Integrated photonic systems for applications in telecommunications and biosensing

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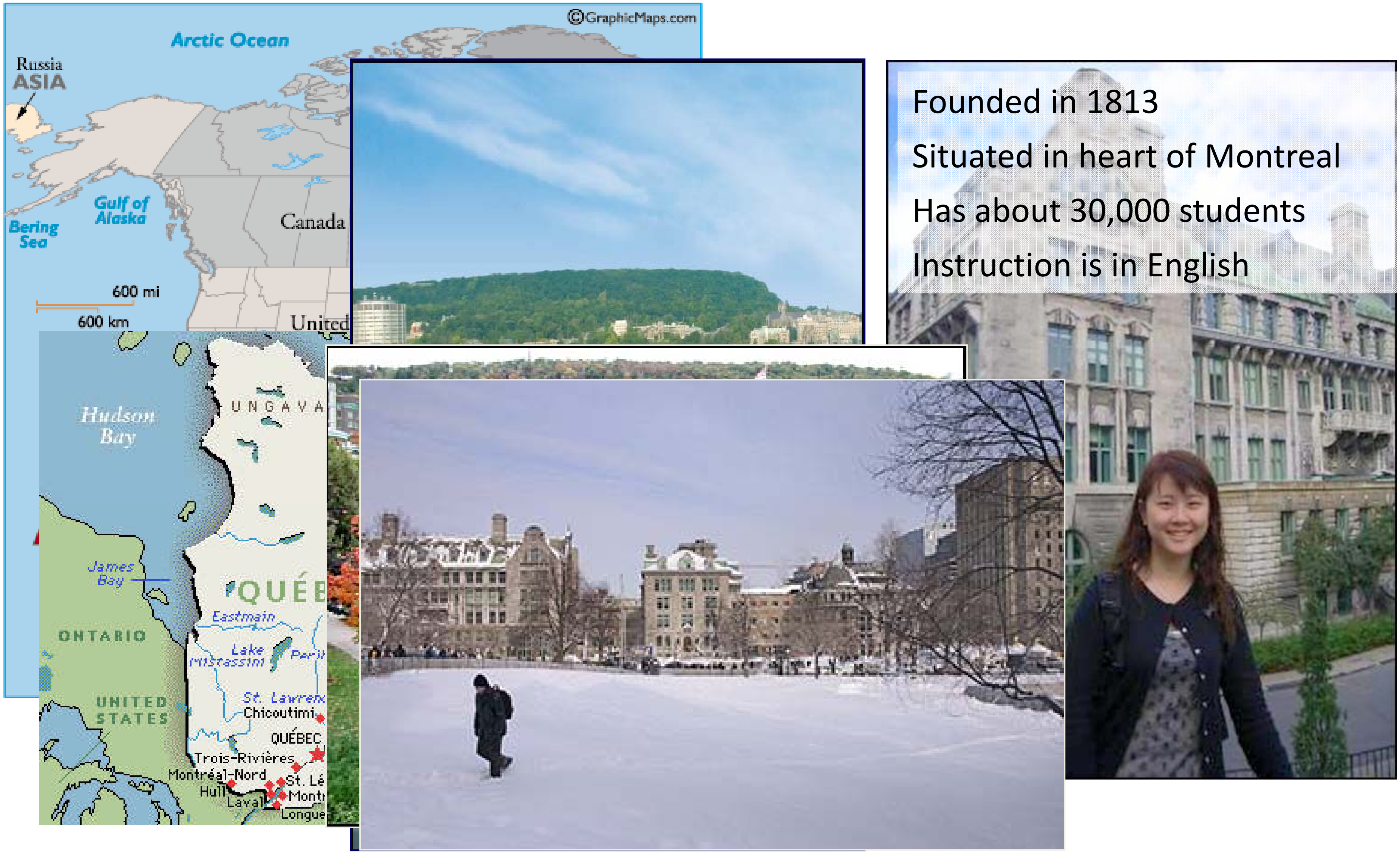

- Founded in 1813
- Situated in heart of Montreal
- Has about 30,000 students
- Instruction is in English

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Integrated Nanophotonics Research Group

May 2010

Jeremy Wong Philip Roche Eric Waldman Songzhe Wong Amin Khorshidahmad Mohamed Najih

Ahmed Abumazwed Amir Jafari Arya Fatehi Roy Zhang

Venkat Veerasubramanian

Imran Cheema Andrew Kirk Shaz Taslimi Sandrine Cote

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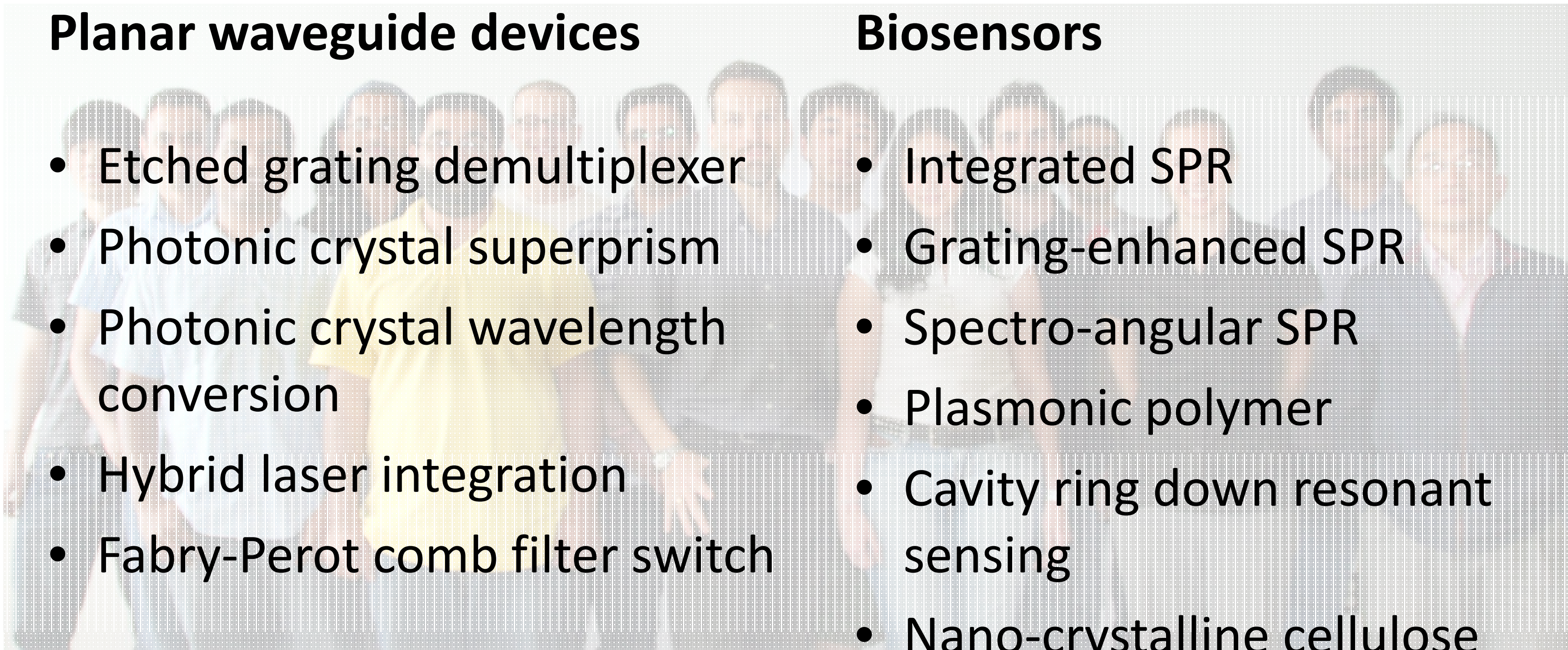
Current projects



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

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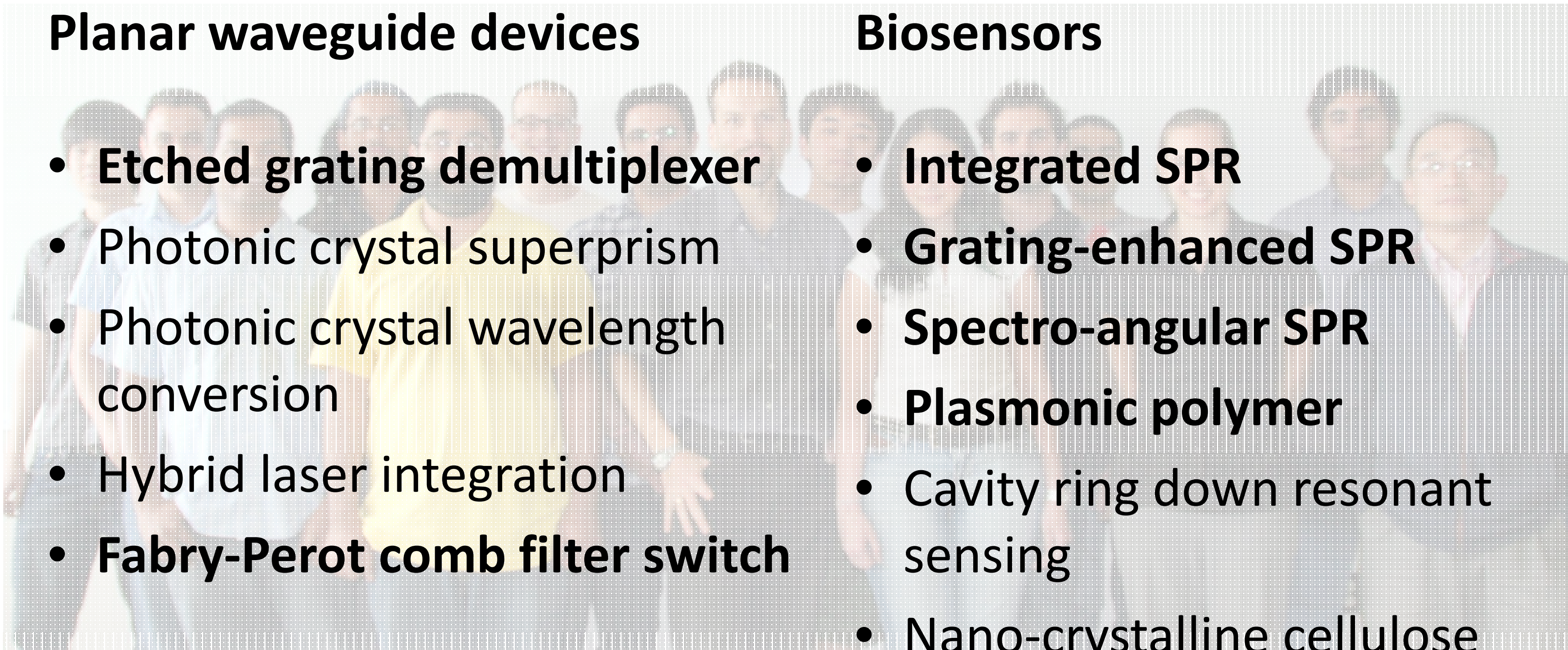
Current projects



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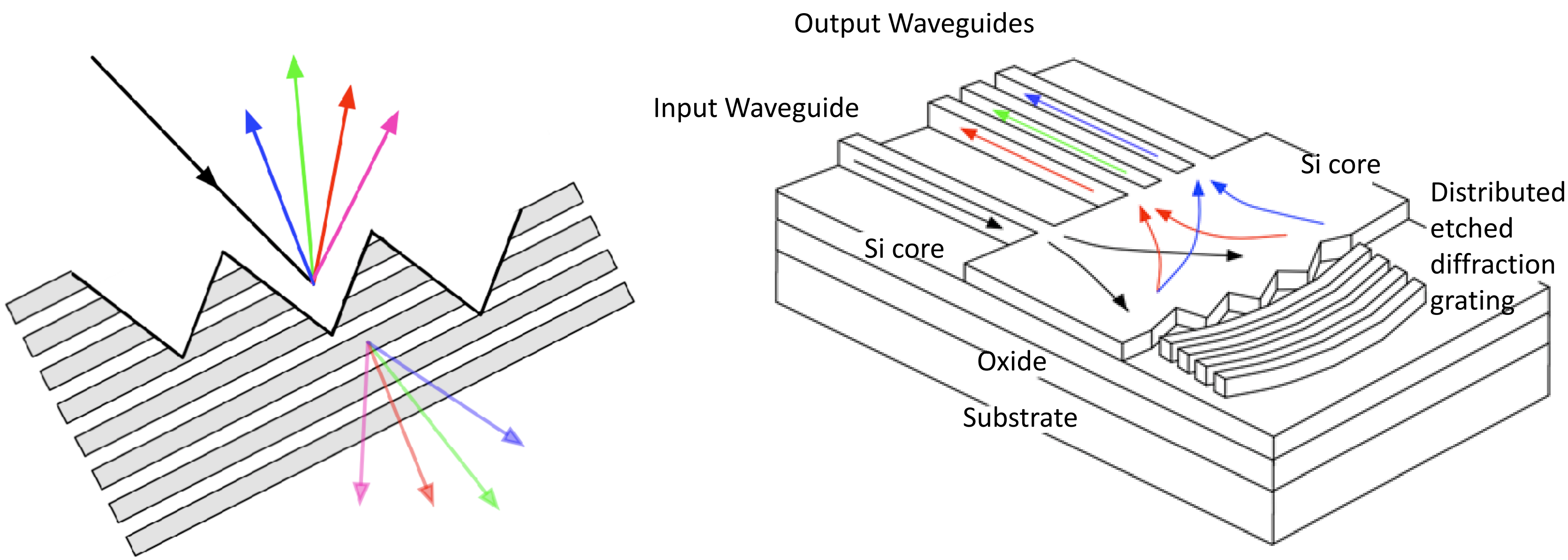
Distributed Etched Diffraction Grating (DEDG)

- Deeply etched sidewalls replaced by distributed reflector
  - E. Bisaillion and A.Kirk, IEEE-LEOS Annual meeting 2006
- Single shallow etch depth simplifies fabrication
  - J . Brouckaert et. al. IEEE PTL Vol. 2, No. 4, 2008
- *Dispersive and reflective properties tailored individually*
  - ***This work***



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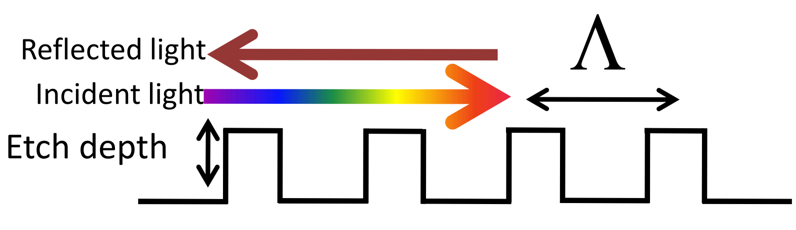
Distributed Etched Diffraction Grating

Reflective properties

Reflectivity and bandwidth determined by

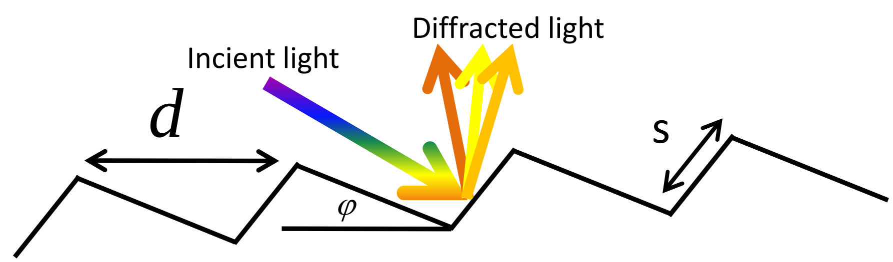
- Etch depth (index contrast)
- Bragg order (periodicity Λ)
- Number of periods



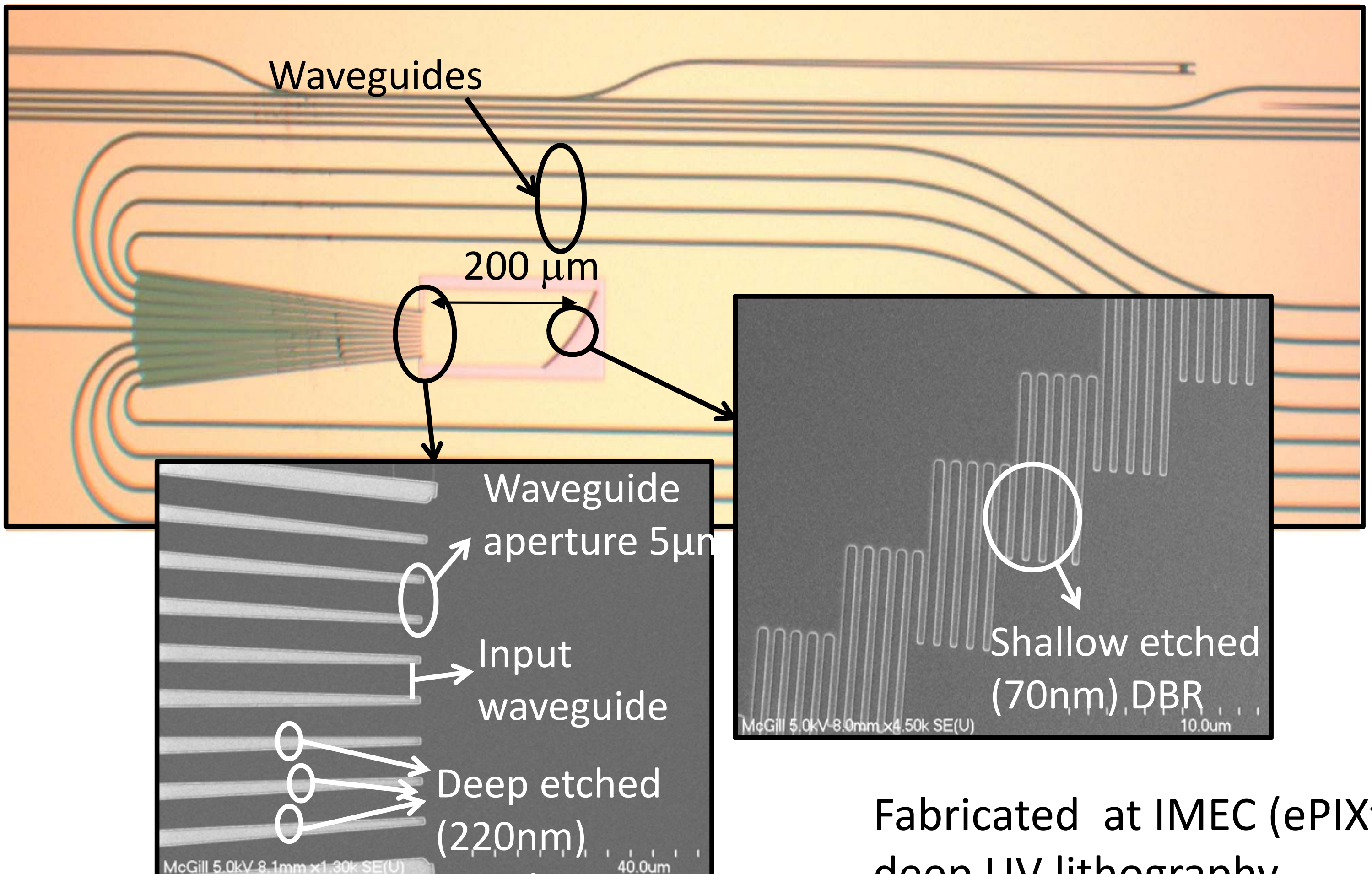
Dispersive properties

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

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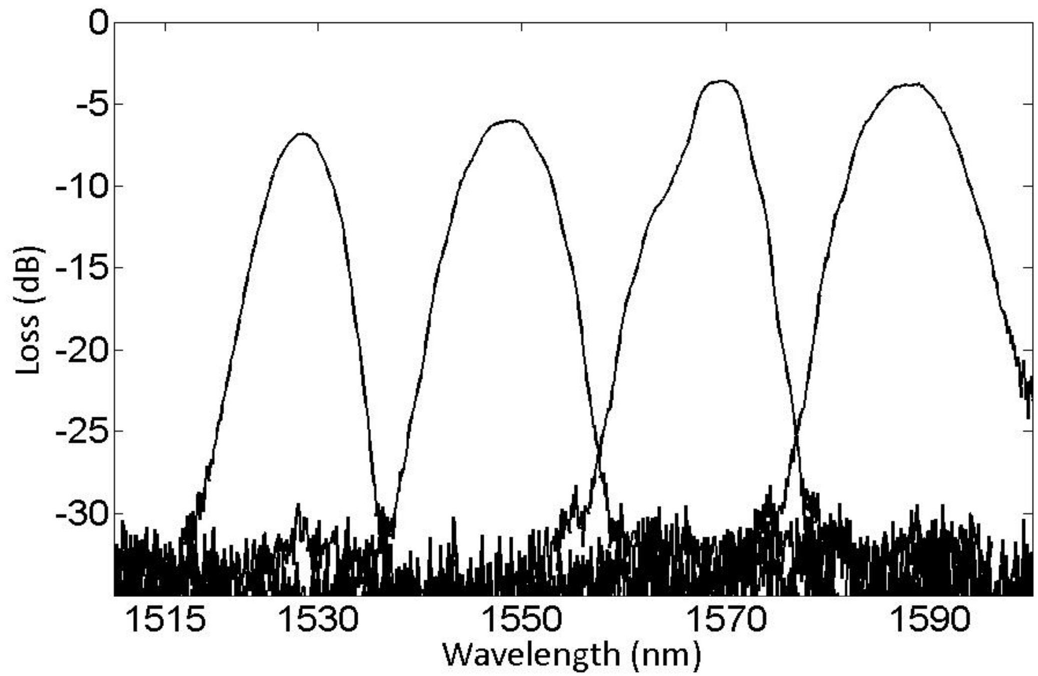
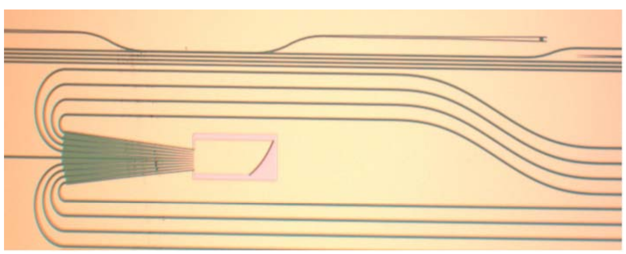
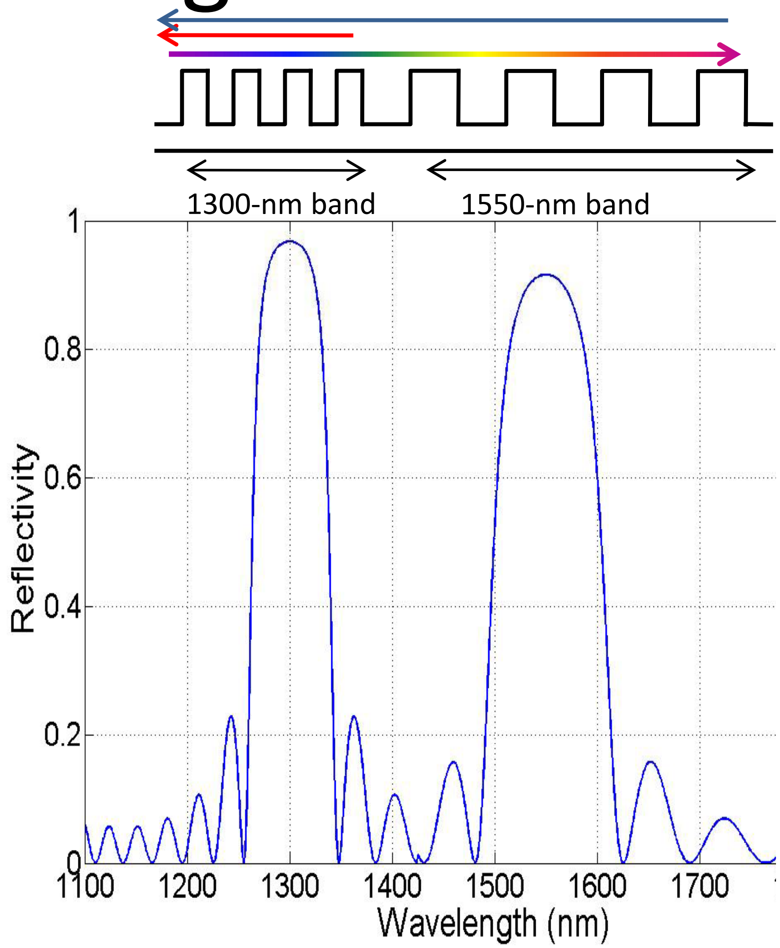
Performance

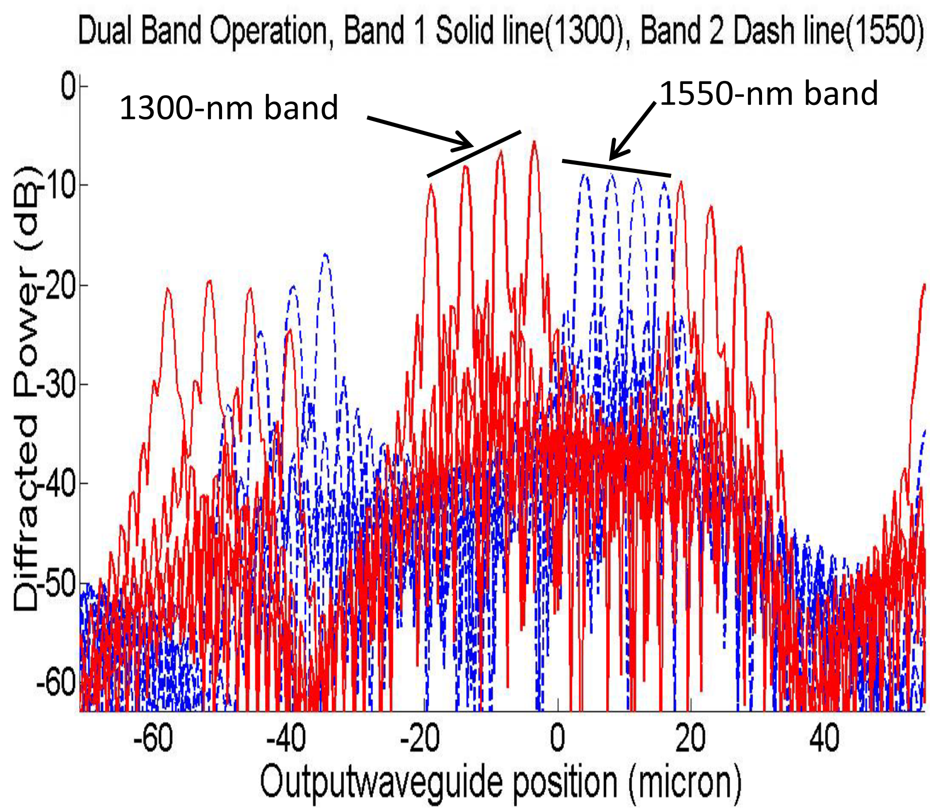
- 4 channel CWDM
- TE polarization
- 5 dB insertion loss
- 25 dB crosstalk





Spectral engineering
E.g. Dual band operation (simulation)





A.Jafari and A.G.Kirk, 'Distributed Etched Diffraction Grating Demultiplexer with Engineered Response', *Proc. IEEE-LEOS Annual Meeting 2008*, Newport Beach, CA, 2008

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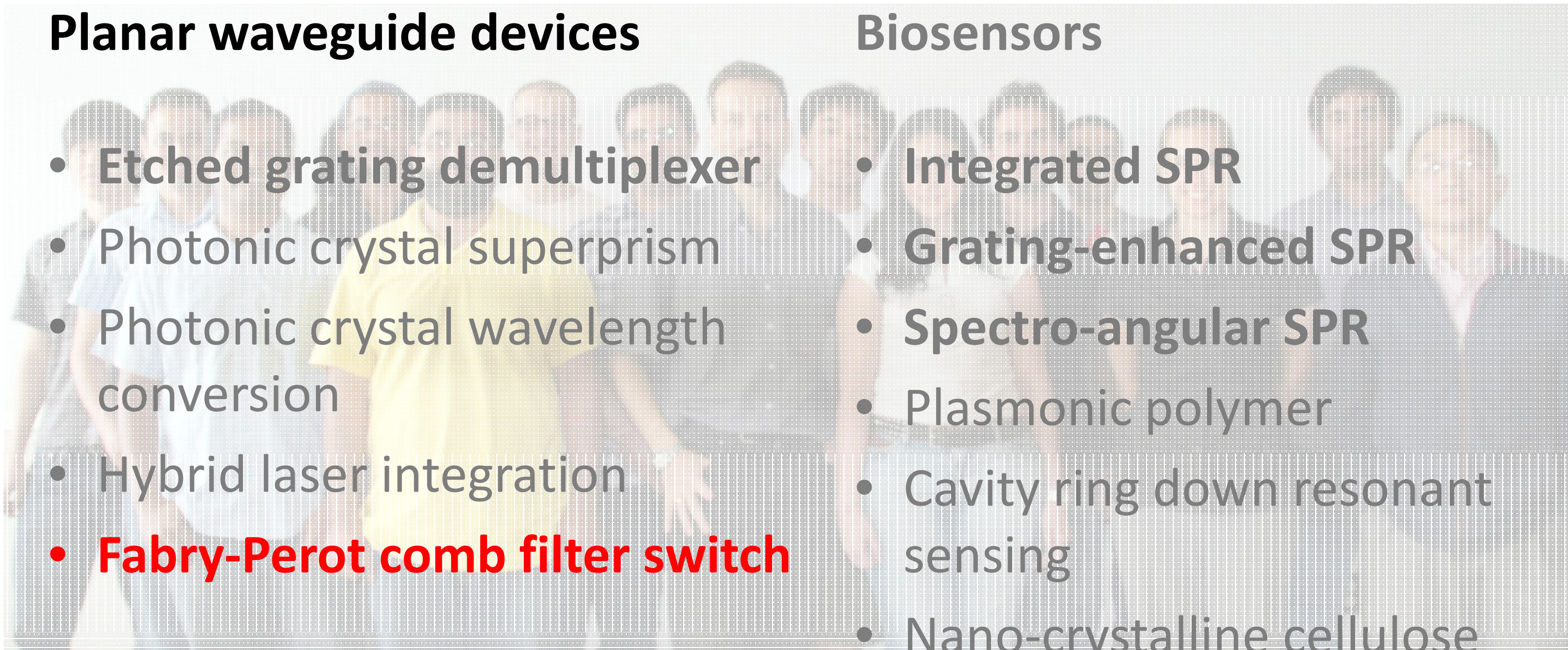
Current projects



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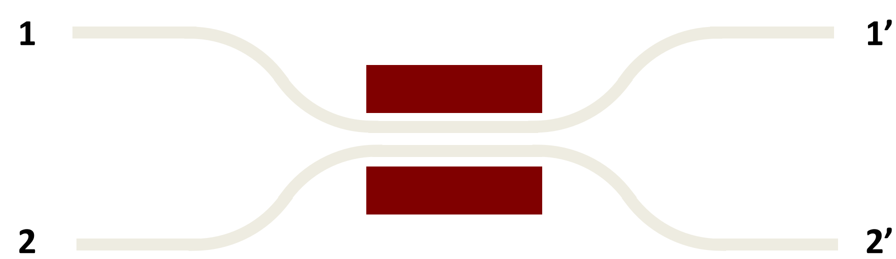
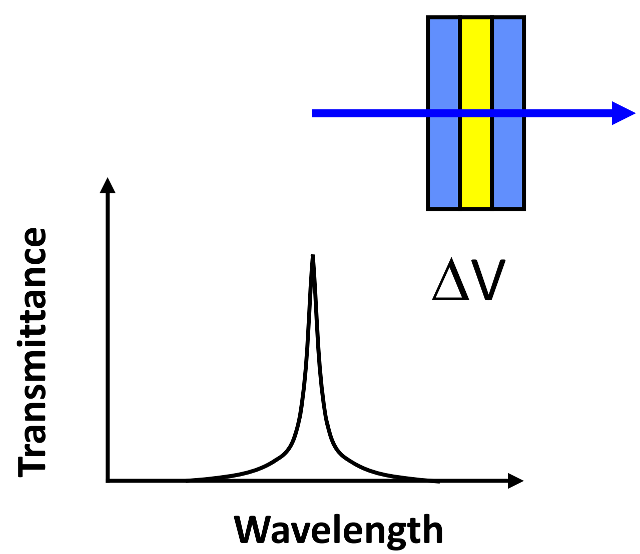
Interferometric electro-optic switches

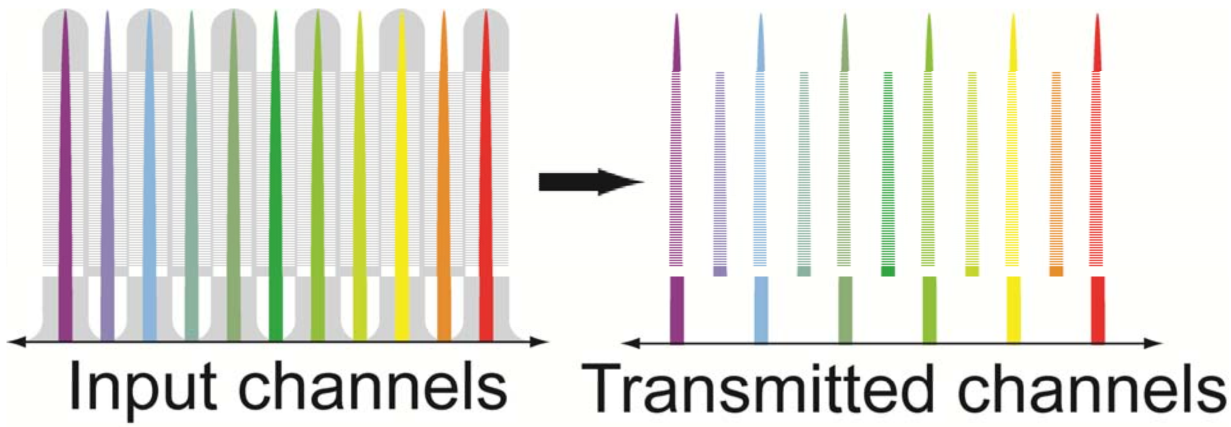
- Integrated Mach-Zender waveguide switches developed 30 years ago, demonstrated in $LiNbO_3$
- Scaling beyond 8x8 challenging due to waveguide bend limits

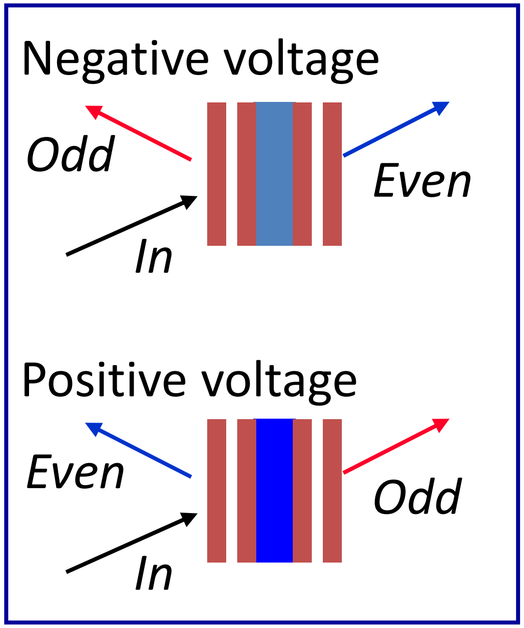


- Electro-optic switches based on Fabry-Perot etalon filters are typically narrow band due to small Δn
- However there is the possibility of using free-space slab approach for better scalability



Filter Design: Comb Response

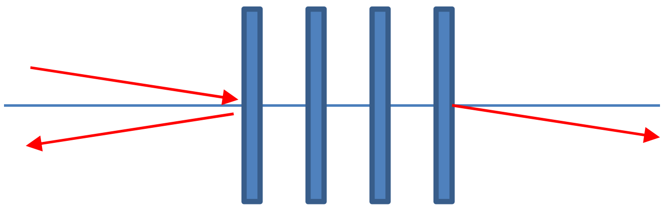




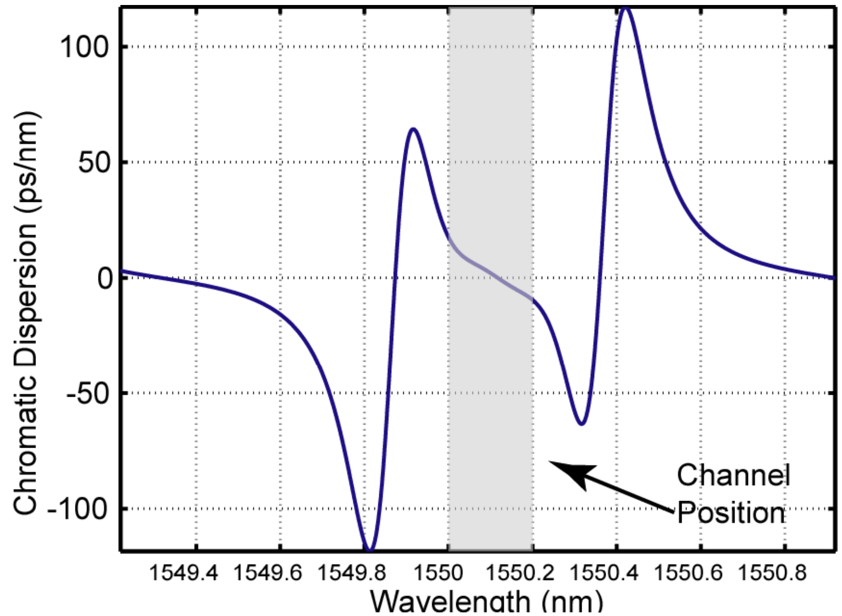
- EO effect shifts the filter response by 1 nm only
- Reduced the filter free-spectral range to create a comb filter with a 200 GHz Spacing
- Bandwidth > 30 nm

M.Menard, A.G.Kirk ,'Integrated Fabry-Perot Comb Filters for Optical Space Switching', *J.Lightwave Technol.*, **28**, pp 768-775, 2010

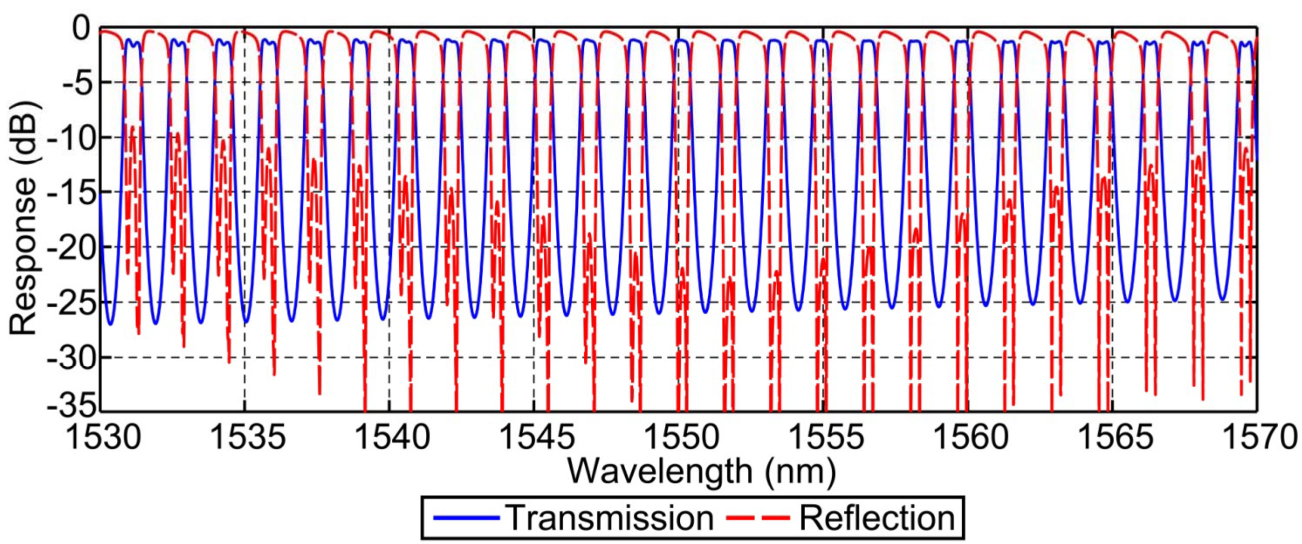
Four coupled cavities, 2nd order mirrors



Chromatic dispersion (simulated):



Spectral response (simulated):



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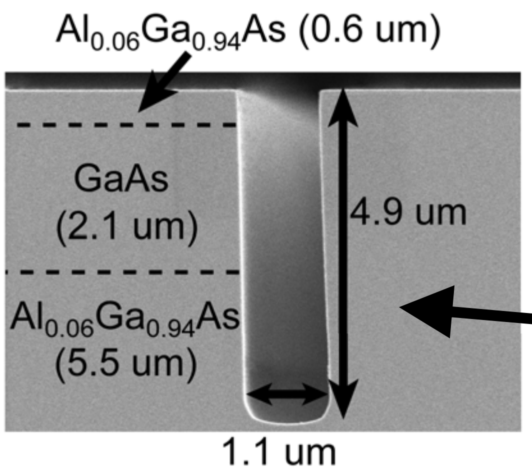
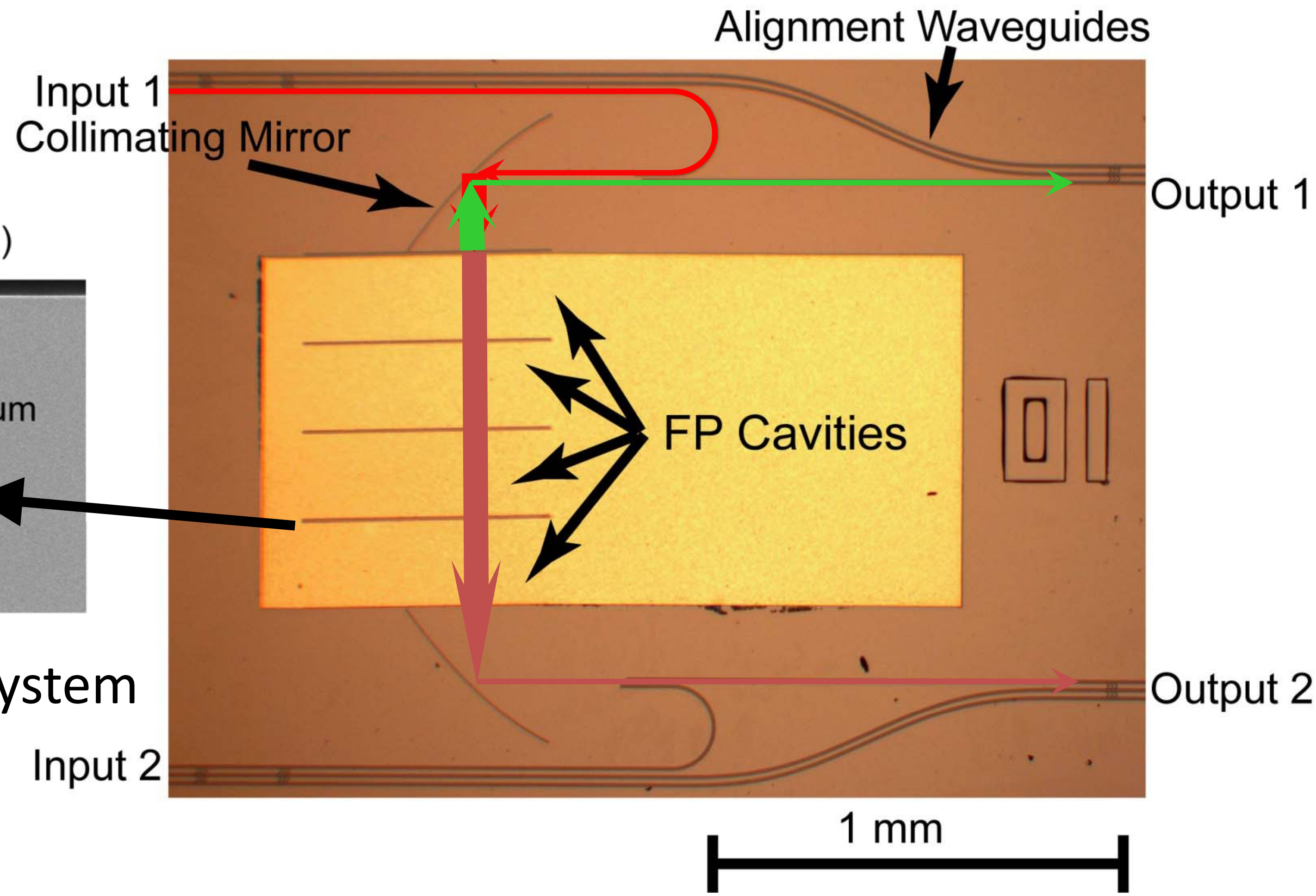
Integrated 2 x 2 optical switch

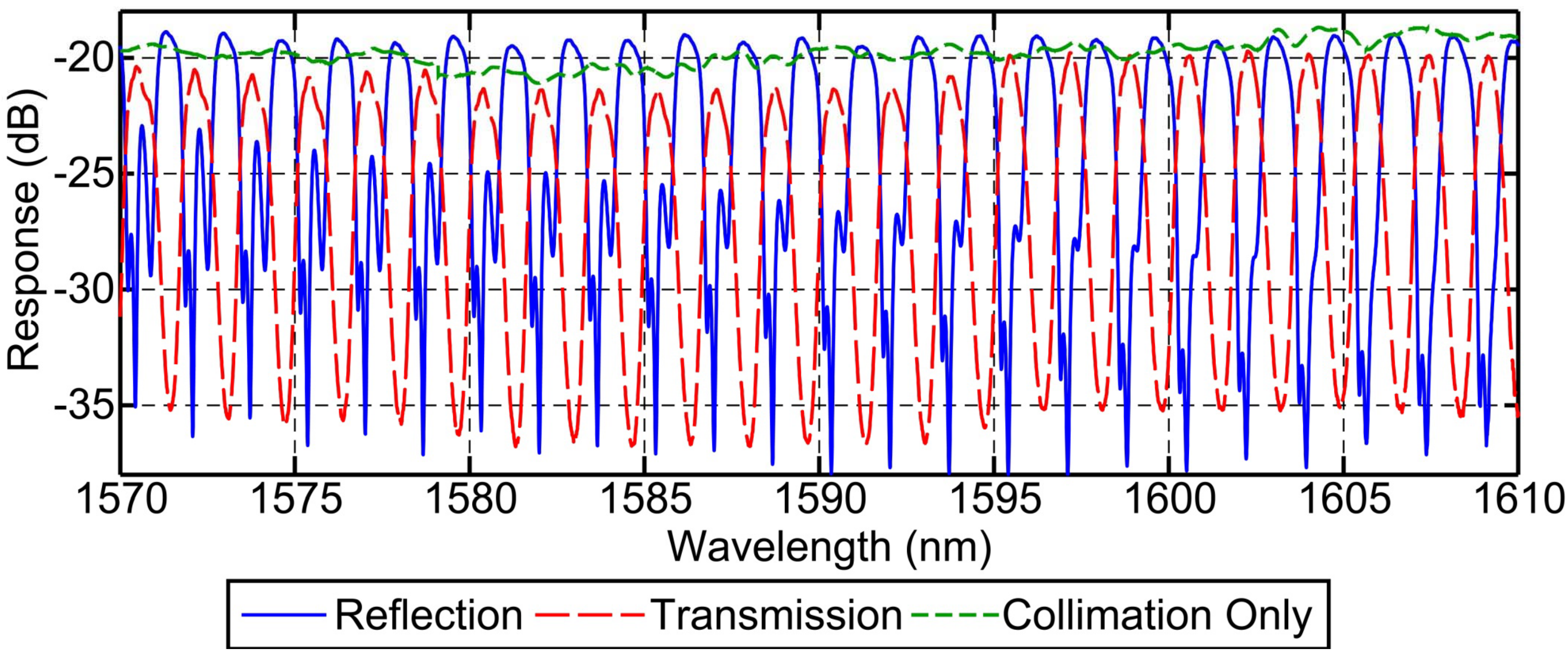


GaAs material system



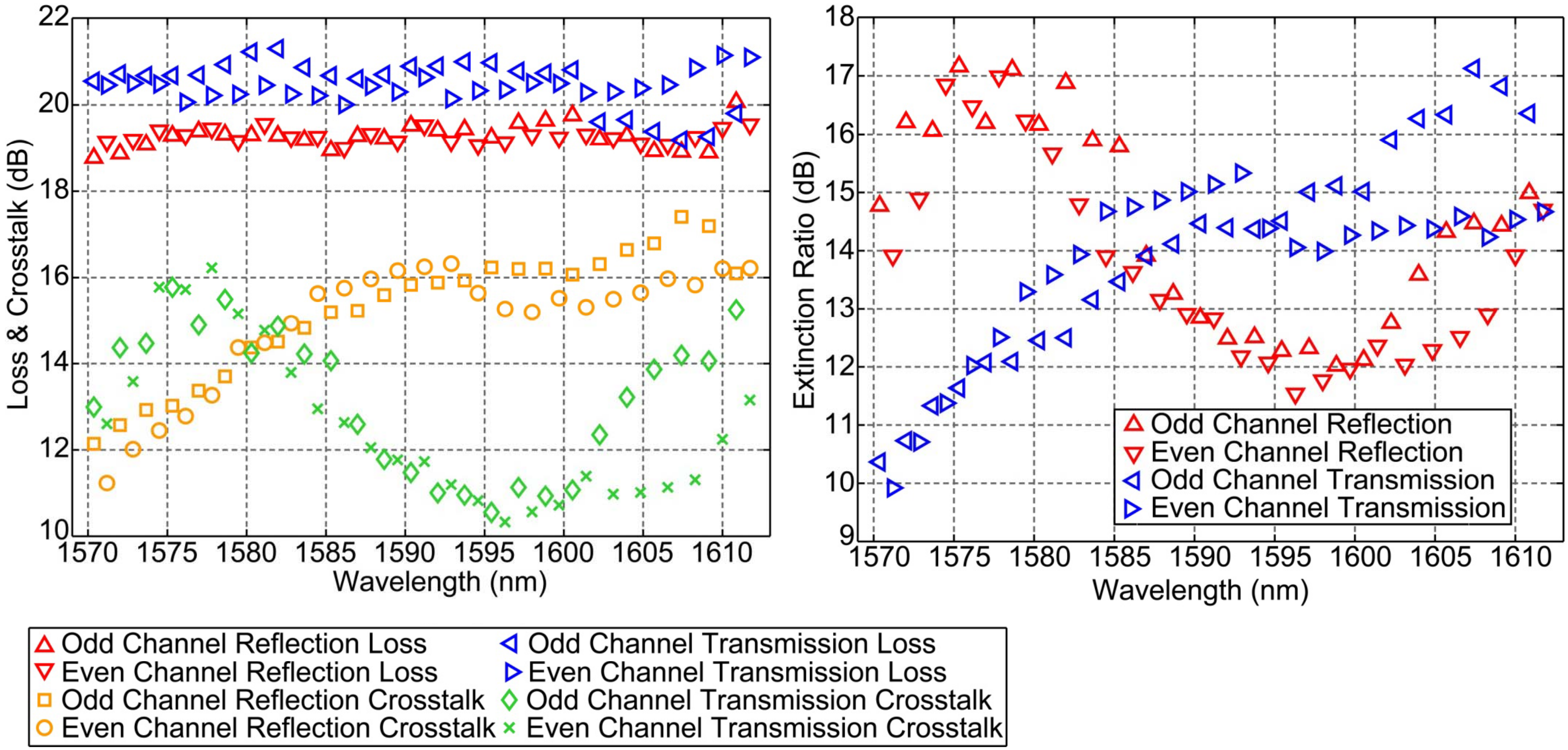
M.Menard, A.G.Kirk, 'Integrated Fabry-Perot Optical Space Switches ',*Optics Express*, **17** pp 17614-17629, 2009

Prototype Spectral Response



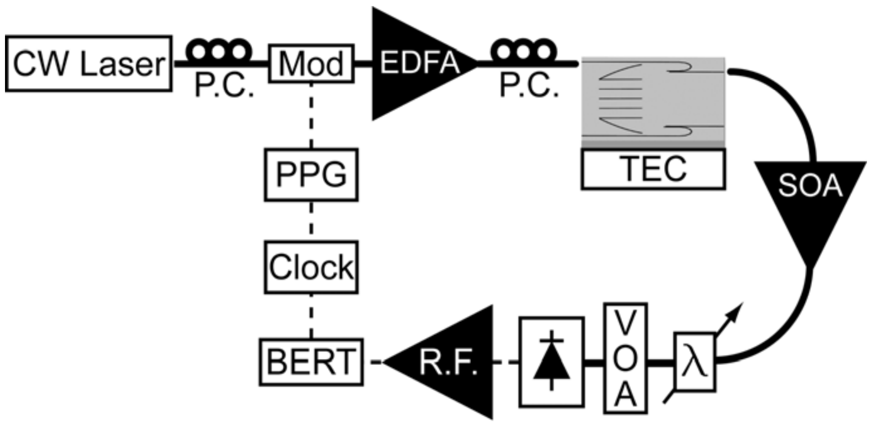
- Fabrication errors shifted the response to the L-band and reduced cavity coupling
- High loss (20 dB) due to misalignment of the input/output waveguides. Additional loss due to filters < 1dB

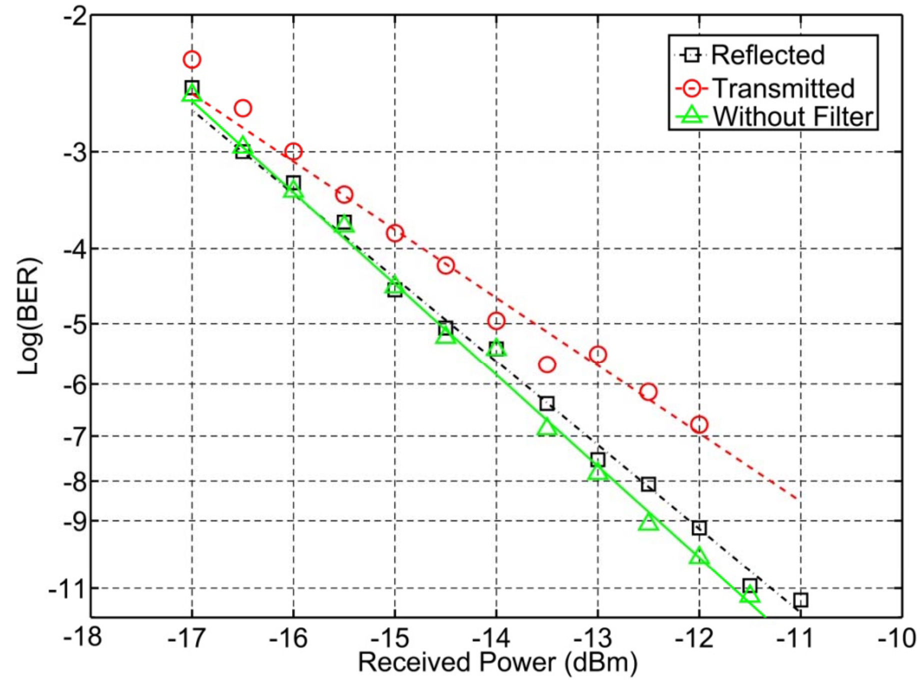
Prototype Channel Performance



- Fluctuation in crosstalk and extinction ratio due to ripples in the wavelength response

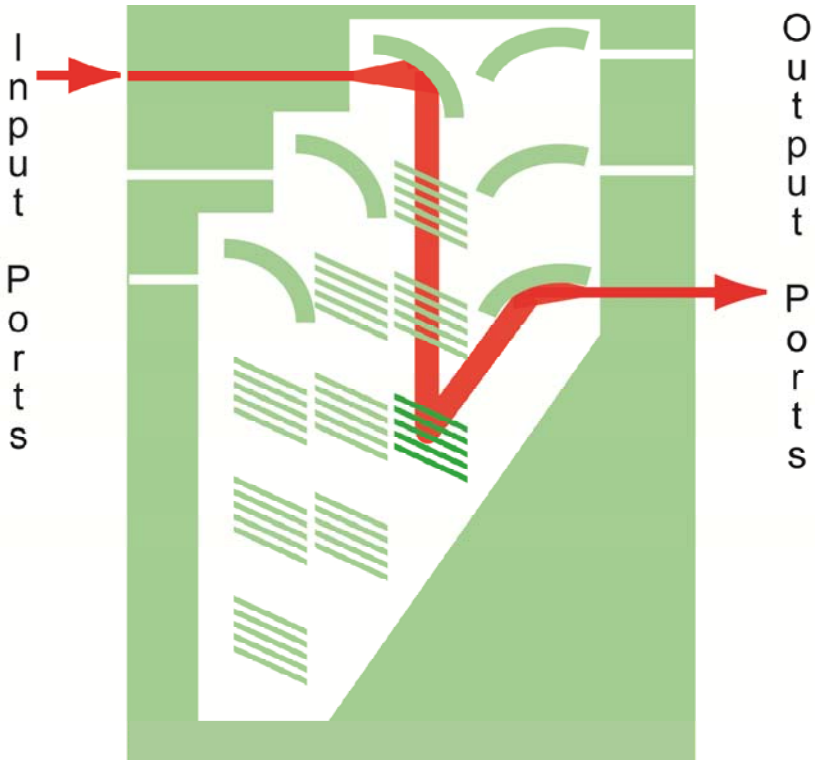
Prototype 10 Gb/s BERT



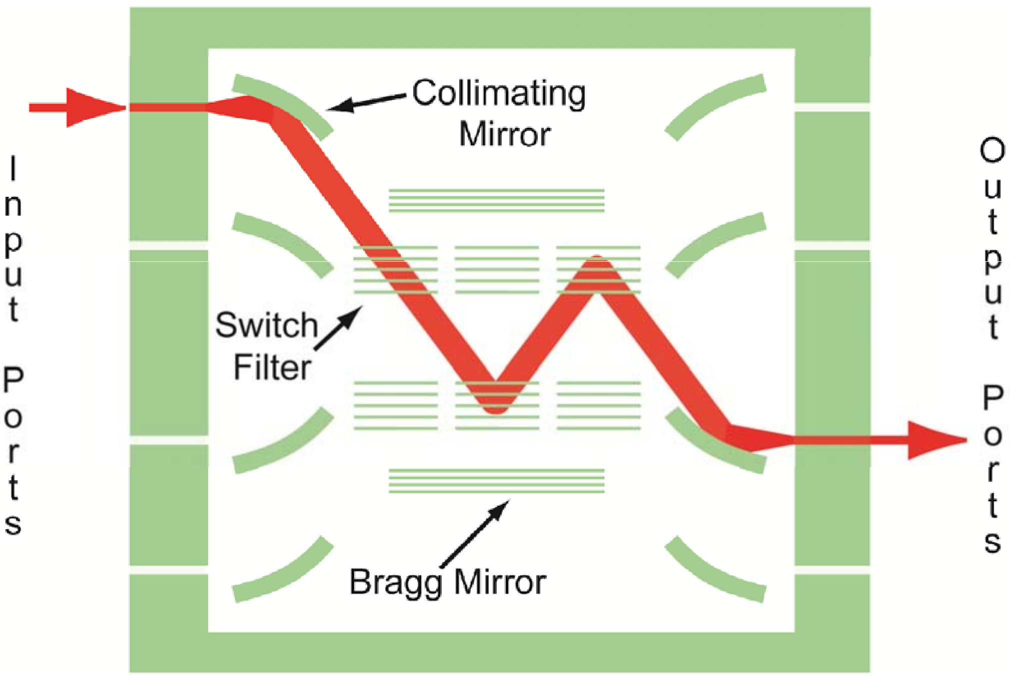


- Transmission power penalty caused by the combination of collimation & radiation, which brought the output power below the SOA sensitivity floor

Switch Fabric Layouts



3x3 Crossbar



4x4 Shuffle Benes

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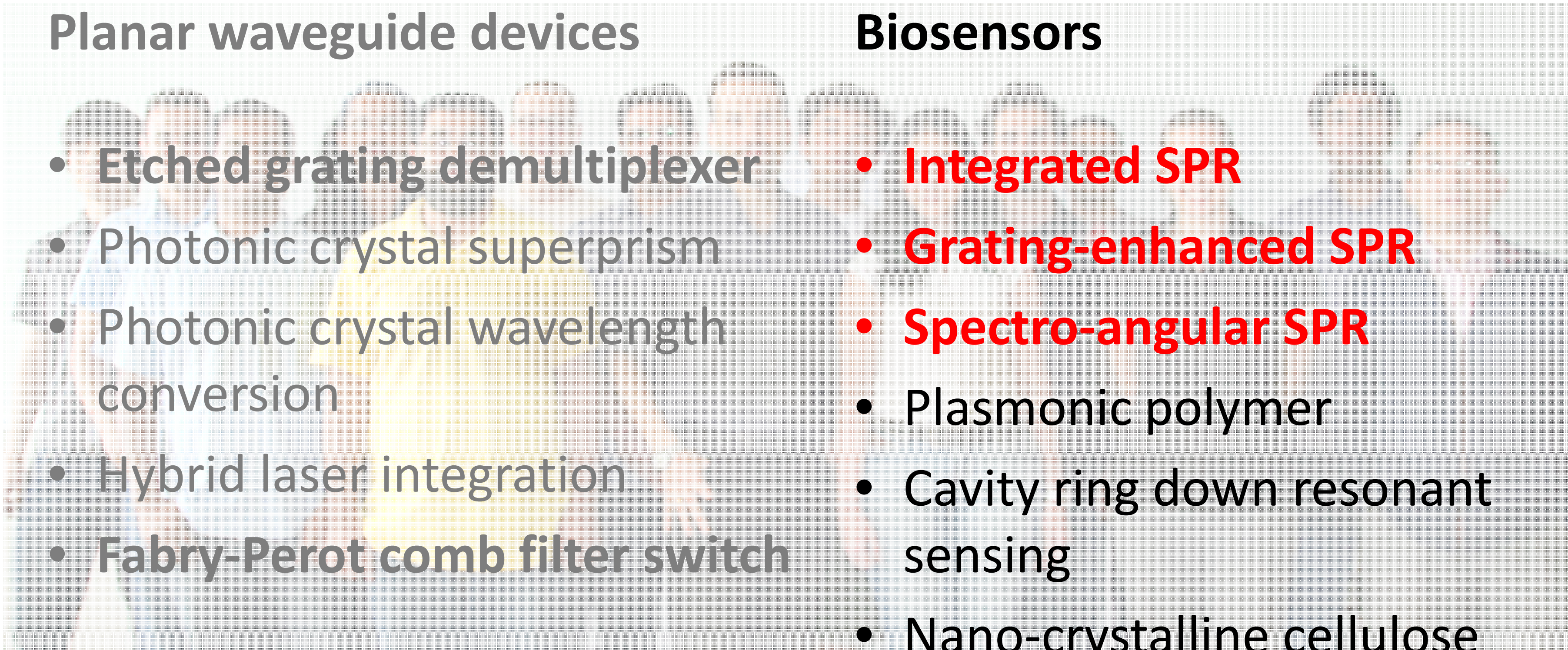
Current projects



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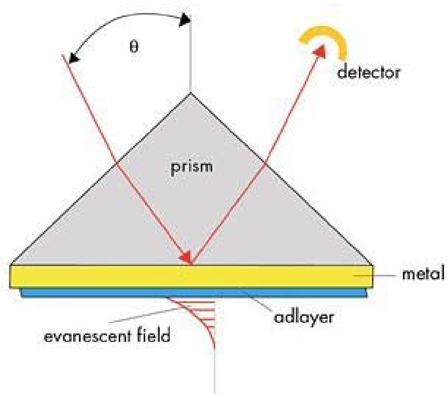
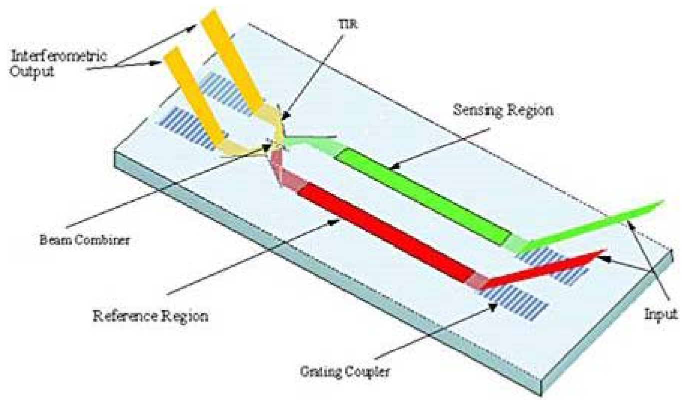
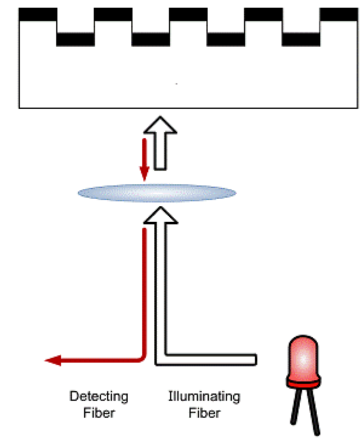
Photonic biosensor Types



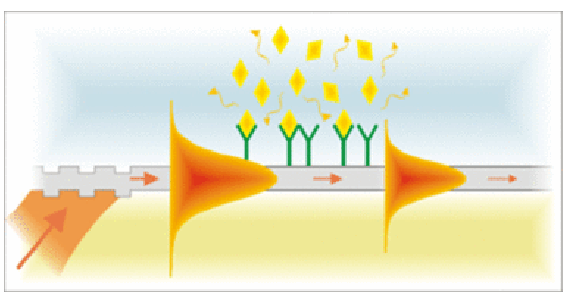
SPR Biosensor



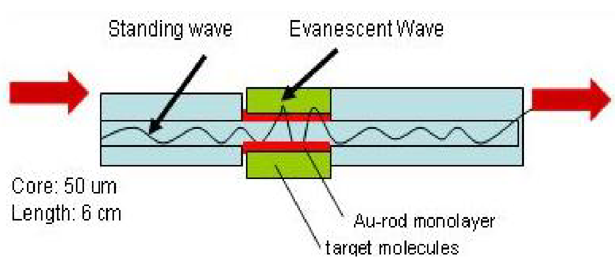
Interferometer Biosensor



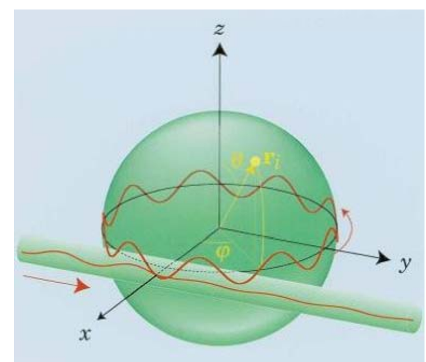
Photonic Crystal Biosensor



Waveguide Biosensor



Optical Fiber Biosensor



Micro-Cavity Biosensor

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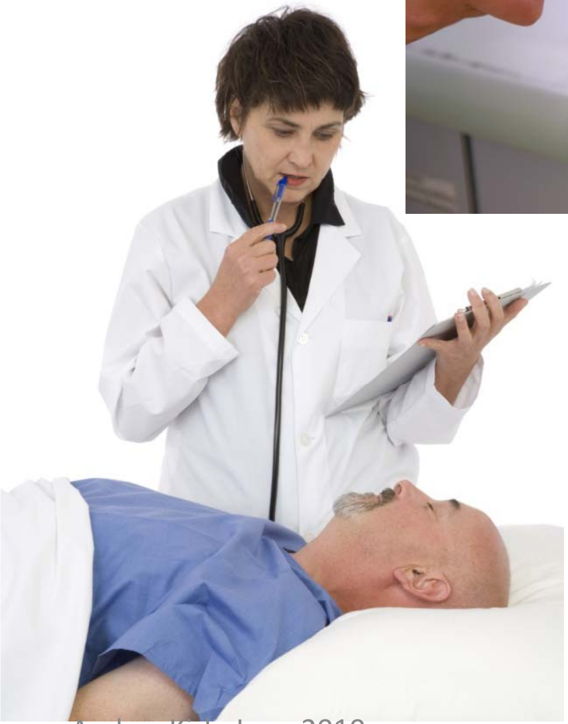
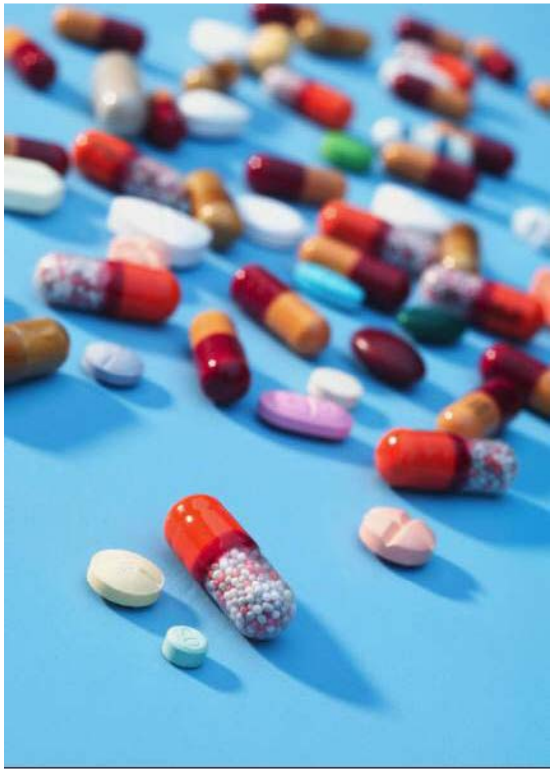
Motivation

1. Improving Sensitivity for Biomarker-Based Diagnosis





2. Drug discovery

Motivation:
Improving Sensitivity for Biomarker-Based Diagnosis

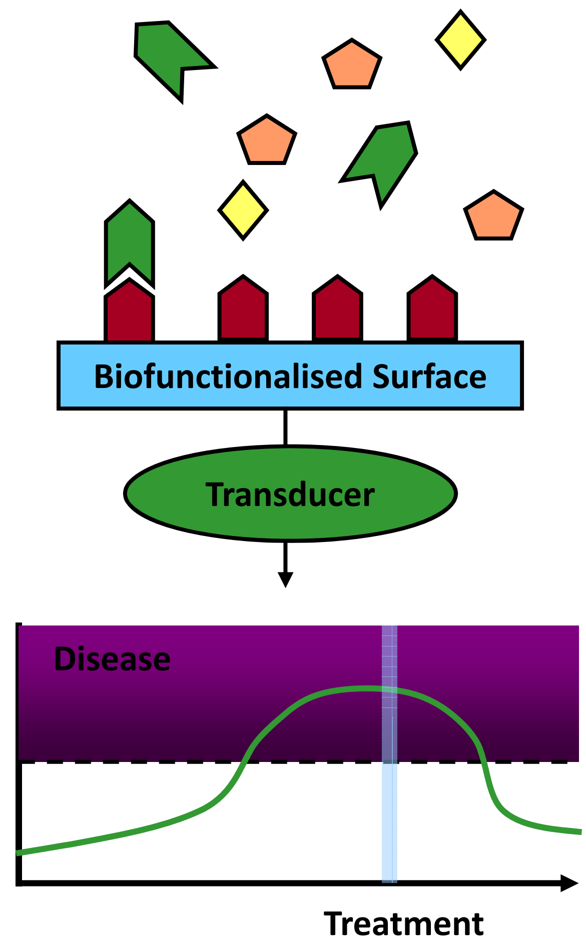
Biosensor Requirements

- 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

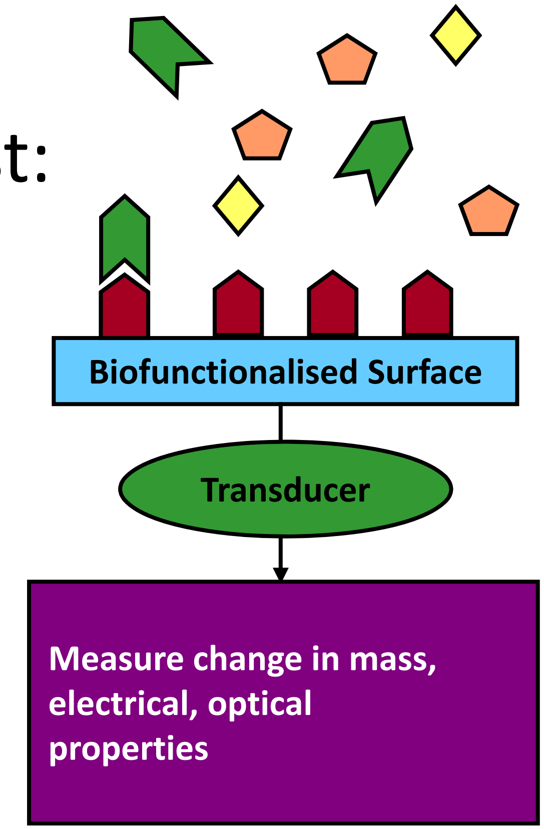
⇩

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



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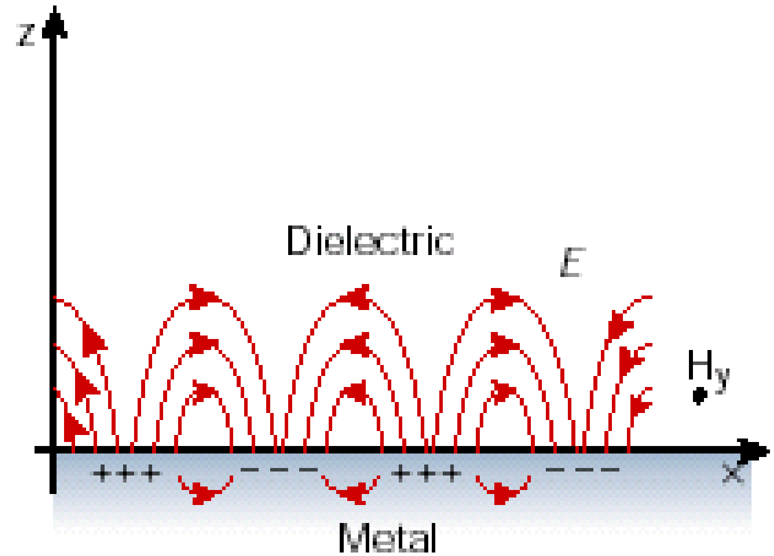
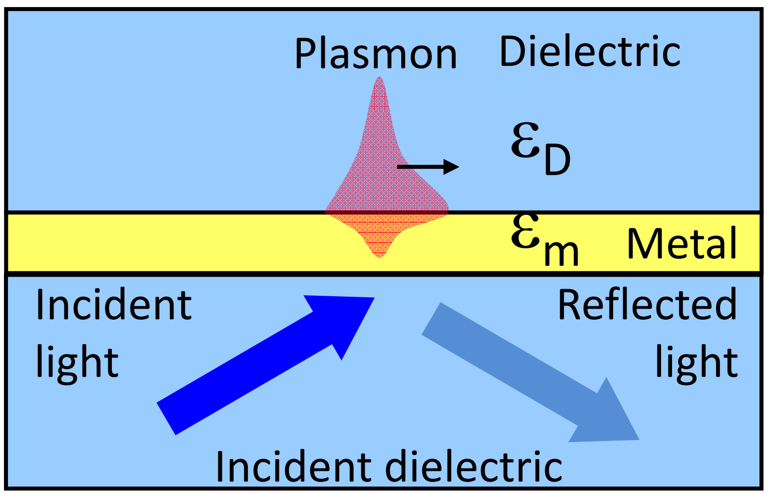
Surface plasmon polariton

- 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*





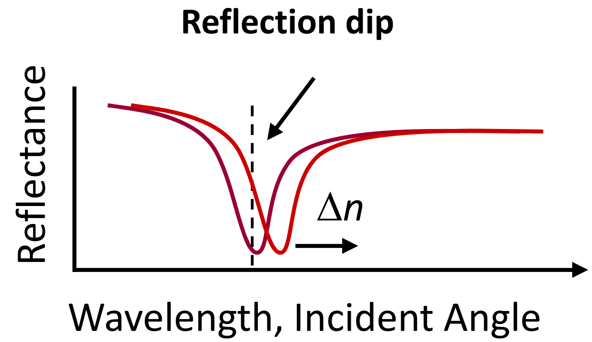
Plasmon momentum:

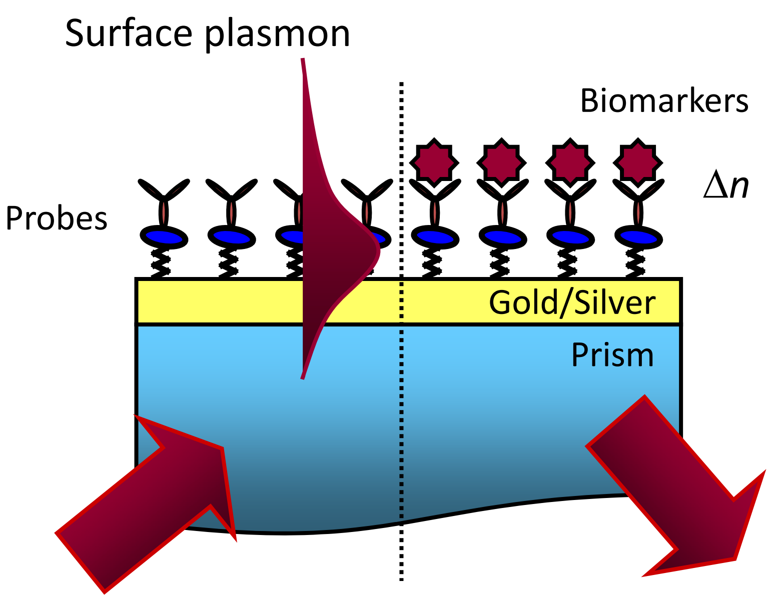
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_D \varepsilon_m}{\varepsilon_D + \varepsilon_m}}$$

ω: frequency, ε: dielectric constant: c: speed of light

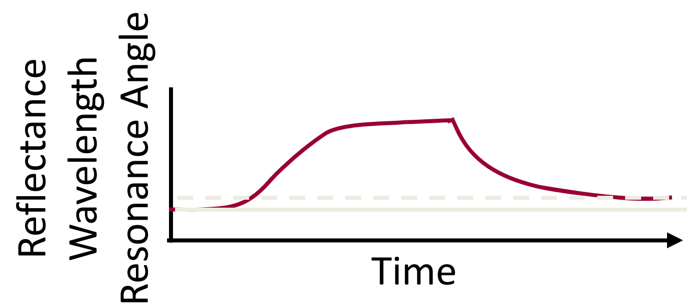
Surface Plasmon Resonance Sensing

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





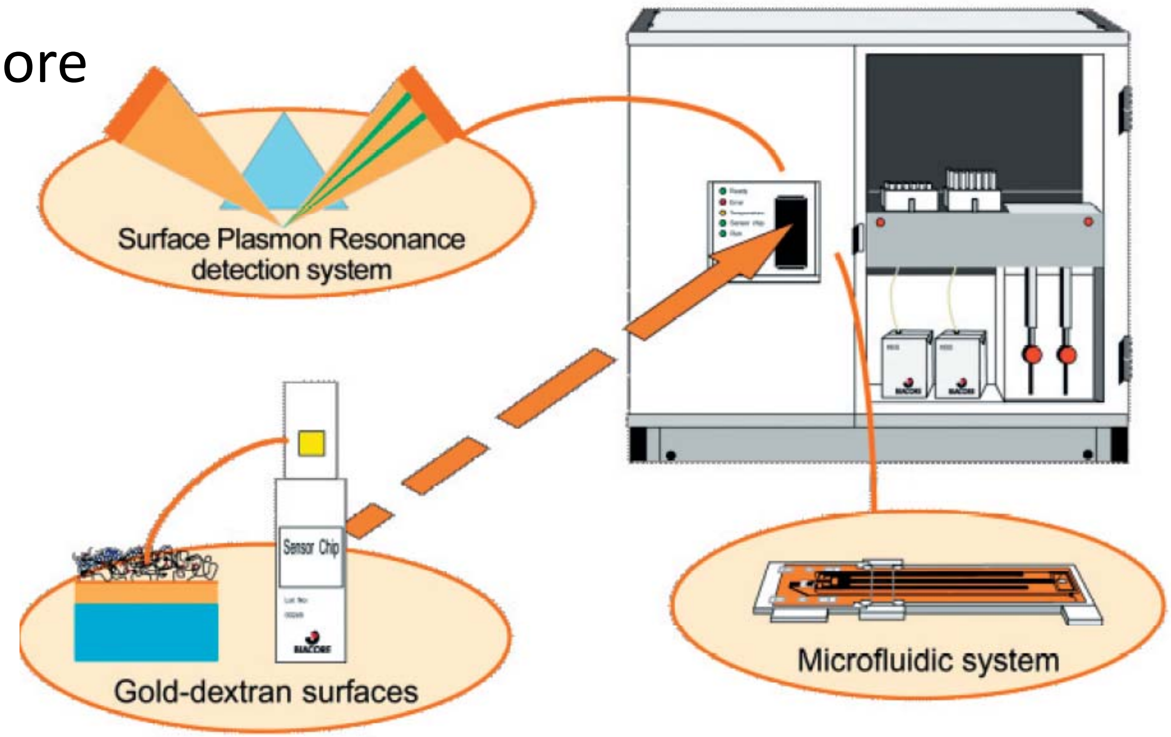
$$\theta_{res} \cong \sin^{-1}\left(\frac{1}{n_S}\sqrt{\frac{\varepsilon_M \varepsilon_D}{\varepsilon_M + \varepsilon_D}}\right)$$



Commercial SPR

Several commercial SPR analysis systems exist

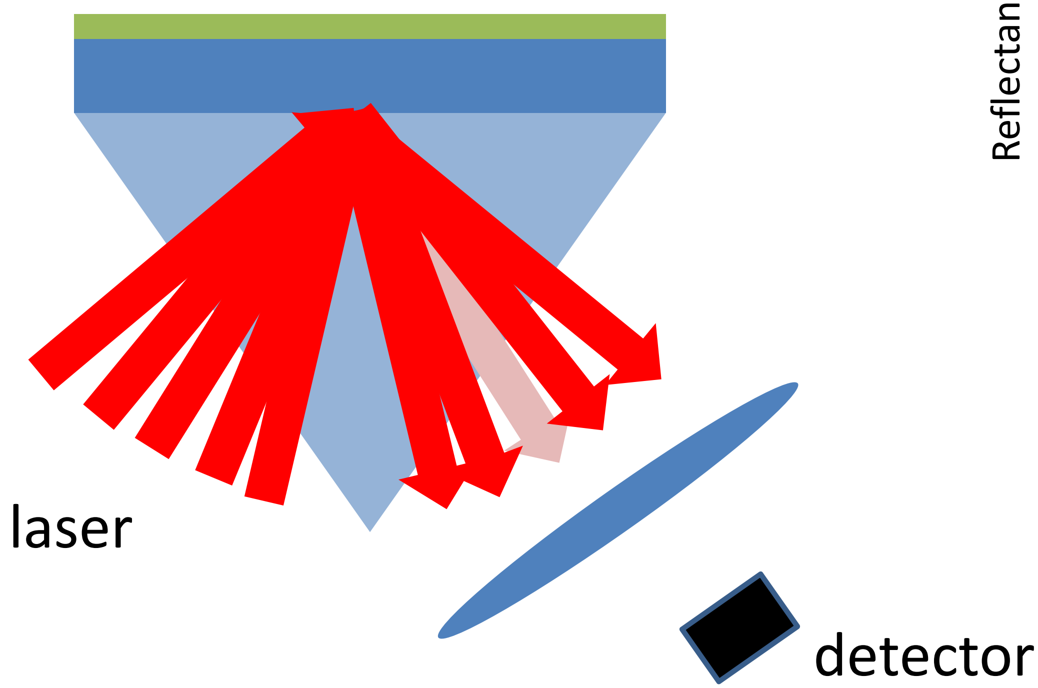
Biacore

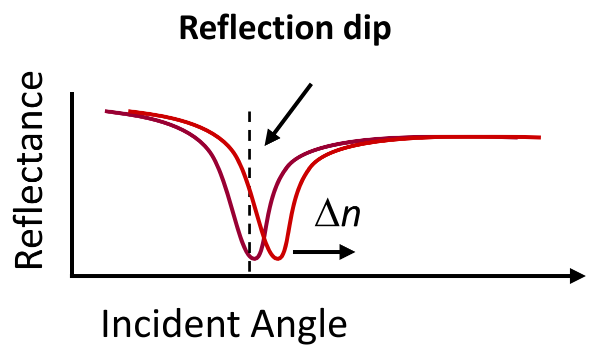


SPREETA (Sensata Inc)

Angle scanning sensors

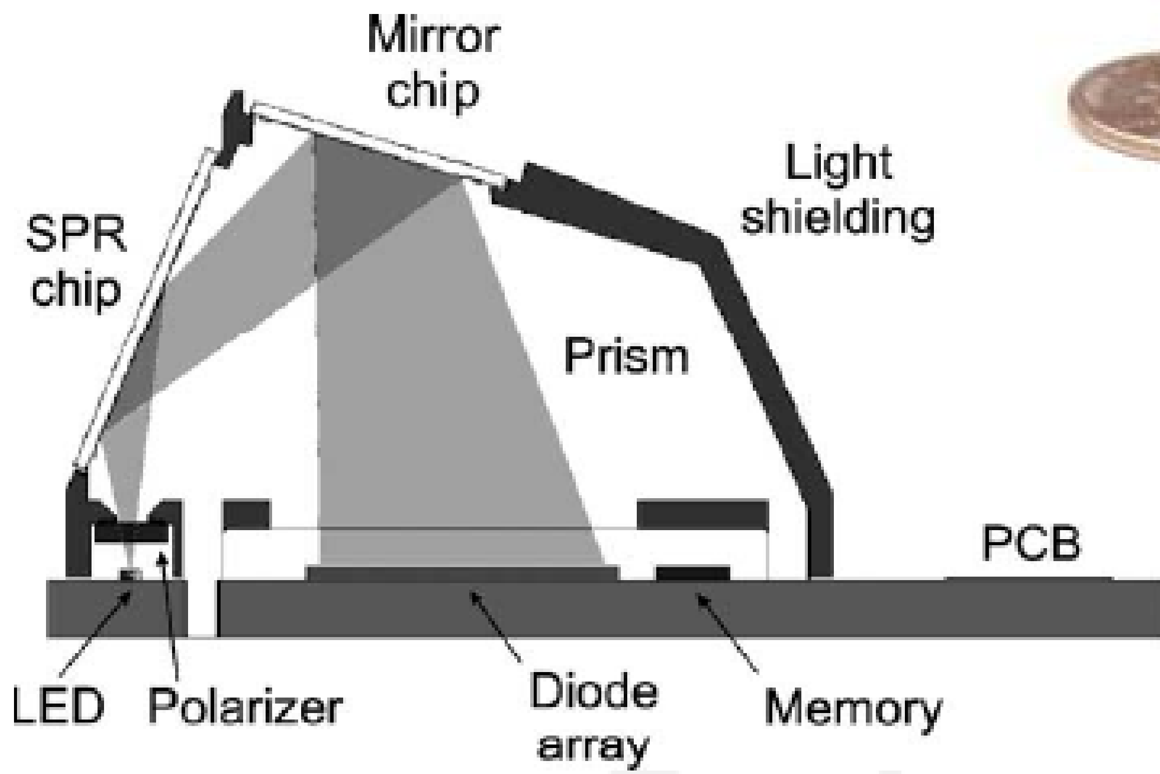
- E.g. Biacore

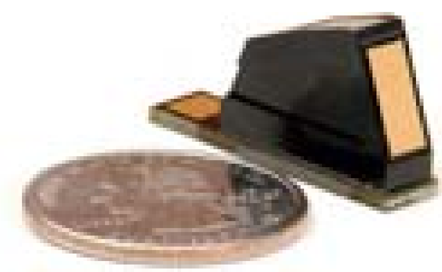




Angular spectrum sensor

- SPREETA sensor



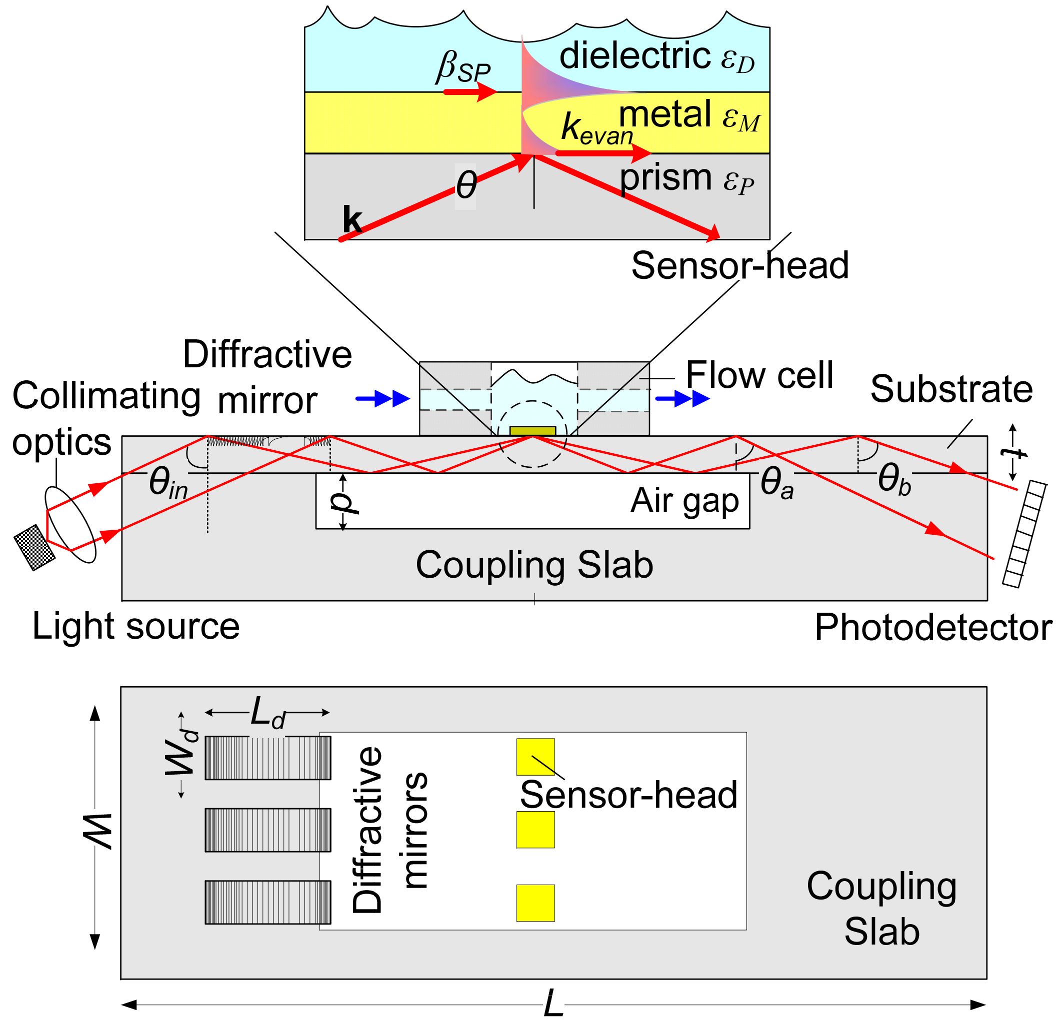


Integated SPR sensor

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

Side

Top



W-Y Chien, M. Z. Khalid, X.D. Hoa, A. G. Kirk, 'Monolithically Integrated Surface Plasmon Resonance Sensor Based on Focusing Diffractive Optic Element for Optofluidic Platforms', *J.Sensors and Actuators B*, **138**, 441-445, 2009

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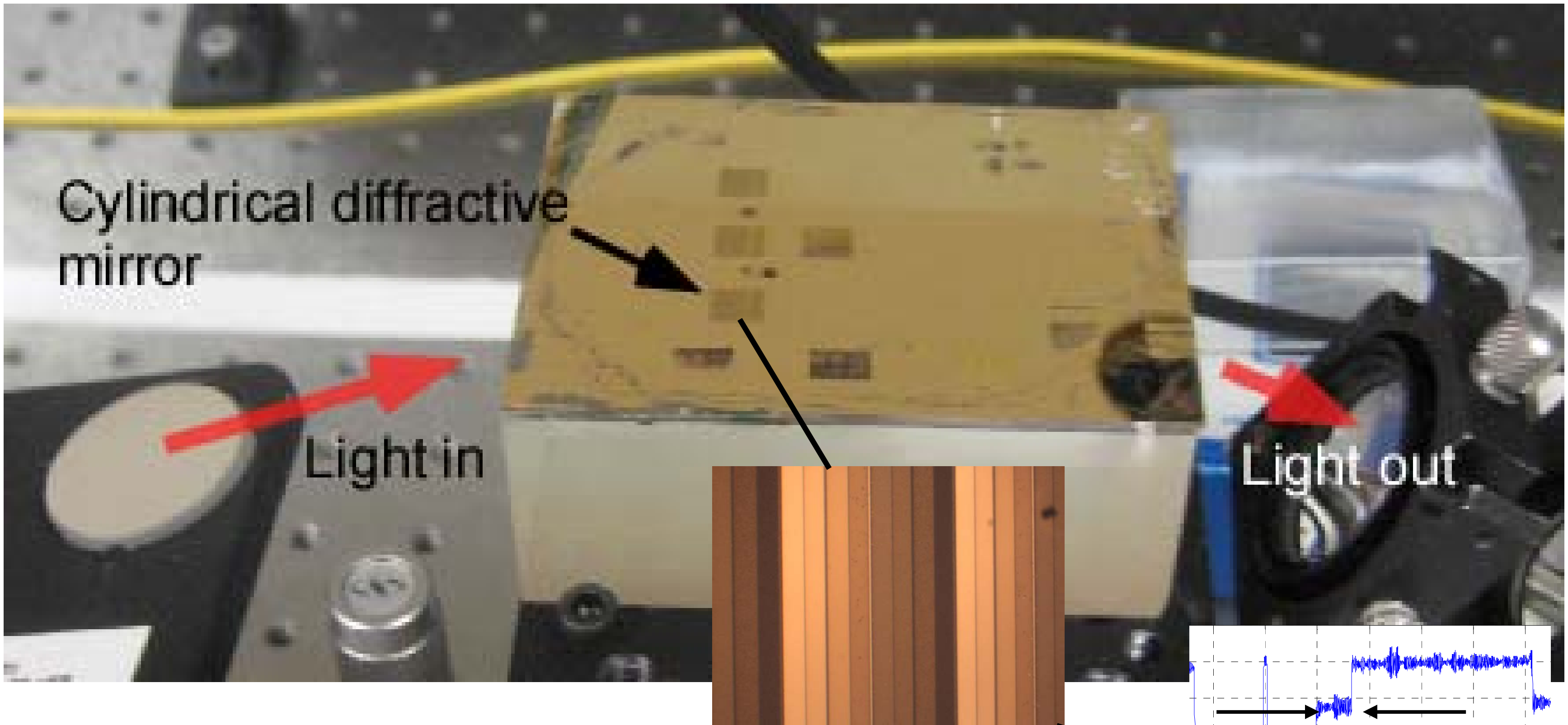
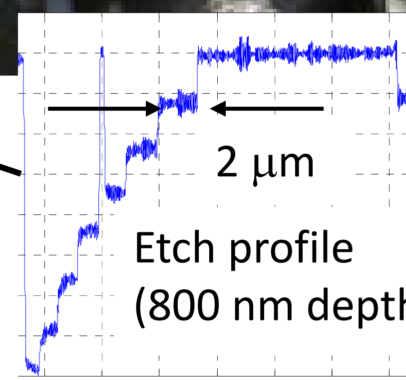
Fabricated device



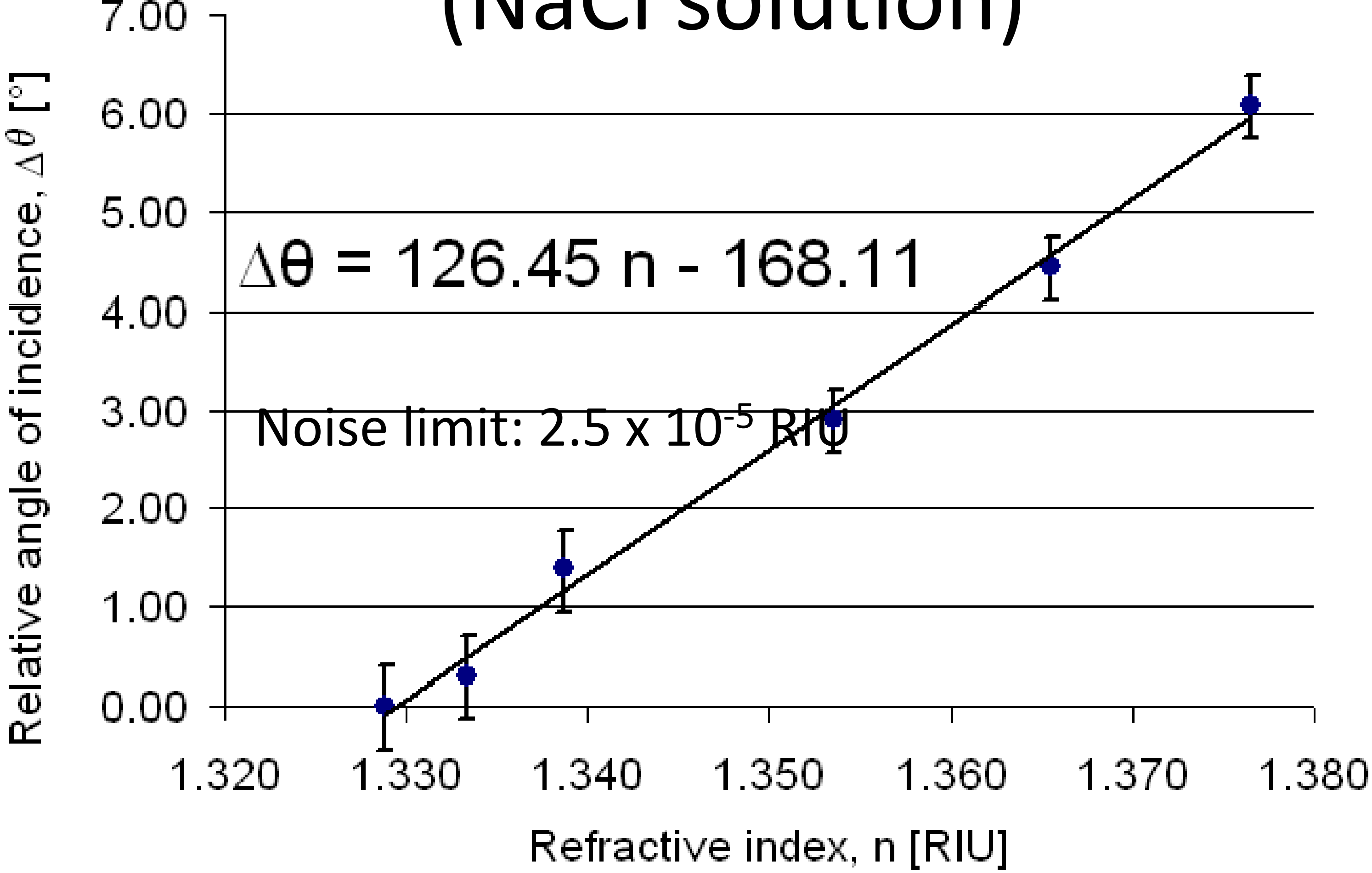
8-level diffractive cylindrical mirror etched in fused silica



Etch profile (800 nm depth)

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

Results: Refractive index measurement (NaCl solution)



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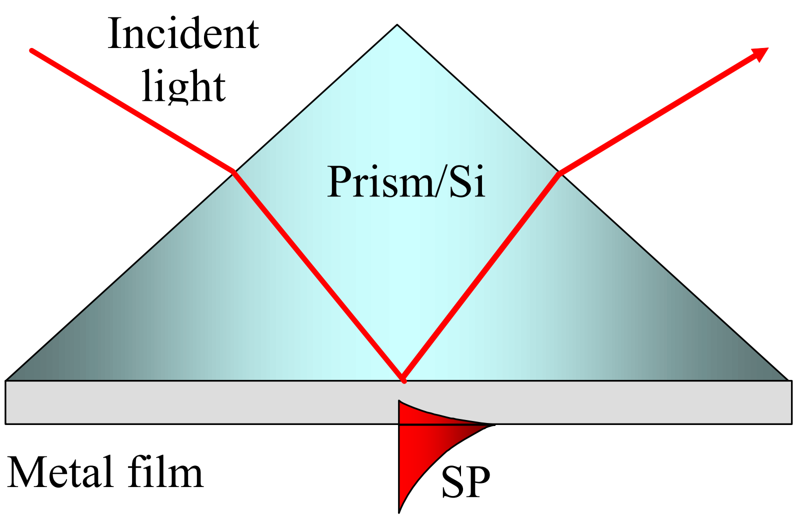
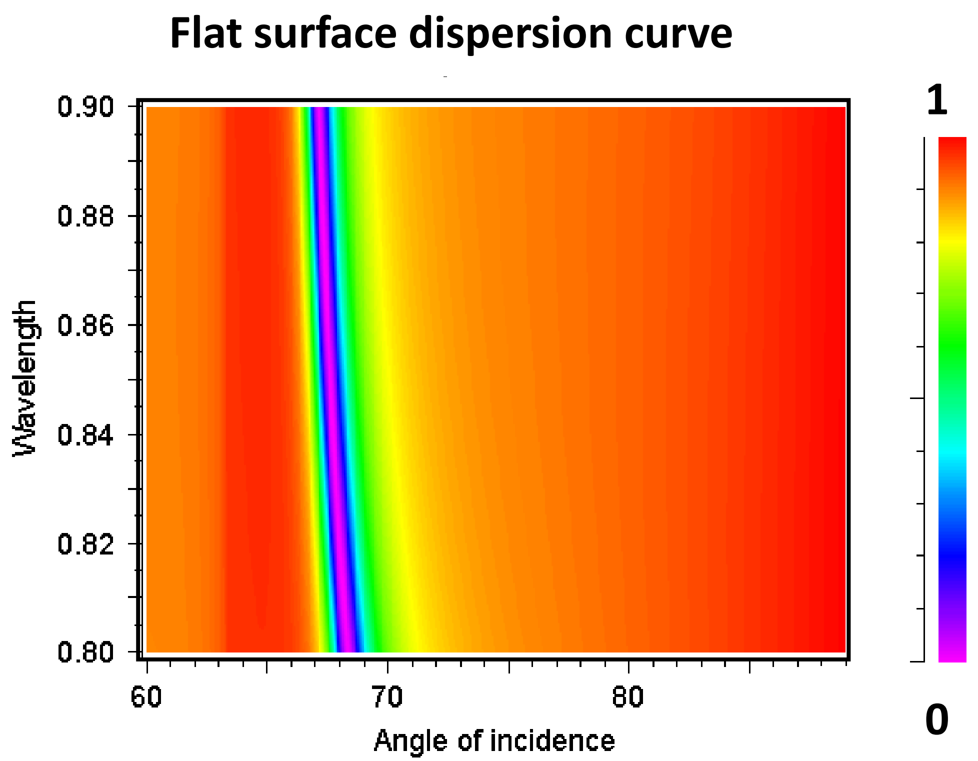
Enhancing SPR response

- 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





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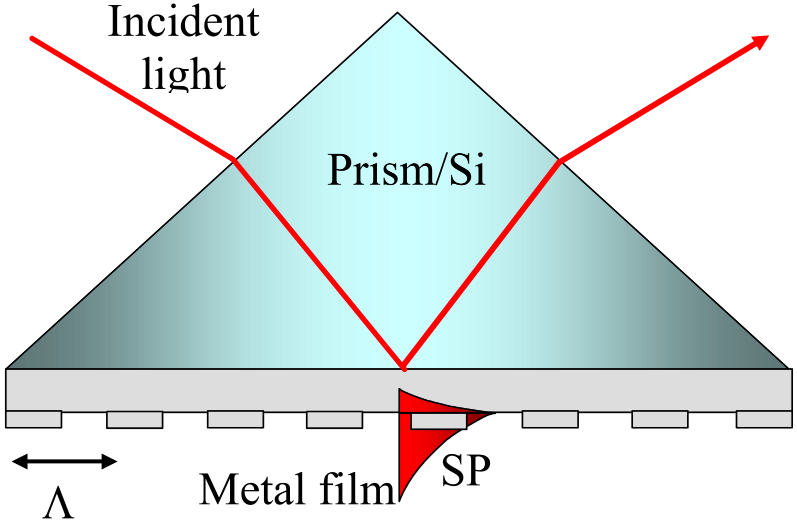
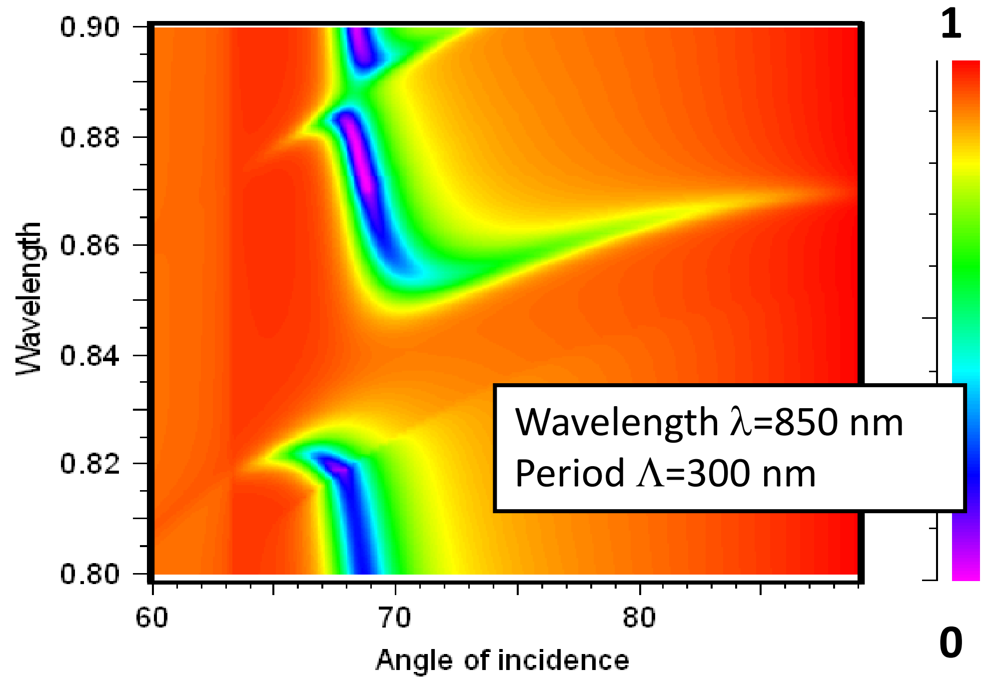
Periodic metallic gratings

- Creates bandgap in dispersion curve



10 nm grating dispersion curve



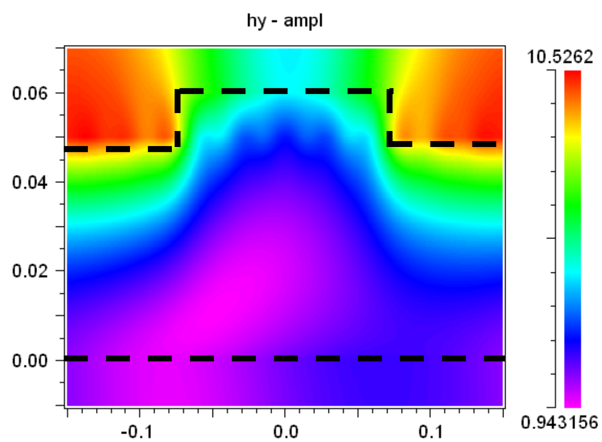
Bandgap appears at Bragg wavelength:

$$\Lambda_B = \frac{\lambda_{sp}}{2}$$

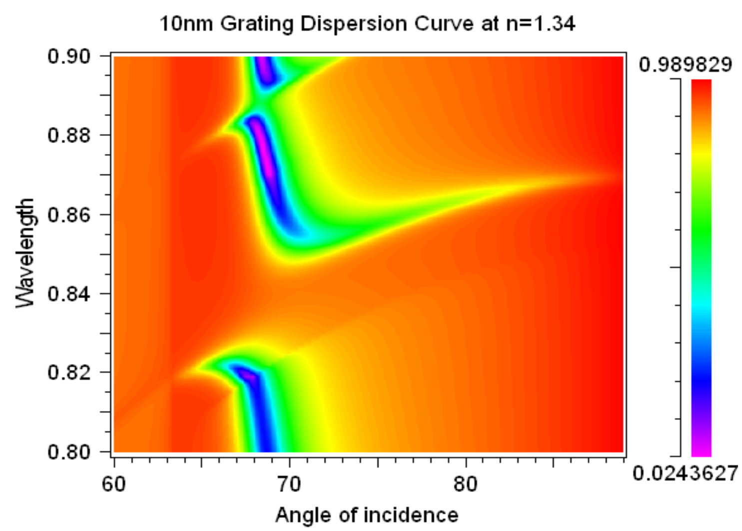
Effect of grating

- 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



Magnetic field



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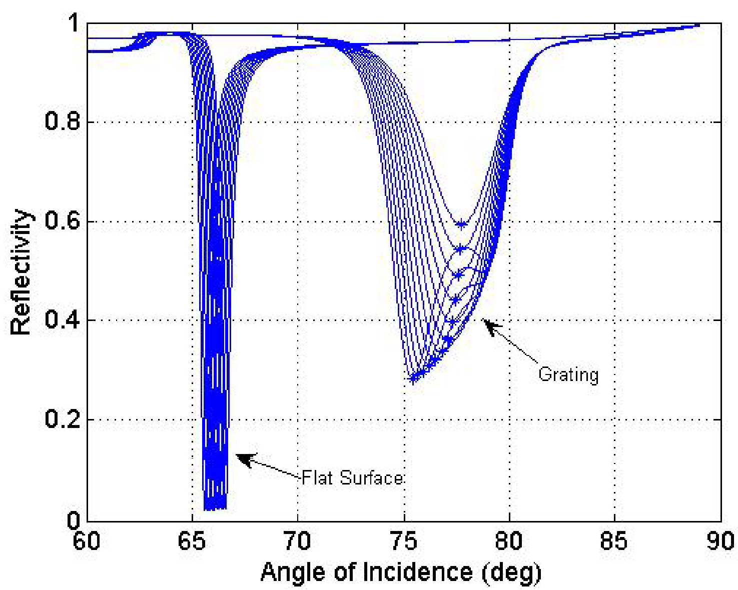
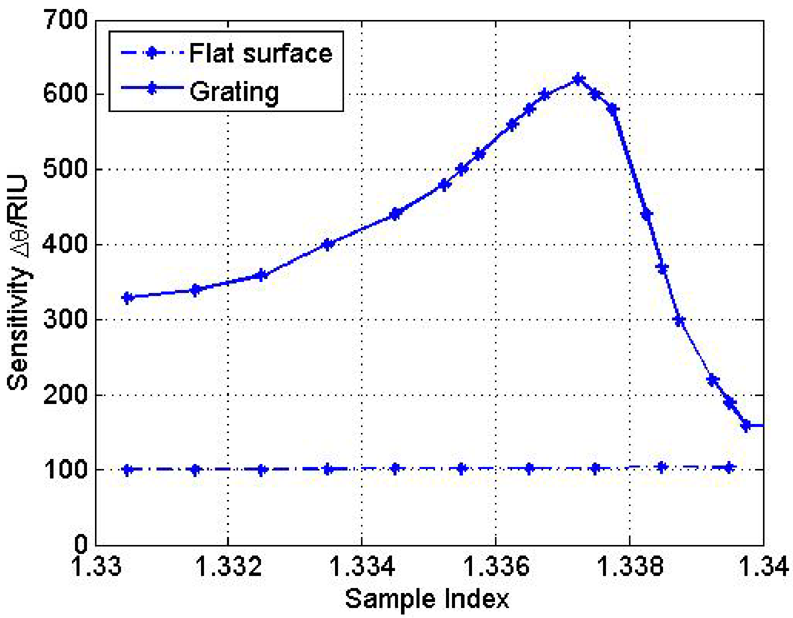
Sensitivity enhancement

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

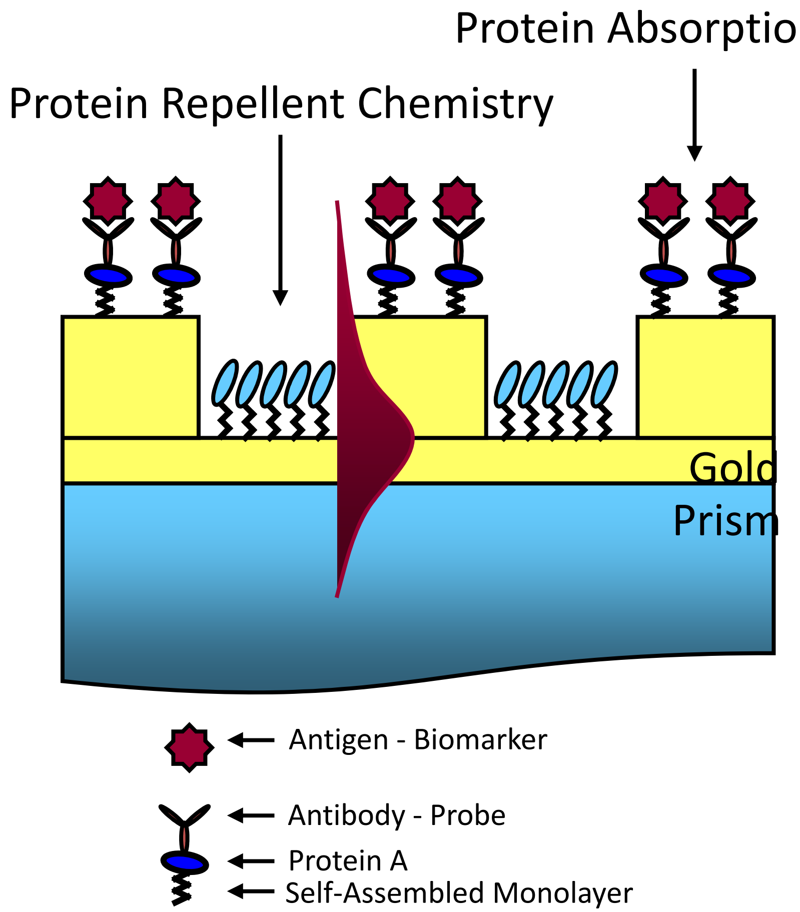




However, for a given wavelength, range is limited. Increase range by measuring in two-dimensions (wavelength and angle)

C.J. Alleyne, A.G. Kirk, R.C. McPhedran, N-A.P. Nicorovici, and D. Maystre, ‘Enhanced SPR sensitivity using periodic metallic structures’, *OSA Optics Express*, **15**, pp 8163-1869, 2007

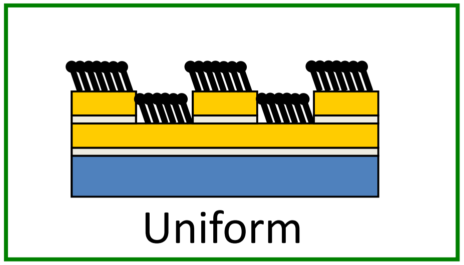
Experimental evaluation: Grating + patterned surface chemistry

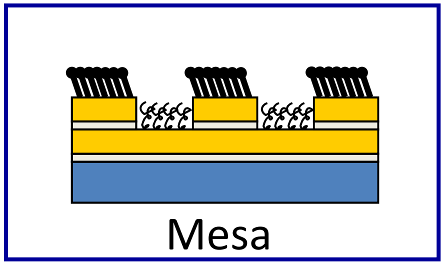


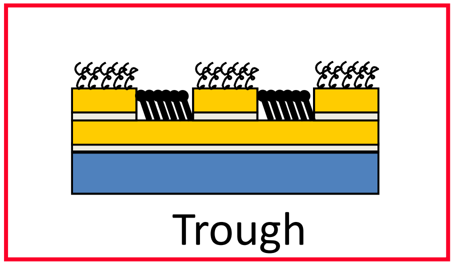
- Enhanced SPR response
- Increased electromagnetic gradients
- Surface receptors with optimized orientation, density and non-specific absorption
- Generate biochemical optical contrast

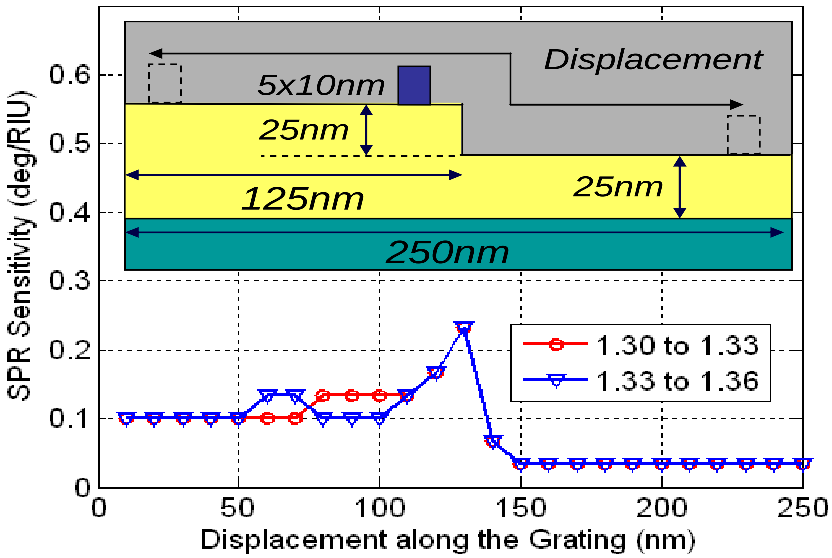
X.D. Hoa, M. Tabrizian, A. G. Kirk, Enhanced SPR Response from Patterned Immobilization of Surface Bioreceptors on Nano-gratings, *J.Biosensors and Bioelectronics*, 24 (2009) 3043–3048, 2009.

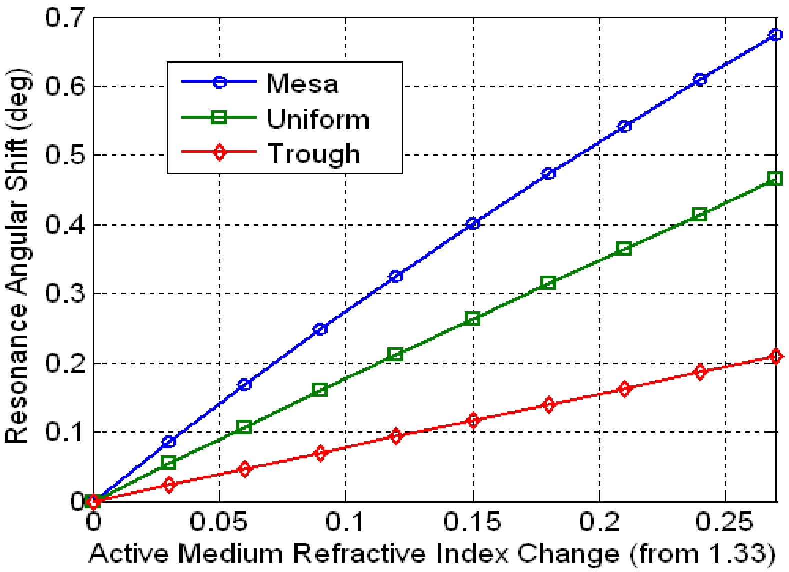
Rigorous Coupled Wave Analysis Modelling











X.D. Hoa, M. Tabrizian, A. G. Kirk, 'Rigorous Coupled-Wave Analysis of Surface Plasmon Enhancement from Patterned Immobilization on Nano-Gratings', *J.Biosensors*, doi:10.1155/2009/713641, 2009.

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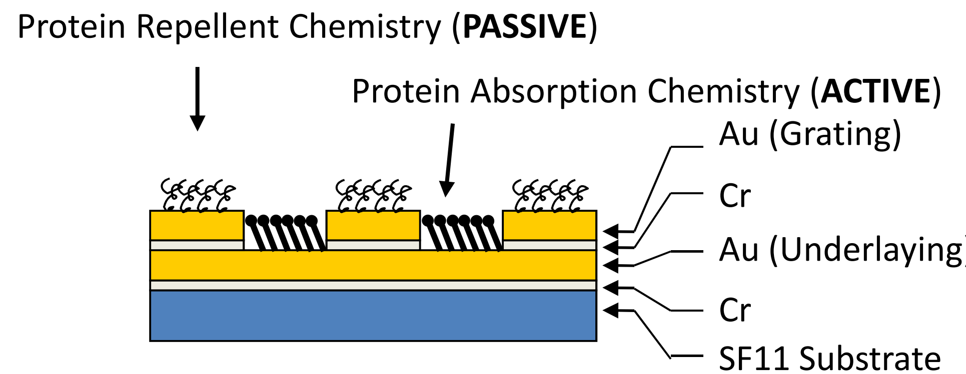
Microfabrication and Surface Chemistry



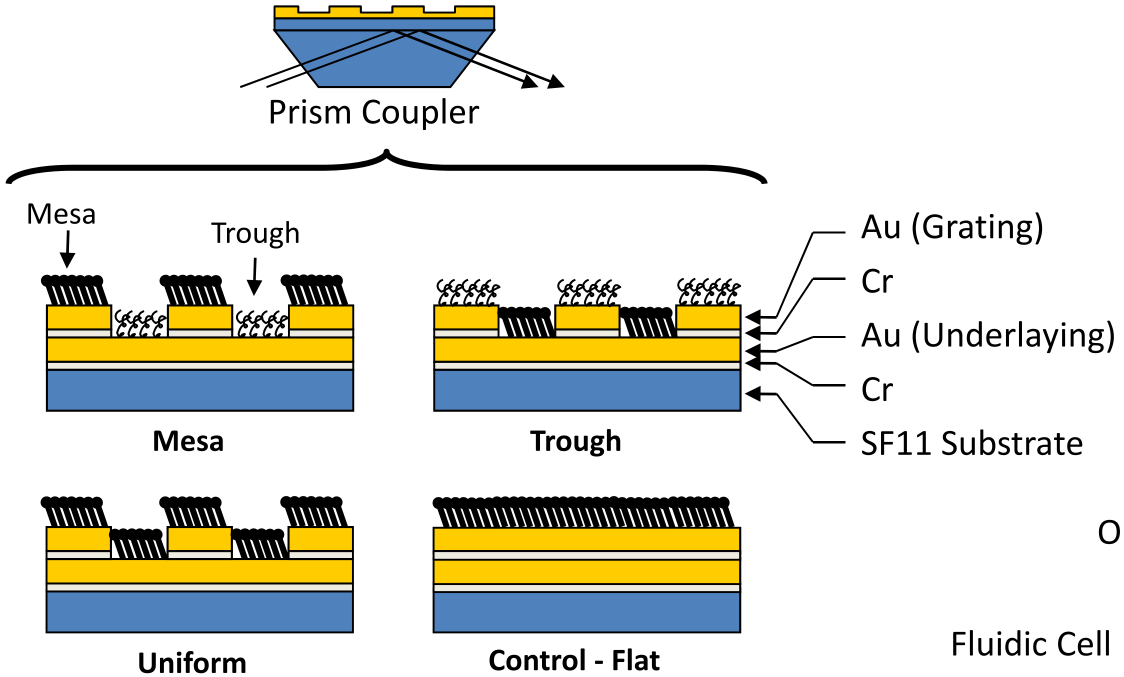
- 1mM of PEO in water
- Overnight incubation

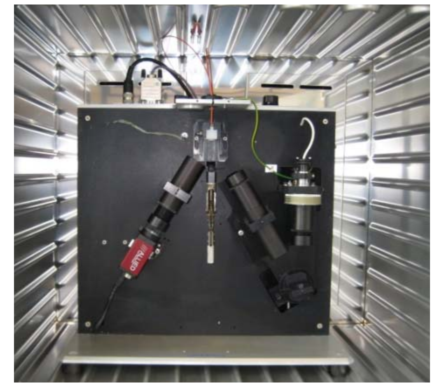
- 1H in Acetone/MEK
- 1 min ultrasonication

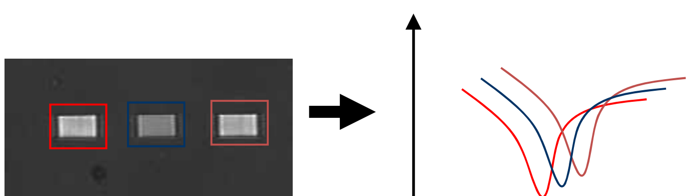
- 1mM of MCHA in ethanol
- 3H incubation time

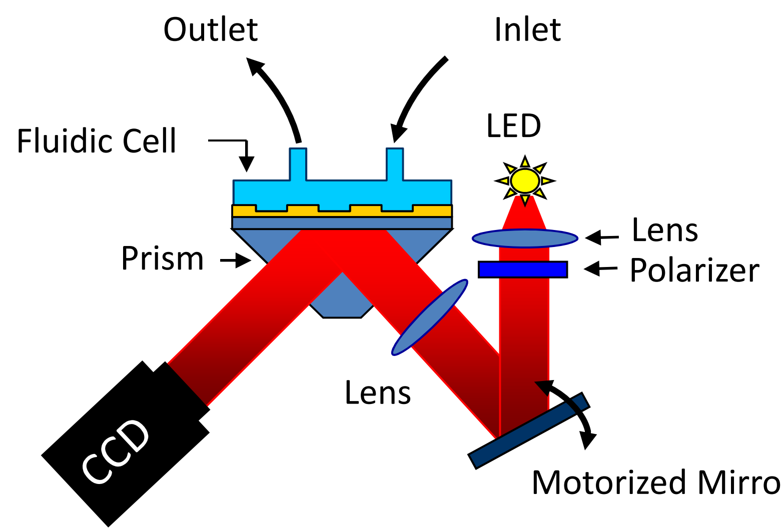
X.D. Hoa, M. Tabrizian, A. G. Kirk, Enhanced SPR Response from Patterned Immobilization of Surface Bioreceptors on Nano-gratings, *J.Biosensors and Bioelectronics*, 24 (2009) 3043–3048, 2009.

Characterization via SPR-Imaging









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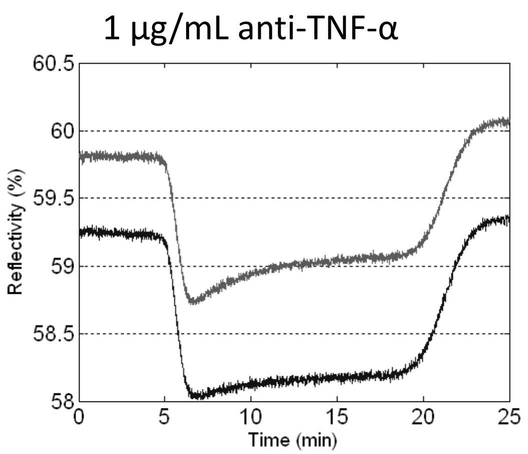
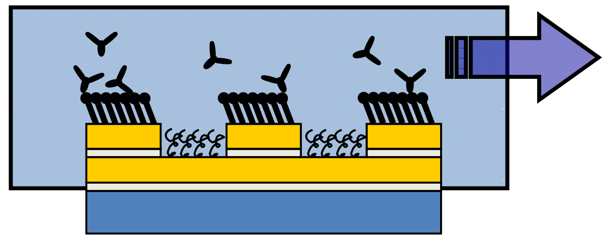
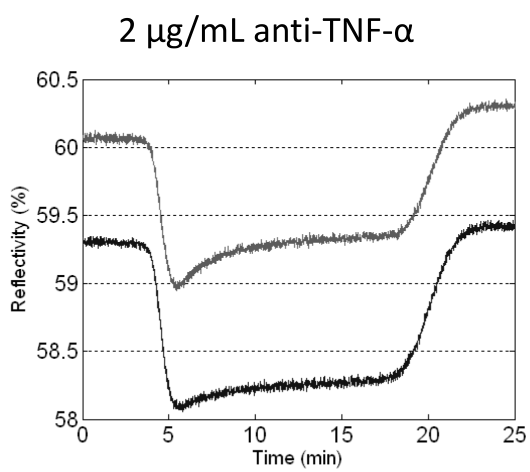
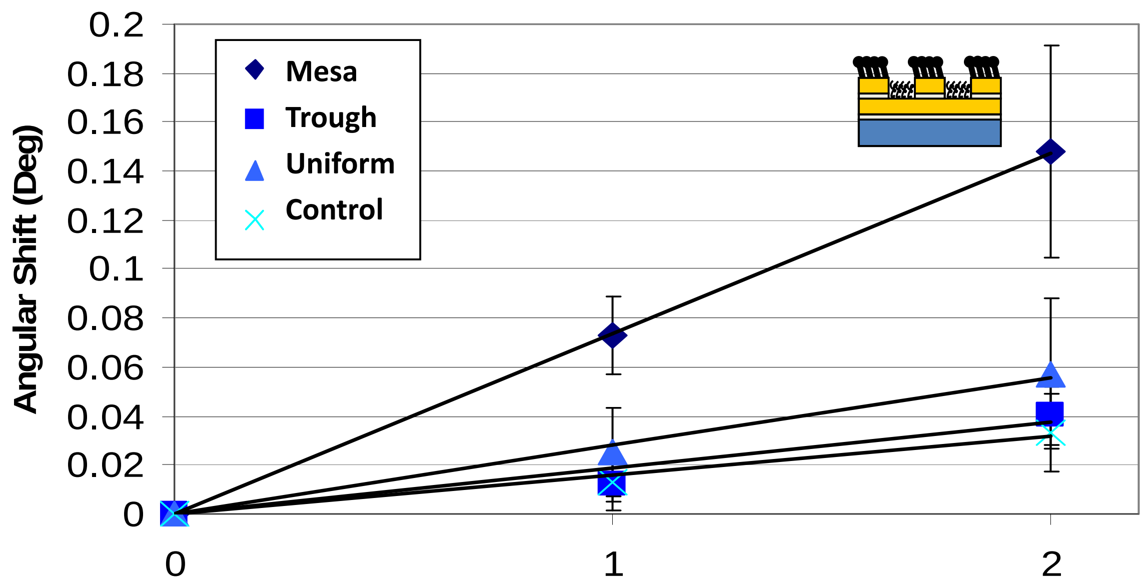
Injection of Anti-TNF-α









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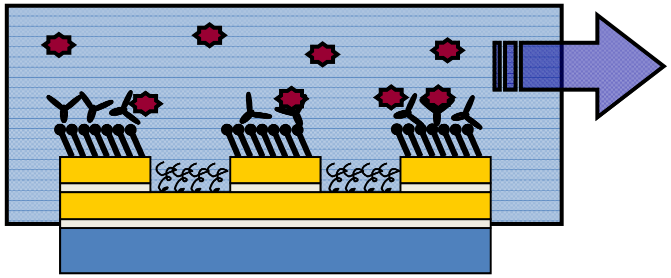
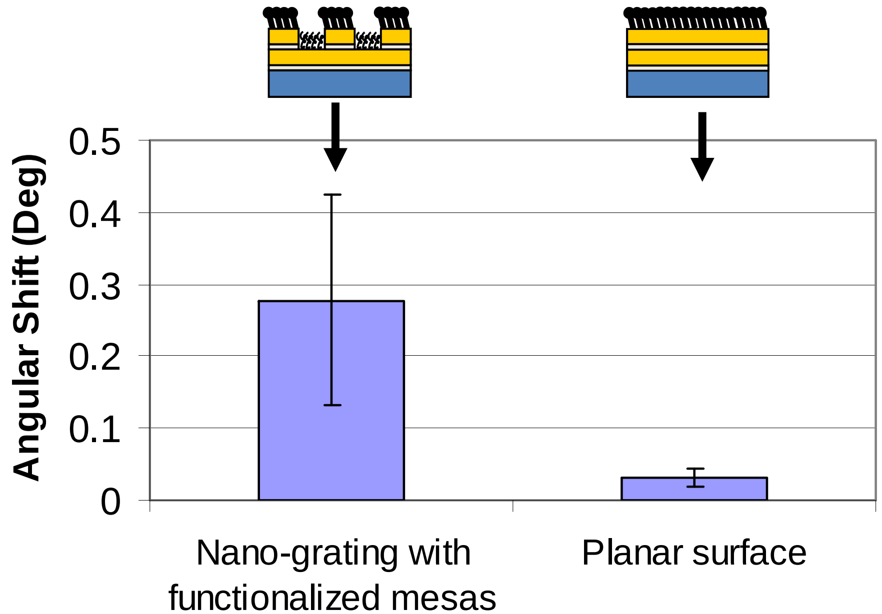
SPR-Imaging – Injection of TNF-α

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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Integrated Nanophotonics Research Group

Current projects

Planar waveguide devices

- **Etched grating demultiplexer**
- Photonic crystal superprism
- Photonic crystal wavelength conversion
- Hybrid laser integration
- **Fabry-Perot comb filter switch**

Biosensors

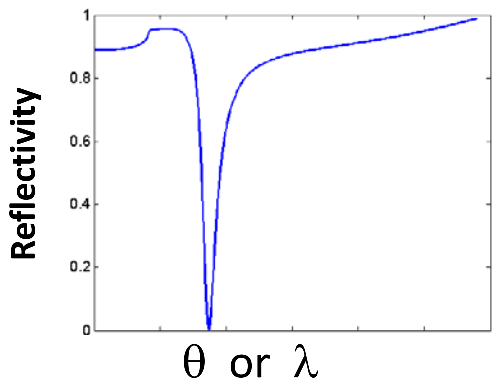
- **Integrated SPR**
- **Grating-enhanced SPR**
- **Spectro-angular SPR**
- Plasmonic polymer
- Cavity ring down resonant sensing
- Nano-crystalline cellulose

2D vs. 1D SPR

Why use 2D SPR?

Possibility of using image analysis techniques.

1D



Dip finding Algorithms

2D

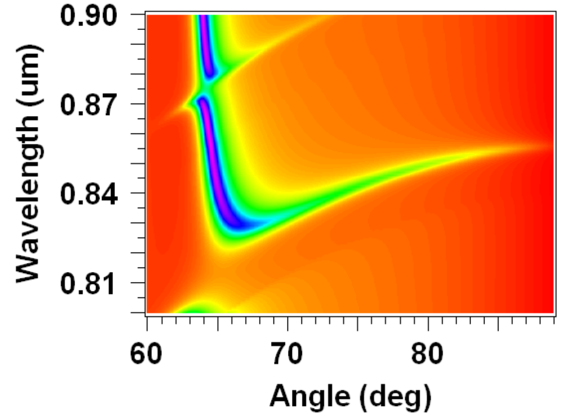


Image analysis techniques

Image Analysis Technique

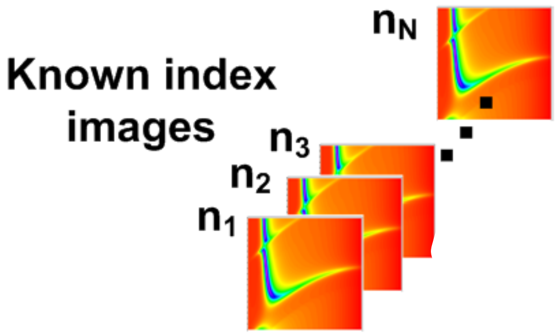
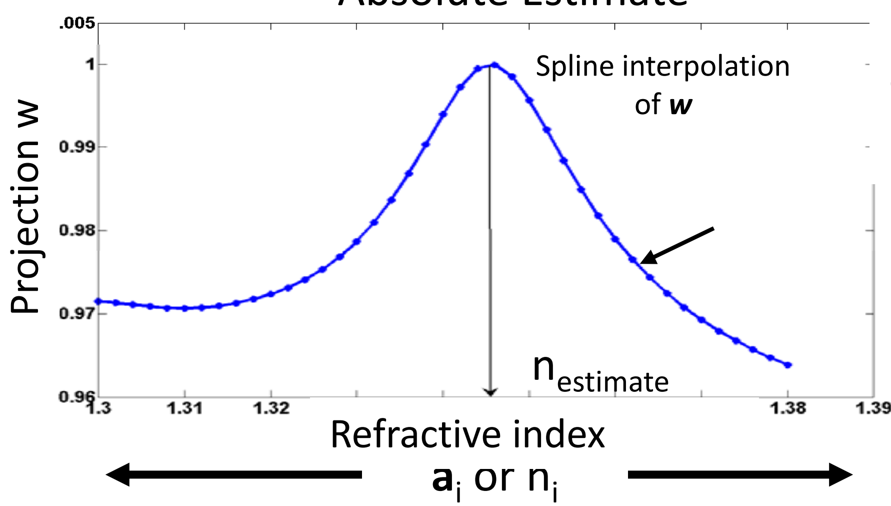


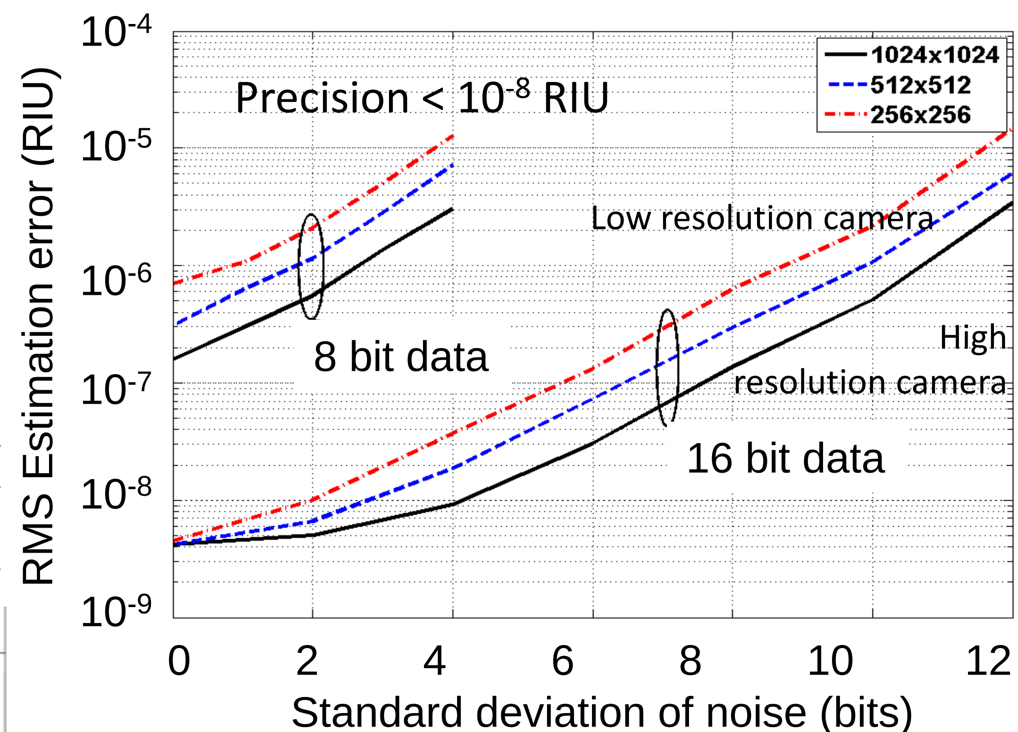
Image Analysis Technique

Associate the weights w_i with initial index n_i

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} \Rightarrow \begin{bmatrix} \vec{a}_1 \\ \vec{a}_2 \\ \vdots \\ \vec{a}_N \end{bmatrix} \Rightarrow \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

Absolute Estimate



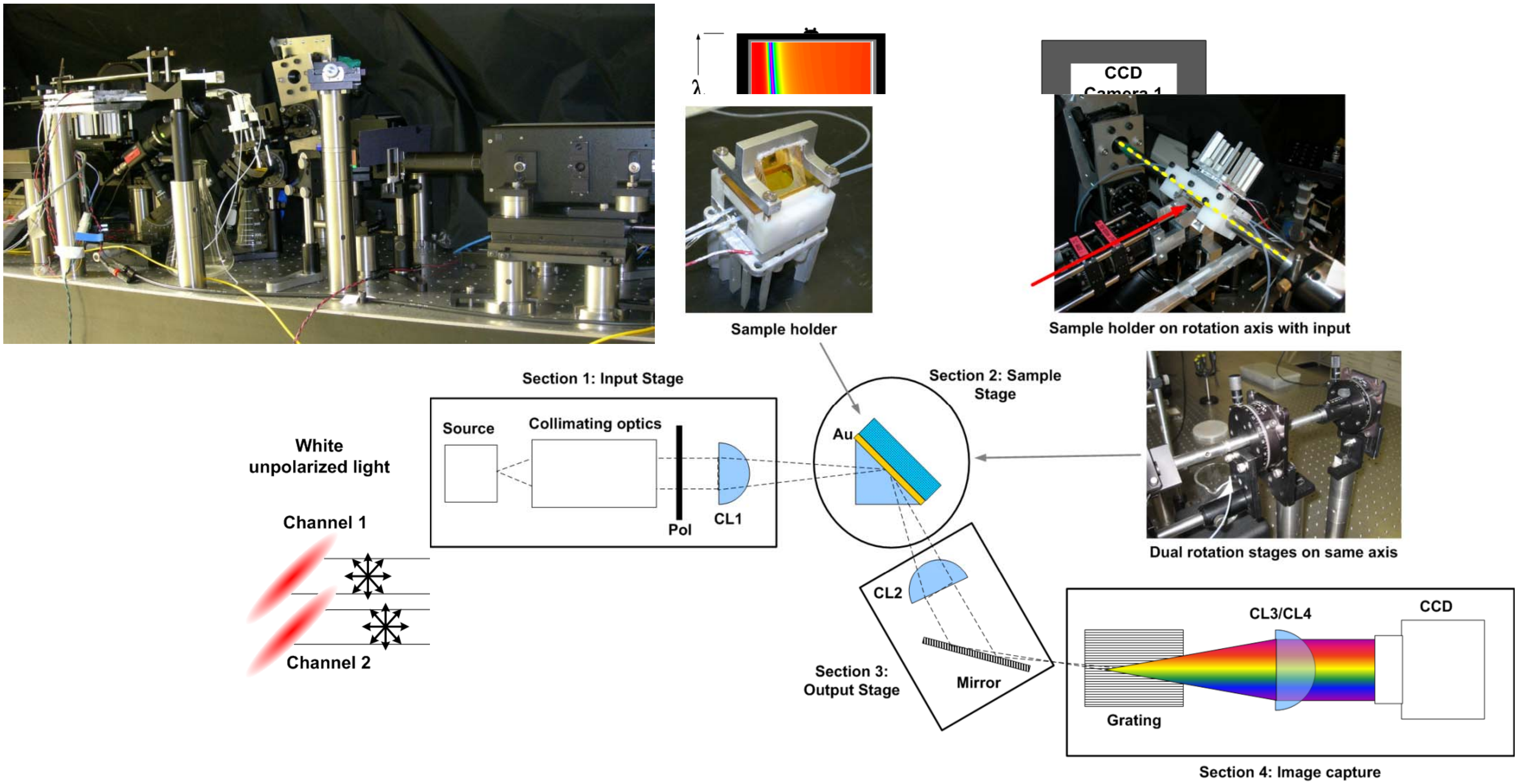


C.J. Alleyne, A. G. Kirk, P.G. Charette, 'Numerical method for high accuracy index of refraction estimation from surface plasmon photonic bandgap structures.', *OSA Optics Express* **16** (24) pp 493-503, 2008

Experimental Implementation

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

- The second channel is used as a reference for drift elimination



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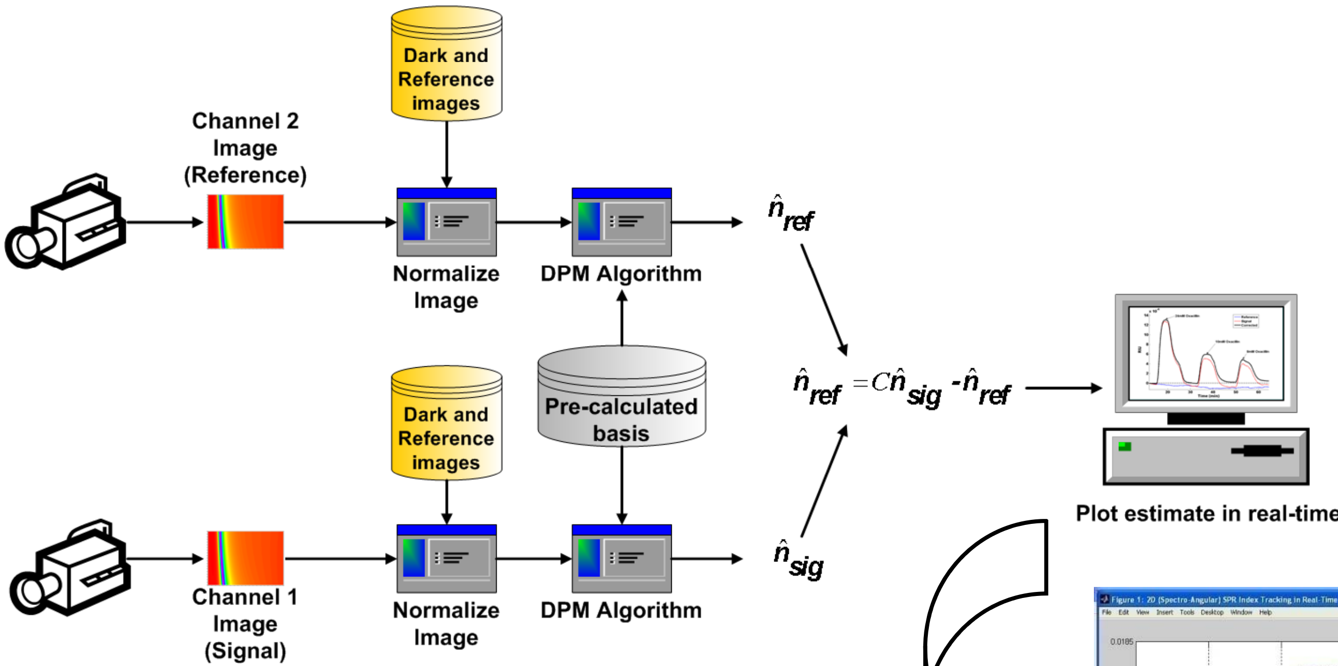
Real-Time Data Analysis

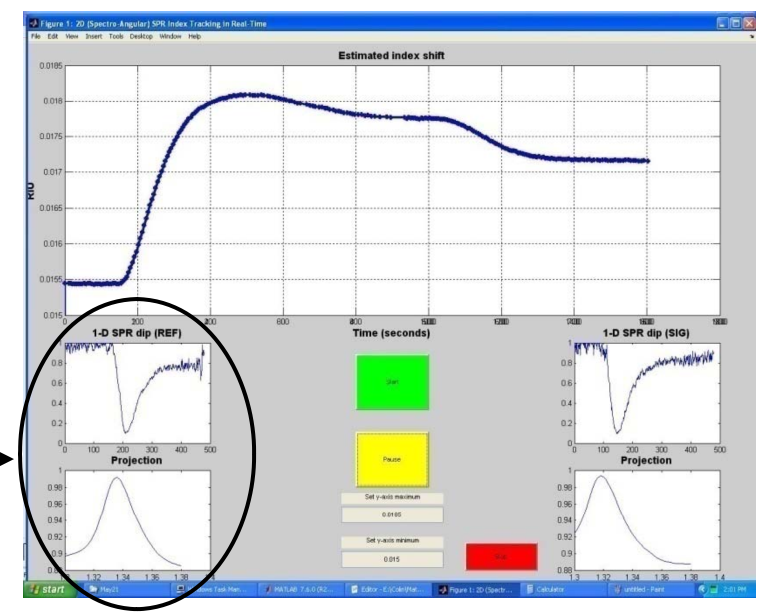


- Real-time output of index estimate (15 frames/sec, 2-4 seconds/sample)
- Monitoring of dip quality in both channels.
- Monitoring of DPM projection curve in both channels.

Channel 1

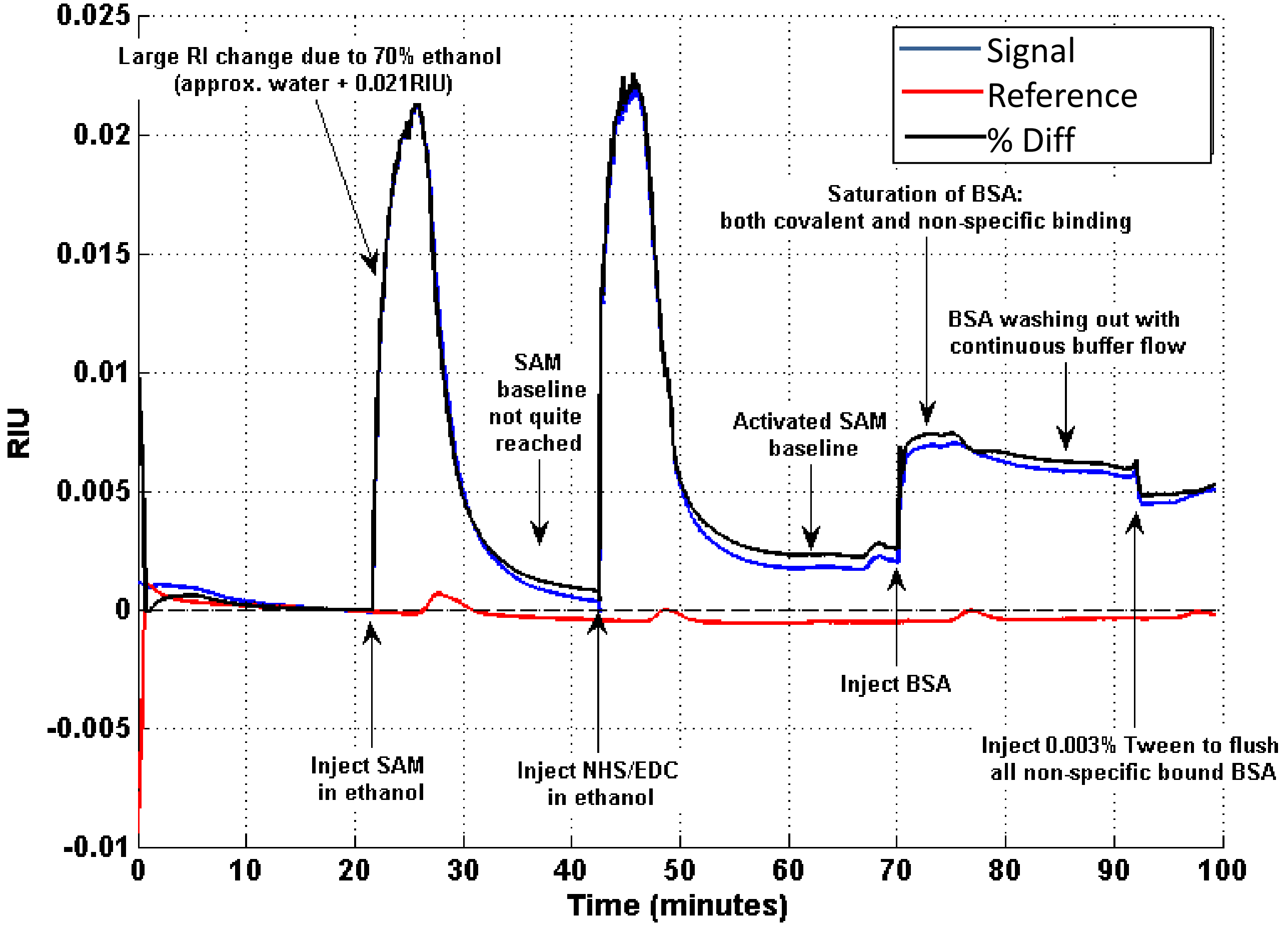
•SPR dip (top)

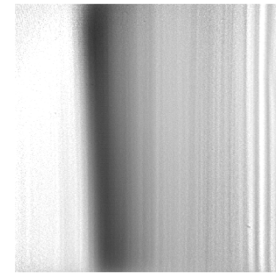
•DPM projection, **s** (bottom)



Spectro-Angular experimental results

Monitoring SAM deposition and BSA binding





2D image

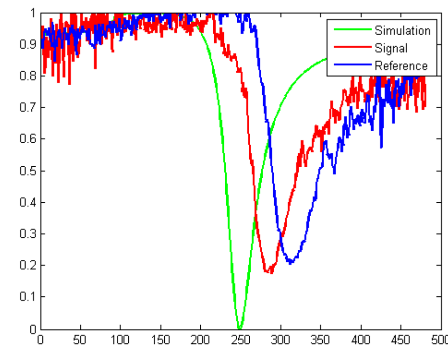
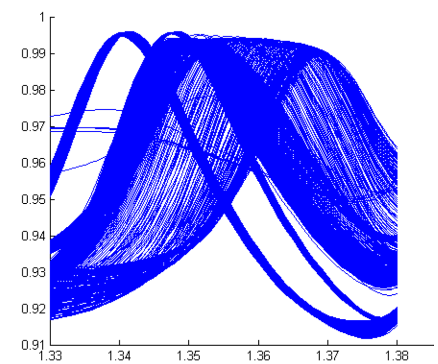


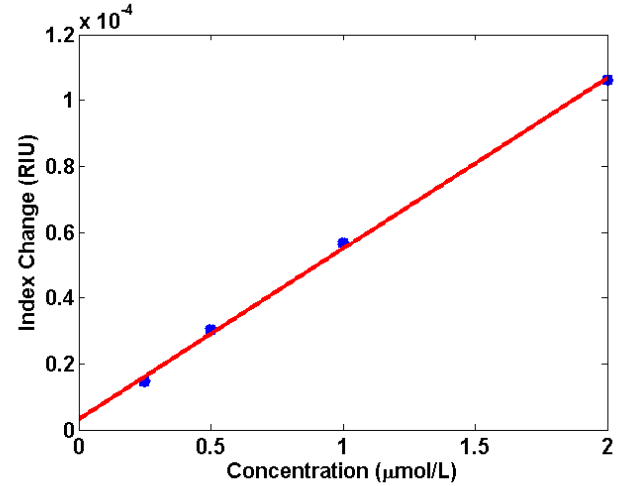
Image slice

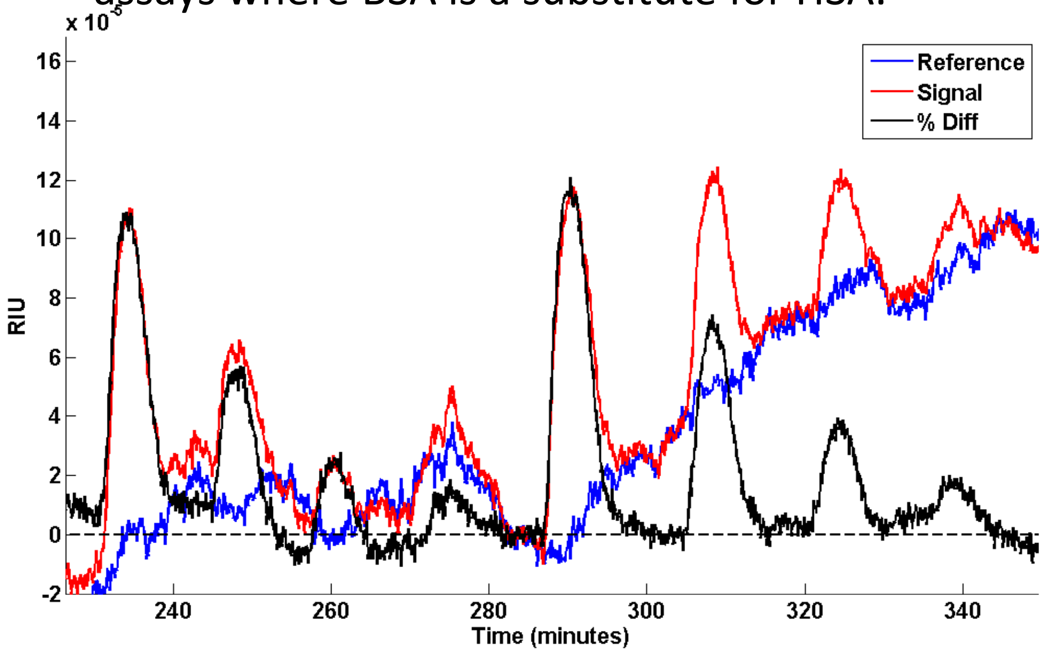


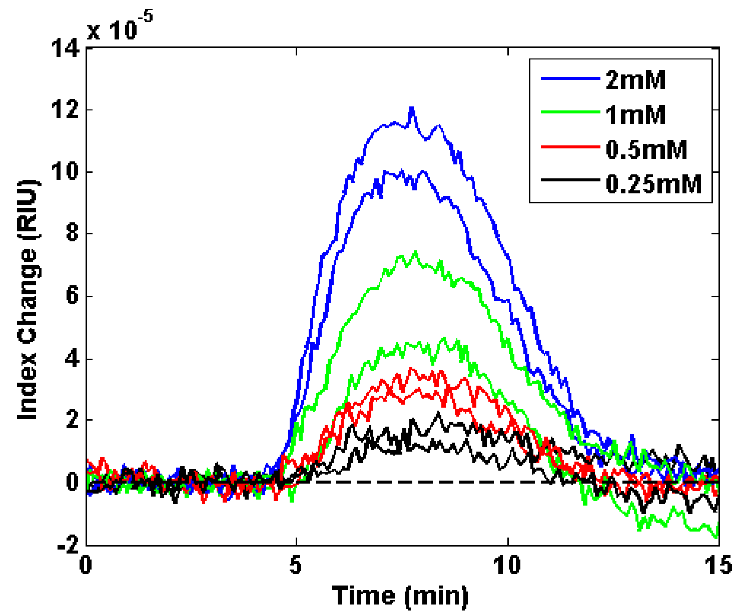
DPM projections

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.



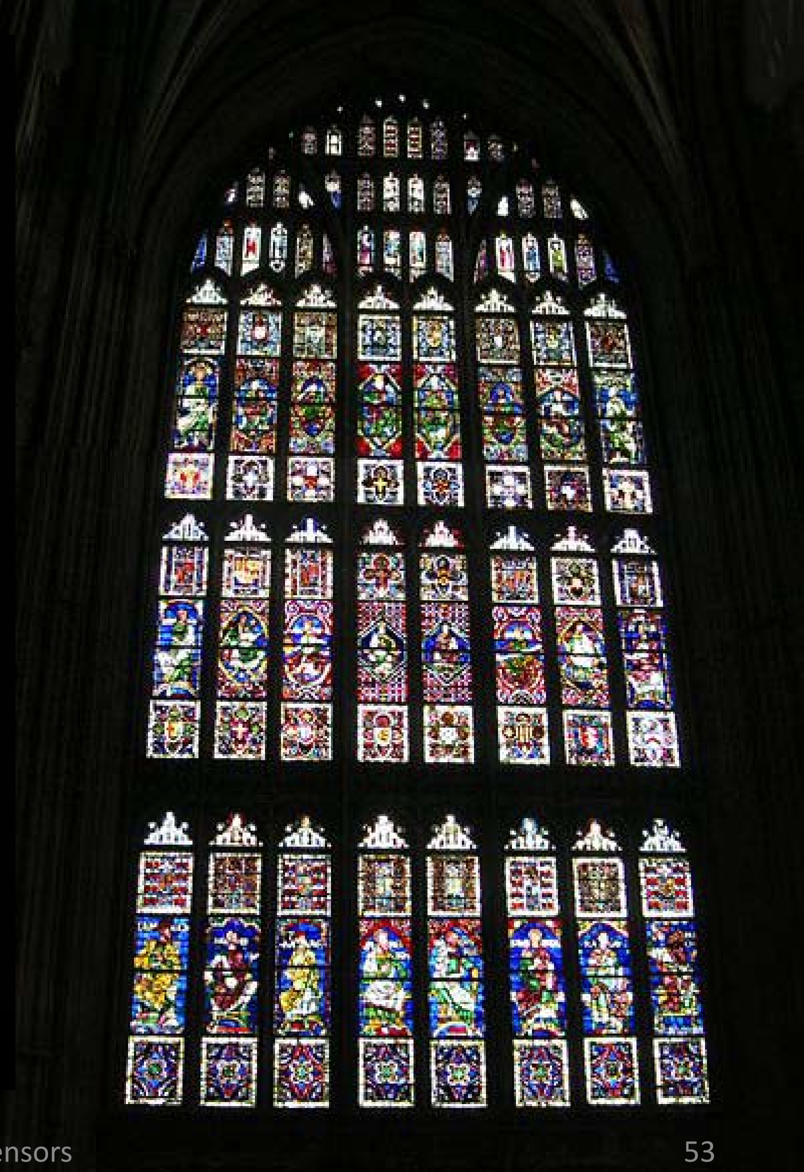




C.Alleyne, P.Roche, A.G.Kirk, 'Spectro-angular surface plasmon biosensor applied to drug binding assays', *Proc. IEEE-Photonics Society Annual Meeting*, WR3, Antalya, Turkey, 2009

Localised surface plasmon resonance

Lycergus cup (British museum)



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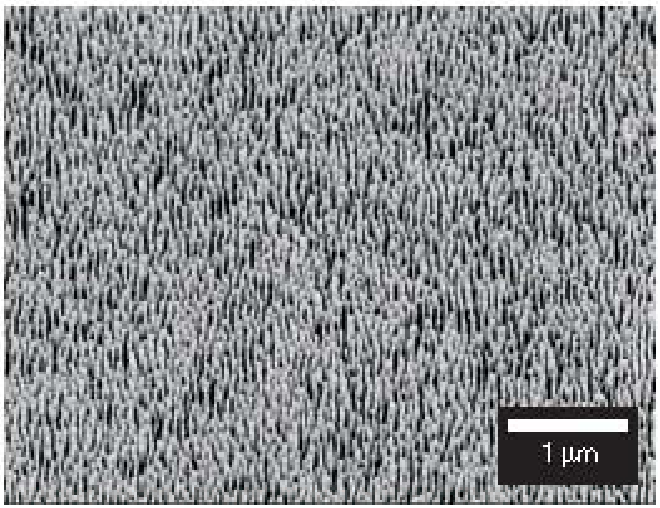
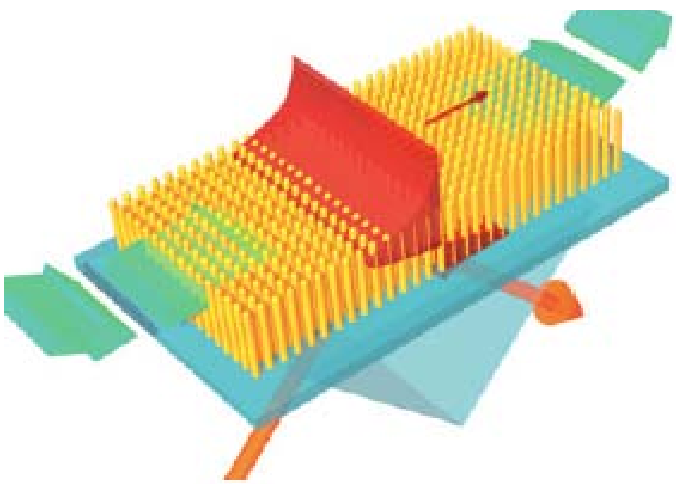
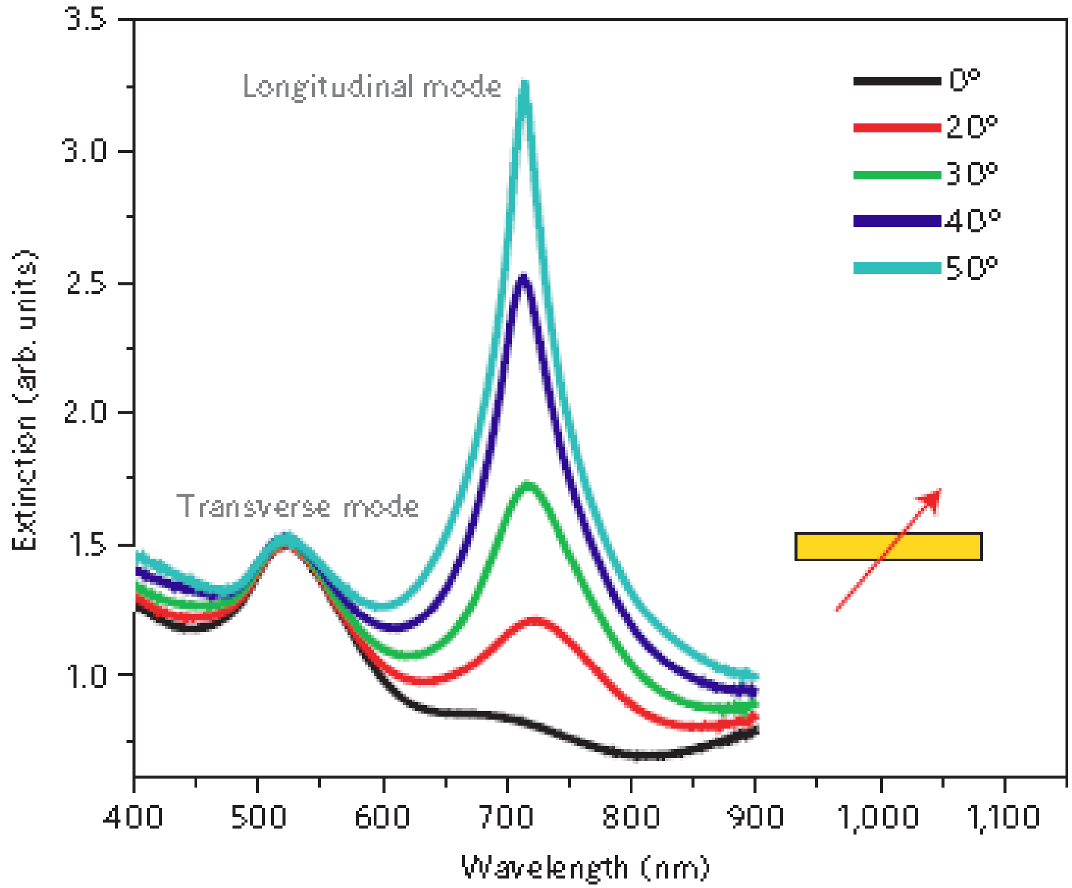
Collective resonance of nanorods

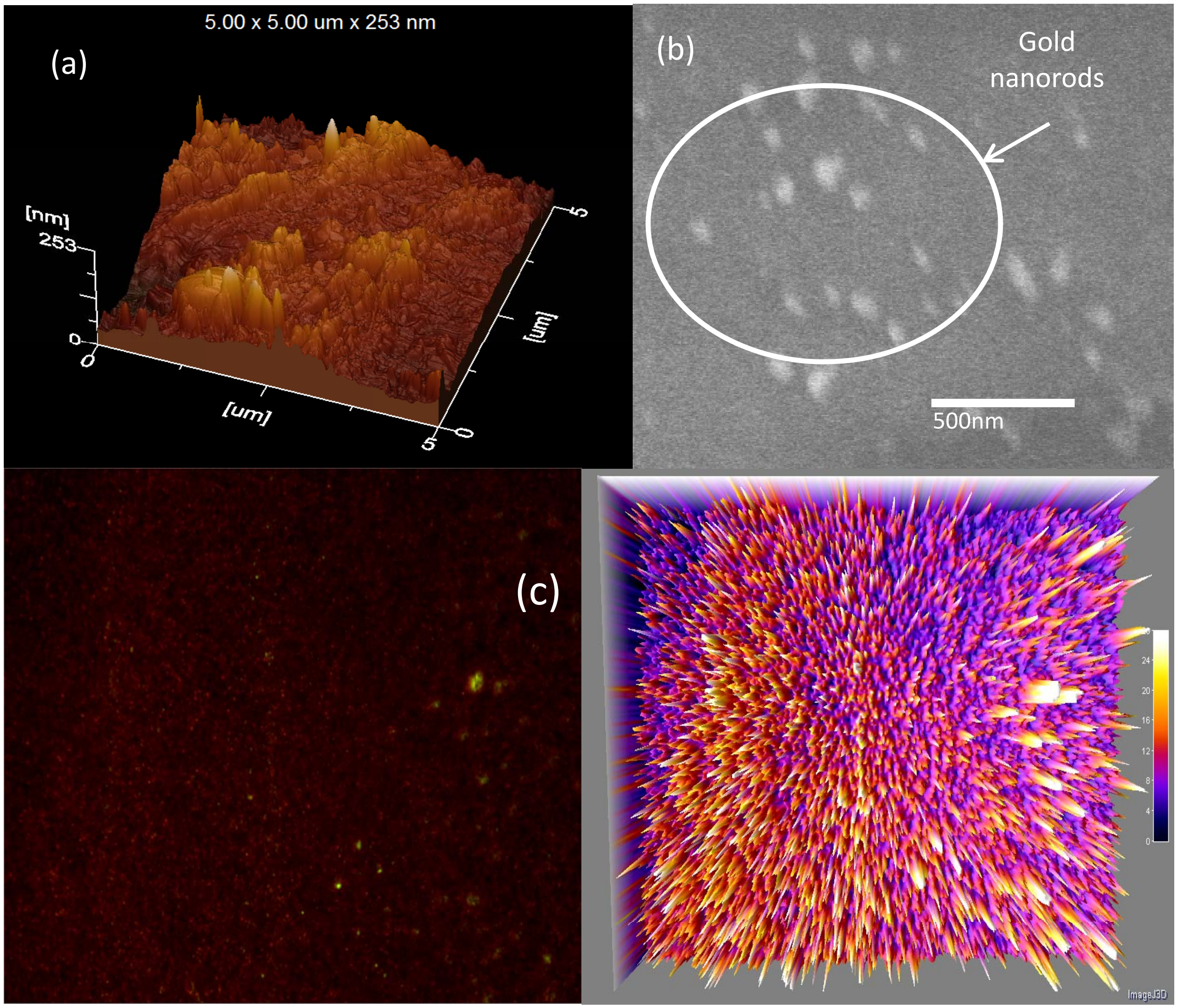
Nanofabricated gold nanorods (500 nm x 50 nm)







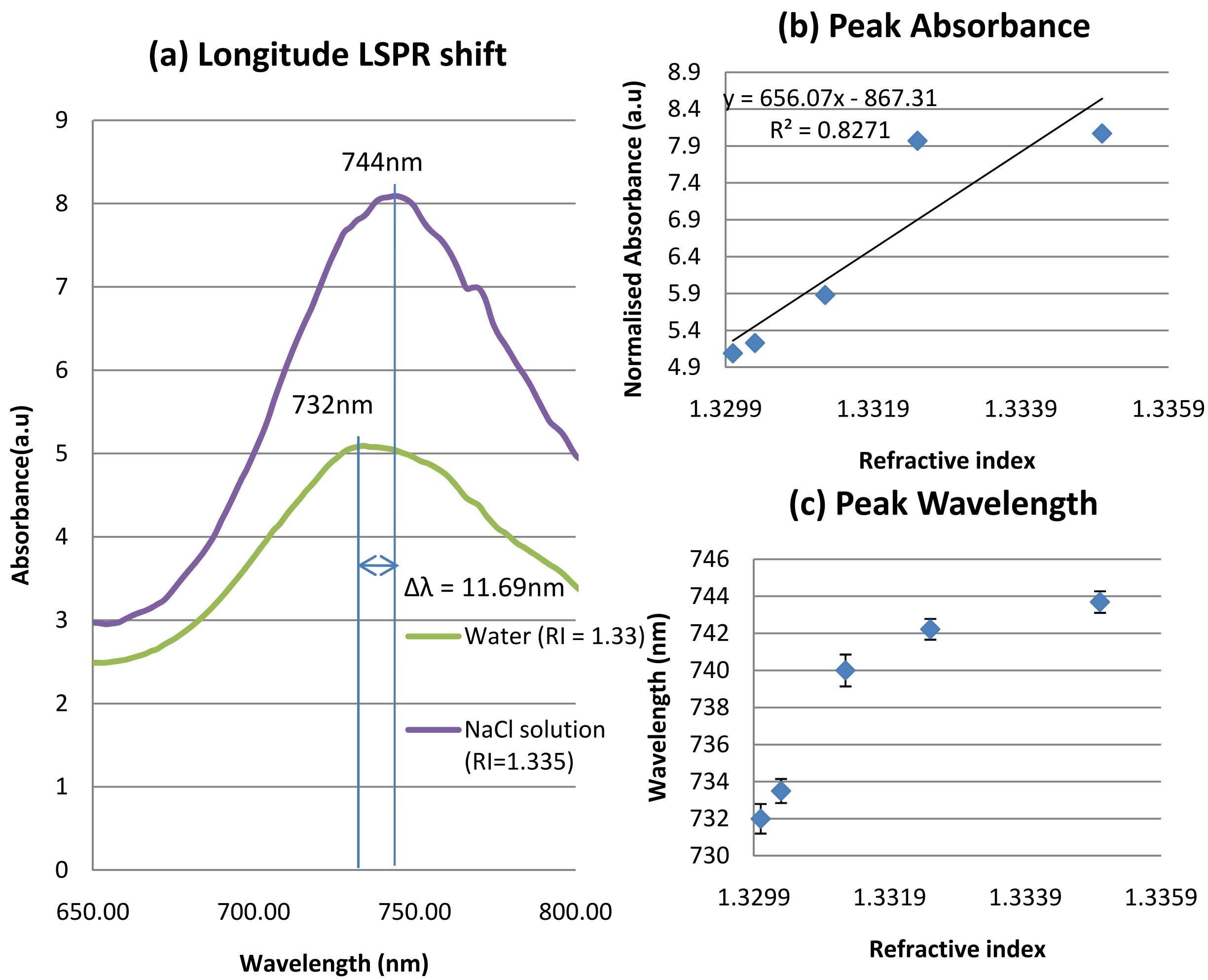
Nanorods in sol-gel



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

P.Roche and A.Kirk, unpublished work

Plasmonic polymer: Sensitivity to index change



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

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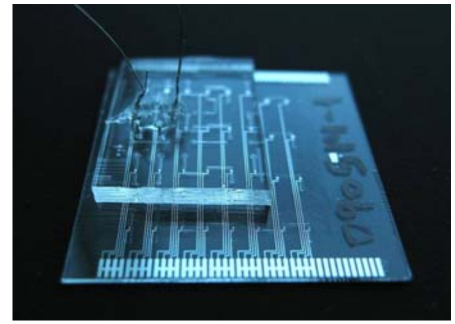
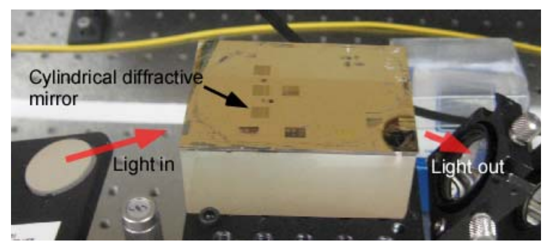
Training program in Integrated Sensor Systems

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



Microfluidics



Optical sensors