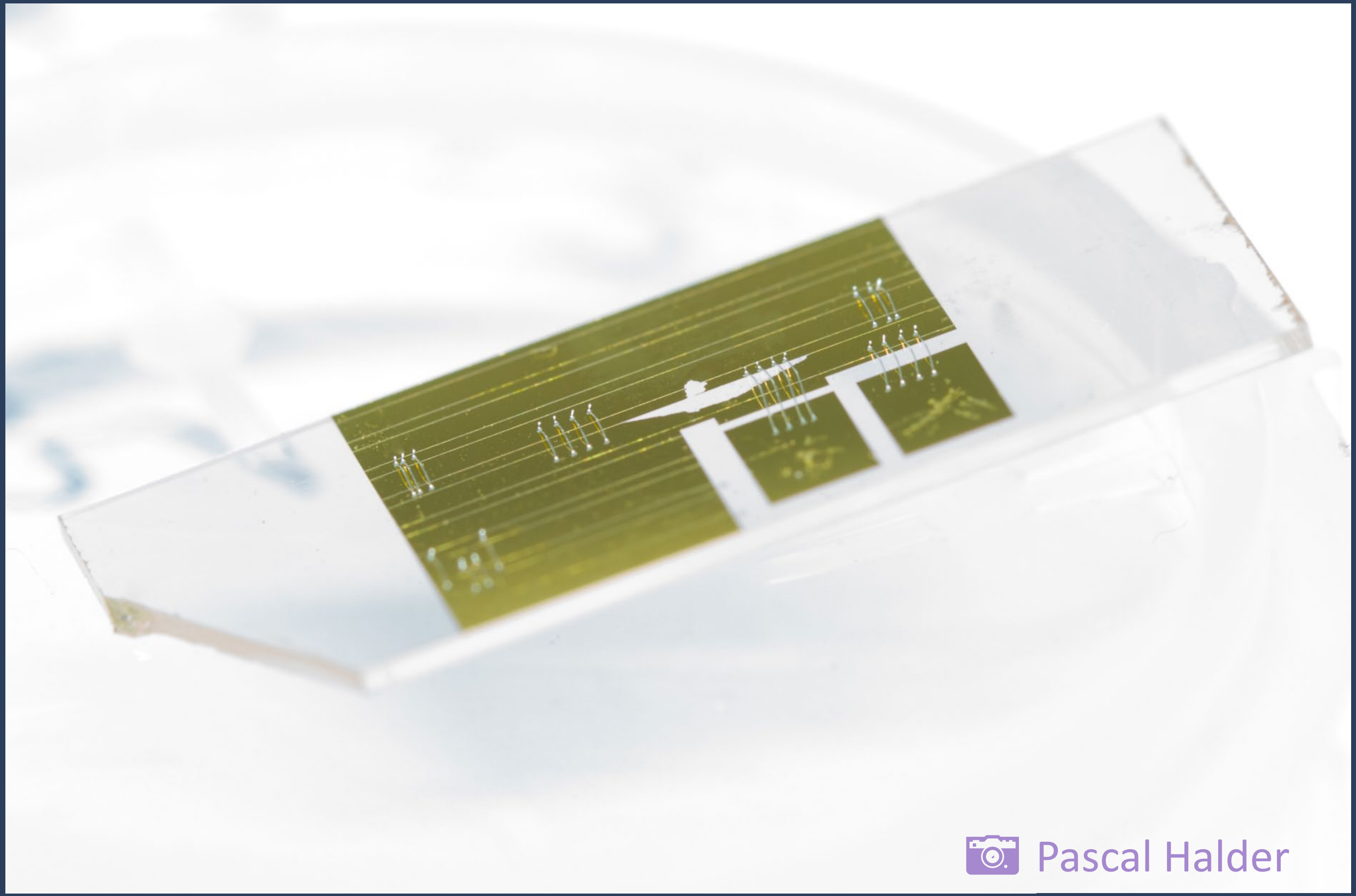
An electro-optic integrated platform for telecom and sensing devices

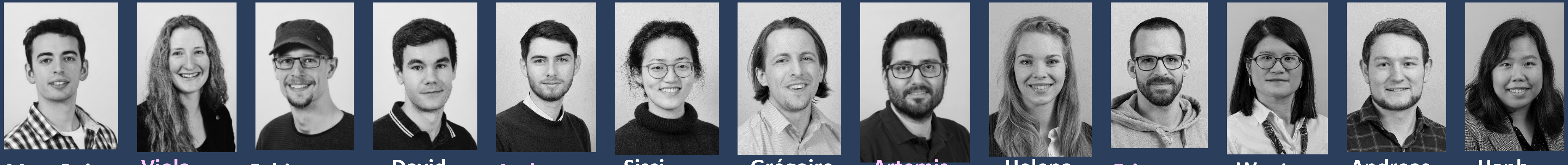
Rachel Grange

ETH Zurich
Department of Physics
Institute for Quantum Electronics
Optical Nanomaterial Group

www.ong.ethz.ch
grange@phys.ethz.ch
@rachel_grange



The Optical Nanomaterial Group ONG



Marc Reig Escalé | Viola Vogler-N | Fabian Kaufmann | David Pohl | Andrea Morandi | Sissi Wang | Grégoire Saerens | Artemis Karvounis | Helena Weigand | Eric Dénervaud | Wentao Qiu | Andreas Maeder | Hanh Duong

Alumni: A. Sergeyev, N. Hendricks, C. Renaut, B. Jordaan, F. Richter, M. Timofeeva, Flavia Timpu, Romolo Savo, Jolanda Mueller, Franciele Henrique

Funding

FNSNF
Fonds National Suisse
Schweizerischer Nationalfonds
Fondo Nazionale Svizzero
Swiss National Science Foundation

State Secretariat for Education, Research and Innovation SERI
Swiss Space Office

swiss space center

BRIDGE

MARIE CURIE ACTIONS

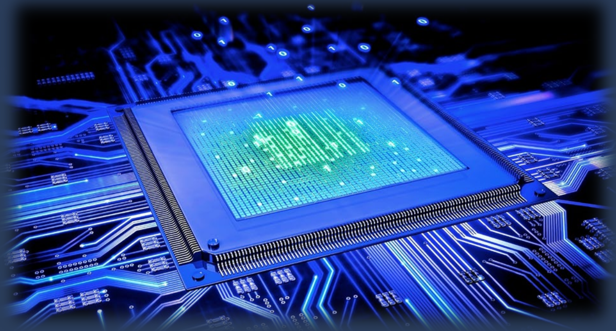
erc
European Research Council
Established by the European Commission

Why miniaturizing quadratic optical materials?

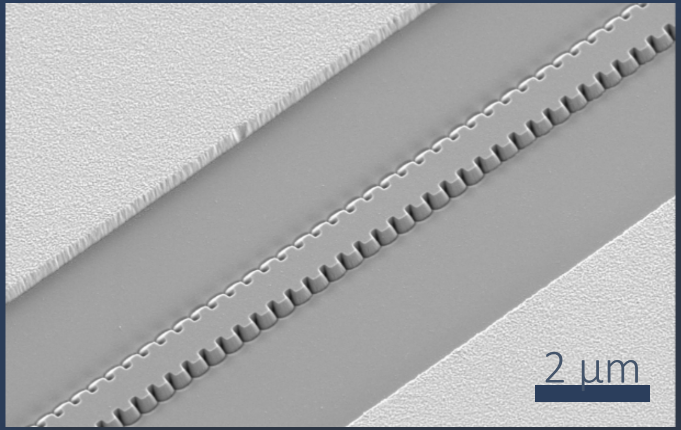
Telecommunication

Sensor

Source

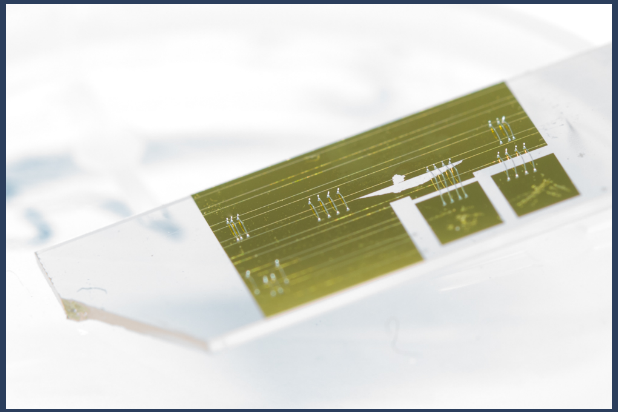


Modulators



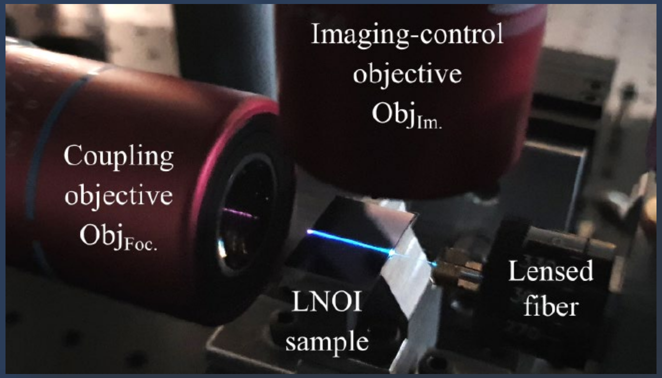
Reig Escalé, et al. OL 43(7) 2018
Pohl, et al. IEEE PTL 33 (2) 2020

Spectrometer



Pohl et al. Nature Photonics 14 (1) 2020

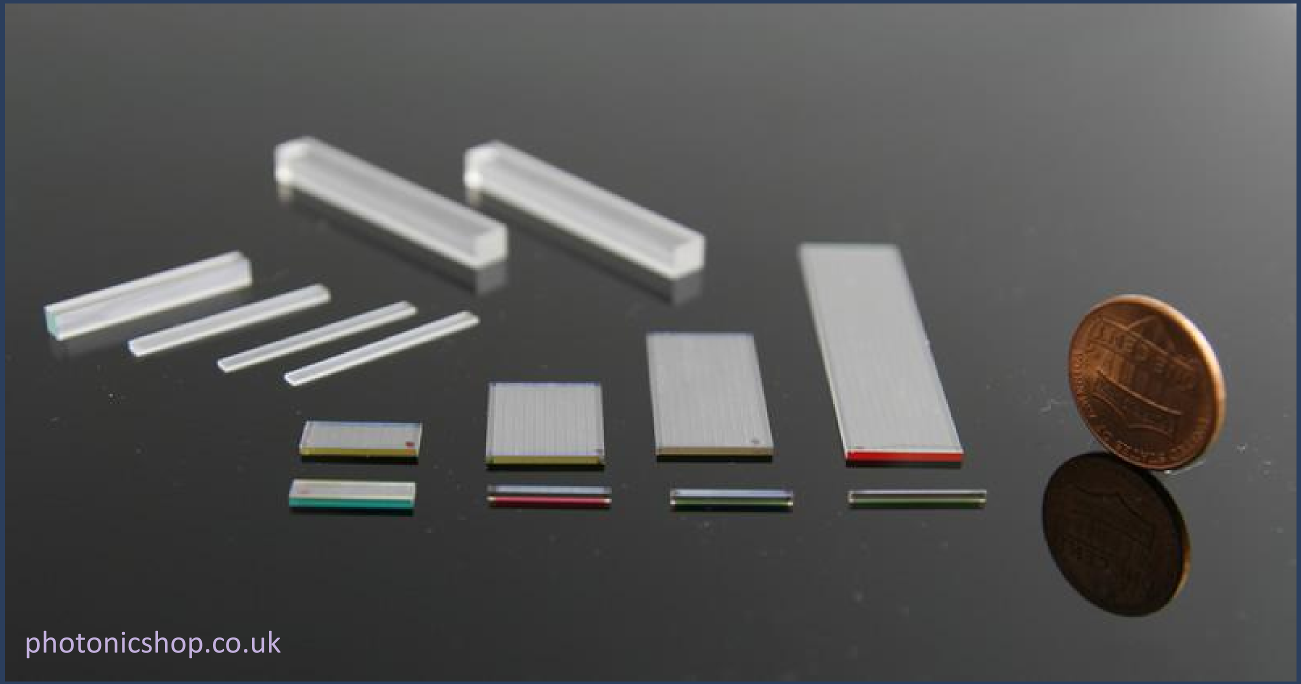
Supercontinuum



Reig Escalé, et al. APL Photonics 5 (12) 2020

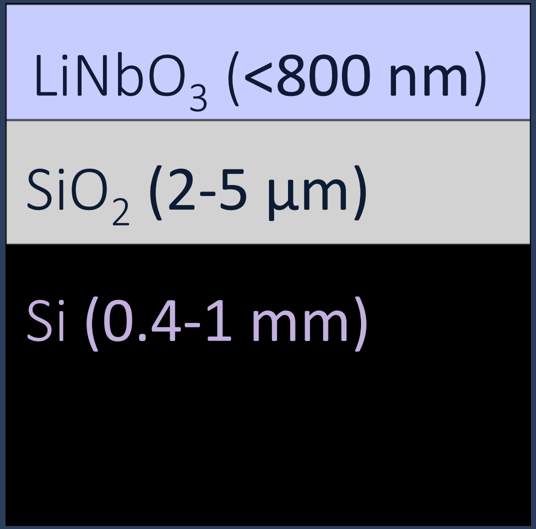
Does this material exist at a small scale?

Bulk crystal

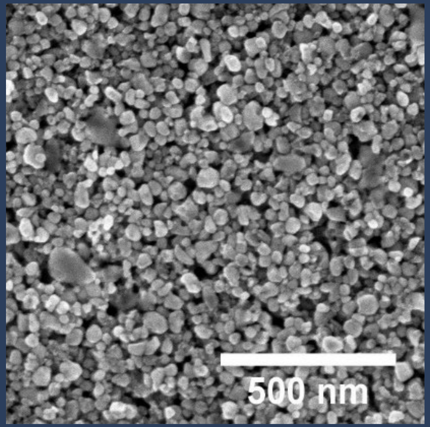


Lithium Niobate ($LiNbO_3$)

At small scale

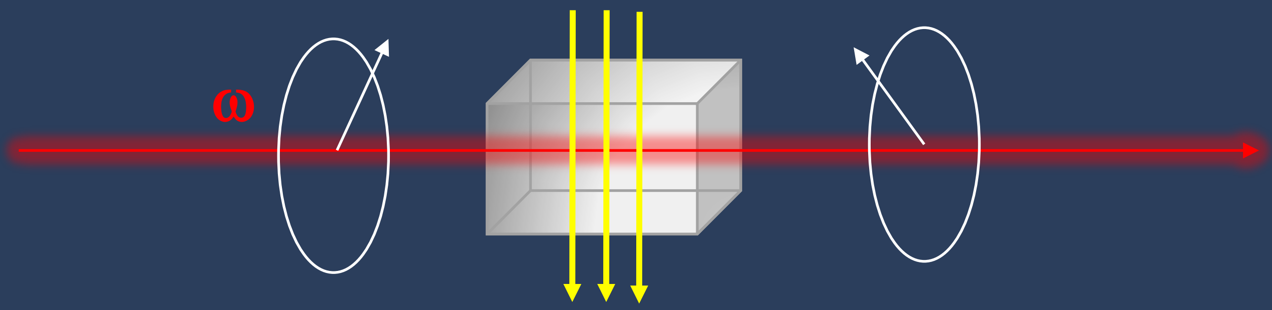


Rabiei, P.; Gunter, P. *Applied Physics Letters* **2004**, *85* (20).



Kim, E.; ... Grange, R. ACS Nano **2013**, 7 (6).

More properties of quadratic $\chi^{(2)}$ materials: $LiNbO_3$



- **Electro-optic**

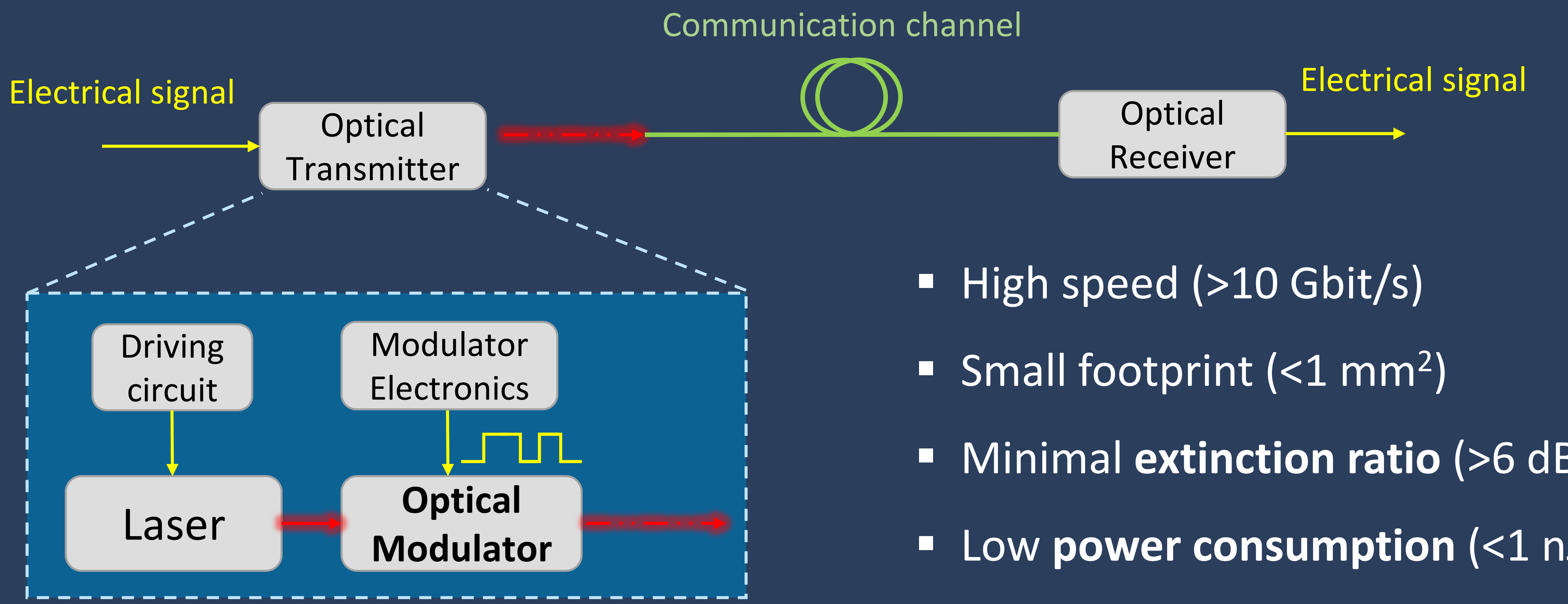
Change in the refractive index linearly proportional to the electric field

Electro-optic tensor $\chi^{(2)}$ of $LiNbO_3$

$$\begin{pmatrix} \Delta(1/n^2)_1 \\ \Delta(1/n^2)_2 \\ \Delta(1/n^2)_3 \\ \Delta(1/n^2)_4 \\ \Delta(1/n^2)_5 \\ \Delta(1/n^2)_6 \end{pmatrix} = \begin{pmatrix} 0 & -3.4 & 8.6 \\ 0 & 3.4 & 8.6 \\ 0 & 0 & 30.8 \\ 0 & 28 & 0 \\ 28 & 0 & 0 \\ -3.4 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

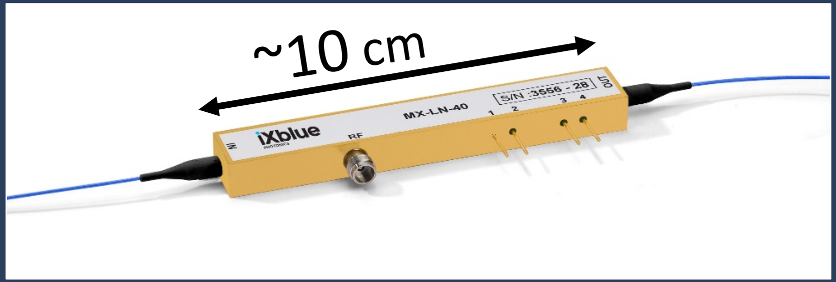
d_{33}= 30.8 pm/V

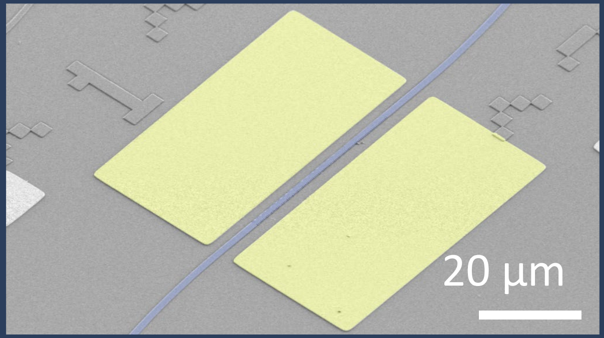
Role of the optical modulator

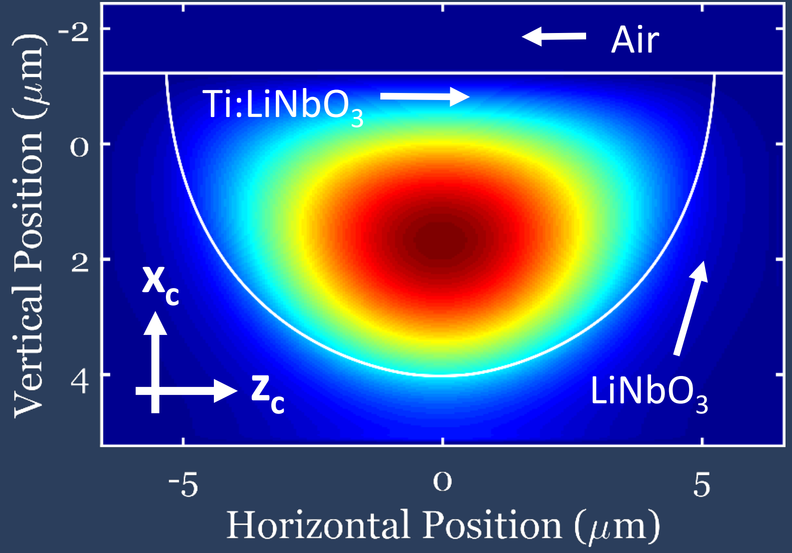


- High speed (>10 Gbit/s)
- Small footprint (<1 mm^2)
- Minimal **extinction ratio** (>6 dB)
- Low **power consumption** (<1 nJ/bit)

Traditional vs integrated modulator design

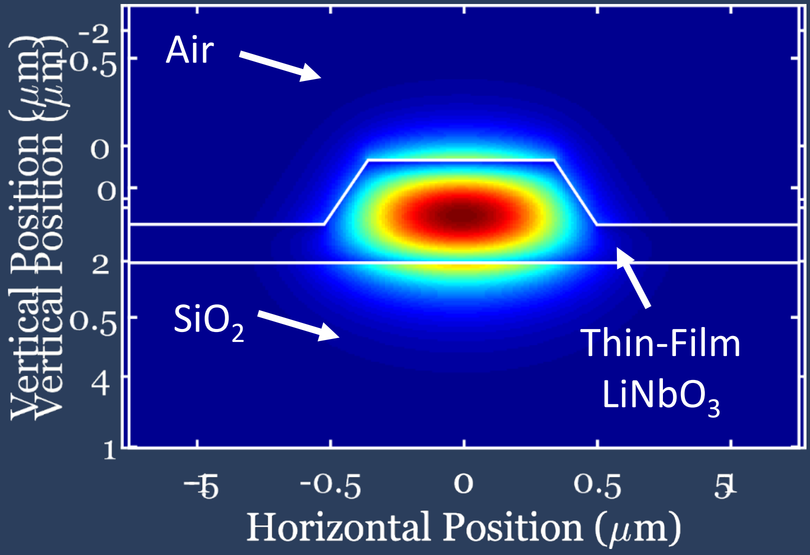






Mode Area > 30 µm^2

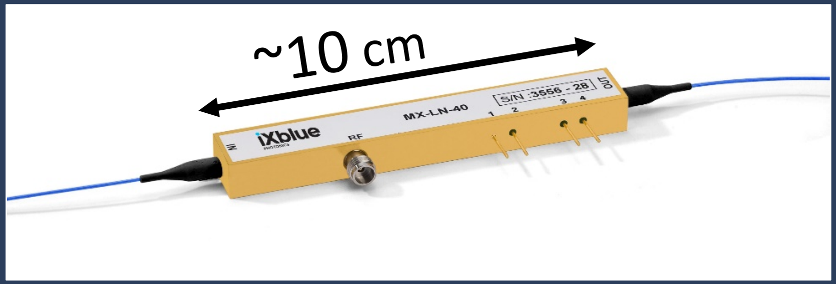
<40 Gbit/s

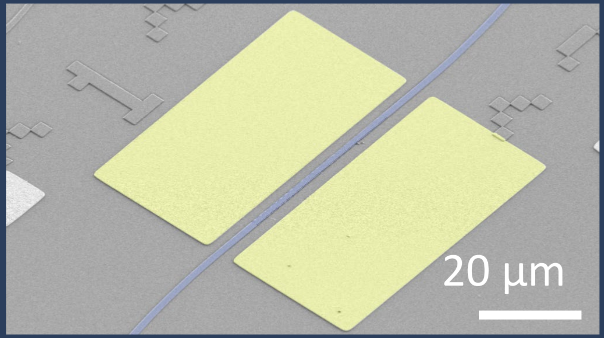


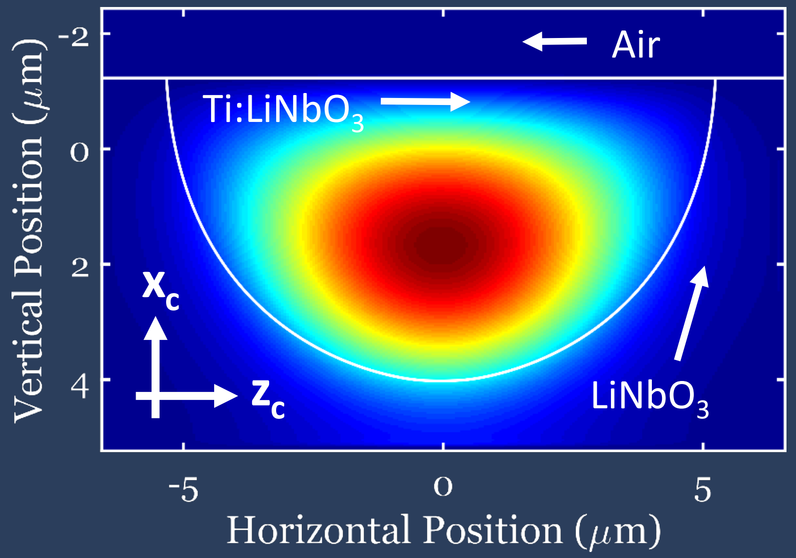
Mode Area < 1 µm^2

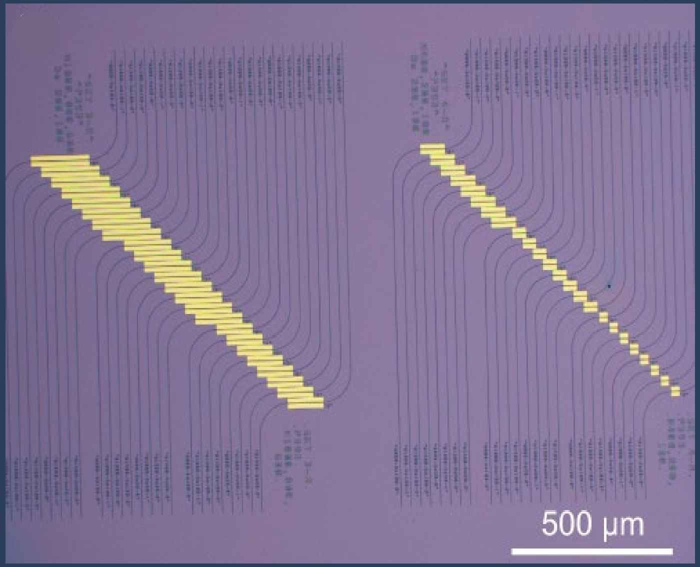
100 Gbit/s

Traditional vs integrated modulator design









Mode Area > 30 µm^2

<40 Gbit/s

Mode Area < 1 µm^2

100 Gbit/s

Parallelization

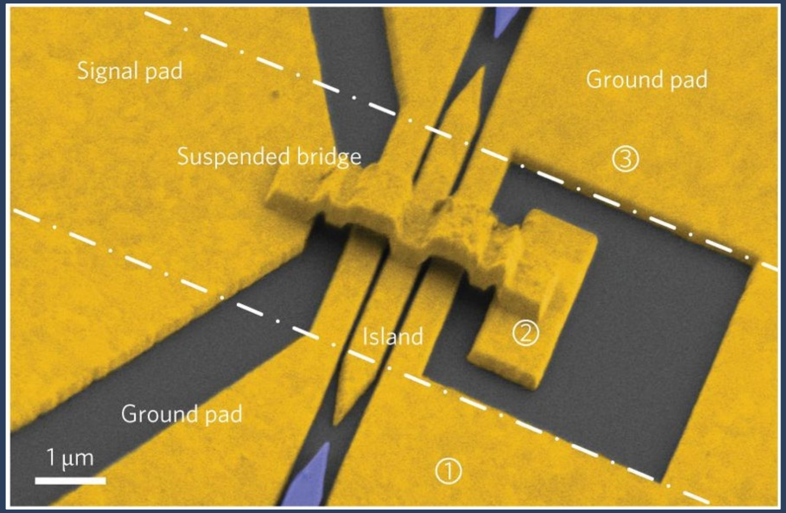
Current on-chip platforms for modulators

- **Plasmonics**: high speed but high optical losses (~dB/µm)

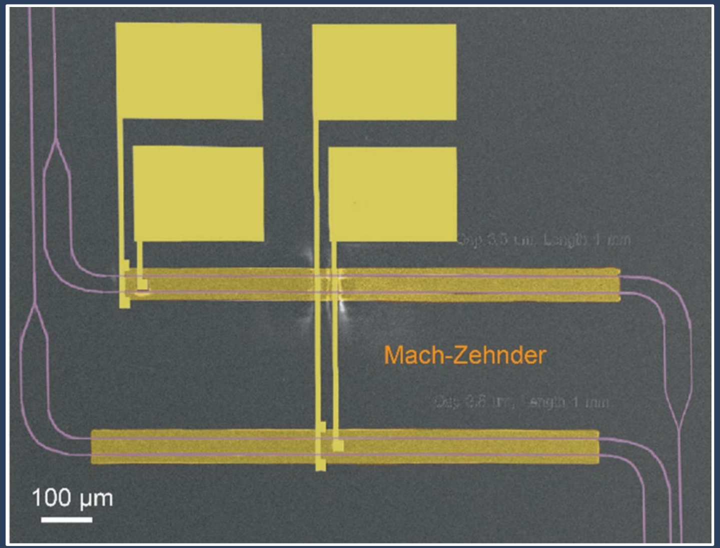
  → **polymers**: material degradation in long term

- **SOI, InP**: Carrier injection but high voltage

- **LNOI**: Low-loss modulator (<0.5 dB/cm) but large foot print, less convenient parallelization

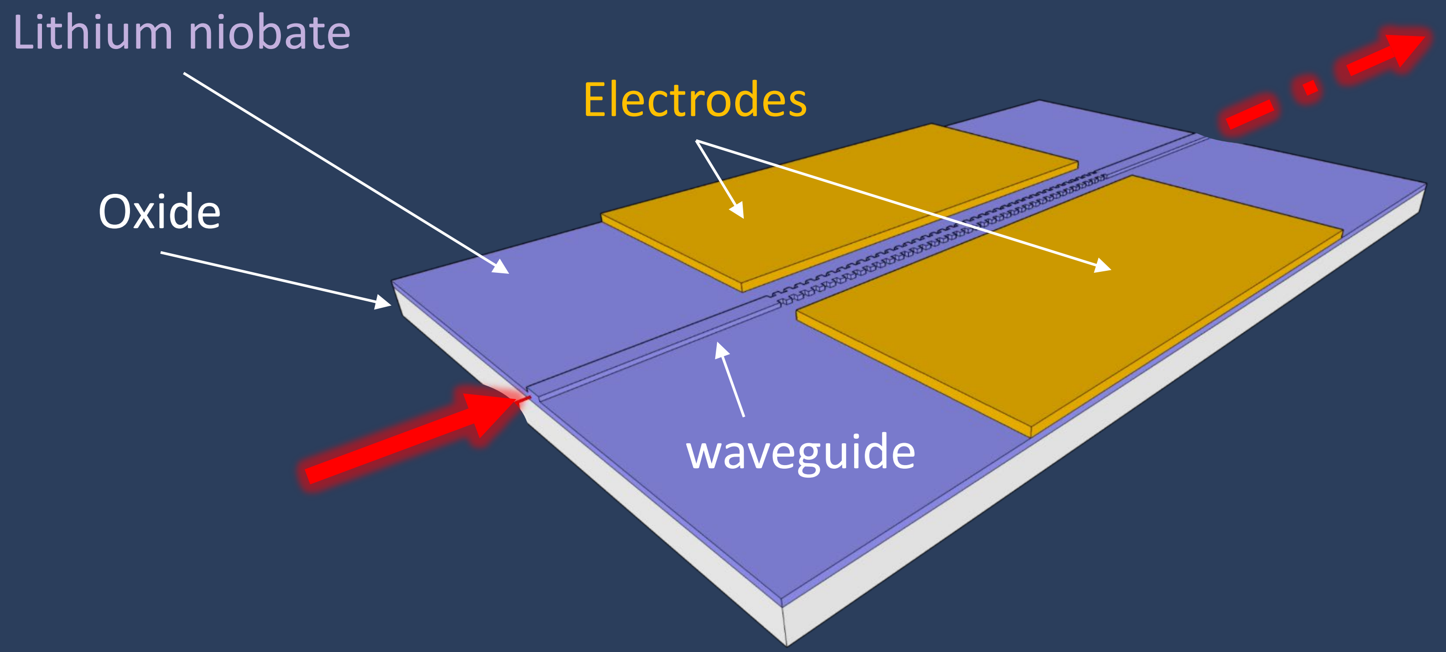


C. Haffner et al., Nature Photonics 9, 525–528, 2015



C. Wang et al., Optics Express 26(2), 1547-1555, 2018

Concept of the integrated Bragg modulator



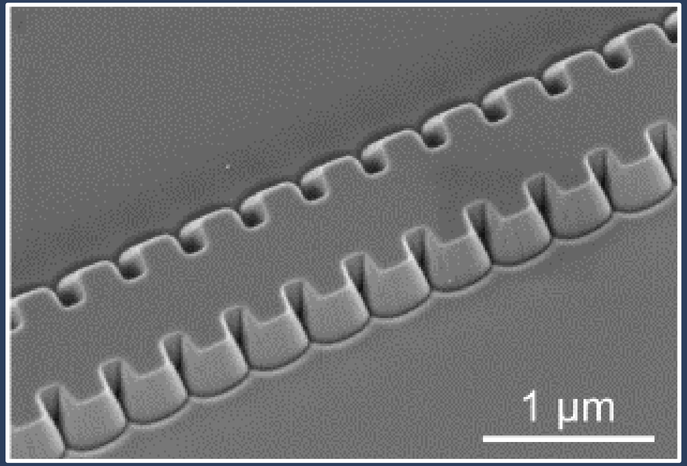
Aim: reduce **footprint** in **LNOI** modulators **10×500 µm²**

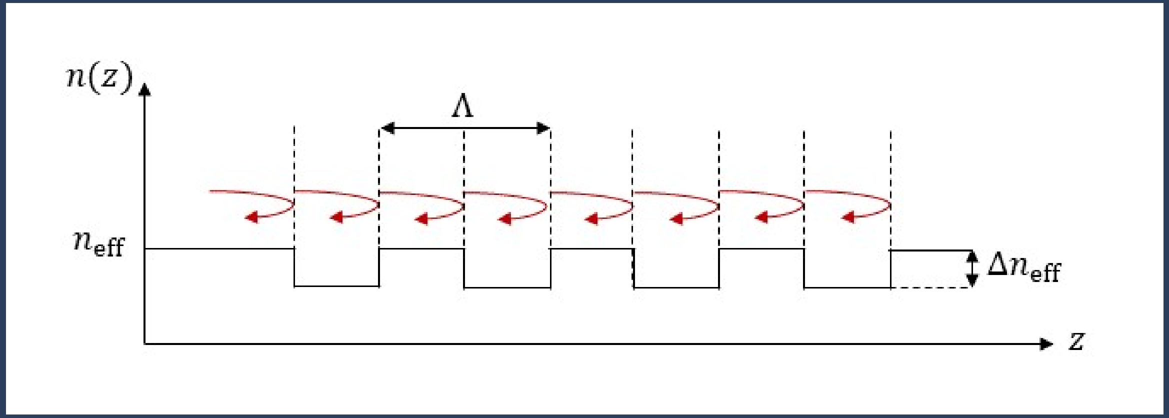
with **a single waveguide** and a modulation at the **Bragg resonance**

Reig Escalé, …, Grange, Optics Letters 43(7) 2018

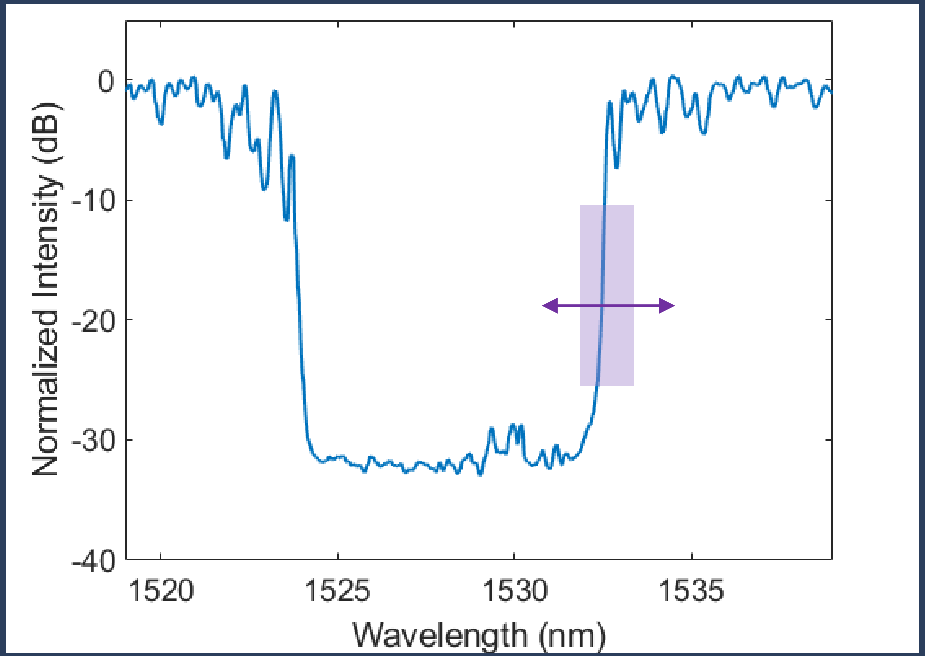
Concept of the integrated Bragg modulator

Multilayers of alternating materials with varying n, each layer causes a partial reflection





Stop band in transmission



Nanofabrication at BRNC and FIRST clean rooms

Reig Escalé, …, Grange, Optics Letters 43(7) 2018

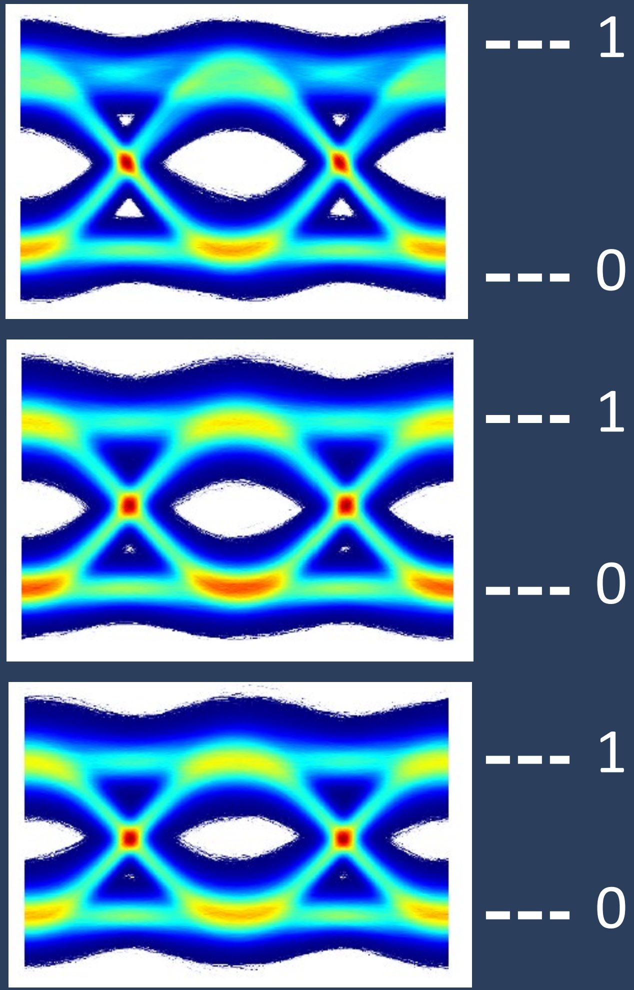
Concept of the integrated Bragg modulator

V_{pp} = 8.9 V at 50 Ω

25 Gbit/s
BER < ~10^{-6}

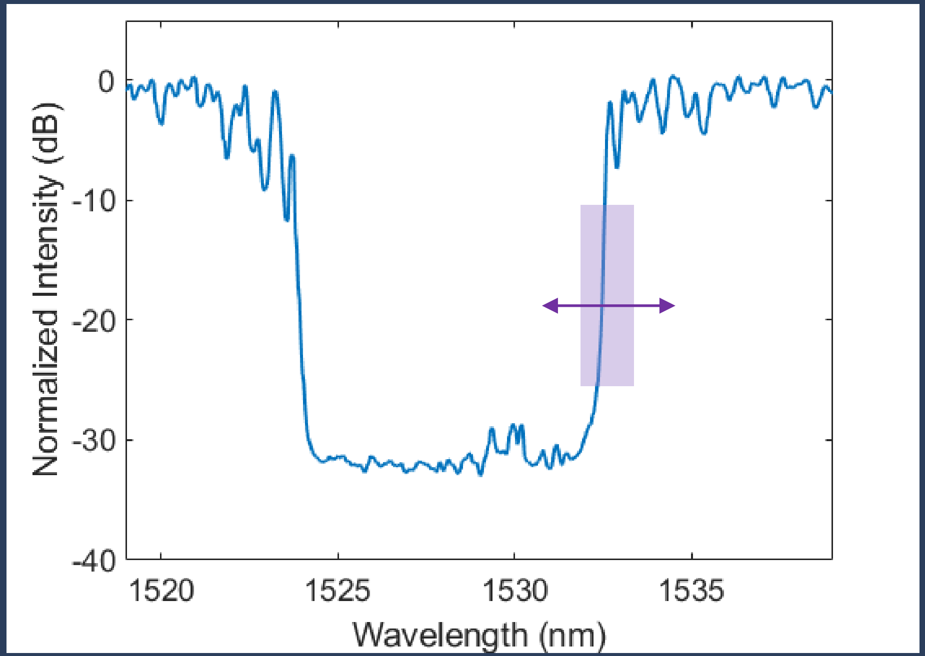
50 Gbit/s
BER = 1.9 10^{-6}

100 Gbit/s
BER = 1.3×10^{-5}



< Hard Decision threshold

Stop band in transmission



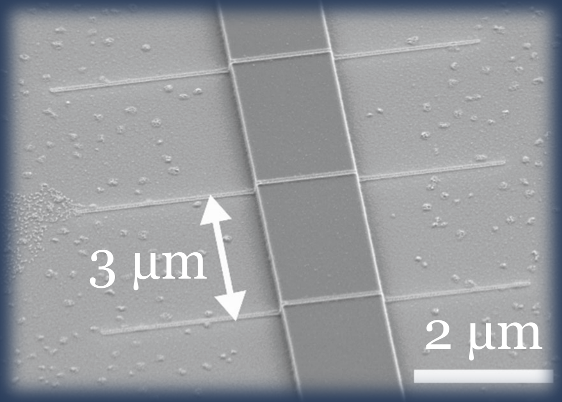
Nanofabrication at BRNC and FIRST clean rooms

Collaboration with Juerg Leuthold, ETH, D-ITET

Pohl, et al. IEEE PTL 33 (2) 2020

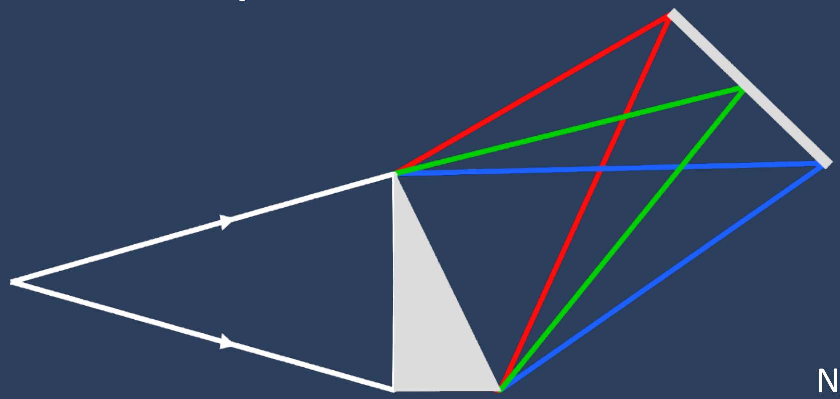
Which integrated devices ?

- A Bragg optical modulator
- A nano spectrometer

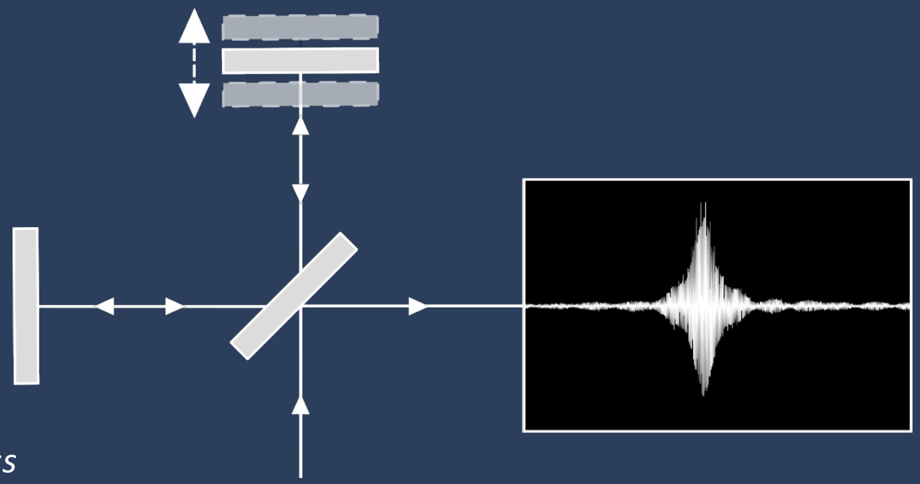


Current spectrometers

Bulk



Grating/Phased-array

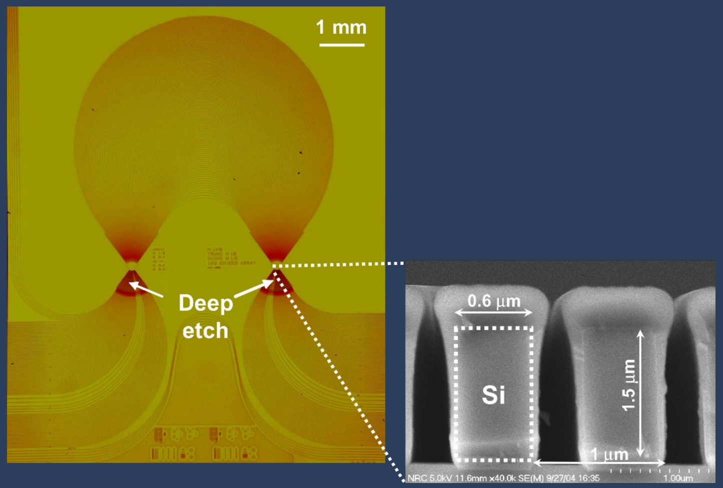


Fourier Transform

N. Blind et al., *Opt. Express 25(22), 27341-27369,* **2017**

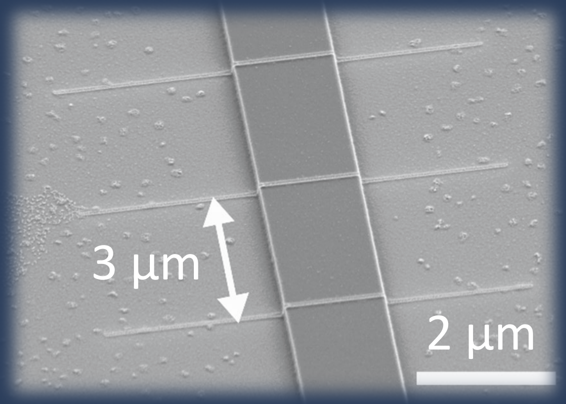
Integrated optics

SOI circuits



P. Cheben et al., Opt. Express 15(5) 2007

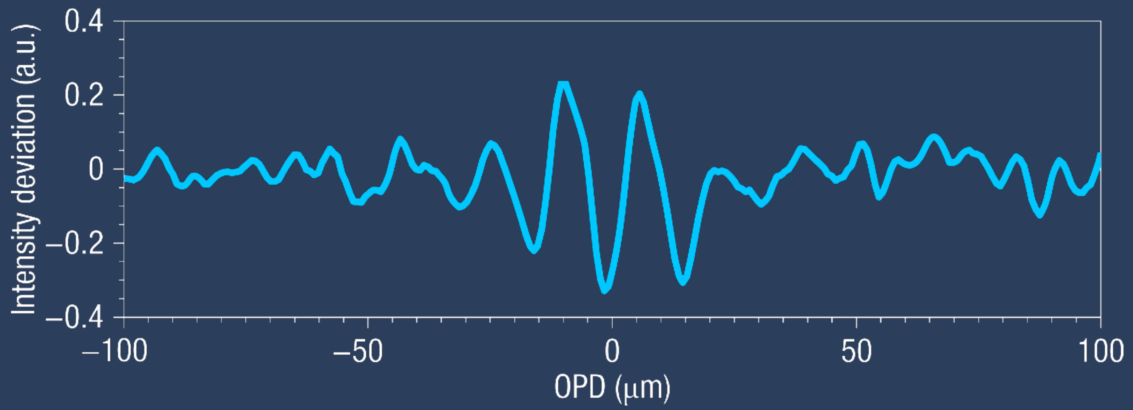
This work



D. Pohl, …, R. Grange, *Nature Photonics 14* (1) **2020**

On-Chip Fourier Transform Spectrometers

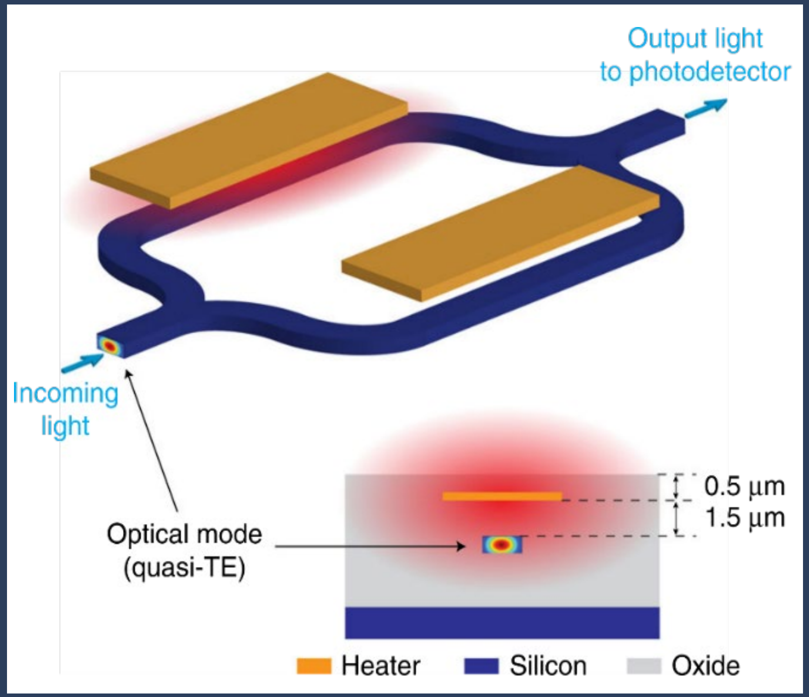
Stationary-wave integrated Fourier-transform spectrometer (SWIFTS)



Undersampling / Limited bandwidth (15 nm)

E. Le Coarer et al., Nature Photonics 1(8), 473-478, 2007

Thermo-optic Fourier-transform spectrometer



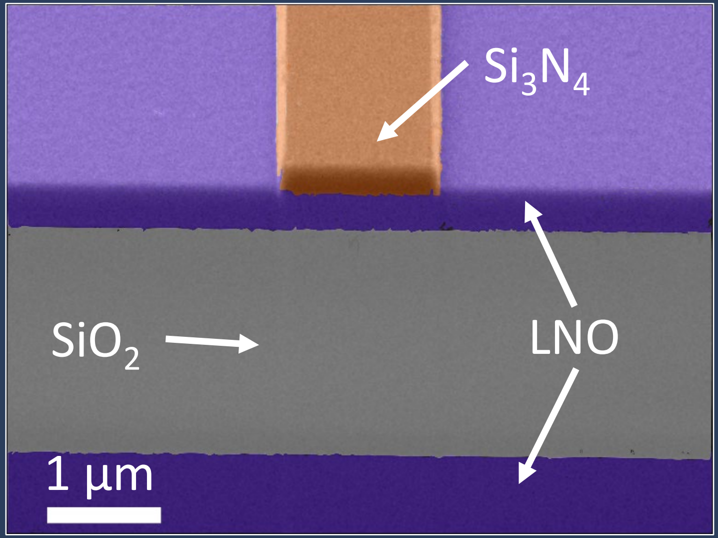
Full sampling (>100 V) / Extended bandwidth

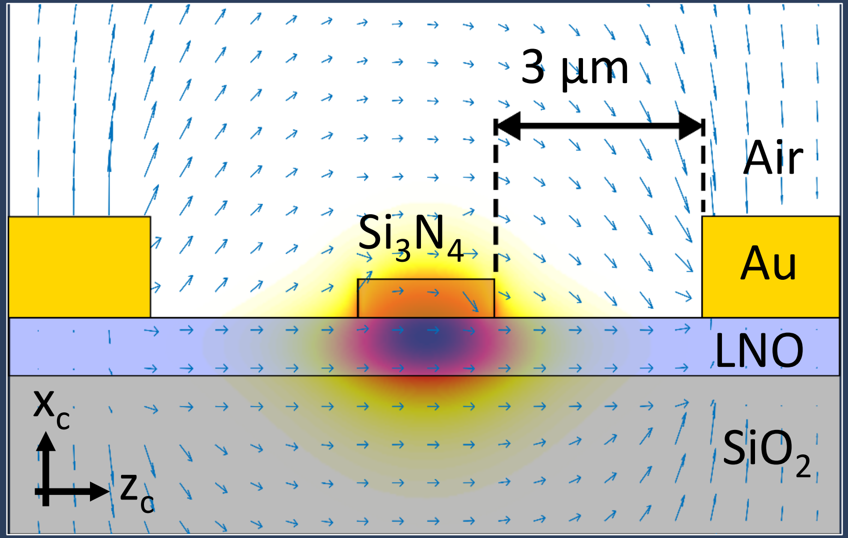
M. Souza et al., Nature Comm. 9(665), 2018

Lithium Niobate Nano Spectrometer V=0

Quasi-TE_{00}, n_{eff} ~1.8 at 1550 nm

~1.39 dB/cm Prop. Losses
~6 dB Insertion Loss

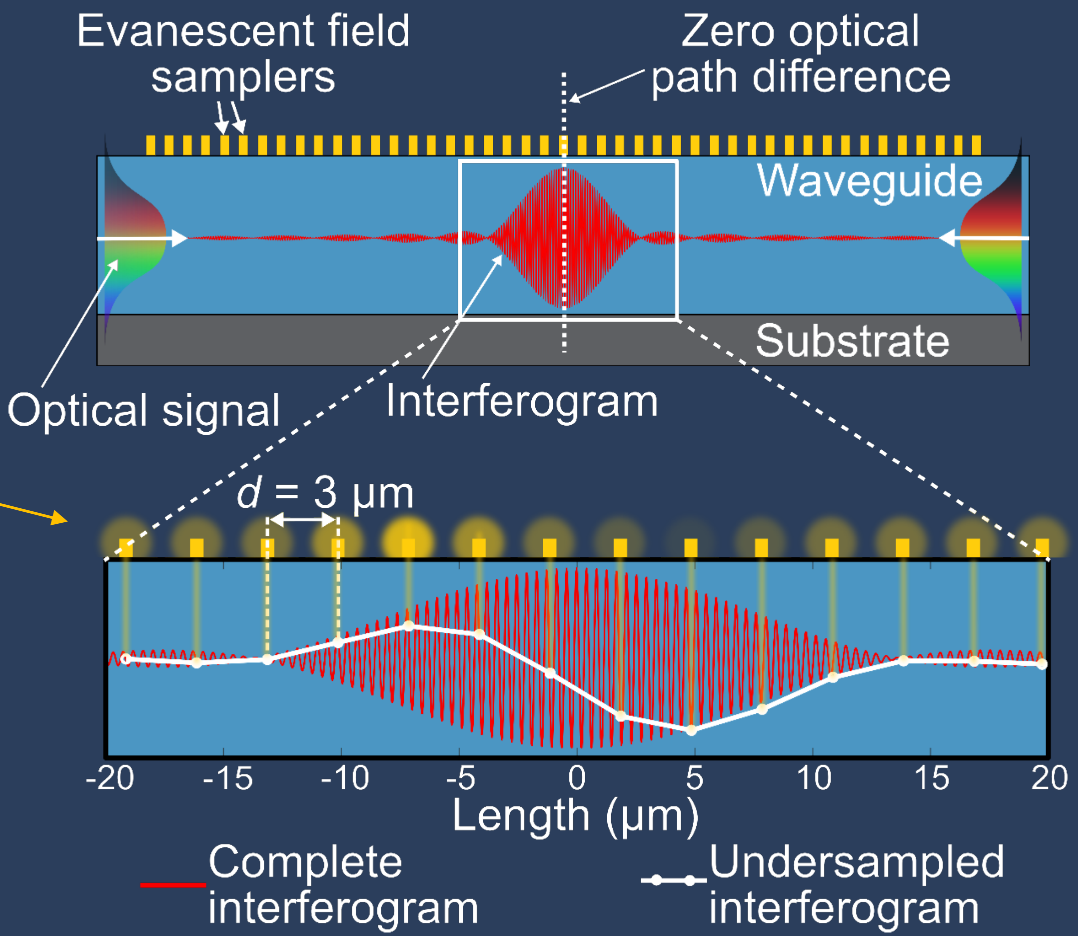




D. Pohl, …, R. Grange, *Nature Photonics 14* (1) **2020**

Undersampling

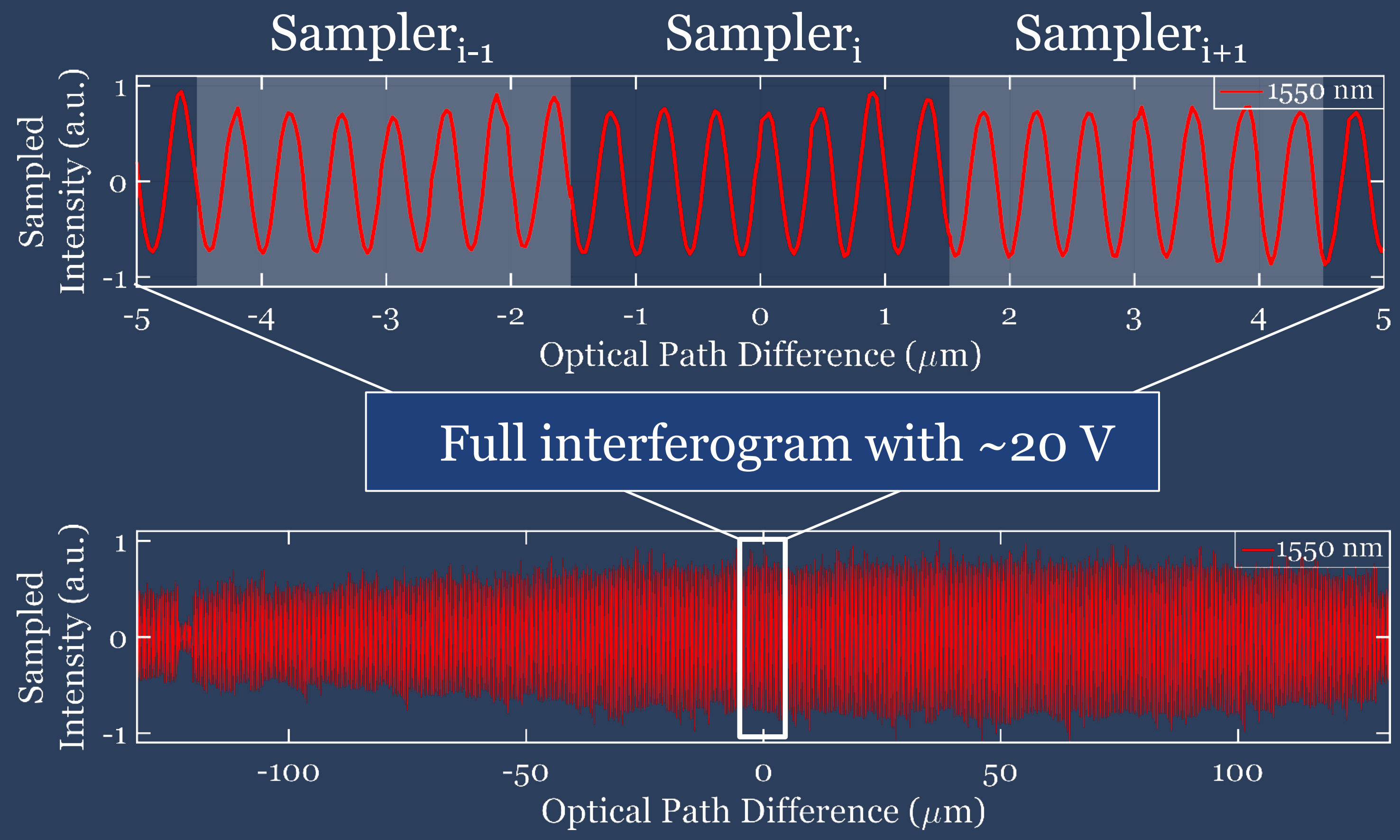
77 Samplers × **3 µm Pitch** = 231 µm

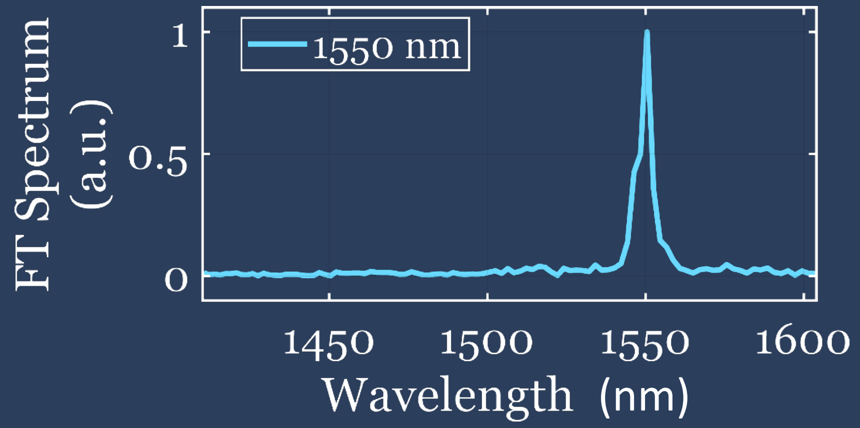


Standing-wave: $\Lambda_{SW} = \dfrac{\lambda}{2\, n_{eff}}$ ~420 nm at 1550 nm

Nyquist-Shannon criterion: $d_{max} \leq \dfrac{1}{2}\Lambda_{SW}$ ~ **210 nm**

Electro-optic sampling: monochromatic

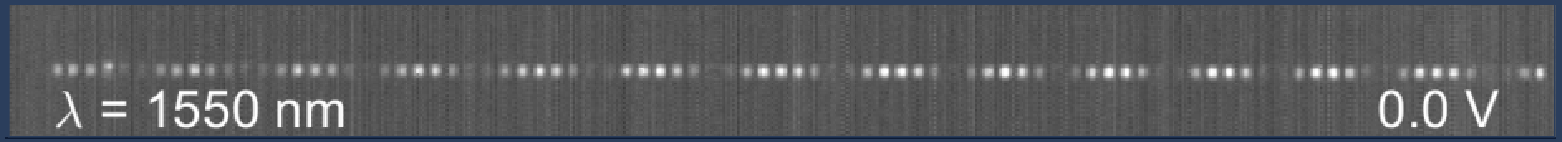




Resolution:

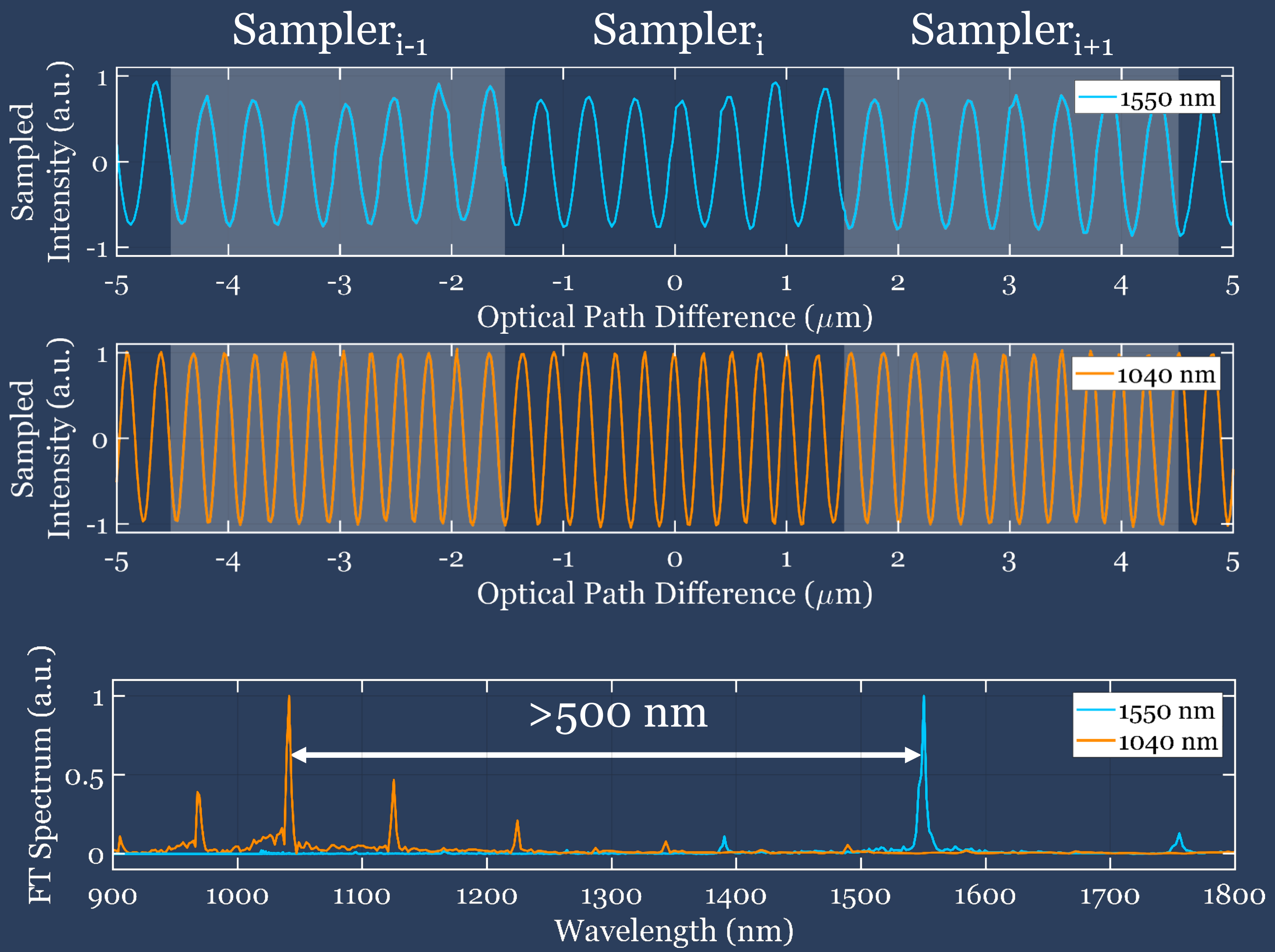
$$R = \frac{\lambda}{\Delta\lambda} = \frac{n_{eff}\,L}{\lambda} \sim 290$$

$\Delta\lambda$ ~ 6 nm at λ = 1550 nm



87 Samplers × 3 µm Pitch = 261 µm

Electro-optic sampling: bandwidth



Retrieval of the standing wave without undersampling

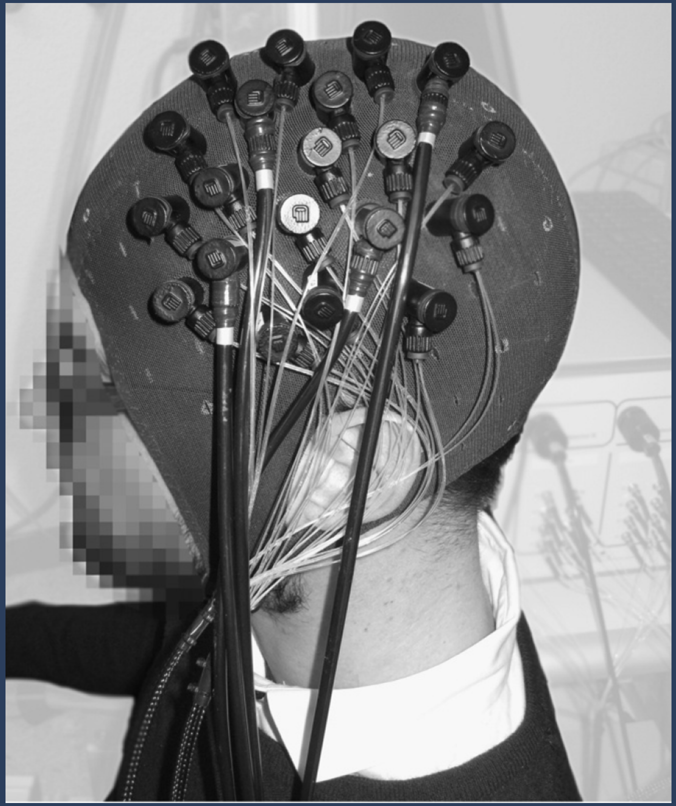
>500 nm bandwidth with <20 V

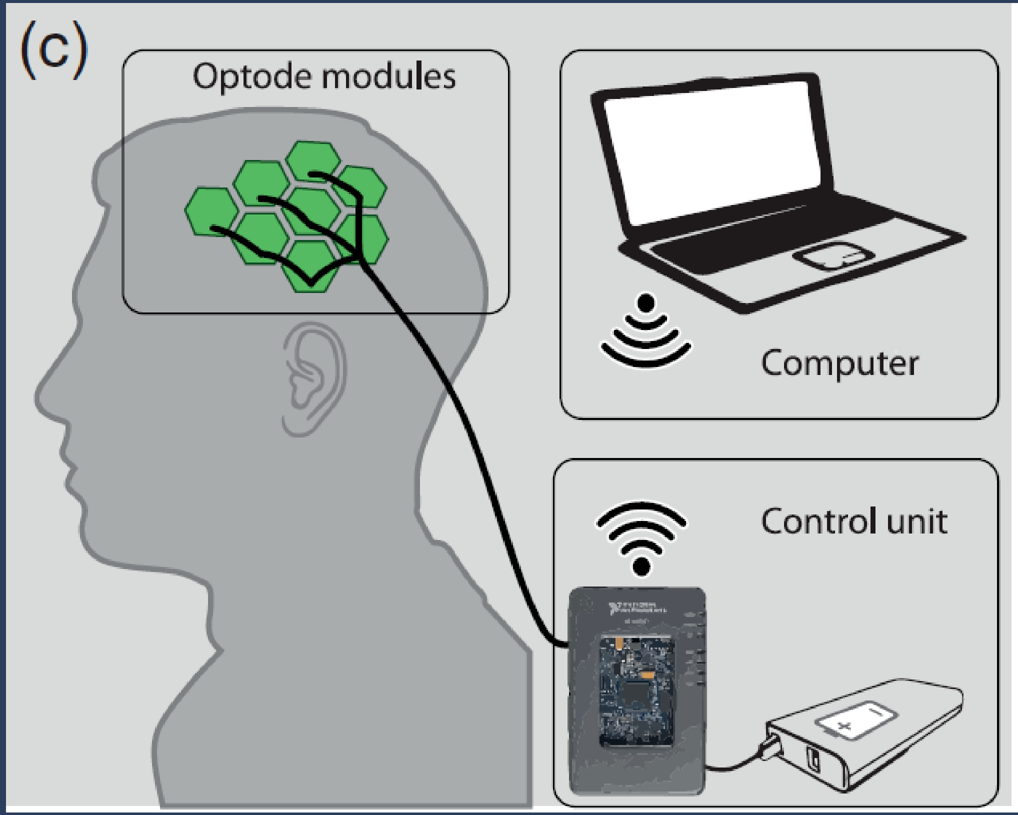
Basically limited by single-mode condition of the waveguide (λ_{SM} ~ 1000-1800 nm)

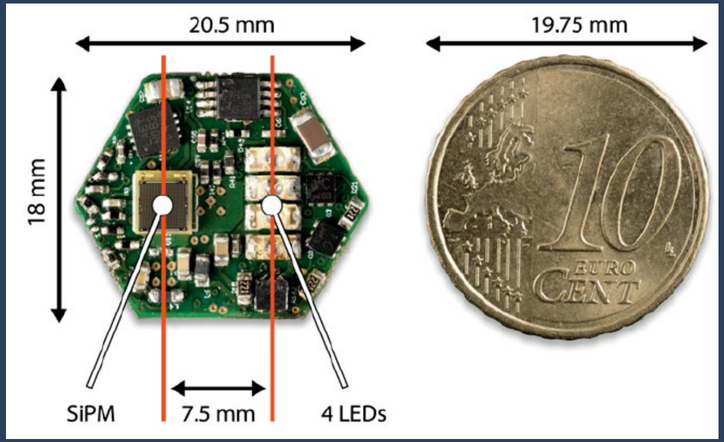
D. Pohl, …, R. Grange, *Nature Photonics 14* (1) **2020**

Applications of the broadband integrated spectrometer

Non-invasive measurement of human brain activity







Wyser et al. Neurophotonics 4(4), 041413, 2017

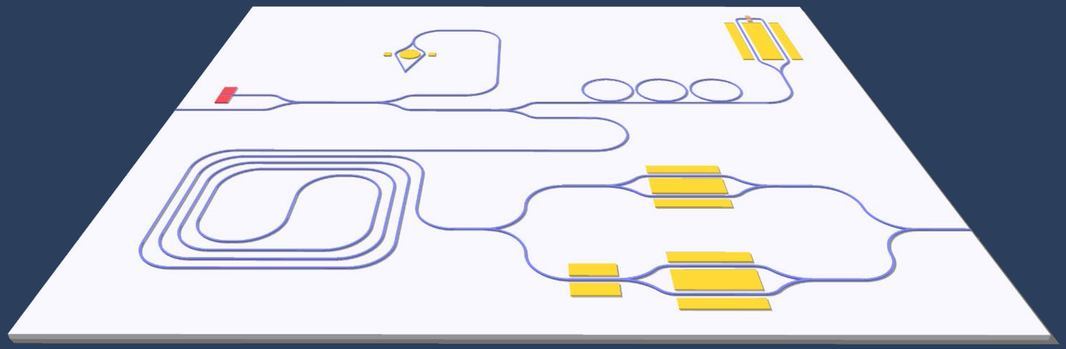
Biomedical Optics Research Laboratory, University Hospital Zurich

Outlook

Lithium niobate platform

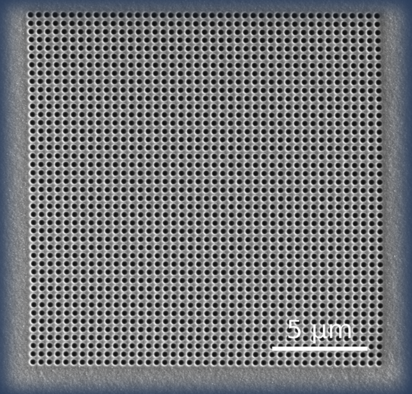
Communication:

Electro-optic modulators
Frequency combs (WDM)

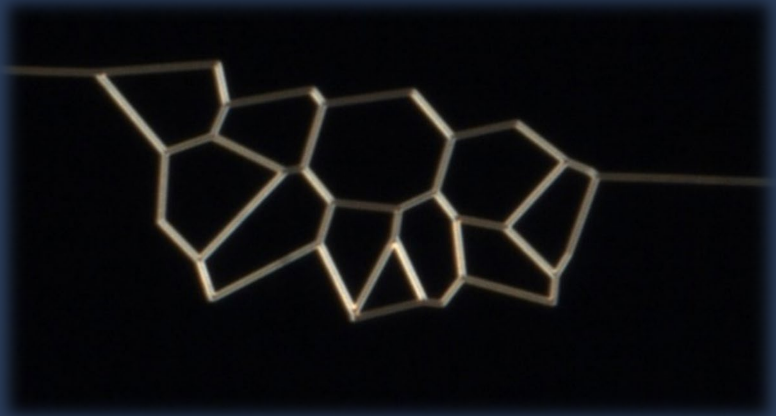


Sensing:

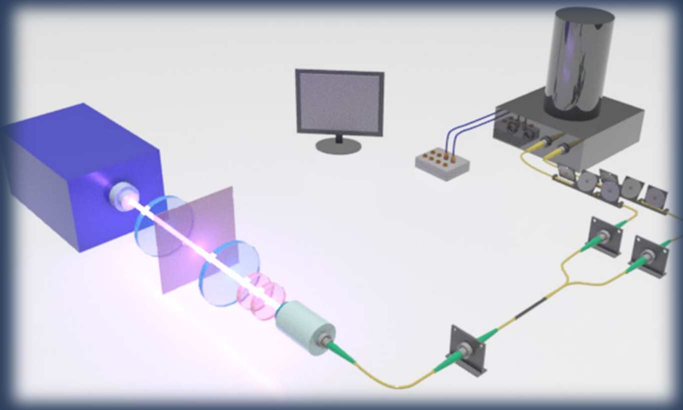
Dual comb spectroscopy
Beam forming (LIDAR)



Bottom up metasurface



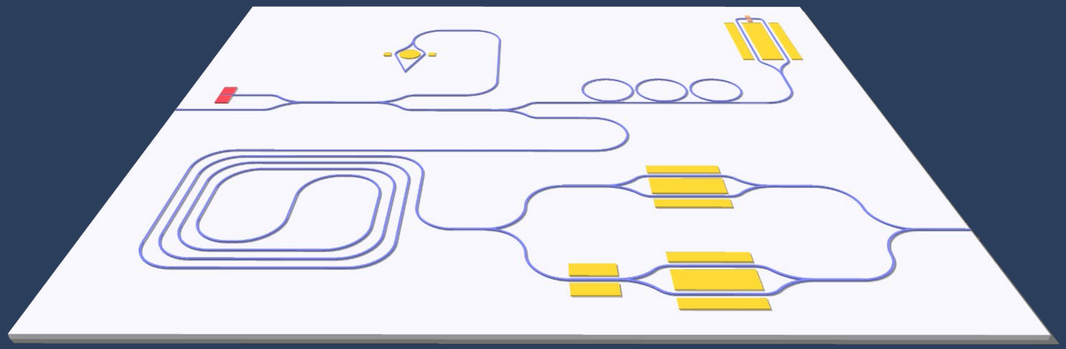
Random network



SPDC

Outlook

Lithium niobate platform



Communication:

Electro-optic modulators

Frequency combs (WDM)

Sensing:

Dual comb spectroscopy

Beam forming (LIDAR)

…

ong.ethz.ch

grange@phys.ethz.ch