Integrated photonic systems for applications in telecommunications and biosensing

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McGill Institute for Advanced Materials
McGill University

Founded in 1813
Situated in heart of Montreal
Has about 30,000 students
Instruction is in English

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Integrated photonic systems
## Current projects

### Planar waveguide devices
- Etched grating demultiplexer
- Photonic crystal superprism
- Photonic crystal wavelength conversion
- Hybrid laser integration
- Fabry-Perot comb filter switch

### Biosensors
- Integrated SPR
- Grating-enhanced SPR
- Spectro-angular SPR
- Plasmonic polymer
- Cavity ring down resonant sensing
- Nano-crystalline cellulose
# Current projects

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Distributed Etched Diffraction Grating (DEDG)

- Deeply etched sidewalls replaced by distributed reflector
  - E. Bisaillion and A. Kirk, IEEE-LEOS Annual meeting 2006
- Single shallow etch depth simplifies fabrication
- Dispersive and reflective properties tailored individually
  - This work
Distributed Etched Diffraction Grating

**Reflective properties**
Reflectivity and bandwidth determined by
- Etch depth (index contrast)
- Bragg order (periodicity $\Lambda$)
- Number of periods

**Dispersive properties**
Resolution, free spectral range, number of channels:
- Operating diffraction order
- Periodicity ($d$)
- Facet size ($s$)
- Number of periods
- Blaze angle
- Focal length
Experimental demonstration in SOI 4 channel, CWDM, 3rd order gratings

Fabricated at IMEC (ePIXfab) via deep UV lithography
Performance

- 4 channel CWDM
- TE polarization
- 5 dB insertion loss
- 25 dB crosstalk
Spectral engineering

E.g. Dual band operation (simulation)

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Interferometric electro-optic switches

- Integrated Mach-Zender waveguide switches developed 30 years ago, demonstrated in LiNbO$_3$
- Scaling beyond 8x8 challenging due to waveguide bend limits
- Electro-optic switches based on Fabry-Perot etalon filters are typically narrow band due to small $\Delta n$
- However there is the possibility of using free-space slab approach for better scalability

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Filter Design: Comb Response

- EO effect shifts the filter response by 1 nm only
- Reduced the filter free-spectral range to create a comb filter with a 200 GHz Spacing
- Bandwidth > 30 nm

M. Menard, A.G. Kirk, 'Integrated Fabry-Perot Comb Filters for Optical Space Switching', *J. Lightwave Technol.*, 28, pp 768-775, 2010
Four coupled cavities, 2\textsuperscript{nd} order mirrors

Chromatic dispersion (simulated):

Spectral response (simulated):
Integrated 2 x 2 optical switch

GaAs material system

$\text{Al}_{0.06}\text{Ga}_{0.94}\text{As} (0.6 \text{ um})$

$\text{GaAs} (2.1 \text{ um})$

$\text{Al}_{0.06}\text{Ga}_{0.94}\text{As} (5.5 \text{ um})$

Input 1
Collimating Mirror

Output 1
Alignment Waveguides

Output 2

FP Cavities


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Prototype Spectral Response

- Fabrication errors shifted the response to the L-band and reduced cavity coupling
- High loss (20 dB) due to misalignment of the input/output waveguides. Additional loss due to filters < 1dB
Prototype Channel Performance

- Fluctuation in crosstalk and extinction ratio due to ripples in the wavelength response
• Transmission power penalty caused by the combination of collimation & radiation, which brought the output power below the SOA sensitivity floor
Switch Fabric Layouts

3x3 Crossbar

4x4 Shuffle Benes

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Photonic biosensor Types

- SPR Biosensor
- Interferometer Biosensor
- Photonic Crystal Biosensor
- Waveguide Biosensor
- Optical Fiber Biosensor
- Micro-Cavity Biosensor
Motivation

1. Improving Sensitivity for Biomarker-Based Diagnosis

2. Drug discovery
Motivation:
Improving Sensitivity for Biomarker-Based Diagnosis

**Biosensor Requirements**

- Multiple biomarker detection for effective diagnosis
- Small proteins (< 100 kDa)
- Low concentration pg – ng/mL
- Require Real-time sampling and on-going measurement for fluctuations
- Label free
- Integrated biosensor

**Nanostructure and Nanoparticles**

Signal Amplification
Transduction mechanisms

- Affinity of sensor is determined by functionalized surface
- Many transduction mechanisms exist:
  - Mass sensing
    - E.g. Quartz crystal microbalance
  - Electrical sensing
    - E.g. Capacitative sensing
  - Optical sensing
    - Evanescent wavesensors
    - Surface plasmon resonance (SPR) sensors
Surface plasmon polariton

- Surface plasmon: electron density wave on a metal, excited by incident light
- Plasmon excited when momentum of incoming wave matches that of plasmon
- Results in reflectance dip

\[ k_{sp} = \frac{\omega}{c} \sqrt{\frac{\varepsilon_D \varepsilon_m}{\varepsilon_D + \varepsilon_m}} \]

\( \omega \): frequency, \( \varepsilon \): dielectric constant; \( c \): speed of light
Surface Plasmon Resonance Sensing

- Label-free sensing technique
- Picomolar concentrations detectable
- $10^{-6} - 10^{-8}$ refractive index units

\[ \theta_{res} \approx \sin^{-1} \left( \frac{1}{n_S} \sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}} \right) \]
Commercial SPR

Several commercial SPR analysis systems exist

Biacore

SPREETA (Sensata Inc)
Angle scanning sensors

• E.g. Biacore
Angular spectrum sensor

- SPREETA sensor
Integated SPR sensor

- Angle sensing SPR

- **Objective:** Replace external focusing optics with moldable diffractive elements on disposable sensor head


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Fabricated device

- Surface plasmon resonance sensing
- Complete optical system integrated onto sensor chip

8-level diffractive cylindrical mirror etched in fused silica

Etch profile
(800 nm depth)
Results: Refractive index measurement (NaCl solution)

$$\Delta \theta = 126.45 \, n - 168.11$$

Noise limit: $2.5 \times 10^{-5}$ RIU

## Integrated Nanophotonics Research Group

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Enhancing SPR response

• To increase SPR sensitivity we need to amplify the effects of small changes in refractive index at the surface

• Sensitivity is measured as either:
  – Change in dip angle vs. refractive index ($\Delta \theta / \Delta RIU$) or
  – Change is dip wavelength vs. refractive index ($\Delta \lambda / \Delta RIU$)

• Two possible approaches:
  – Increase field concentration and penetration (e.g. use nanoparticles)
  – Use optically resonant structures
Periodic metallic gratings

Flat surface dispersion curve

Incident light
Prism/Si
Metal film
SP

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Periodic metallic gratings

- Creates bandgap in dispersion curve

Bandgap appears at Bragg wavelength:

\[ \Lambda_B = \frac{\lambda_{sp}}{2} \]
Effect of grating

- Plasmon propagation is forbidden at the bandgap
- Creates plasmon standing waves:
  - Increases electric field penetration into dielectric
  - Increases speed at which dip moves as a function of refractive index
- Results in increased sensitivity

Rigorous coupled wave analysis simulation for one period of grating

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Sensitivity enhancement

Sinusoidal gratings show a 6 x increase in sensitivity vs. flat

However, for a given wavelength, range is limited. Increase range by measuring in two-dimensions (wavelength and angle)


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Experimental evaluation: Grating + patterned surface chemistry

Protein Absorption Chemistry

- Enhanced SPR response
- Increased electromagnetic gradients
- Surface receptors with optimized orientation, density and non-specific absorption
- Generate biochemical optical contrast

Rigorous Coupled Wave Analysis Modelling

1. Patterned PMMA on gold

Protein Repellent Chemistry (PASSIVE)

Protein Absorption Chemistry (ACTIVE)

Au (Grating)

Cr

Au (Underlaying)

Cr

SF11 Substrate

2. Deposition of gold

Cr

Au (Underlaying)

SF11 Substrate

3. Surface functionalisation 1

• 1 mM of PEO in water
• Overnight incubation

4. Removal of PMMA in solvent

• 1 H in Acetone/MEK
• 1 min ultrasonication

4. Surface functionalisation 2

• 1 min ultrasonication
• 1 mM of MCHA in ethanol
• 3 H incubation time

Characterization via SPR-Imaging

Prism Coupler

Mesa

Trough

Au (Grating)

Cr

Au (Underlaying)

Cr

SF11 Substrate

Mesa Trough

Uniform Control - Flat

Inlet Outlet

LED

Motorized Mirror

Lens

Polarizer

Fluidic Cell

Prism

CCD

Sample
Injection of Anti-TNF-α

1 μg/mL anti-TNF-α

2 μg/mL anti-TNF-α

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SPR-Imaging – Injection of TNF-α

0.5 μg/mL TNF-α (PBS)

- Mapped immobilization is advantageous
- Functionalized trough configuration shows weak response
- Significant improvement is measured in the angular sensitivity
- Increased accessibility of antigen to surface immobilized antibody

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**Planar waveguide devices**

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2D vs. 1D SPR

Why use 2D SPR?

Possibility of using image analysis techniques.
Image Analysis Technique
Associate the weights $w_i$ with initial index $n_i$

\[
\begin{bmatrix}
  w_1 \\
  w_2 \\
  \vdots \\
  w_N
\end{bmatrix} \rightarrow
\begin{bmatrix}
  a_1 \\
  a_2 \\
  \vdots \\
  a_N
\end{bmatrix} \rightarrow
\begin{bmatrix}
  n_1 \\
  n_2 \\
  \vdots \\
  n_N
\end{bmatrix}
\]

Experimental Implementation

Dual channel spectro-angular configuration for measuring SPR in 2D.

- The second channel is used as a reference for drift elimination.
Real-Time Data Analysis

- Real-time output of index estimate (15 frames/sec, 2-4 seconds/sample)
- Monitoring of dip quality in both channels.
- Monitoring of DPM projection curve in both channels.

Channel 1
- SPR dip (top)
- DPM projection, s (bottom)
Spectro-Angular experimental results

Monitoring SAM deposition and BSA binding

- Large RI change due to 70% ethanol (approx. water + 0.02 RIU)
- SAM baseline not quite reached
- Inject SAM in ethanol
- Inject NHS/EDC in ethanol
- Inject 0.003% Tween to flush all non-specific bound BSA
- BSA washing out with continuous buffer flow
- Activated SAM baseline
- Saturation of BSA: both covalent and non-specific binding
- % Diff

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Spectro-Angular as Biosensing Platform

- Oxacillin (mw 441) injections were introduced to flowcell containing BSA:SPR chip
- RIU shift relative to quantity of drug bound
- Illustrates instrument’s utility for drug binding assays where BSA is a substitute for HSA.

Localised surface plasmon resonance

Lycergus cup (British museum)
Collective resonance of nanorods

Nanofabricated gold nanorods (500 nm x 50 nm)

Longitudinal mode

Transverse mode

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Integrated photonic biosensors

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Nanorods in sol-gel

‘Plasmonic sol-gel’: Au Nanorods bound into porous polymer matrix

P. Roche and A. Kirk, unpublished work
Plasmonic polymer: Sensitivity to index change

(a) Longitude LSPR shift

(b) Peak Absorbance

(c) Peak Wavelength

P. Roche and A. Kirk, unpublished work
Summary

• Applications of slab mode propagation in waveguides:
  – Distributed etched grating demultiplexer
  – Integrated comb filter switch

• Surface plasmon resonance sensors
  – Integrated systems
  – Applications of nanostructures and patterned chemistry
  – Spectro-angular (2-D) system
Training program in Integrated Sensor Systems
*McGill, Ecole Polytechnique, Sherbrooke, INRS*

- Multidisciplinary training program focusing on the design, fabrication, integration and packaging of sensors
- 104 graduate and undergraduate students to be trained over 6 years
- Extensive hands-on training in design, fabrication and characterization
- International exchange and industrial internships form a key part of the program
- First graduate trainees will commence in September 2010
- Director: Andrew Kirk