

# ESA NAVISP-EL1-081: Lithium Niobate Photonic Integrated Circuit Based High Speed, Low Voltage Modulators For Microwave Photonics

Dr. Mohammad Bereyhi, Co-founder and CEO  
*mohammad.bereyhi@luxtelligence.ai*

Luxtelligence SA  
November 2024





Germany

Belgium

Luxembourg

Czechia

Slovakia

Hungary

Austria

LXT

Switzerland

Slovenia

Croatia

Bosnia and Herzegovina

San Marino

Monaco

Italy

Andorra

English Channel

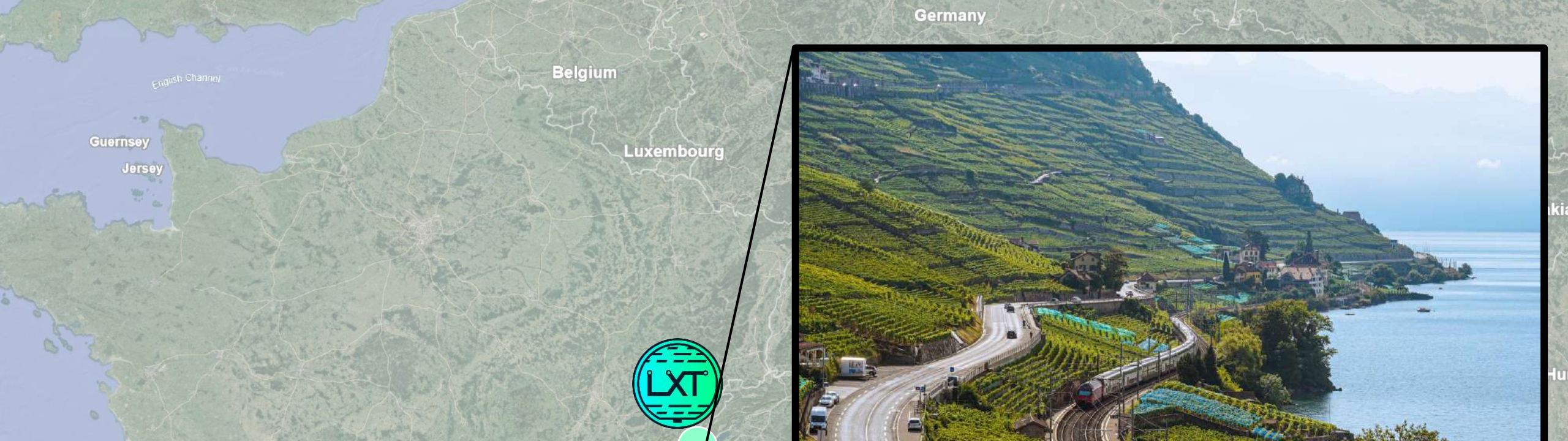
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Jersey

Biscay

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France

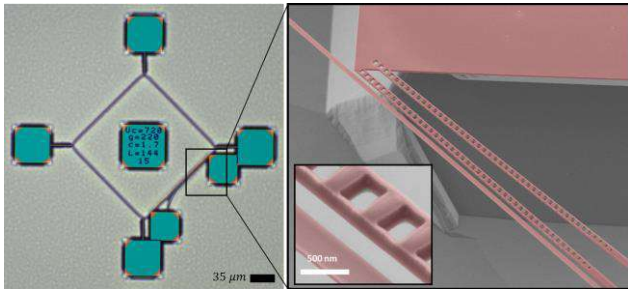


# Hands-on entrepreneurs



**Mohammad Bereyhi**  
Co-founder and CEO

- PhD in Electrical Engineering

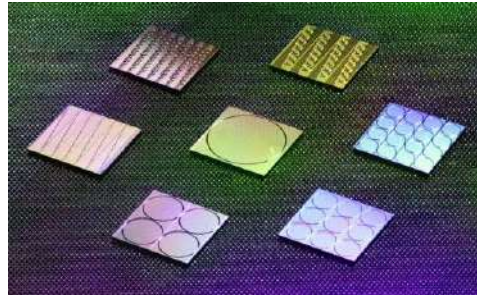


Quantum opto-mechanical sensors



**Rui Wang**  
Head of Microfabrication

- PhD in Physics

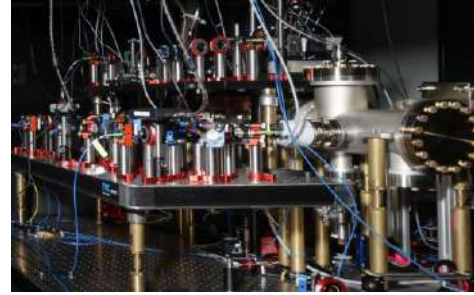


Photonics and material science



**Nick Sauerwein**  
Head of Engineering

- PhD in Physics

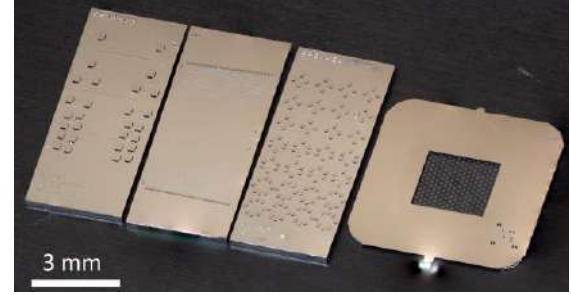


Atomic physics



**Alberto Beccari**  
Head of Photonic Design

- PhD in Photonics



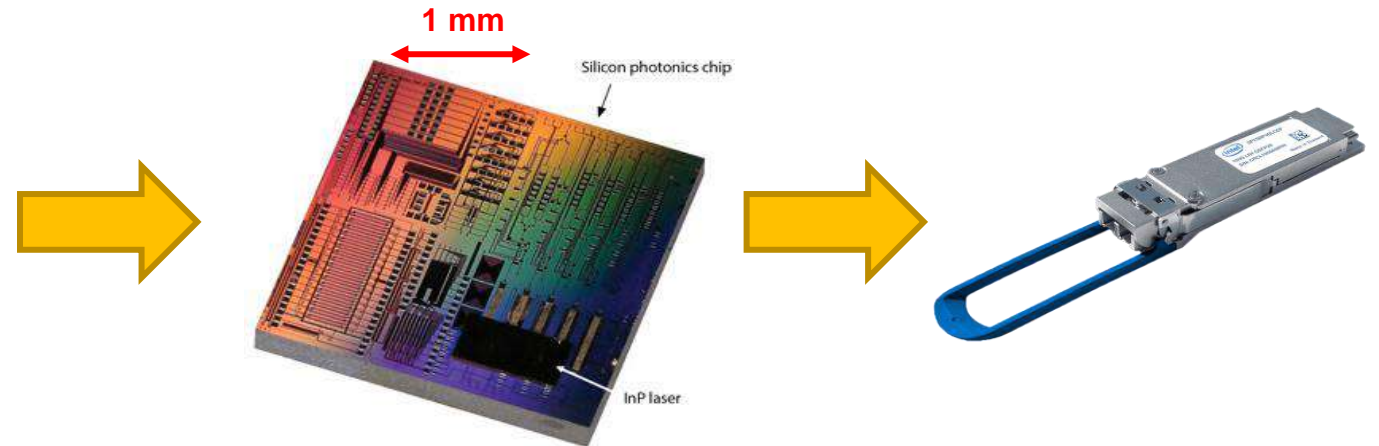
Advanced MEMS

Total team size of 11 FTE: 8 PhD, 3 MSc

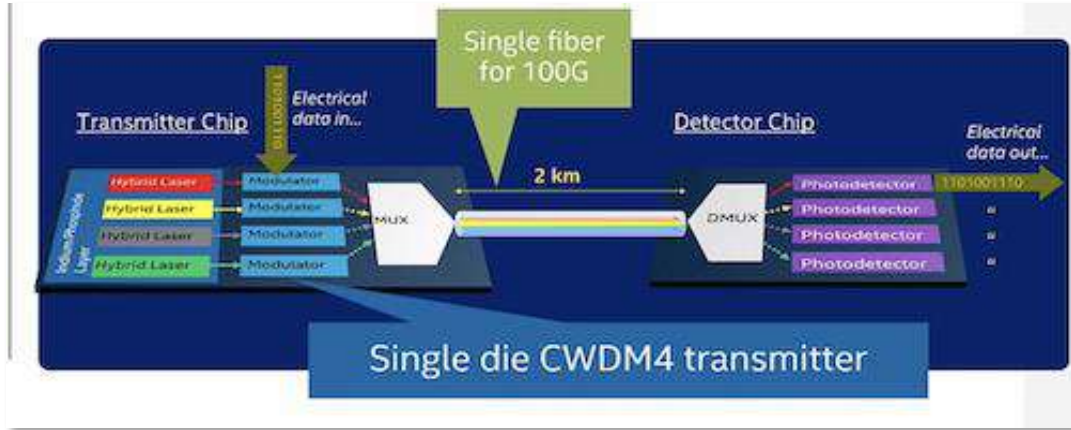
# Photonics as an enabler

## Photonics is a key-enabling technology:

- Photonic integration allows for reduction in size, increased robustness & performance, reduced complexity with scalable manufacturing
- Mature platforms SOI and InP for optical transceivers (>1 MUnits/year)

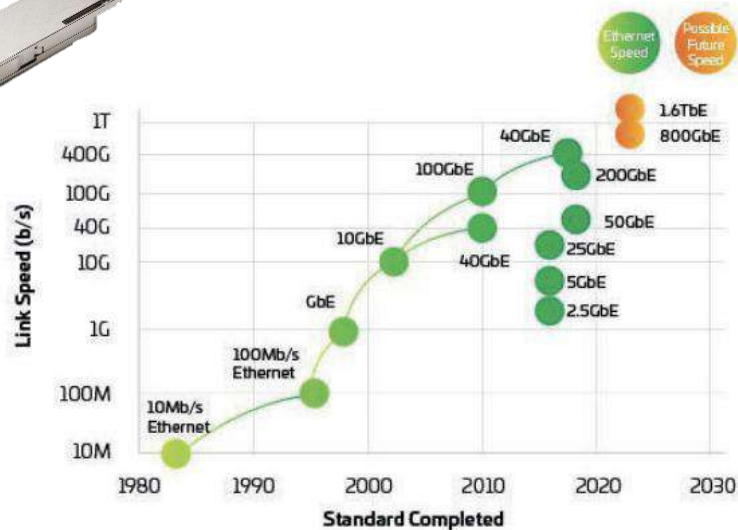
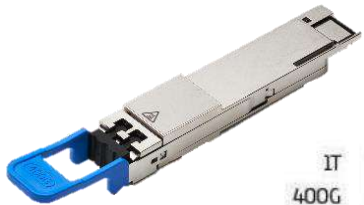


# Driver for photonic integration: silicon photonics

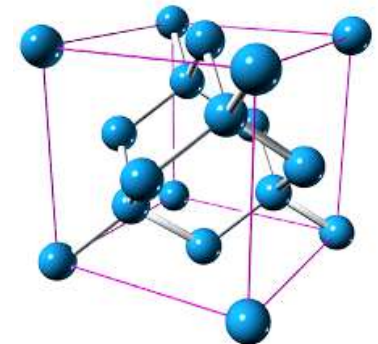


## Silicon; versatile platform with a few weaknesses:

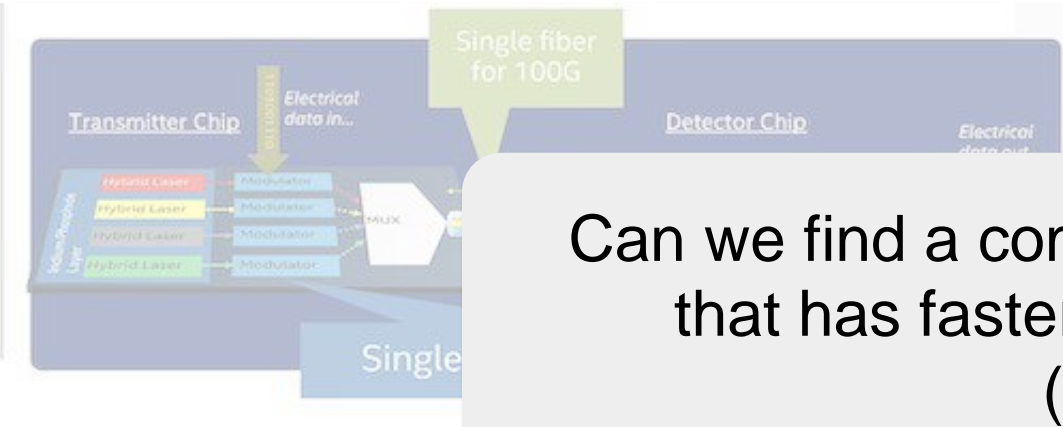
- Modulation bandwidth of carrier-injection devices limited
- Large optical losses (~dB/cm)
- Two photon absorption in the telecom band (limiting power)
- Operation not possible in the visible (bio and quantum technologies)



Credit: Intel



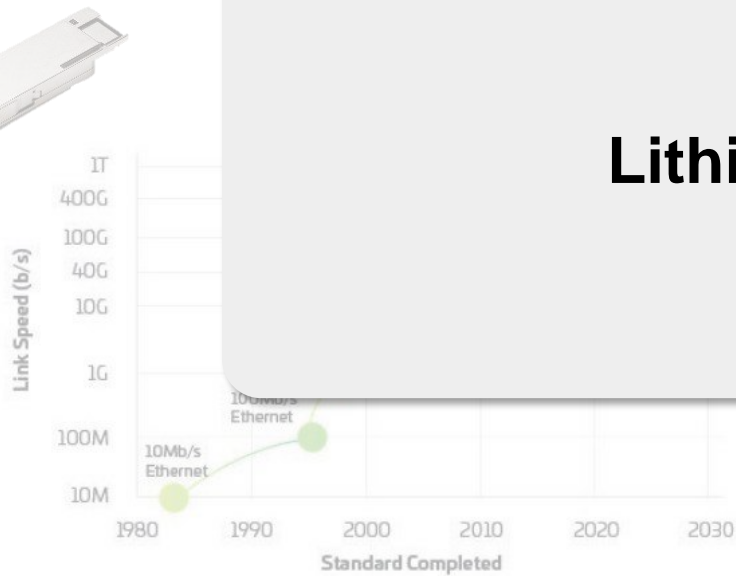
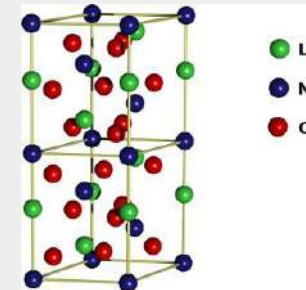
# Driver for photonic integration: silicon photonics



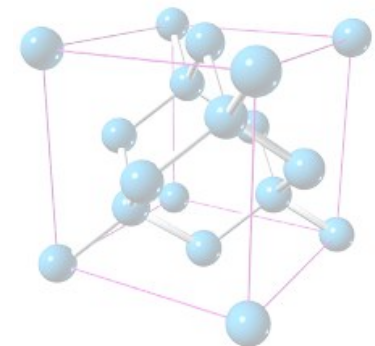
Silicon; versatile platform with a few weaknesses:

Can we find a complement to silicon photonics that has faster electro-optic capabilities (>100 GHz)?

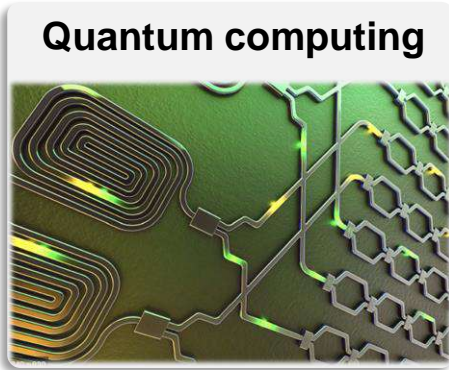
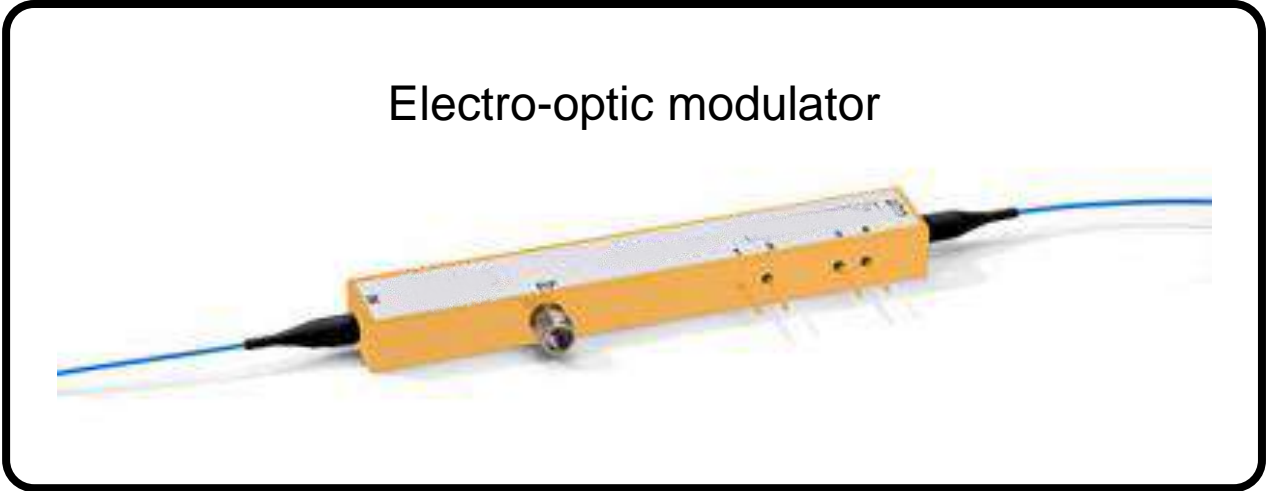
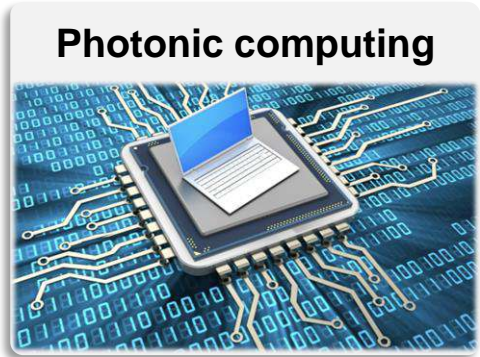
**Lithium Niobate (LiNbO<sub>3</sub>)**



Credit: Intel



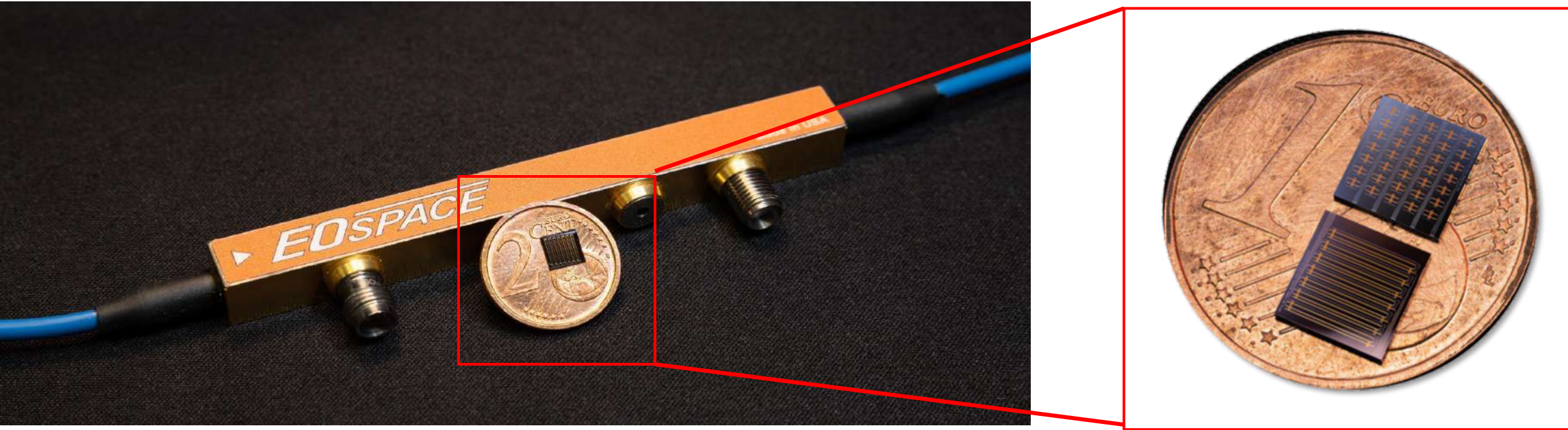
# Electro-optic modulation



# Electro-optic modulation: power of integrated photonics



On-chip modulators are >100X more compact than bulk devices

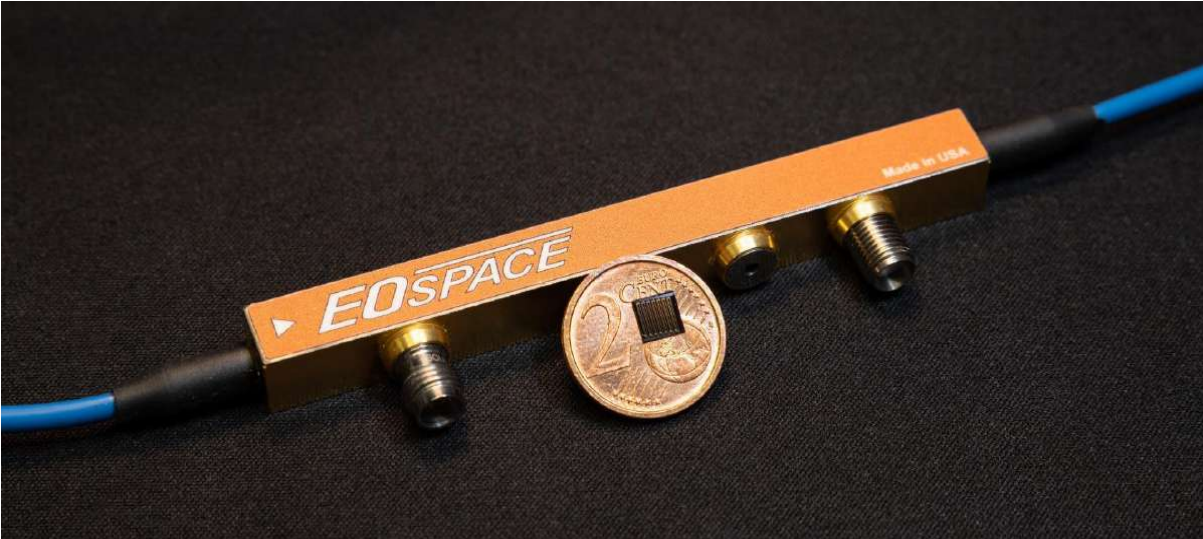


A bulk intensity modulator next to a thin-film lithium niobate chip

# Legacy PIC platforms



	Silicon (Si)	Indium Phosphide (InP)	LiNbO <sub>3</sub> (bulk)
Device footprint	millimetre	millimetre	centimetre
Power handling	10 mW	100 mW	100 mW
Bandwidth	40 GHz	40 GHz	40 GHz
Driving voltage	4 V	2 V	4 V



# Thin film lithium niobate: faster and more efficient



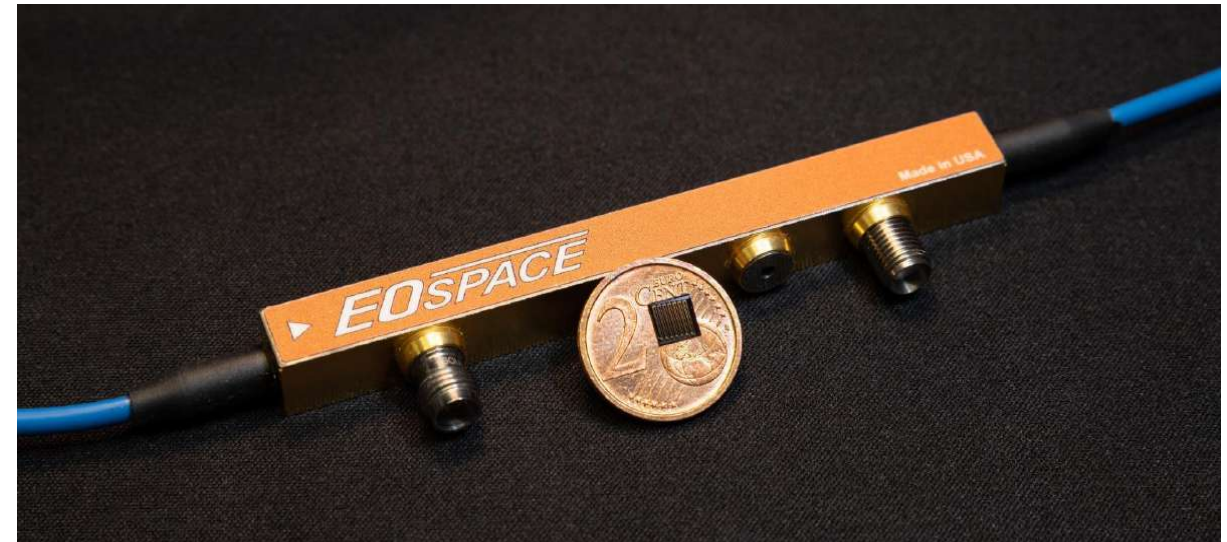
	Silicon (Si)	Indium Phosphide (InP)	LiNbO <sub>3</sub> (bulk)	Thin film LiNbO <sub>3</sub> (TFLN)
Device footprint	millimetre	millimetre	centimetre	<b>millimetre</b>
Power handling	10 mW	100 mW	100 mW	<b>&gt; 1 W</b>
Bandwidth	40 GHz	40 GHz	40 GHz	<b>&gt; 150 GHz</b>
Driving voltage	4 V	2 V	4 V	<b>&lt; 1 V</b>



Commercial TFLN on a SiO<sub>2</sub>-Si carrier

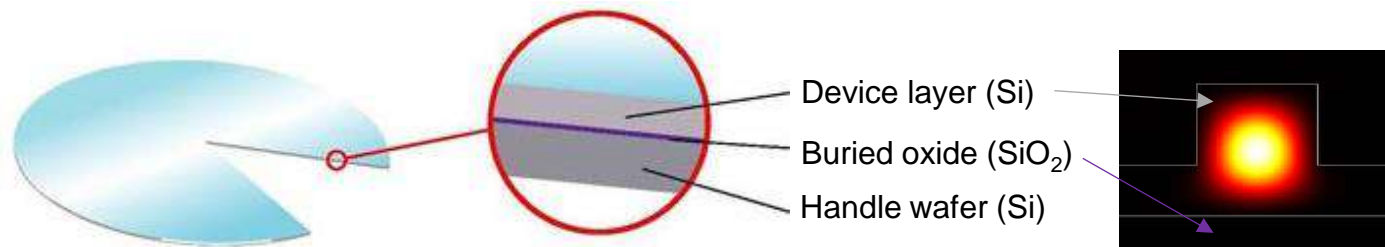
TFLN offers **multiple advantages**:

- Large electro-optical Pockels coefficient
- Wide bandgap (5 eV) (visible operation)
- Ultra low optical losses (dB/m)

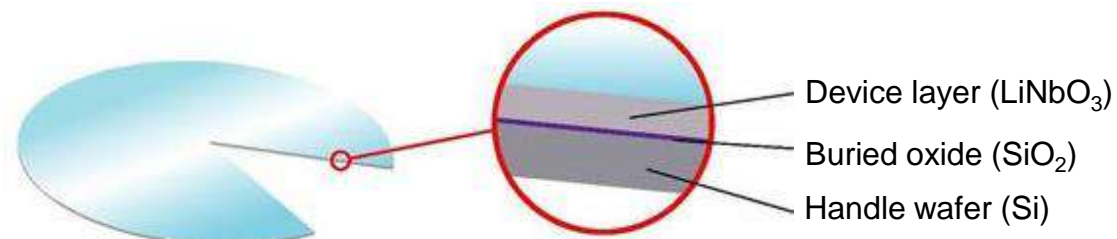


## Silicon On Insulator Wafers (SOI)

## SOI waveguide



## Thin-film LiNbO<sub>3</sub> (TFLN) Wafers



### SOI is the core of silicon photonics

- Confined optical waveguides in crystalline silicon (device layer)
- Manufactured using smart-cut in large volumes (>10 Mio. SOITEC 300mm line)
- Commercially manufactured worldwide

### TFLN is a promising platform for

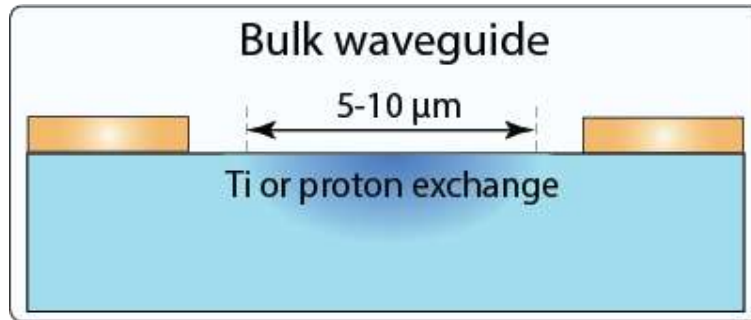
- Confined electro-optic waveguides (compact and high-speed modulators)
- Applications in RF MEMS and pyroelectric detectors.
- Commercially manufactured only in China

# LiNbO<sub>3</sub>: A Pockels material



1974

R. V. Schmidt and I. P. Kaminow  
Appl. Phys. Lett. 25, 458 (1974)



Substrate

LiNbO<sub>3</sub>

SiO<sub>2</sub>

Electrodes

- Bulk devices, large footprint
- Large switching voltage  
( $V_{\pi} \times L > 10 \text{ Vcm}$ )

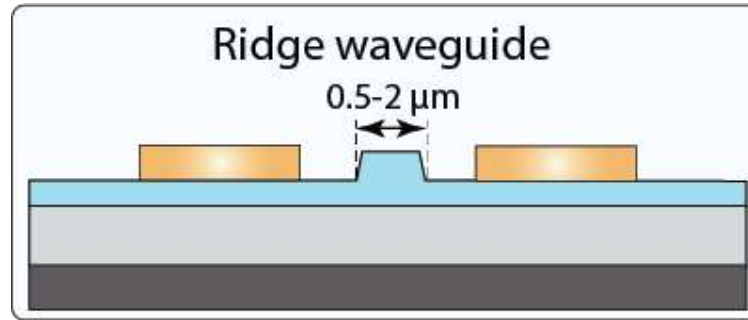
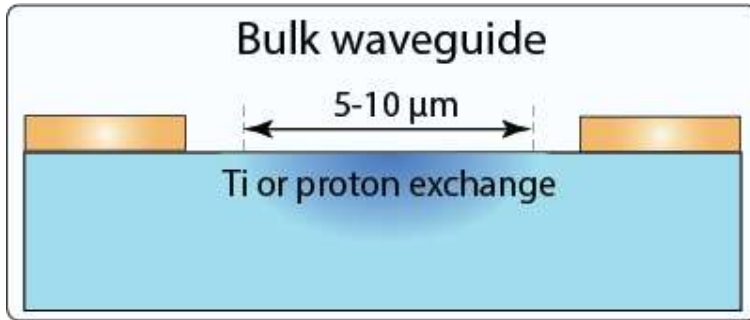
# Thin-film LiNbO<sub>3</sub> for integrated circuits

1974

2018

R. V. Schmidt and I. P. Kaminow  
Appl. Phys. Lett. 25, 458 (1974)

C. Wang, M. Zhang, *et al.*  
Nature 562, 101–104 (2018)



Substrate

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SiO<sub>2</sub>

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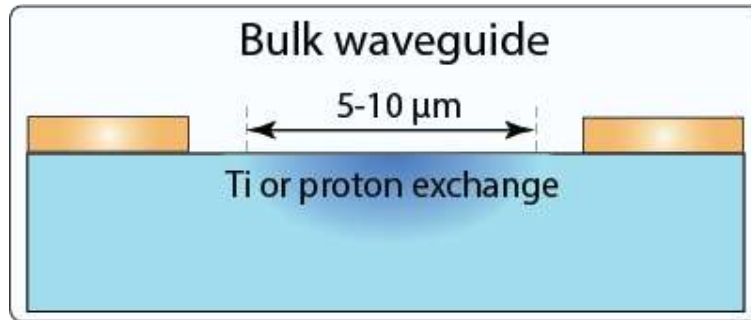
- Small footprint, on chip
- Low switching voltage  
( $V_{\pi} \times L \approx 3 \text{ Vcm}$ )
- Large WG bend loss,  
( $R > 50 \mu\text{m}$ )

# Thin-film LiNbO<sub>3</sub> for integrated circuits



1974

R. V. Schmidt and I. P. Kaminow  
Appl. Phys. Lett. 25, 458 (1974)

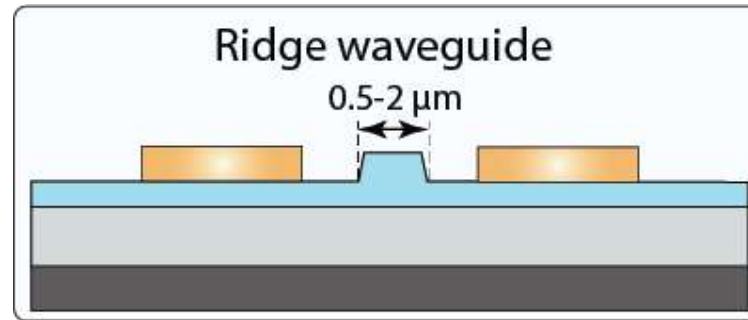


Substrate

- Bulk devices, large footprint
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( $V_{\pi} \times L > 10 \text{ Vcm}$ )

2018

C. Wang, M. Zhang, *et al.*  
Nature 562, 101–104 (2018)



LiNbO<sub>3</sub>

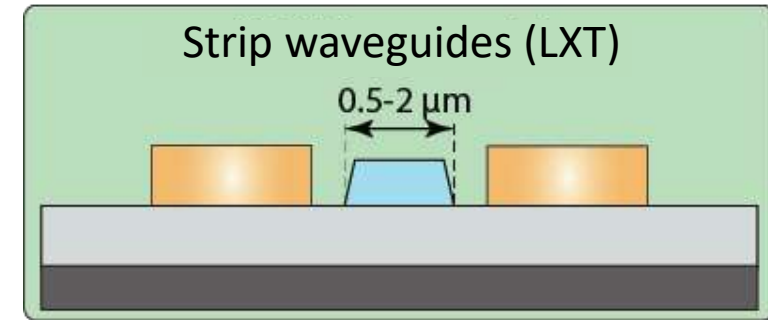
SiO<sub>2</sub>

Electrodes

- Small footprint, on chip
- Low switching voltage  
( $V_{\pi} \times L \approx 3 \text{ Vcm}$ )
- Large WG bend loss,  
( $R > 50 \mu\text{m}$ )

2023

Z. Li, R.N. Wang, G. Lihachev, *et al.*  
Nature Communications (2023)



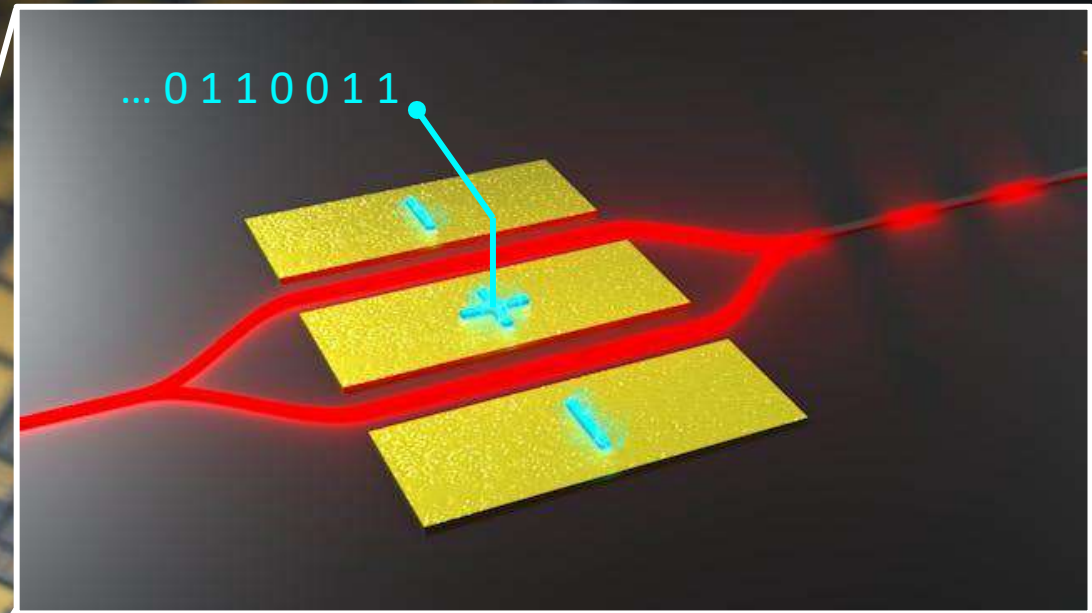
- Small footprint, on chip
- Low switching voltage  
( $V_{\pi} \times L \approx 3 \text{ Vcm}$ )
- High density integration  
( $R < 10 \mu\text{m}$ )

## Telecommunication

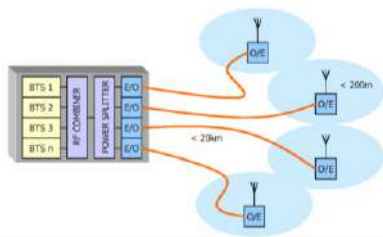


HUBER+SUHNER  
THALES

NOKIA  
BELL  
LABS



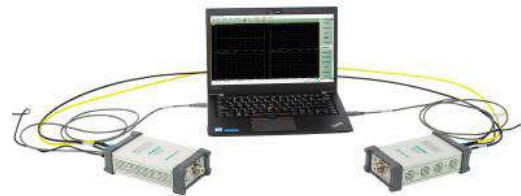
## 5G/6G



SAMSUNG

NOKIA

## mmW testing



Anritsu  
envision:ensure

KEYSIGHT  
TECHNOLOGIES

## Navigation



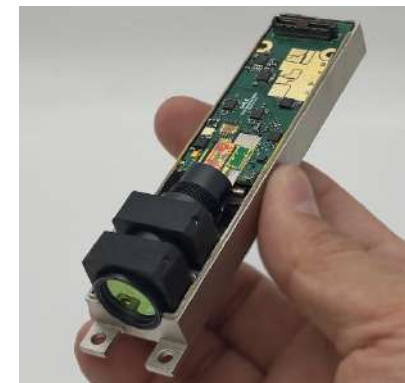
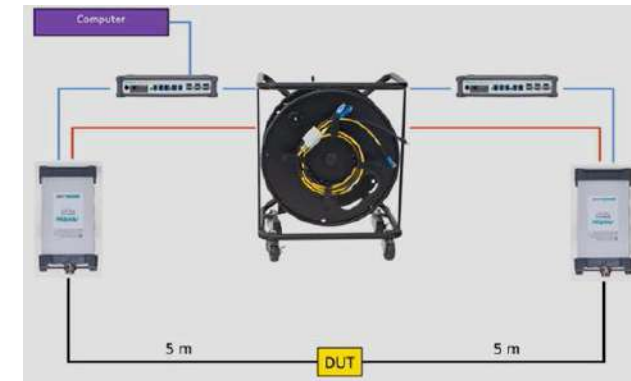
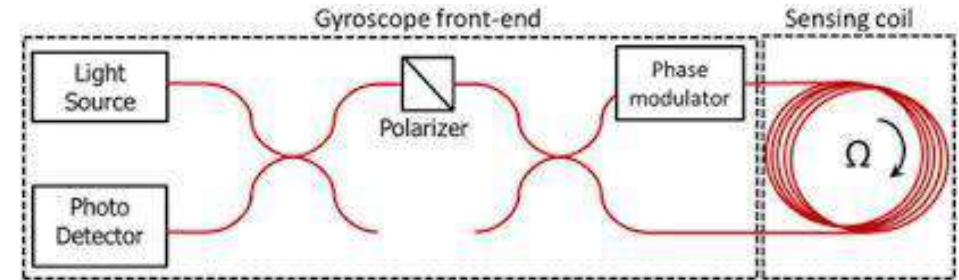
ADVANCED  
NAVIGATION

ANALOG  
PHOTONICS

LXT LUXTELLIGENCE

# Electro-optic modulators in PNT systems

- Optical gyroscopes:
  - miniaturization and lower power consumption
  - lower drifts compared to MEMS gyroscopes
  
- Microwave photonics:
  - higher frequencies at lower loss
  - enabling 5G/6G infrastructure
  
- Light Detection and Ranging (LiDAR):
  - faster systems



*Credit: Anritsu & SiLC*

# Current value chain: from idea to PIC prototypes



### Customer idea



### Photonic Chip

▪ Capacity: 200 wafers/year



### LXT Photonic design

### LXT Fabrication services

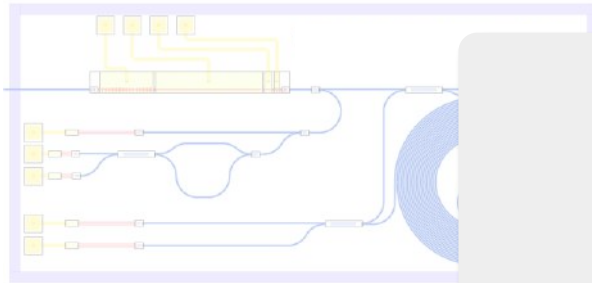
### LXT Automated testing



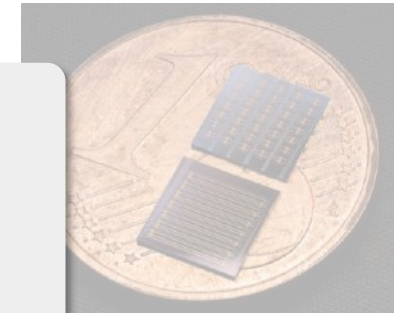


# Current value chain: from idea to PIC prototypes

Customer idea

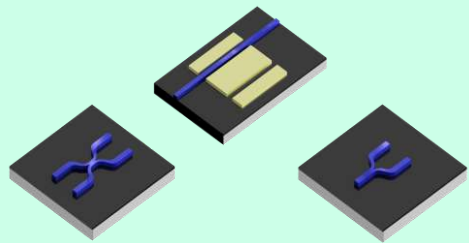


Photonic Chip

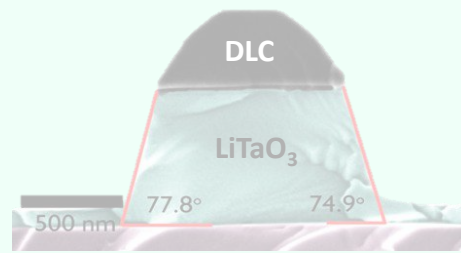


ESA – NAVISP EL1 – 081 project targeted at developing a verified component library for design PICs using LNOI platform

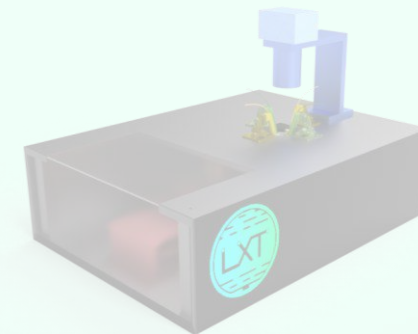
 Photonic design

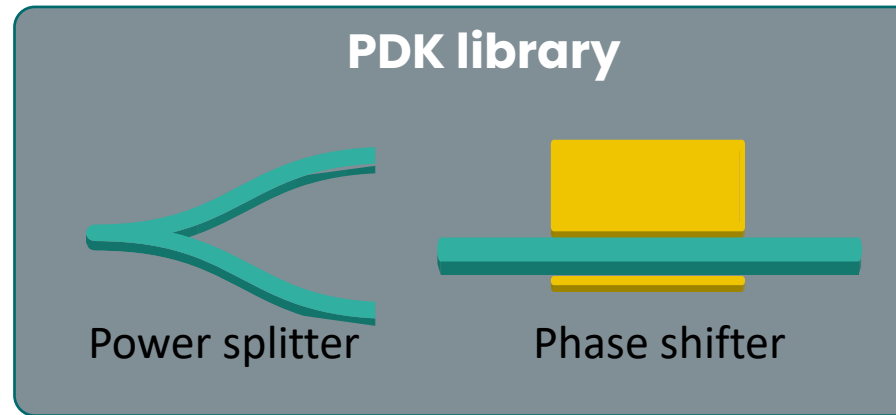


 Fabrication services



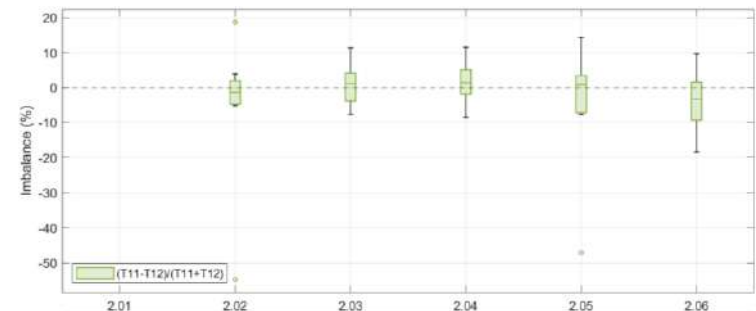
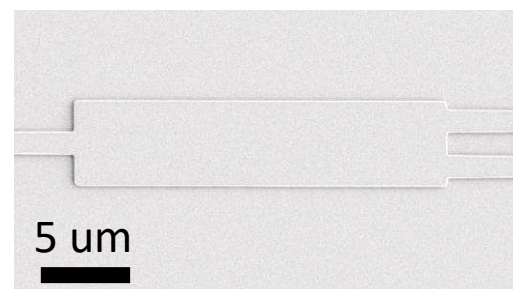
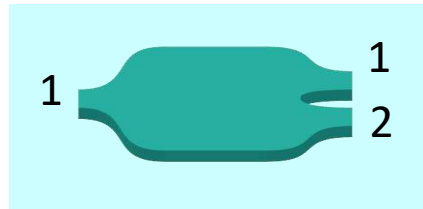
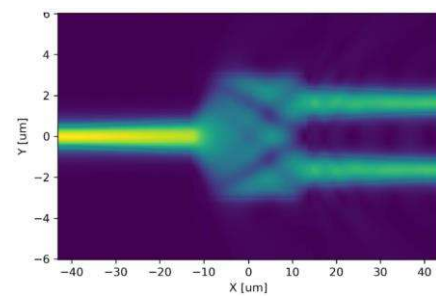
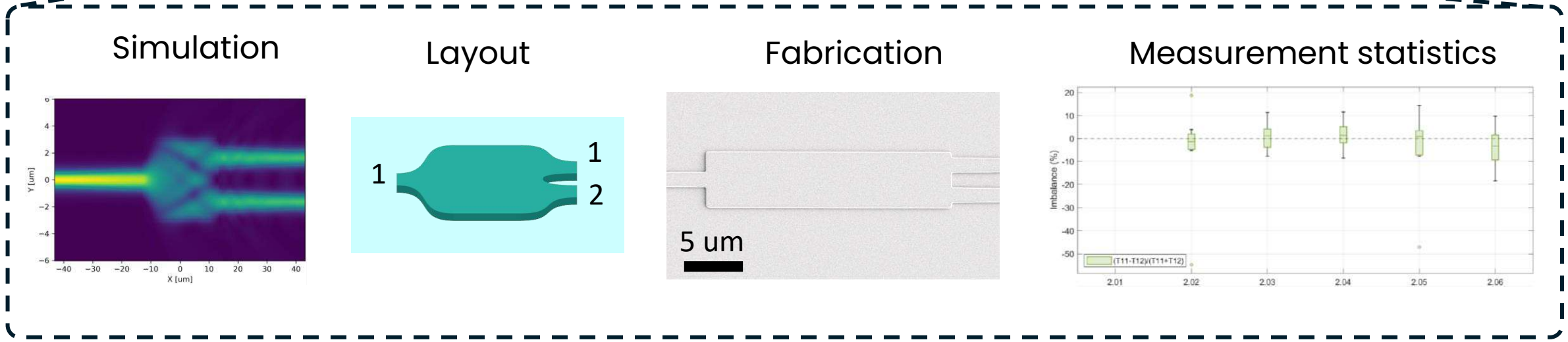
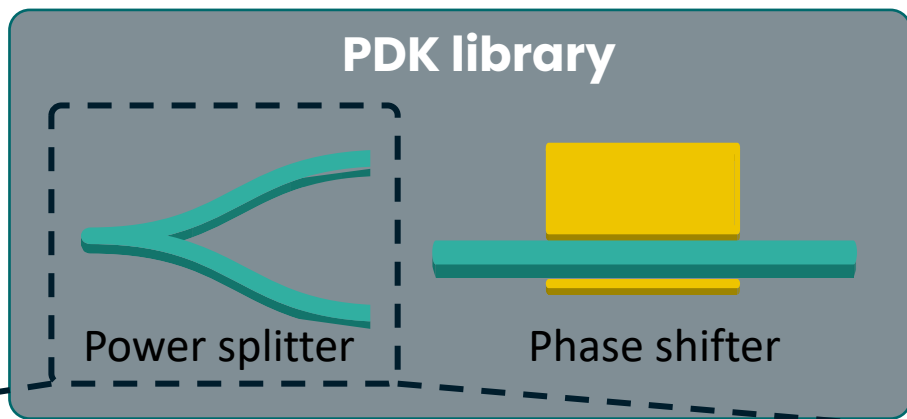
 Automated testing



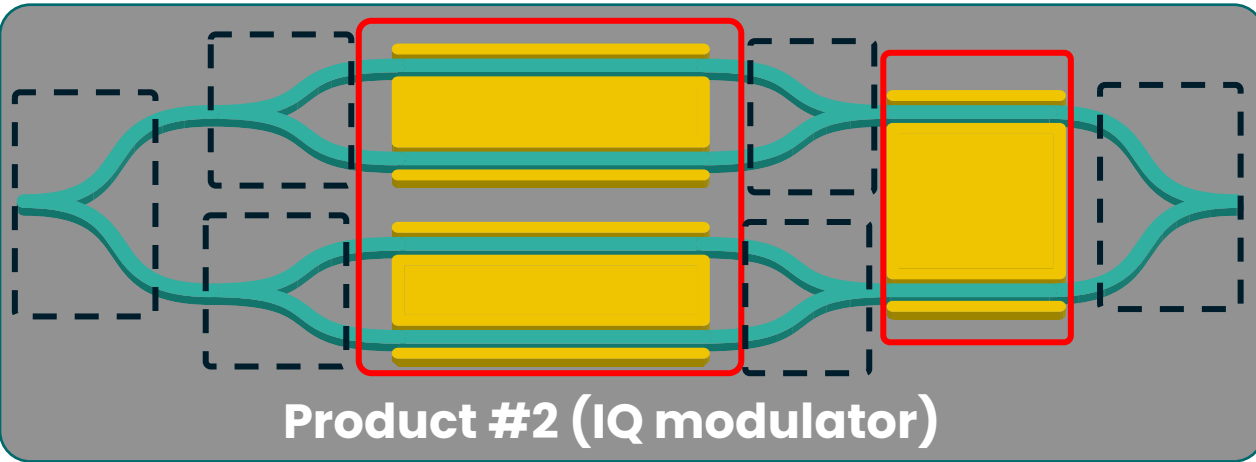
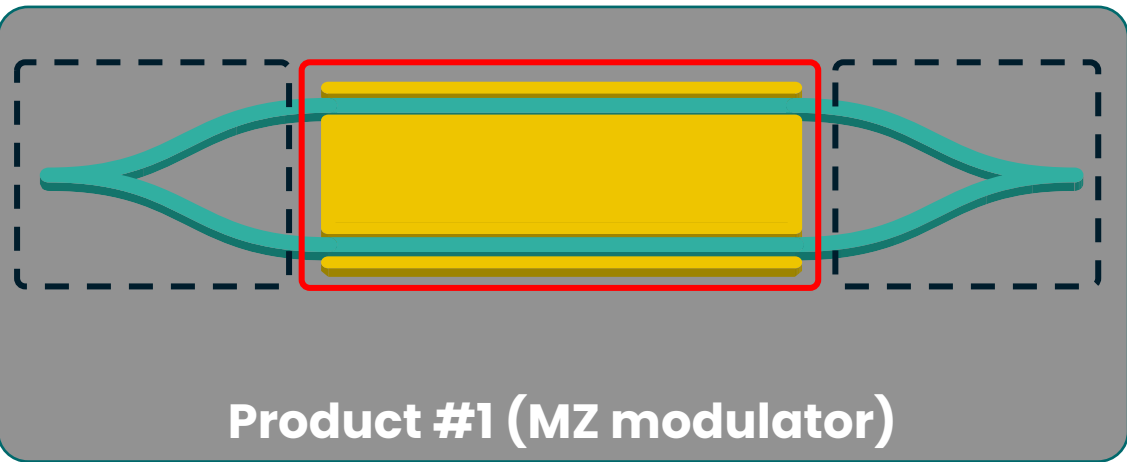
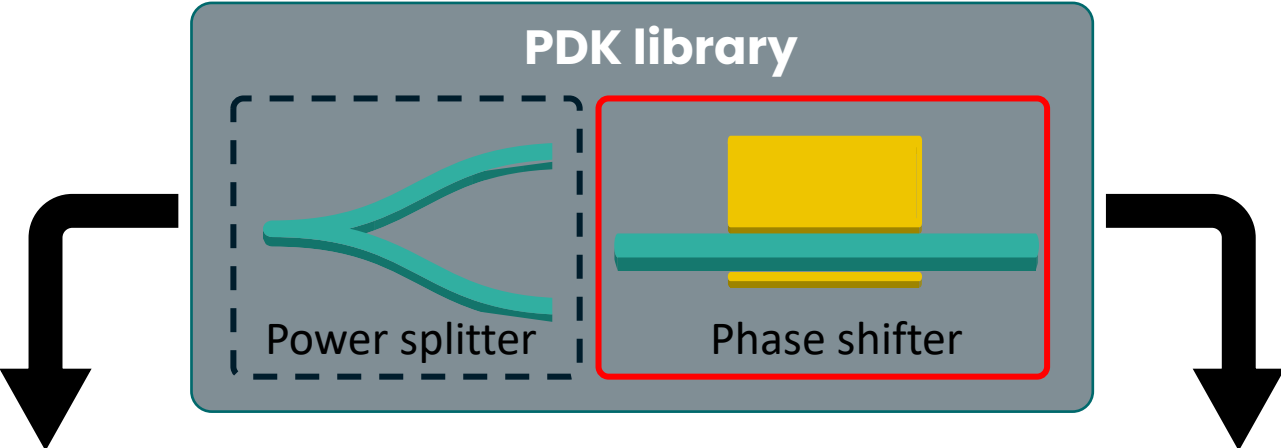


- PDK democratizes the access to the LNOI technology, given the complexity of the design and realization process.

# Process design kit (PDK): foundry view



# Process design kit (PDK): client view



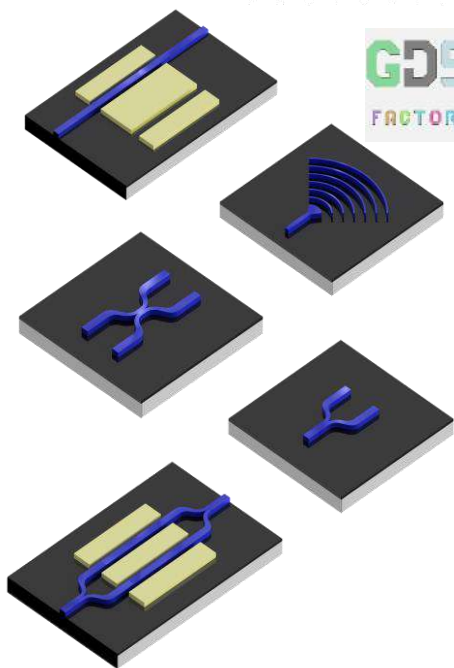
# Photonic design using a verified component library



## Process Design Kit (PDK)

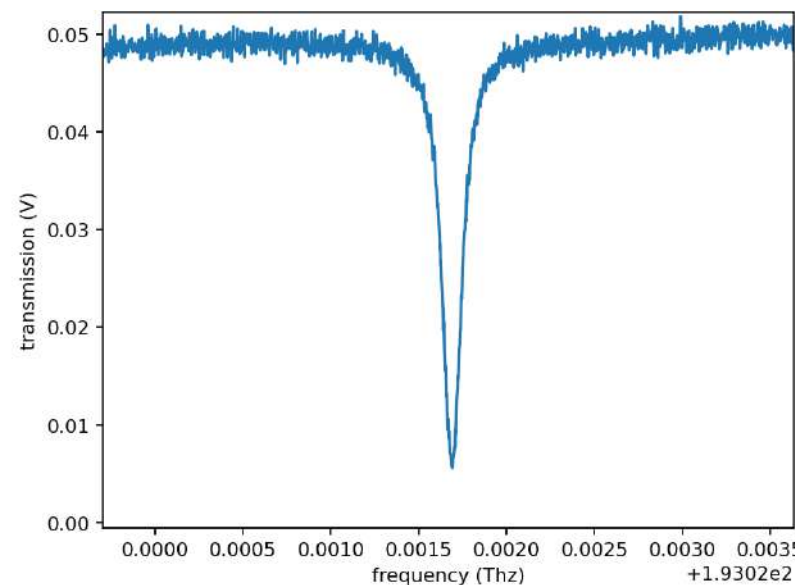
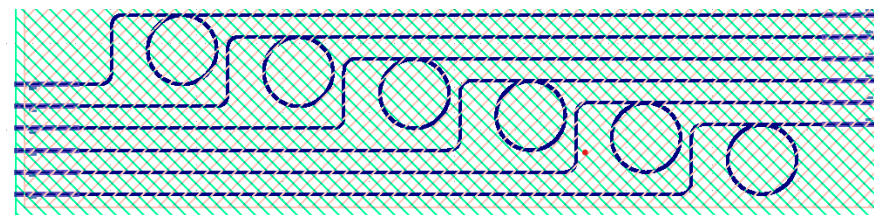
LUCEDA

GDS  
FACTORY

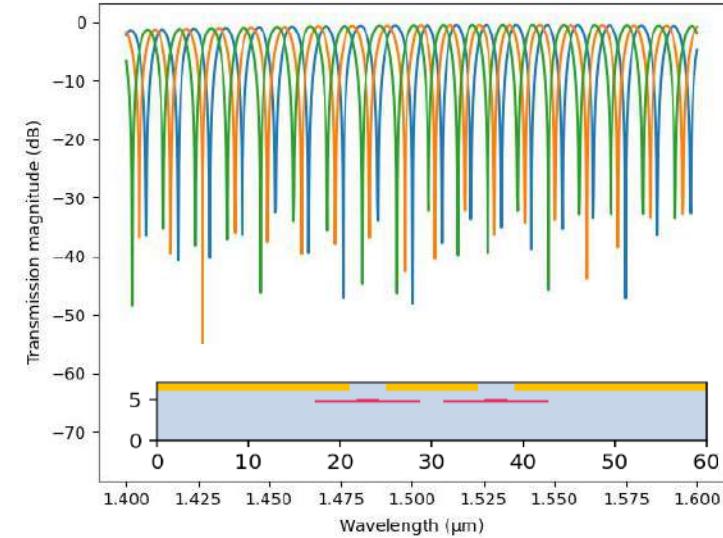
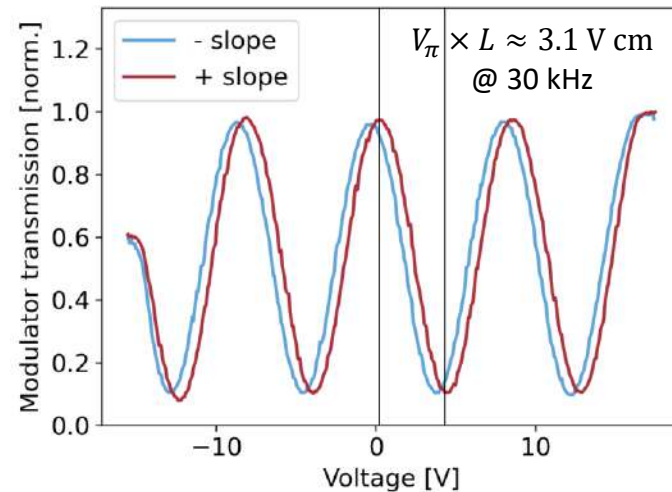
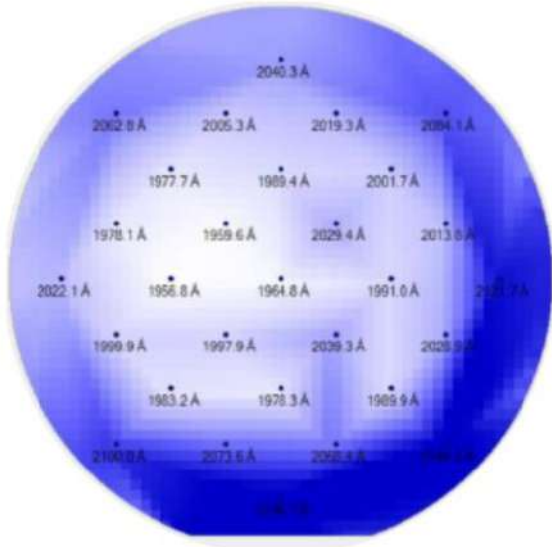


First open-access LNOI PDK debuted in Photonic West, February 2024.

Optical propagation loss	<20 dB/m (best: 3 dB/m)
Electro-optic bandwidth	75 GHz (3dB)
Electro-optic efficiency	$V_{\pi}L < 3Vcm$
Splitter imbalance	<5%
Coupling loss	~1.5 dB/facet
Fabrication duration	10-12 weeks



- Facilitate design for LNOI **MPW** runs
- Verified building blocks for **C-band** photonic circuits



- Offer a fast turnaround (**12 weeks**), while:
  - Granting high-efficiency fiber coupling
  - Maintaining state-of-the-art propagation losses
  - Offering RF modulation and DC tuning
  - Performing run metrology and PCM

# Open access PDK: design manual and compact models



- Design guidelines based on tested fabrication process.
- Compact models using GDS designs and measurement results.



## 7. Design Manual

### Cross sectional layout for PDK stack

For MPW runs, we utilize x-cut LNOI wafers (see Figure 2): the single crystalline LN crystal is grown, cut, and bonded on the carrier wafer such that the x crystalline axis is normal to the wafer surface. In this configuration, the strongest phase modulation (electro-optical tensor component  $r_{33} = 30 \text{ pm/V}$ ) can be obtained with waveguides oriented along the y direction, the electric field polarization oriented along z (waveguide TE mode), and symmetric electrode placement like the illustration in Figure 2. In MPW designs, we assume the horizontal direction to be y and the vertical direction to be z: modulator waveguides should run horizontal.

The MPW fabrication process utilizes two masks for optical components, and one mask layer for electrical components, such as microwave transmission lines and heaters. The material crosssection used for the MPW runs is portrayed in Figure 2, with relevant geometric dimensions indicated. The starting LN thickness is 400 nm, and LN is separated from the silicon substrate by a buried oxide layer ( $t_{\text{BOX}} = 4.7 \mu\text{m}$ ). Waveguides are defined by partially etching ridges into the lithium niobate film ( $t_{\text{ridge}} = t_{\text{slab}} = 200 \text{ nm}$ , typical uniformity on the wafer around 5%). Etched ridge sidewalls are quasi-vertical, typically oriented between  $75 - 78^\circ$  from the slab surface. The second optical etch step removes the remaining LN slab in selected regions, generally with the goal of defining bilayer edge couplers. A silicon oxide cladding is deposited on the LN waveguides, with a thickness of  $t_{\text{CO}} = 2.0 \mu\text{m}$ . Gold electrodes with a thickness of  $t_{\text{Au}} = 900 \text{ nm}$  are fabricated inside a recess in the top cladding. A vertical offset of  $t_{\text{CO}} = 1.0 \mu\text{m}$  separates the top of the optical waveguides from the bottom surface of the electrodes.

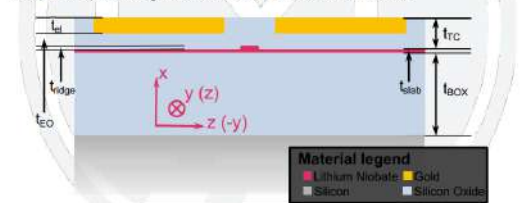
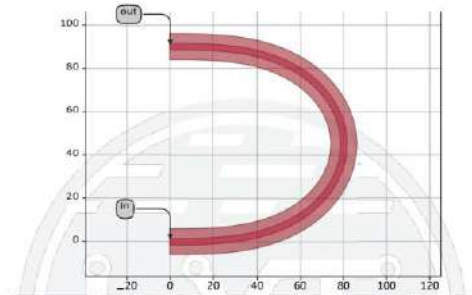


Figure 2: Cross-sectional view of the material stack for multi-project wafers, including the waveguide, cladding and electrode layers. The relevant film thickness parameters are marked. The orientation of the crystal axes of lithium niobate is described by the middle red markers.

The effective and group indices for various waveguide widths and propagation along the y direction (with TE polarization,  $TE_{\text{y}}$  mode) have been simulated, and the results are shown in...



Name	Type	Position	Angle	Waveguide Template	Inclination
in	Optical	(0.0,0.0)	180.0	RWG1000	0.0
out	Optical	(0.0,80.0)	180.0	RWG1000	0.0

U-bendRaceTrack

A U-bend with fixed cross-section and dimensions, suitable for building a low-loss racetrack resonator.

from line400 import technology from line400.lib

import U-bendRaceTrack is = U-bendRaceTrack() Layout() is:resizable(animate=True)

Name	Type	Position	Angle	Waveguide Template	Inclination
in	Optical	(0.0,0.0)	180.0	RWG3000	0.0
out	Optical	(0.0,90.0)	180.0	RWG3000	0.0

LtUmBend

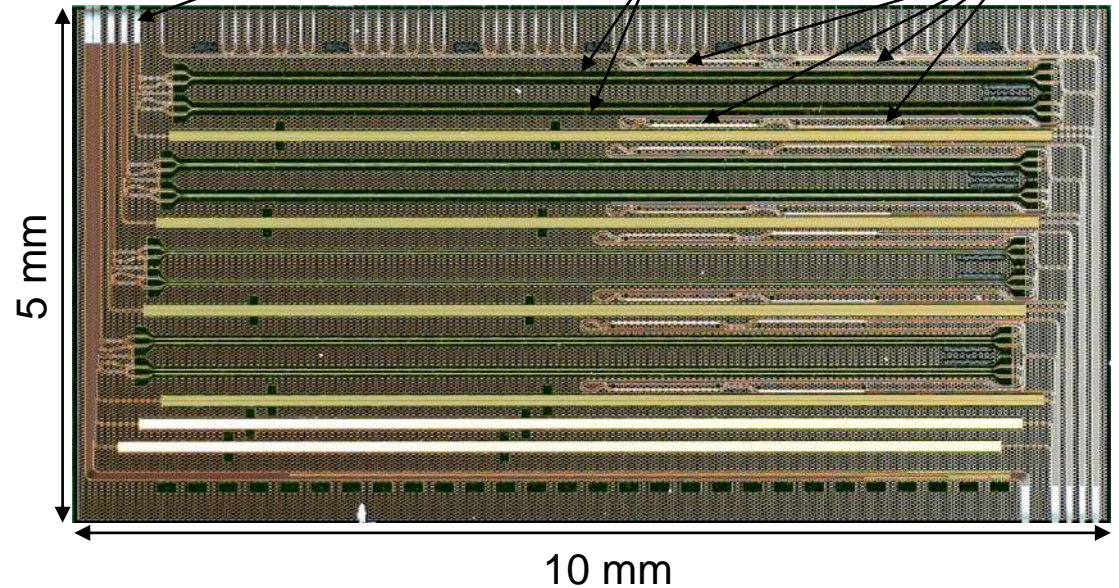
A 90-degree turn following the shape of an Euler bend, with linearly-varying curvature (increasing and decreasing).

Specify the effective radius, i.e. the radius of an imaginary circular bend bridging the same vertical and horizontal distances

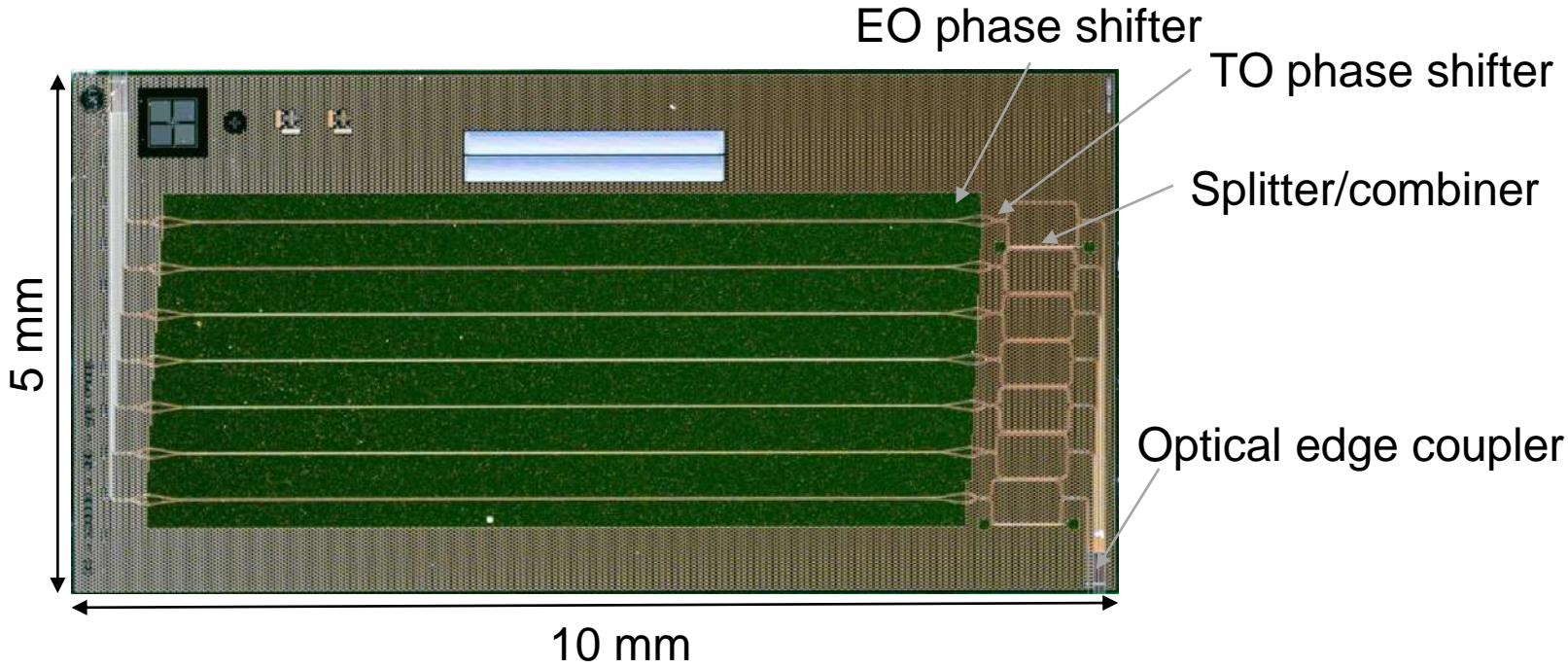
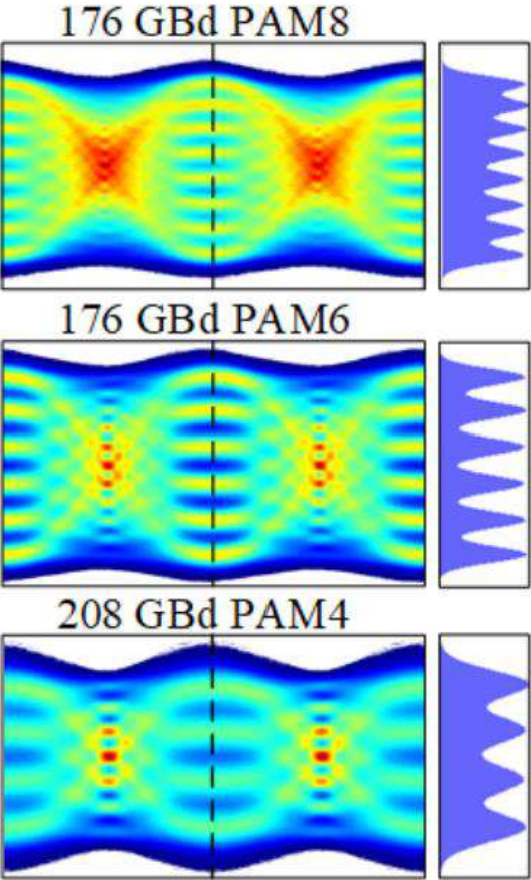
Parameters effective\_radius: float

and number > 0

Optical edge coupler EO phase shifter TO phase shifter



# Highest symbol rate in optical communication



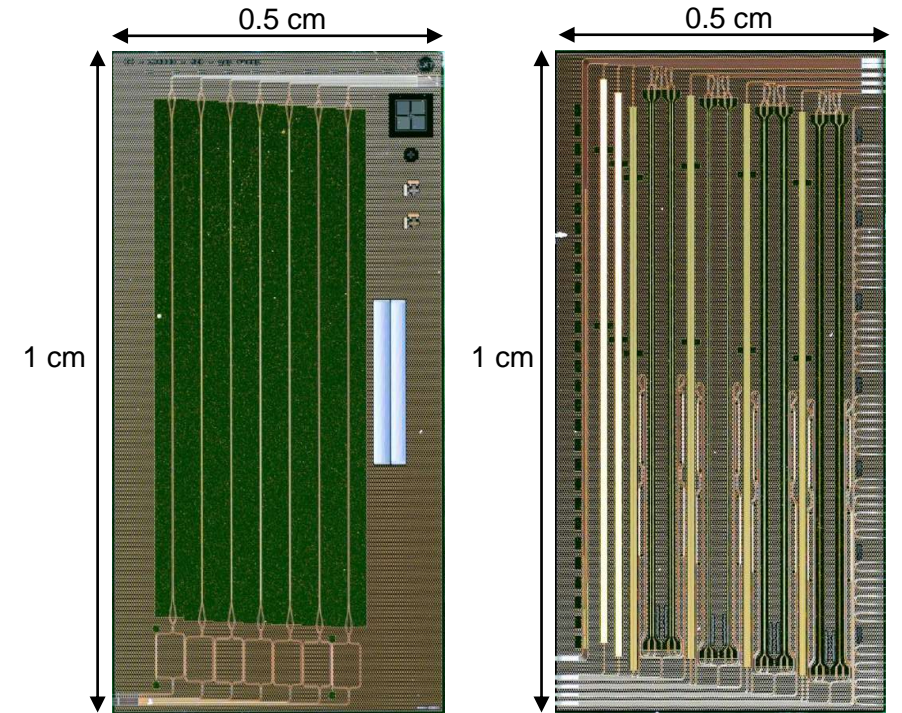
110 GHz electro-optic modulator



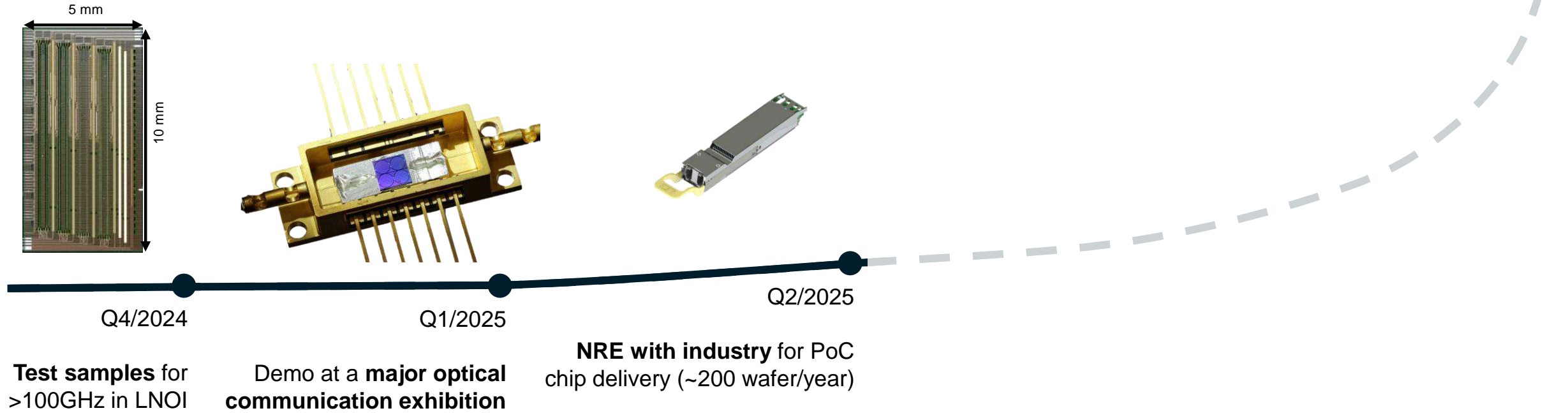
# Open-source PDK for prototyping

- Luceda Photonics PDK:  
<https://www.lucedaphotonics.com/luceda-design-kits>
- gdsfactory:  
[https://luxtelligence.github.io/lxt\\_pdk\\_gf/](https://luxtelligence.github.io/lxt_pdk_gf/)

Process Design Kit available on



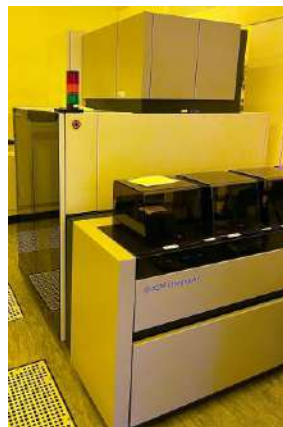
# Luxtelligence scale-up roadmap



- Ongoing MPW runs using the LNOI PDK
- Demo experiments to showcase the technology in tradeshow
- NRE contracts with industry for completion of the commercialization

# Available facilities

- Center of micro-technology (CMi) in Lausanne:
  - ASML DUV stepper lithography
  - Dry and wet etching
  - Metallization (Ti, Pt, Al, Au, Cu, W)
  - Dicing, grinding and CMP
  - Dedicated tool for hardmask process
  - Metrology (3 SEMs and 2 AFMs)

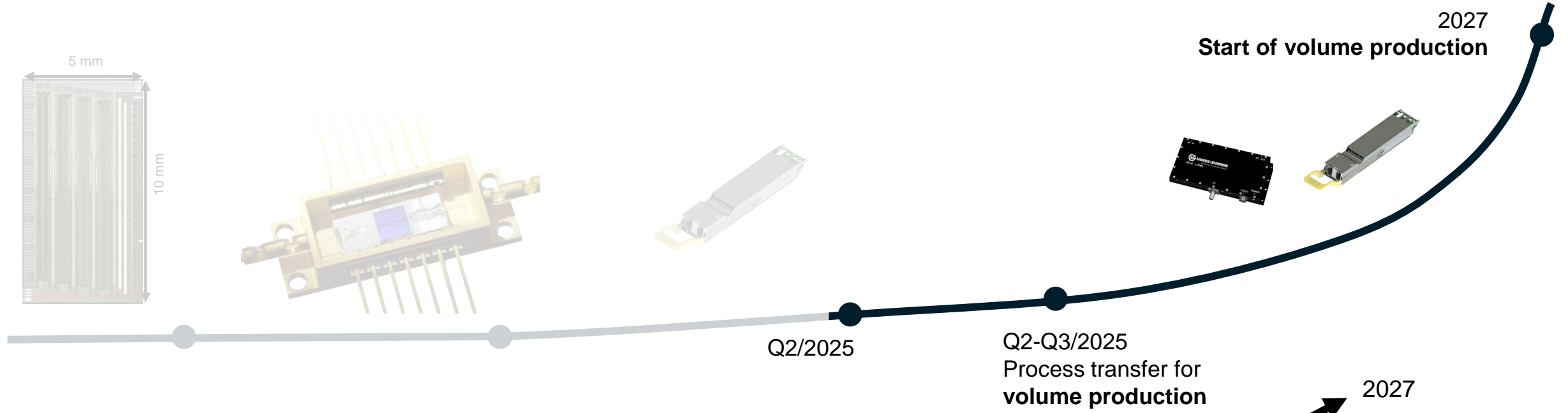


# Automated testing: a bottom-up approach

- An automated probing system specialized for testing optical modulator chips.
- LXT is building a fully automated optical and electrical testing machine based on a successful prototype from EPFL.

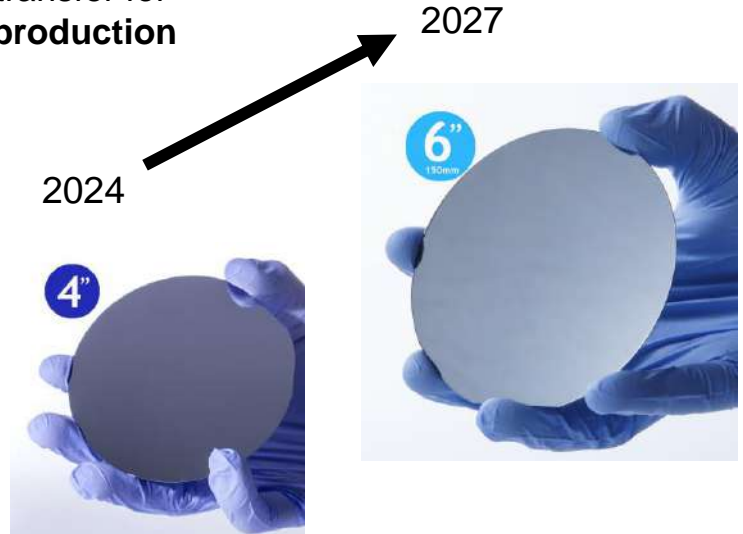


# Luxtelligence scale-up roadmap



## Scale-up

- Process transfer to a 150mm industrial foundry
- Revenue growth through industry NREs based on the foundry process
- Team growth to 20 FTE





- Luxtelligence is providing the project results as part of a PDK that is being explored by ESA LSIs.
- Devices produced during the project are being packaged and tested for in-situ space compatibility tests such as radiation hardness and acceleration shocks by LSIs and SMEs in ESA ecosystem.



# End of the presentation