Integrated Photonics on Silicon for the Visible Spectrum

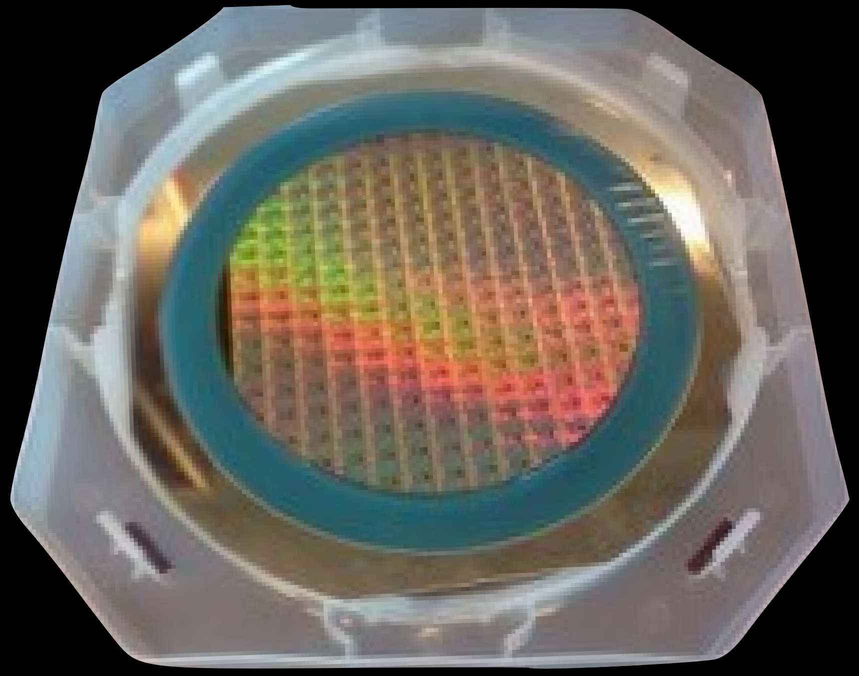
Joyce Poon
Max Planck Institute for Microstructure Physics
University of Toronto

OSA Integrated Photonics Technical Group Webinar, July 7, 2021

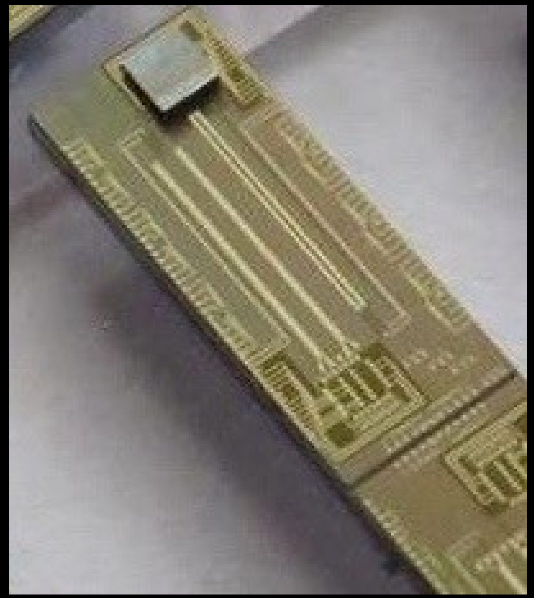
Foundry silicon photonics

Manufacture photonic chips in microelectronics infrastructure
⇒ scalability, $B industry

A*STAR, Singapore



200 or 300 mm dia.



amf ADVANCED MICRO FOUNDRY · imec · TOWERJazz · intel · tsmc · leti ceatech · ihp · AIM photonics · GLOBALFOUNDRIES · ST

Foundry silicon photonics: the opportunity

Large wafers

⇒ Mass-manufacturing, reduce cost

High density integration

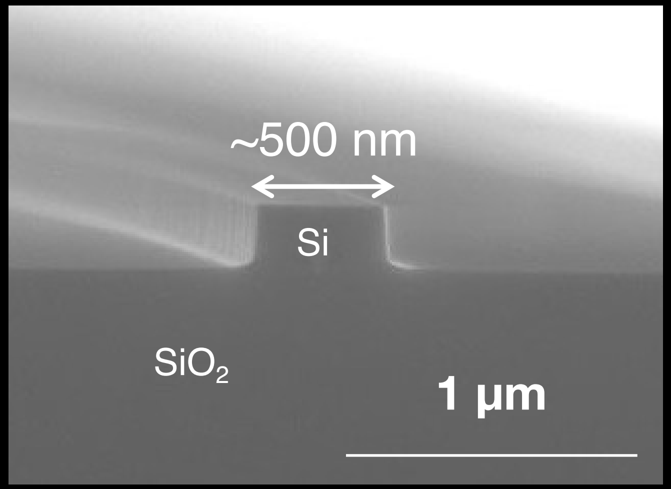
⇒ Sophisticated photonic circuits

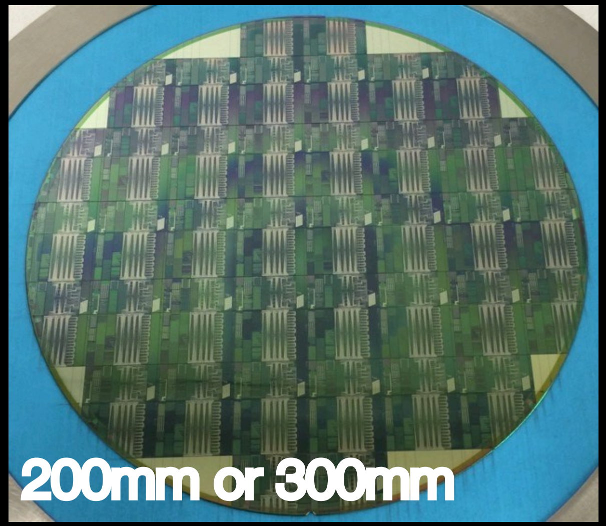
2D and 3D integration

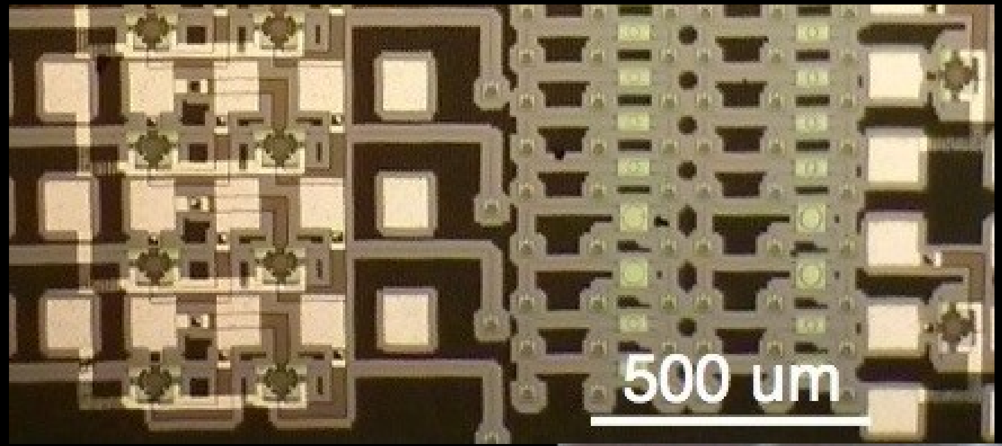
⇒ Combine photonics with electronics, other technologies

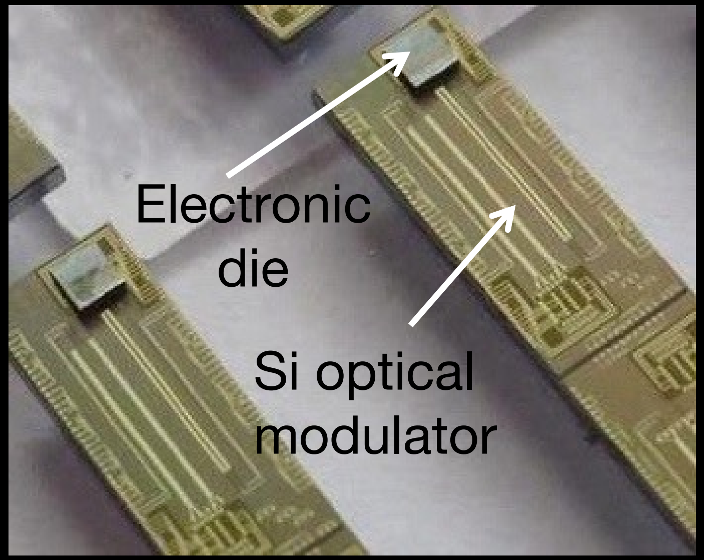
Photonics for a broader range of applications

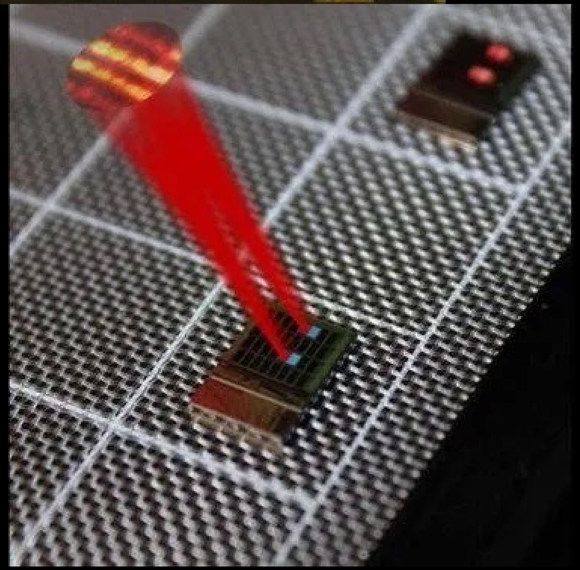
⇒ Go beyond telecom



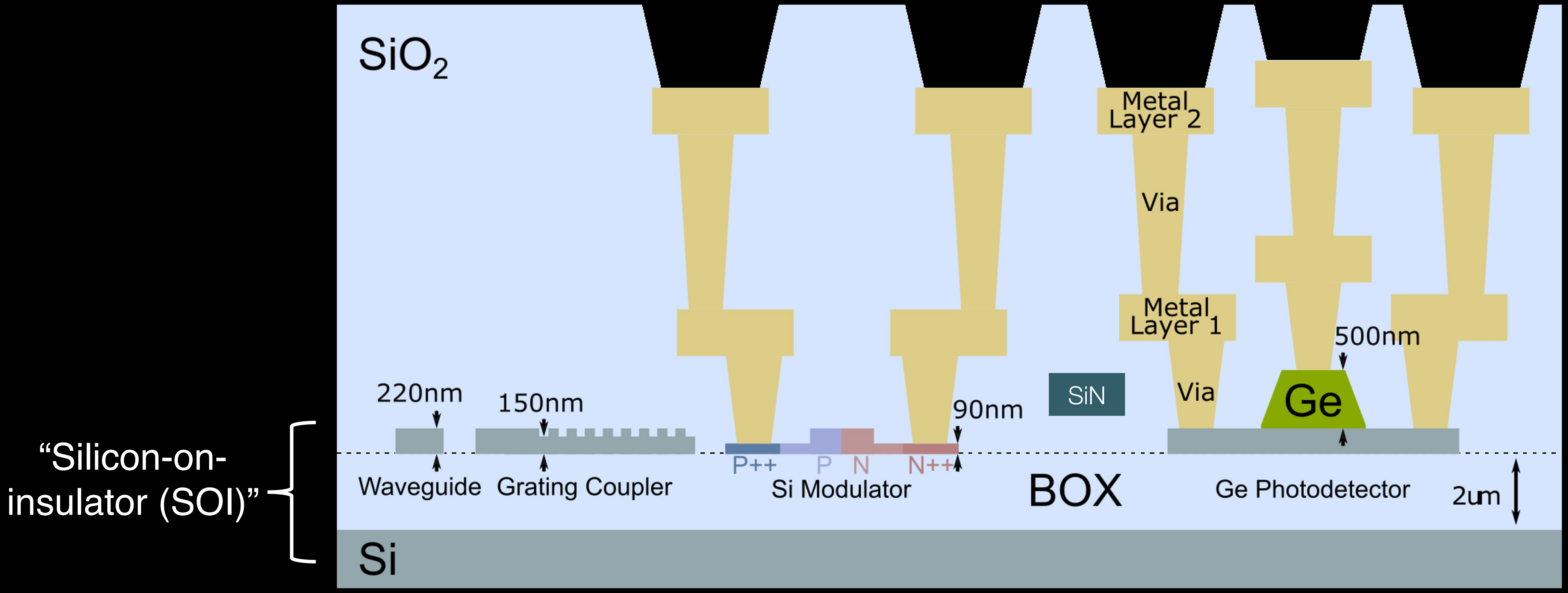






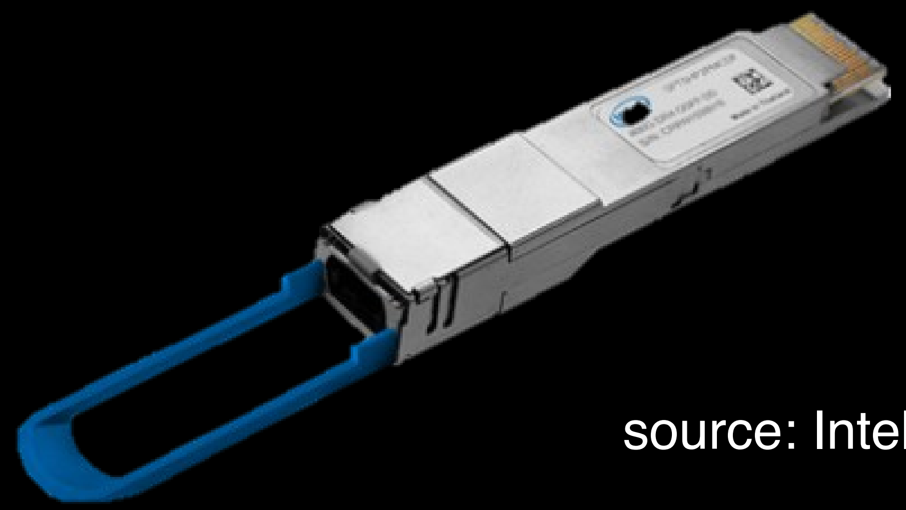


Cross-section of a typical Si photonic platform



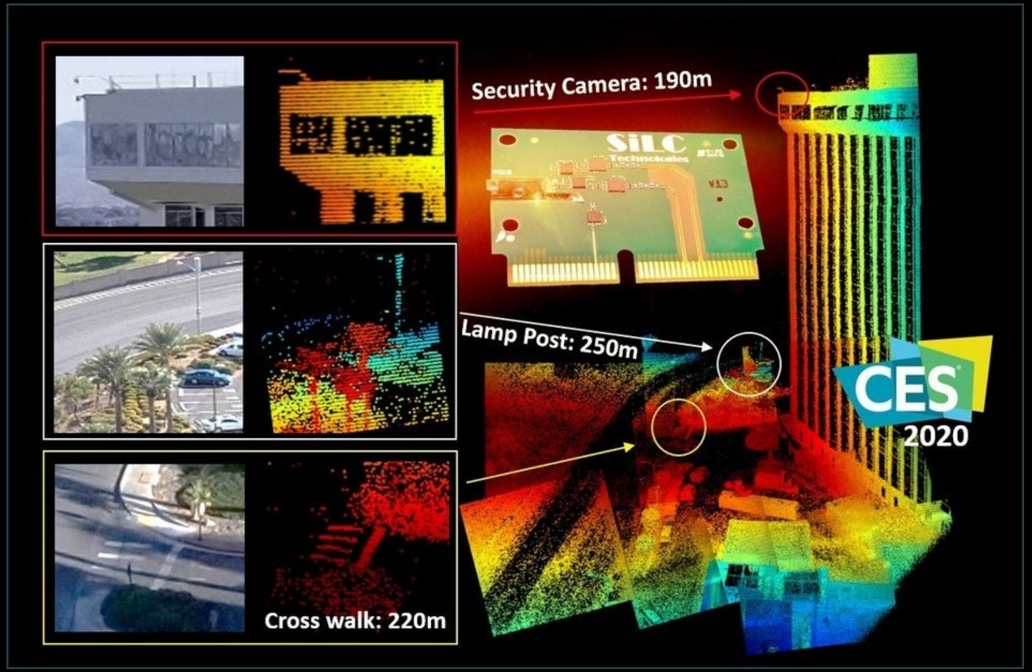
- Si waveguide (2-3 etch depths)
- Silicon nitride waveguide
- 2-3 routing metal layers
- Silicon modulators (P, N implants)
- Germanium photodetectors
- Telecom applications

Commercialization ongoing



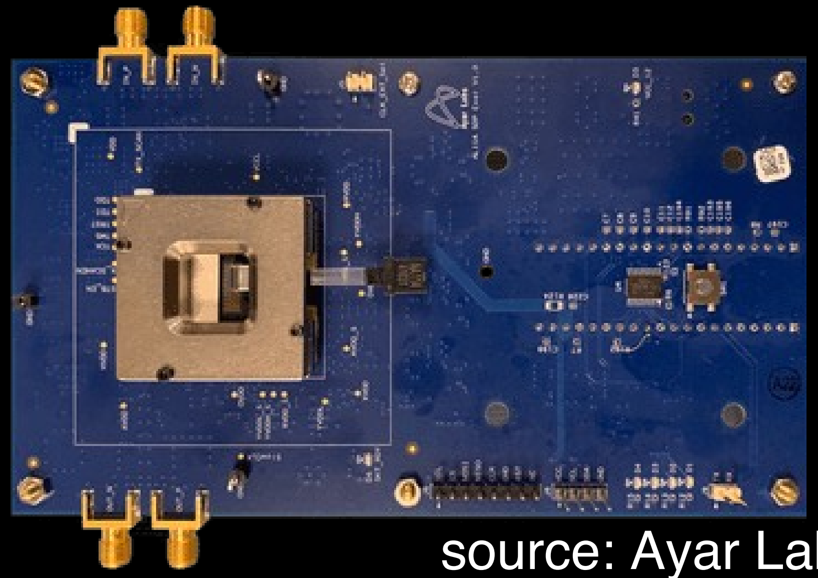
source: Intel

Transceivers



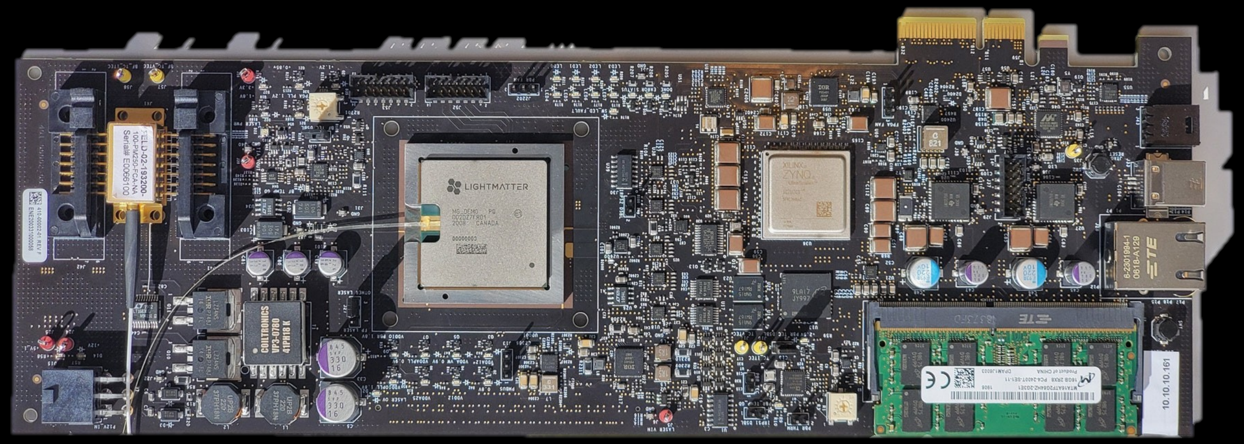
LiDAR

source: SiLC



source: Ayar Labs

Optical I/O

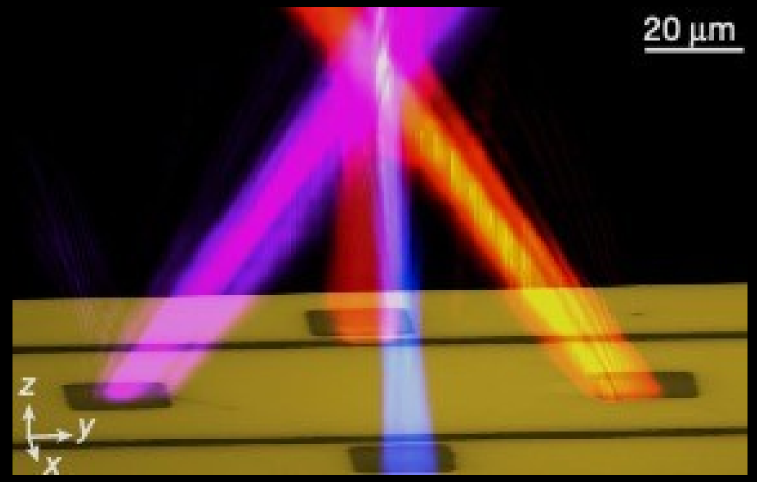


source: LightMatter

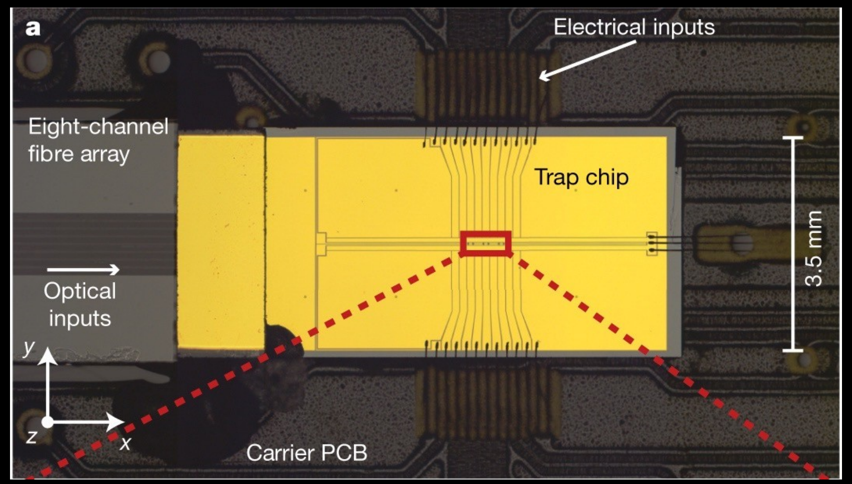
Special Purpose Compute Engines

Si photonics for the visible spectrum?
Some applications

Quantum Science and Computing (ion traps and cold atoms)

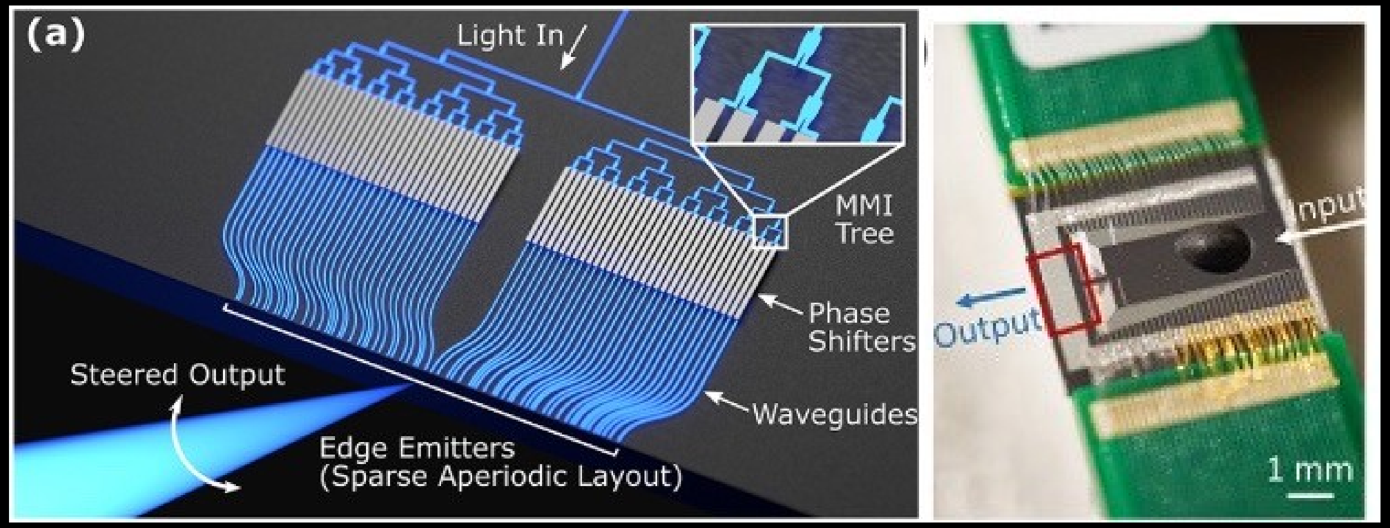


R. J. Niffenegger et al., Nature, 2020.



K. K. Mehta et al., Nature, 2020.

Beam-Scanners

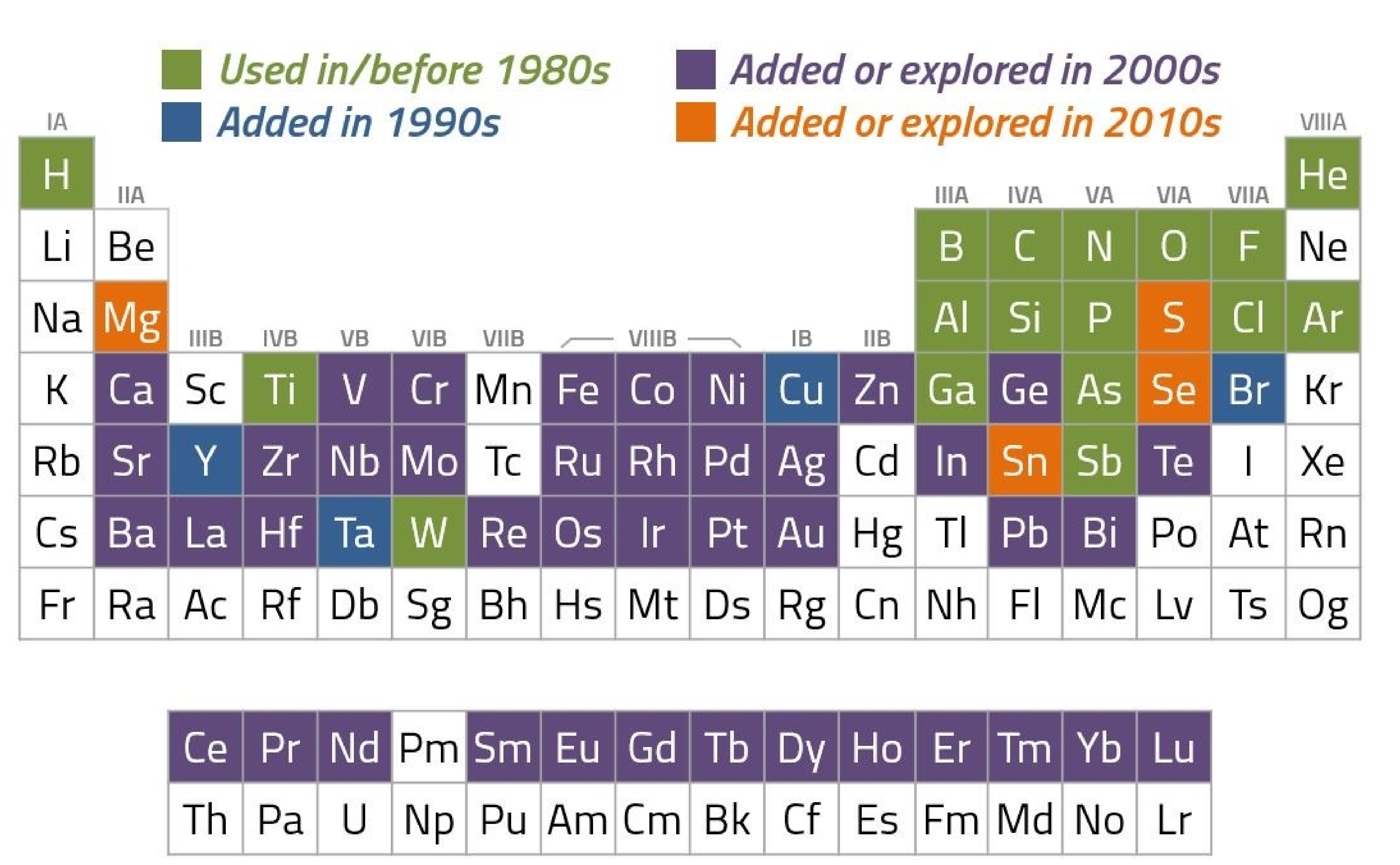


Shin et al., Optics Letters, 2020.

Spectroscopy and Fluorescence Sensing

Benefits of silicon photonics $\neq$ Silicon waveguides!

Elements used in the semiconductor industry

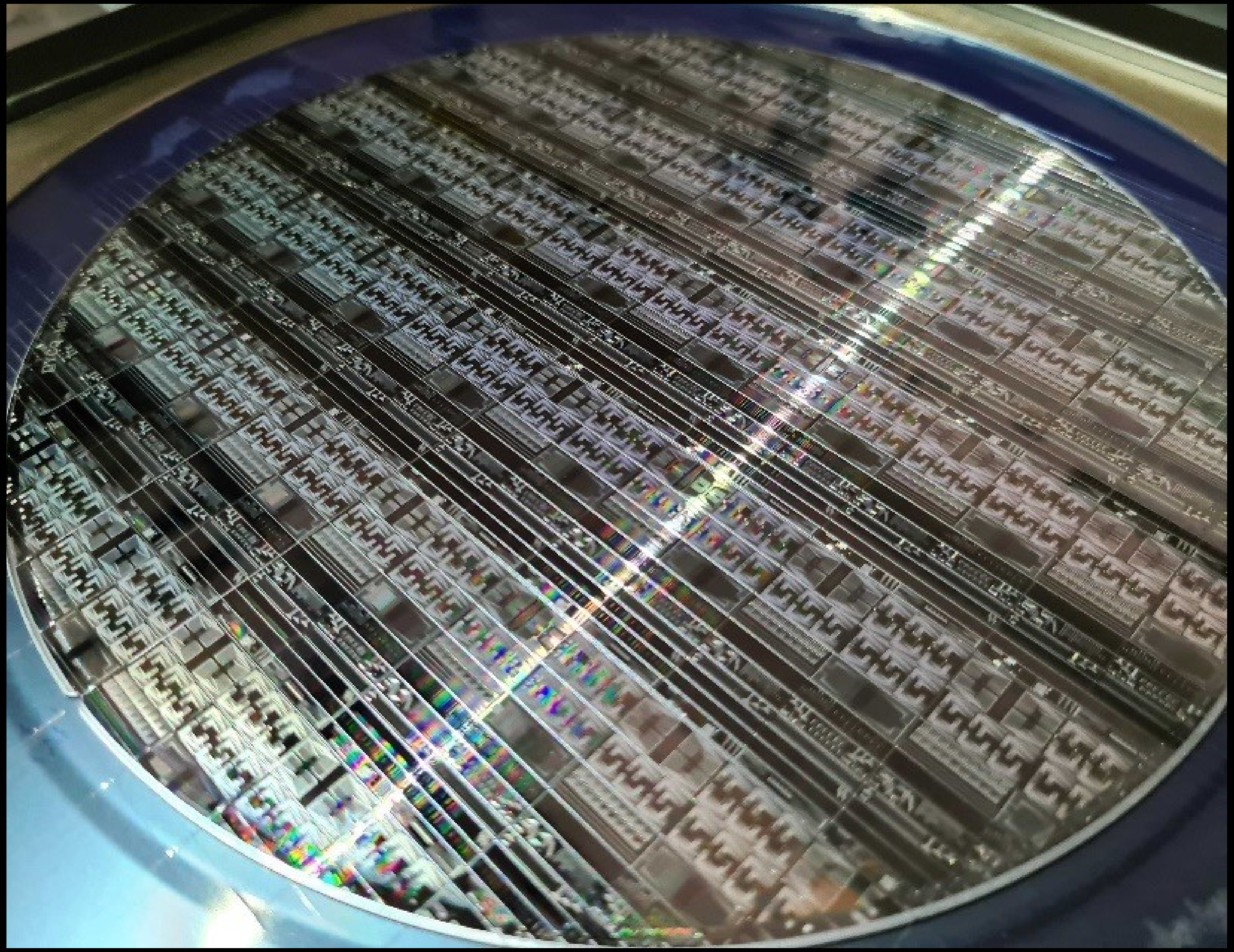


https://blog.lamresearch.com/happy-150th-birthday-to-the-periodic-table/

SiN or Al_2O_3 as waveguides
Selected progress on 200mm or 300mm Si

Material	Foundry	Reported Wavelength	Waveguide Loss	Reference
SiN (PECVD)	IMEC → Pix4Life BioPIX	532-900nm	< 1dB/cm @532nm	A. Z. Subramanian et al., IEEE Photonics Journal, 2013.
SiN	Witzens Group, CMOS Pilot Line	660 nm	< 0.5 dB/cm	S. Romero-García et al., Opt. Express, 2013.
SiN	AIM Photonics	635 nm	?	C, V. Poulton, et al. Opt. Lett. 42, 21-24, 2017.
SiN (LPCVD)	Ligentec	?	0.1 dB/cm?	Press releases
SiN (LPCVD)	LioniX	405-640 nm	0.3-0.4dB/cm @405nm	Mashayekh et al., Opt. Express. 29, 8635, 2021.
Al_2O_3	MIT Lincoln Labs	371-1092 nm	2.6 dB/cm @371nm 0.6 dB/cm @458nm	C. Sorace-Agaskar, et al., Proc. SPIE, 2018.
Al_2O_3	Ram Group, MIT with MIT Lincoln Labs	371-458 nm	3dB/cm @371nm ~1dB/cm @ 458nm	G. N. West et al., APL Photonics, 2018.

Our approach:
SiN on 200mm Si, 193nm DUV



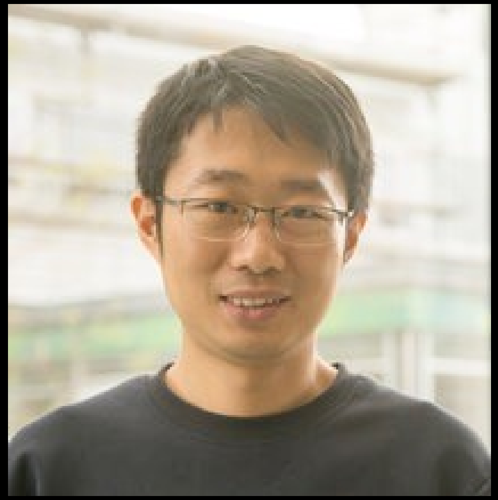
- with Advanced MicroFoundry (Singapore)
  - Dr. Xianshu Luo
  - Dr. Patrick Lo

amf ADVANCED MICRO FOUNDRY

Acknowledgment: Visible Photonics Team

Wesley Sacher

Zheng Yong

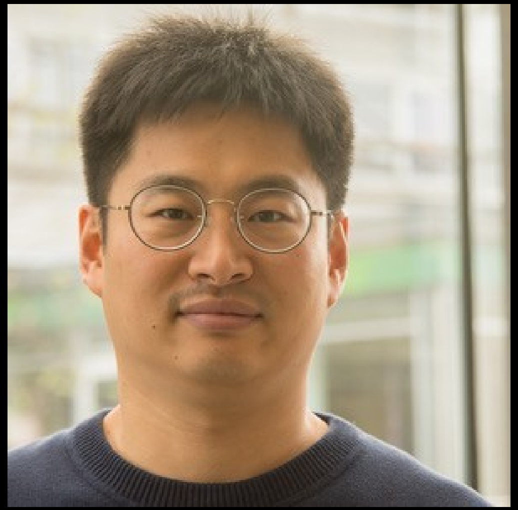


Yiding Lin

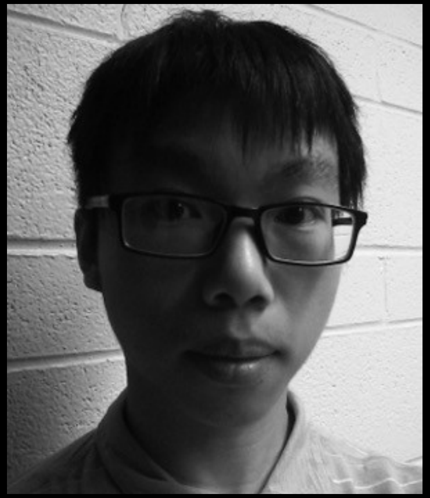
Saeed Azadeh

Hong Chen

Alperen Gövdeli



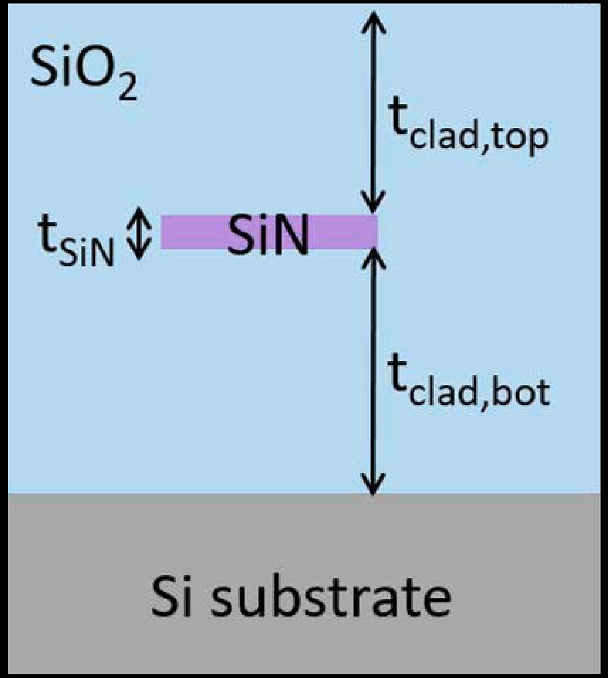
Youngho Jung

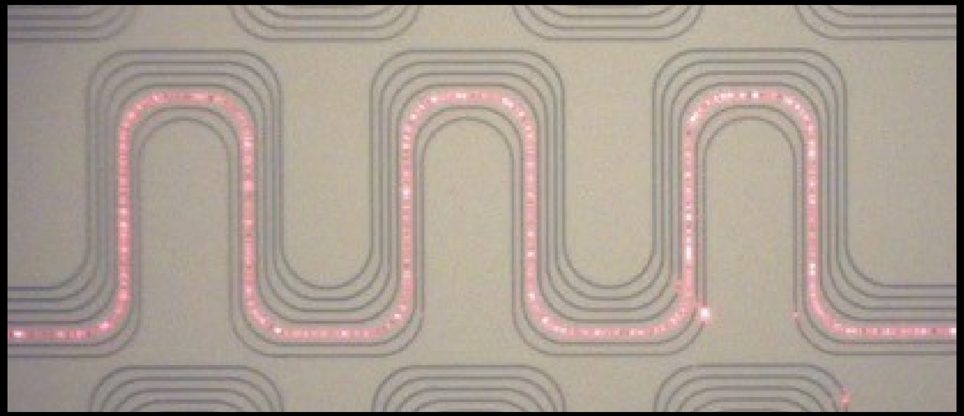


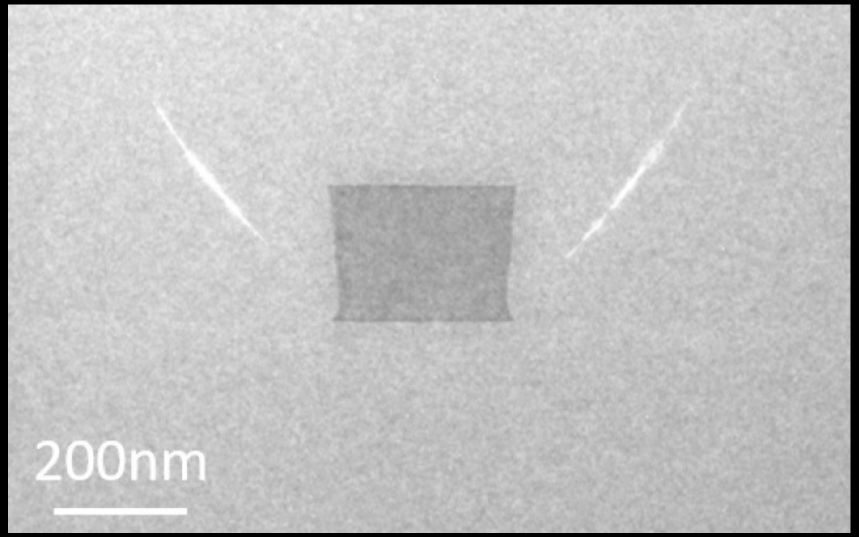
Jason Mak

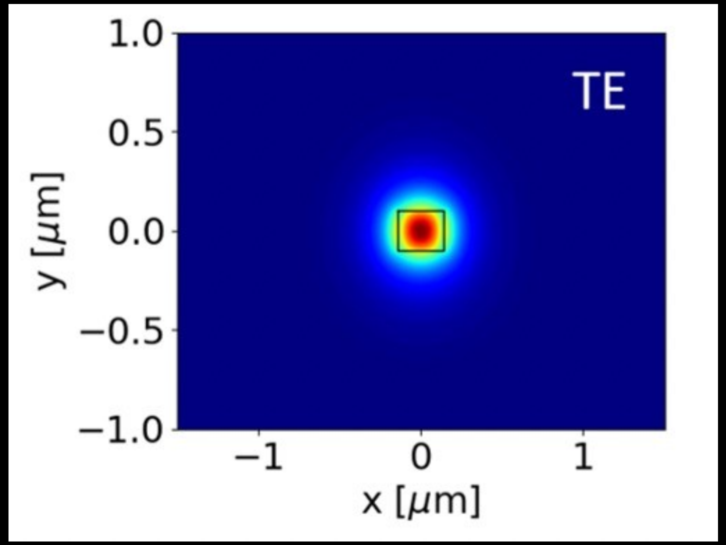
Andrei Stalmashonak

Single-mode, high confinement waveguides

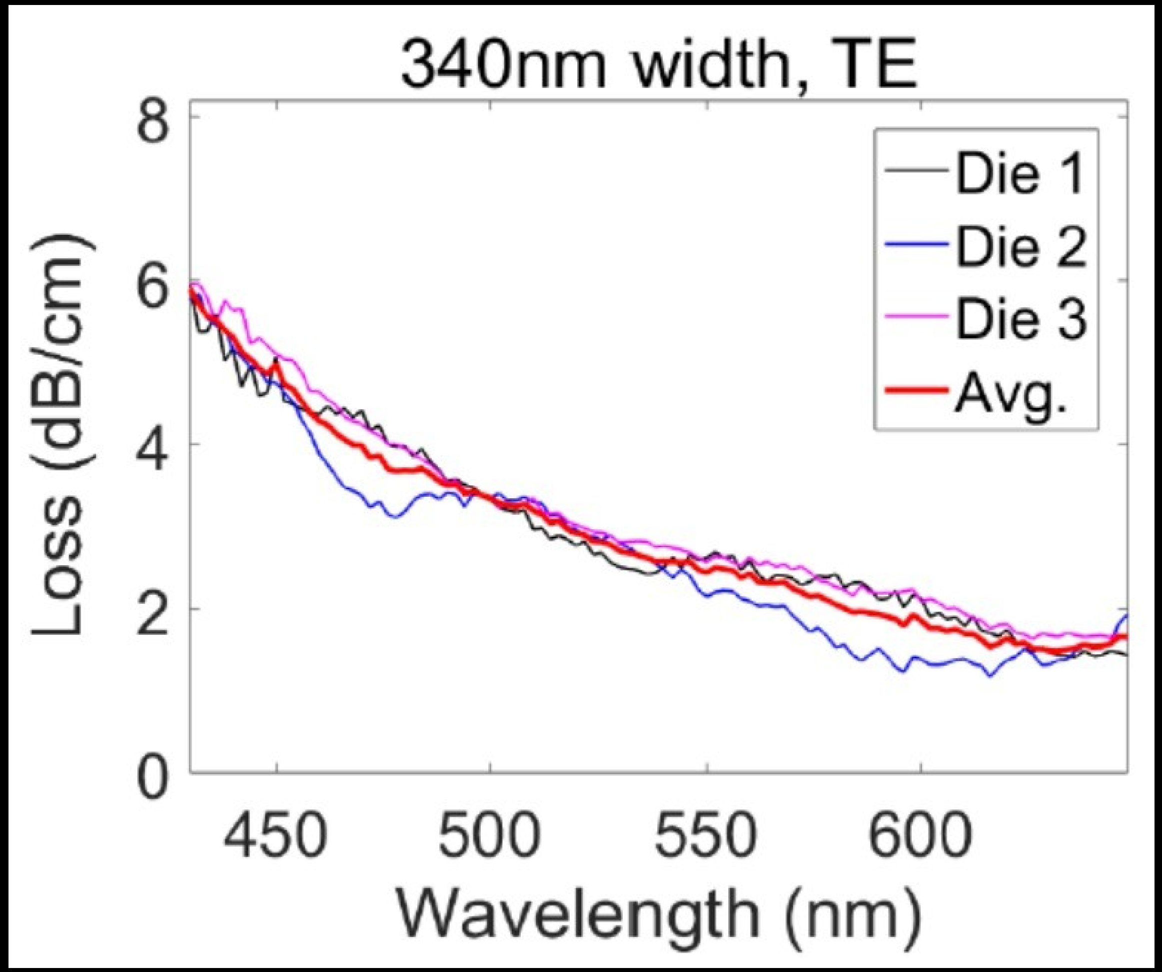








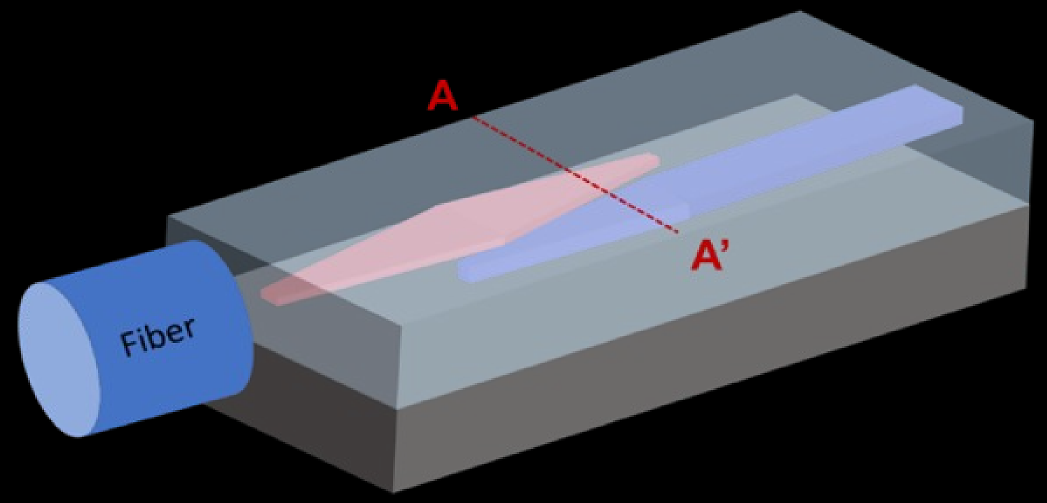
Single-mode waveguide loss
PECVD SiN, 135nm thickness

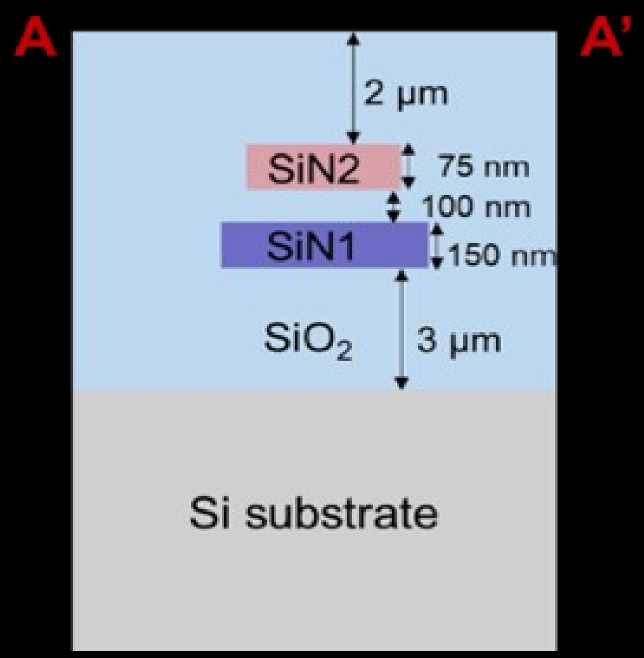


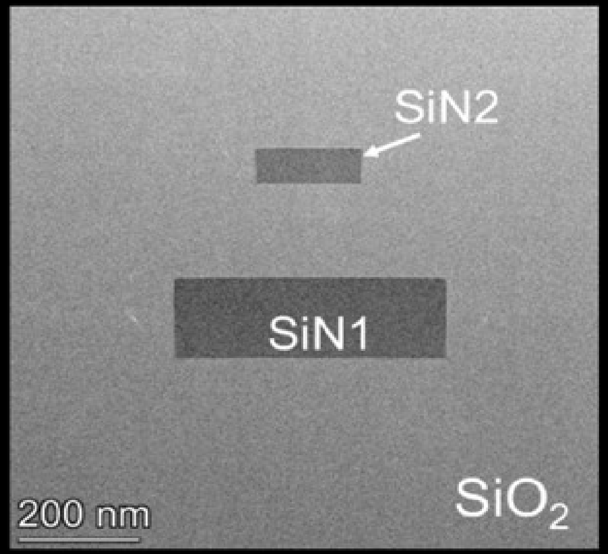
LPCVD SiN similar to PECVD

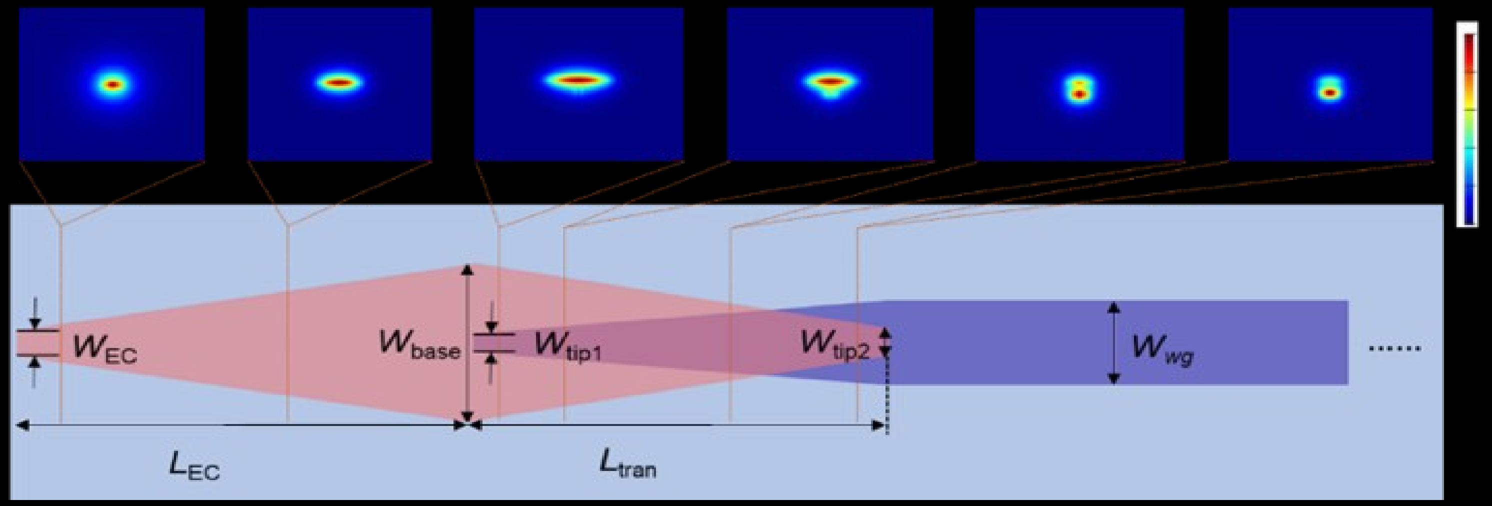
W. D. Sacher et al., Optics Express, 2019.

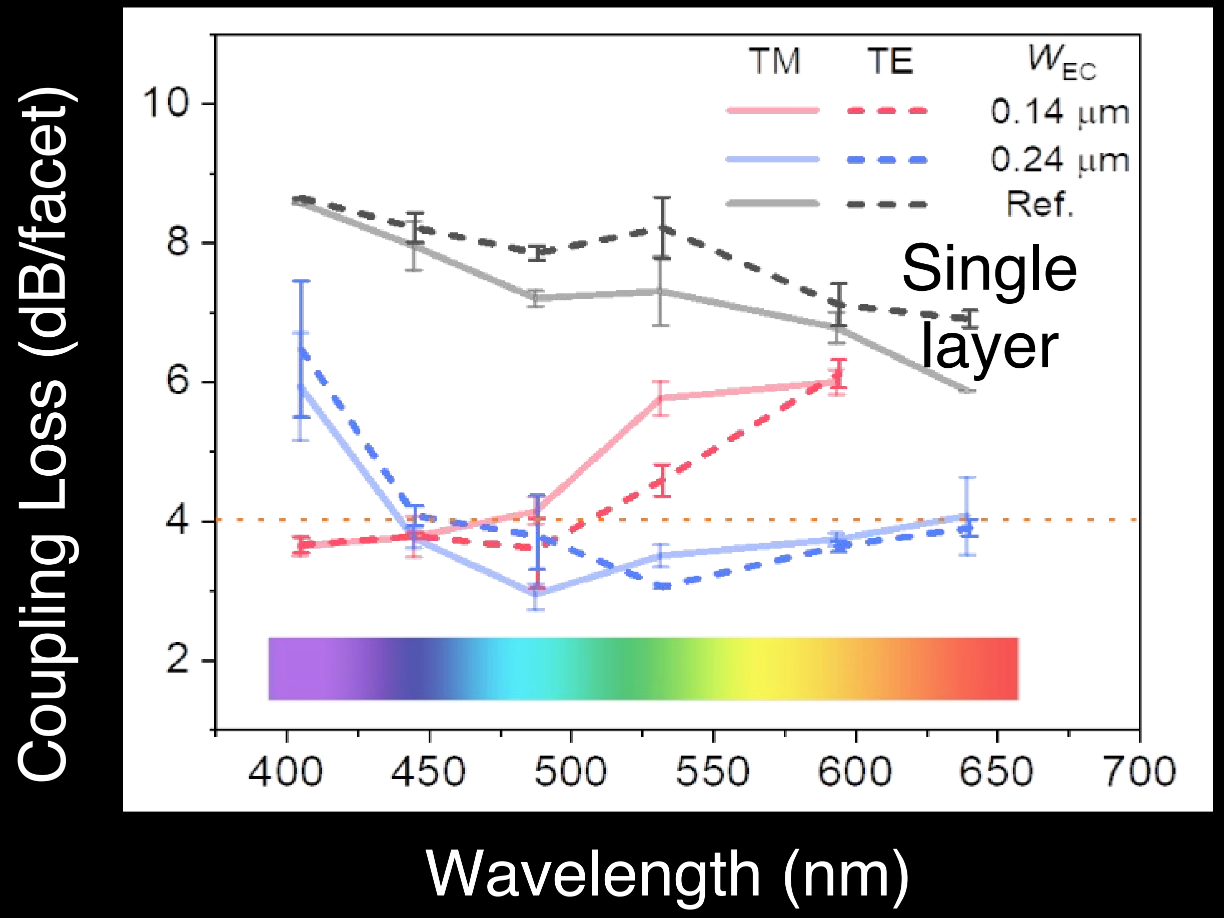
Bilayer edge couplers





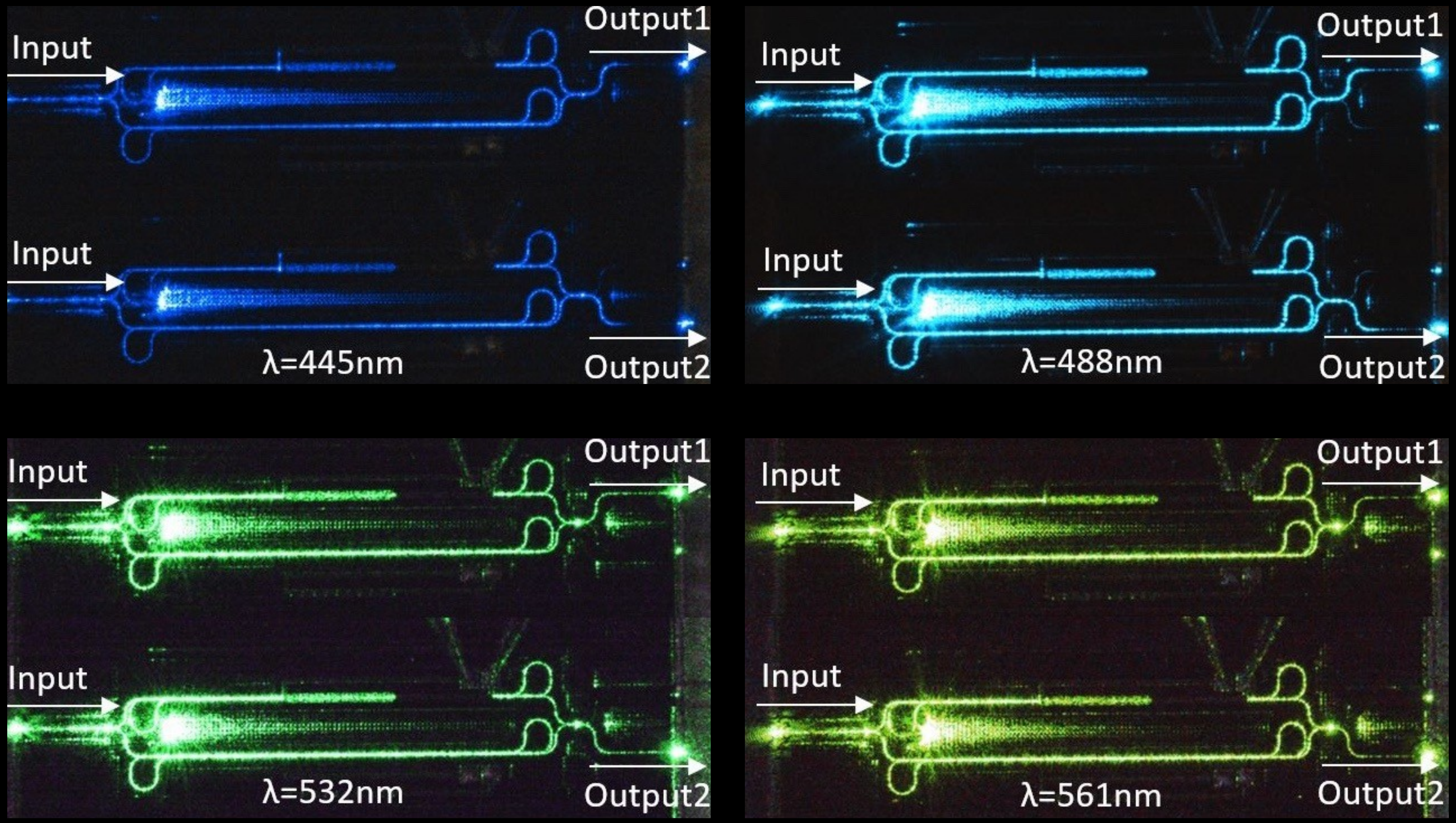




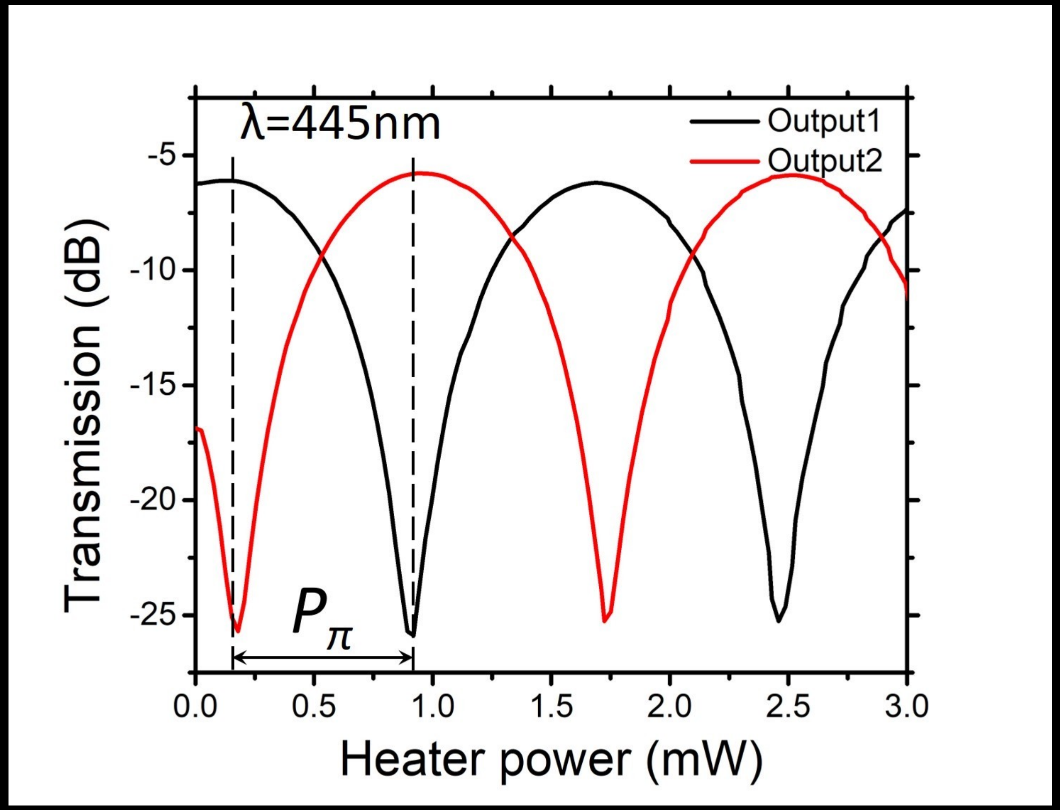


Lin et al., CLEO 2021
Manuscript submitted.

Thermo-optic phase-shifters



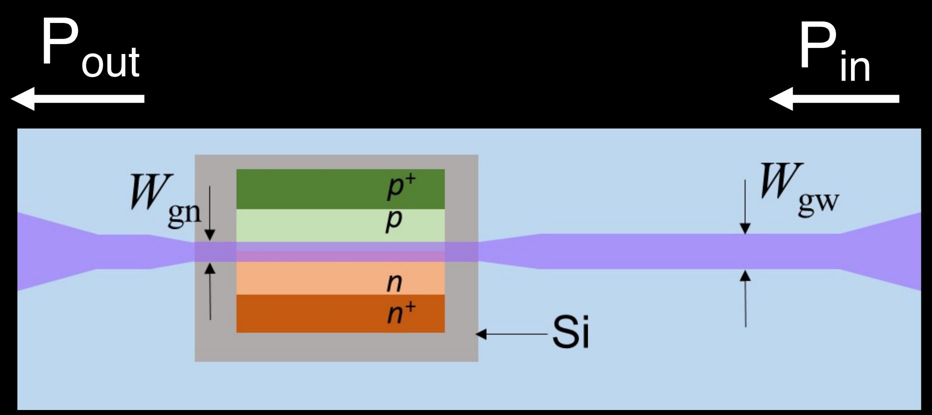
$P_\pi \sim 0.8$ mW @ 445nm

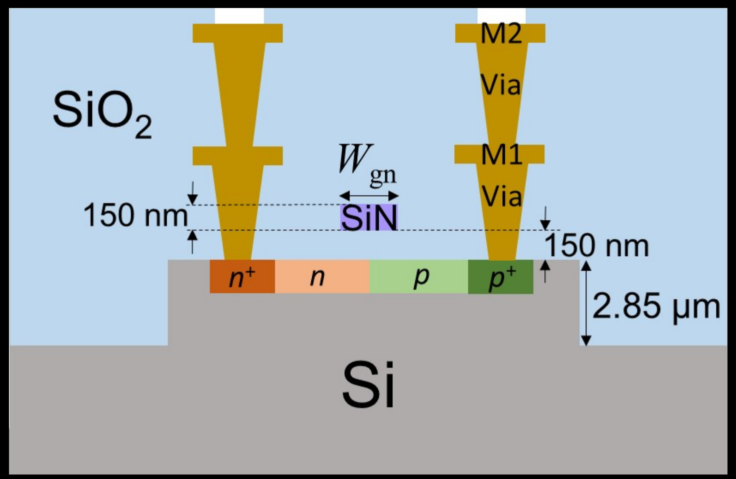


10%-90% Rise/fall time: 570/590us

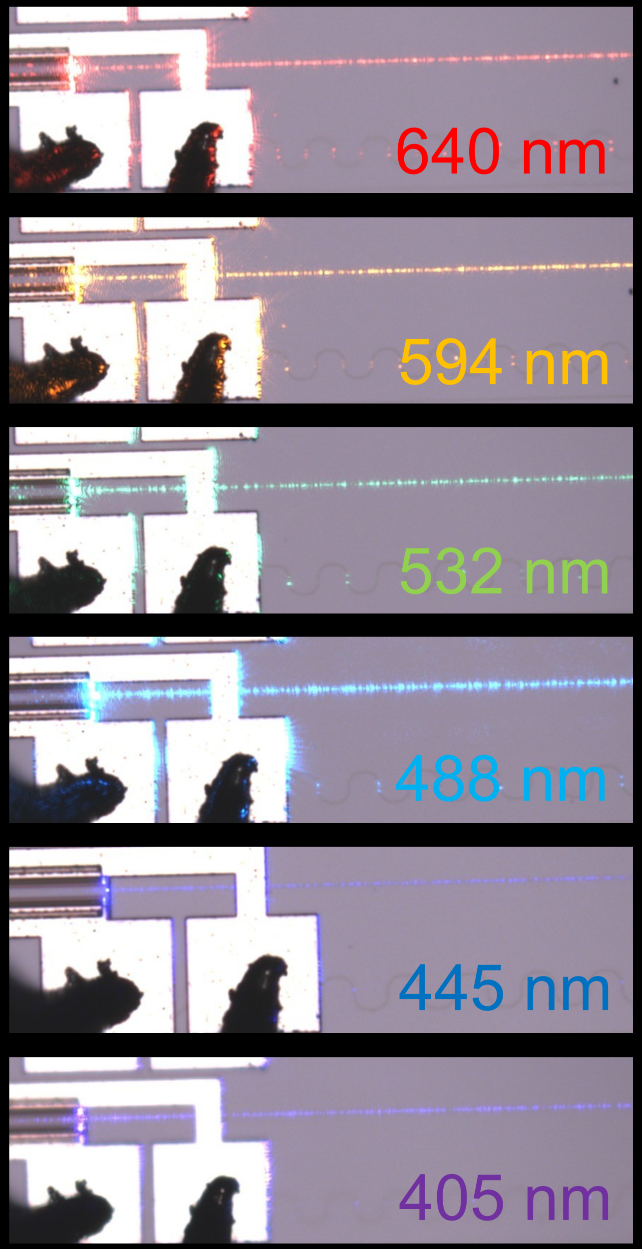
Manuscript in preparation.

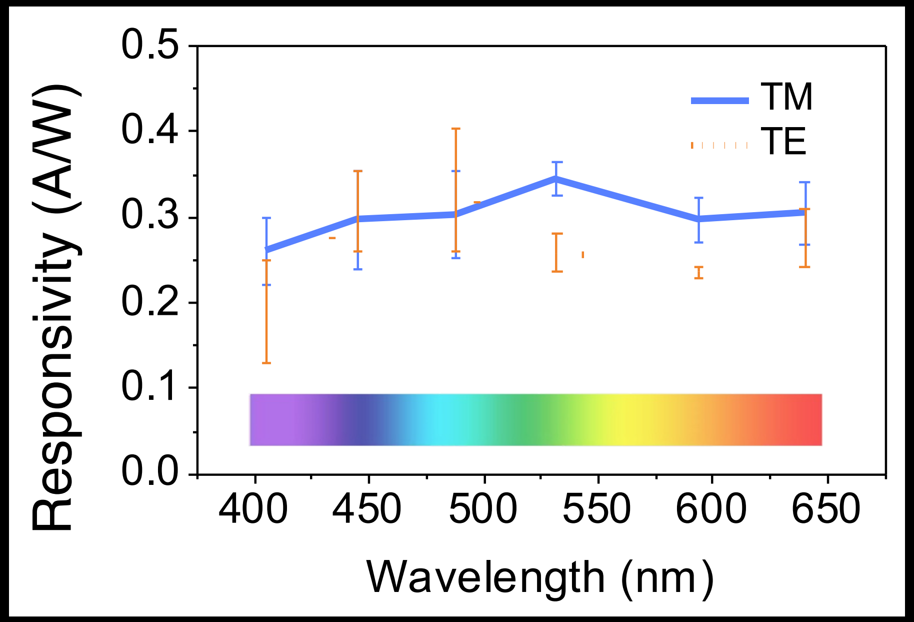
SiN-Si waveguide photodetectors

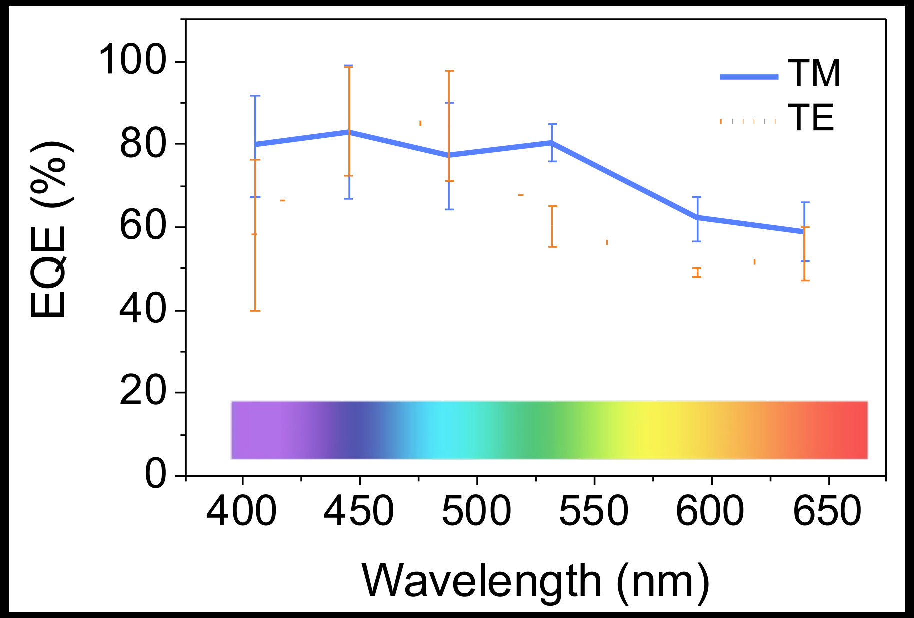




PIN diodes also



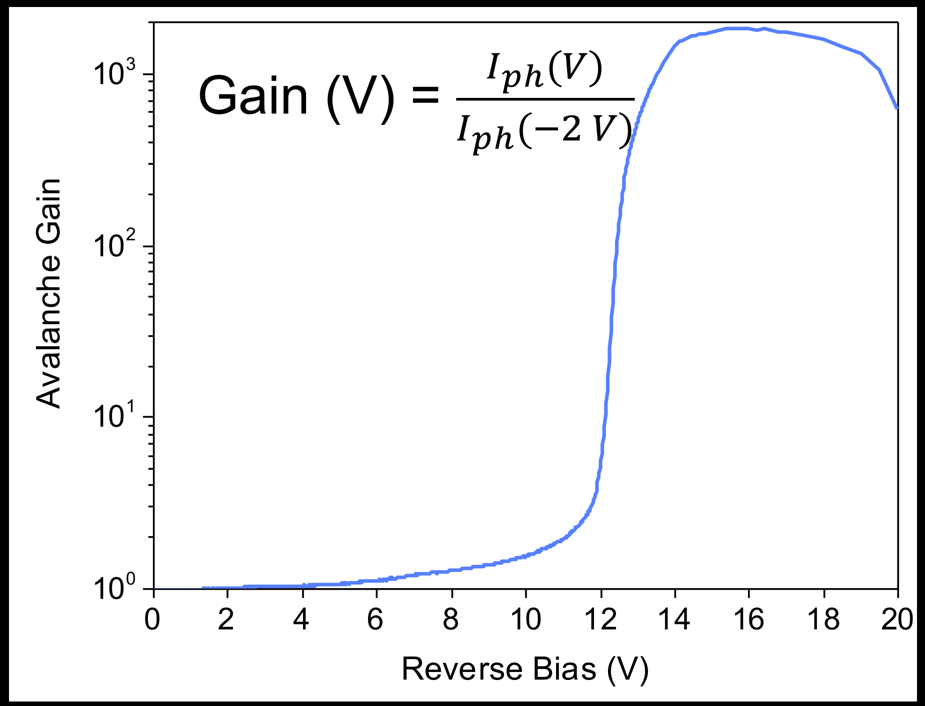




Dark current: 28pA @-2V

l = 50um

Avalanche Gain
(PN junction)

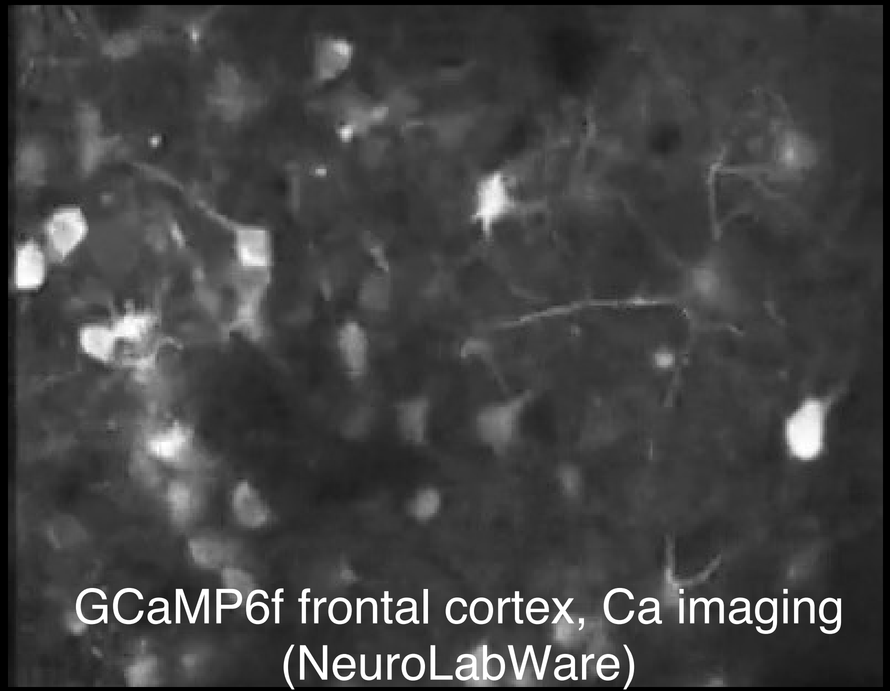


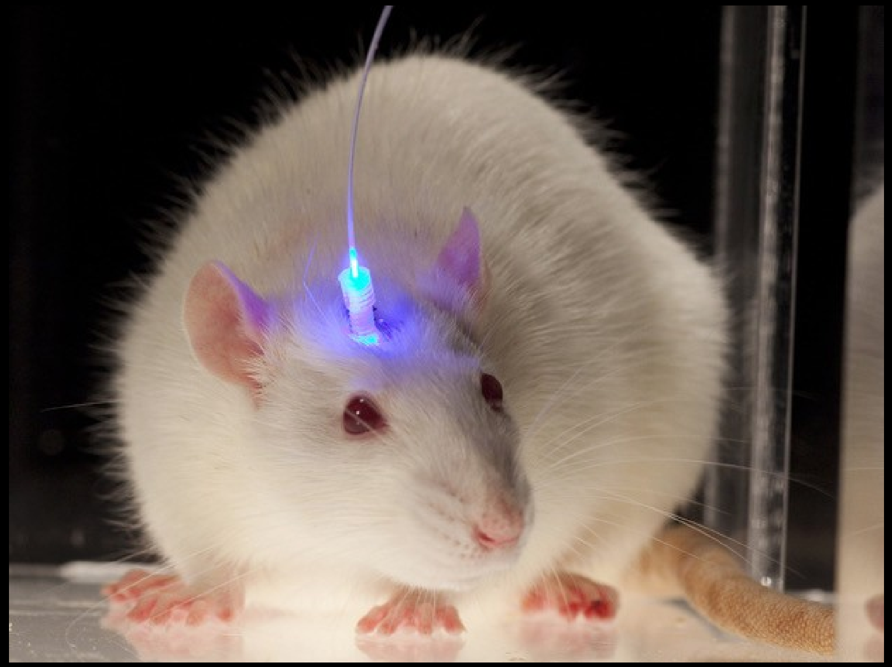
Avalanche gain up to 1800 at -17V at $P_{in,PD}$ of -23.9±0.3 dBm

Lin et al., CLEO 2021

Application:
Light for brain activity mapping

- Genetically modified neurons actuated by or emit light



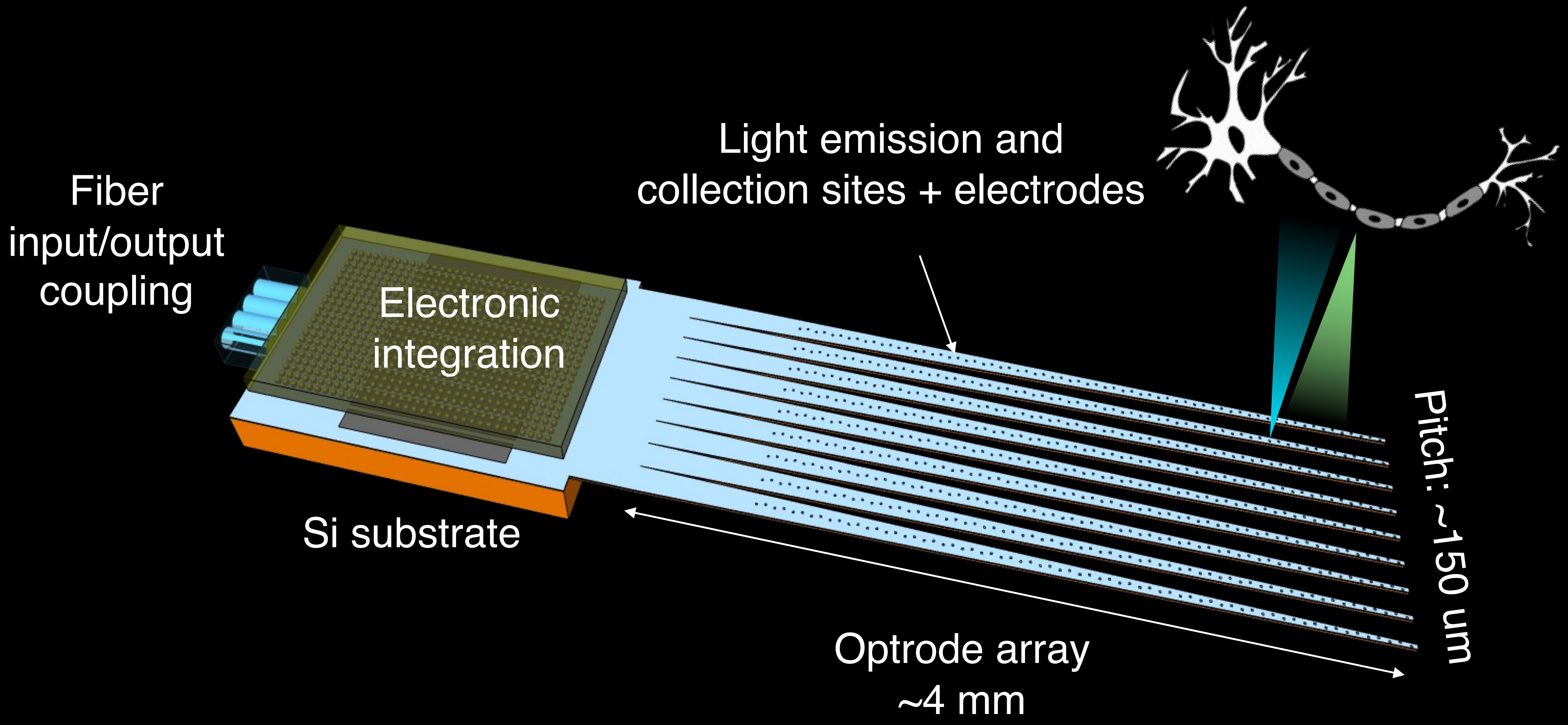


Deisseroth lab

Functional optical (fluorescence) imaging
genetically encoded calcium or voltage indicators

Optogenetics
deterministic photo-actuation of neurons

Implantable neurophotonic probes



Overcome optical scattering limit for deep (> mm) brain access

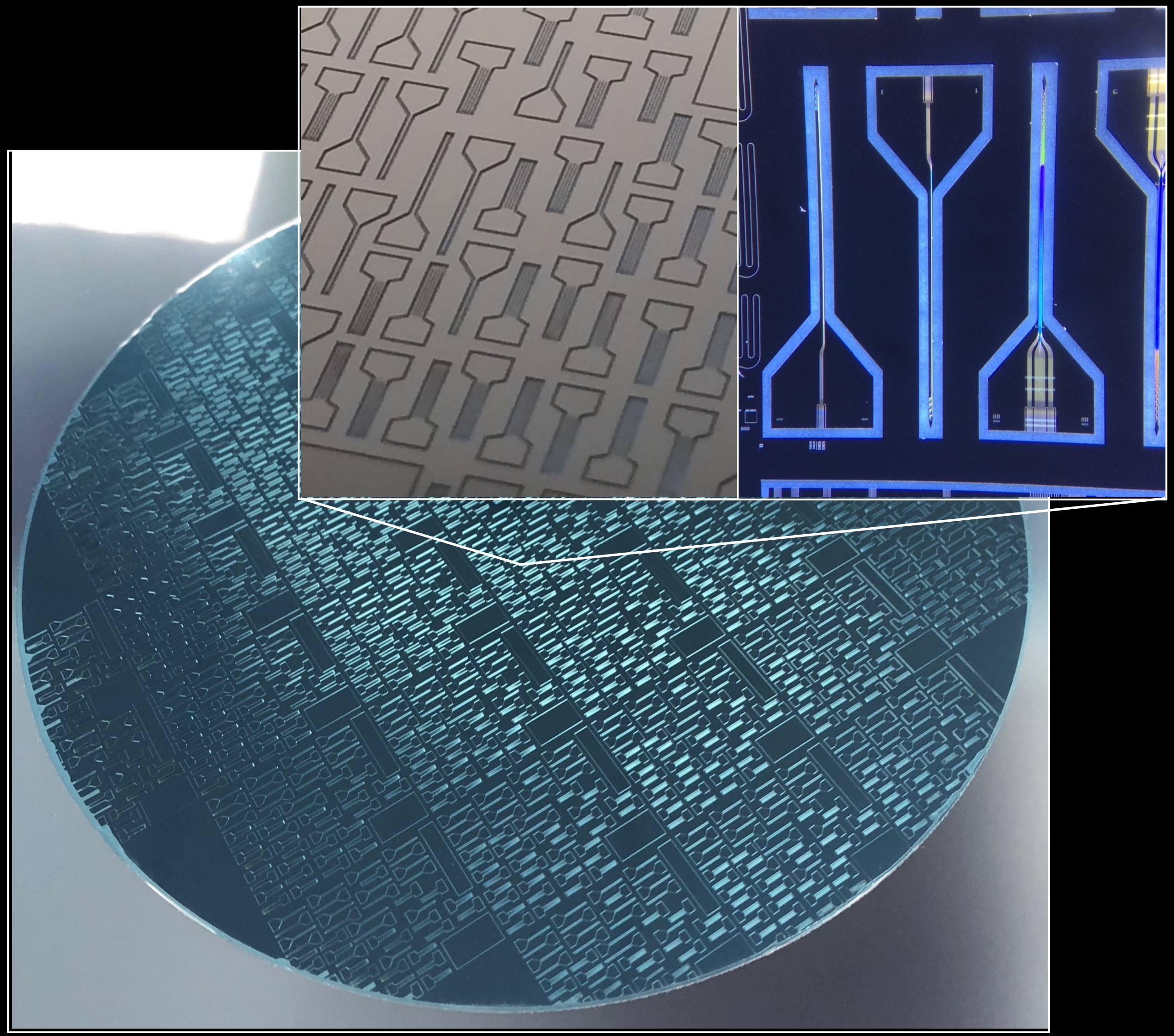
Massively parallel interrogation with single neuron resolution

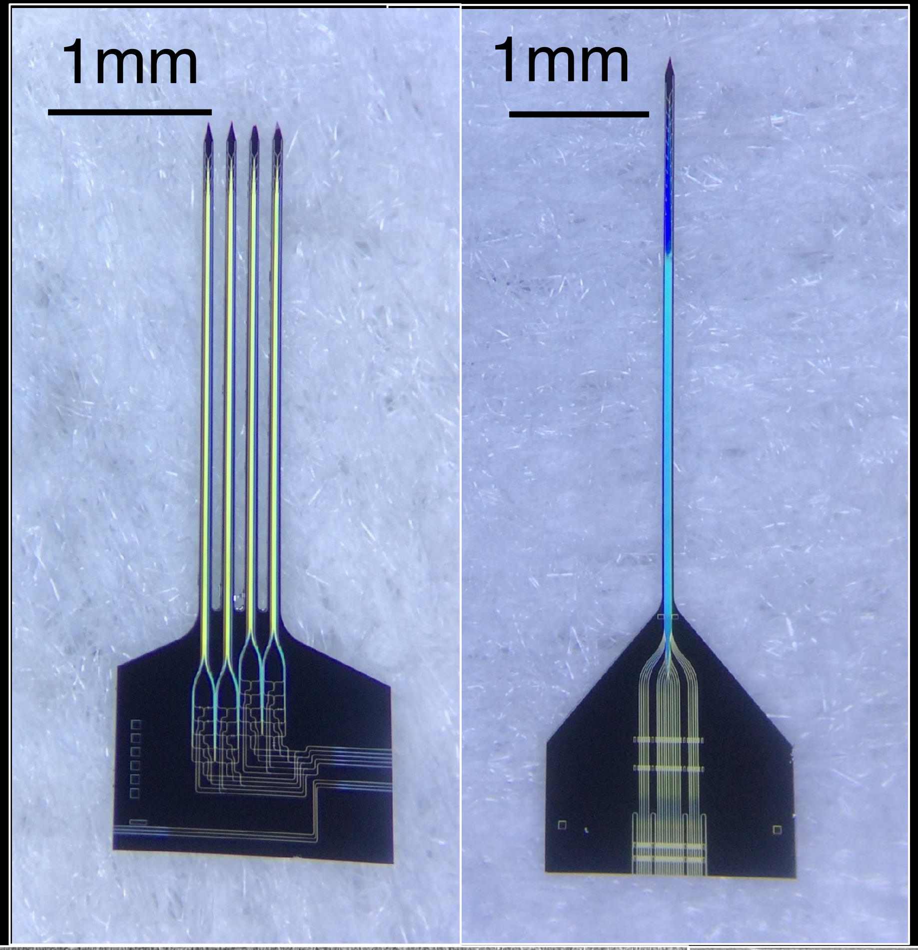
Foundry manufacturing for complexity and broad dissemination

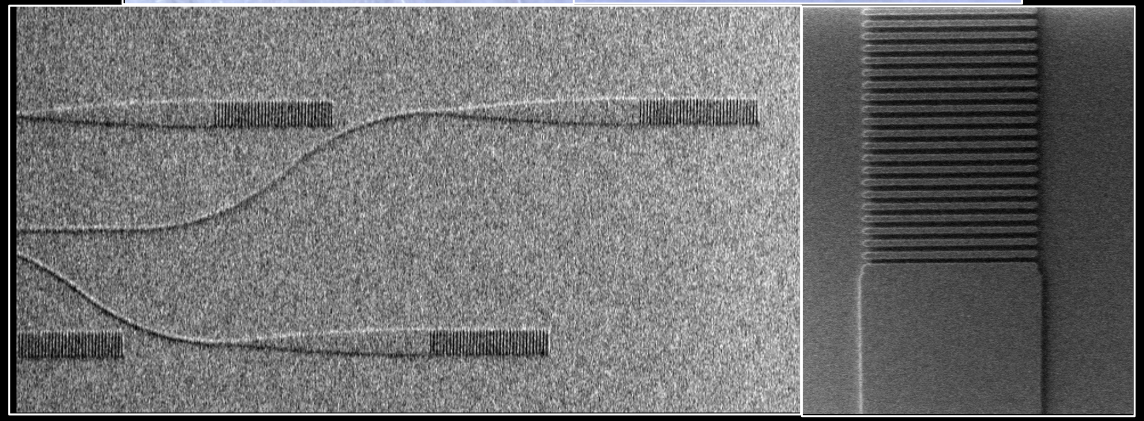
Foundry-fabricated neurophotonic probes

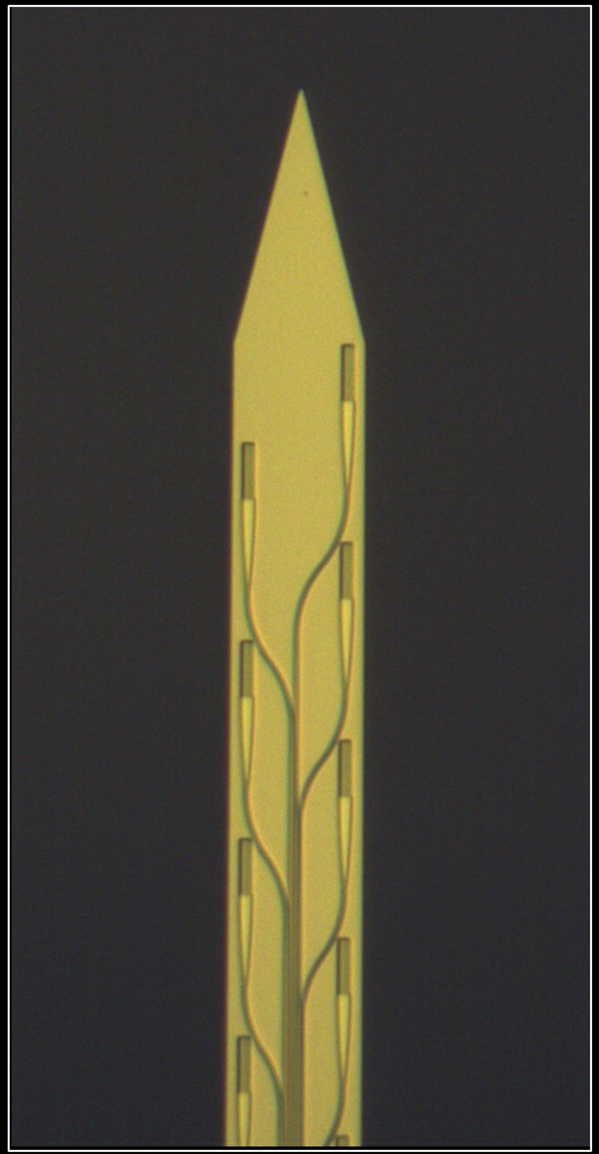
Xianshu Luo
Patrick Lo

- 200mm (8”) wafers, DUV lithography, full-wafer thinning
- >1600 probes on 1 wafer



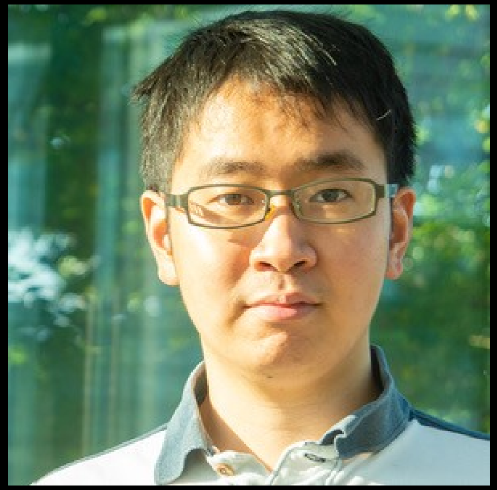






Acknowledgment: Neuroprobe Team

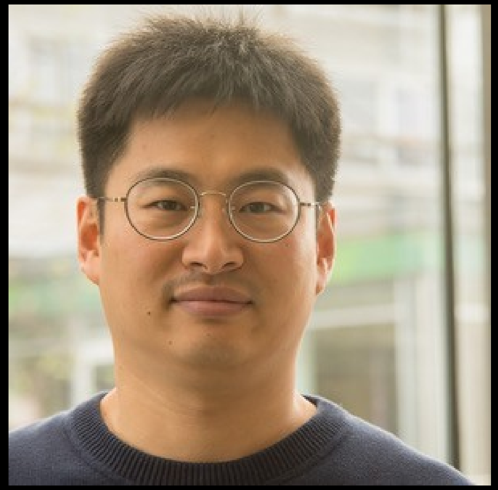
Wesley Sacher



Fu-Der Chen

John Straguzzi

Hannes Wahn



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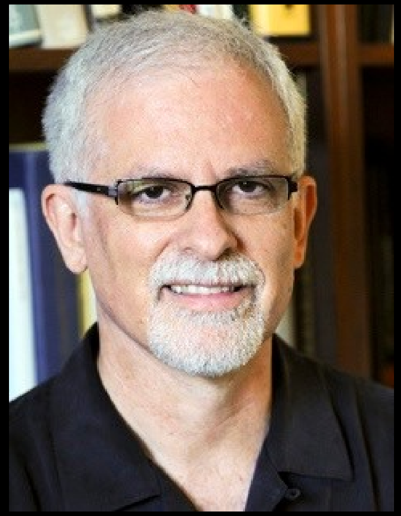
Andres Lozano
(UHN, U of T)



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Sara Mahallati
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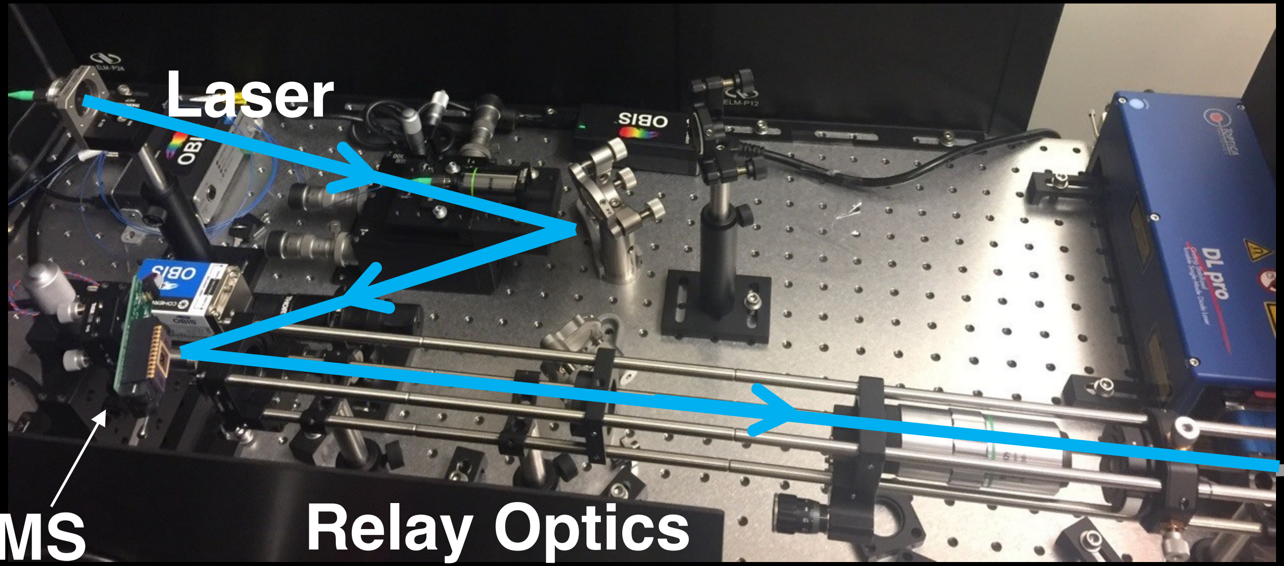
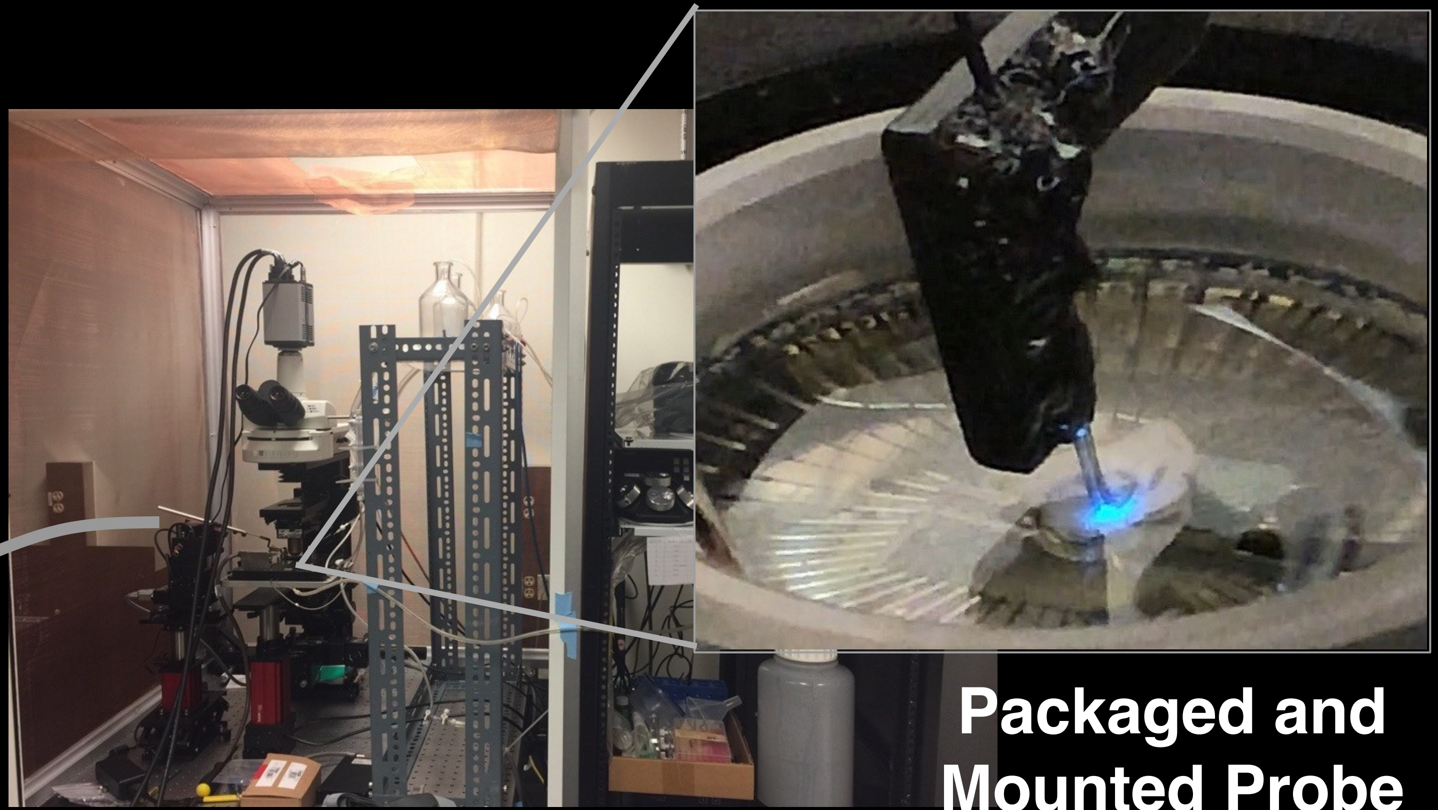
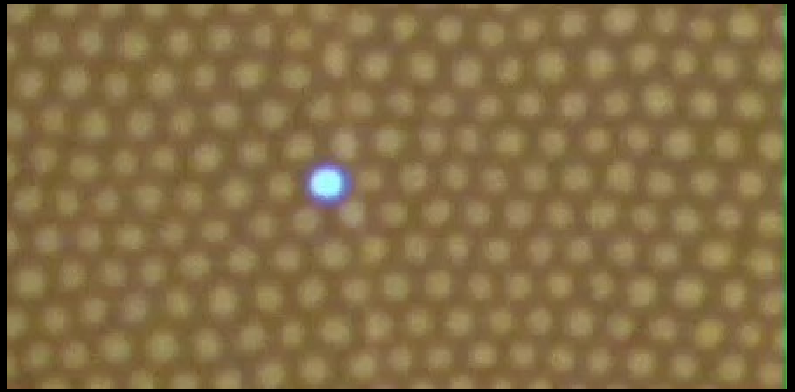
Approach:
Passive neurophotonic probe with spatial addressing



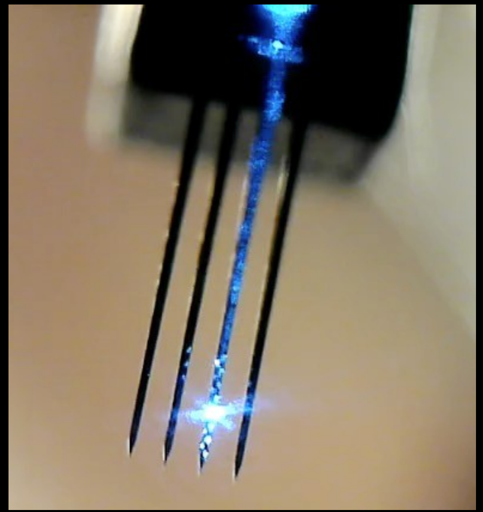


Packaged and
Mounted Probe

Fiber Bundle Cross-Section



with Auto-Pix:
the Pixel Dance!

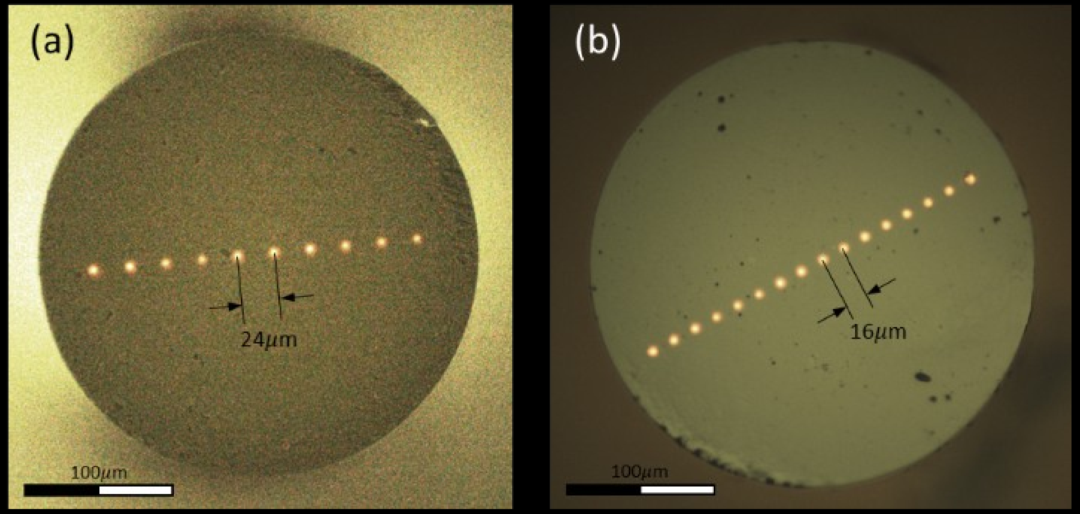


Improvements:
Custom multi-core optical fibers & Mini-Scan

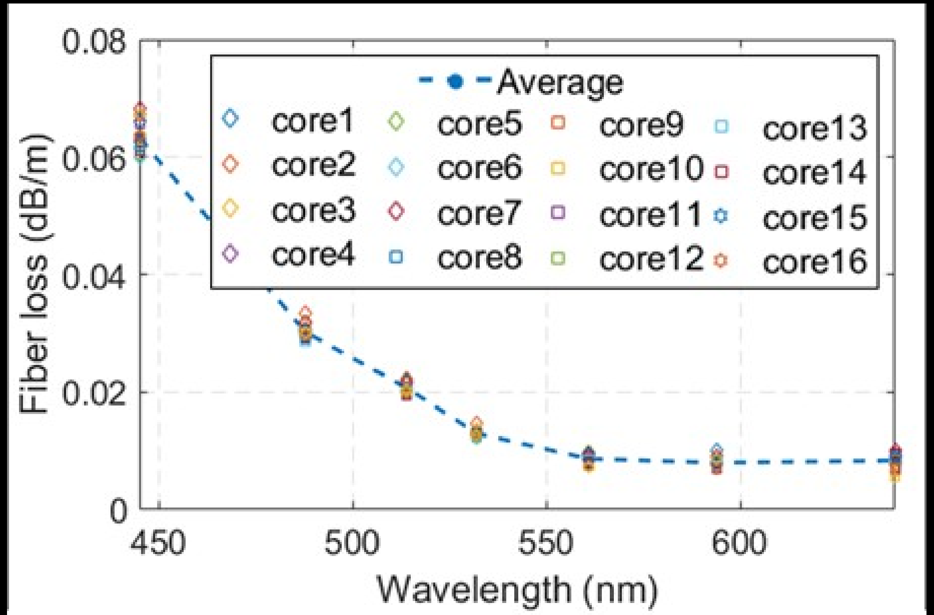
- 10 and 16 single-mode cores
  - Nominal pitch: 24um, 16um
  - Fiber diameter: 300um

CORNING

Kevin Bennett

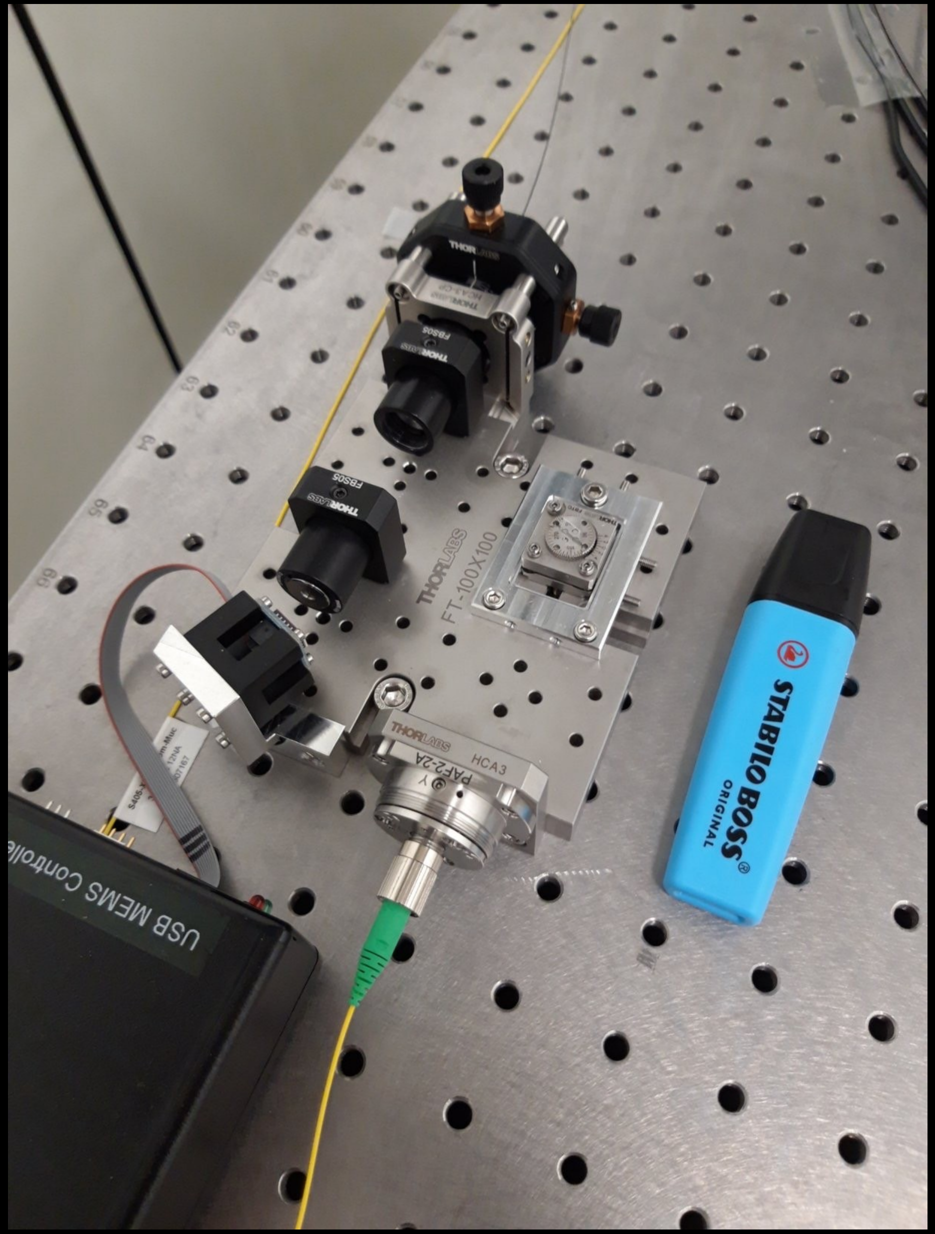


Fiber loss



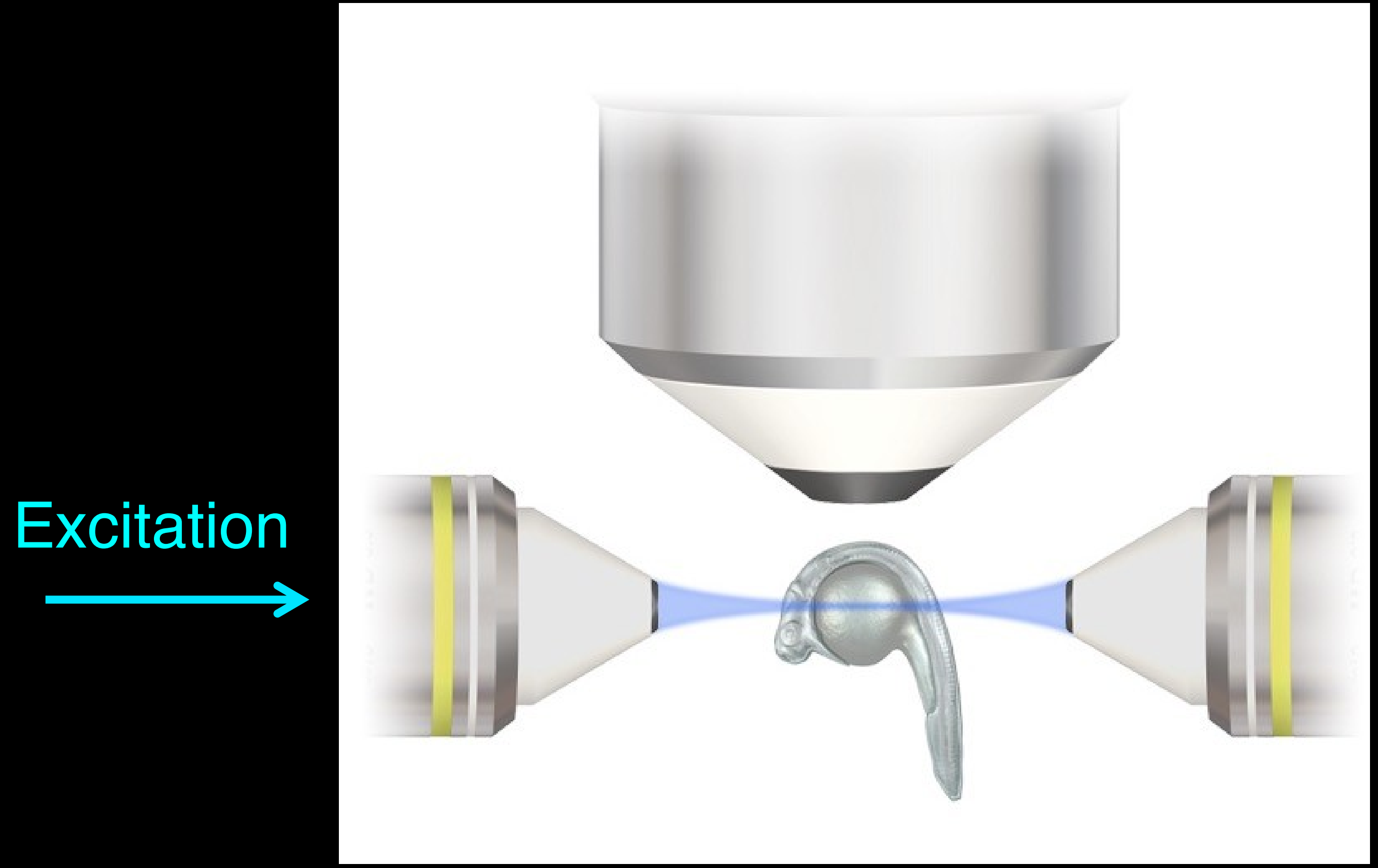
Azadeh et al., CLEO, 2021.

Miniaturized scanning unit

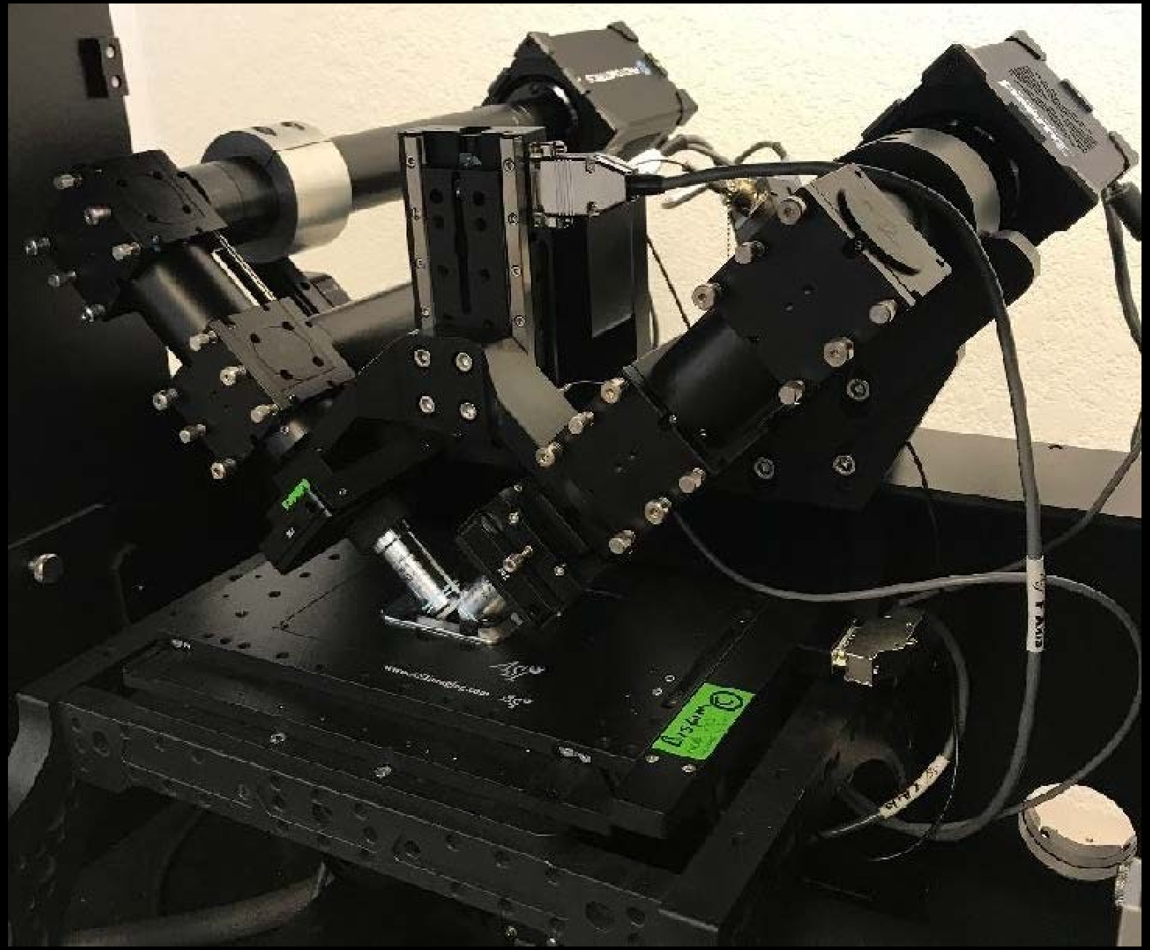


Lightsheet fluorescence microscopy

- Selective Plane Illumination Microscopy
- Image 1 plane at a time ⇒ Large volume imaging
- So far, only applies to transparent small organisms due to bulkiness of the optics



https://www.microscopyu.com/techniques/light-sheet/light-sheet-fluorescence-microscopy

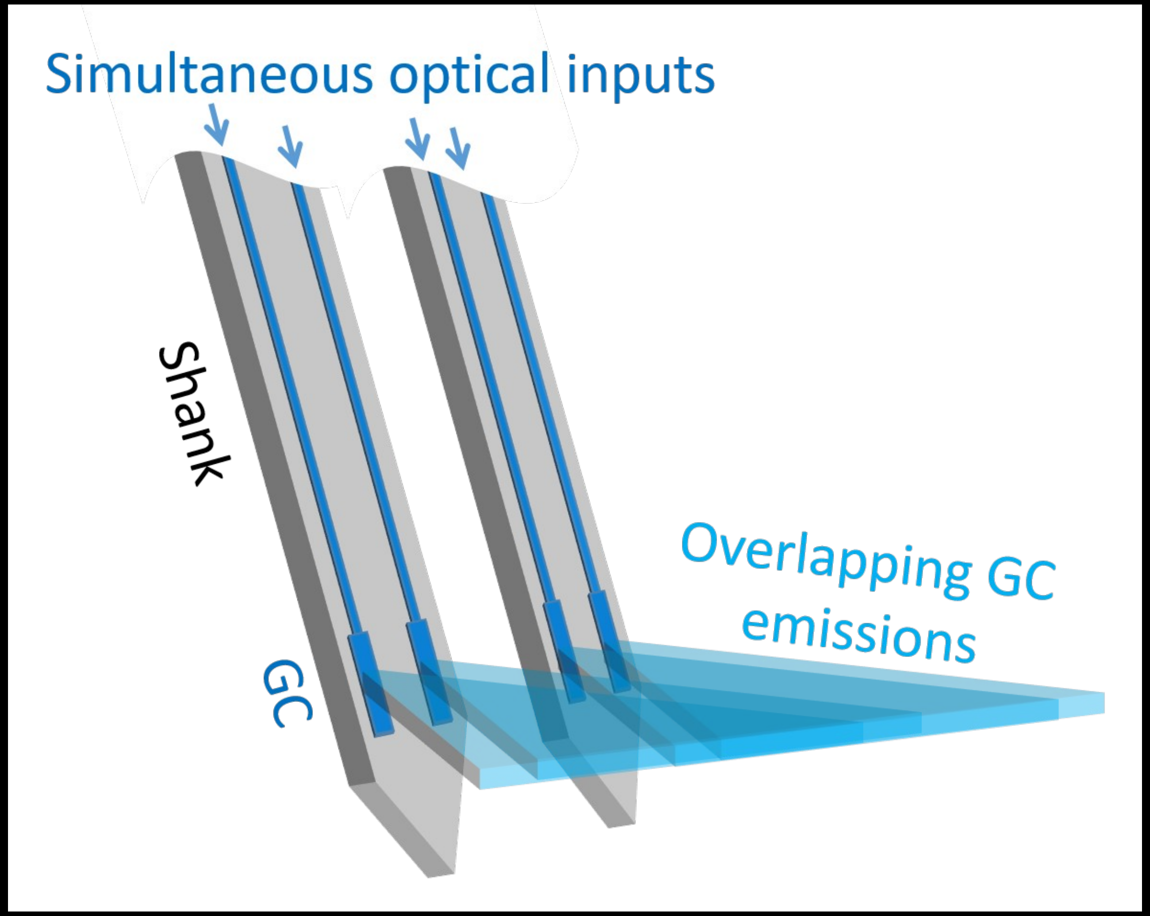


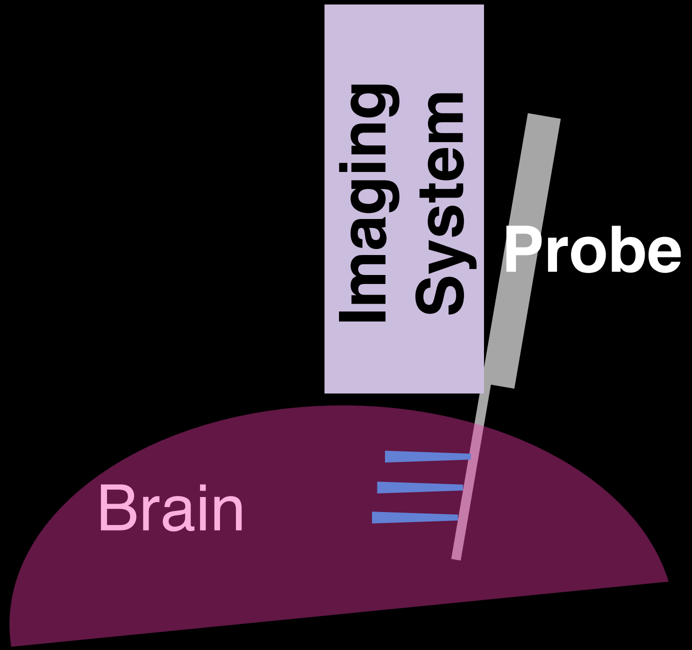
https://www.photometrics.com/applications/appnotes/dispim

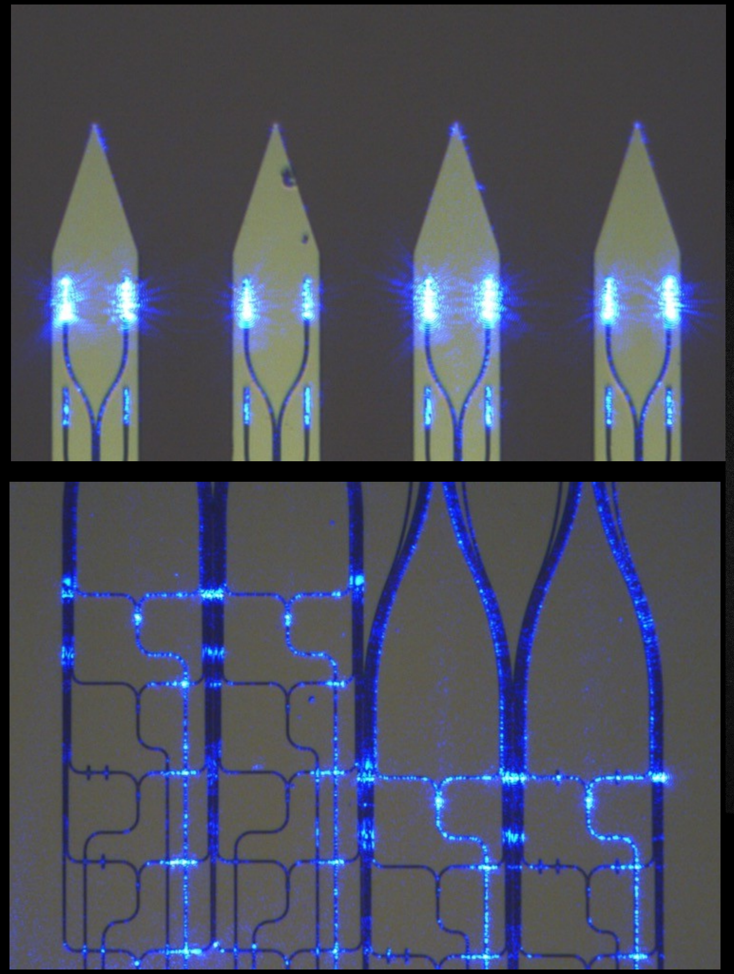
Lightsheet imaging neurophotonic probe

Michael Roukes
Taufik Valiante, Andres Lozano

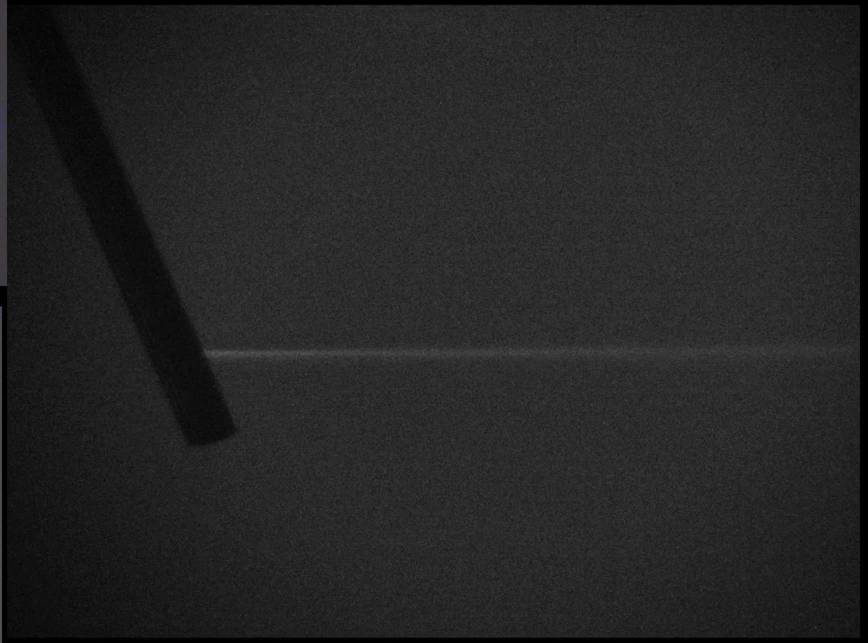
- Synthesize lightsheet from multiple grating couplers
- Implantable miniature light source ⇒ lightsheet microscopy in non-transparent organisms







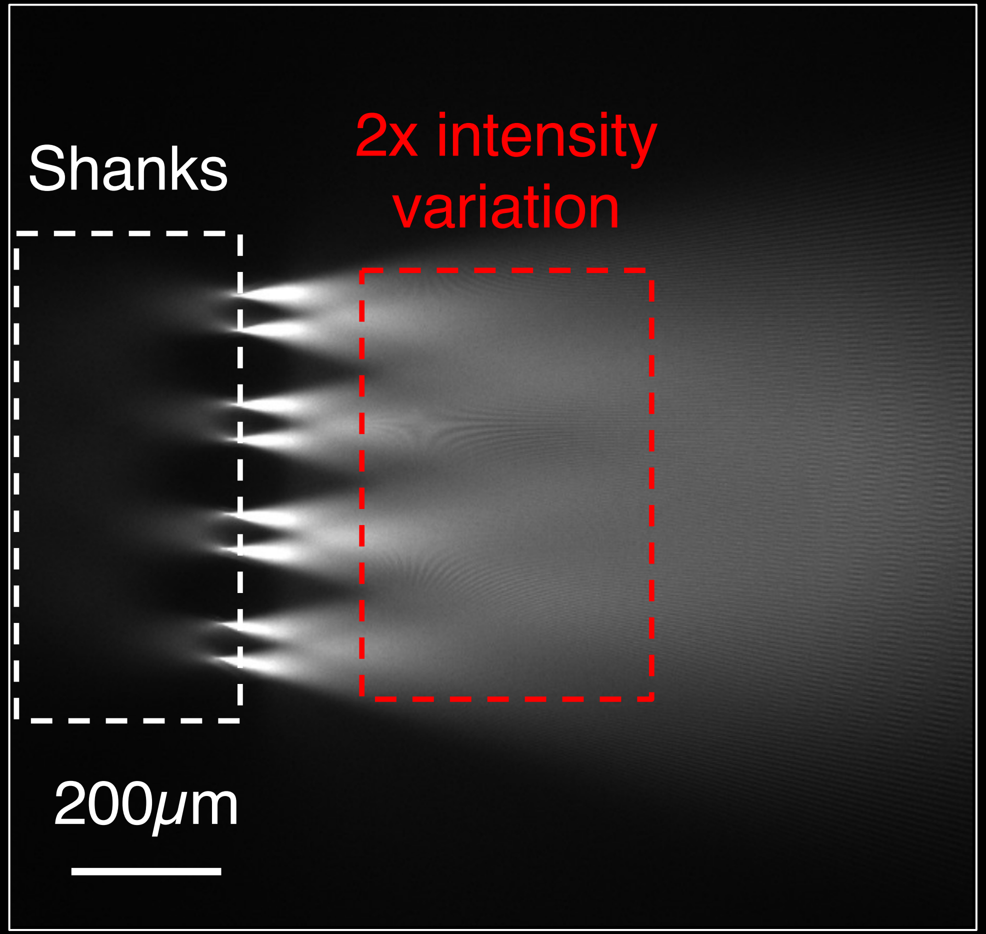
Fluorescein side profile



Sacher et al., Neurophotonics, 2021.

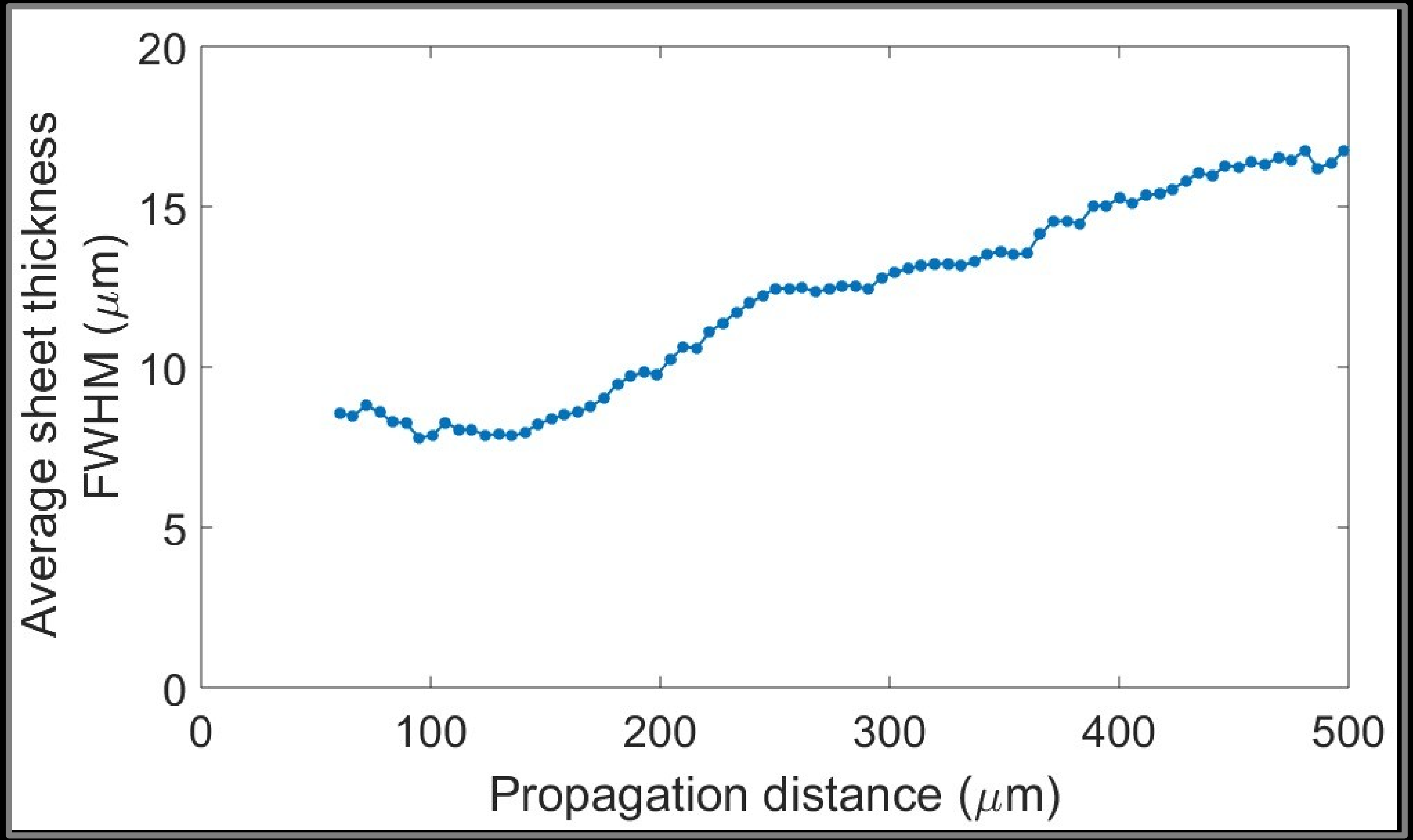
Light-sheet characterization

Top-down image
in fluorescein solution



In scattering media, uniformity is higher

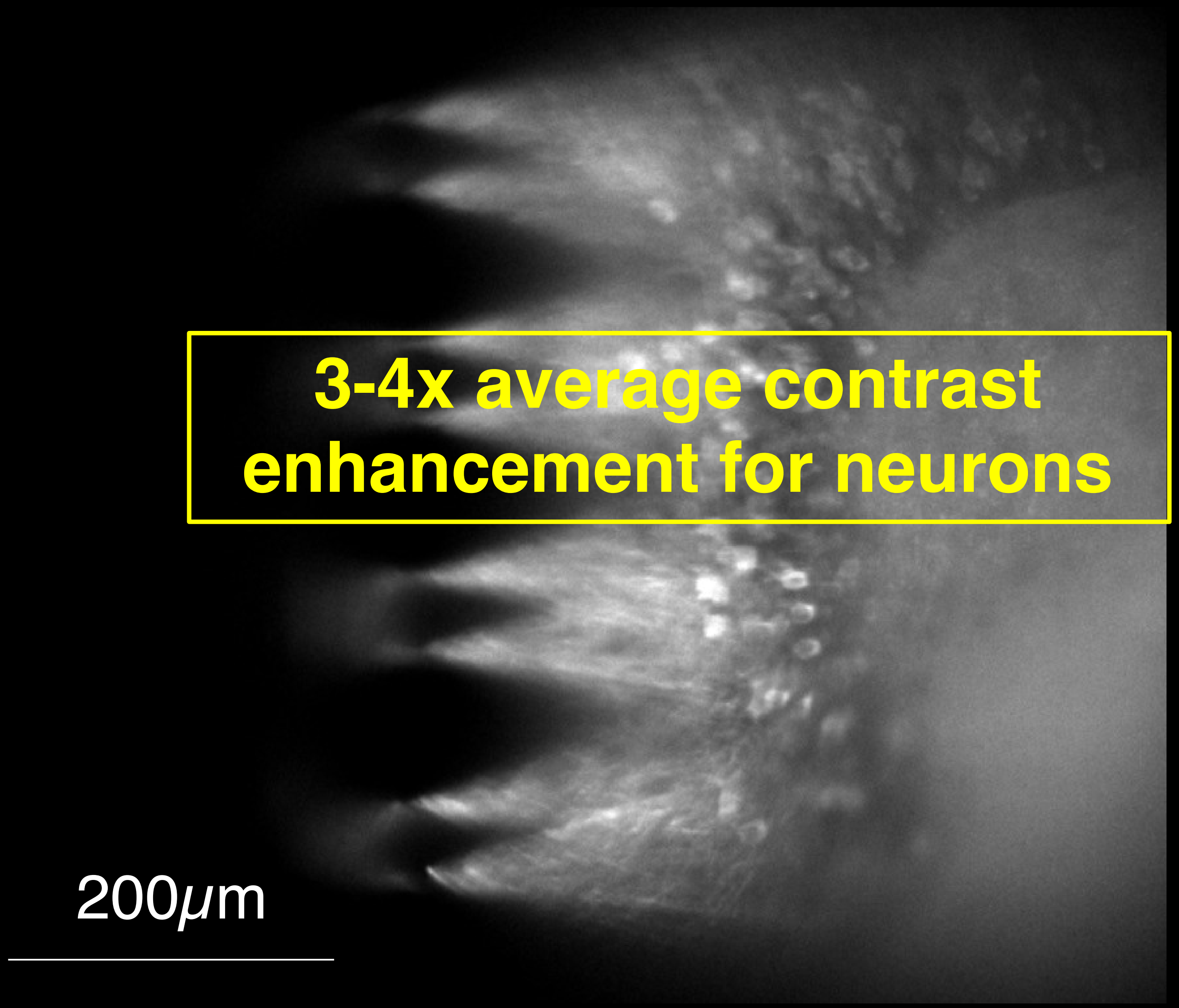
Extracted average sheet thickness in free space from imaging a fluorescent thin film



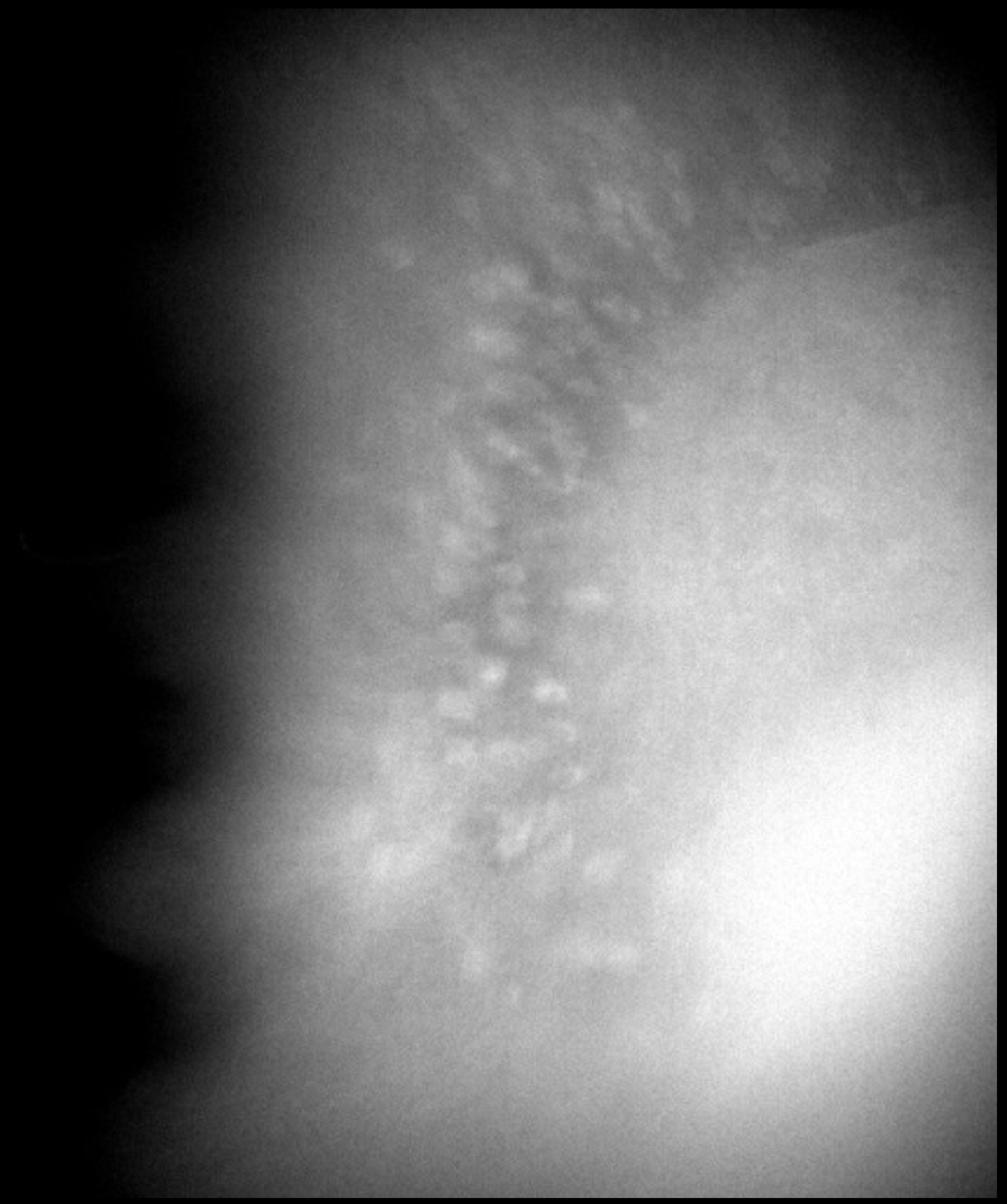
Fixed Tissue validation

- ≈1mm thick fixed slice from Thy1-GCaMP6s transgenic mouse
- Dentate gyrus, < 100μm depth

Light-sheet probe illumination

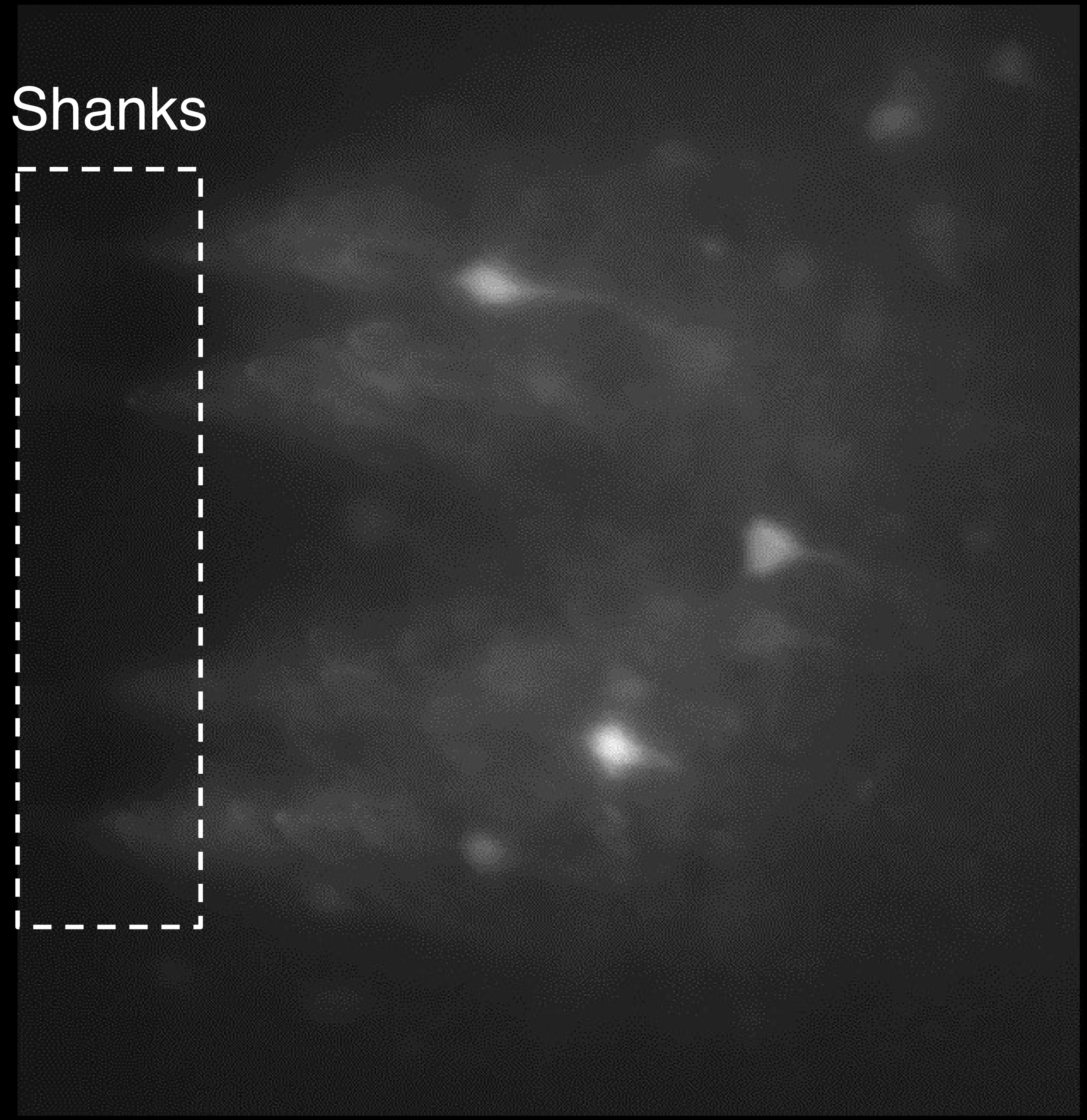


Epifluorescence

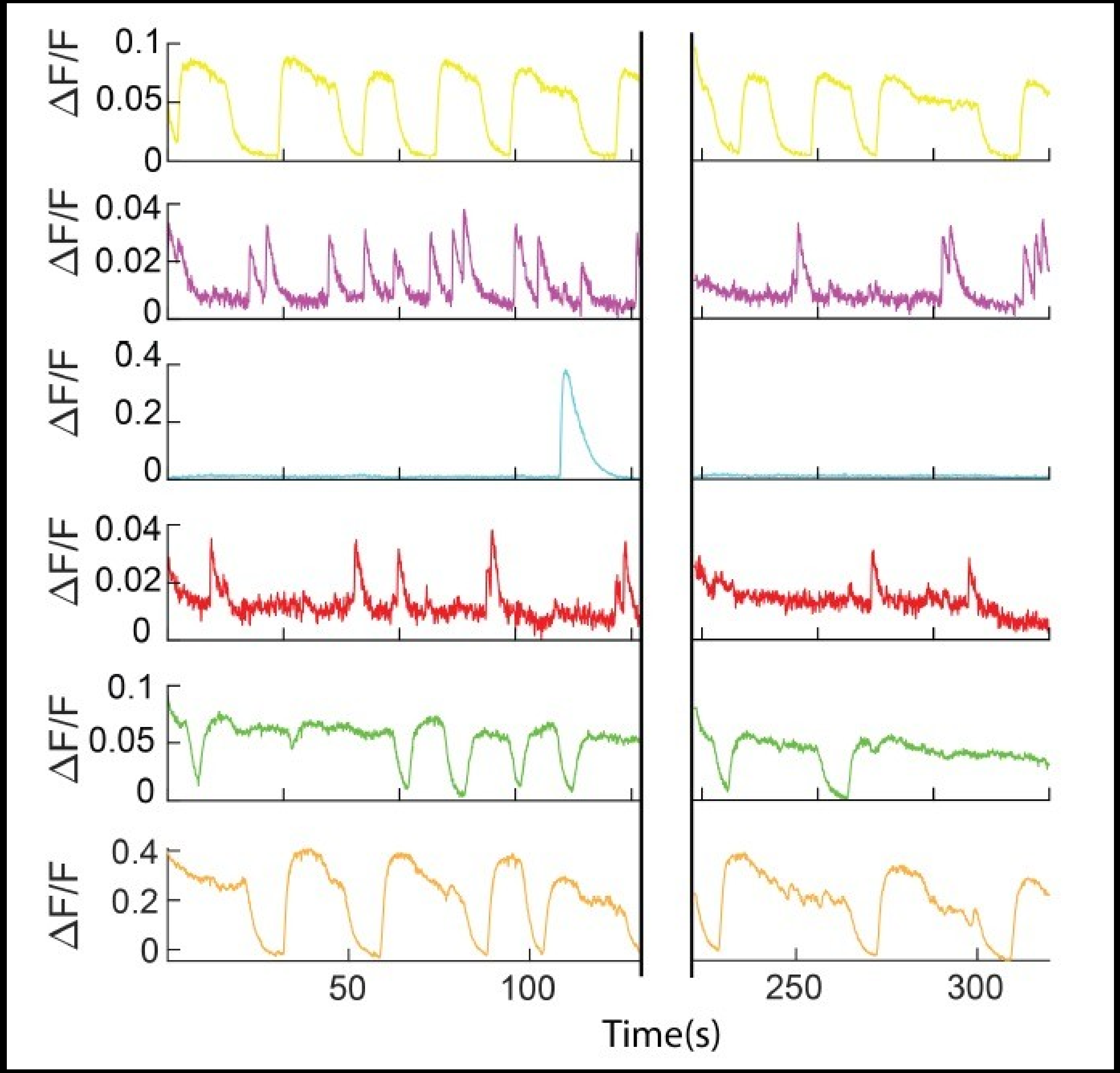


Brain slice functional imaging

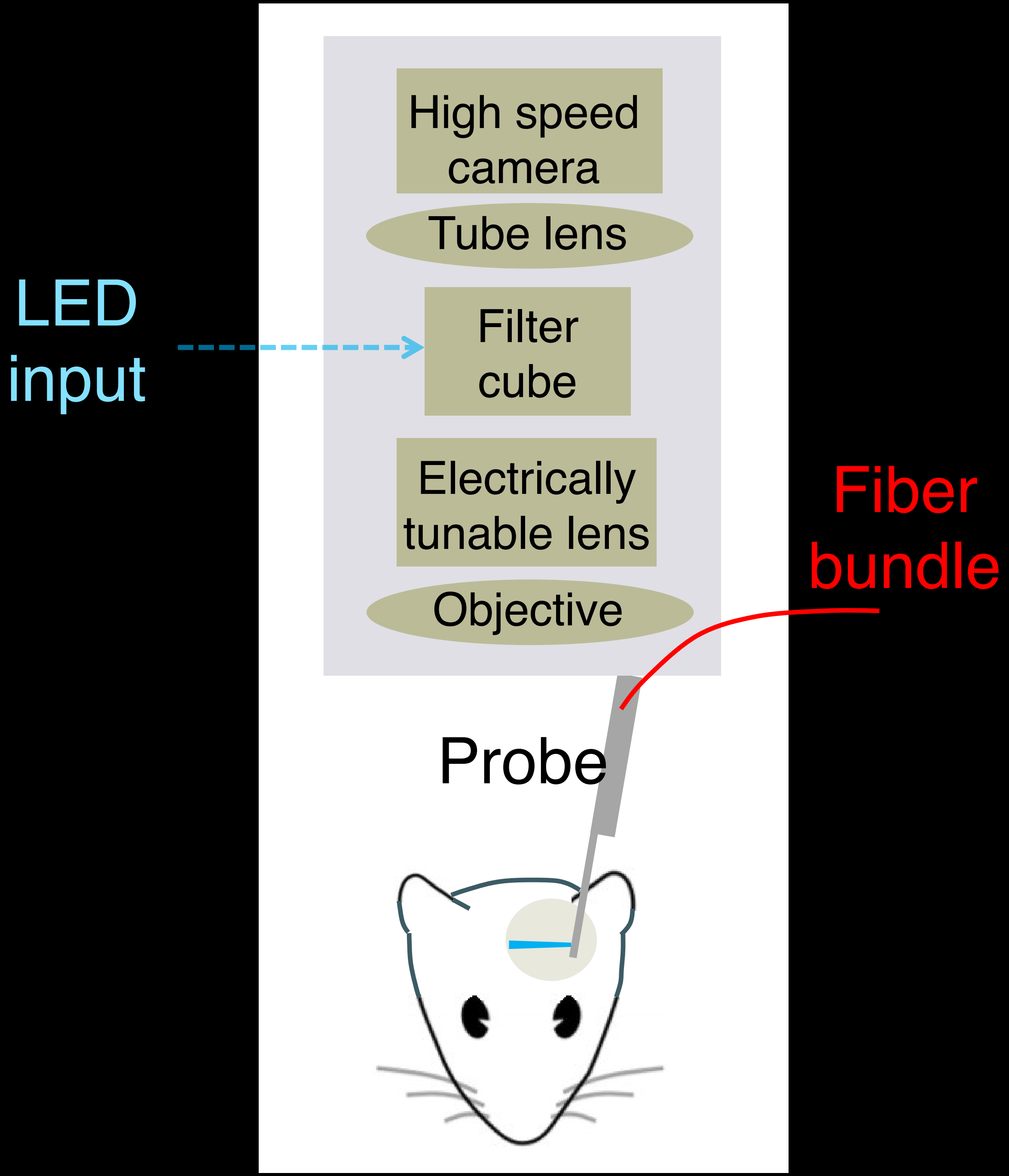
- ≈450μm thick perfused cortical brain slice from Thy1-GCaMP6s transgenic mouse.



Video accelerated 10x

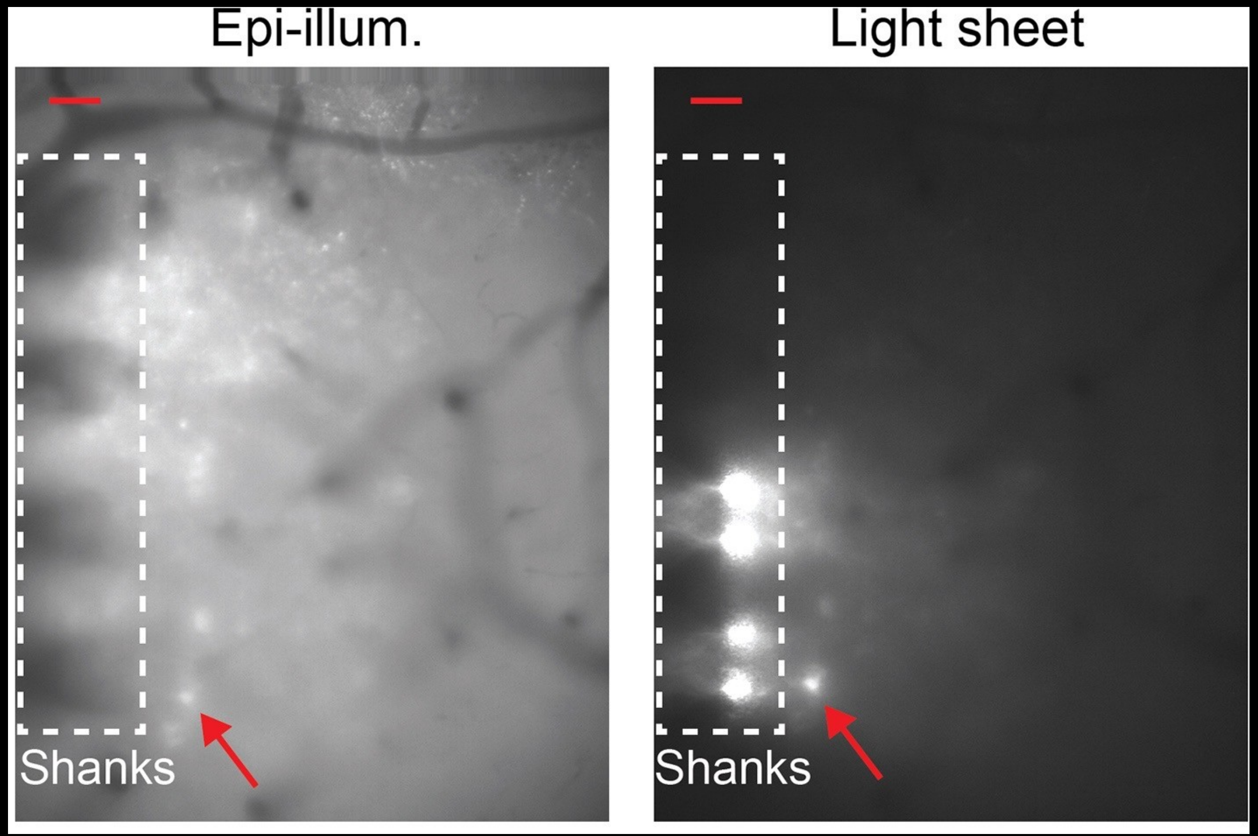


In vivo experiments

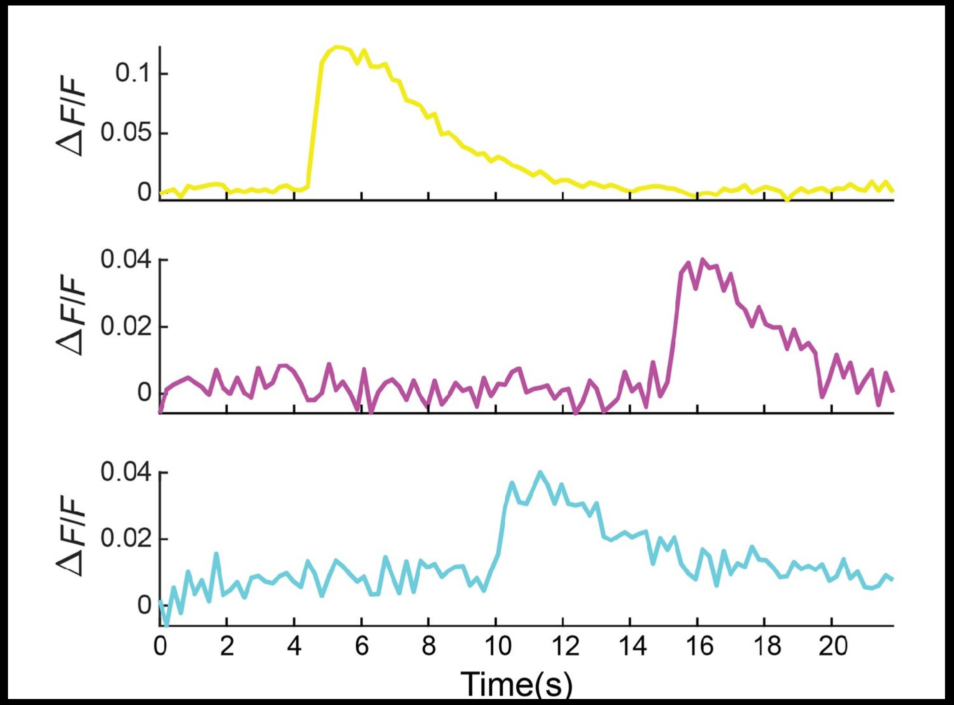


In vivo

Comparison in the same setup



Activity imaged

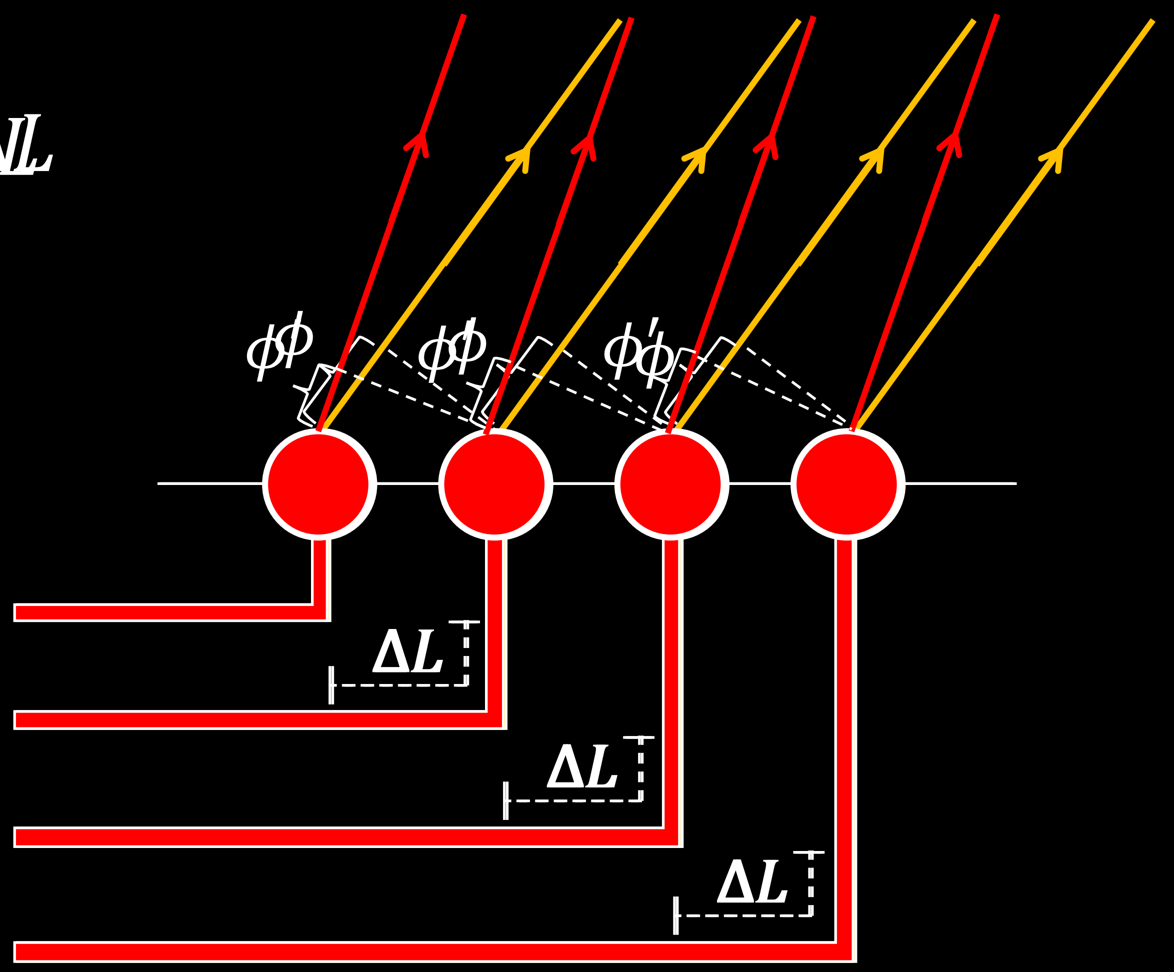


- Anesthetized Thy1-GCaMP6s mouse
- Parietal cortex, < 200μm sheet depth

Beam-steering neurophotonic probes

- High spatial resolution optogenetics and functional optical imaging
- Miniature optical phased array; No moving parts in tissue

$$\phi' = \frac{2\pi n}{\lambda'} \Delta L$$

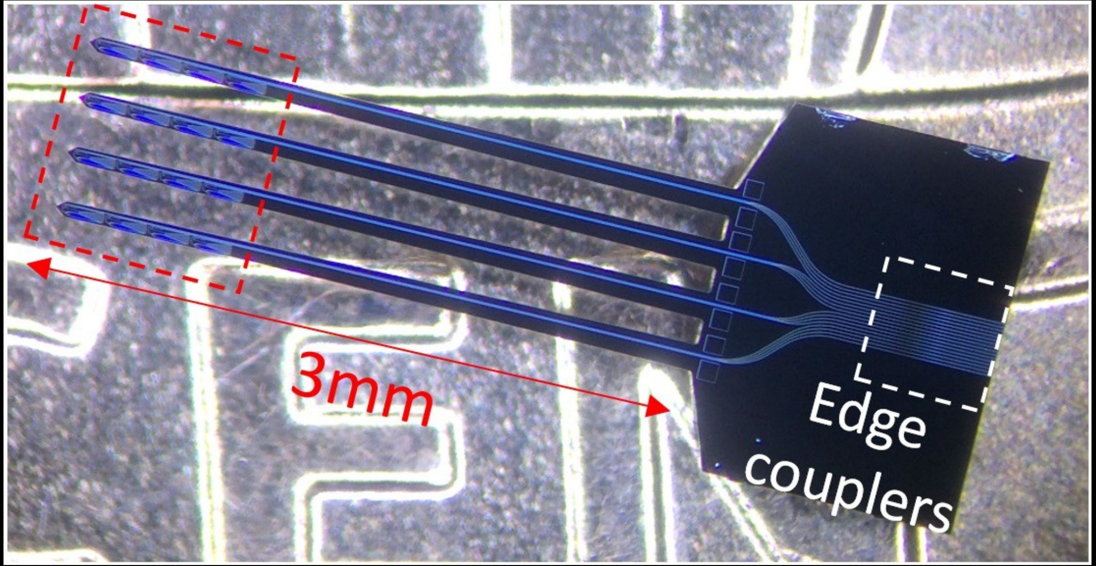


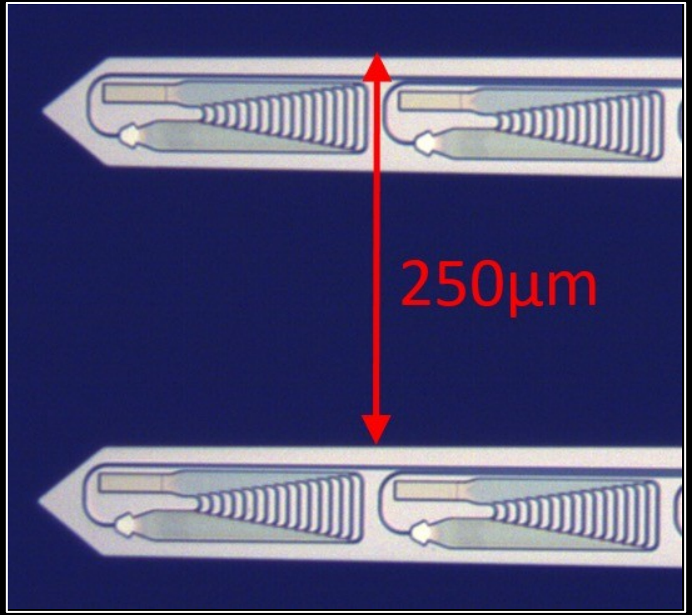
Beam-steering by wavelength tuning (external cavity single-mode laser)

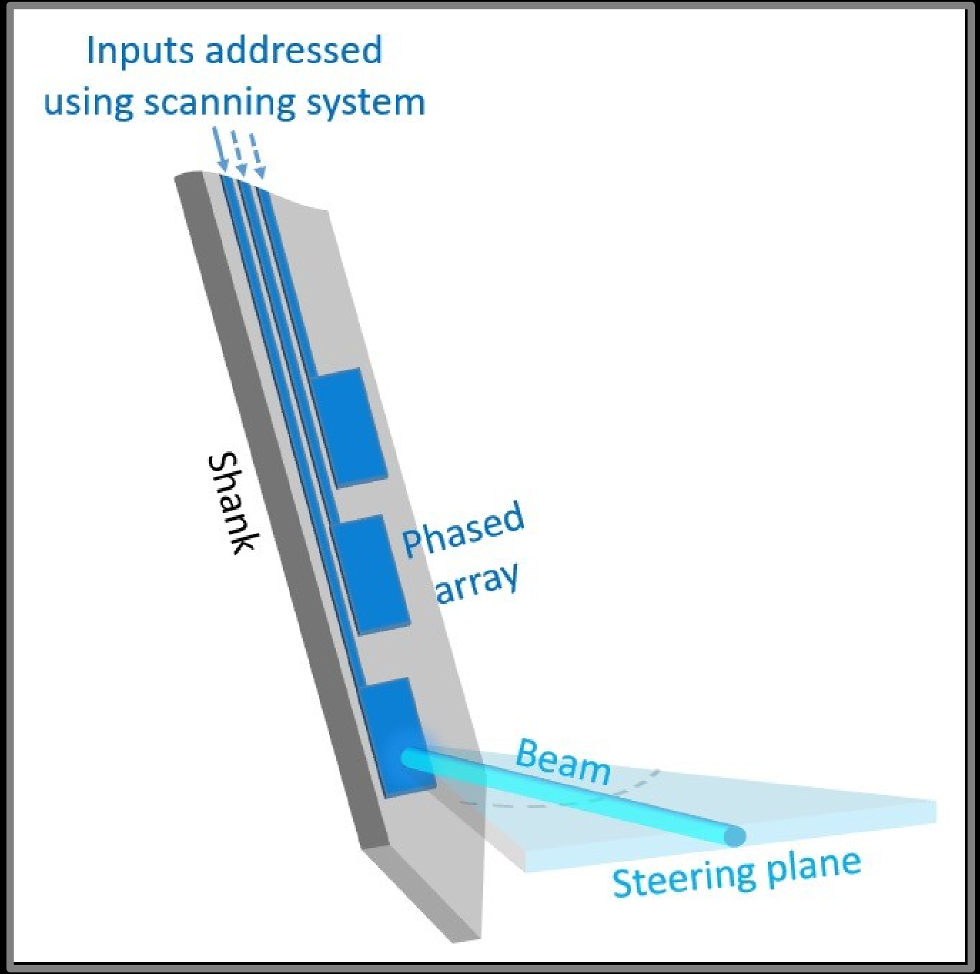
Beam-steering neurophotonic probes

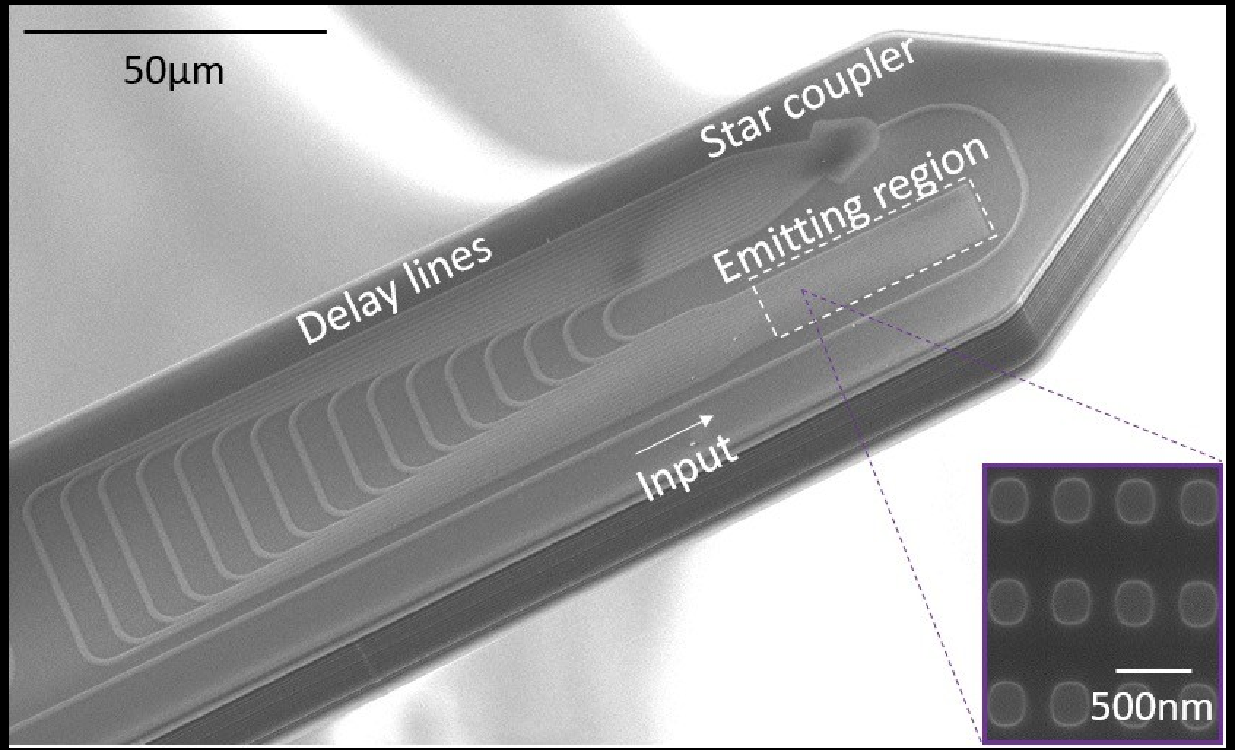
Michael Roukes
Taufik Valiante

- Gratings as light emitters





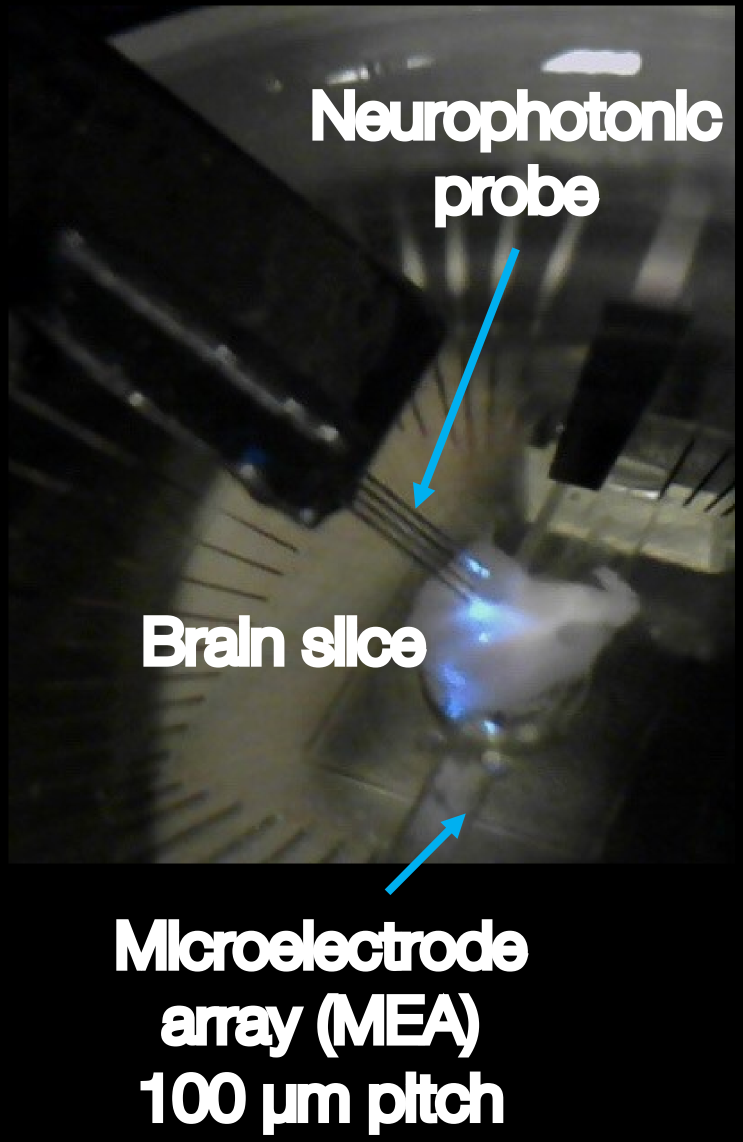


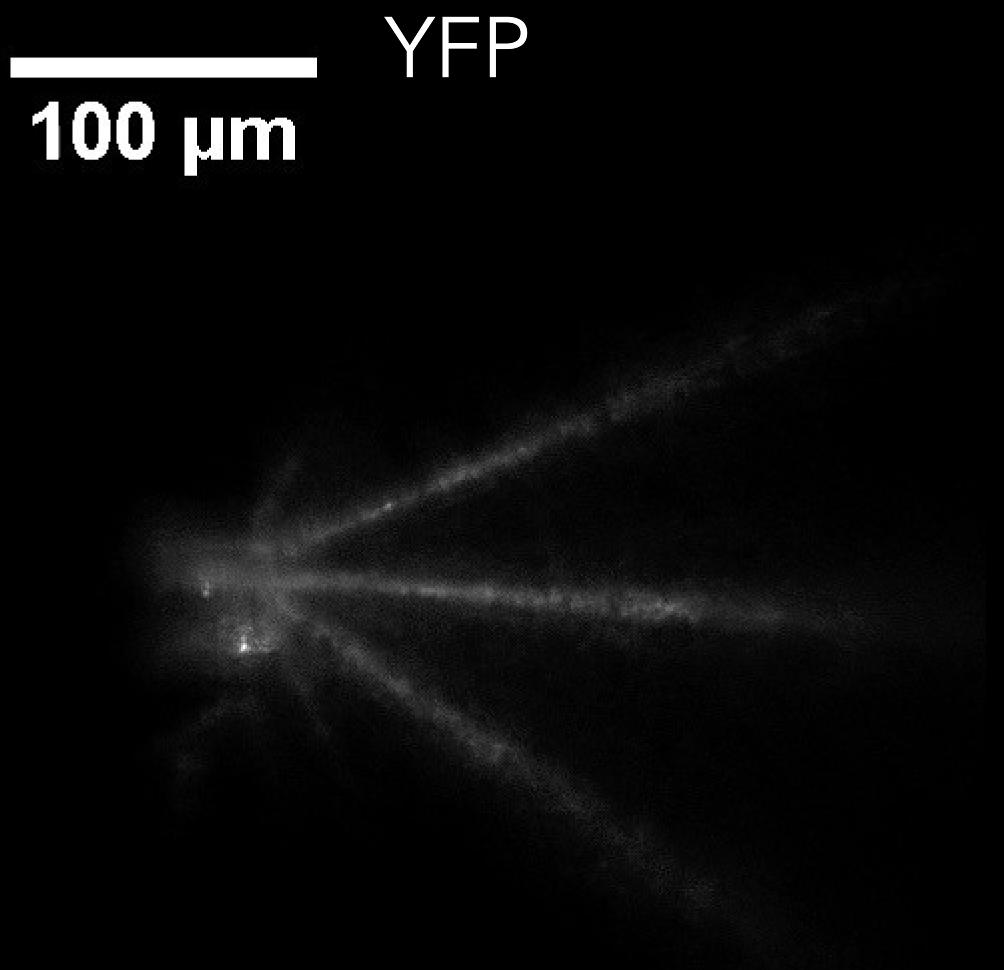


Sacher et al., CLEO 2019. Paper ATh4I.4
Manuscript in preparation

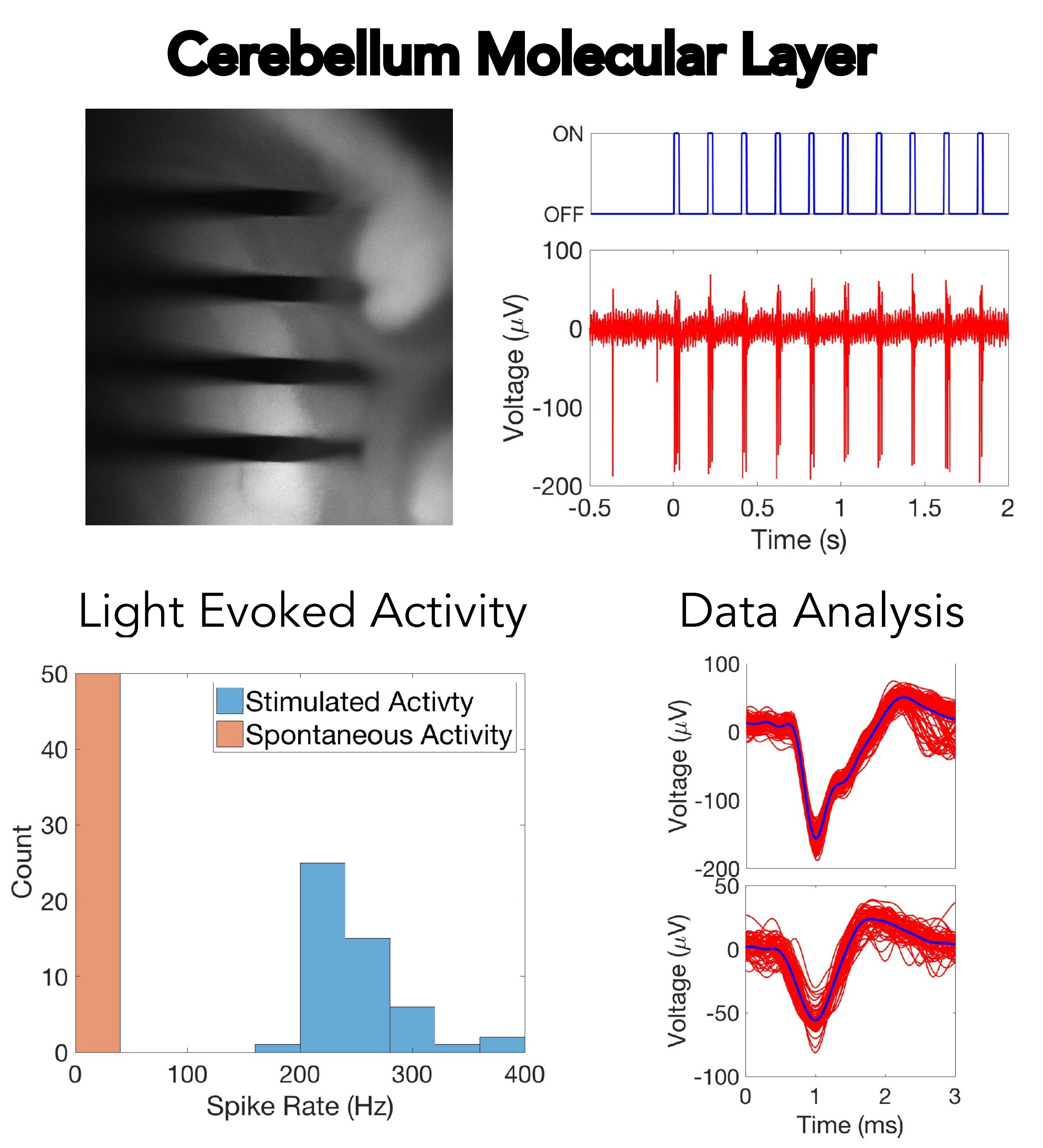
In vitro validation
Optogenetic stimulation

- VGAT-ChR2-EYFP: ChR2 expressed in interneurons
- Very low power: max. laser output power ~10mW

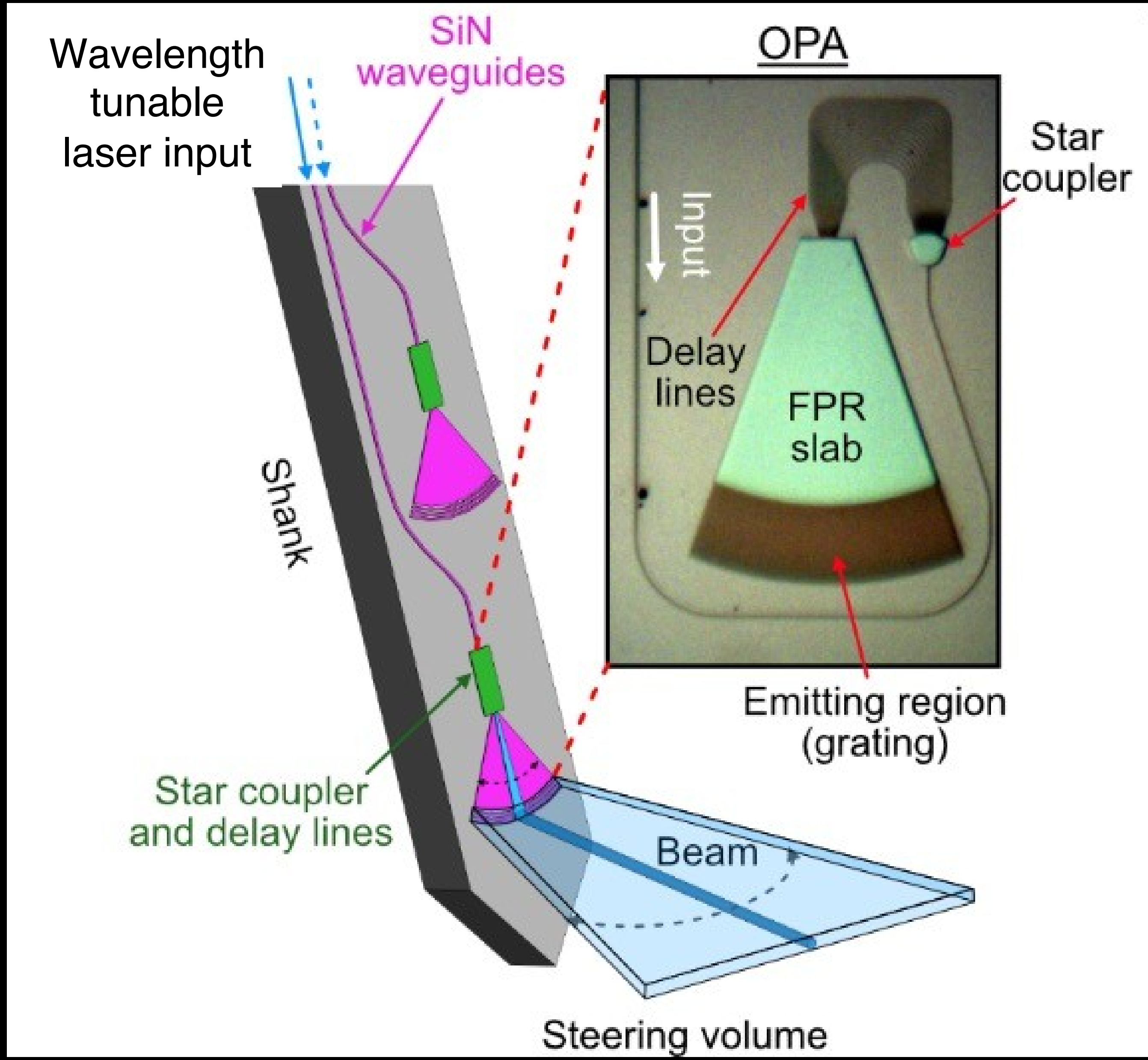




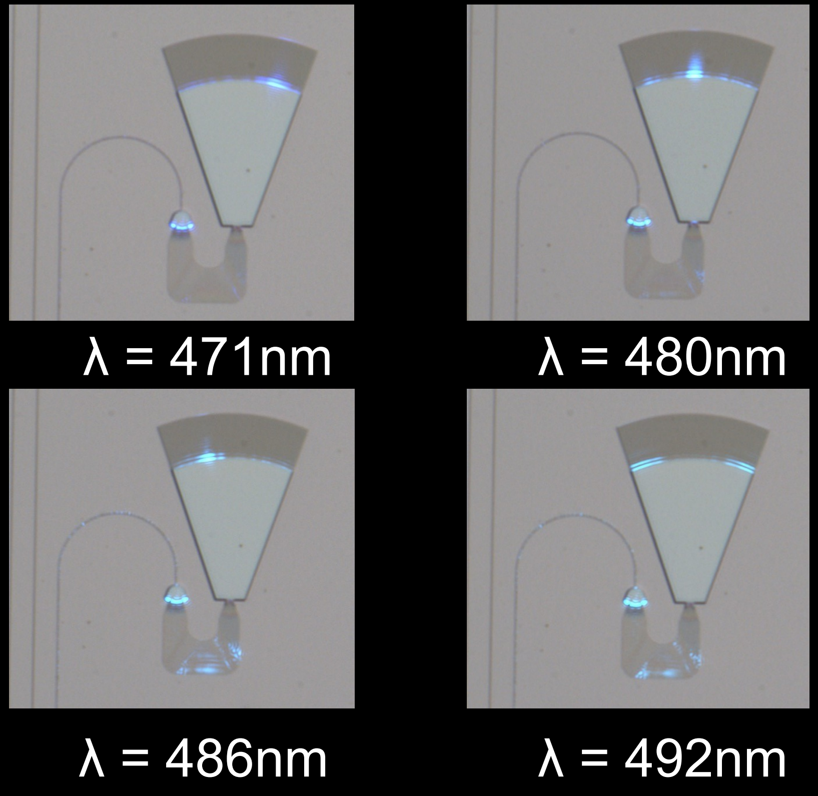
Beam-forming possible in tissue!



Sidelobe-free beam-steering OPA



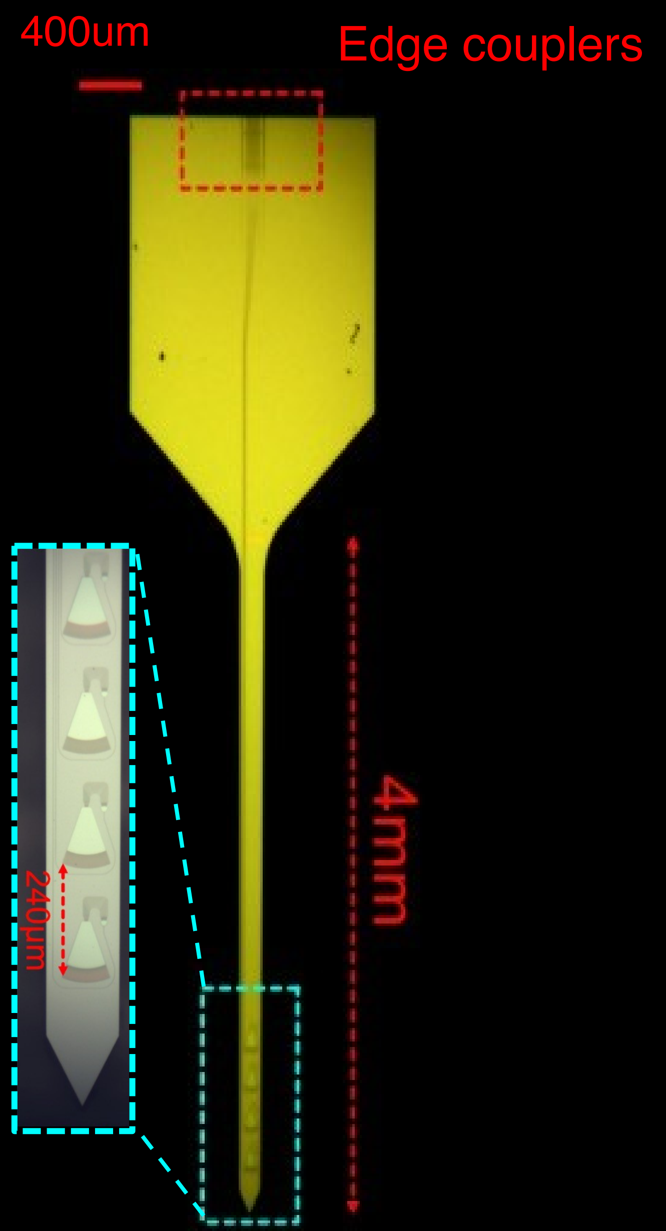
- End-fire phased array into free propagation region slab
- Sidelobes are separated from the main beam in the slab
- Out-of-plane emission by the grating



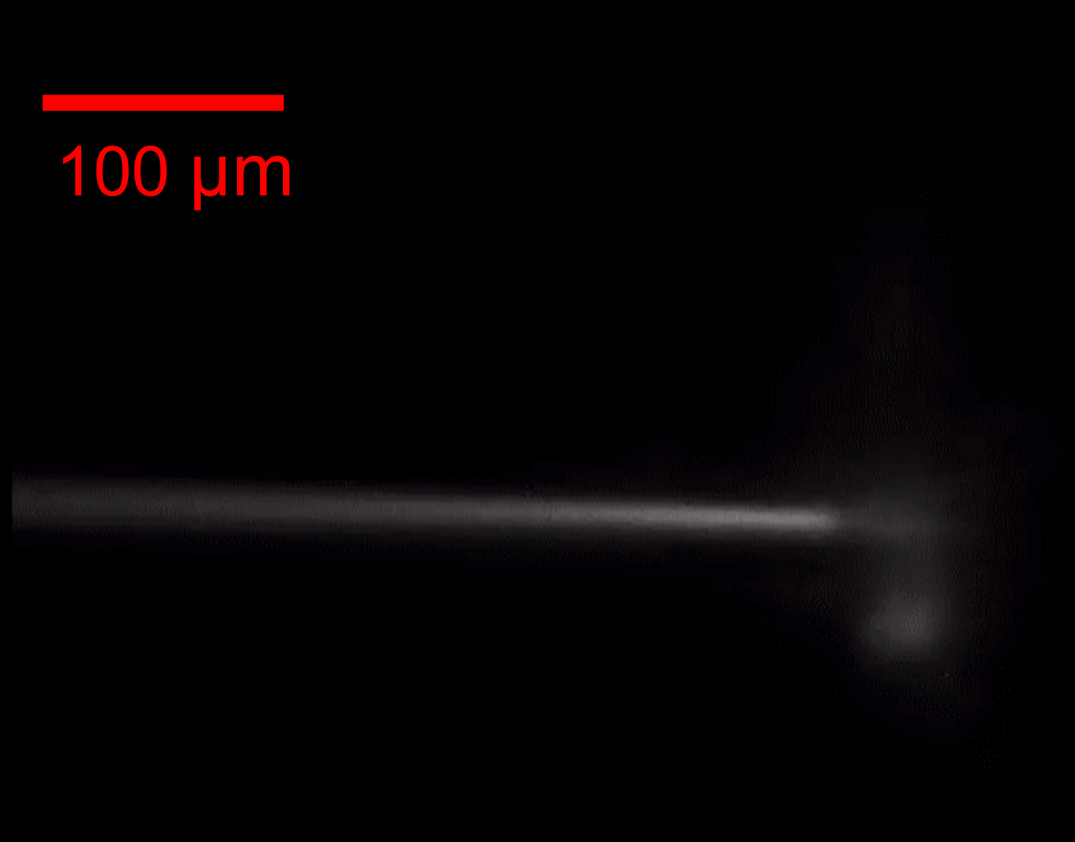
Property	Value
Free spectral range	23 nm near λ=470nm
Full steering range	23.7^{o}
Single-lobe steering range	16^{o}
Beam width (FWHM)	2.2^{o}

Chen et al., CLEO 2021.

Neuroprobe characterization

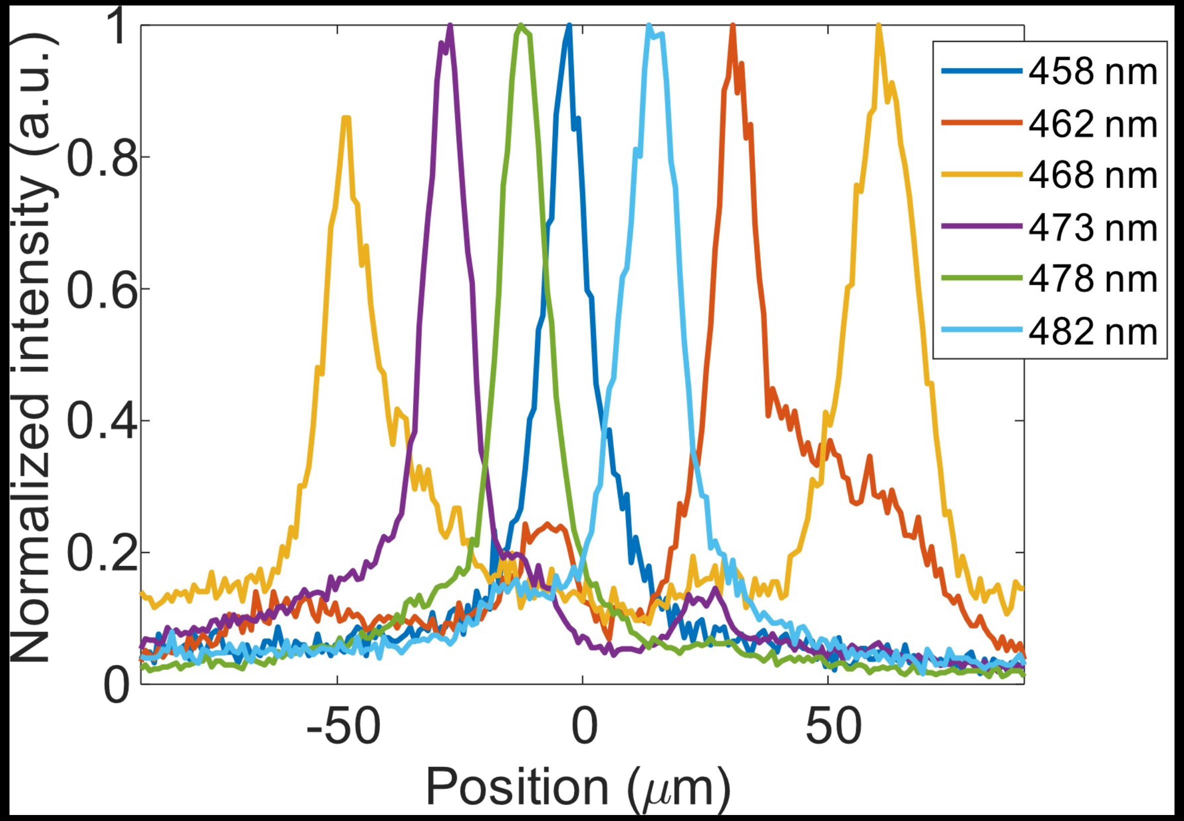


Beam profile in fluorescein



wavelength tuning:
469 to 481 nm

Cross-section profile at 100 µm

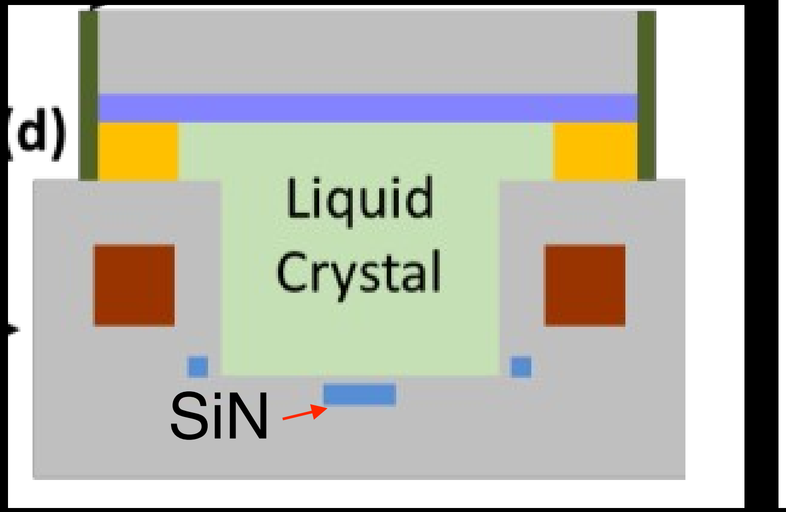


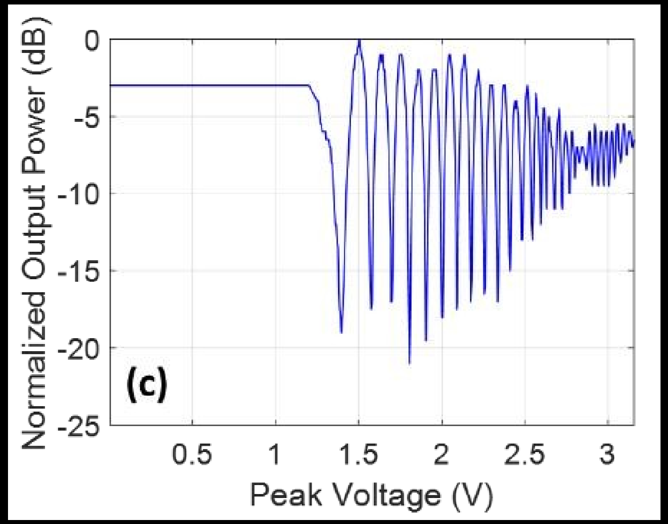
At 100µm from the OPA, single-lobe operation:

- Steerable distance = 57µm
- Average beam FWHM = 11.2 µm

Open challenge:
High-speed modulator or phase-shifter

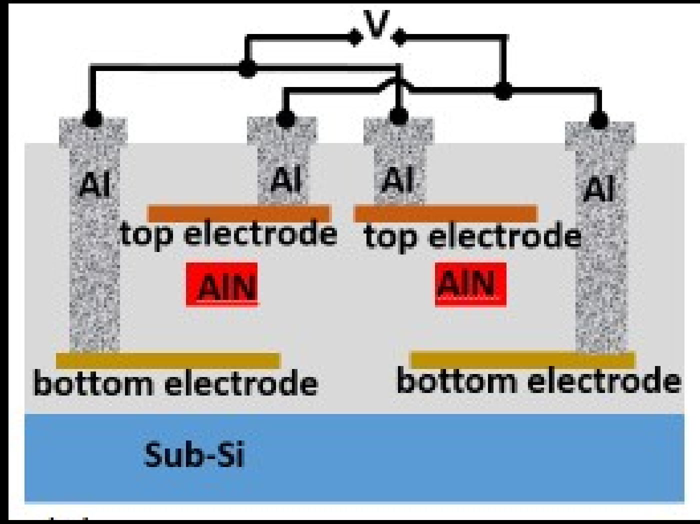
Liquid crystal?

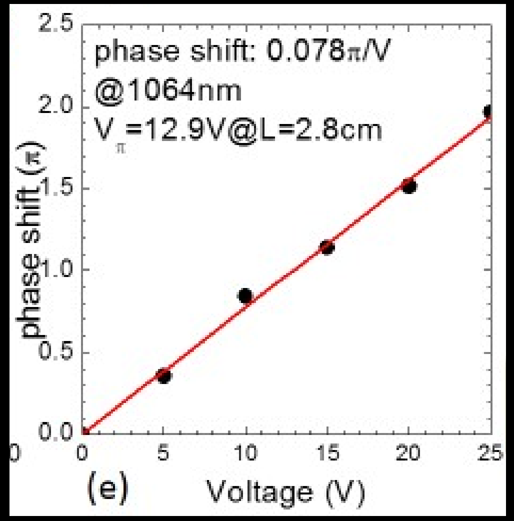




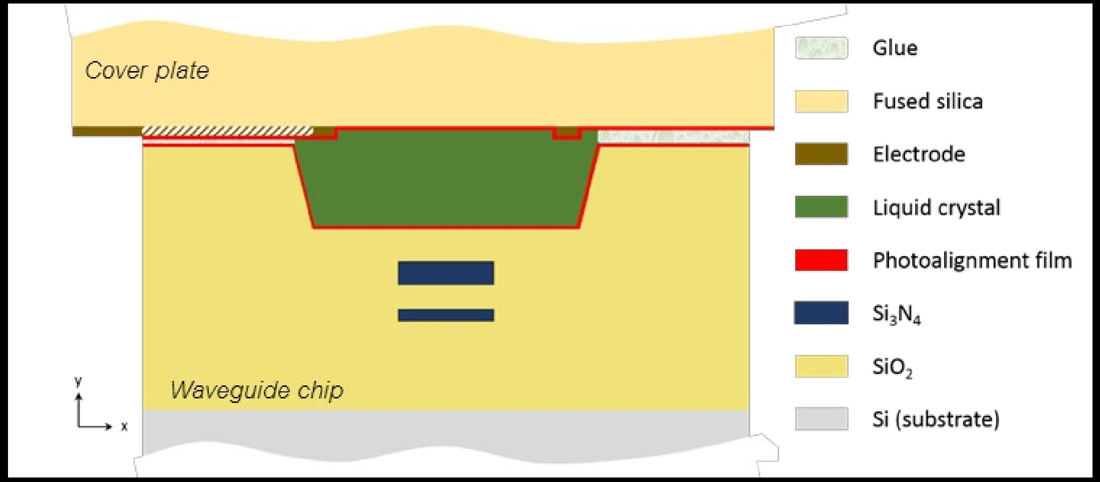
M.Notaros et al., Frontiers in Optics, 2018. FW6B.5

Aluminum Nitride (AlN)?



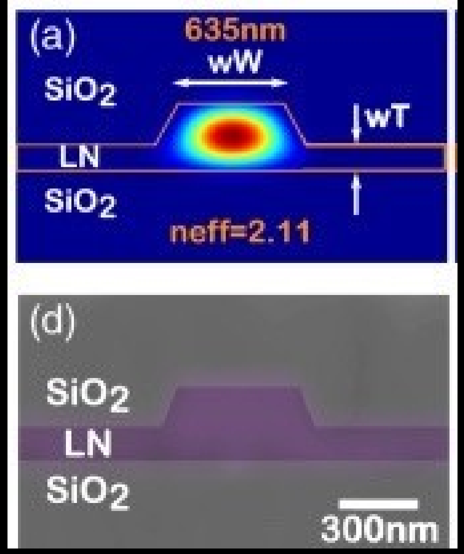


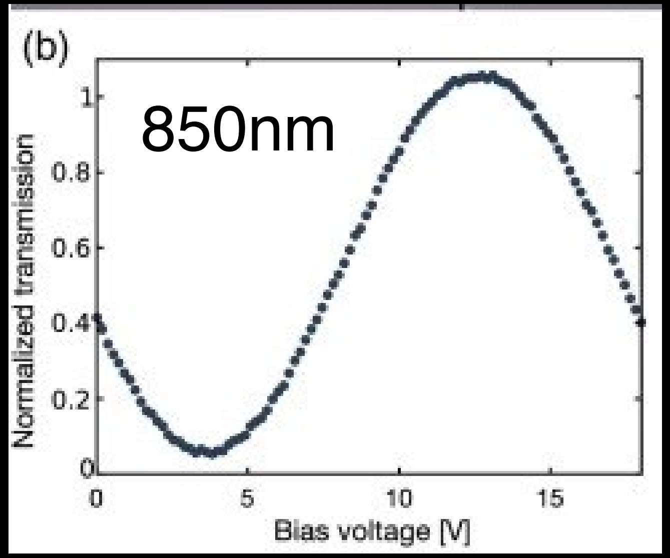
S. Zhu et al., OFC 2019, W2A.11.



K. Wörhoff et al., Proc. SPIE, 2019.

$LiNbO_3$?

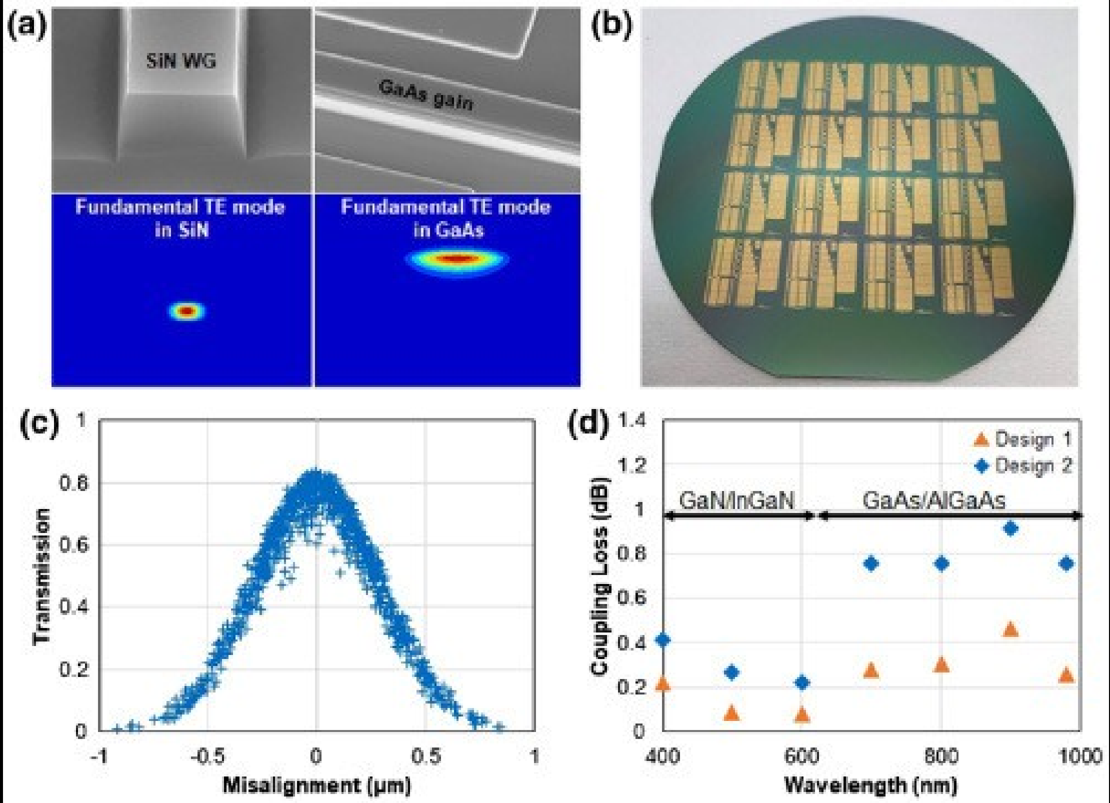


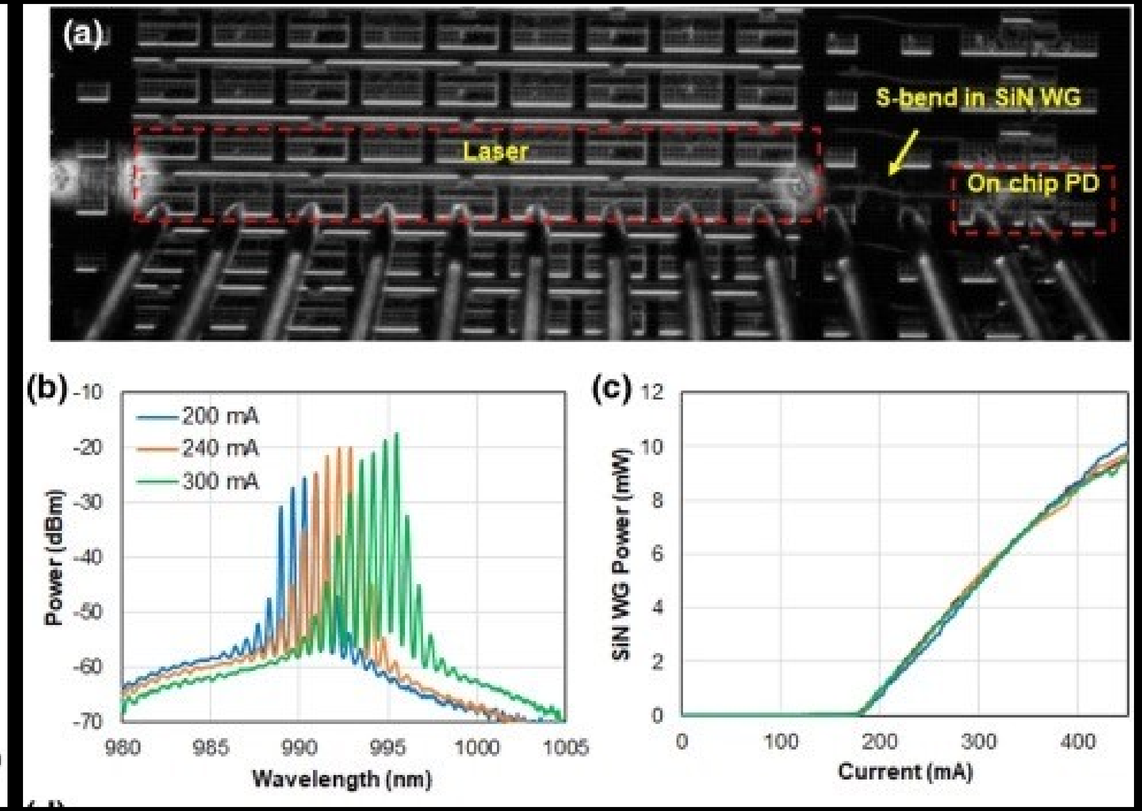


B. Desiatov et al., Optica, 2019.

Open challenge:
Laser integration

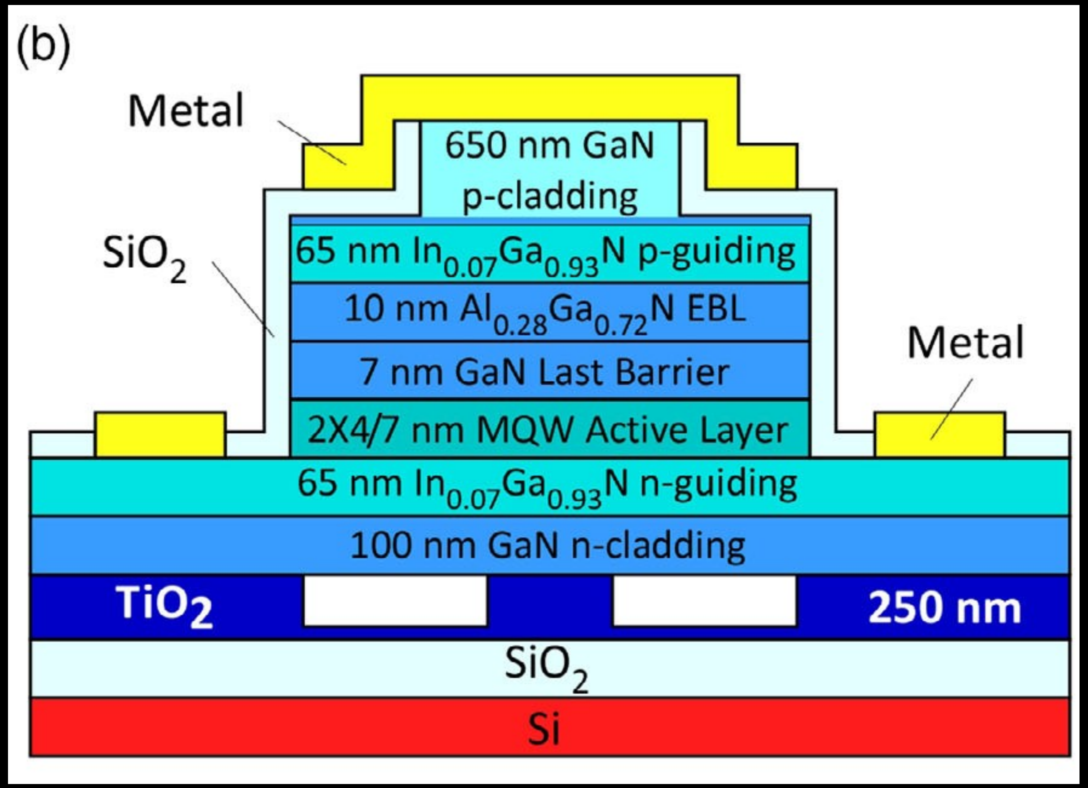
GaAs and GaN (?) integration on SiN??
(Nexus Photonics)





H. Park et al., Optica, 7: 336-337, 2020

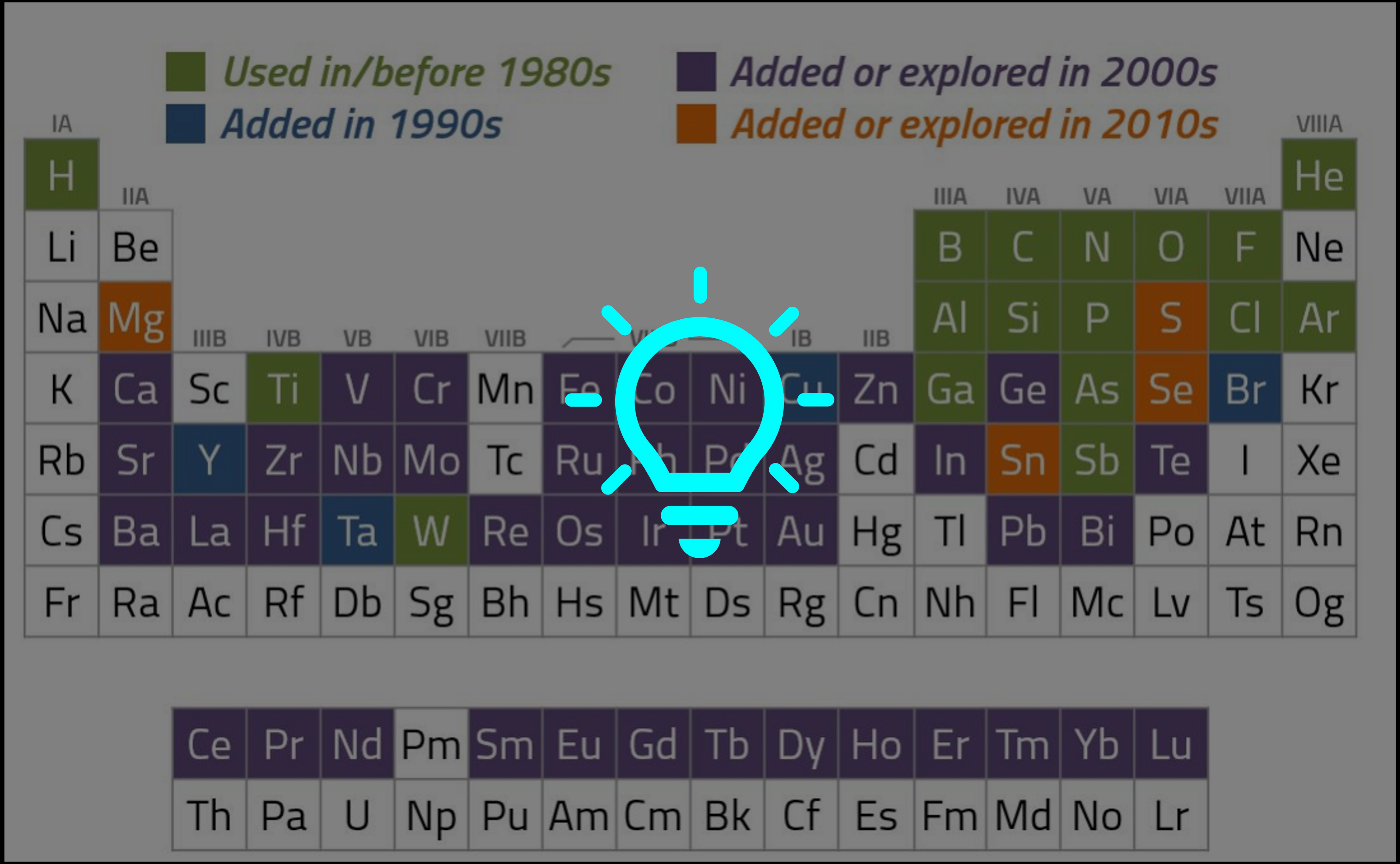
GaN integration on TiO_2??
(UCSB, Bowers Group)



Bonding was not successful…

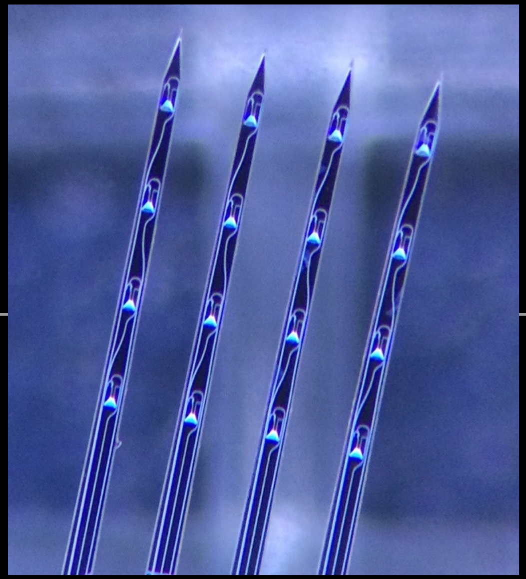
T. Kamei et al., Physica Status Solidi A, 1900770, 2020

Many elements used in the semiconductor industry!

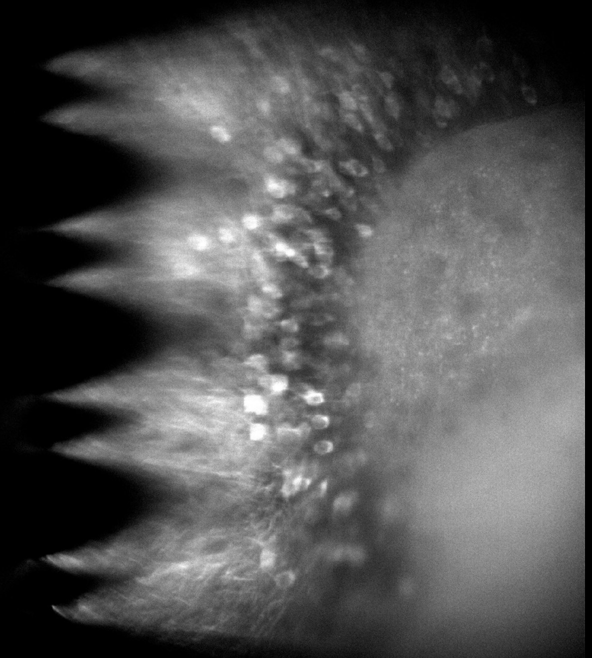


https://blog.lamresearch.com/happy-150th-birthday-to-the-periodic-table/

Summary:
Visible light photonics and neurophotonics



- Foundry Si photonics for visible light ⇒ **A new class of nano-neurophotonic tools for brain recording & stimulation**



- Passive neurophotonic probes bring patterned photostimulation into brain tissues without any lenses
- Applications of visible light photonics: biosensing, quantum photonics, optical phased arrays
- Opportunities for new devices, platforms, and integration approaches

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www.photon.utoronto.ca | www.mpi-halle.mpg.de/NINT

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