INTEGRATED OPTICS

Summer School on Optics & Photonics 2.6.2017
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OUTLINE

Introduction

- What is integrated optics?
- Main concepts
- Operation principles of the components

Applications

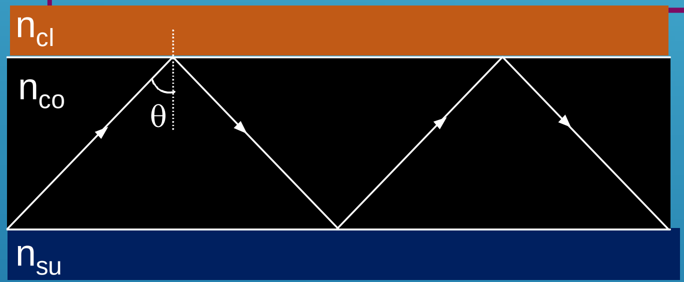
- Main applications
- Example component

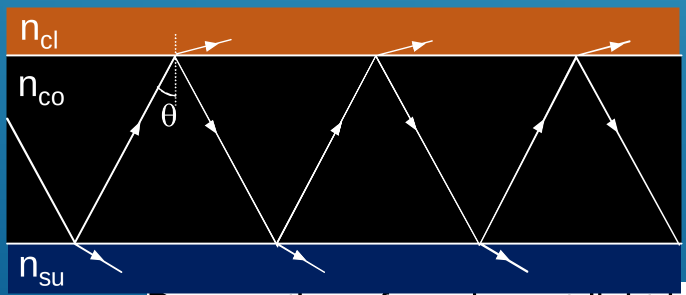
INTEGRATED OPTICS

- Term integrated optics means implementation of the optical properties on single substrate.
- Similar than electric integrated circuit (IC-circuit), PIC - Photonic Integrated Circuit
- Several different materials and material combinations available for integrated optics.
- The main structure is waveguide, which is used to guide and manipulate light signal.
- The operation of the waveguide is based on the total reflection of the light

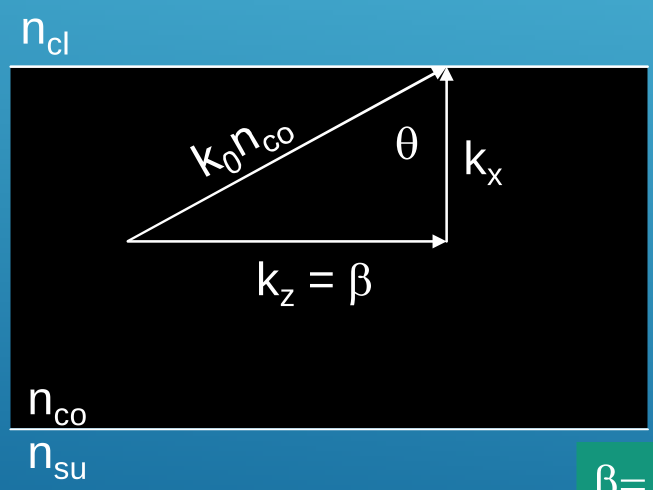
Principles of waveguide

- Light propagates in the material with a higher refractive index $n_{co} > n_{su}, n_{cl}$
- Higher RI of the core layer allows total internal reflection of the light in core-cladding interface
- Resonance conditions fulfills (standing wave), when the phase shift ($m*2\pi$) of the ray occurs
- Due to the resonance condition, the light propagates only with the discrete angles, which are smaller than the critical angle of incidence
- Waveguide dimensions, refractive index contrast between materials and the used wavelength determinates if the only one or multiple guided modes can propagate in the waveguide
- Singlemode (SM) and multimode (MM) technology

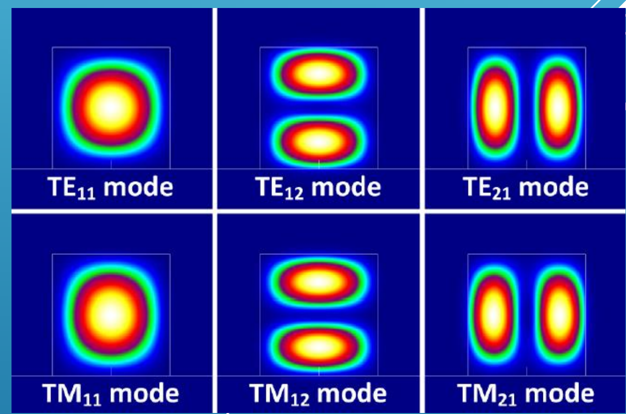




Propagation of a coherent light beam in a slab waveguide structure. Guided mode $\theta_{su} < \theta < 90°$, substrate-cladding radiation mode $\theta < \theta_{cl}$.



"Integrated Optics, Theory and technology", Robert Hunsperger



$\beta = k_0 n_{co} \sin\theta$

$k_0 = 2\pi/\lambda_0$

$n_{su} < n_{eff} < n_{co}$

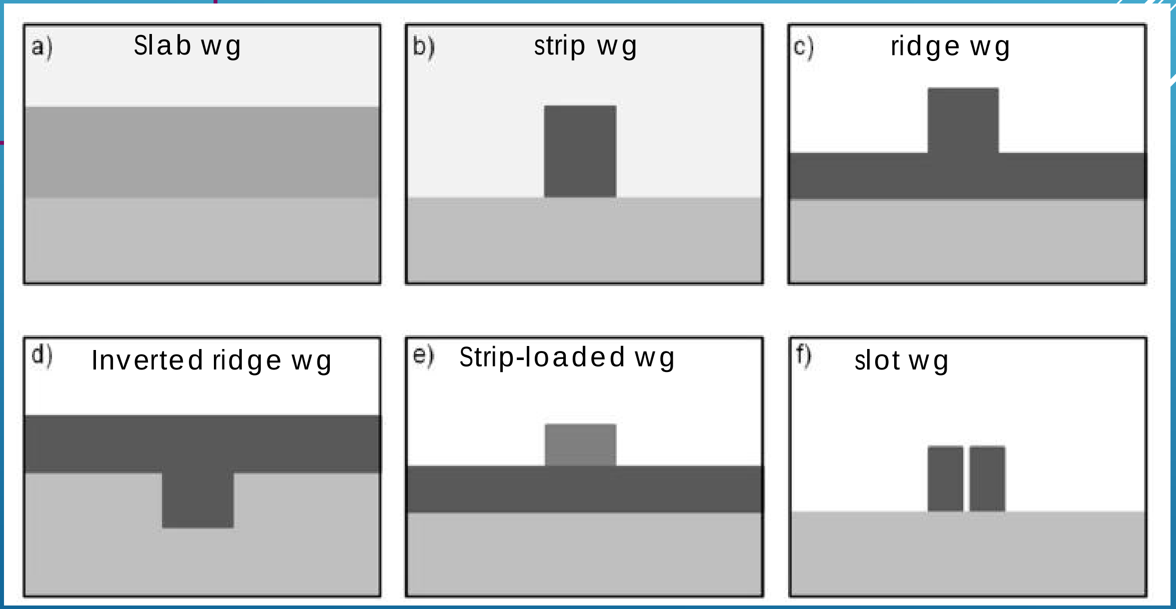
Dai, Opt. Exp. Vol 23, No 22, (2015)

Example of different waveguide geometries

- Waveguide have a core with a higher refractive index n_{co} than the substrate n_{su} or the cladding n_{cl} and therefore the light can be guided

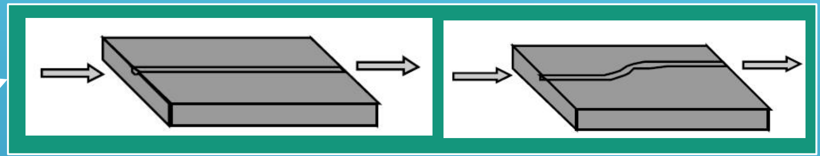
- Typical waveguide dimensions
  - SM waveguide <1 – 10 µm
  - MM waveguide 20-100 µm

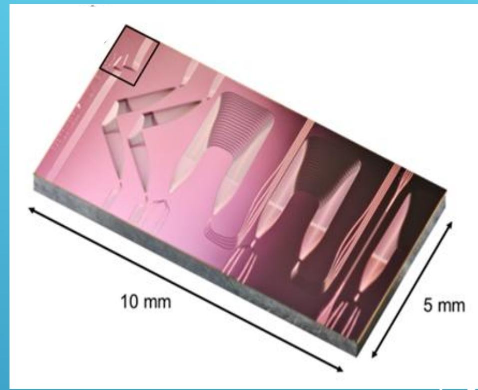
  Materials
  - Semiconductors (silicon) n=3.45
  - Glass n≈1.45
  - Polymers n≈1.5 -1.6



APPLICATIONS: COMMUNICATION

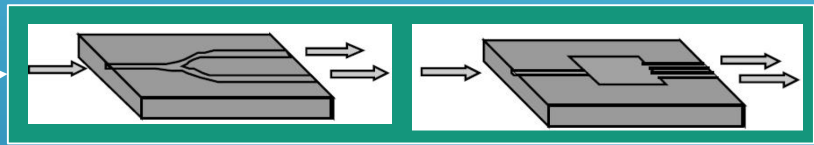
High speed optical communication (next generation computers)
Optical interconnects (chip-to-chip, board-to-board, cabinet-to-cabinet)
Ultrafast signal processing
Optoelectronics integration
Low loss, immune to the ambient

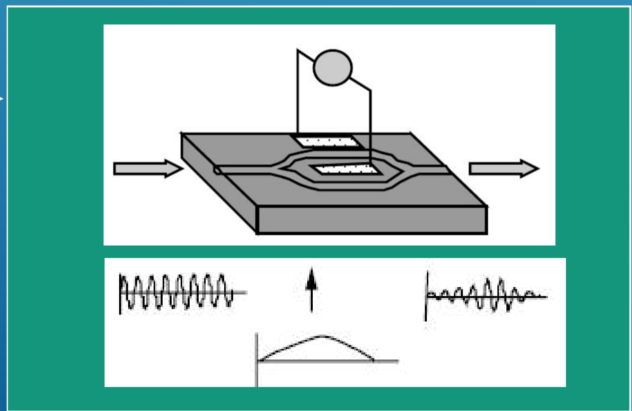


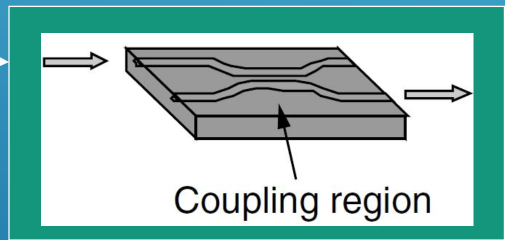


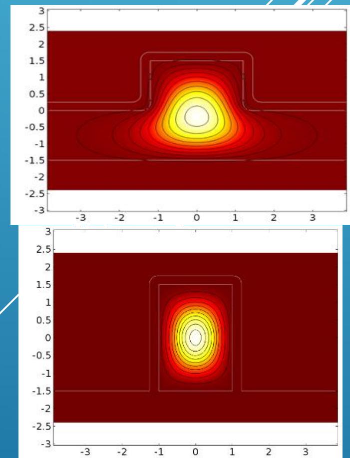
Components

- ❖ Interconnect
- ❖ Power splitter
- ❖ Waveguide reflector
- ❖ Directional coupler
- ❖ Polarizer
- ❖ Phase modulator
- ❖ Intensity modulator
- ❖ Frequency shifter
- ❖ Multiplex
- ❖ Filters







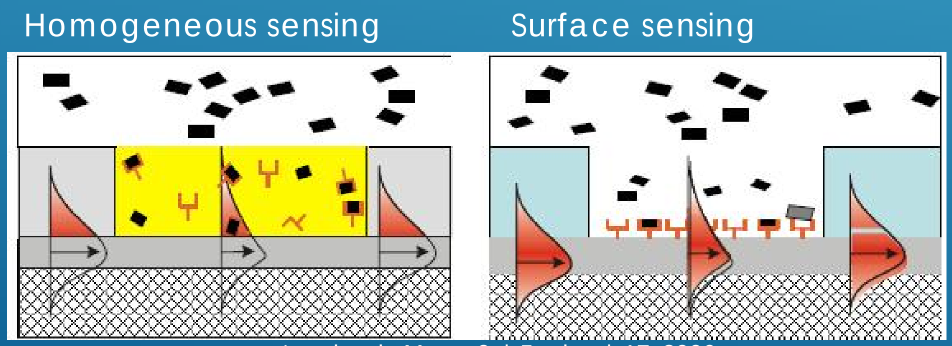


Soren;Silicon 2010
Book, Lifante; Integrated photonics, Fundamentals

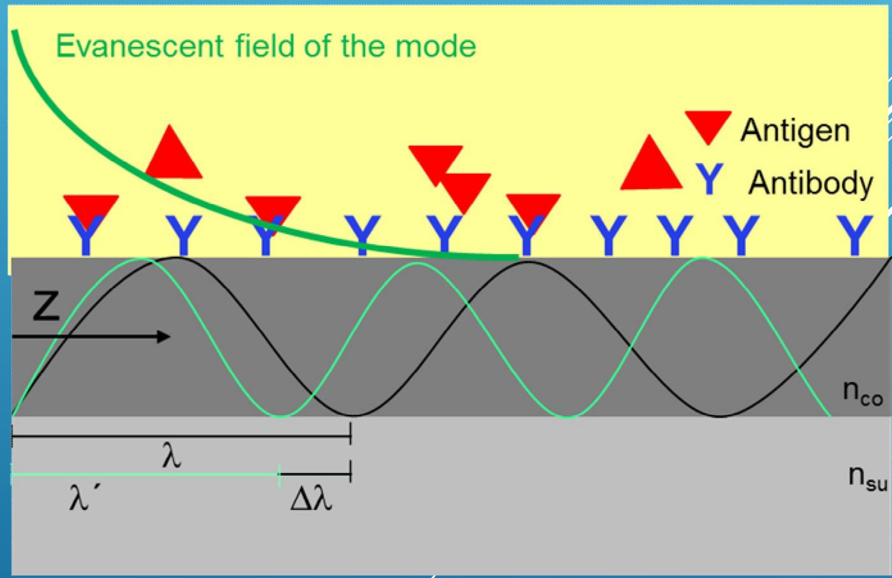
APPLICATIONS: SENSOR

Waveguide based chemical and biosensors: detects perturbation of the evanescent field

- Measures changes of the RI, absorbance or fluorescence
- Evanescent field sensing
- Homogeneous/bulk sensing: the variation of the RI occurs in all the volume above the sensor surface (example glucose sensing)
- Surface sensing: a thin layer of bioreseptors is immobilized on the surface and interact selectivel with the corresponding analyte
- Biomelecule binding increases the n_{eff} of the mode
- Label free detection
- Integration with fluid handling
- Multi-analyte detection



Lambeck: Meas. Sci. Technol, 17, 2006

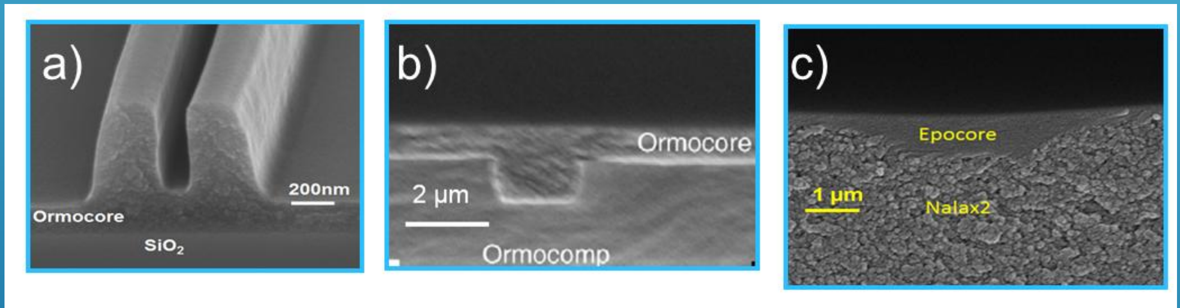


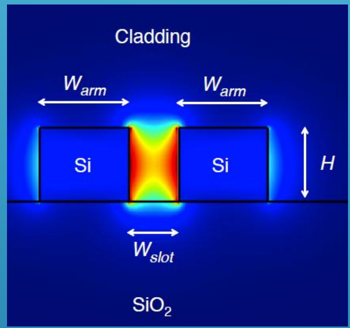
WAVEGUIDE CONFIGURATIONS FOR IMPROVING SENSITIVITY OF THE WAVEGUIDE BASED SENSOR

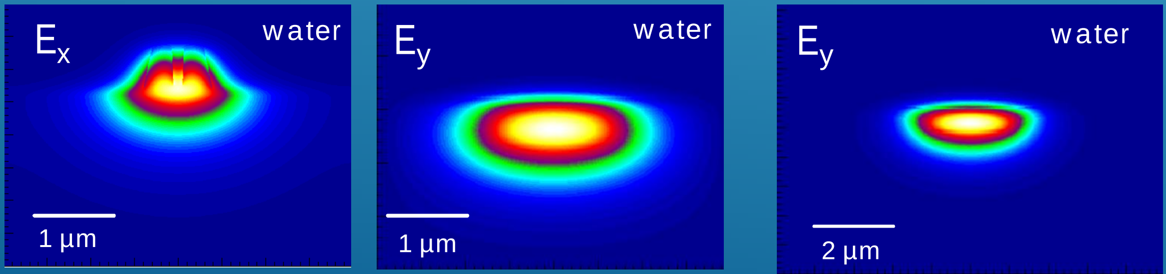
- The optical mode have to interact with the ambient and therefore, the mode has to partly propagate in the cladding
- Different waveguide structures to increase light-analyte interaction
- Materials, costs, RI
- $S= \Delta n_{eff}/\Delta n_{ambient}$

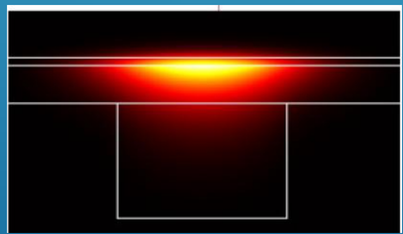
Compromise between the waveguide loss and a light-analyte interaction

- ❖ Composite waveguide
- ❖ Slot waveguide
- ❖ Gratings
- ❖ Tapers





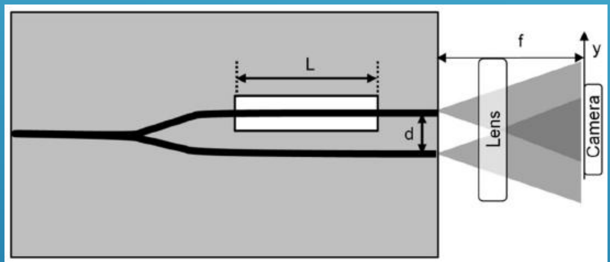




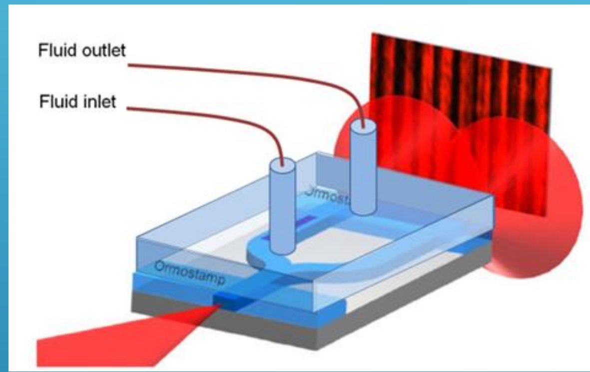
Hiltunen. Opt. Express, 22, no6, 7229, 2014
Aikio: Applied Opt., Vol. 54, 4771, 2015
Aikio, Opt. Express, Vol. 24, 2539, 2016
Wang: Opt Exp, 20, 2012

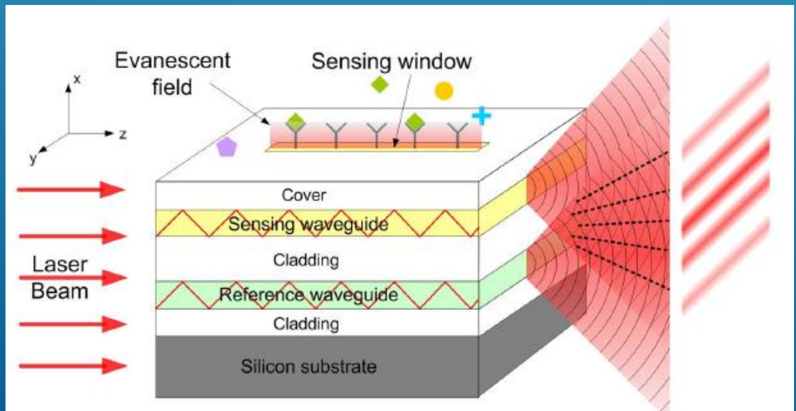
WAVEGUIDE BIOSENSORS: YOUNG INTERFEROMETERS

- Integration with fluid handling
- Changes of the mutual optical path length difference of waveguide arms induces a shift of the interference fringes. Interferograms analyzed by 2D FFT yielding the phase of the fringes.
- Detection limit 10^{-5} to 10^{-8} RIU

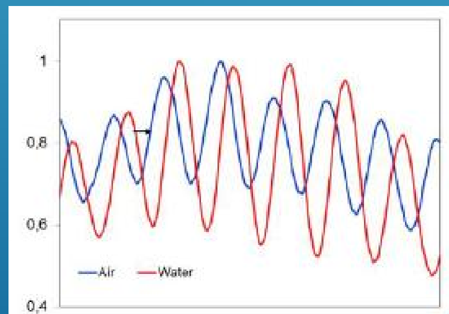


$$\Delta\phi = 2\pi \frac{\ell\left(\Delta n_{\mathrm{eff,m}} - \Delta n_{\mathrm{eff,r}}\right)}{\lambda}$$





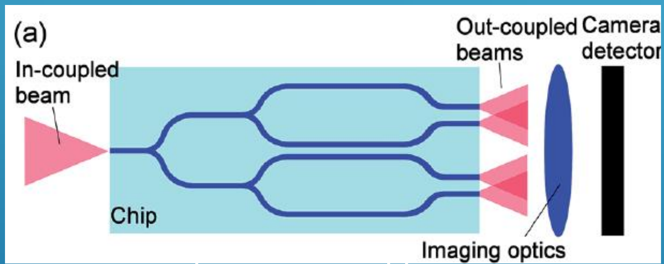
Meng,
Appl. opt.
5, 2012



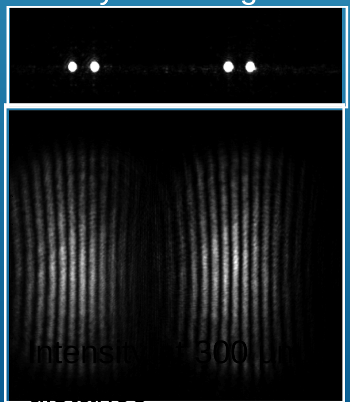
MULTI-ANALYTE DETECTION OF BIOMOLECULES

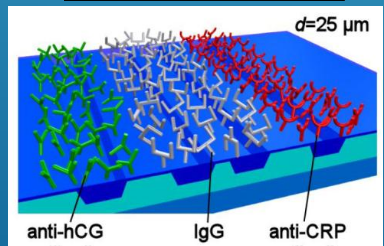
- Multi-analyte detection with integrated optics
- Antibodies for human chorionic gonadotropin (hCG) and C-reactive protein (CRP) inkjet printed on sensor surface.
- Mouse immunoglobulin G (IgG) inkjet printed

  for reference layer.

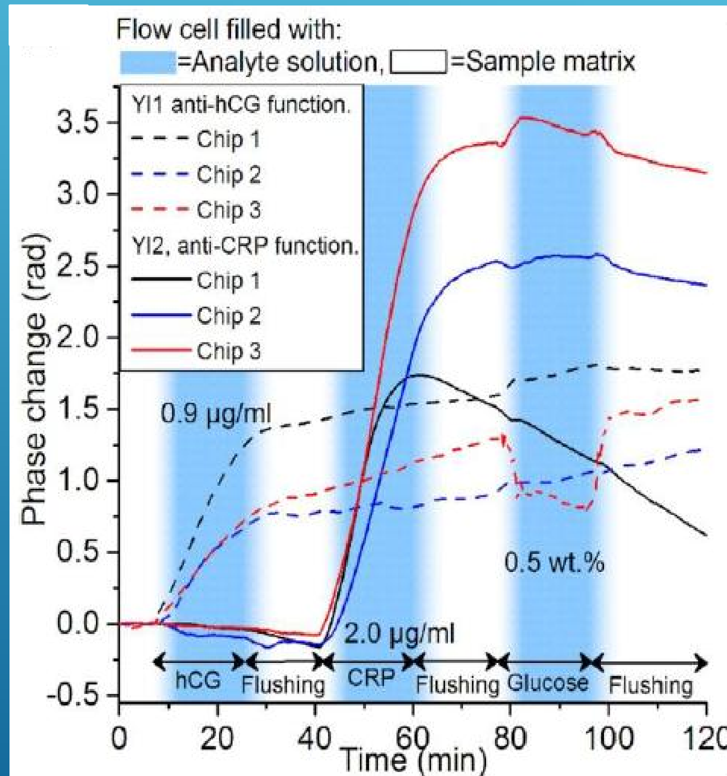


Intensity at waveguide output



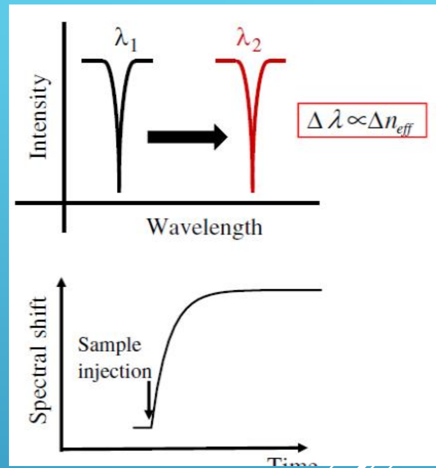


Aikio, RSC Adv., 2016, 6,50414

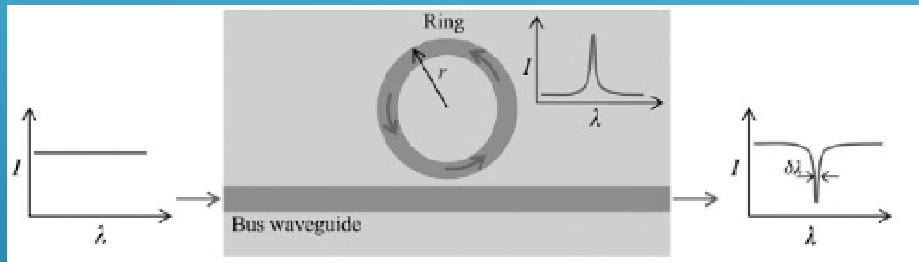


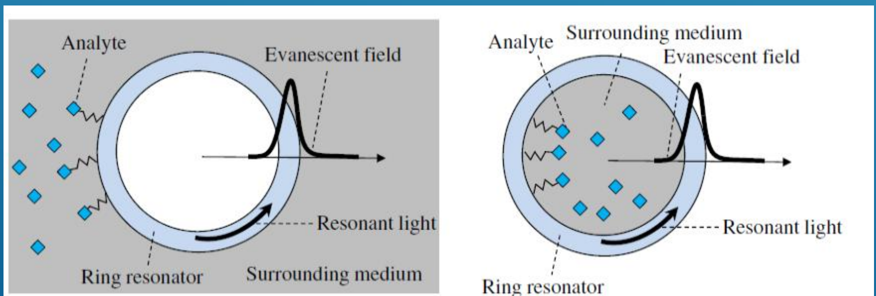
WAVEGUIDE BIOSENSORS: RESONATORS

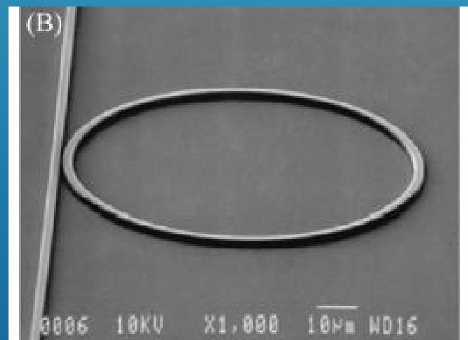
- Ring resonators
- Resonant wavelength $\lambda=2\pi n_{eff}/m$
- Circulating nature of the resonant mode gives long interaction length
- Broad band wavelength is coupled into the single mode waveguide and read out of $\Delta\lambda$ is measured
- Spectrogram obtained by monitoring the spectral shift



Sun, Anal Bioanal Chem, 399, (2011)



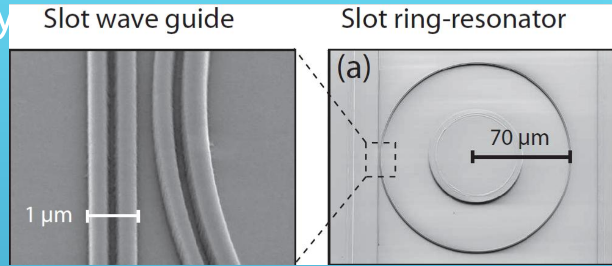




David L. Andrews "Photonics, biomedical Photonics, Spectorscopy and Microscopy", 2015

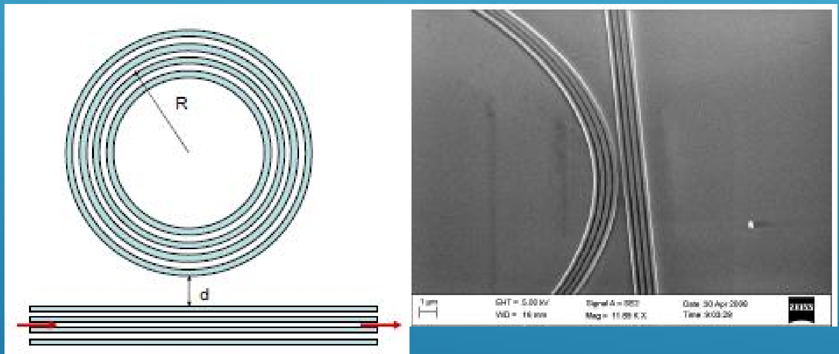
WAVEGUIDE BIOSENSORS: RESONATORS

- Effective interaction length L_{eff} is related on the resonator quality factor (Q-factor) $Q=\lambda/\Delta\lambda$
- Resonant wavelength $L_{eff} = Q\ (\lambda/2\pi n)$
- Configurations, materials etc. influences the Q-factor
- Small physical size, low sample volumes, high sensitivity
- Multi-analyte detection
- Detection limit 10^{-5} to 10^{-8} RIU

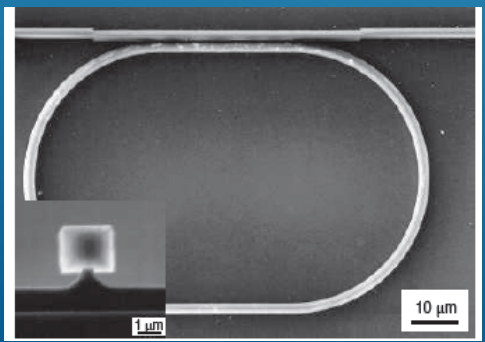


Gylfason, Opt. Exp. 2010

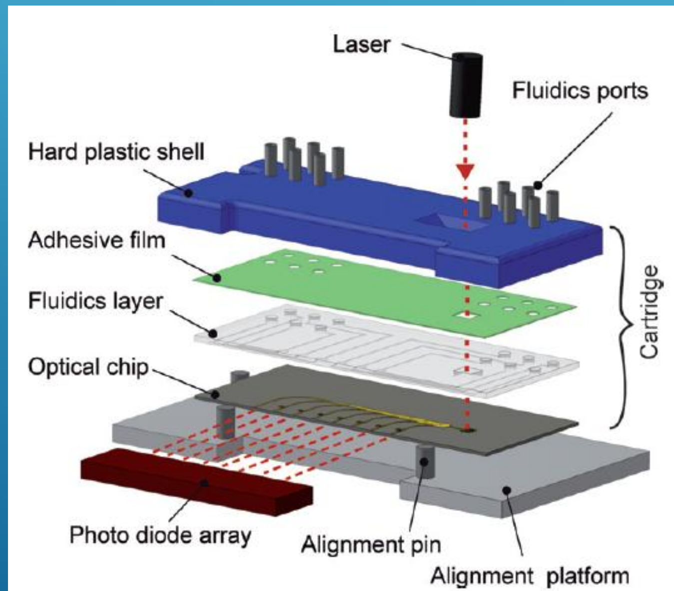
Carlborg, Lab on chip, 2010



Vivien, Opt. Exp. 2008

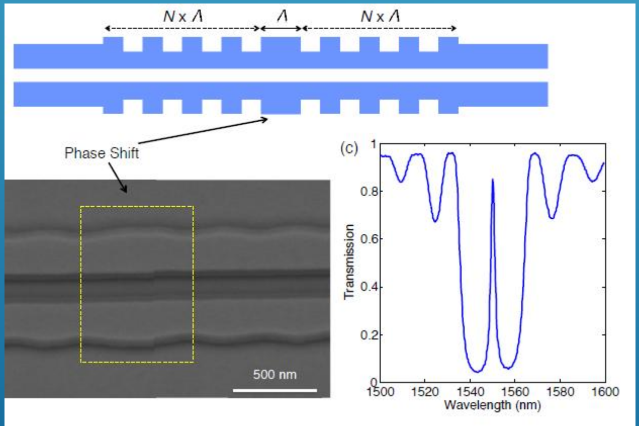


Polystryrein microring, Chao, Appl. Phys. Lett, 83, 2003

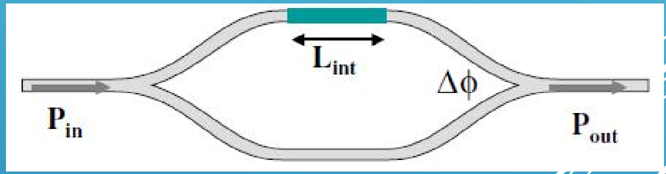


WAVEGUIDE BIOSENSORS: MACH-ZEHNDER INTERFEROMETERS AND BRAGG GRATINGS SENSORS

- Same principle than in Young interferometer
- Phase shift in measurement arm induces modulation of the signal
- Sensitivity S=ΔP/Δn in M-Z interferometer
- Limit of detection order of 10^{-7} RIU



- Wavelength shift measured with Bragg grating sensor



$$\frac{I}{I_0} = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\partial\lambda_{res}/\partial N_{eff} = \lambda/N_{eff}$$

Wang, Opt. Exp, 2013

CONCLUSION

- Basic structure of the integrated optics is waveguide
- Waveguides can be single modal or multimodal in their operation
- Several different materials are available for IO-applications
- Main applications utilizing waveguides are optical communication and sensor applications
- Several different waveguide configurations
- Several different components from waveguide

THANK YOU FOR YOUR ATTENTION