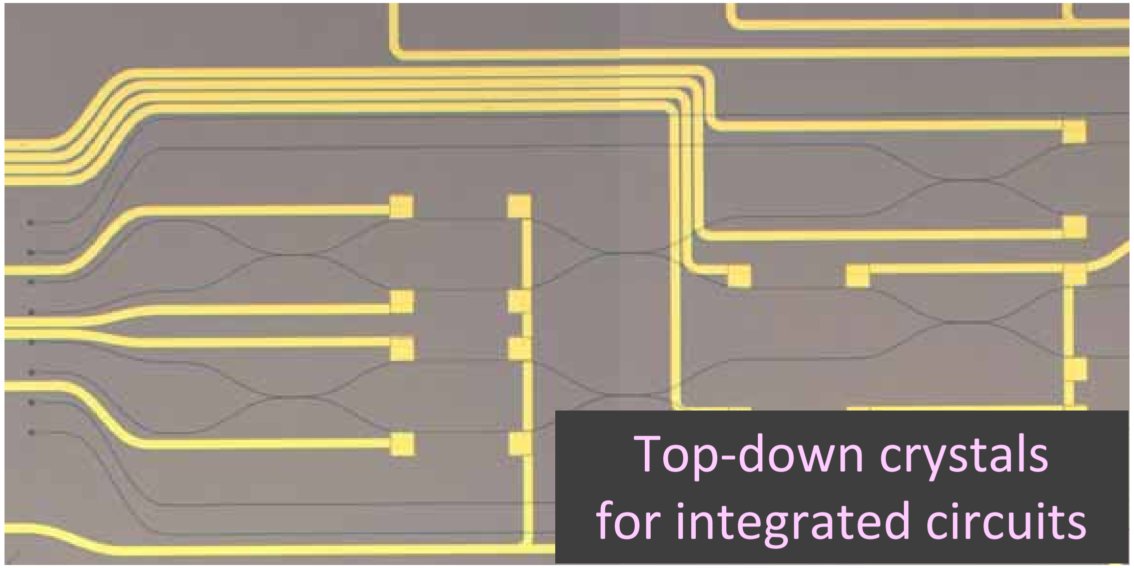
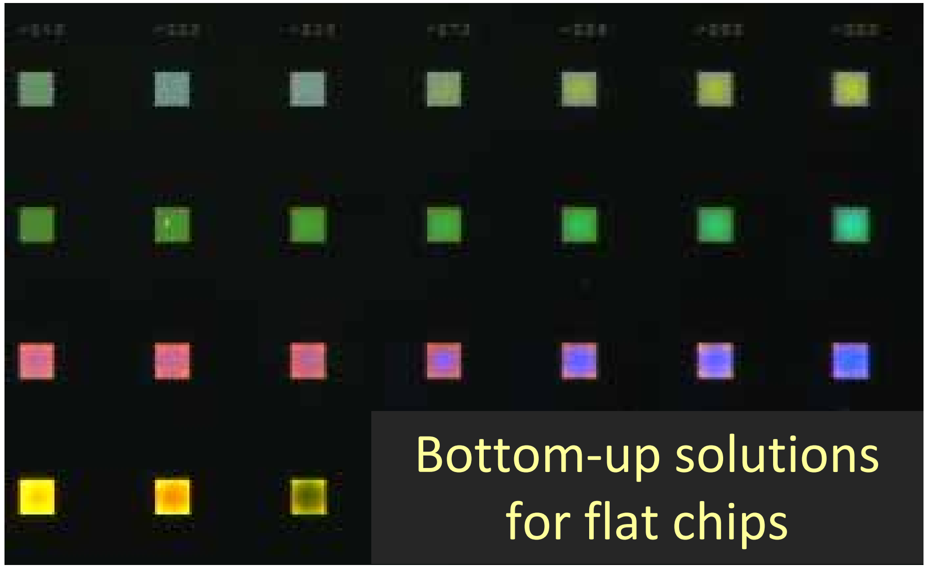
# Thin Film Lithium Niobate for Modulators and Beyond

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September 2025

# The Optical Nanomaterial Group ONG


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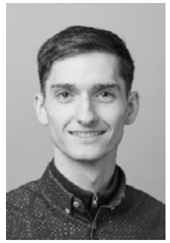
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Virginia Falcone


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Alessandro Palermo

## Funding

Swiss National Science Foundation

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SPACE INNOVATION

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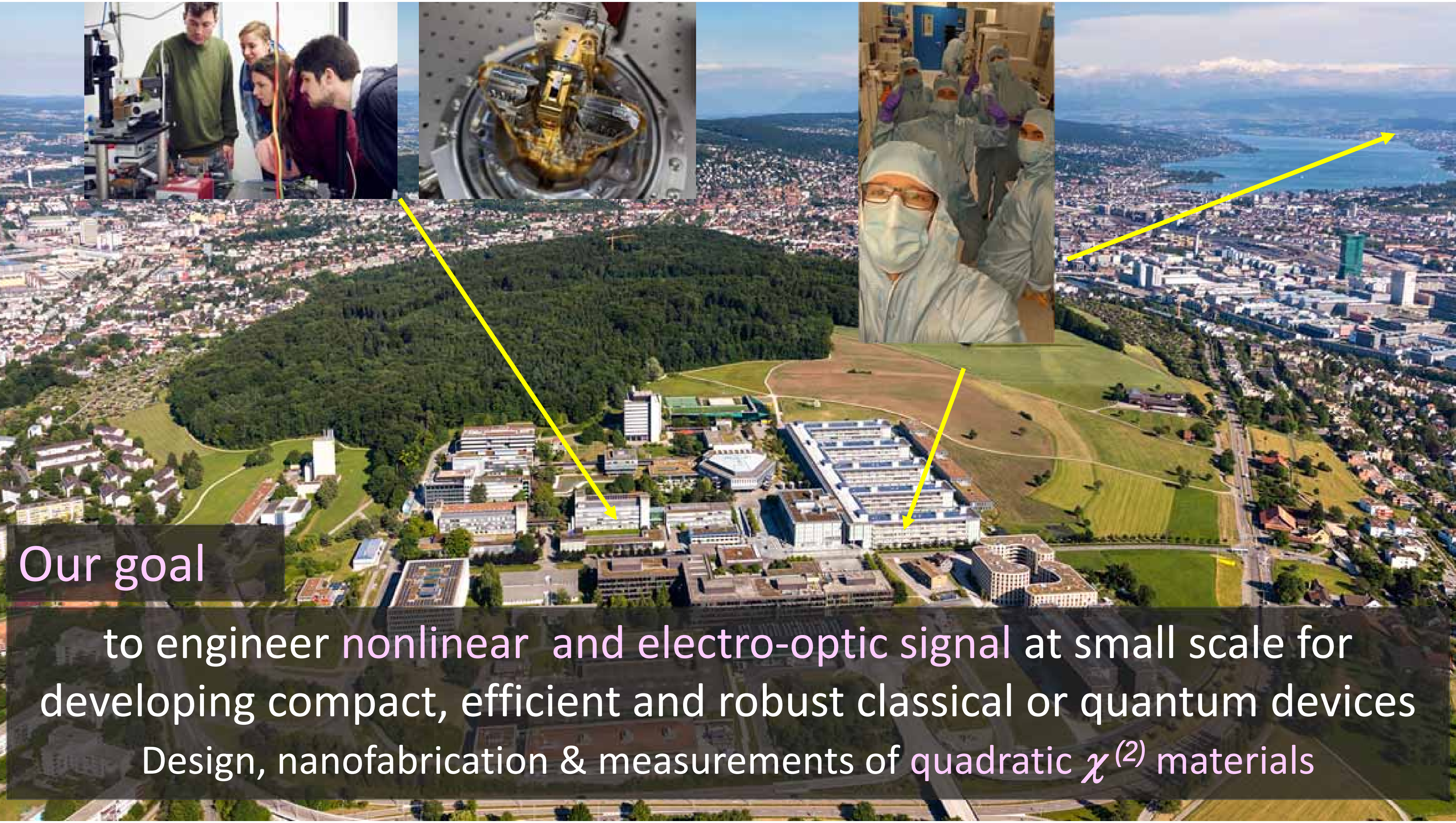
MARIE CURIE ACTIONS

erc European Research Council

## Startups

VERSICS
HIGH-SPEED PHOTONIC SOLUTIONS



# Our goal

to engineer nonlinear and electro-optic signal at small scale for developing compact, efficient and robust classical or quantum devices

Design, nanofabrication & measurements of quadratic $\chi^{(2)}$ materials

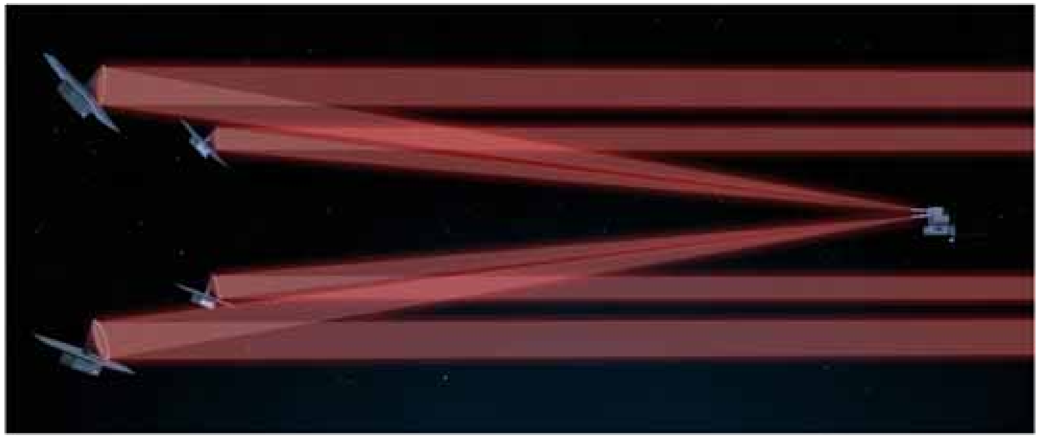
# Why miniaturizing quadratic optical materials?

©ESA/ATG medialab

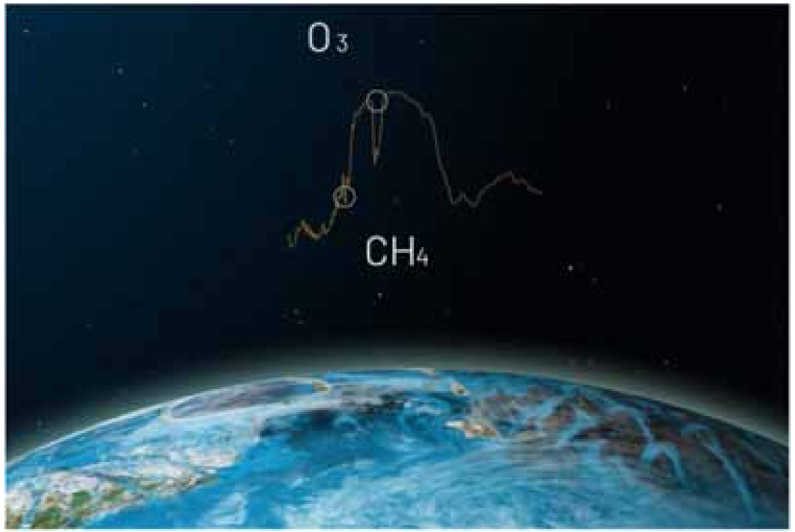
**For data transport**

- Small footprint
- High yield
- Low power
- Fast speed
- Low losses
- Light weight
- Robust

# Why miniaturizing quadratic optical materials?



**LIFE** mission: **L**arge **I**nterferometer **F**or **E**xoplanets




**For data transport**
**For sensing**

- Small footprint
- High yield
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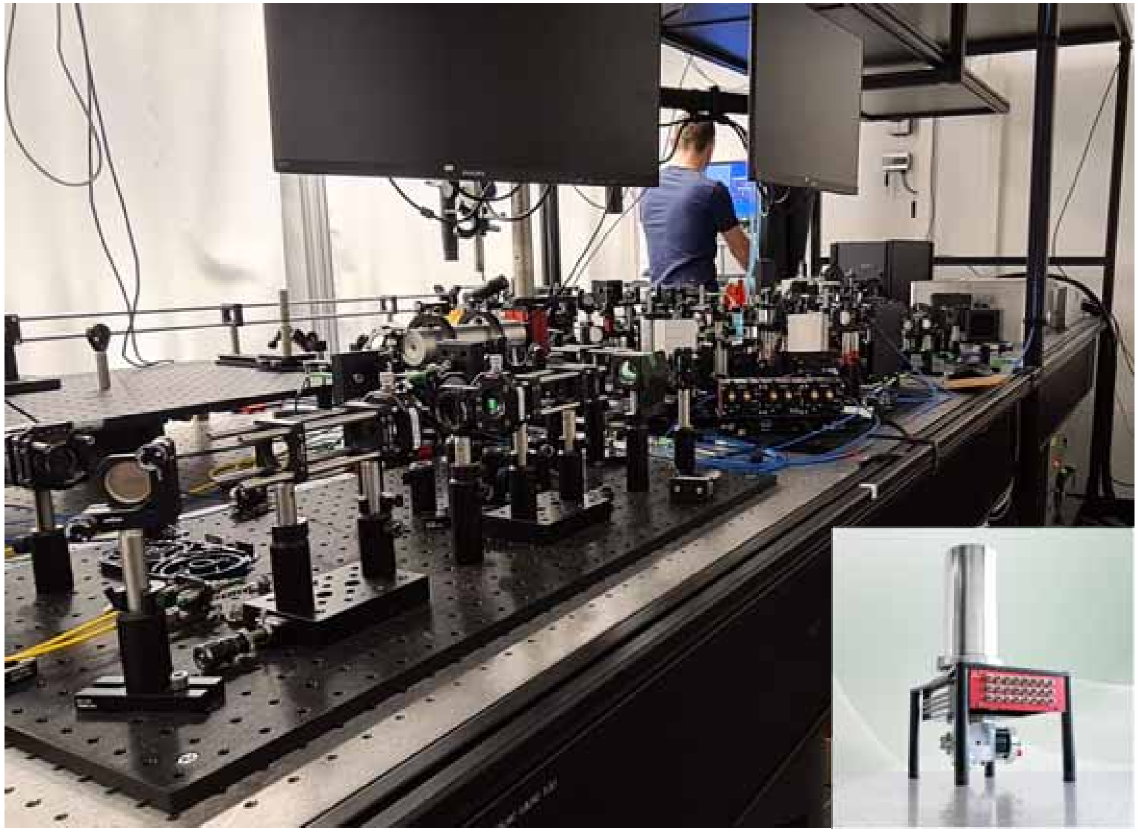
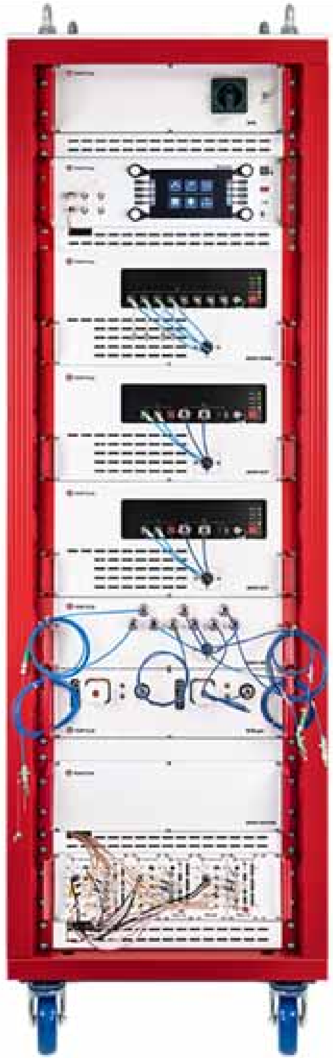
- Light weight
- Robust
- Broadband

# Why miniaturizing quadratic optical materials?



Bulk and free space optics

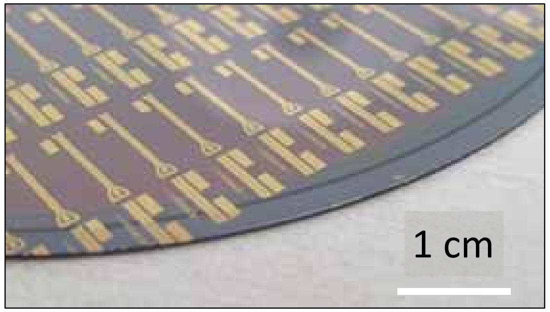


**For data transport**
**For sensing**
**For computing**

- Small footprint
- High yield
- Low power
- Fast speed
- Low losses
- Light weight
- Robust
- Broadband

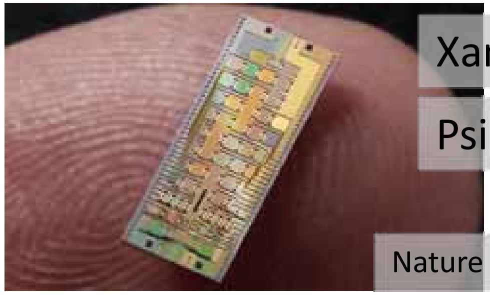
# State of the art

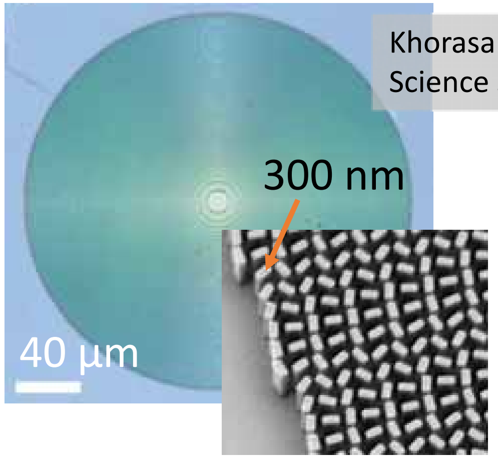
## Material platform?




generate, route, process, modulate and detect light on a chip

## Current material

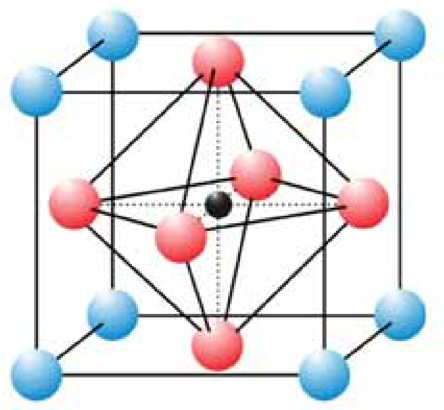


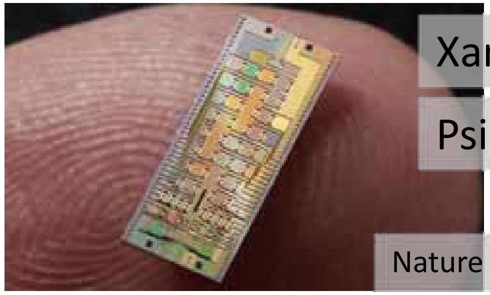

Silicon (Si), silicon nitride (SiN) or $TiO_2$

# State of the art

Centrosymmetric



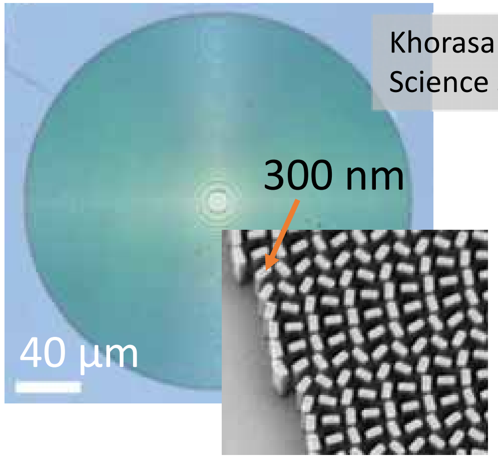
## Current material



Xanadu

Psi Quantum

Nature 638/641 2025

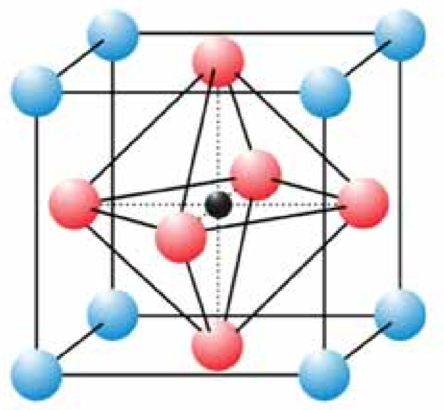



Khorasaninejad et al, Science 352, 2016

Silicon (Si), silicon nitride (SiN) or $TiO_2$

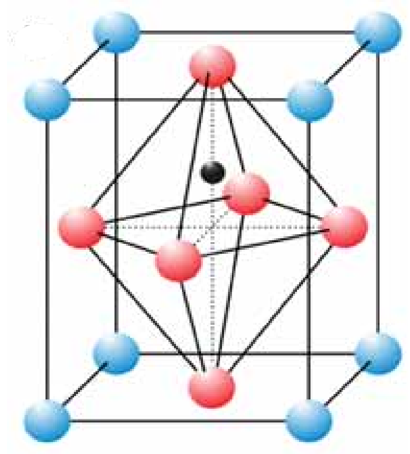
# State of the art

Centrosymmetric



Silicon (Si), silicon nitride (SiN) or $TiO_2$

Non-Centrosymmetric



$SiO_2$ (crystalline quartz)

Gallium arsenide (GaAs)

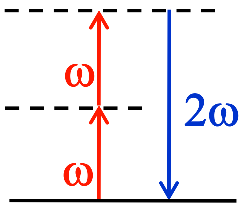
Barium titanate ($BaTiO_3$)

Lithium niobate ($LiNbO_3$)

# Nonlinear and quantum optics

## Missing properties of Si, SiN, $TiO_2$

### Frequency conversion



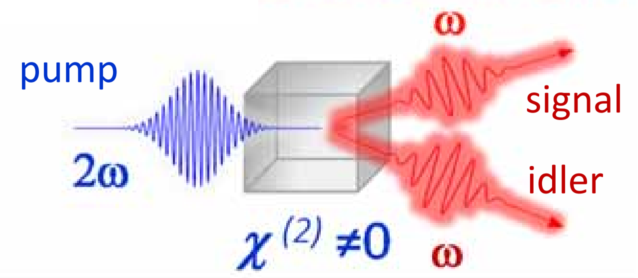

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \ldots$$

### Electro-optic control

1 0 1 0 1 0 0 1 0 1 1 0 1 0 1 0

$\Delta n \sim E$

### Entangled photon generation (SPDC)



# Nonlinear and quantum optics

## Missing properties of Si, SiN, $TiO_2$

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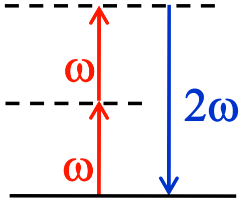


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### Electro-optic control


$$\Delta n \sim E$$

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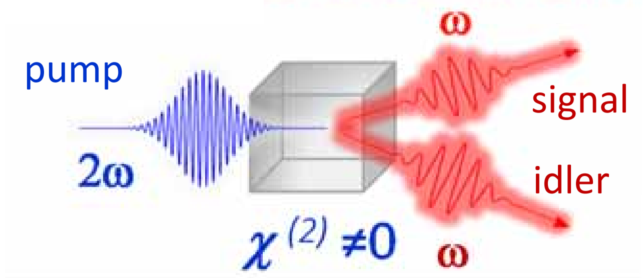
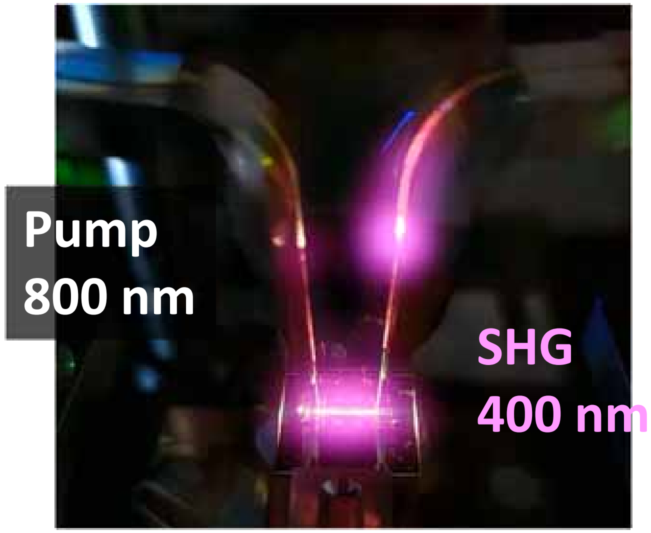
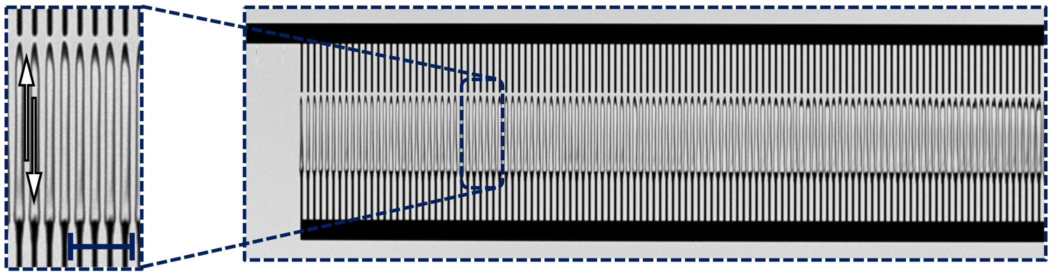



### Second-Harmonic Generation (SHG)



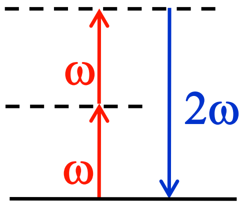

Up to 6 mm long PPLN waveguide



# Nonlinear and quantum optics

## Missing properties of Si, SiN, $TiO_2$

### Frequency conversion



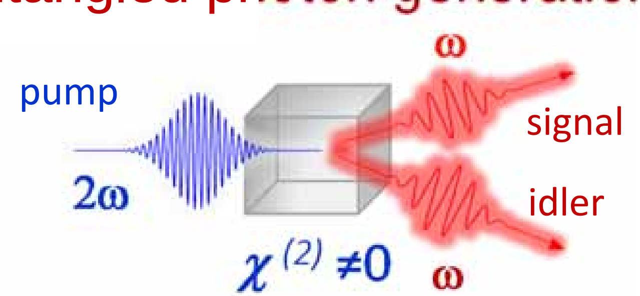

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \dots$$

### Pockels effect


### Electro-optic control


$$\Delta n \sim E$$

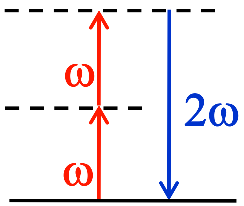
### Entangled photon generation (SPDC)



# Nonlinear and quantum optics

## Missing properties of Si, SiN, $TiO_2$

### Frequency conversion

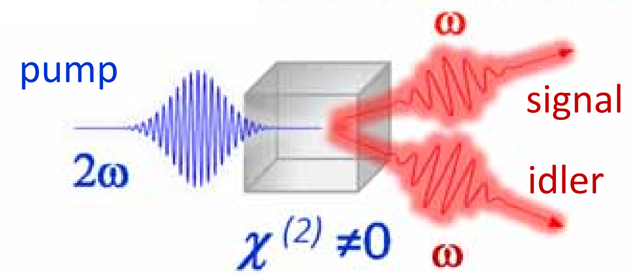



$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \dots$$

### Electro-optic control

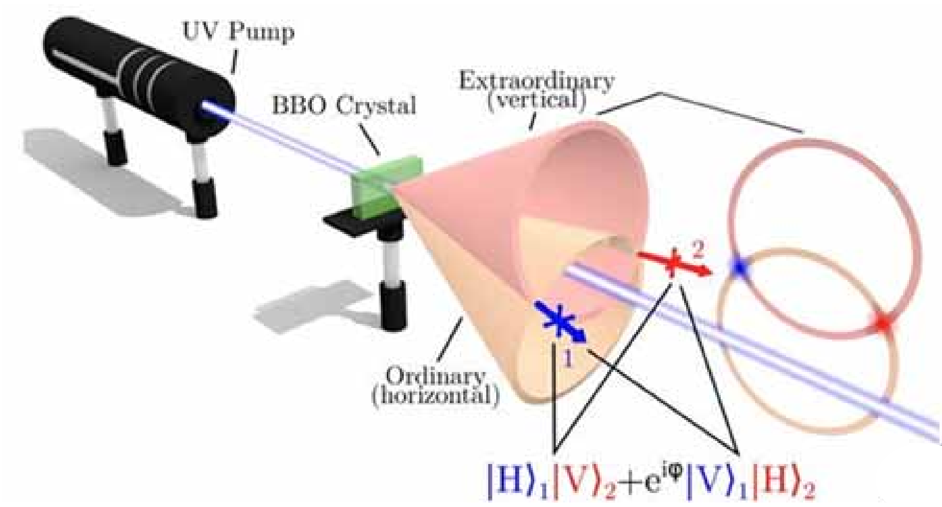

$$\Delta n \sim E$$

### Entangled photon generation




Spontaneous Parametric Down Conversion (SPDC)

Source for quantum cryptography, teleportation, …



# Why $BaTiO_3$ and $LiNbO_3$ in particular?

**λ Frequency conversion λ/2**

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \ldots$$

Lithium niobate ($LiNbO_3$)

$$d_{il} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{31} & -d_{22} \\ -d_{22} & d_{22} & 0 & d_{31} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}$$

Barium titanate ($BaTiO_3$)

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{pmatrix}$$

| Material | $d_{ij}$ (pm/V) |
|---|---|
| **Silicon** | **0** |
| **$SiO_2$** | **0.335** |
| **$BaTiO_3$** | **6.8 to 17** |
| **$LiNbO_3$** | **6 to 34** |
| **GaAs** | **134 to 256** |

# Why $BaTiO_3$ and $LiNbO_3$ in particular?

**λ Frequency conversion λ/2**

**Electro-optic effect**

1 0 1 0 1 0 0 1 0 1 1 0 1 0 1 0

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| **GaAs** | **134 to 256** | **1-2** |

del Rocio Camacho-Morales et al., Adv. Phot, 3, 2021

Santiago-Cruz, et al. *Science*, *377*, 2022

Lithium niobate ($LiNbO_3$)

$$r_{lk} = \begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix}$$

Barium titanate ($BaTiO_3$)

$$r_{ij} = \begin{pmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{23} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{51} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



*D. A. Kleinman et al., Phys. Rev. 126, 1977*

# Why $BaTiO_3$ and $LiNbO_3$ in particular?

**λ Frequency conversion λ/2**

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**Frequency conversion ($d_{ij}$) vs Electro-optic ($r_{ij}$) coefficients**

$LiNbO_3$ $d_{ij} \approx r_{ij}$

$BaTiO_3$ $d_{ij} < r_{ij}$

GaAs $d_{ij} > r_{ij}$

**Electro-optic effect**

1 0 1 0 1 0 0 1 0 1 1 0 1 0 1 0

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Barium titanate ($BaTiO_3$)

$$r_{ij} = \begin{pmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{23} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{51} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

# Why $BaTiO_3$ and $LiNbO_3$ in particular?

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Barium titanate ($BaTiO_3$)

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{pmatrix}$$

- ✓ Large band gap: 3-4 eV
  Transparency: UV to MIR
- ✓ Refractive index > 2
  Light confinement
- ✓ Very inert
  solid but **hard to process**

**Frequency conversion ($d_{ij}$) vs Electro-optic ($r_{ij}$) coefficients**

$LiNbO_3$ $d_{ij} \approx r_{ij}$
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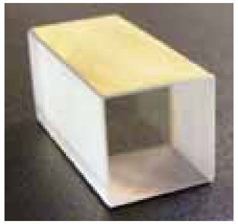
# How small quadratic $\chi^{(2)}$ materials can be?

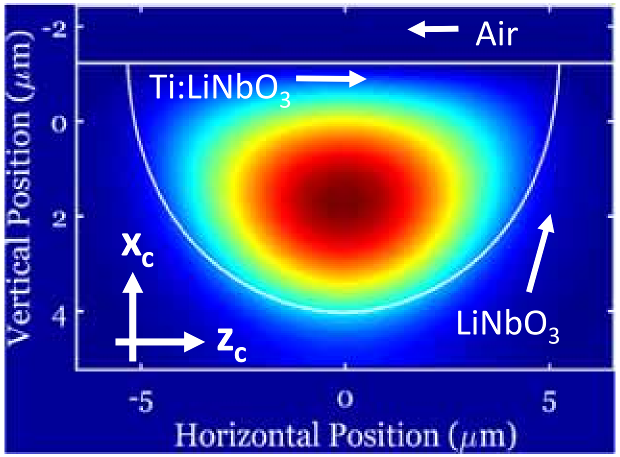
## Top-down fabrication

### Bulk crystals

Bulk mm

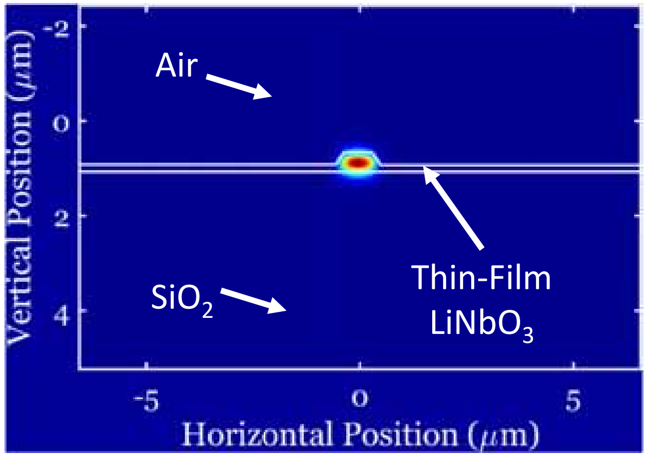


Wafer 500 µm



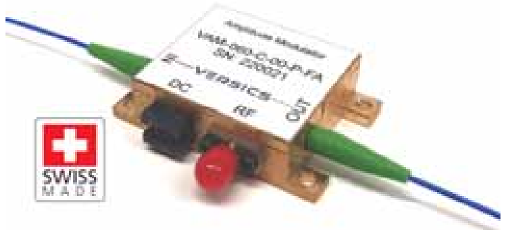

**Mode Area > 30 µm²**

40 Gbit/s




**Mode Area < 1 µm²**

100 Gbit/s

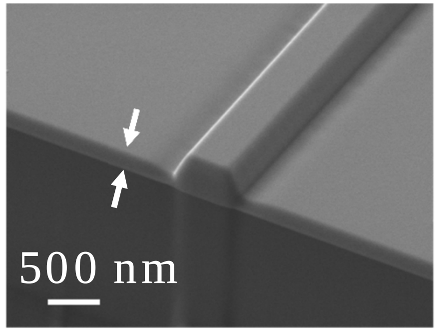


Thin film < 1 µm

$LiNbO_3$ (<800 nm)

$SiO_2$ (2-5 µm)

Si (0.4-1 mm)
Sapphire
$LiNbO_3$

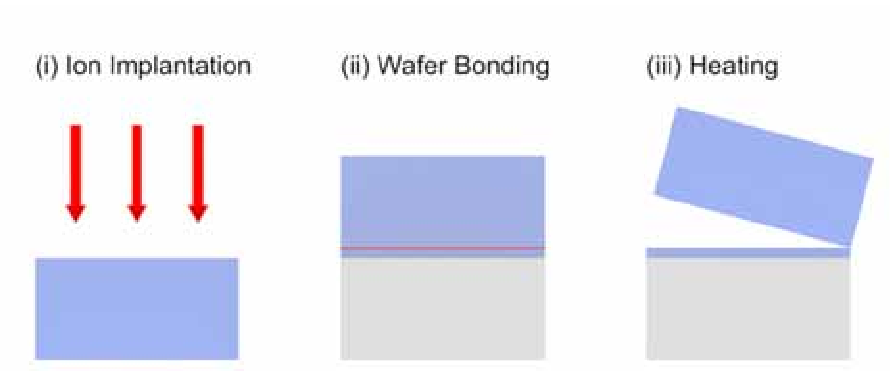



Rabiei, P.; Gunter, P. *Applied Physics Letters* **2004**, *85* (20).

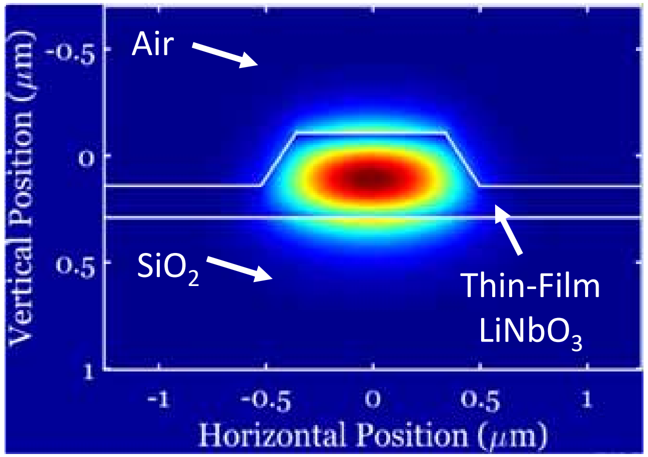
# Demanding top-down fabrication process

**Challenge 1 :** Thin film substrate

## Ion slicing

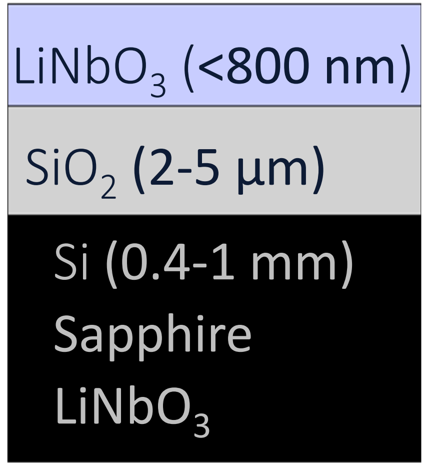


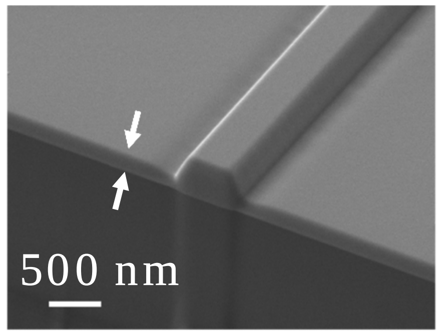

LNOI PIC Platform, H2020
https://www.project-elena.eu/




**Mode Area < 1 µm²**

Thin film < 1 µm

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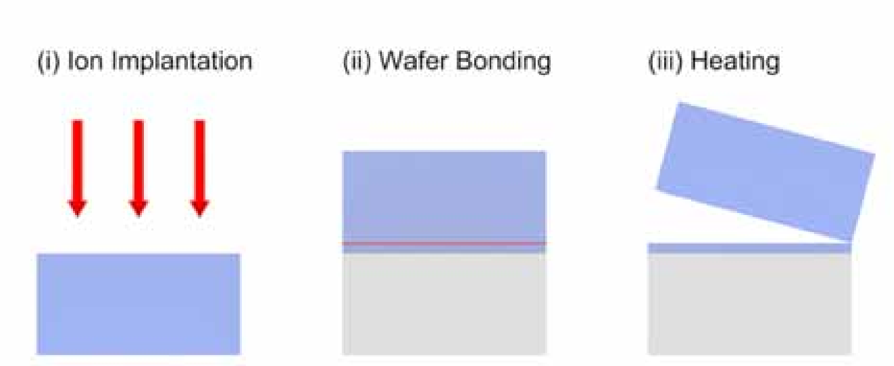
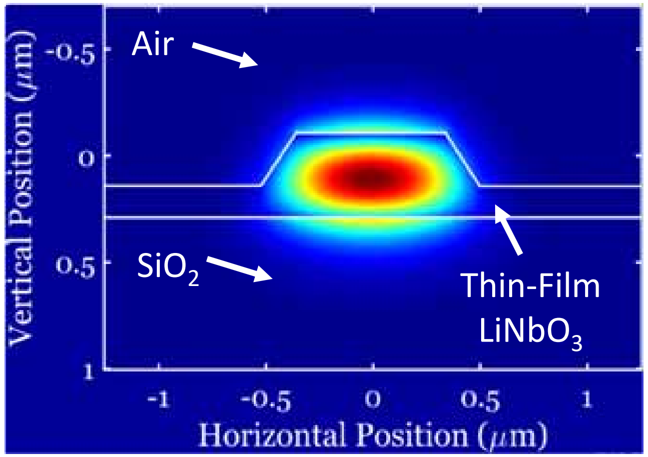


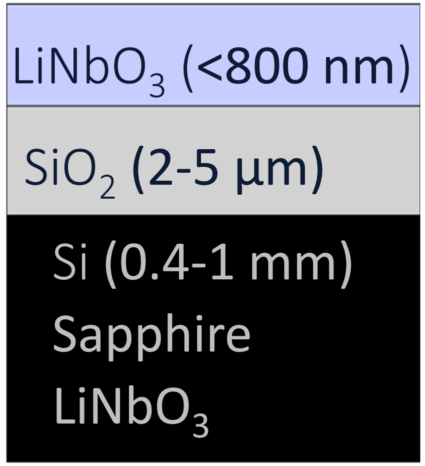

LNOI PIC Platform, H2020
https://www.project-elena.eu/

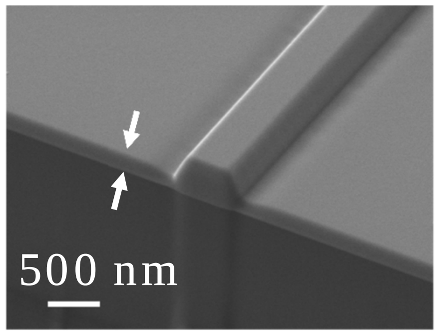
Smart cut fab at CEA-LETI, France




**Mode Area < 1 μm²**

Thin film < 1 μm



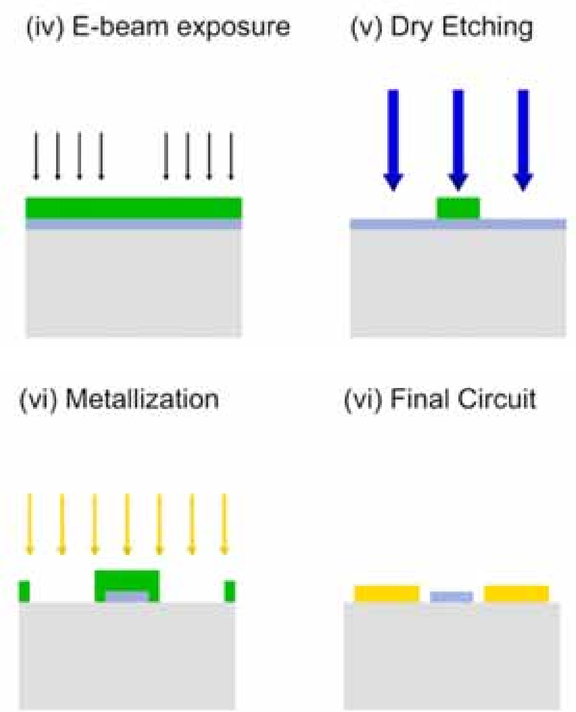

Maeder, Weigand, & Grange. Photoniques, 116 (2022)

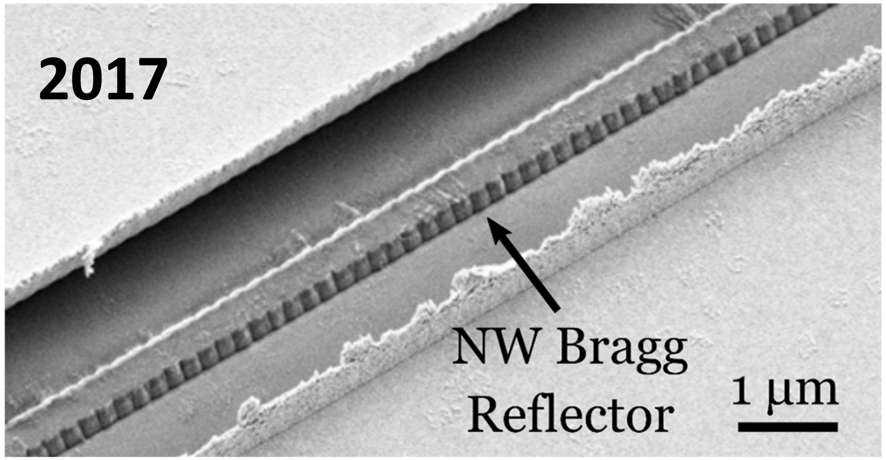
Rabiei, P.; Gunter, P. *Applied Physics Letters* **2004**, *85* (20).

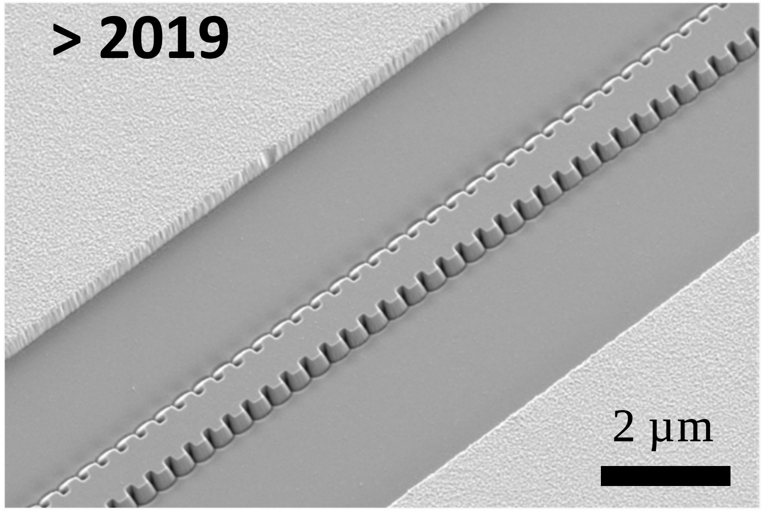
# Demanding top-down fabrication process

**Challenge 1 :** Thin film substrate

**Challenge 2 :** Film patterning



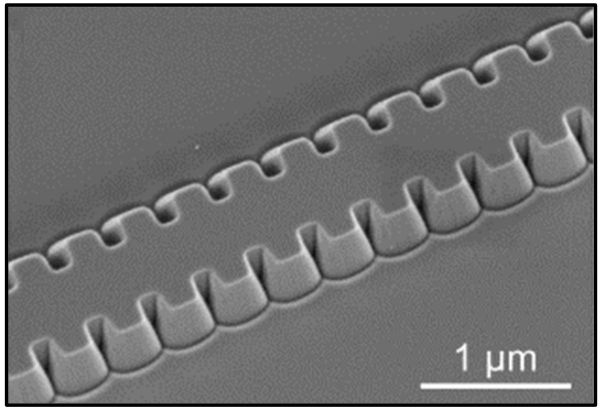



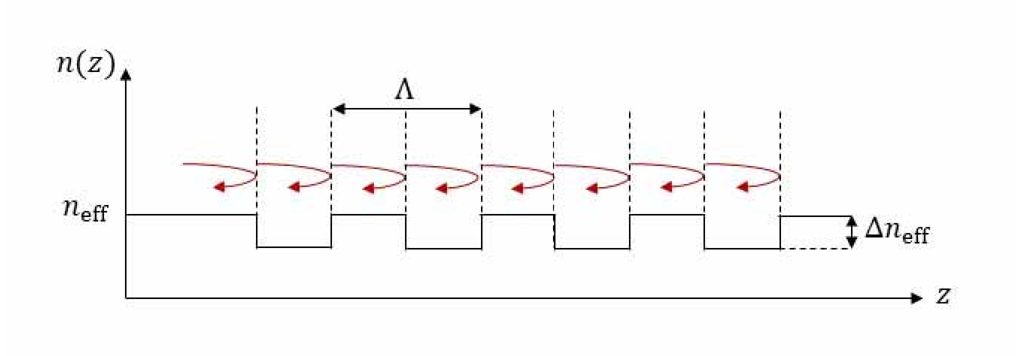

Maeder, Weigand, & Grange. Photoniques, 116 (2022)

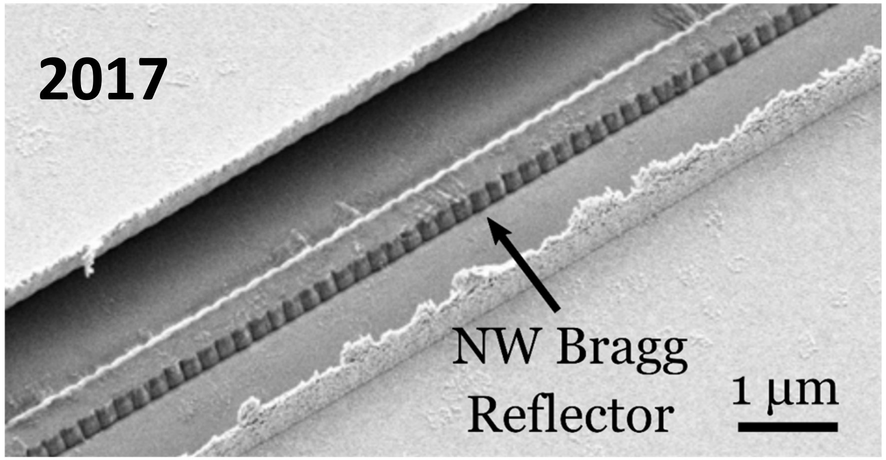
# Demanding top-down fabrication process

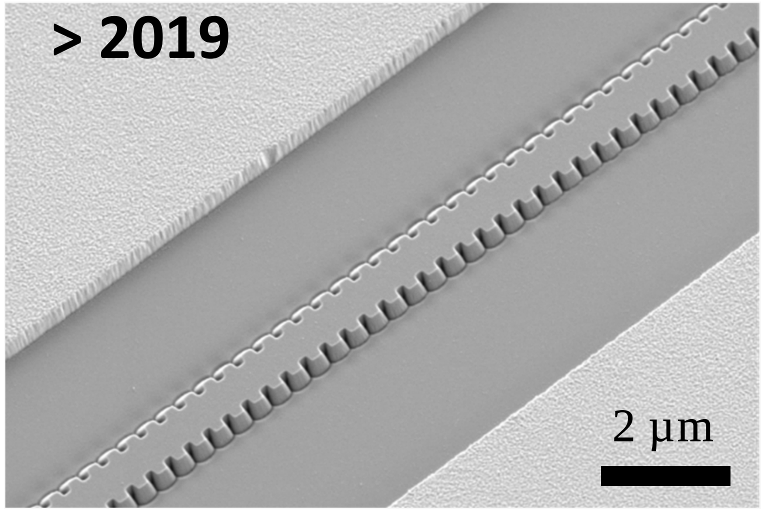
## Distributed Bragg reflector

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



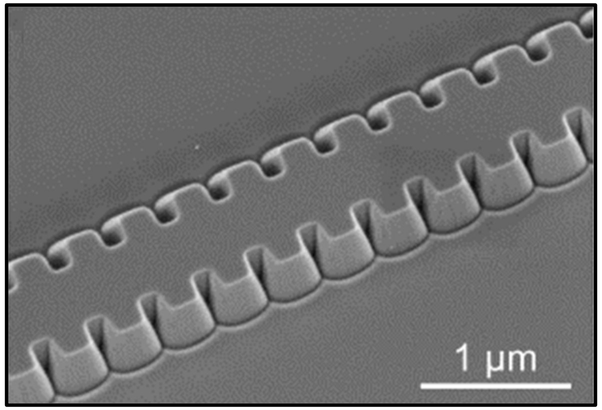



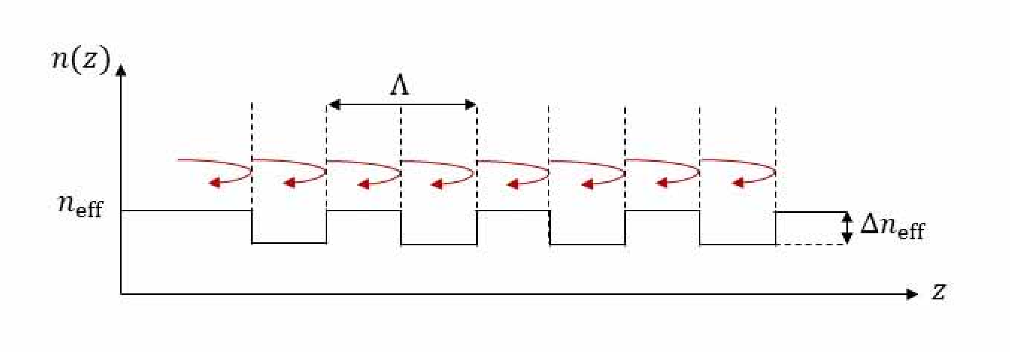



# Concept of the Bragg Modulator

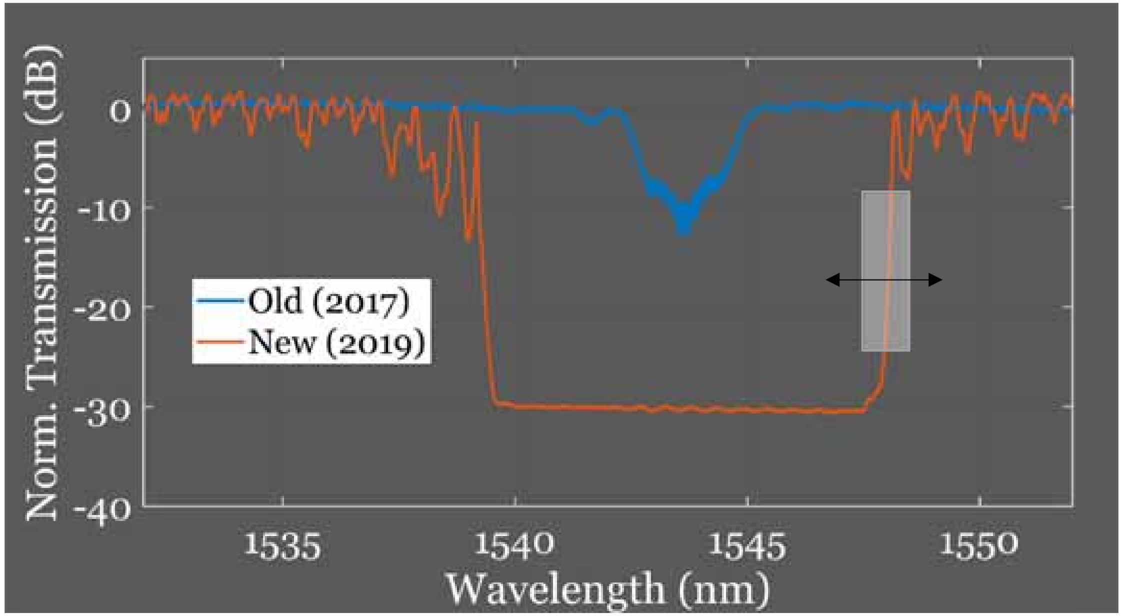
## Distributed Bragg reflector

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



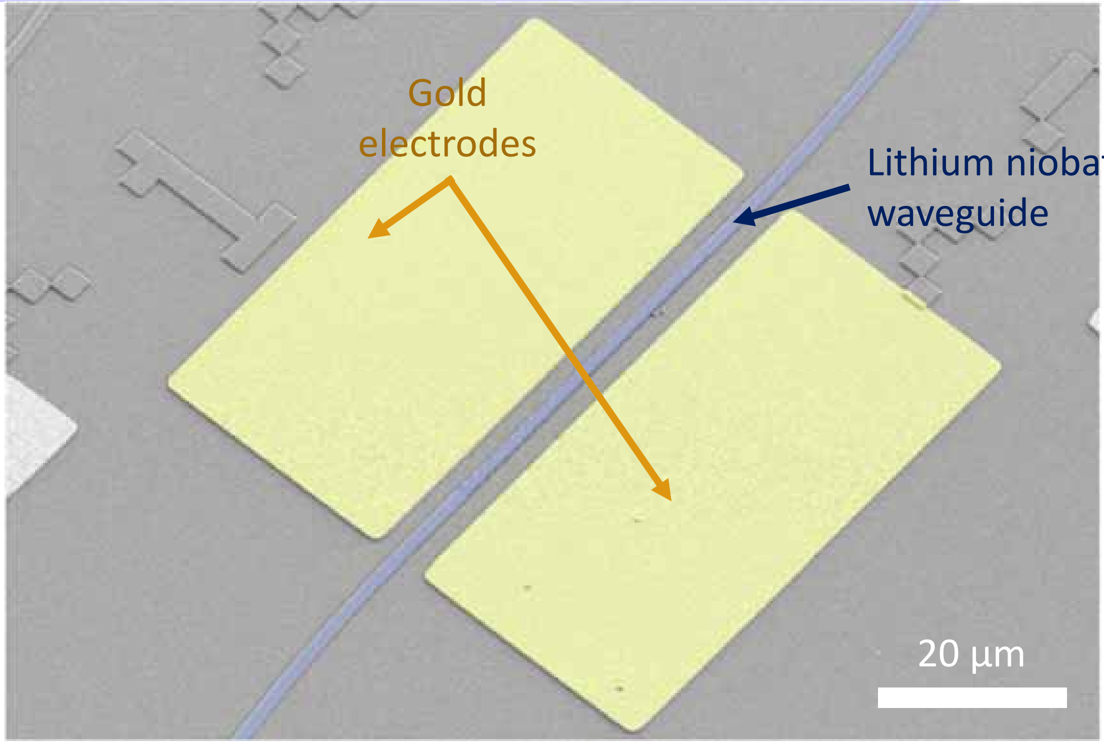

## Stop band in transmission



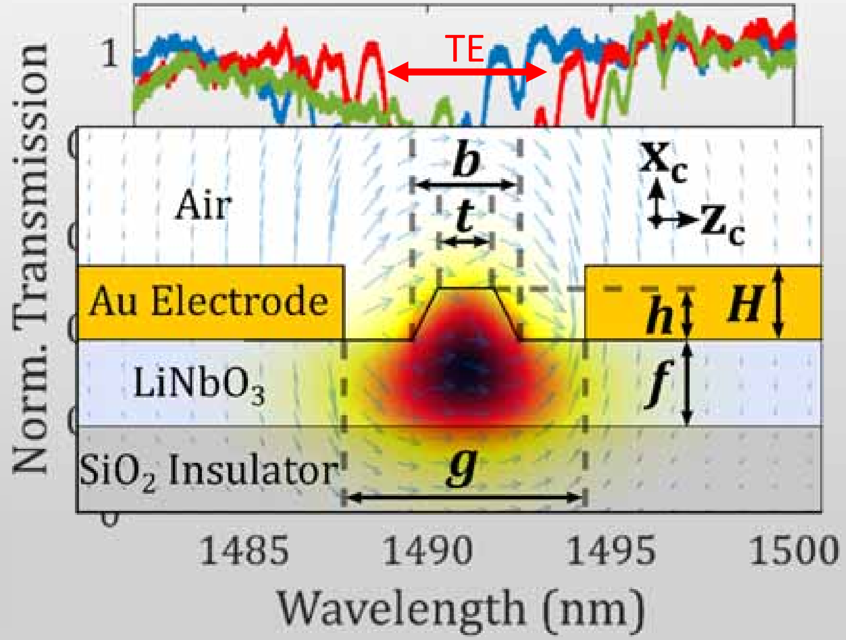
# Concept of the Bragg Modulator

## Electro-optic modulation

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

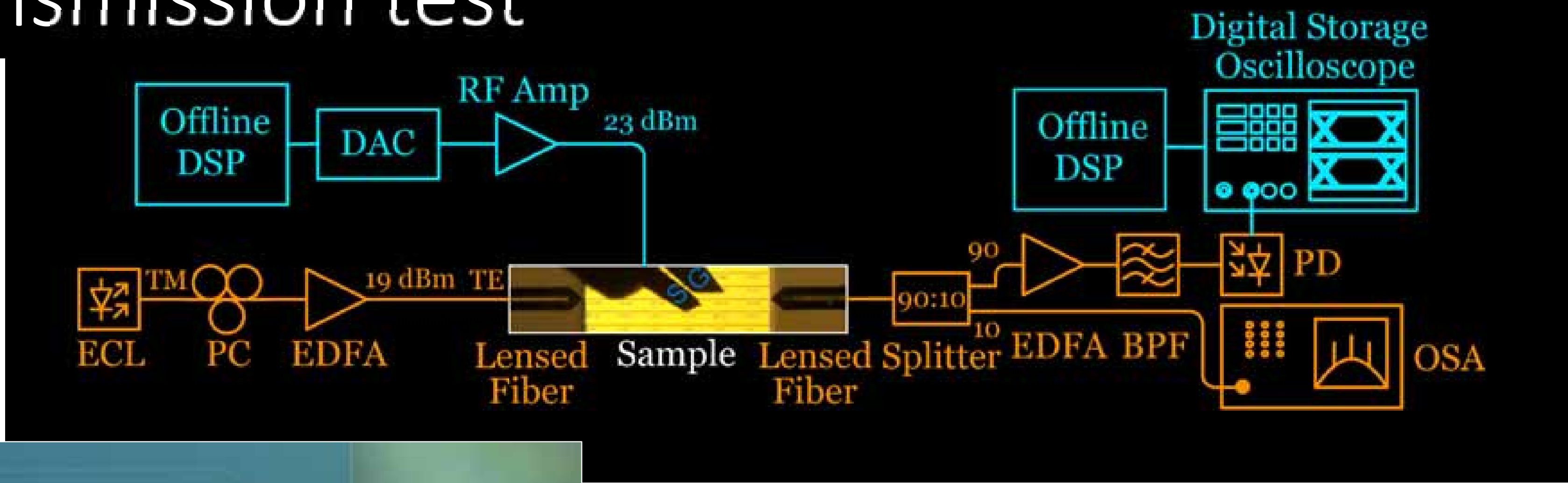


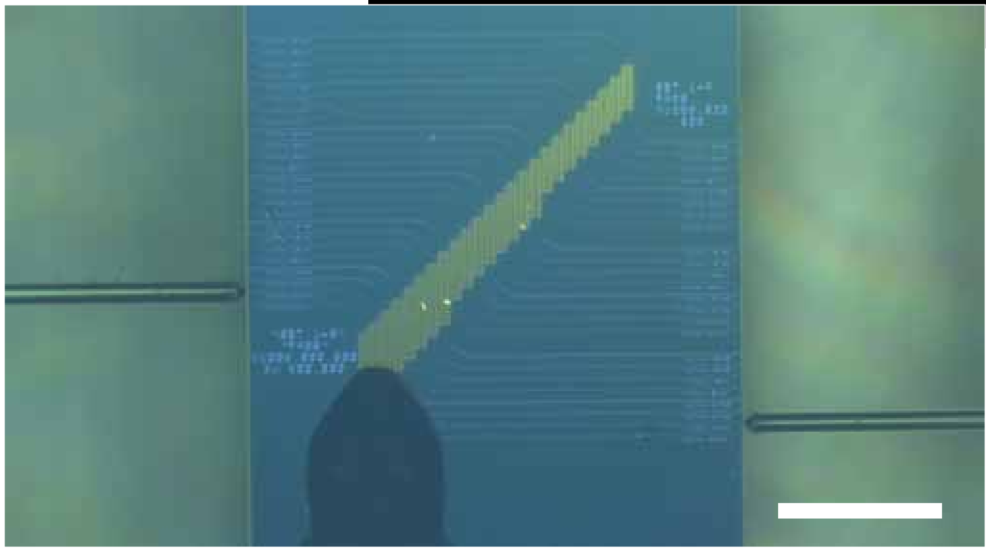

**Wavelength tuning of the stop band**




M. Reig Escalé et al., Optics Letters 43(7), 1515-1518, **2018**

# Data transmission test

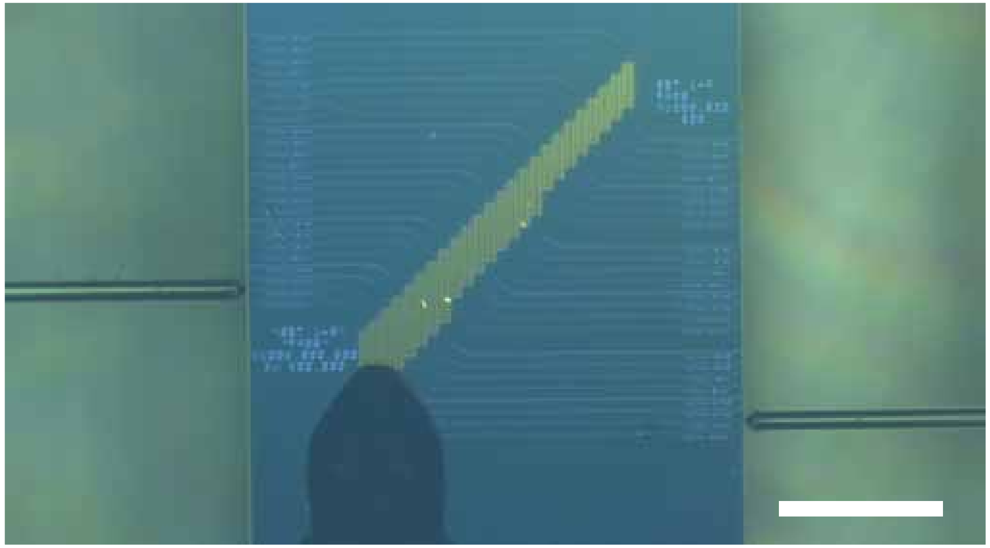


Collaboration with Juerg Leuthold, ETH, D-ITET

# Data transmission test

100 Gbit/s with 10×500 μm² footprint

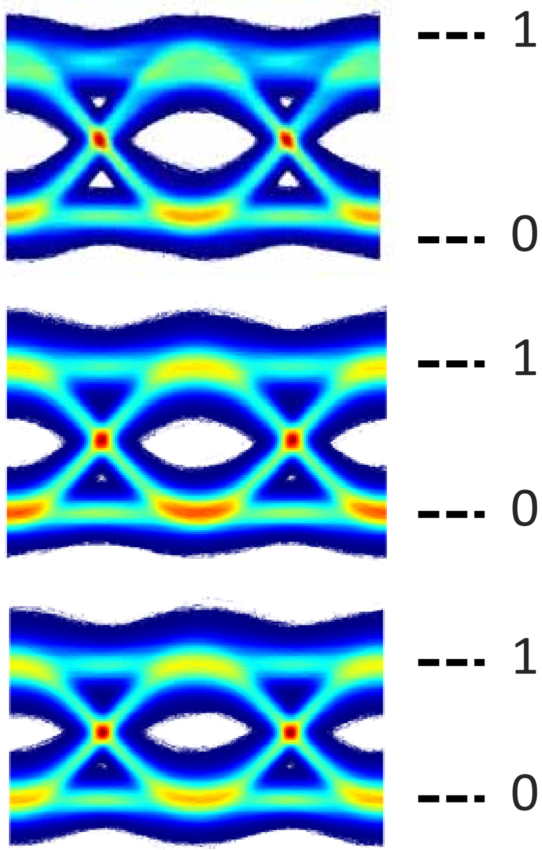


Collaboration with Juerg Leuthold, ETH, D-ITET

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

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

100 Gbit/s
BER = 1.3×$10^{-5}$



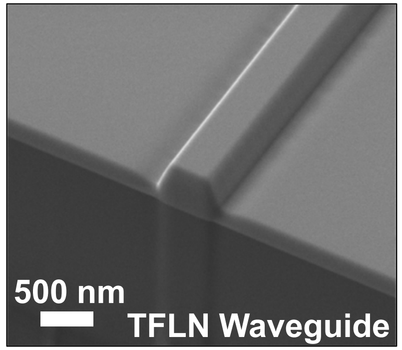

$V_{pp}$ = 8.9 V at 50 Ω < Hard Decision threshold

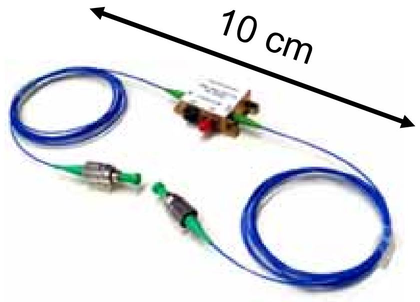
# Vertically Integrated Device Manufacturer

VERSICS
HIGH-SPEED PHOTONIC SOLUTIONS

## Design
Simulation, Process Design Kit (PDK)

## Microfabrication
Test Design Kit (TDK), Process Control

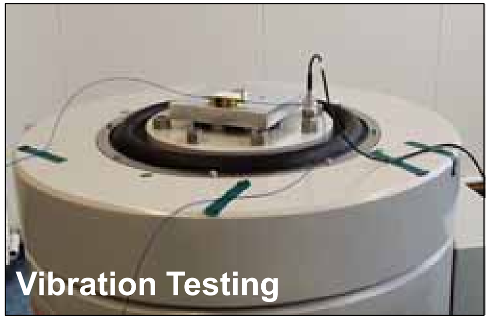




## Assembly
Assembly Design Kit (ADK)


## Reliability
Telcordia GR-468-CORE

### Versics Reliability Labs





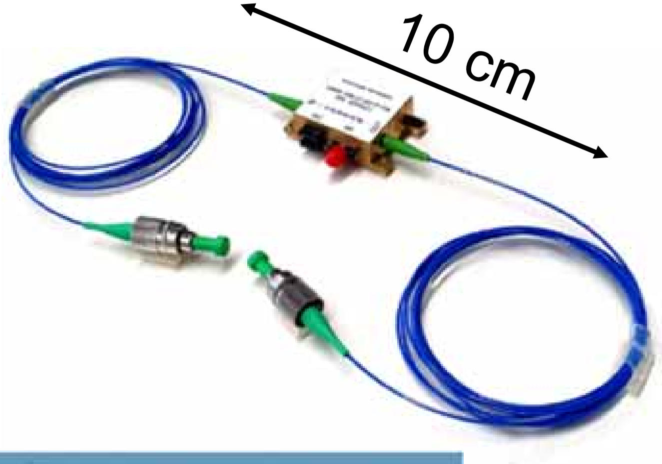

## Sales

IAS ACCREDITED Management Systems Certification Body

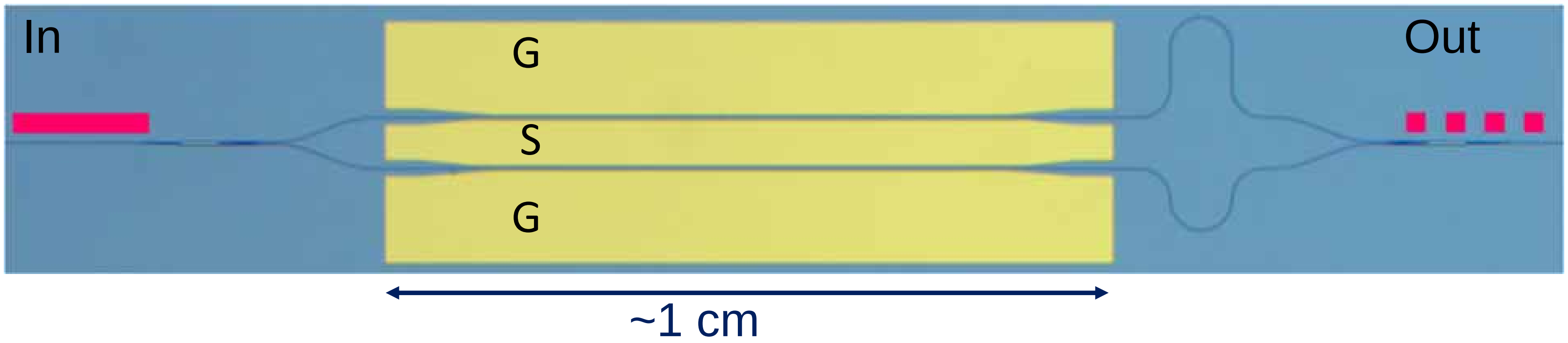
ISO 9001:2015
ISO 14001:2015

# Example: Versics Amplitude Modulator (VAM)

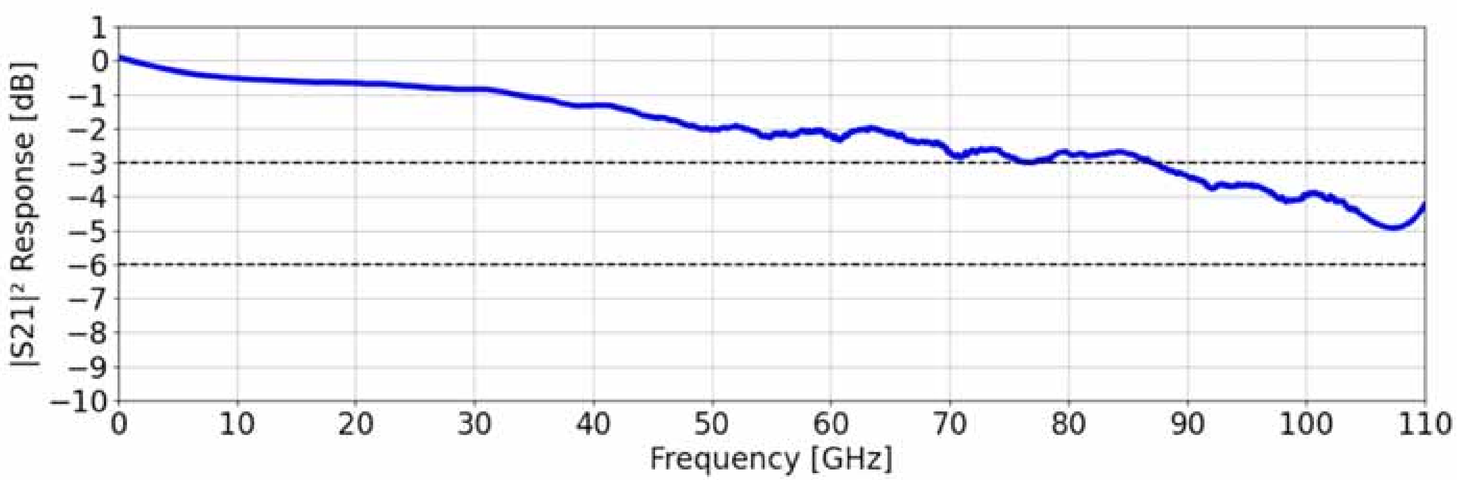
- Assembled modulator
- Ideal for Test & Measurement applications




**Mach-Zehnder configuration (example)**



# Example: Versics Amplitude Modulator (VAM)



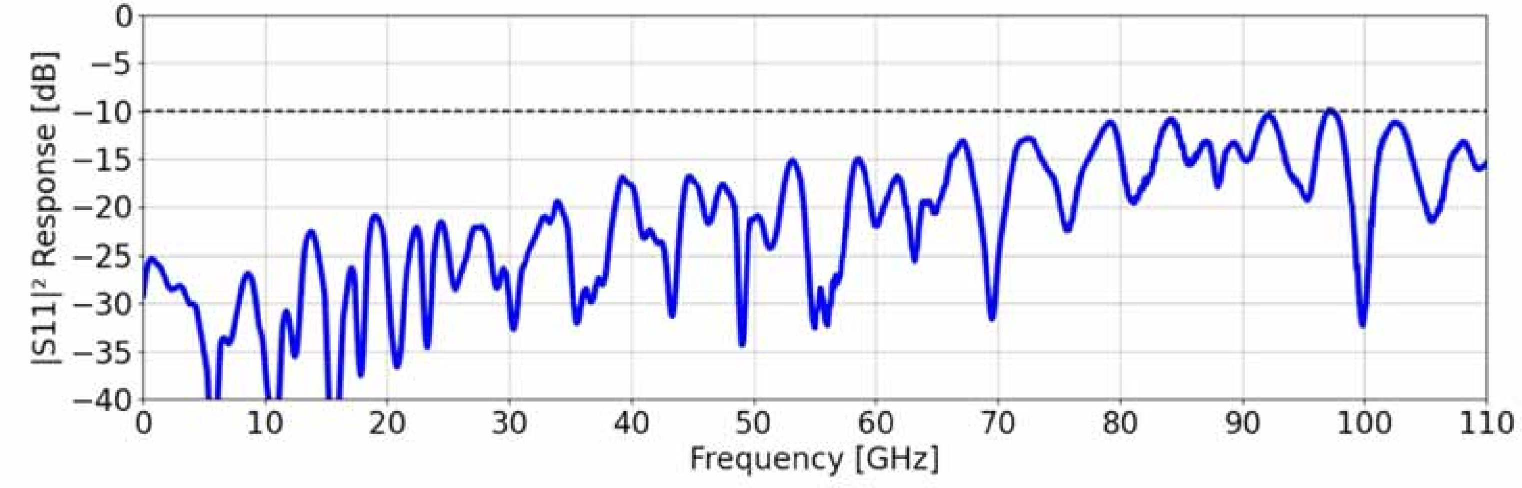

**85 GHz with 1.8V in O-band and 2.1V in C-band**

| | | | |
|---|---|---|---|
| **Electrical** | Electro-optic bandwidth | $S_{21}$ | >85 GHz |
| | Electrical reflection coefficient | $S_{11}$ | <10 dB |
| | $V_{\pi}$RF @ 200 kHz (O / C-band) | $V_{\pi\text{-RF200kHz}}$ | 1.8 V / 2.1 V |
| | RF input impedance | $Z_{\text{in-RF}}$ | 50 Ω |
| | RF connector | W-type | 1.00 mm |

marc.reig@versics.com

VERSICS HIGH-SPEED PHOTONIC SOLUTIONS

# Example: Versics Amplitude Modulator (VAM)




- for the data center and telecom market, Versics AG is currently developing the 1.6T and 3.2T PICs

- only PICs to be integrated within transceivers by customers

**Optical**

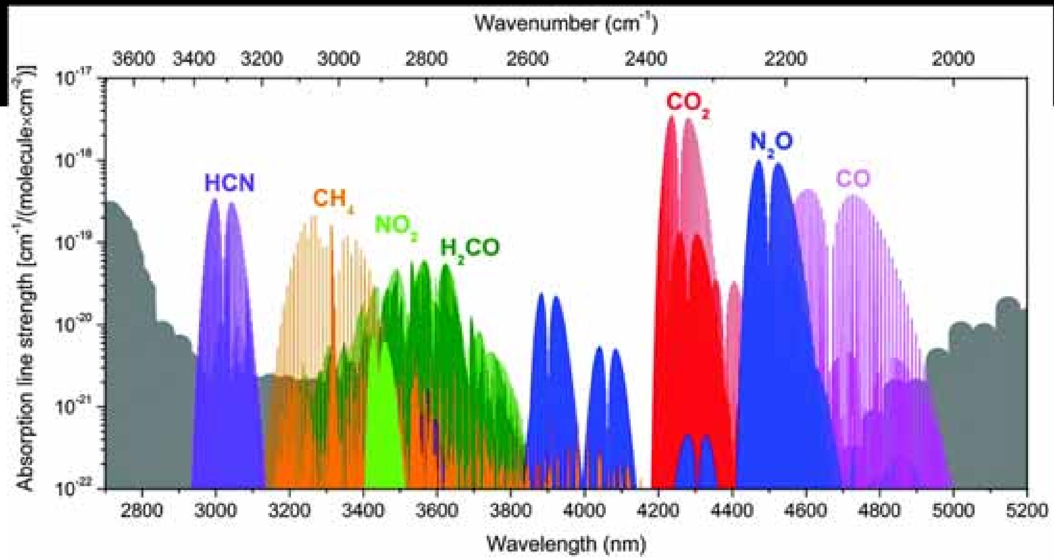
| | | |
|---|---|---|
| Crystal | - | LNOI, X-cut, Y-prop |
| Insertion loss (O / C-band) | IL | <7 dB |
| DC extinction ratio | ER | >25 dB |
| Optical return loss | ORL | >20 dB |

All specifications are given at 25ºC, unless differently specified.

marc.reig@versics.com

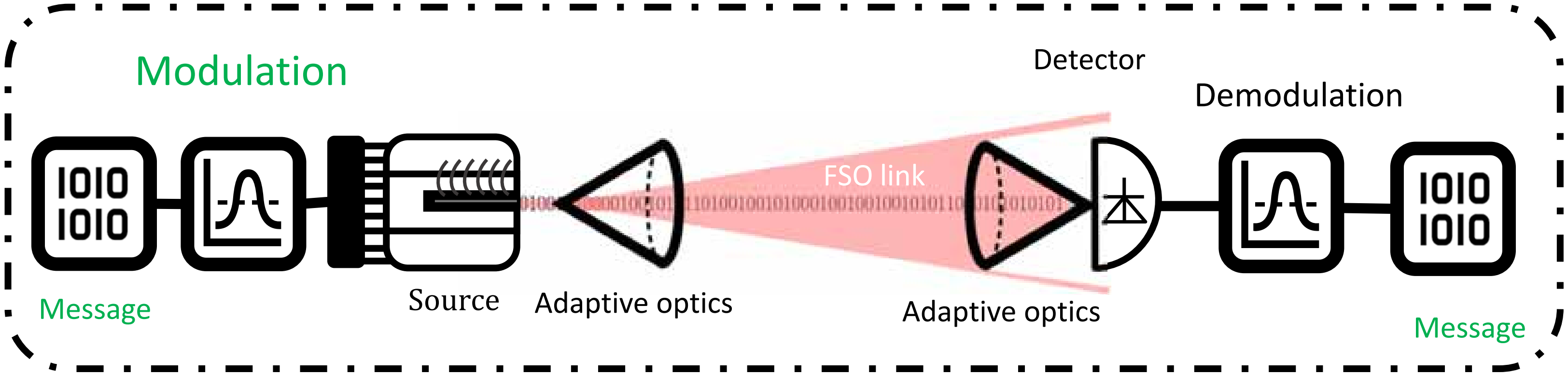
VERSICS HIGH-SPEED PHOTONIC SOLUTIONS

# Why LiNbO3 on Sapphire?




**Strong absorption of important environmental molecules**

## High-speed Free Space Optics (FSO)




**High speed/high bandwidth**

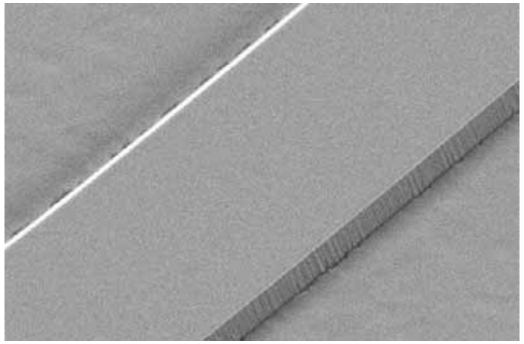
**Low cost**

**Interference free**

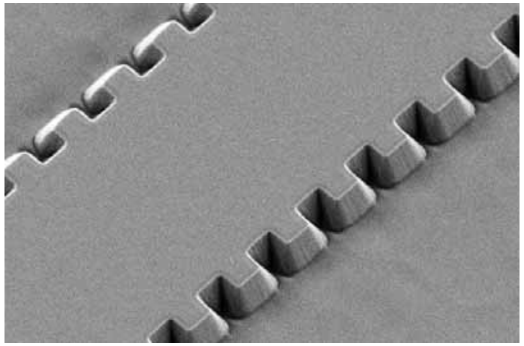
[1] Vainio, M., & Halonen, L. (2016). Physical Chemistry Chemical Physics, 18(6), 4266-4294.
[2] Schliesser, A., Picqué, N., & Hänsch, T. W. (2012). Nature photonics, 6(7), 440-449.

# Fabrication of LNOS for mid-infrared applications

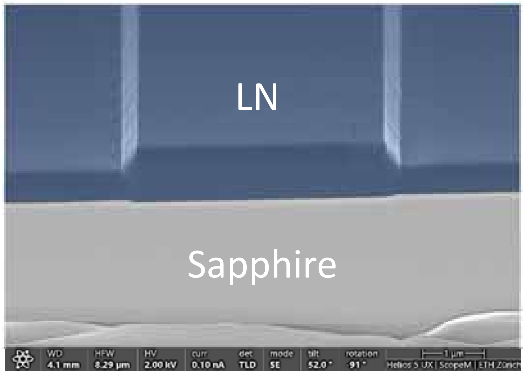
Waveguide



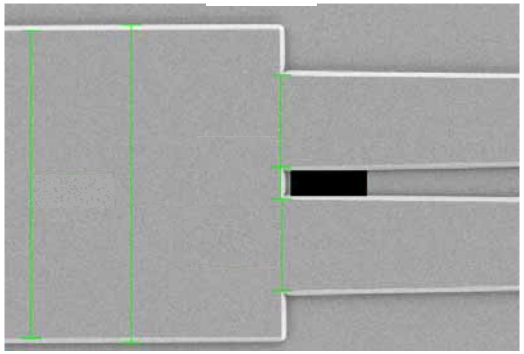
Bragg reflector (for 3.7 and 4 µm)



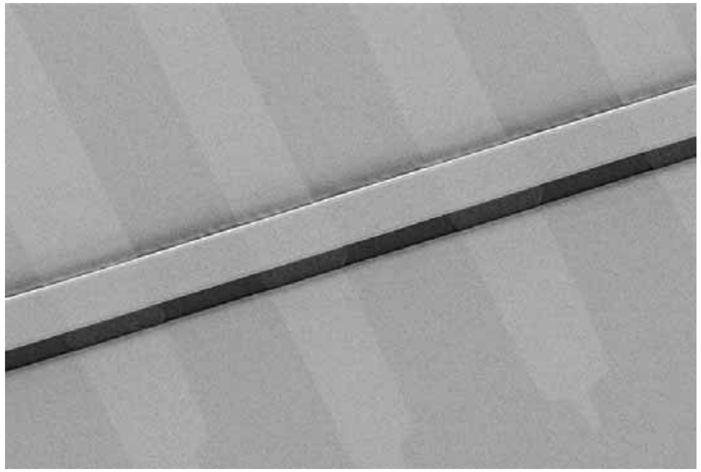
Facet




MMI



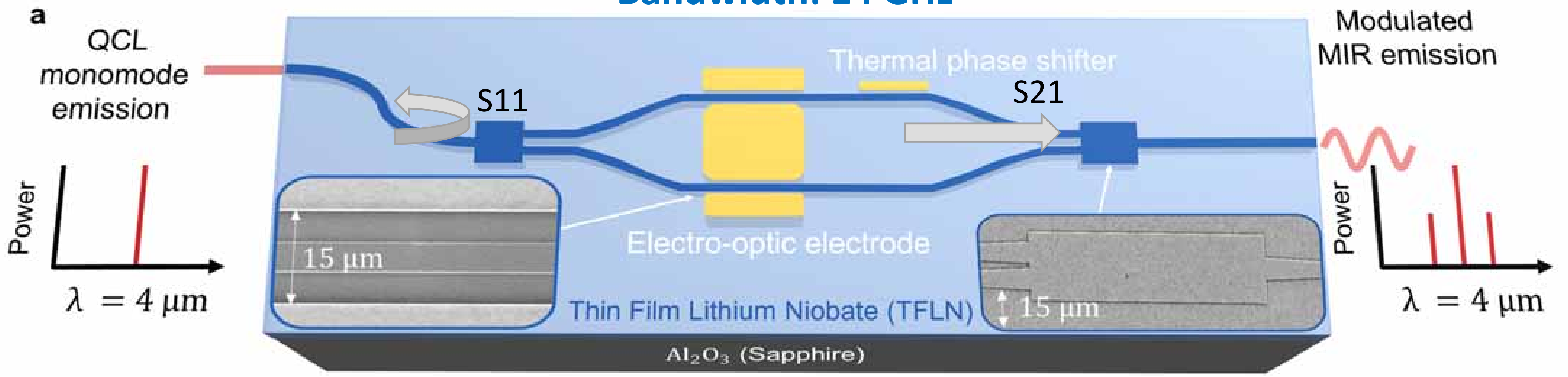
Periodically poled lithium niobate on sapphire

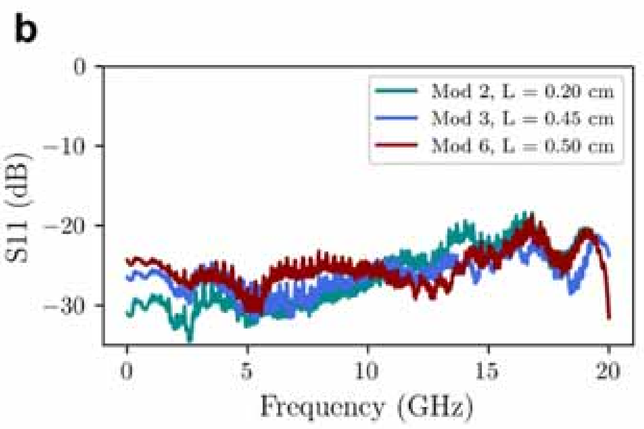


Pierre Didier, Prakhar Jain, Oliver Pitz, arxiv.org/abs/2505.23632

# Mid-Infrared modulators in LiNbO3 on Sapphire

**Bandwidth: 14 GHz**



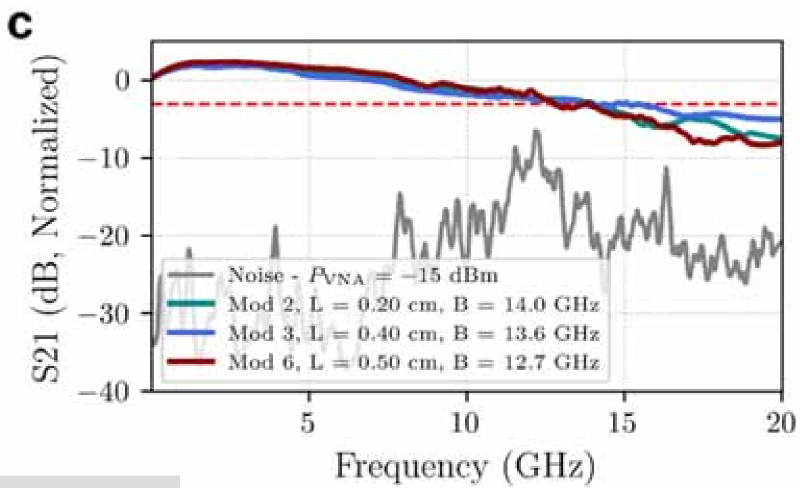




$V_\pi$ 31 V·cm

**Prop. Losses** 1.9 dB/cm

**Device lengths** 0.25 to 0.5 cm

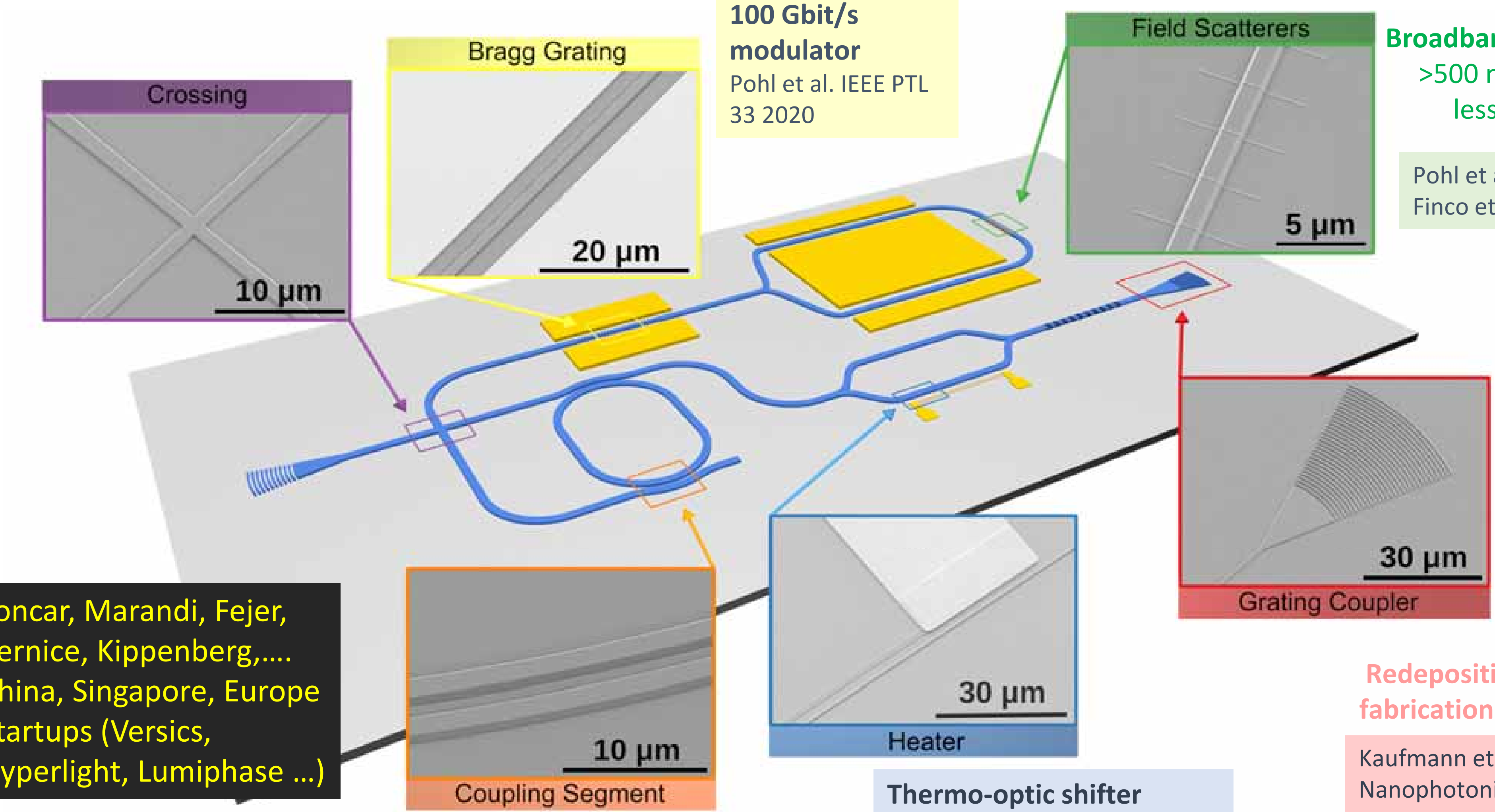
**Electrode gaps** 4.5 and 5 µm.






Pierre Didier, Prakhar Jain, Oliver Pitz, arxiv.org/abs/2505.23632

# Lithium niobate on insulator for photonic integrated circuit (PIC)




**100 Gbit/s modulator**
Pohl et al. IEEE PTL 33 2020

**Broadband spectrometer**
>500 nm bandwidth
less than 20 V

Pohl et al. Nat. Phot, 2020
Finco et al. Nat Comm 2024

Loncar, Marandi, Fejer, Pernice, Kippenberg,….
China, Singapore, Europe
Startups (Versics, Hyperlight, Lumiphase …)

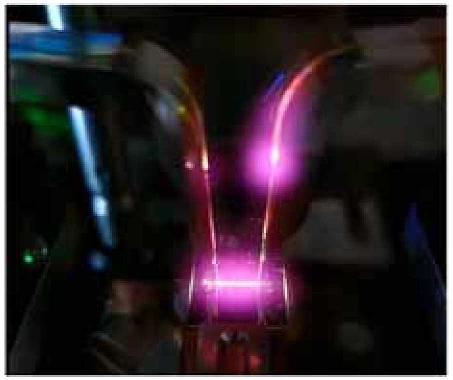
**Thermo-optic shifter**
Maeder et al. Opt. Letters 2022

**Redeposition-free fabrication process**

Kaufmann et al. Nanophotonics,2023.

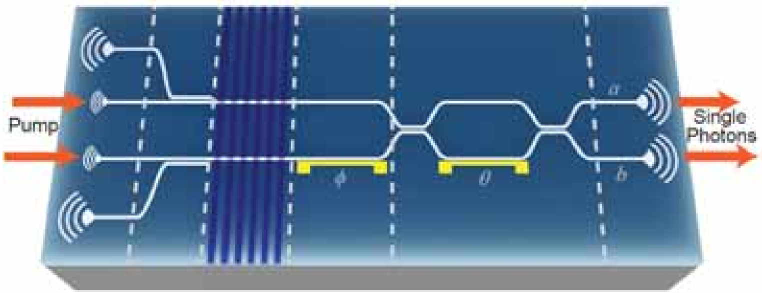
# Perspective 1: SPDC for photonic integrated circuits

## Periodically Poled LNOI

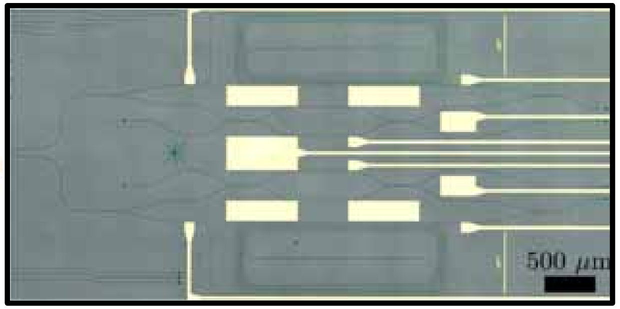


Sabatti, Kellner et al, **OPTICA, 12, 5, 2025**

## On chip source for inverse HOM/ QKD

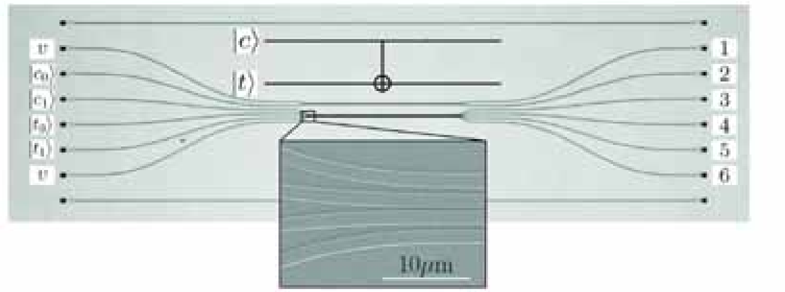



Chapman R. et al. PRL 2025
Maeder et al. 2024




Finco et al. npj Quantum Information 2025

## Two-qubit controlled-NOT gate

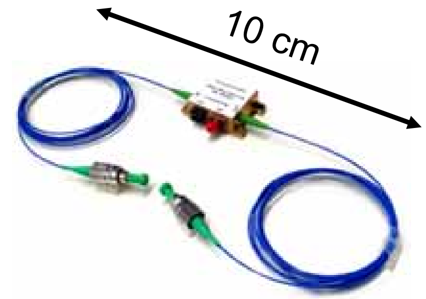



Chapman R. et al. Quantum Sci. Technol. 9 2024

## LNOI for quantum

Zhao et al.  Physical Review Letters 124, (2020)
Nehra, et  al. Science 377, 1333–1337 (2022)
Sund, et al. Science Advances 9, eadg7268 (2023)
Warner et al. Nature Physics 21, 831–838 (2025).

# $\chi^{(2)}$ materials for top-down & bottom-up for PICs

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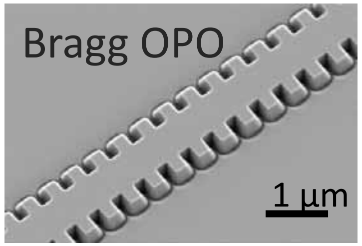
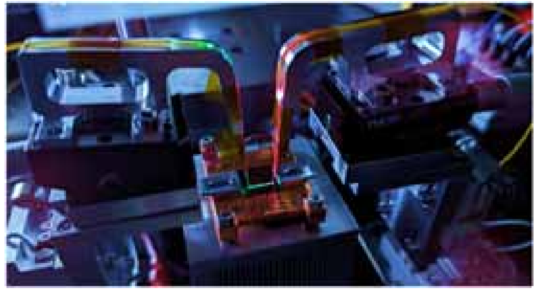
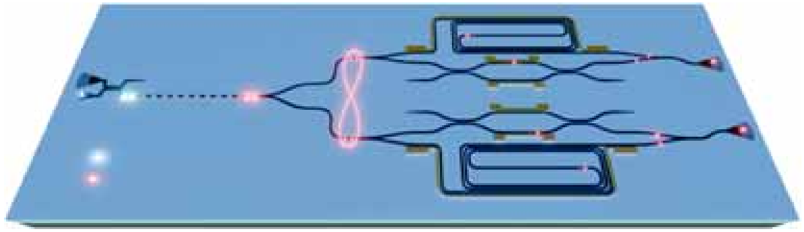



Sabatti, Kellner et al.
Optica 2025

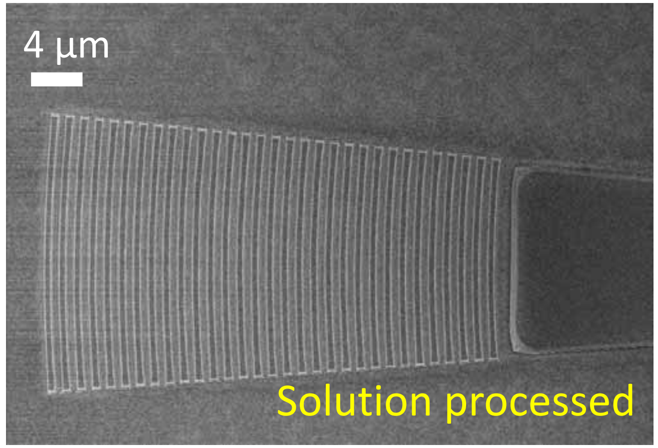


ong.ethz.ch
grange@phys.ethz.ch

Entangled qubit generation by SPDC



Finco et al. npj Quantum Information 2024
Maeder,Quantum Sci. Technol. 9 2024
Chapman et al. PRL 2025




Talts et al. Adv. Materials 2025
Weigand et al, Nano Lett 24