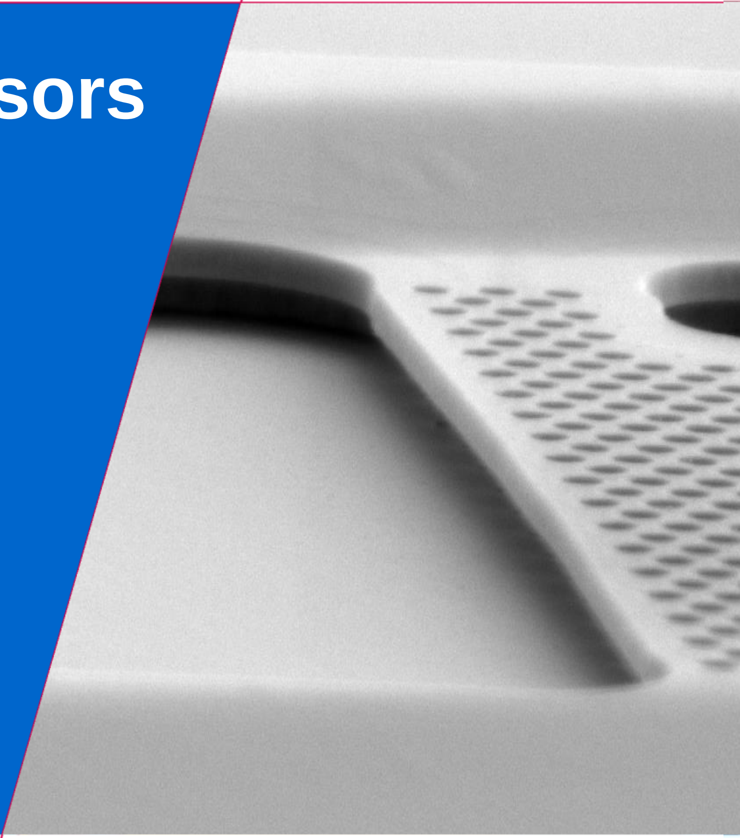
Enabling new technology

Integrated, scalable spectral sensors



A. Fiore, Ž. Zobenica, R.W. van der Heijden, T. Liu, M. Petruzzella, F. Pagliano, F.W.M. van Otten
Institute for Photonic Integration
Eindhoven University of Technology

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Where innovation starts

COBRA

Our dream

Replace this:

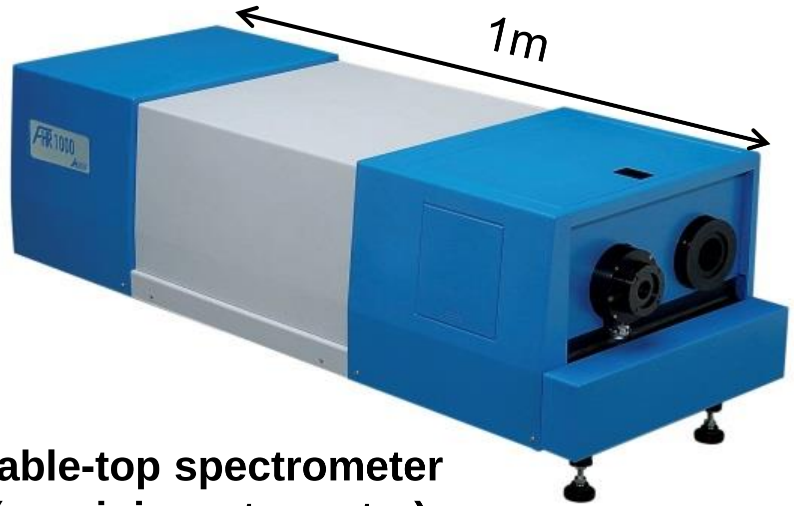
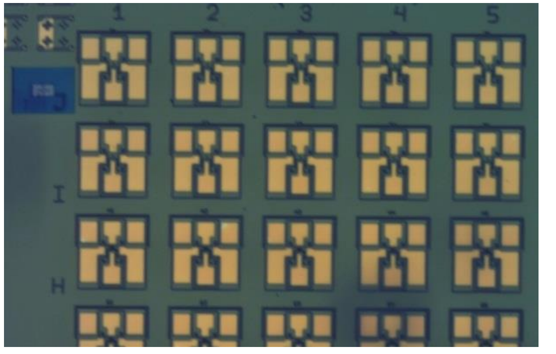


Table-top spectrometer (or minispectrometer)

- Bulky
- Expensive (1’000-10’000 EUR)
- High-performance
- General purpose
- Single-pixel

With this:



Microspectrometer

- Integrated
- Cheap (10-100 EUR)
- High-performance
- Dedicated to specific application
- Arrays

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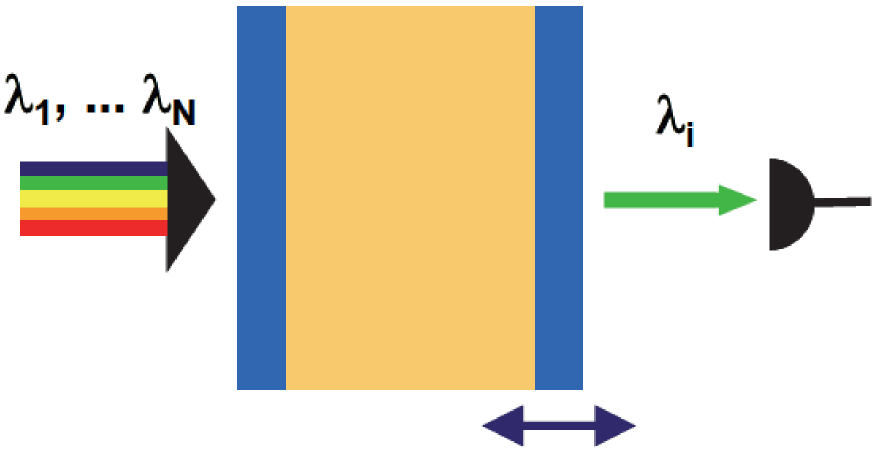
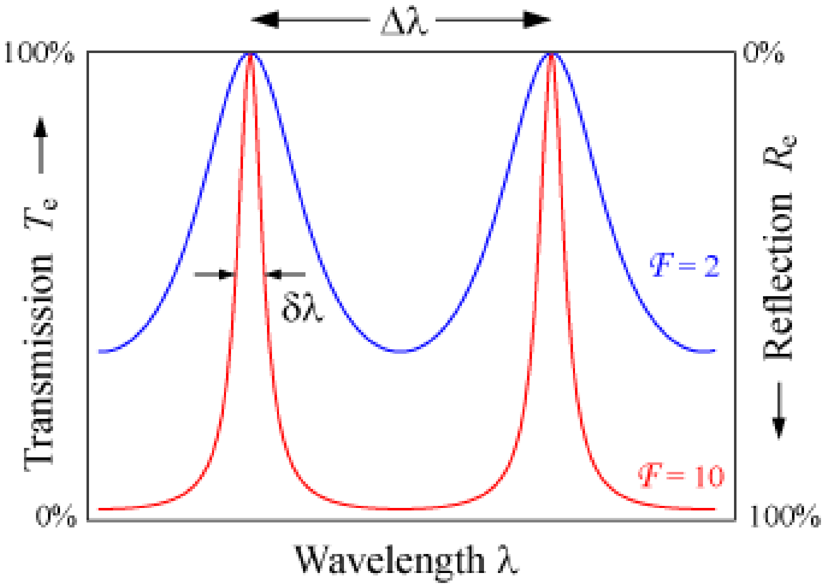
How to integrate a spectrometer

<u>*Getting spectral information by filtering*</u>



Fabry-Perot cavity

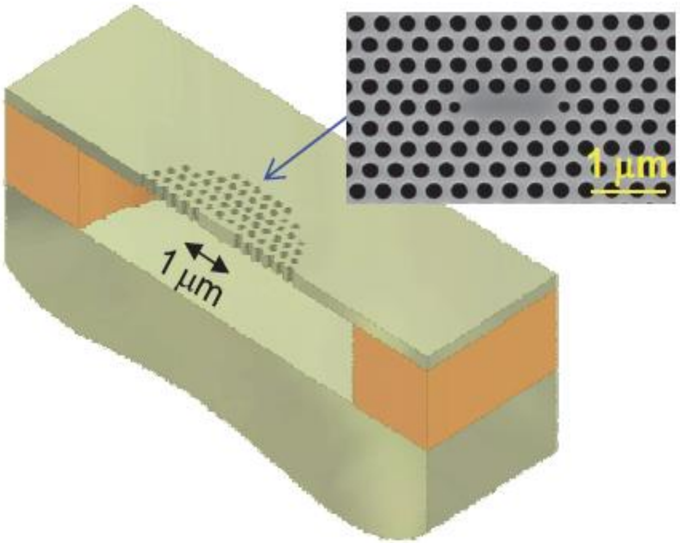


(resolution determined by the linewidth)

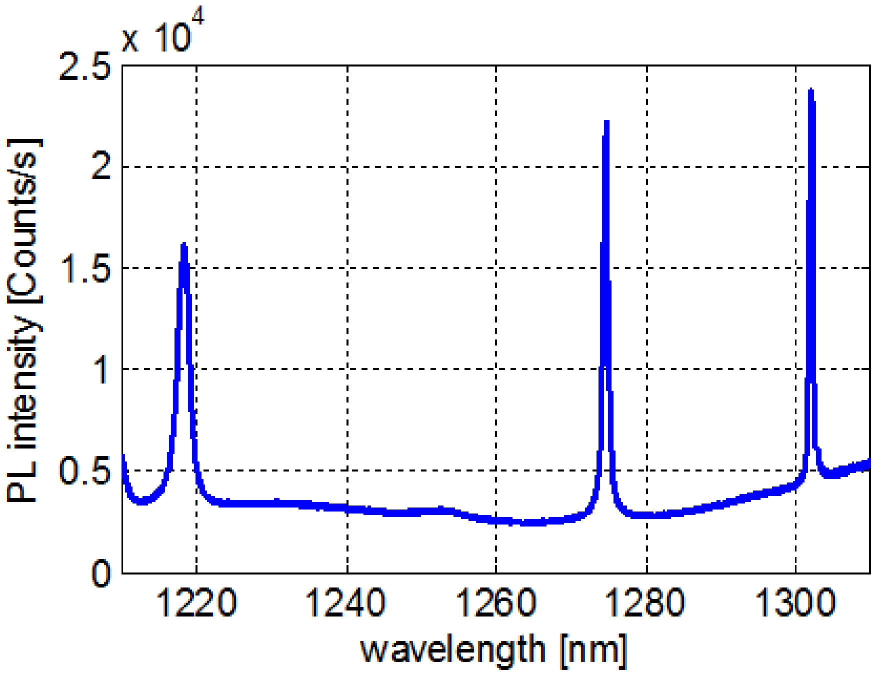
Key functionalities:

1) Filtering
2) Actuation
3) Detection

Filtering with photonic crystal cavities



Photonic crystal slab



- Very **high Q** factor possible (up to 10^6)
- Small Volume ~ λ^3 → **Large free spectral range possible**
- Light mass (**~ 10 picograms**) → high speed

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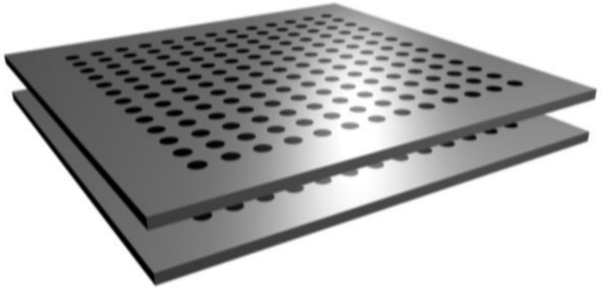
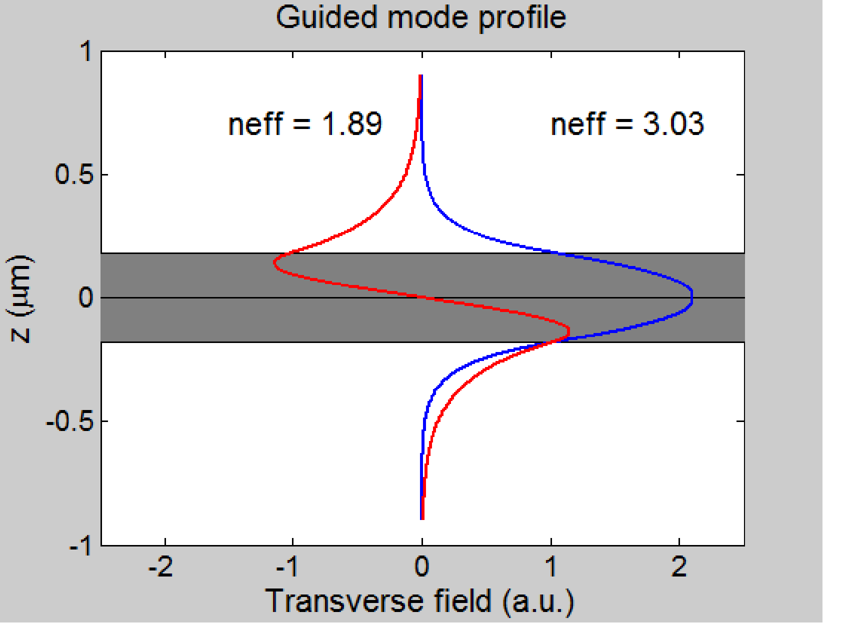
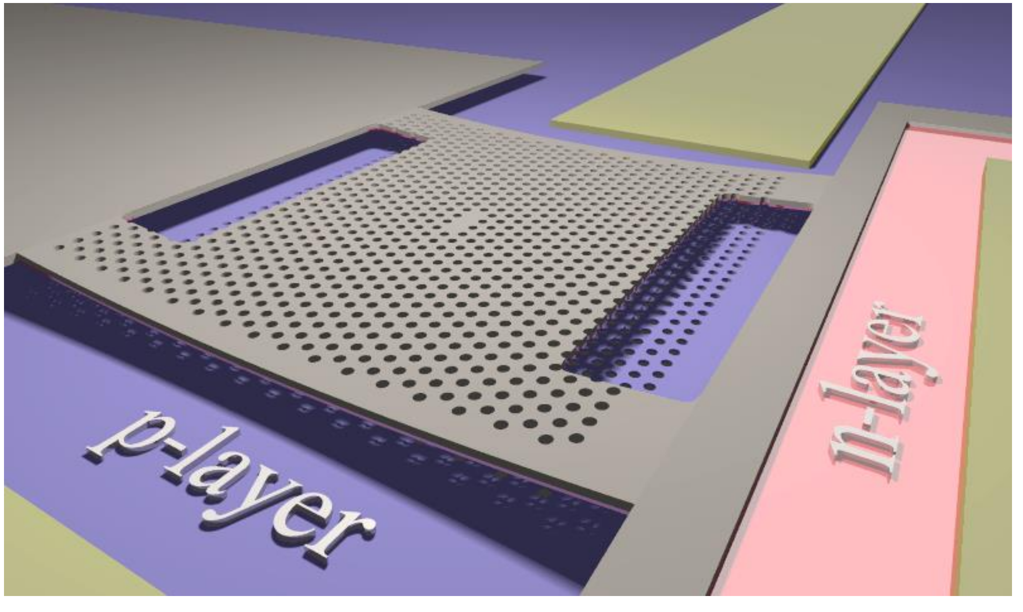
Cavity actuation

Double-membrane structures:
Change *effective index*

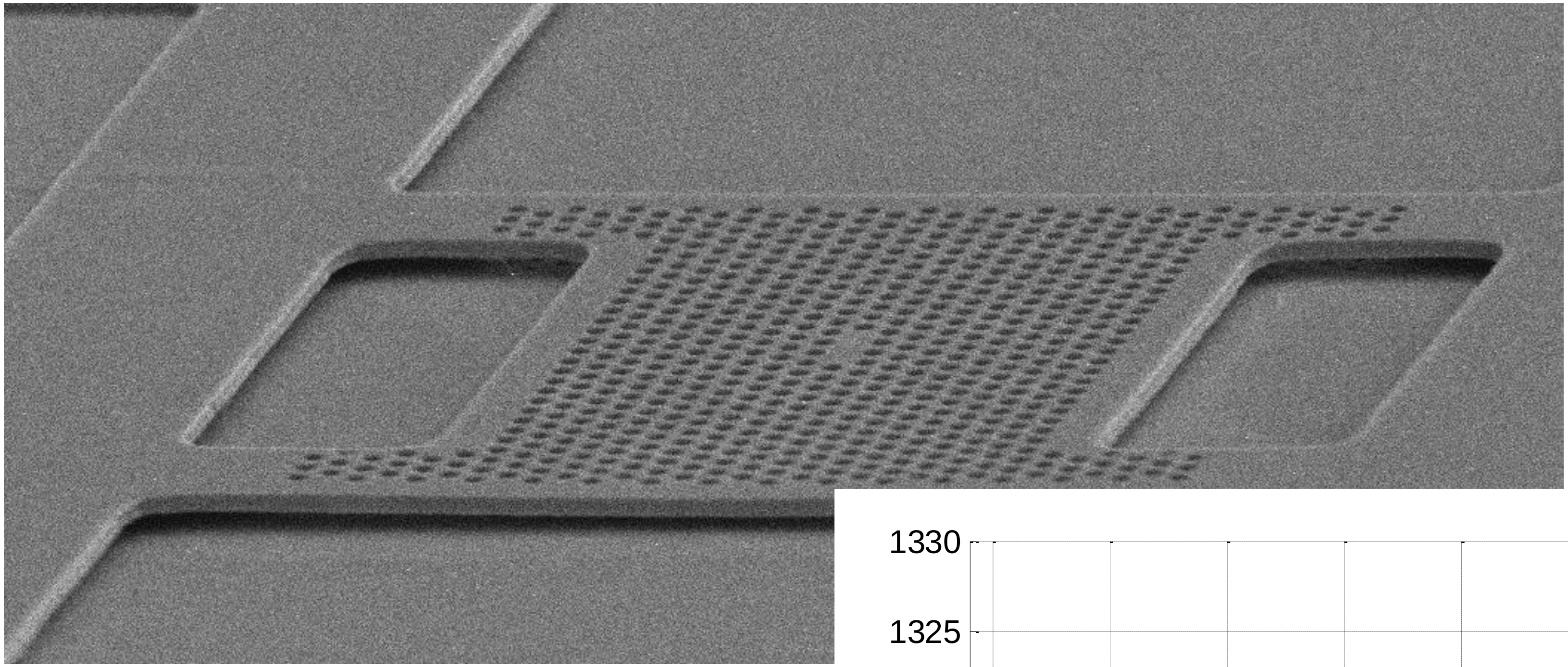


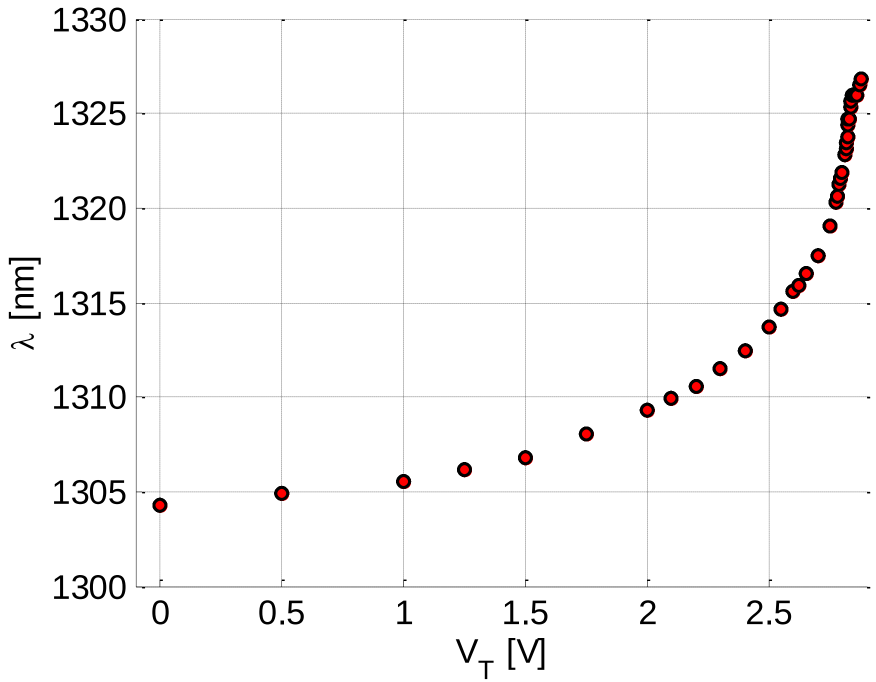


Electrostatic actuation:



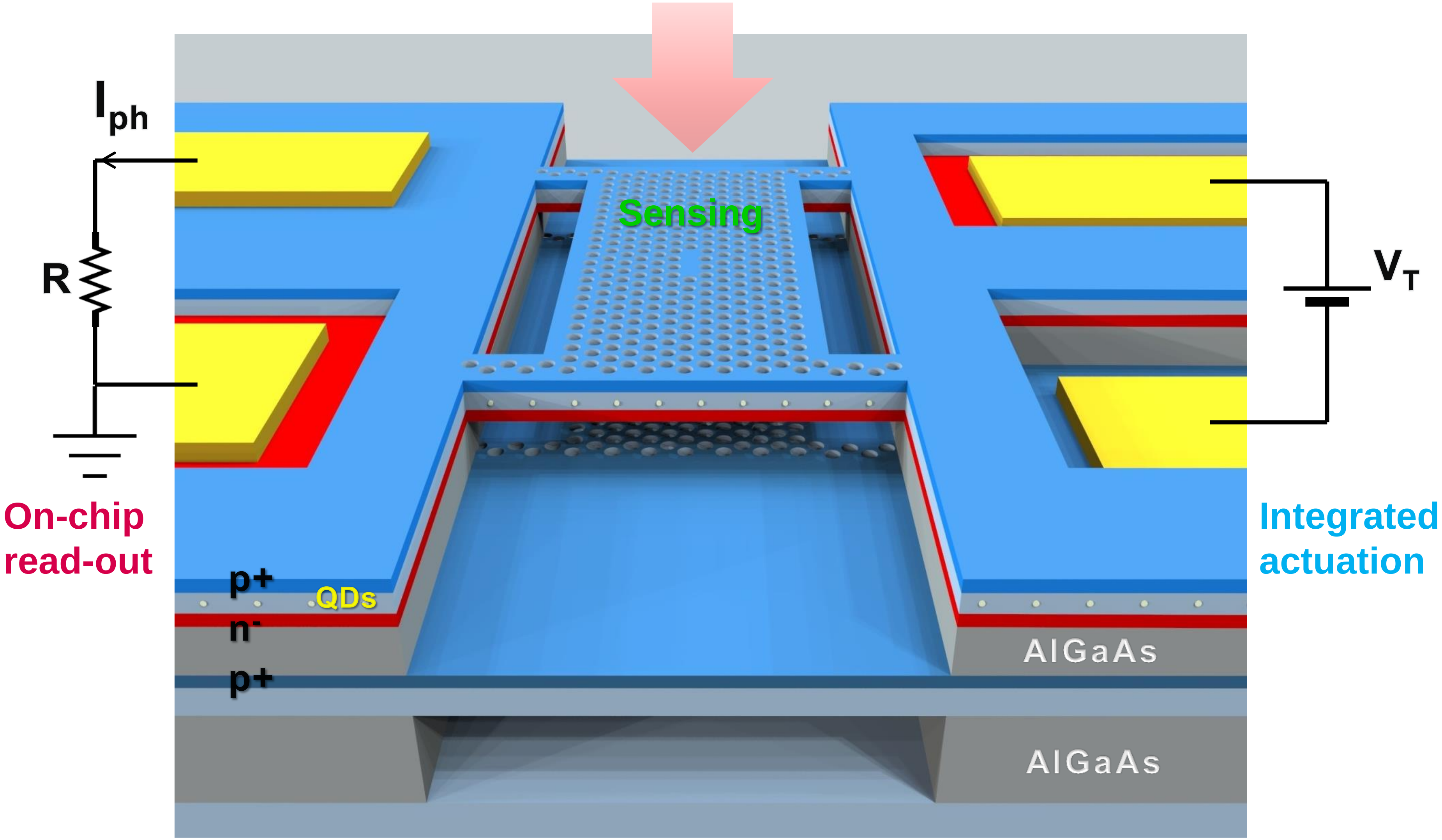
Nanomechanical cavities





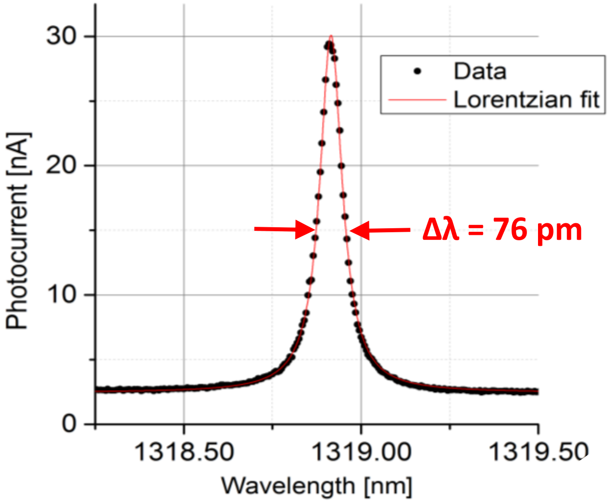
Experimental tuning range: 20-30 nm

Integrated microspectrometer

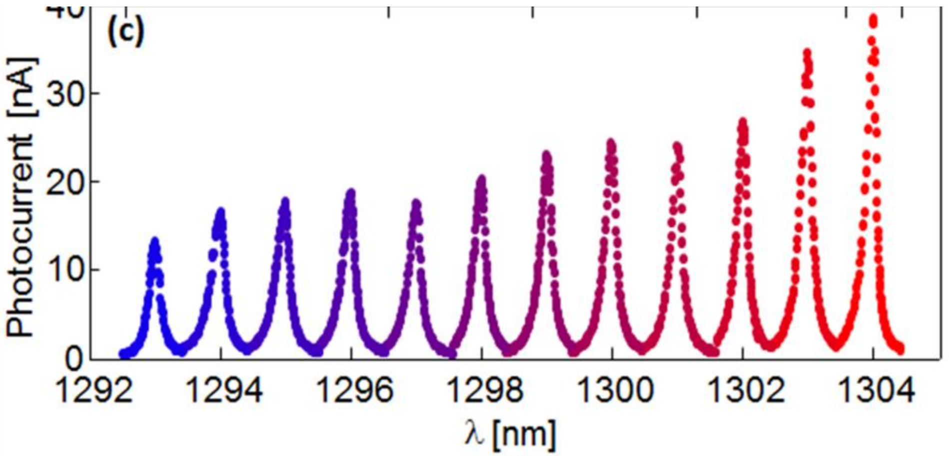


Microspectrometers: Results

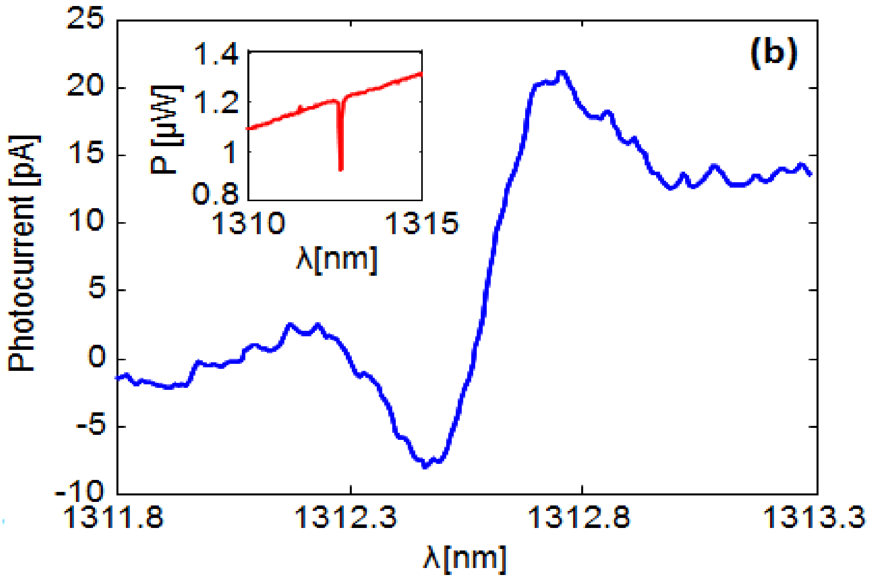
Sharp optical resonances:



Tuning ⇒ Spectrum



HF absorption line (16 pm):



Example of application:
Gas sensing

Microspectrometer: Perspectives

Present devices offer high resolution (100 pm) but low spectral range (20 nm)

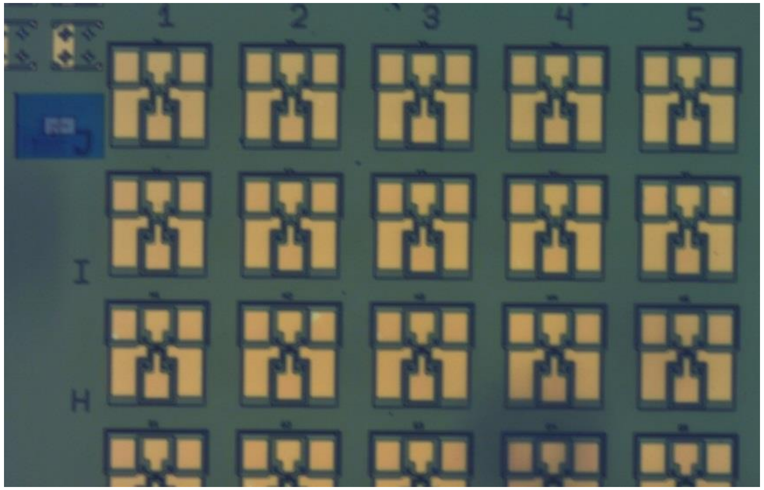
Our next goal: Microspectrometer with 0.5-1 nm resolution, 200 nm spectral range in the 1500-2000 nm region

Applications:

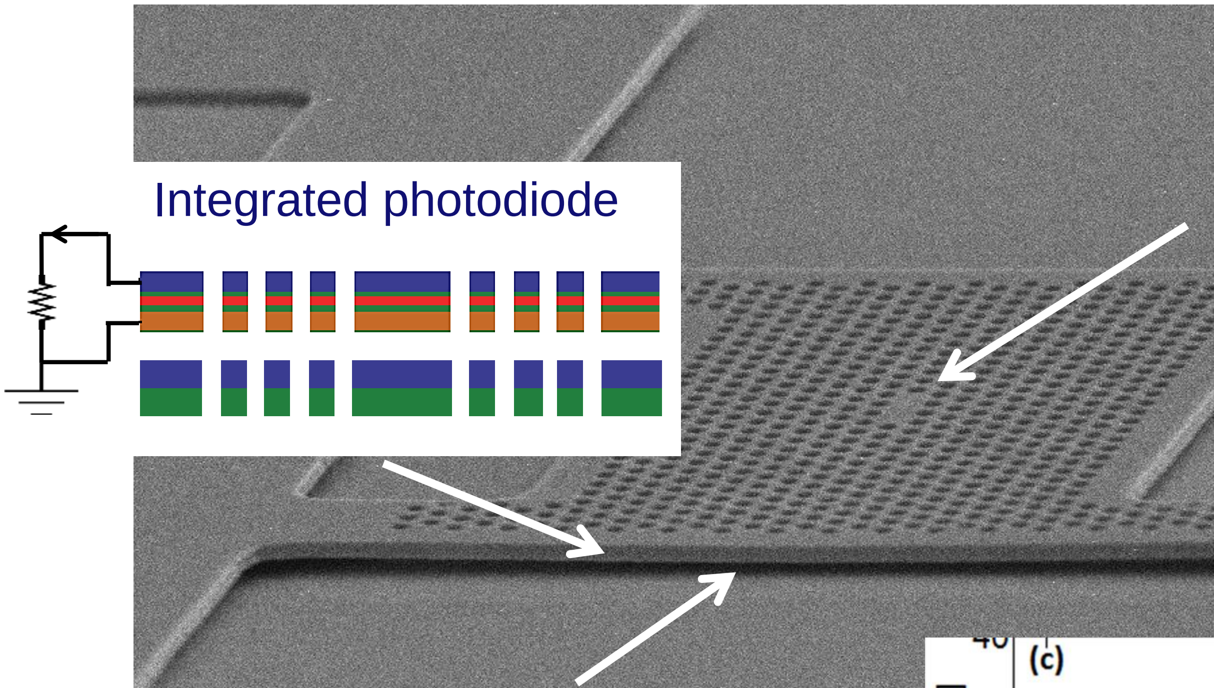
- Mobile healthcare (monitoring of glucose, triglycerides, …)
- Gas sensing
- etc

Notes:

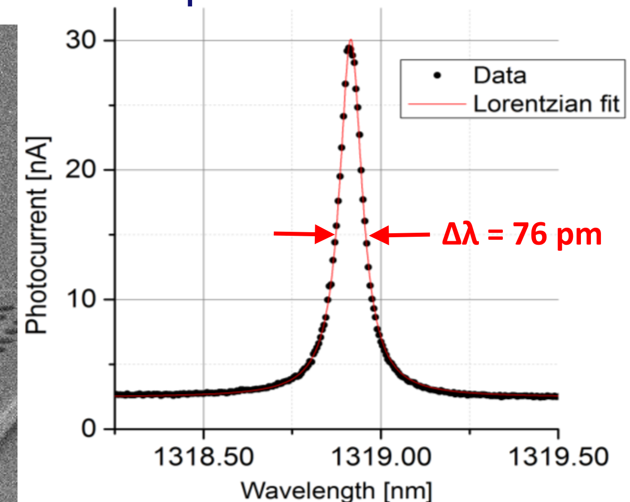
- Light source and spectrometer can be integrated and fitted in a smartphone
- Imaging arrays can be fabricated
- Concept can be extended to other types of optical detectors



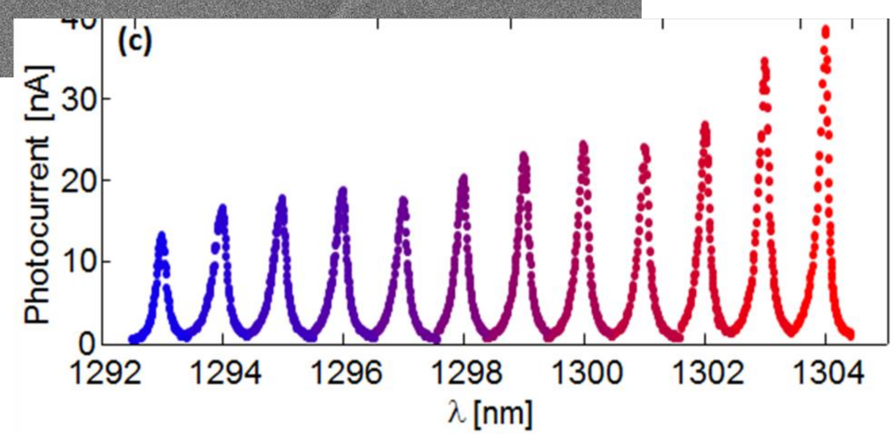
Electromechanically-tuneable photonic crystal cavity:



Optical resonance



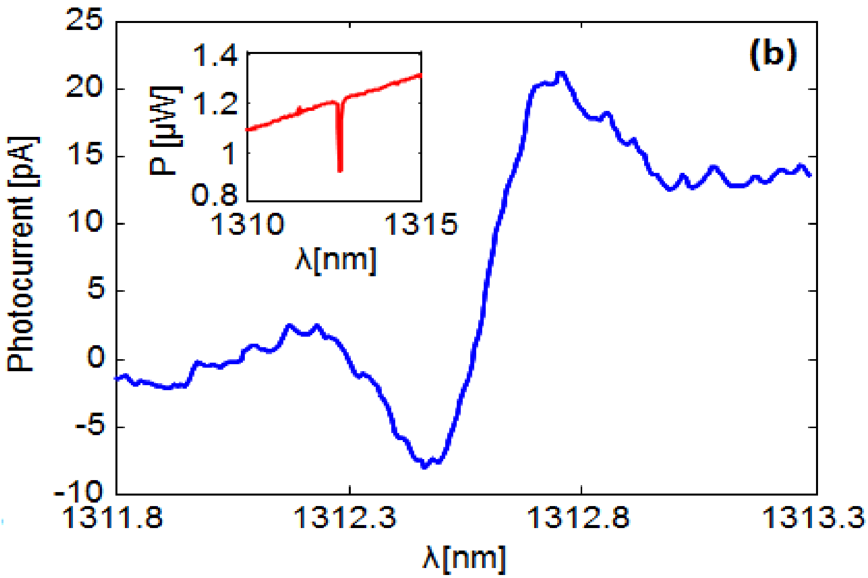
Tuning by electromechanical actuation:



Prof. Andrea Fiore

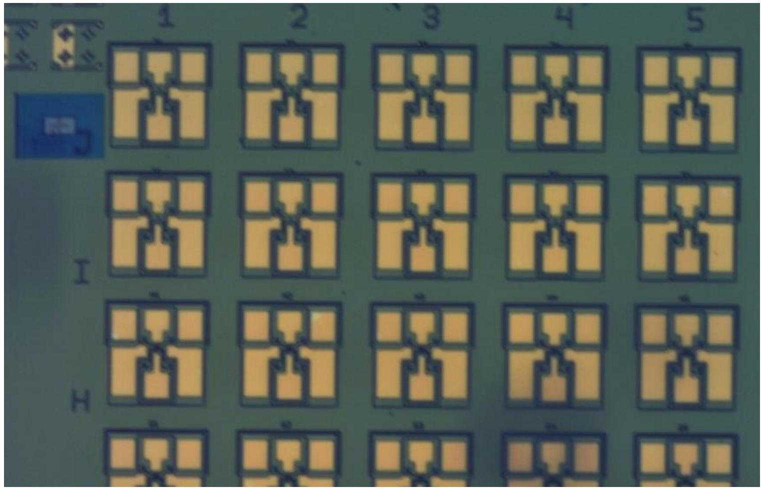
NOEMS: Application as microspectrometers

HF absorption line (16 pm):



- Can measure emission or absorption lines
- Resolution down to 100 fm/(Hz)$^{0.5}$

- Fully-integrated, mass-manufacturable

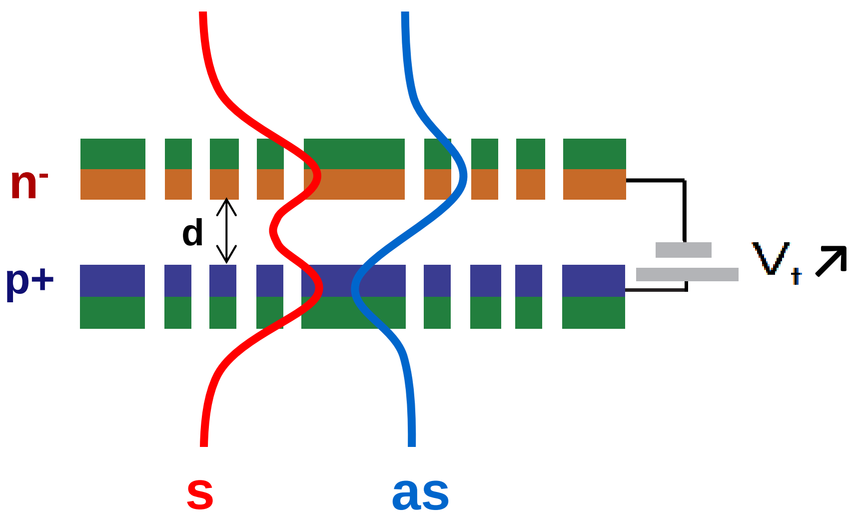


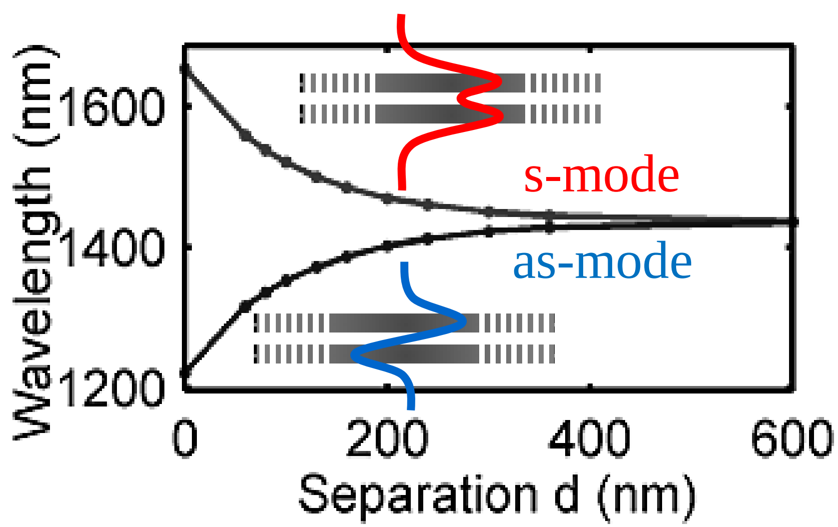
Patent filed

2) Nano-opto-electro-mechanical actuation

Double-membrane photonic crystal

- Modes hybridize and form supermodes
- Changing separation tunes the supermodes
- Electrostatic actuation via p-i-n junction

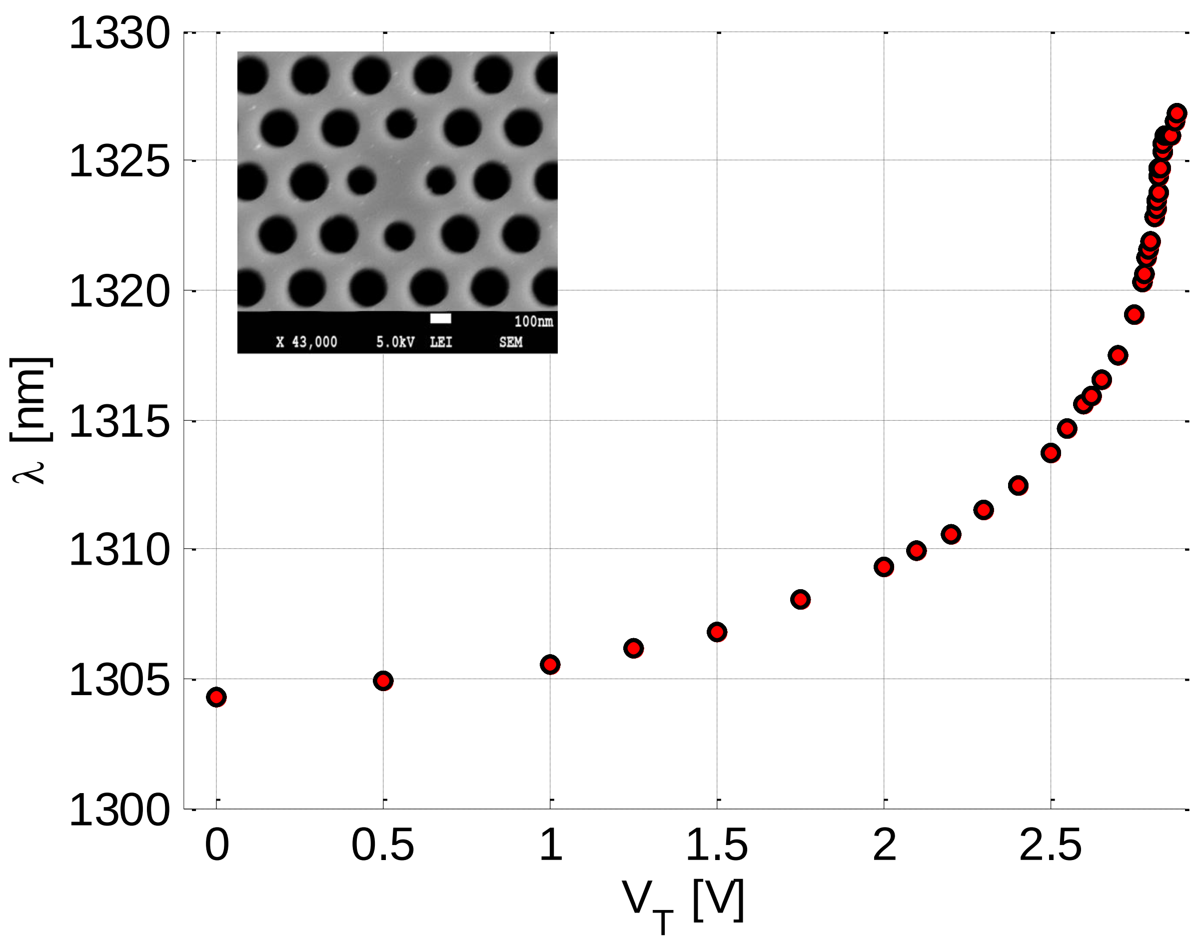




L.Midolo et al. APL 98, 211120 (2011)

Nanomechanical tuning: experimental results

23 nm tuning of monopole mode in H0 cavity:



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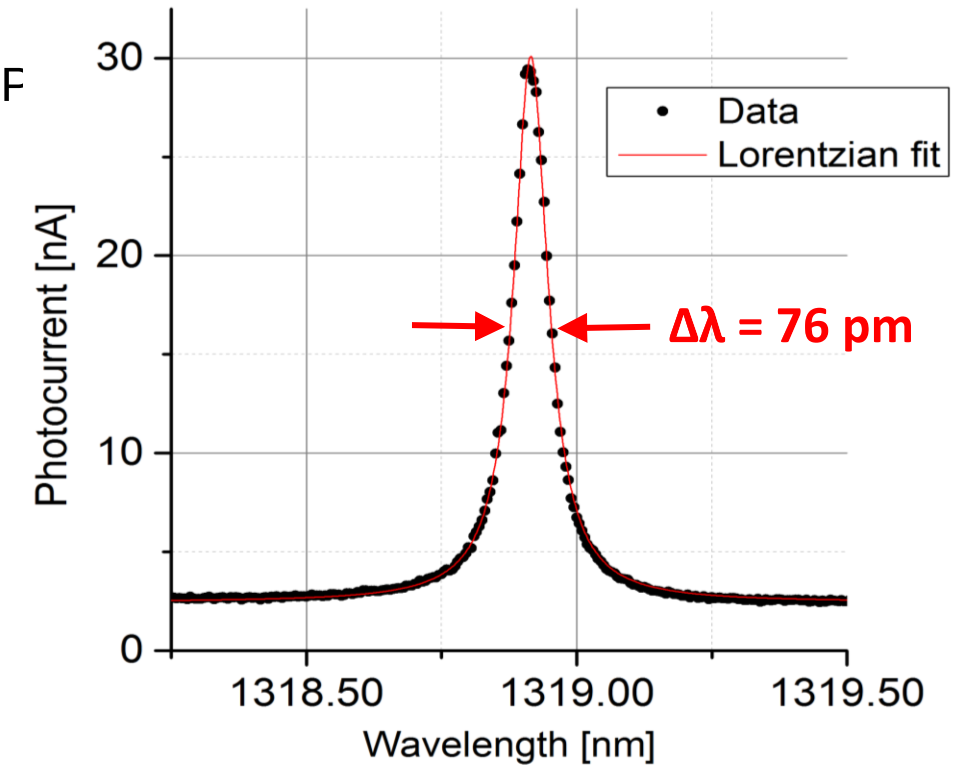
3) Detection

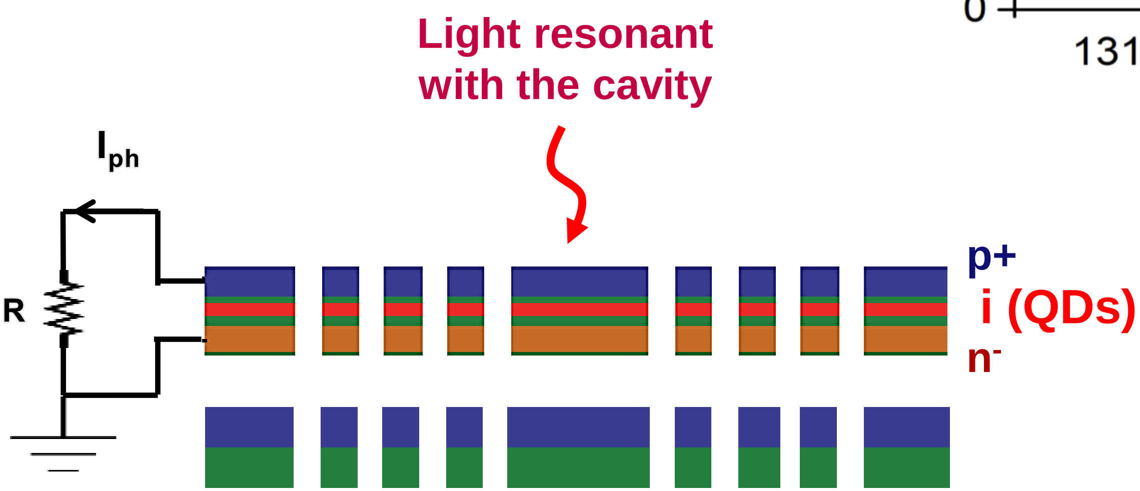
- **Absorber:** Quantum dots inside the F

- Vertical **P-i-N photodiode**
  FWHM = **76 pm** → **Q = 17200**

(comparable to a table-top spectrometer)

Responsivity up to **20 mA/W**





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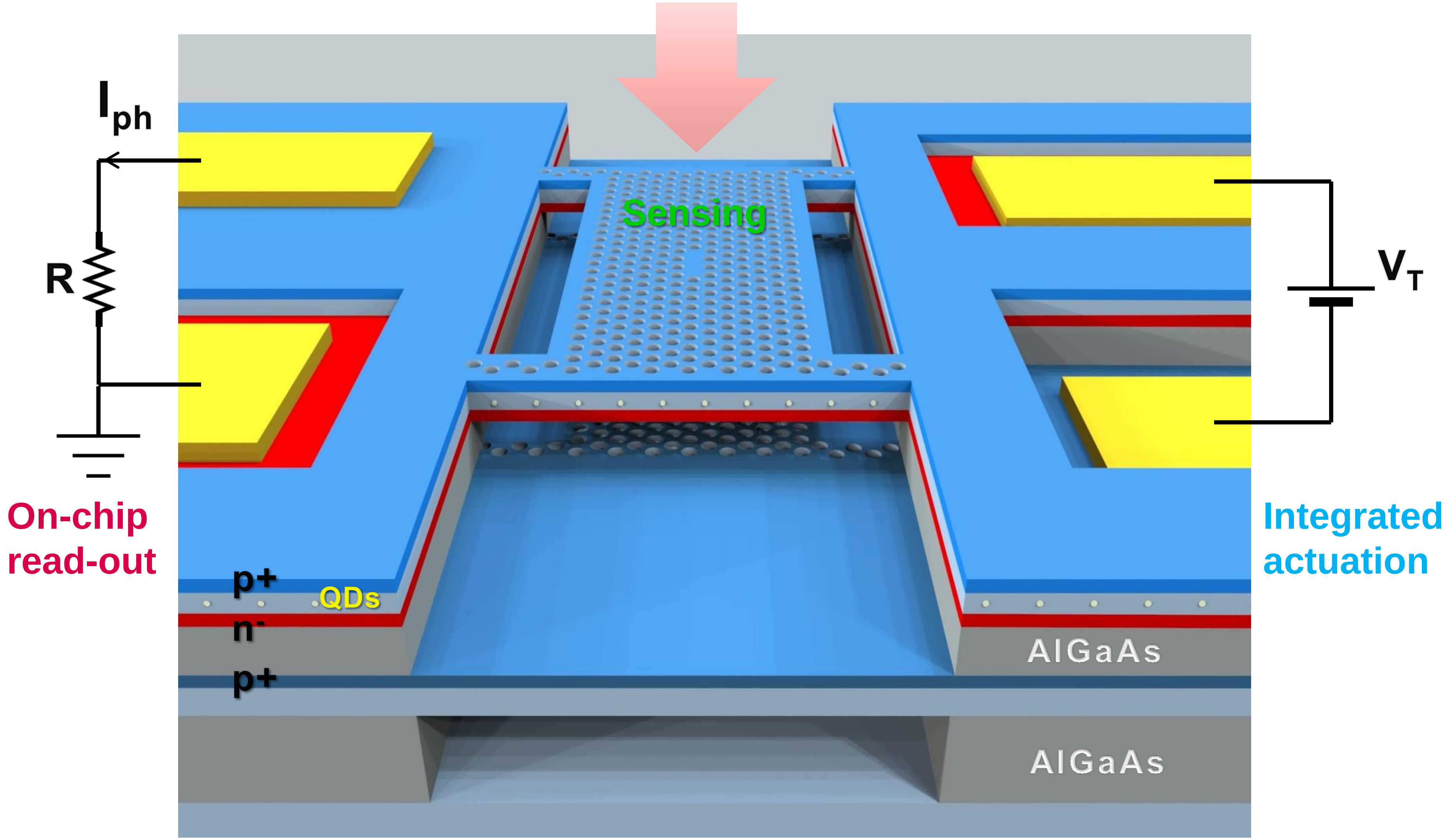
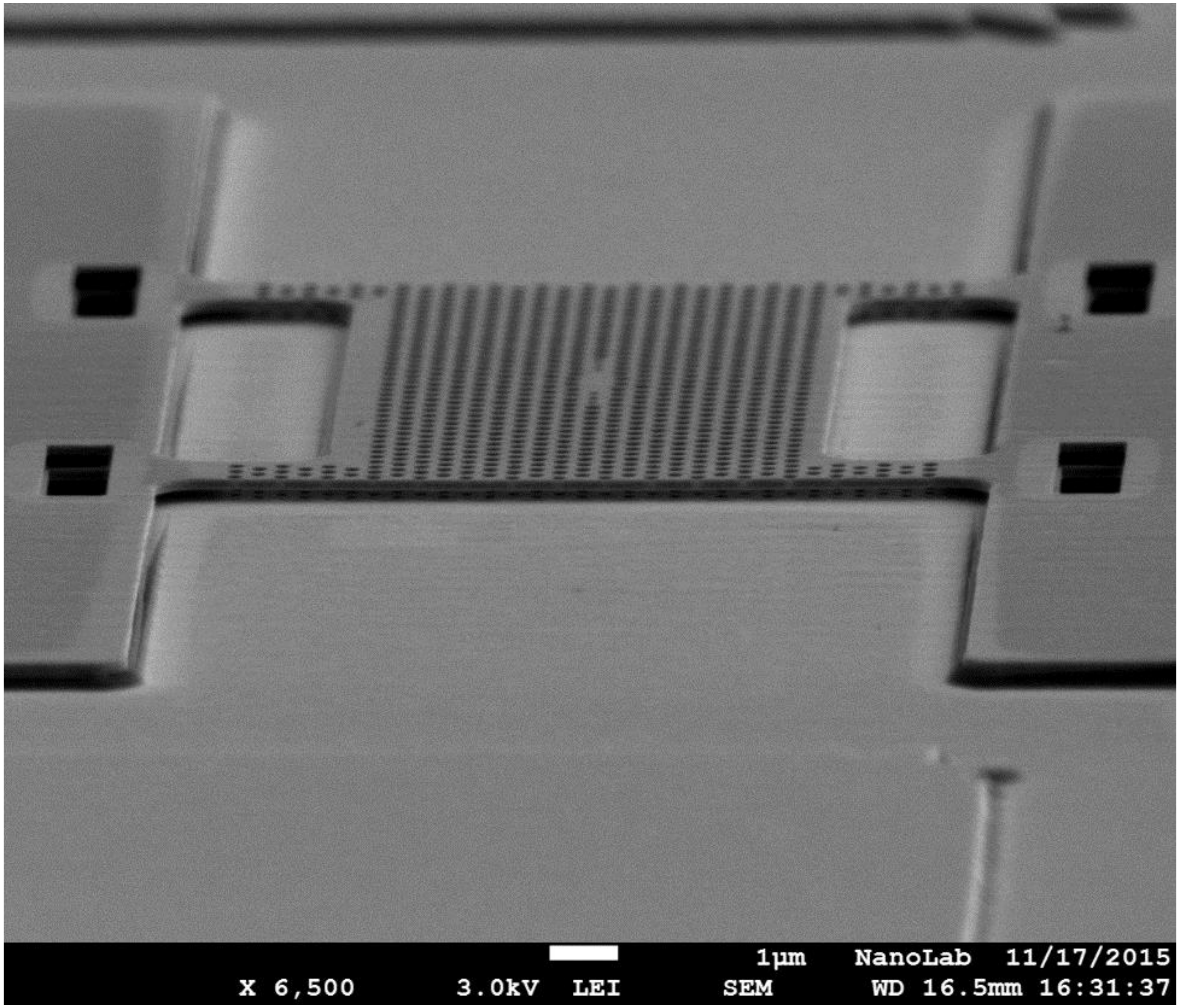
Concept: Detector + Tuneable Filter



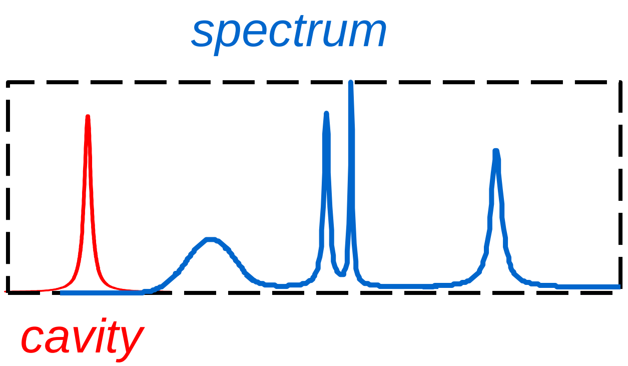
Fabricated structure



Sensing: Modes of operation

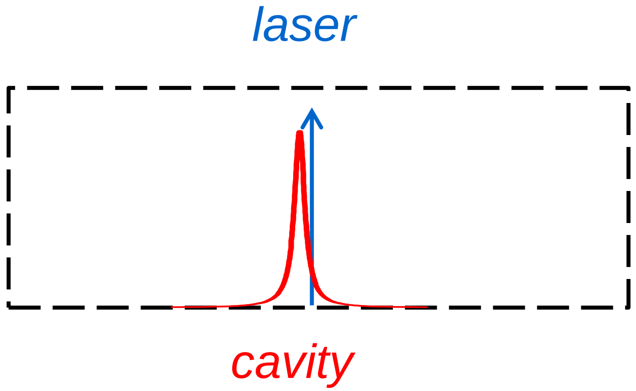
Spectrometer action (tuneable filter):

- Changing **Voltage** changes **λ**
- Incoming light read as photocurrent

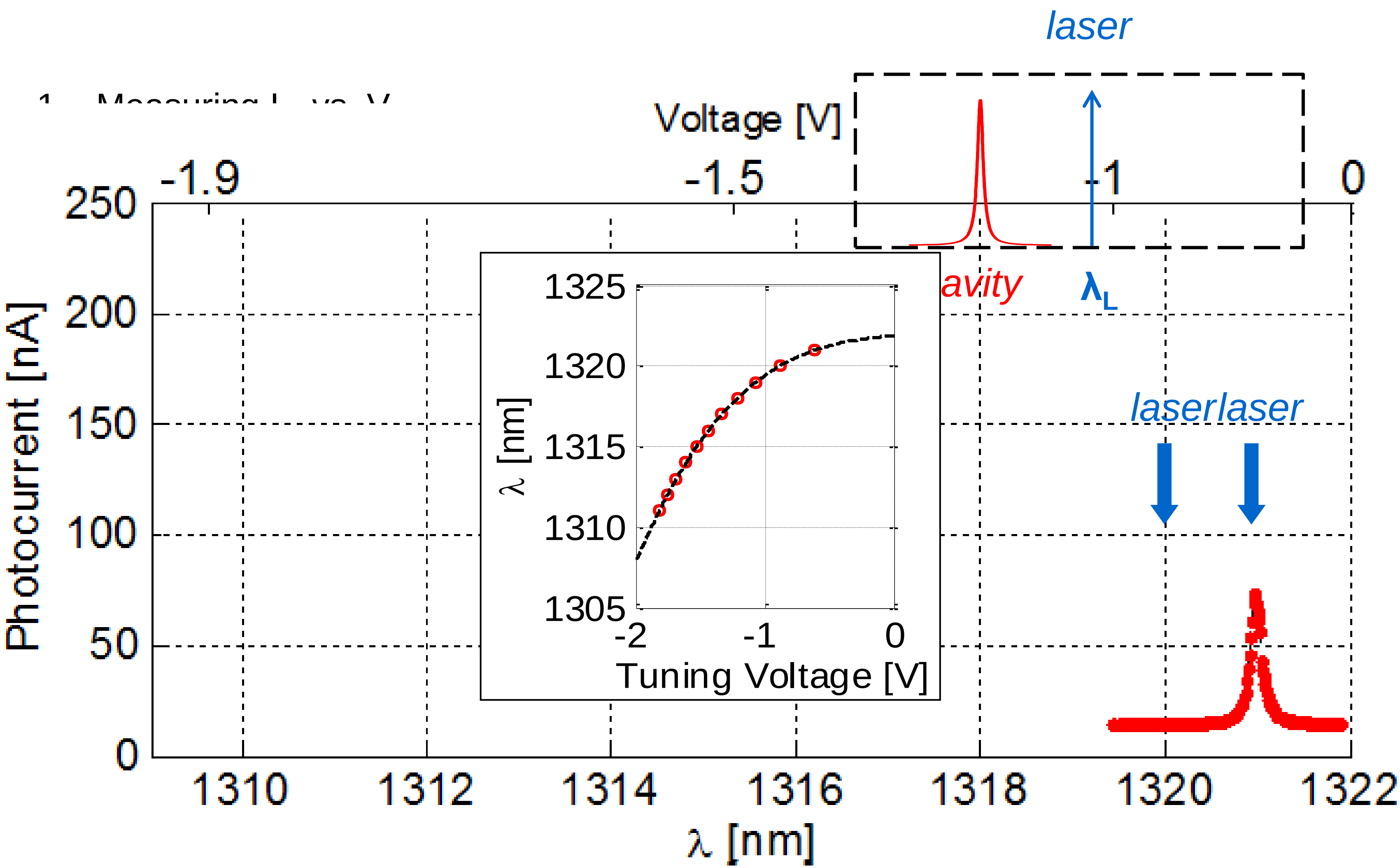


Optomechanical displacement sensor:

- **Displacement** transduced as a small change in photocurrent



μ –spectrometer demonstration



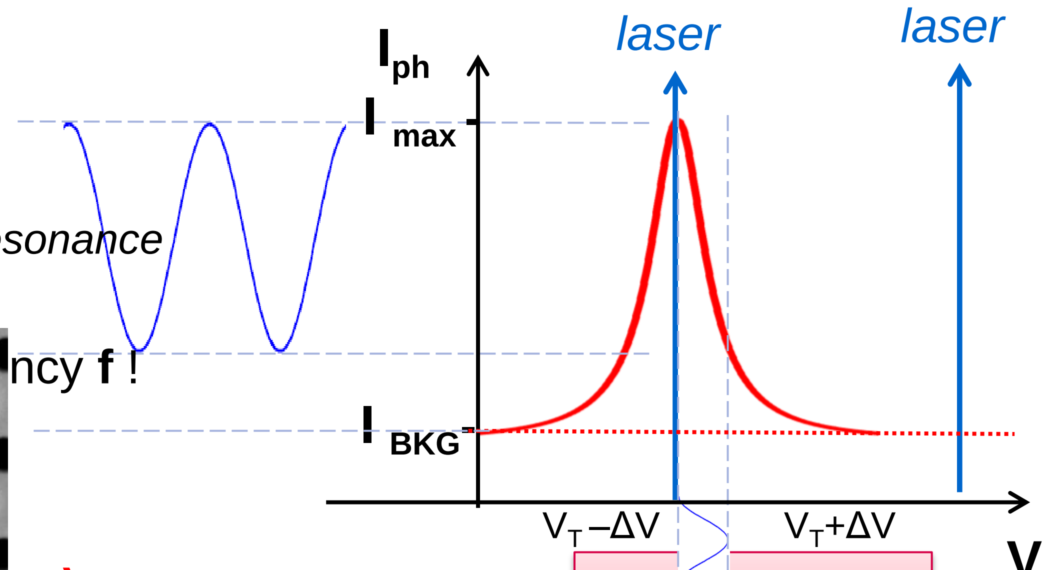
- Resolution ~ 150 pm
- Responsivity changes due to changing field overlap with QDs

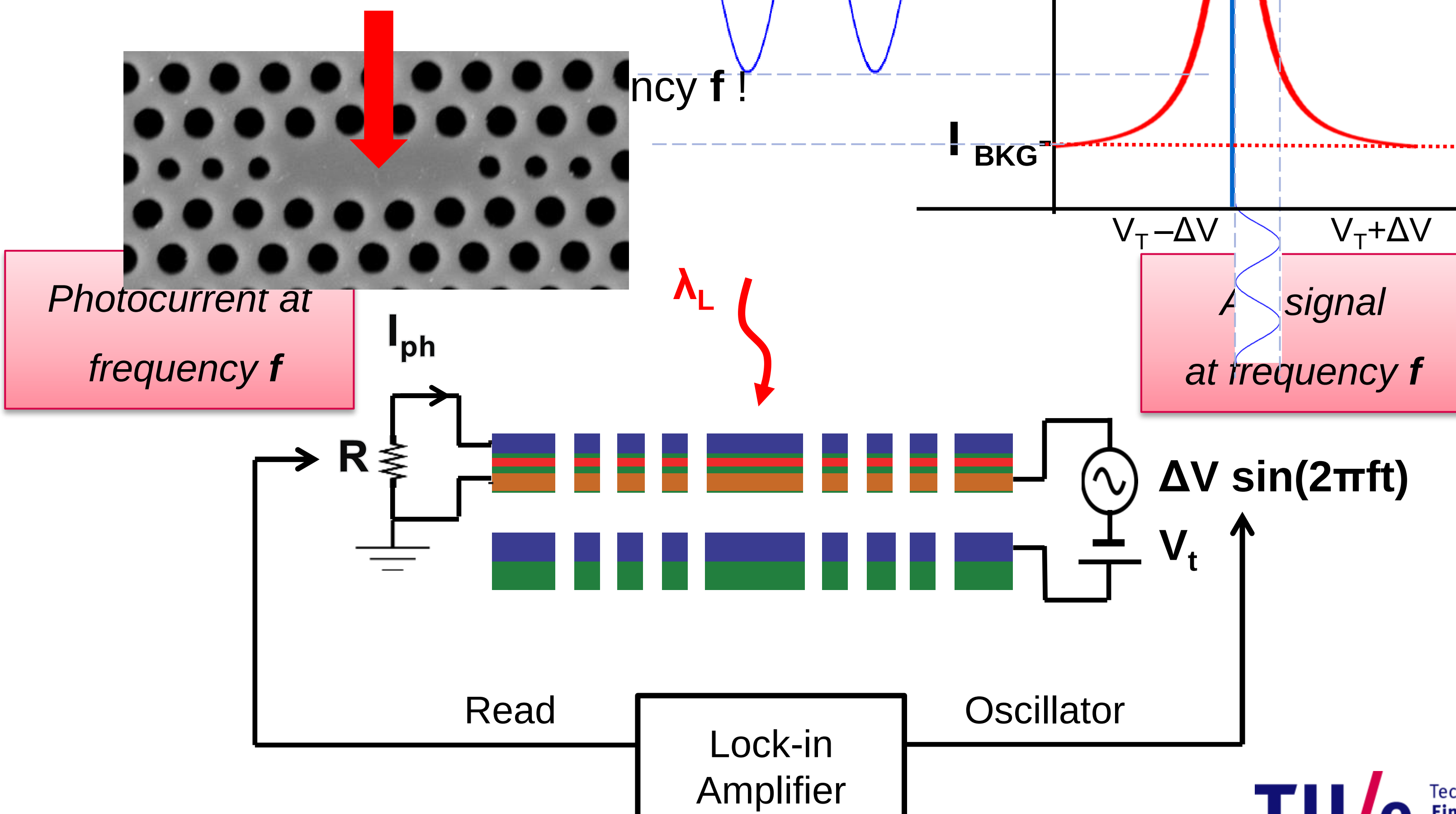
Signal to background limitation

Resonance modulation spectroscopy

- S/BKG = I_{max}/ I_{BKG} < 20

  Limited by the absorption of the dots outside of the cavity resonance





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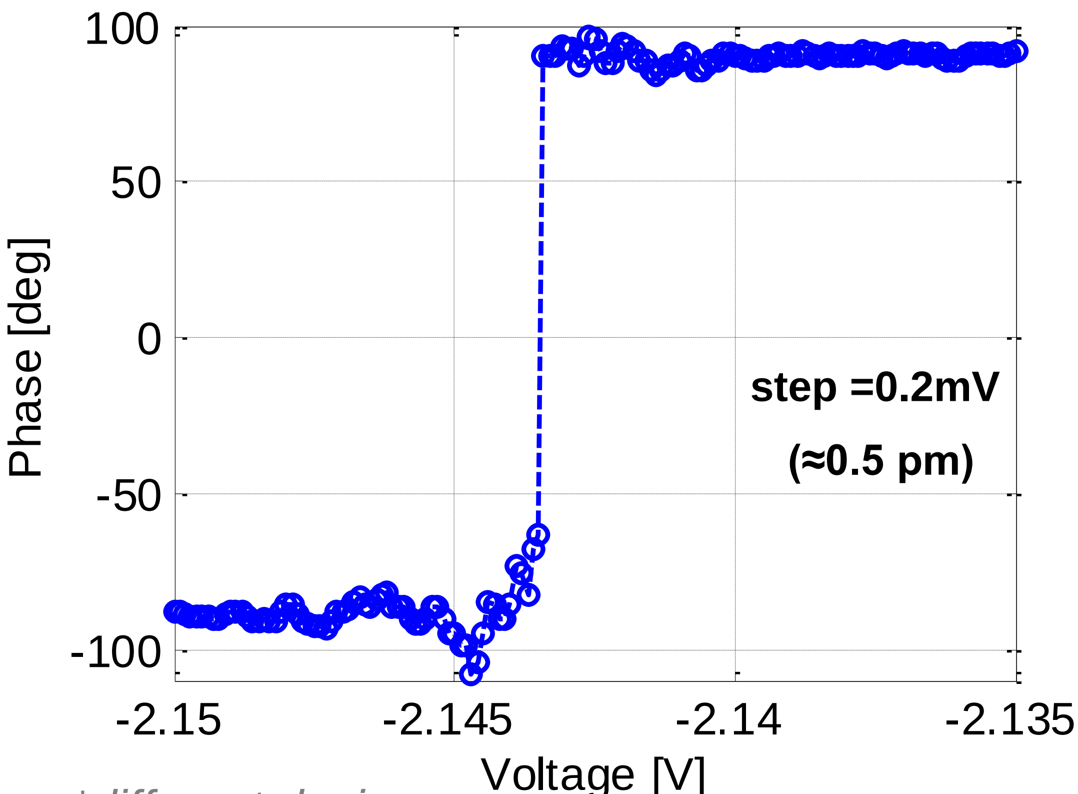
Demonstration of background suppression



**different device*

Standard technique (DC):

S/BKG = 7 dB

Resonance modulation scheme (DC + AC):

S/BKG = **30 dB**

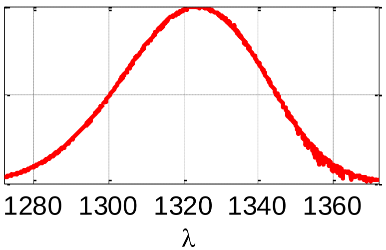
Ultimate resolution is limited by noise:

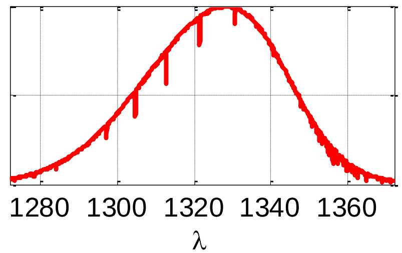
$$\delta\lambda_{min} = \frac{\delta I_{noise}}{\frac{dI}{d\lambda}} \sim \mathbf{0.1\ pm}$$

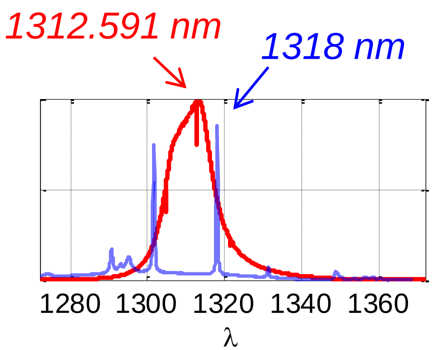
Additional advantage:
Higher wavelength resolution on a single line

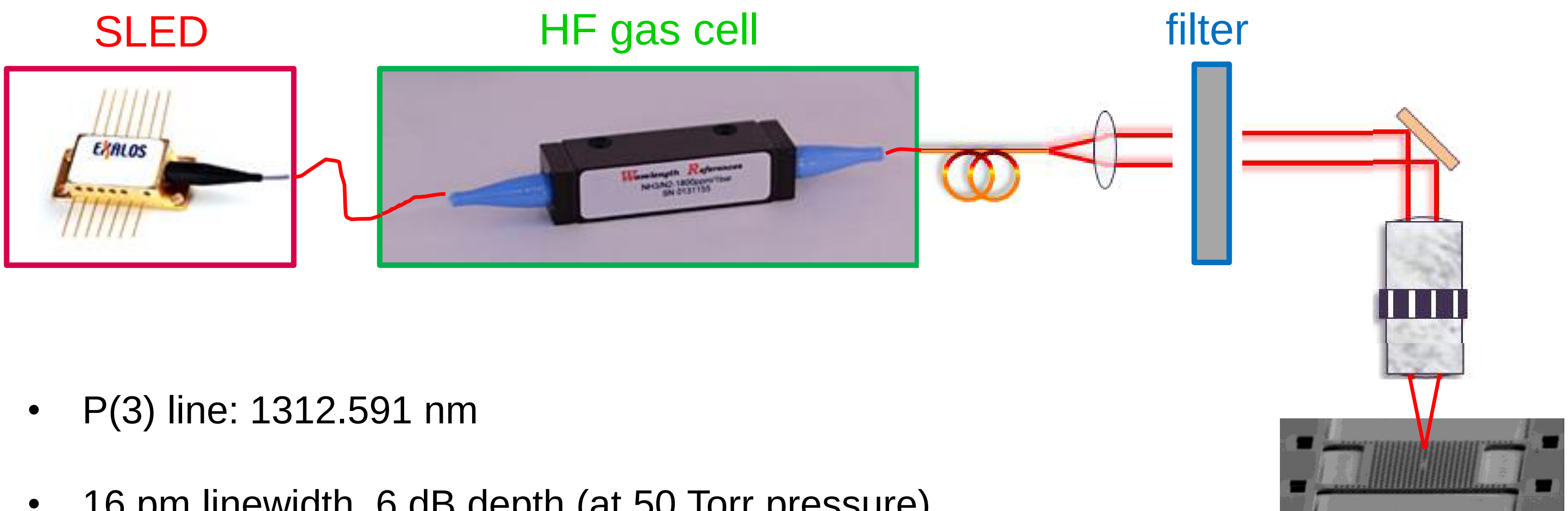
Application of microspectrometer in gas sensing

Measuring HF absorption lines in O-band







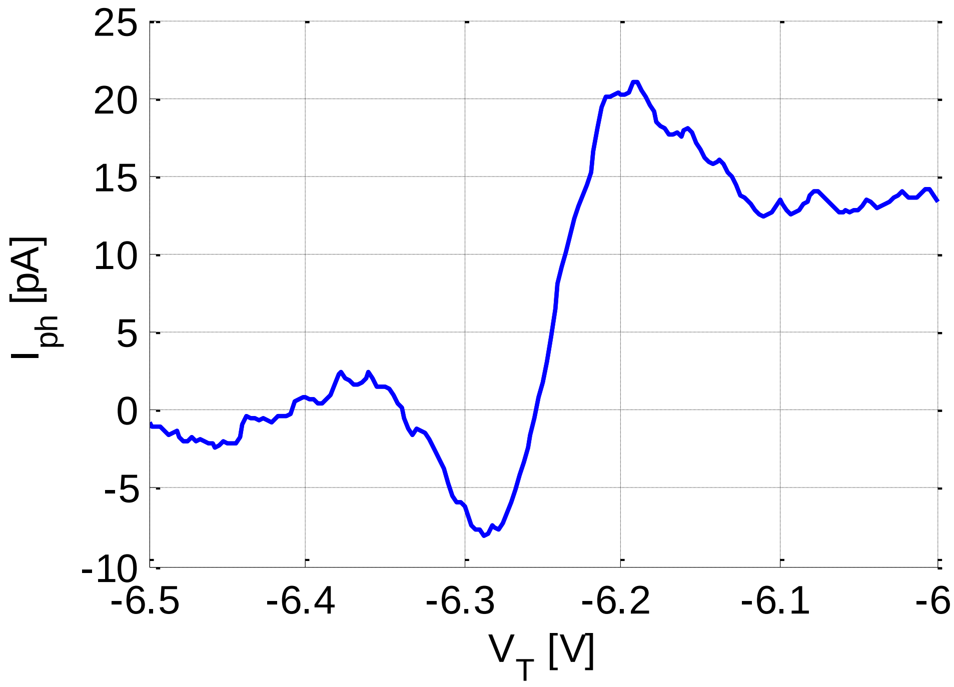


- P(3) line: 1312.591 nm
- 16 pm linewidth, 6 dB depth (at 50 Torr pressure)
- Use of resonance modulation scheme is crucial!

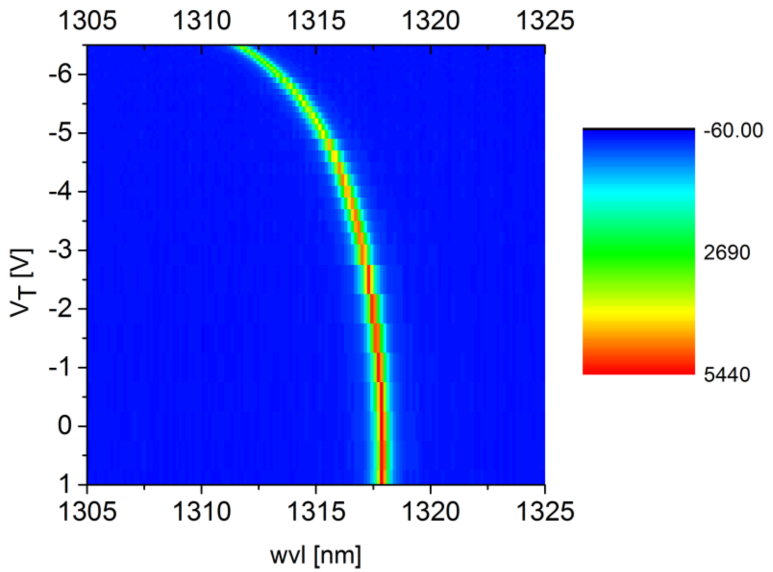
Gas sensing: Measurements

Excitation: SLED + HF cell + filter (1310 nm)

Detection: cavity mode sweeping



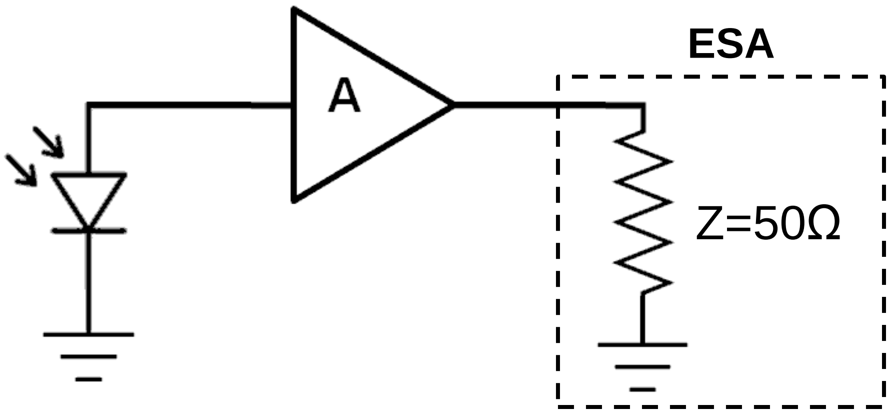
Calibration:

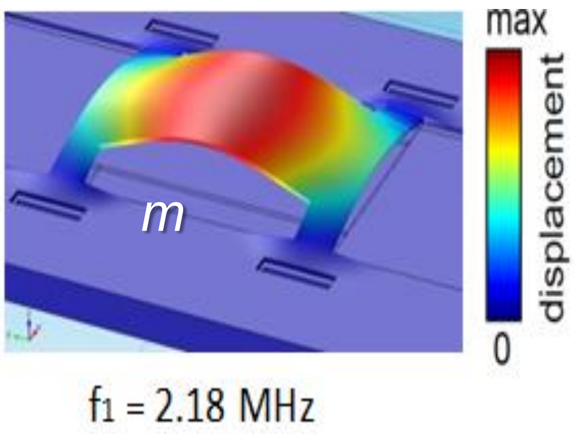


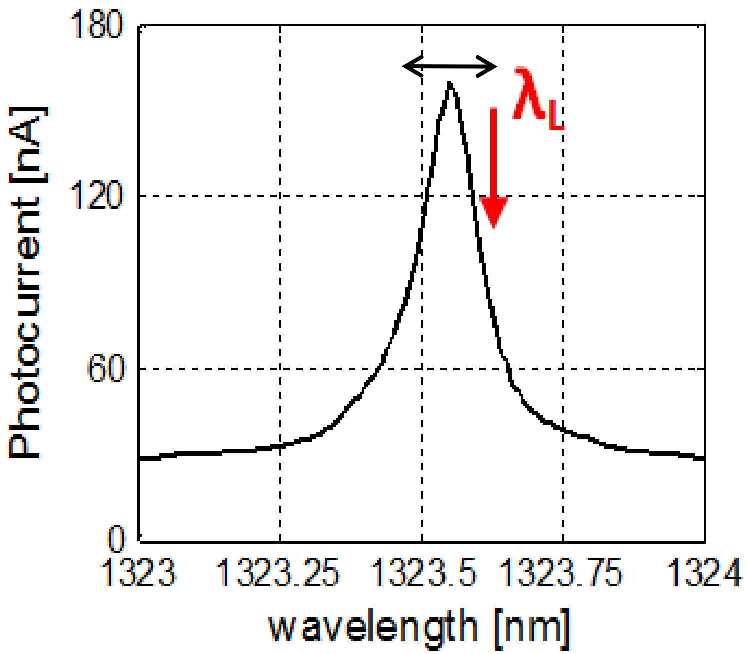
HF absorption line P(3) @ 1312.59 nm detected

Displacement sensor demonstration

Measuring thermal motion:



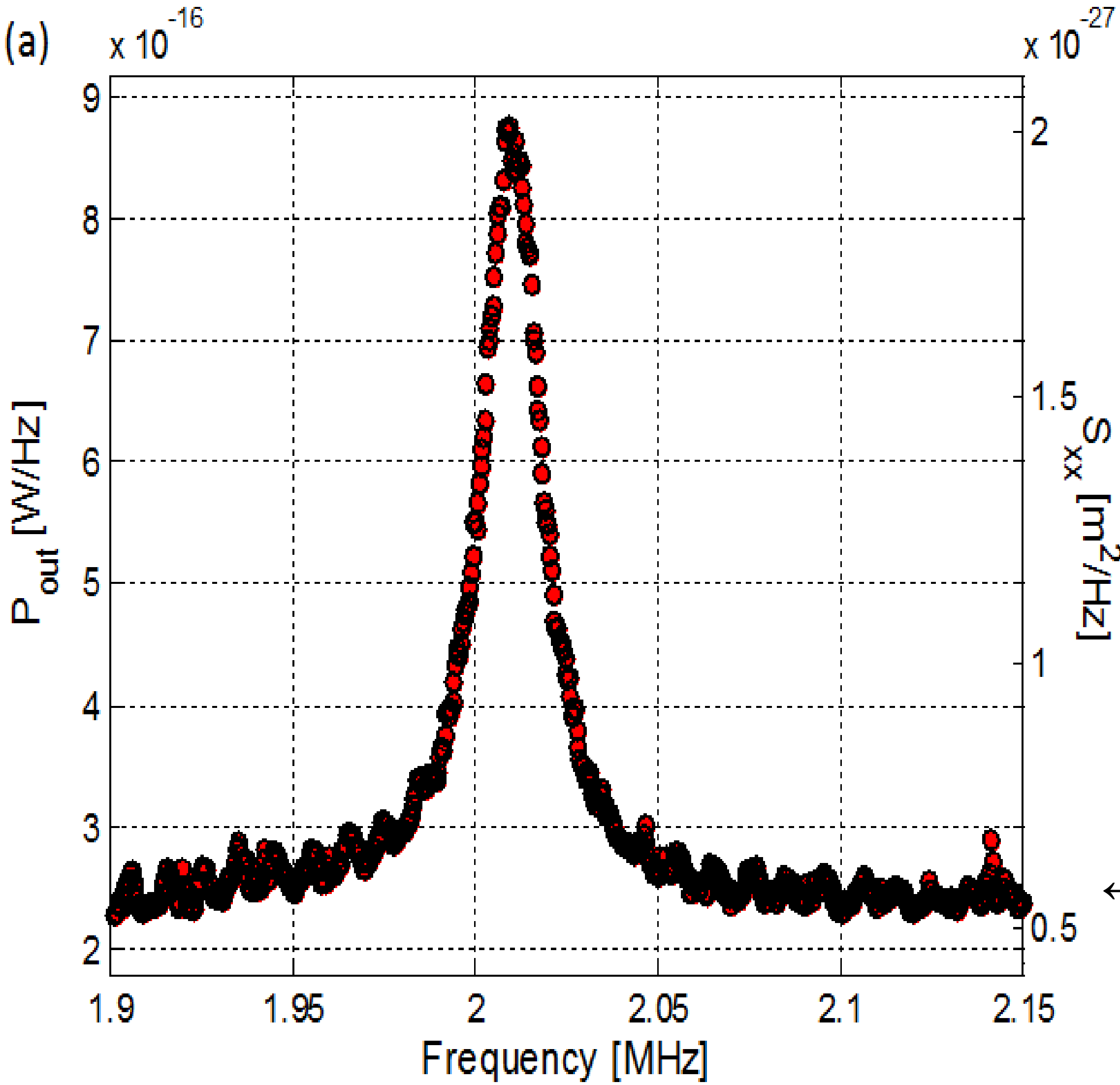


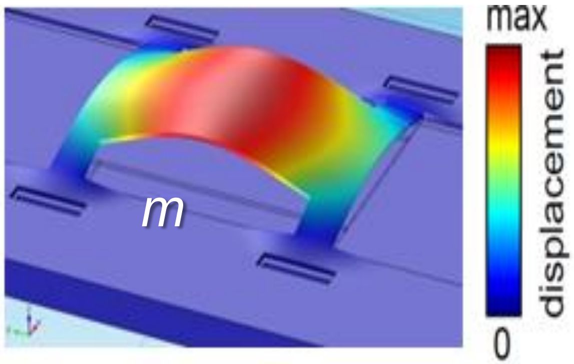


Estimated amplitude of thermal motion:

$z_{RMS} \approx 20$ *pm (@RT)*

Displacement sensor demonstration





$f_1 = 2.18$ MHz

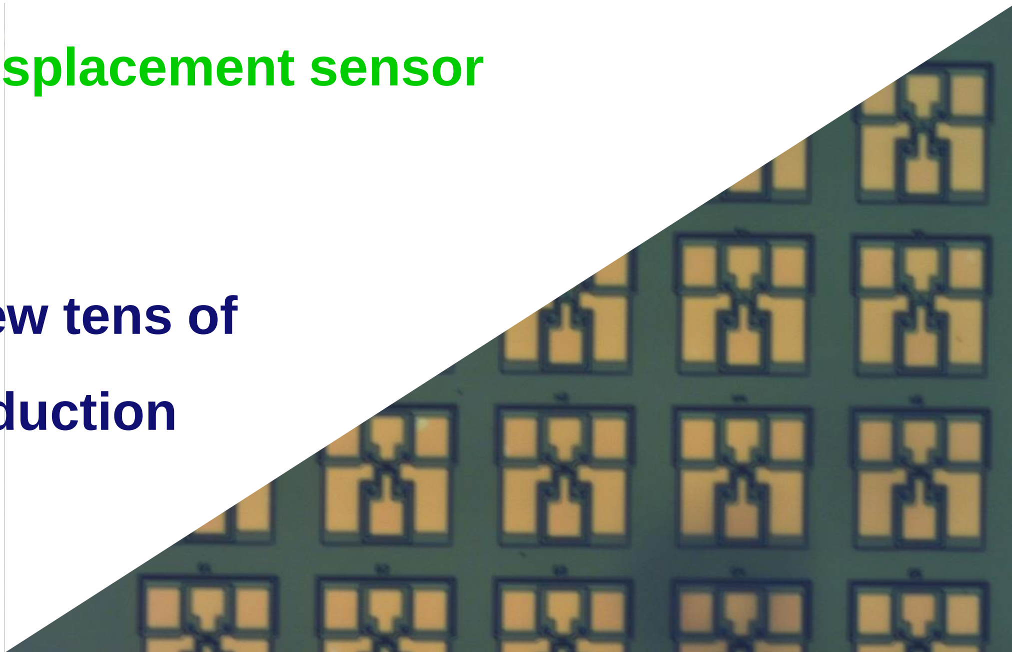
Estimated amplitude of thermal motion:

$z_{RMS} \approx 20$ pm (@RT)

← *Sensitivity < **100 fm/(Hz)$^{1/2}$***

Conclusions

- ✓ μ-spectrometer with resolution down to **80 pm** over a range of up to **23 nm**
- ✓ Resonance modulation scheme with high rejection ratio (**30dB**) and resolution (**<1 pm** when used as a **wavemeter**)
- ✓ Application as **gas sensor** (HF detection)
- ✓ Fully integrated optomechanical **displacement sensor**



All this in an integrated device, few tens of μm in size, suitable for mass production

Questions?

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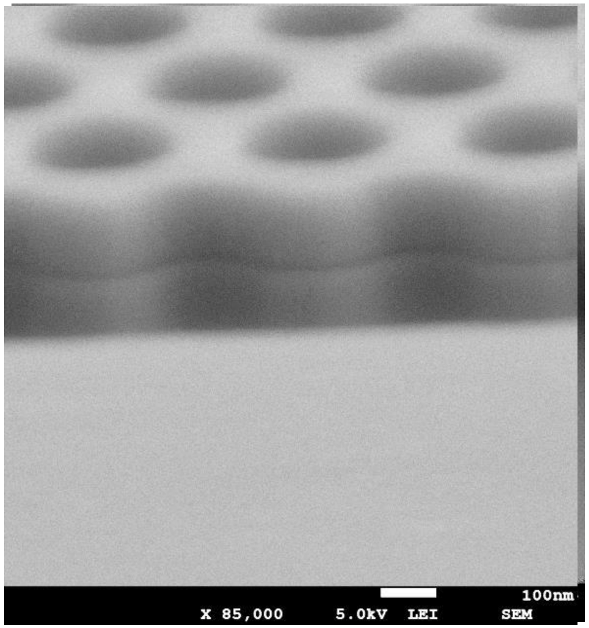
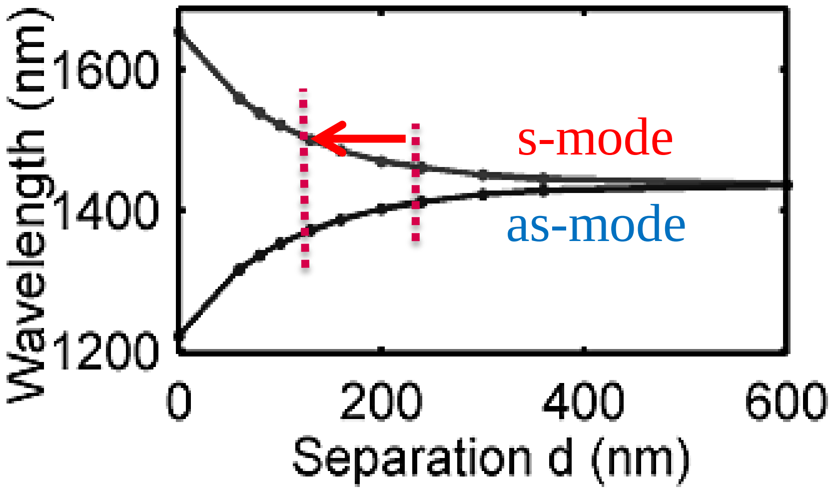
Tuning: pull-in limitation

- ❑ **Tuning is limited by pull-in effect to 2/3 of nominal distance**



M.Cotrufo



Simulation: Tuning from d = 240nm to 160nm provides: **Δλ =28 nm**

- ❑ Pull-in effect is **not reversible**

Displacement sensor demonstration- Measuring Brownian motion

Experimental: $\langle x^2 \rangle_{th} = \int S_{xx} df = (6.3\ pm)^2$

Model: $k_B T / m_{eff} \Omega_M^2 = (22\ pm)^2$

- Transduction currently limited
- by diode speed ($f_{cut\text{-}off} < f_1$)
- To be addressed: Non-ohmic contacts

Displacement PSD:

$$S_{xx}(\mathrm{f}) = \frac{P_{out}(\mathrm{f})}{Z\ A\ {g_{OM}}^2 \left(\frac{\partial I}{\partial \omega}\right)^2}$$

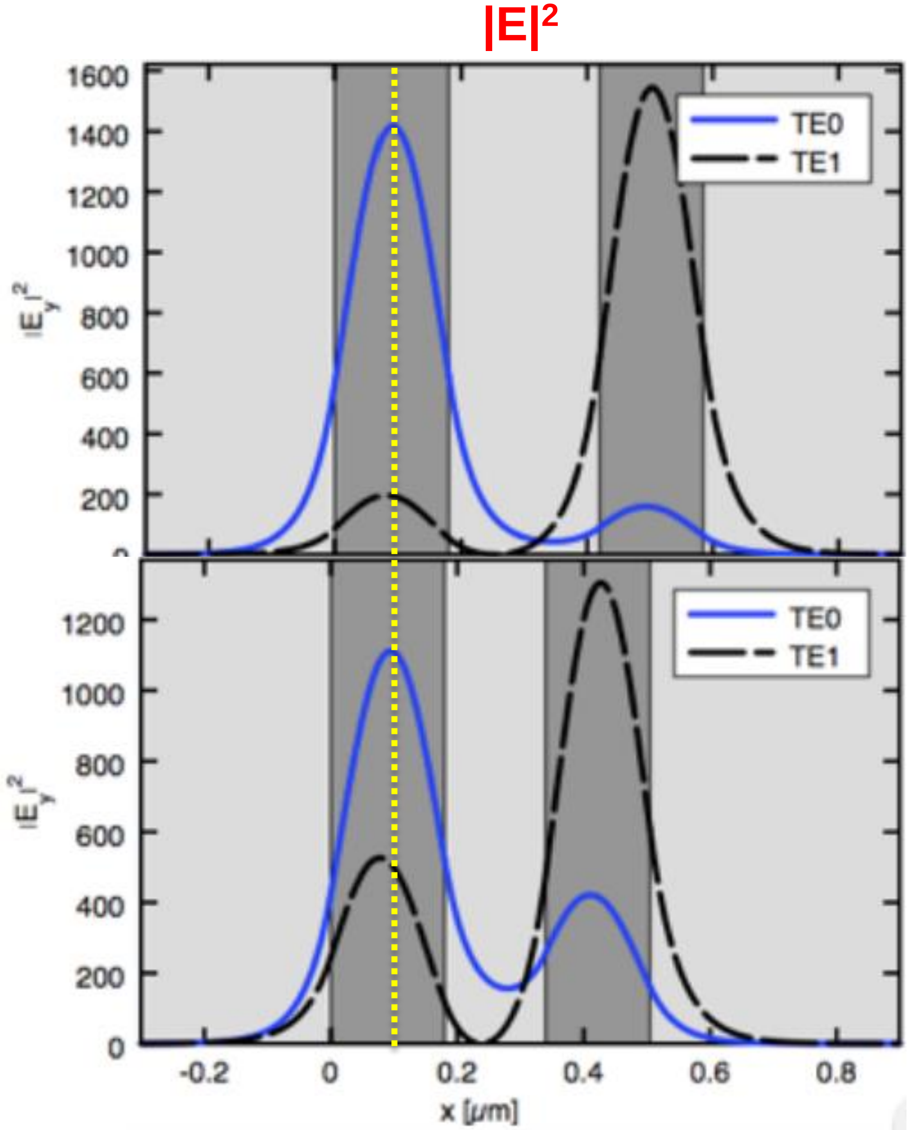
$$g_{OM} = \frac{\partial \omega}{\partial x} = 2 \cdot 10^{20}\ s^{-1}/m$$

Mode distribution in an asymmetric system

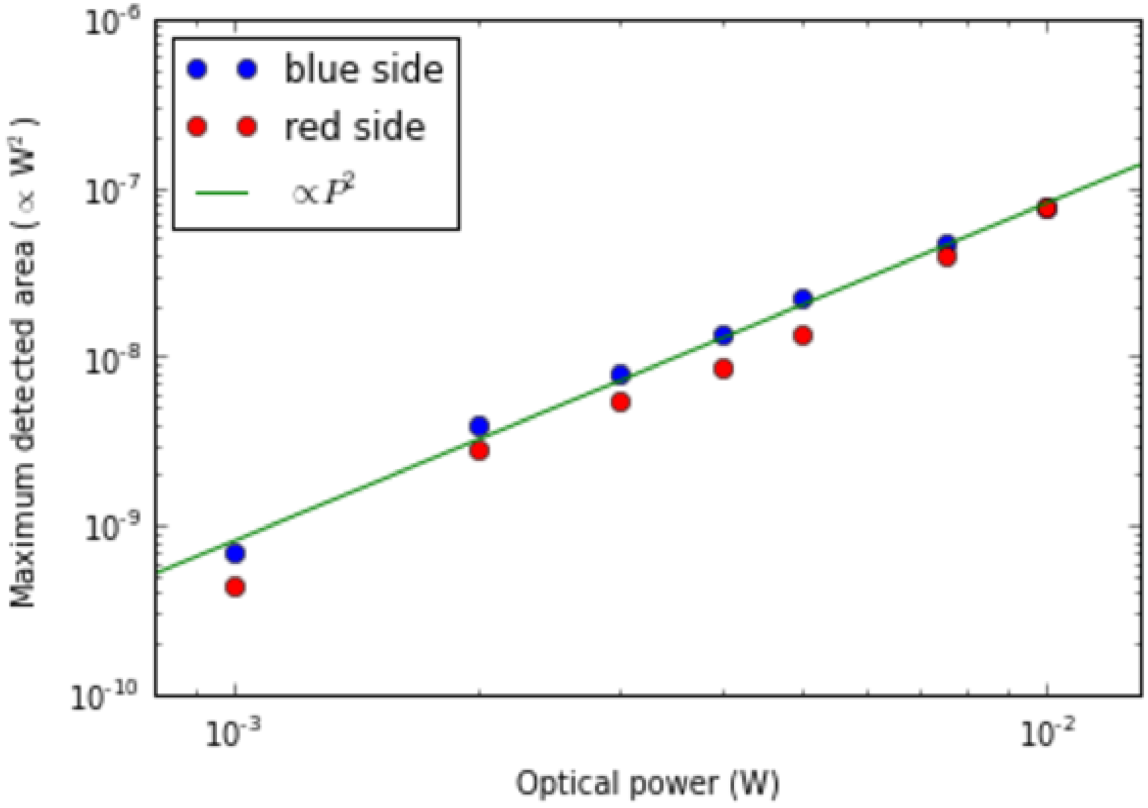
t_1=180, t_2=165nm

d=240nm

d=160nm



Surface under the curve vs. laser power



R. Leijssen

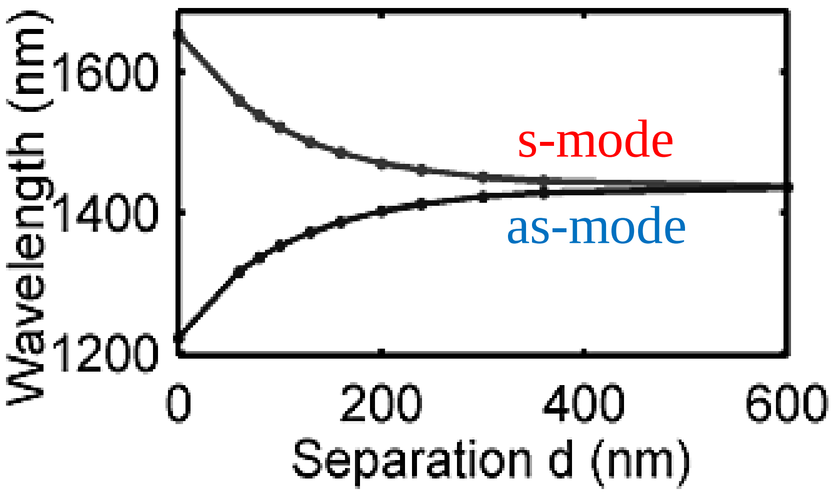
Pull-in

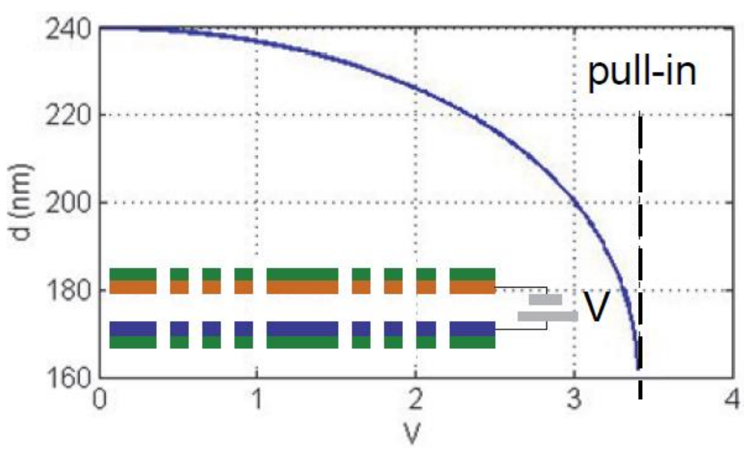
- Tuning is limited by pull-in effect to 2/3 of nominal distance

$$\mathcal{E} = -\frac{\varepsilon_0 S U^2}{2z} + \frac{k_+(z - z_0)^2}{2}$$

Electrostatic *Elastic*

$$\partial \mathcal{E}/\partial z = 0 \rightarrow z^3 - z^2 z_0 = -\frac{\varepsilon_0 S U^2}{2k_+}$$

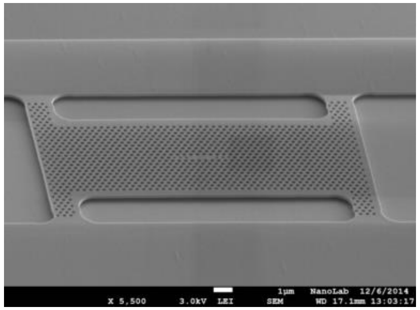


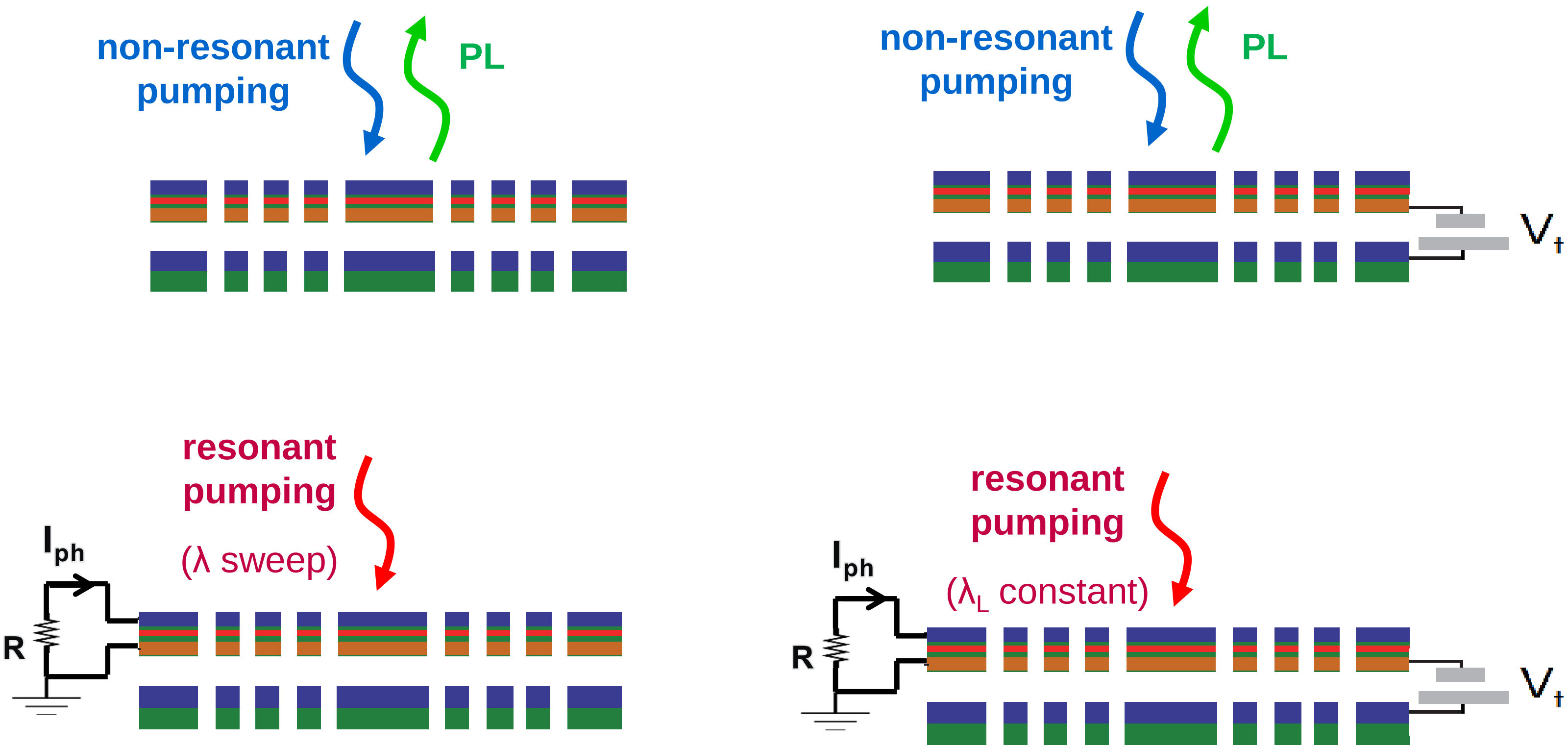


Simulation: Tuning from d = 240nm to 160nm provides: **Δλ =28 nm**

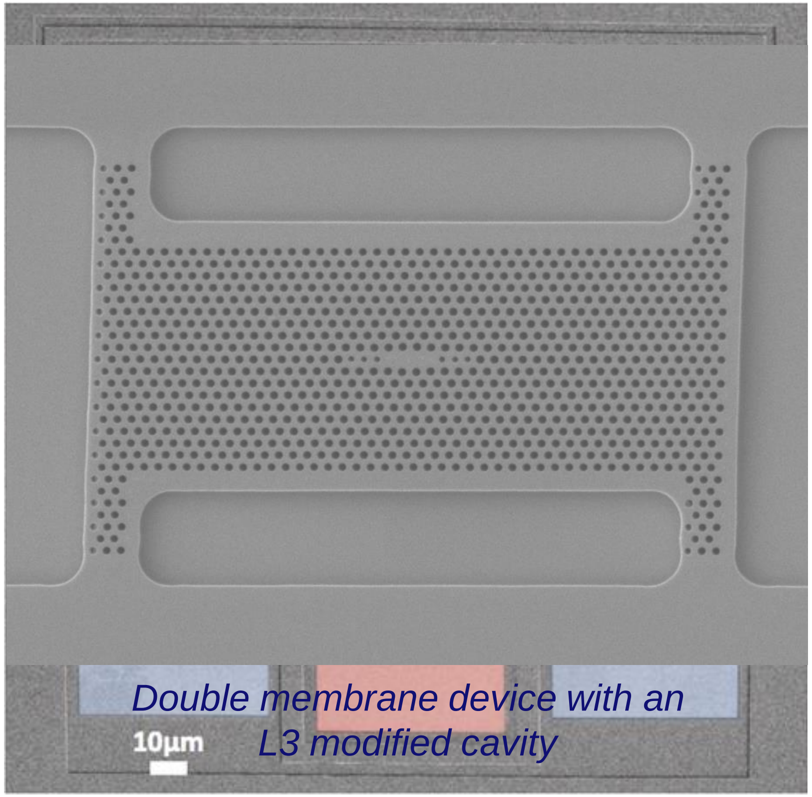
Current status: μ-spectrometer progress

- Tuning range (Δλ) > 50 nm → (7nm extended to 25 nm)
- Resolution (δλ) < 100 pm → (76 pm)
- Free spectral range (FSR) > 50 nm → (up to 30 nm for H0 cavity)
- Responsivity = 0.05 A/W → (up to 0.02 A/W)
- Rejection ration > 15 dB → (30 dB)




non-resonant pumping
PL
non-resonant pumping
PL
V_t
resonant pumping
I_{ph}
(λ sweep)
R
resonant pumping
I_{ph}
($λ_L$ constant)
R
V_t

Fabrication of full devices:



Double membrane device with highlighted contact pads

* M. Petruzzella

- ***Over 50 fabrication steps:***
- Multiple wet and dry etching steps
- 3 Optical lithography steps
  (for defining contact pad positions)
- Metal evaporation
- Electron beam lithography
  (for patterning the photonic crystal)