = \frac{S_1 S_2 \sqrt{\gamma_1 \tilde{z}_1^{-1}}}{1 - C_1 C_2 \gamma_1 \tilde{z}_1^{-1}} \times \frac{S_3 S_4 \sqrt{\gamma_2 \tilde{z}_2^{-1}}}{1 - C_3 C_4 \gamma_2 \tilde{z}_2^{-1}} \]

Mason’s rule formulation applied to the product of the two cascade-coupled racetrack resonators.
**PHOTONIC SENSORS BASED ON THE VERNIER EFFECT**

Transmittance of the photonic sensor based on the Vernier effect

\[
T_{tot}(z) = T_{filter} \cdot T_{sensor}(n_c)
\]

\[
T_{tot}(z) = \frac{\sqrt{k_1 k_2 k_3 k_4} \sqrt{\gamma_1 \gamma_2 z_{tot}}}{1 - \gamma_1 \gamma_2 z_{tot} - \gamma_2 z_2 \sqrt{(1 - k_1)(1 - k_2)} + \gamma_1 \gamma_2 z_{tot} \sqrt{(1 - k_1)(1 - k_2)(1 - k_3)(1 - k_4)}}
\]

Photonic sensor based on the Vernier effect
**PHOTONIC SENSORS BASED ON THE VERNIER EFFECT**

**OPERATIVE REGIMES**

### FIRST OPERATIVE REGIME

- **Single ring resonator**
  \[
  \Delta \lambda_{\text{sensor}} = \lambda_{\text{sensor}} \cdot \left( \frac{\Delta n_{\text{eff}}}{\Delta n_{c}} \right)
  \]

- **Gain Factor**
  \[
  G = \frac{\text{FSR}_{\text{filter}}}{\Delta \text{FSR}}
  \]

### SECOND OPERATIVE REGIME

- **Cascaded ring resonators**
  \[
  \Delta \lambda_{\text{tot}} = \Delta \lambda_{\text{sensor}} \cdot G
  \]
  \[
  S_{\lambda,\text{tot}} = \Delta \lambda_{\text{tot}} / \Delta n_{c} = S_{\lambda} \cdot G
  \]

\[
\Delta \text{FSR} > \Delta \lambda_{\text{FWHM (filter, sensor)}} \]

\[
\Delta \text{FSR} < \Delta \lambda_{\text{FWHM (filter, sensor)}}
\]

[second regime]
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Vernier sensors based on cascaded ring resonator and MZI

Working Principle & Transfer Function

Working principle

\[ E_i = \bar{e}_0(x, y)e^{-j\Phi_i}e^{-j\phi_i} ; \quad i = (1,2) \]

\[ E_{out} = 2\bar{e}_0(x, y)e^{-j\Phi_2}e^{-j\phi_2}\cos(\Delta\phi/2) \]

\[ \Delta\Phi = \Phi_2 - \Phi_1 \]

\[ T = \left| \frac{E_{out}}{E_{in}} \right|^2 = \left( \cos\left( \frac{\Delta\phi}{2} \right) \right)^2 \]

The phase difference between the two arms carries the information about the substance to be detected. One of the two arms is exposed to the analyte by means of a sensitive area.

Interrogation schemes

- Amplitude interrogation;
- Wavelength interrogation.


MACH – ZEHNDER INTERFEROMETER SENSORS
AMPLITUDE AND WAVELENGTH INTERROGATION

Output power varying sinusoidally depends on the concentration of the detecting substance

Zero-transmittance wavelength varying linearly with the concentration of the detecting substance/analyte

$$\Delta \lambda_{MZI} = \frac{\lambda_m}{\Delta n_{g,MZI}} S_w \Delta n_c$$

MZI wavelength shift can be $G_S$ times the RR shift.
MACH-ZEHNDER ENHANCED VERNIER EFFECT (RR-MZI)

Mixing architectures, Maximizing Performance

MZI Sensor ↔ Ring resonator

MZI-Enhanced Vernier Sensor

Improvement of MZI refractive index sensing performance compared to RR can be further boosted by cascading a RR and a MZI sensor in order to operate in the second regime of the Vernier effect.
**MACH-ZEHNDER ENHANCED VERNIER SENSORS**

Mixing architectures, Maximizing Performance

Overall wavelength shift of RR-MZI sensors due to cladding refractive index variation:

\[
\Delta \lambda_{tot} = \left( \frac{FSR_{tot}}{FSR_{MZI}} \right) \Delta \lambda_{MZI} = \left( \frac{FSR_{filter}}{\Delta FSR} \right) \Delta \lambda_{MZI} = G_A \cdot \frac{\lambda_m}{\Delta n_{g,MZI}} S_w \Delta n_c
\]

Limit of detection (LOD) of RR-MZI sensors:

\[
LOD = \frac{FSR_{filter} \cdot \Delta n_{g,MZI}}{G_A \cdot \lambda_m \cdot S_w} = \frac{\Delta FSR \cdot \Delta n_{g,MZI}}{\lambda_m \cdot S_w}
\]

Limit of detection (LOD) of standard RR-RR Vernier:

\[
LOD_{RR-RR} = \frac{\Delta FSR \times n_{g(RR)}}{\lambda_{res} S_w}
\]

RR-MZI sensors can exhibit wavelength shifts **14 times larger** as well as limits of detection **1 order of magnitude better** than standard Vernier devices.

---

**Performance parameters for the standard Vernier sensor and the MZI-Enhanced Vernier sensor with SU8 cladding.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Vernier sensor</th>
<th>MZI-Enhanced Vernier sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( FSR_{filter} )</td>
<td>2.791 nm</td>
<td>2.791 nm</td>
</tr>
<tr>
<td>( FSR_{sensor} )</td>
<td>2.776 nm</td>
<td>2.771 nm</td>
</tr>
<tr>
<td>( \Delta FSR )</td>
<td>15.6 pm</td>
<td>19.8 pm</td>
</tr>
<tr>
<td>( G_A )</td>
<td>179.39</td>
<td>140.97</td>
</tr>
<tr>
<td>( \Delta \lambda_{tot} )</td>
<td>3.4 nm</td>
<td>47.3 nm</td>
</tr>
<tr>
<td>( LOD )</td>
<td>8 \cdot 10^{-5} RIU</td>
<td>6 \cdot 10^{-6} RIU</td>
</tr>
</tbody>
</table>

* calculated with \( \Delta n_c = 10^{-4} \)
MACH-ZEHNDER ENHANCED VERNIER SENSORS (RR-MZI)

Pros & Cons

+ Ultra high overall sensitivity;
+ Ultra low LOD;
+ Poor noise sensitivity;
+ Suitable for gas sensing;
+ Many design degrees of freedom.

− Larger bandwidth is required compared to standard Vernier architectures with cascaded ring resonators.

COMPARISON

Limit of detection and dynamic range of Vernier cascaded RR and RR-MZI photonic sensors.

Vernier RR-MZI can exhibit better refractive index sensing performance compared to standard RR Vernier sensors.
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➢ **CONCLUSIONS**
The FSR of the MZI with the Sagnac loop can be changed if compared to the standard MZI by optimized power coupling coefficients, $k_3$ and $k_4$. 
RR-MZI and RR-MZI-Sagnac Vernier Sensors: Comparison

RR-MZI-Sagnac Vernier sensor with balanced MZI

The total Vernier FSR can be halved compared to RR-MZI sensors

Performance are comparable (same sensitivity, gain and LOD)

RR-MZI-Sagnac Vernier sensor with unbalanced MZI

The Vernier FSRs are comparable

Wavelength sensitivity can be double compared to RR-MZI sensors with the same bandwidth

RR-MZI Vernier Sensors with a Sagnac Loop (RR-MZI-Sagnac)

Pros & Cons

+ Same RI performance as RR-MZI Vernier in half the bandwidth (balanced Sagnac-MZI);
+ Double RI performance than RR-MZI in the same bandwidth (unbalanced Sagnac-MZI);
+ Poor noise sensitivity;
+ Suitable for chemical and biochemical sensing;
+ Many design degrees of freedom;
+ To be experimentally verified.

COMPARISON

Vernier RR-MZI-Sagnac can exhibit the same refractive index sensing performance of RR-MZI Vernier sensors in half the bandwidth (balanced MZI).

Vernier RR-MZI-Sagnac can exhibit double refractive index sensing performance compared to RR-MZI Vernier sensors within the same bandwidth (unbalanced MZI).
The contribution of counter-propagating signals can be minimized by optimal design of power coupling coefficient of the ring resonator ($k_1$, $k_2$).
FANO SENSORS IN THE MID-INFRARED

Schematic of a RR-coupled MZI device. Input/output waveguides and MMIZ, the MZI and RR geometrical parameters are labeled.

(top) Theoretical and experimental spectra of a Fano device in a broad spectral range as a function of different values of coupler gap $g$ (a = 400 nm, b = 500 nm, c = 600 nm, d = 700 nm, e = 800 nm, f > 1000 nm).

(left) Zoomed plot of a Fano-shape resonance ($g = 400$ nm).

**Photonic Vernier Sensors: Readout Techniques**

**Intensity readout scheme:**

A low-cost broadband source (e.g., LED) can be used to this purpose. The overlapping integral between the LED spectral power distribution and the Vernier ones, can be used for the detection.

\[
P_s = \int_0^\infty [P_i(\lambda)T_r(\lambda)T_s(\lambda)]d\lambda
\]
Photonic Vernier Sensors: Readout Techniques

Wavelength readout scheme:

A sophisticated and generally expensive OSA (optical spectrum analyzer) can be used for detecting $P_0$ and $P_1$. The sensitivity can be enhanced up to three orders of magnitude.

Other approaches:
- Use of a reference Vernier device to be cascade-coupled to that employed for sensing purposes. Integrated microheaters on the «sensing» ring resonator of the reference device can generate Vernier peak wavelength shifts opposite to those of the sensing Vernier architecture.
OUTLINE

➢ Photonic sensing applications

➢ Photonic devices for sensing applications
  ▪ Design of photonic waveguides;
  ▪ Optical sensing principles;
  ▪ Group IV material systems and alloys.

➢ Photonic architectures based on Vernier effect
  ▪ The Vernier effect for photonic sensing;
  ▪ Vernier sensors based on cascaded microring resonators;
  ▪ Vernier sensors based on cascaded ring resonator and MZI;
  ▪ Vernier sensors based on cascaded ring resonator and MZI with a Sagnac loop.

➢ Advanced photonic sensors operating in the near-IR and mid-IR
  ▪ Sensing principles for gas detection in the mid-IR;
  ▪ Photonic sensors based on the Vernier effect for methane and ethane detection;
  ▪ Experimental demonstration of the Vernier effect in integrated Photonics.

➢ Conclusions
DESIGN OF PHOTONIC GAS SENSORS OPERATING IN THE MID-IR

Explosion limits of harmful gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lower Explosive Limit LEL (%)</th>
<th>Upper Explosive Limit UEL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butane (C₄H₁₀)</td>
<td>1.8</td>
<td>8.4</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>12.5</td>
<td>74.0</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>5.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Ethane (C₂H₆)</td>
<td>3.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>2.1</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Optical sensing principles

Homogeneous sensing

\[ n_{\text{mixture}} = n_{\text{gas}} \cdot C_{\text{gas}} + n_{\text{air}} \cdot C_{\text{air}} \]

\[ C_{\text{air}} = 1 - C_{\text{gas}} \]

\( CH_4 \) refractive index = 1.000444 @ 3.39μm

Air refractive index = 1 @ 3.39μm

<table>
<thead>
<tr>
<th>Methane (CH₄)</th>
<th>( C_{\text{CH₄}} )</th>
<th>( C_{\text{air}} )</th>
<th>( n_{\text{mixture}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEL = 5%</td>
<td>0.05</td>
<td>0.95</td>
<td>1.0000222</td>
</tr>
<tr>
<td>UEL = 15%</td>
<td>0.15</td>
<td>0.85</td>
<td>1.0000666</td>
</tr>
</tbody>
</table>

Optical absorption

\[ I = I_0 \exp(-\alpha_{\text{gas}} \cdot L_{\text{sensore}}); \quad \alpha_{\text{gas}} = \varepsilon \cdot C_{\text{gas}} \]

\[ \alpha_{\text{tot}} = \alpha + C_{\text{gas}} \cdot \Gamma_s \cdot \alpha_{\text{gas}}(\lambda) + C_{\text{air}} \cdot \Gamma_s \cdot \alpha_{\text{air}}(\lambda) \]

Design requirements

\[ \Delta n_{c,\text{min}} = 2.22 \times 10^{-5} \text{ RIU (limit of detection – LOD)} \]

\[ \Delta n_{c,\text{max}} = 6.66 \times 10^{-5} \text{ RIU} \]
APPLICATION OF THE DESIGN TOOL: VERNIER DEVICES FOR GAS SENSING

Homogeneous sensing

\[ n_{\text{mix}} = n_{\text{gas}} \cdot C_{\text{gas}} + n_{\text{air}} \cdot C_{\text{air}}, \text{ with } C_{\text{air}} = 1 - C_{\text{gas}} \]

<table>
<thead>
<tr>
<th>( E L_{CH_4} )</th>
<th>( C_{CH_4} )</th>
<th>( C_{air} )</th>
<th>( n_{\text{mix}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEL = 5%</td>
<td>0.05</td>
<td>0.95</td>
<td>1.00002185</td>
</tr>
<tr>
<td>UEL = 15%</td>
<td>0.15</td>
<td>0.85</td>
<td>1.00006555</td>
</tr>
</tbody>
</table>

\[ \Delta n_{c,\text{min}} = n_{CH_4,LEL} - n_{air} = 2.185 \times 10^{-5} \text{ RIU}; \]
\[ \Delta n_{c,\text{max}} = n_{CH_4,UEL} - n_{air} = 6.555 \times 10^{-5} \text{ RIU}. \]

Absorption based sensing:

Methane absorption spectrum in the MIR.

\[ \alpha_{\text{mix}} = \alpha_{\text{gas}}(\lambda) \cdot C_{\text{gas}} \cdot \Gamma_c + \alpha_{\text{air}}(\lambda) \cdot C_{\text{air}} \cdot \Gamma_c \]

Flowchart of the algorithmic procedure developed for the design of ultra-high performance Vernier photonic sensors
DESIGN OF PHOTONIC GAS SENSORS OPERATING IN THE MID-IR

Operation of the SINGLE RING RESONATOR supposed to be exposed to a CH$_4$ concentration of 15%

\[ \Delta T_{\text{peak}} \approx 0.25 \text{ (a.u.)} \]
\[ \Delta \lambda_{\text{peak}} \approx 130 \text{pm} \]

Cavity length $\approx 270 \mu$m

Performance

\[ S_\lambda = S_w \frac{\lambda}{n_{\text{eff}}} = 1966 \left( \frac{\text{nm}}{\text{RIU}} \right) \]

\[ \text{LOD} = \frac{\Delta \lambda}{S_\lambda} = 4.0694 \times 10^{-5} \left( \text{RIU} \right) \]

Minimum resolution assumed for the optical spectrum analyzer (OSA): $\Delta \lambda = 80 \text{pm}$

Comment

The wavelength shift of the resonant peak calculated in case of a methane concentration of 5% is lower than 80 pm, but it can be still detected by a high performance OSA!

In addition, the LOD achieved by this sensor does not satisfy design requirements (LOD = $2.22 \times 10^{-5}$ RIU)!
### Design of Photonic Gas Sensors Operating in the Mid-IR

**Performance**

<table>
<thead>
<tr>
<th></th>
<th>Single ring resonator</th>
<th>Vernier sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_\lambda$</td>
<td>1.966 µm/RIU</td>
<td>224.4 µm/RIU</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>†0.130 nm</td>
<td>*4.982 nm</td>
</tr>
<tr>
<td>$FSR_{tot}$</td>
<td>6.5825 nm</td>
<td>484.3 nm</td>
</tr>
<tr>
<td>LOD</td>
<td>$4.0694 \times 10^{-5}$ RIU</td>
<td>$1.9568 \times 10^{-5}$ RIU</td>
</tr>
</tbody>
</table>

† induced by $\Delta n_c = 6.66 \times 10^{-5}$ RIU

* induced by $\Delta n_c = 2.22 \times 10^{-5}$ RIU

**Comparison between theoretical results of single ring resonator and photonic sensor based on the Vernier effect:**

- $\Delta \lambda_{peak} = 0$ nm (Reference @ 3.39 µm)
- $\Delta \lambda_{peak} = 9$ nm
- $\Delta \lambda_{peak} = 18$ nm
- $\Delta \lambda_{peak} = 31$ nm

**Methane (CH₄) signature**

- $c_{CH₄} = 0\%$
- $c_{CH₄} = 5\%$
- $c_{CH₄} = 10\%$
- $c_{CH₄} = 15\%$
**Design of Photonic Gas Sensors Operating in the Mid-IR**

Operation of the photonic sensor based on the Vernier effect as a function of different methane concentrations.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Numerical results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{filter}}$</td>
<td>1200.4 µm</td>
</tr>
<tr>
<td>$L_{\text{sensor}}$</td>
<td>1516.25 µm</td>
</tr>
<tr>
<td>$\Delta n_{c,\text{min}}$</td>
<td>$1.9568 \times 10^{-5}$ RIU</td>
</tr>
<tr>
<td>$\Delta n_{c,\text{max}}$</td>
<td>$2.158 \times 10^{-3}$ RIU</td>
</tr>
<tr>
<td>$\Delta FSR$</td>
<td>39.46 pm</td>
</tr>
<tr>
<td>$S_{\lambda,\text{tot}}$</td>
<td>224.4 µm/RIU</td>
</tr>
<tr>
<td>$FSR_{\text{tot}}$</td>
<td>484.3 nm</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{tot}}$</td>
<td>4.982 nm (induced by $\Delta n_c = 2.22 \times 10^{-5}$)</td>
</tr>
<tr>
<td>$G$</td>
<td>111.3</td>
</tr>
</tbody>
</table>

**“Digital” sensor**

($\alpha_{\text{CH}_4} = 0$)

- Dynamic range = 13 nm;
- Number of quantization levels = 4;

($\alpha_{\text{CH}_4} \neq 0$)

- Dynamic range = 31 nm;
- Number of quantization levels = 8;
Design of photonic gas sensors operating in the mid-IR

Explosion limits of harmful gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>LEL (%)</th>
<th>UEL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butane (C₄H₁₀)</td>
<td>1.8</td>
<td>8.4</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>12.5</td>
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</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>2.1</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Optical sensing principles

Homogeneous sensing

\[
\begin{align*}
    n_{\text{mixture}} &= n_{\text{gas}} \cdot C_{\text{gas}} + n_{\text{air}} \cdot C_{\text{air}} \\
    C_{\text{air}} &= 1 - C_{\text{gas}}
\end{align*}
\]

Linear approximation

**C₂H₆** refractive index = 1.00076 @ 3.39μm
Air refractive index = 1 @ 3.39μm

<table>
<thead>
<tr>
<th>Ethane (C₂H₆)</th>
<th>C_{C₂H₆}</th>
<th>C_{air}</th>
<th>n_{mixture}</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEL = 3%</td>
<td>0.03</td>
<td>0.97</td>
<td>1.0000228</td>
</tr>
<tr>
<td>UEL = 12.5%</td>
<td>0.125</td>
<td>0.875</td>
<td>1.000095</td>
</tr>
</tbody>
</table>

Design requirements

- Δn_{c,\text{min}} = 2.28×10⁻⁵ RIU (limit of detection – LOD)
- Δn_{c,\text{max}} = 9.5×10⁻⁵ RIU

Optical absorption

\[
I = I₀ \exp(-\alpha_{\text{gas}} L_{\text{sensore}}; \quad \alpha_{\text{gas}} = \varepsilon C_{\text{gas}}
\]

\[
\alpha_{\text{tot}} = \alpha + C_{\text{gas}} \cdot \Gamma_s \cdot \alpha_{\text{gas}}(\lambda) + C_{\text{air}} \cdot \Gamma_s \cdot \alpha_{\text{air}}(\lambda)
\]
Design of photonic gas sensors operating in the mid-IR

$\Delta \lambda_{peak} = 0 \text{nm}$
Reference @ 3.39$\mu$m

$\Delta \lambda_{peak} = 9 \text{nm}$

$\Delta \lambda_{peak} = 18 \text{nm}$

$\Delta \lambda_{peak} = 27 \text{nm}$

Ethane (C$_2$H$_6$) signature

ETHANE
**DESIGN OF PHOTONIC GAS SENSORS OPERATING IN THE MID-IR**

Operation of the photonic sensor based on the Vernier effect as a function of different ethane concentrations.

### Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{filter}}$</td>
<td>1200.4 µm</td>
</tr>
<tr>
<td>$L_{\text{sensor}}$</td>
<td>1516.25 µm</td>
</tr>
<tr>
<td>$\Delta n_{c,\text{min}}$</td>
<td>$2.0096 \times 10^{-5}$ RIU</td>
</tr>
<tr>
<td>$\Delta n_{c,\text{max}}$</td>
<td>$2.2163 \times 10^{-3}$ RIU</td>
</tr>
<tr>
<td>$\Delta FSR$</td>
<td>39.46 pm</td>
</tr>
<tr>
<td>$S_{\lambda,\text{tot}}$</td>
<td>218.51 µm/RIU</td>
</tr>
<tr>
<td>$FSR_{\text{tot}}$</td>
<td>484.3 nm</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{tot}}$</td>
<td>4.982 nm (induced by $\Delta n_c = 2.28 \times 10^{-5}$)</td>
</tr>
<tr>
<td>$G$</td>
<td>111.3</td>
</tr>
</tbody>
</table>

### Numerical results

- Dynamic range = 31 nm - CH$_4$
- Dynamic range = 27 nm - C$_2$H$_6$

#### “Digital” sensor

- $\alpha_{\text{C2H6}} = 0$
- Dynamic range = 27 nm;
- Number of quantization levels = 7;

---

**PHOTONICS RESEARCH GROUP**
DESIGN AND FABRICATION OF SOI RIB WAVEGUIDES OPERATING IN THE MID-IR (IN COLLABORATION WITH ORC – UNIVERSITY OF SOUTHAMPTON)

SOI rib waveguide designed at $\lambda = 3.75 \, \mu m$ (H = 220 nm).

SEM image of a SOI rib waveguide.

Real waveguide dimensions after the fabrication:
• 407 nm-thick Si top layer ($h$);
• Etch depth of 234 nm ($d$);
• Silicon slab of 173 nm;
• Sidewall tilting angle $\approx 90^\circ$.

$$\alpha = 1.46 \pm 0.2 \, \frac{dB}{cm} @ 3.77 \, \mu m$$
DESIGN OF SOI DIRECTIONAL COUPLERS BASED ON RIB WAVEGUIDES OPERATING IN THE MID-IR

3D map of the power coupling coefficient as a function of fabrication tolerances

SOI directional couplers based on rib waveguides and designed at $\lambda = 3.75 \, \mu m$ [4].

- $g_0$ is the constant directional coupler gap in the coupling region;
- $L_i$ is the interaction length;
- $R$ is the ring resonator radius;
- $L_{tr}$ is the transition length ($\frac{3}{4} \, R$);
- $g(z)$ is the $z$-dependent directional coupler gap in the transition region;

2D map of the power coupling coefficient as a function of the directional coupler gap $g_0$. 

- $g_0$ is the constant directional coupler gap in the coupling region;
- $L_i$ is the interaction length;
- $R$ is the ring resonator radius;
- $L_{tr}$ is the transition length ($\frac{3}{4} \, R$);
- $g(z)$ is the $z$-dependent directional coupler gap in the transition region;
EXPERIMENTAL RESULTS OF SOI DIRECTIONAL COUPLERS BASED ON RIB WAVEGUIDES OPERATING IN THE MID-IR (~3.8 M) AND NEAR-IR
DESIGN AND FABRICATION OF RING RESONATORS IN THE MID-IR
**DESIGN AND FABRICATION OF RING RESONATORS IN THE MID-IR**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Vernier #A</th>
<th>Vernier #B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Racetrack label</strong></td>
<td>Ring #1</td>
<td>Ring #2</td>
</tr>
<tr>
<td>FSR (nm)</td>
<td>5.33</td>
<td>5.06</td>
</tr>
<tr>
<td>L (μm)</td>
<td>714</td>
<td>753.5</td>
</tr>
<tr>
<td>R (μm)</td>
<td>98</td>
<td>104</td>
</tr>
<tr>
<td>Lᵢ (μm)</td>
<td>49.2</td>
<td>50</td>
</tr>
<tr>
<td>g₀ (nm)</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>ILavg (dB)</td>
<td>1.77</td>
<td>1.33</td>
</tr>
<tr>
<td>ERmax (dB)</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>Q-factor</td>
<td>~ 2,900</td>
<td>~ 2,500</td>
</tr>
<tr>
<td>ΔλFWHM (nm)</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Vernier A: n = 19**

18/19 = 0.947

(control over the third decimal digit)

**Vernier B: n = 28**

27/28 = 0.964

\[
\frac{FSR'}{FSR''} = \frac{L'}{L''} = \frac{n - 1}{n}
\]
CASCADE-COUPLED RACETRACK RESONATORS IN THE MID-IR

Legend:
- Sensing ring
- Filtering ring
- Vernier

Fabrication of devices at ORC (Southampton) by:
1) e-beam lithography
2) dry etching

Micrograph of a representative Vernier device.
### Optical parameters

<table>
<thead>
<tr>
<th></th>
<th>Vernier #A</th>
<th>Vernier #B</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL (dB)</td>
<td>3.6</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>ER (dB)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Q-factor</td>
<td>8,000</td>
<td>3,200</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{Vernier}}$ (nm)</td>
<td>$\sim 5.5$</td>
<td>$\sim 14$</td>
</tr>
<tr>
<td>$\Delta$FSR (nm)</td>
<td>0.27</td>
<td>0.74</td>
</tr>
<tr>
<td>FSR$_{\text{Vernier}}$ (nm)</td>
<td>98</td>
<td>249</td>
</tr>
<tr>
<td>G</td>
<td>19.40</td>
<td>18.87</td>
</tr>
</tbody>
</table>

**Lengths:** > 700 µm

**SOI rib waveguides**

**Vernier A:** $n = 19$

**mid infrared range**
CASCADE-COUPLED RACETRACK RESONATORS – SHORT RACETRACKS

Optical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vernier #A</th>
<th>Vernier #B</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL (dB)</td>
<td>3.6</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>ER (dB)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Q-factor</td>
<td>8,000</td>
<td>3,200</td>
</tr>
<tr>
<td>Δλ_{Vernier} (nm)</td>
<td>~ 5.5</td>
<td>~ 14</td>
</tr>
<tr>
<td>ΔFSR (nm)</td>
<td>0.27</td>
<td>0.74</td>
</tr>
<tr>
<td>FSR_{Vernier} (nm)</td>
<td>98</td>
<td>249</td>
</tr>
<tr>
<td>G</td>
<td>19.40</td>
<td>18.87</td>
</tr>
</tbody>
</table>

Lengths < 300 µm
SOI rib waveguides
Vernier B: n = 28

mid infrared range
### Cascade-Coupled Racetrack Resonators

#### Optical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vernier #A</th>
<th>Vernier #B</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL (dB)</td>
<td>3.85</td>
<td>2.39</td>
</tr>
<tr>
<td>ER (dB)</td>
<td>16.97</td>
<td>18.19</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{Vernier}}$ (nm)</td>
<td>$\sim 4$</td>
<td>$\sim 6$</td>
</tr>
<tr>
<td>$\Delta \text{FSR}$ (nm)</td>
<td>0.19</td>
<td>0.32</td>
</tr>
<tr>
<td>$\text{FSR}_{\text{Vernier}}$ (nm)</td>
<td>71.81</td>
<td>99.32</td>
</tr>
<tr>
<td>$G$</td>
<td>19.94</td>
<td>18.12</td>
</tr>
</tbody>
</table>

SOI wire waveguides

*Mid infrared range*
SENSING FUNCTIONALITIES

- PDMS microfluidic channel placed on top of the SOI chip. Perfluorodecalin (a liquid fluorocarbon to dissolve gases), which is low loss at mid-infrared wavelengths, has been used as liquid sample in the sensing chamber.

Without liquid

With liquid
(wavelength shift of ~38 nm)
**Germanium Vernier-effect ring resonators (for longer wavelengths ~10 micron)**

Cross-sectional view of the Ge-on-Si waveguide operating at 3.8 μm.

First experimental demonstration of integrated ring resonator based on Ge-on-Si technology platform operating in the mid-IR. A quality factor of $Q \sim 1,700$ has been achieved.

$$\frac{FSR''}{FSR'} = \frac{L'}{L''} = \frac{n - 1}{n}$$

Vernier A: $n = 45$, $G = 43.4$

Vernier B: $n = 27$, $G = 25.4$

**Table 1. Geometrical Parameters of Vernier #A and Vernier #B Architectures**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Vernier #A</th>
<th>Vernier #B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ (μm)</td>
<td>RR #A1 439.60</td>
<td>RR #A2 449.60</td>
</tr>
<tr>
<td>$R$ (μm)</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>$L_i$ (μm)</td>
<td>34.44</td>
<td>39.44</td>
</tr>
<tr>
<td>$\xi_0$ (nm)</td>
<td>450</td>
<td>450</td>
</tr>
</tbody>
</table>
**GERMANIUM VERNIER-EFFECT RING RESONATORS**

Vernier #B spectra in the mid-IR.

A good agreement between theoretical and experimental spectra can be seen.

The periodicity of the Vernier spectra cannot be measured because of the limited laser wavelength range.

---

**Device dimensions:**
- Ring radius = 77 μm;
- Overall length = 500.7 μm;
- Directional coupler gap = 500 nm;
- Interaction length = 8.4474 μm.

**Extinction ratio is a function of wavelength-dependent coupling coefficient**
**EXPERIMENTAL DEMONSTRATION OF THE VERNIER EFFECT IN THE NIR-IR**

Vernier configuration operating in the second regime: very good agreement between theory and experiments in near-IR.

**Device dimensions:**
- Ring radius (filter) = 77 μm
- Ring radius (sensor) = 79 μm
- Ring radius (filter) = 49 μm
- Ring radius (sensor) = 52 μm
Experimental demonstration of the Vernier effect in the near-IR

Vernier configuration operating in the second regime: very good agreement between theory and experiments.

<table>
<thead>
<tr>
<th>Device</th>
<th>$FSR_v$ (nm)</th>
<th>$FSR_{v,exp}$ (nm)</th>
<th>$\varepsilon_{r,FSR_v}$ %</th>
<th>$G$</th>
<th>$G_{exp}$</th>
<th>$\varepsilon_{r,G}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>35.86</td>
<td>35.50</td>
<td>1.00</td>
<td>20.18</td>
<td>20.20</td>
<td>-0.09</td>
</tr>
<tr>
<td>B</td>
<td>35.86</td>
<td>35.61</td>
<td>0.69</td>
<td>30.28</td>
<td>30.30</td>
<td>-0.06</td>
</tr>
<tr>
<td>C</td>
<td>9.00</td>
<td>8.89</td>
<td>1.22</td>
<td>17.42</td>
<td>17.30</td>
<td>0.68</td>
</tr>
<tr>
<td>D</td>
<td>7.91</td>
<td>7.84</td>
<td>0.88</td>
<td>16.53</td>
<td>16.40</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Reducing the Vernier FSR and Vernier gain going from A to D.
OUTLINE

➢ PHOTONIC SENSING APPLICATIONS

➢ PHOTONIC DEVICES FOR SENSING APPLICATIONS
  ▪ Design of photonic waveguides;
  ▪ Optical sensing principles;
  ▪ Group IV material systems and alloys.

➢ PHOTONIC ARCHITECTURES BASED ON VERNIER EFFECT
  ▪ The Vernier effect for photonic sensing;
  ▪ Vernier sensors based on cascaded microring resonators;
  ▪ Vernier sensors based on cascaded ring resonator and MZI;
  ▪ Vernier sensors based on cascaded ring resonator and MZI with a Sagnac loop.

➢ ADVANCED PHOTONIC SENSORS OPERATING IN THE NEAR-IR AND MID-IR
  ▪ Sensing principles for gas detection in the mid-IR;
  ▪ Photonic sensors based on the Vernier effect for methane and ethane detection;
  ▪ Experimental demonstration of the Vernier effect in integrated Photonics.

➢ CONCLUSIONS
**Conclusions**

Ultra-high performance photonic sensors based on Vernier effect

- *Real-time* monitoring;
- High-throughput screening;
- Immunity to electromagnetic interferences;
- Intensity and wavelength optical readouts;
- Customizable photonic sensor designed as a function of the sensing application.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Performance @ 3.39 μm</th>
<th>m-xilene detection</th>
<th>Pb(II) detection in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>149.74 μm/RIU</td>
<td>182.36 μm/RIU</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt; 60 ppm</td>
<td>&lt; 50 ppb</td>
<td></td>
</tr>
<tr>
<td>Limit of detection (LOD)</td>
<td>4.0403×10⁻⁶ RIU</td>
<td>3.5373×10⁻⁶ RIU</td>
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</tbody>
</table>

**Silicon-on-insulator (SOI) and Germanium-on-Silicon CMOS-compatible technologies**

- CMOS-compatible;
- Small footprint (~mm²);
- Large scale production;
- Low cost;
- *Lab-on-chip* (state-of-the-art).

<table>
<thead>
<tr>
<th>Performance @ 3.39 μm</th>
<th>methane</th>
<th>ethane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>224.4 μm/RIU</td>
<td>218.51 μm/RIU</td>
</tr>
<tr>
<td>Resolution [% in air volume]</td>
<td>~ 2 %</td>
<td>~ 1 %</td>
</tr>
<tr>
<td>Limit of detection (LOD)</td>
<td>1.9568×10⁻⁵ RIU</td>
<td>2×10⁻⁵ RIU</td>
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</tbody>
</table>
Some papers on integrated photonic sensors and Vernier effect devices