Transatlantic Partnerships for Hybrid Electro-Optic Modulation

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NLM Photonics in Brief

UNIVERSITY of WASHINGTON

Materials Development

Top team and key patents developed out of 25+ year legacy of world-leading organic electro-optic (OEO) research at the University of Washington

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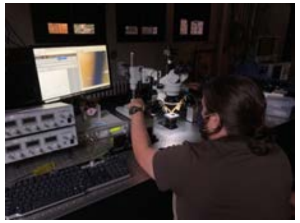
AIM PHOTONICS | leti cea tech | tok | HAMAMATSU | POLARITON TECHNOLOGIES

Partnerships

Extensive collaborations with leading translational research fabs, industry partners, startups, and academia

MATERIALS + PROCESSES + DEVICE TECHNOLOGY

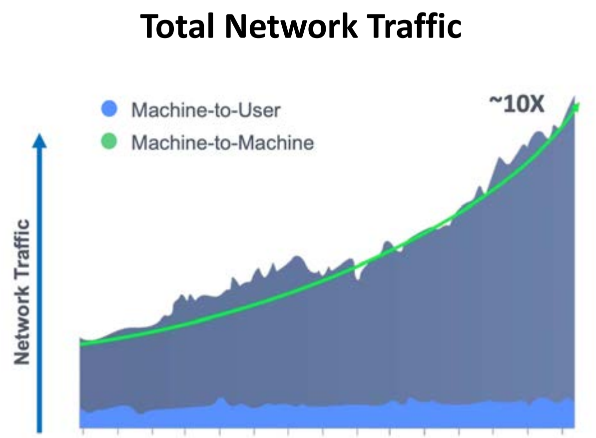
Process Technology



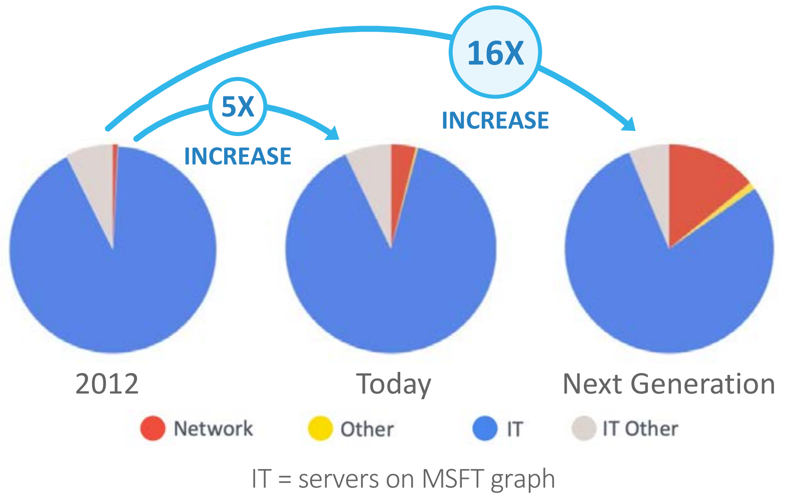
Unique technologies for high performance and stability optimized for hybrid EO devices and backed by years of processing and deployment experience

Ubiquitous computing and AI require enormous bandwidth and power

RAPIDLY GROWING DEMAND FOR NETWORK CAPACITY[1]



EXPANDING NETWORK POWER USE[2]



What are the criteria for SUCCESS?

MAXIMIZE

- ✓ Data throughput
- ✓ Compute performance

MINIMIZE

- ✓ Data transport power requirements
- ✓ Resource duplication

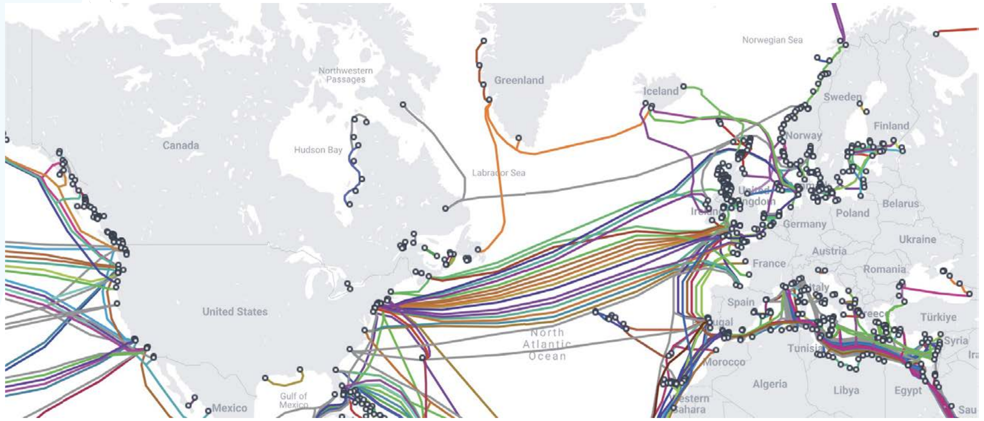
STAY UNDER

- ✓ Infrastructure power and cooling constraints

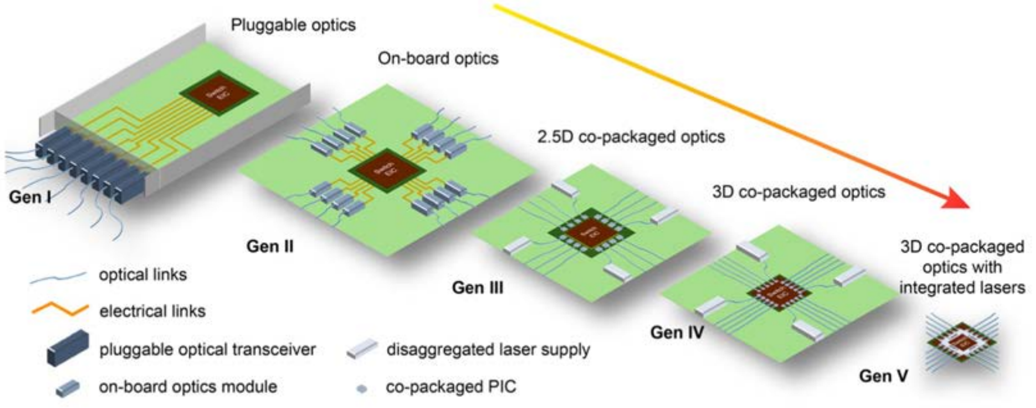
[1] Source: Meta
[2] Sources: Meta, Microsoft

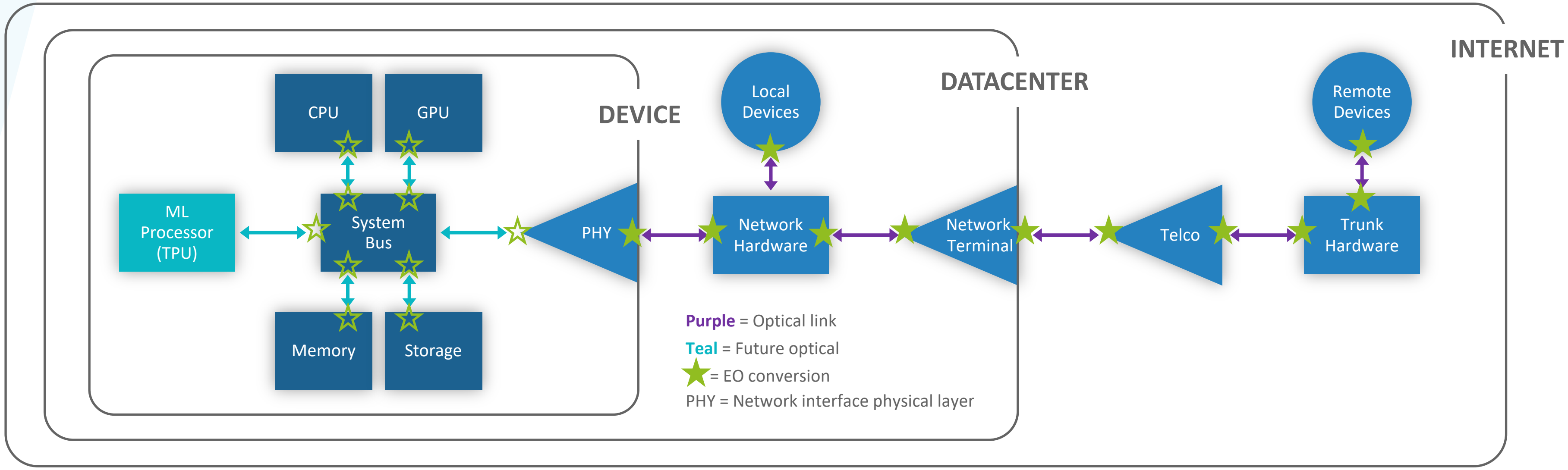
The critical role of electro-optic modulation

From telecom…



…to CPO and 3DHI





More Connections
Shorter distances
Faster Links

=

Modulation technology demand

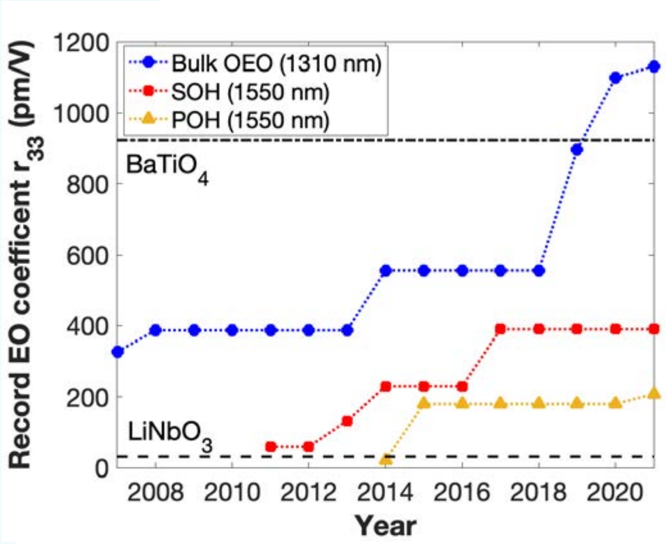
Upper left: submarinecablemap.com
Upper right: Appl. Phys. Lett. 118, 220501 (2021)

What do we want out of integrated modulators?

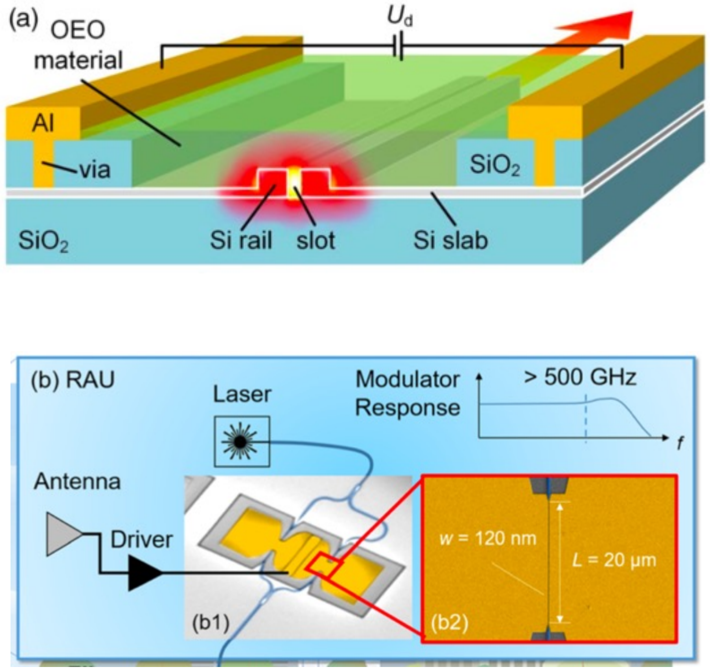
- Scalable bandwidth – can deliver 100+ GHz for 200G and 400G per λ
- Power efficient – low drive voltage, low capacitance, high extinction ratio
- Clean, low-chirp modulation
- Low optical loss
- Linear drive capable
- Good compatibility with existing PIC manufacturing processes
- Thermally stable, can last for lifetime of hardware even under demanding conditions

Hybrid Organic Technology can deliver.

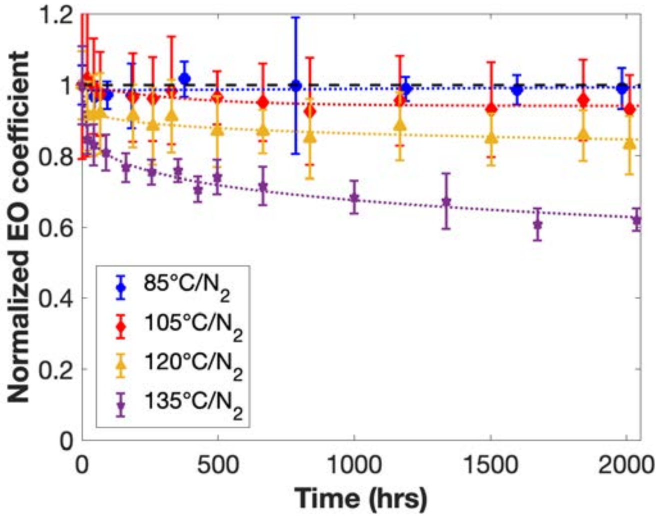
High-performance Materials



Optimized Device Architectures



Robust Stability



L. R. Dalton, et. al. APL Materials 2023, doi: 10.1063/5.0145212
C. Kieninger et al. *Optica* **2018**, doi: 10.1364/OPTICA.5.000739
M. Burla et al. *APL Photonics* **2019**, 4. doi:10.1063/1.5086868
S. R. Hammond et al, *Proc. SPIE* **2022**, doi: 10.1117/12.2622099

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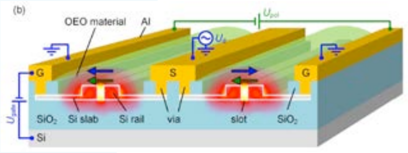
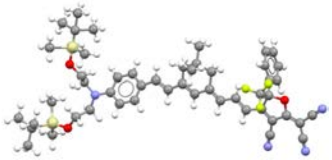
Factors influencing modulation efficiency



Device-level

Materials-level



$$V_\pi L = \frac{\lambda_0}{2} \cdot \frac{w_{slot}}{\Gamma} \cdot \frac{1}{n_e^3 r_{33}}$$

$$r_{33} = \beta_{zzz} \cdot \rho_N \left\langle \cos^3 \theta \right\rangle \cdot G$$

Drive voltage (V) & Device length (µm) required for digital switching

Wavelength of light e.g. 1550 nm (design parameter)

Field confinement (device parameter)

Depends on:
- Slot width w_{slot} (higher field at given voltage enables lower drive voltage)
- Optical/RF field overlap (Γ)

Materials performance

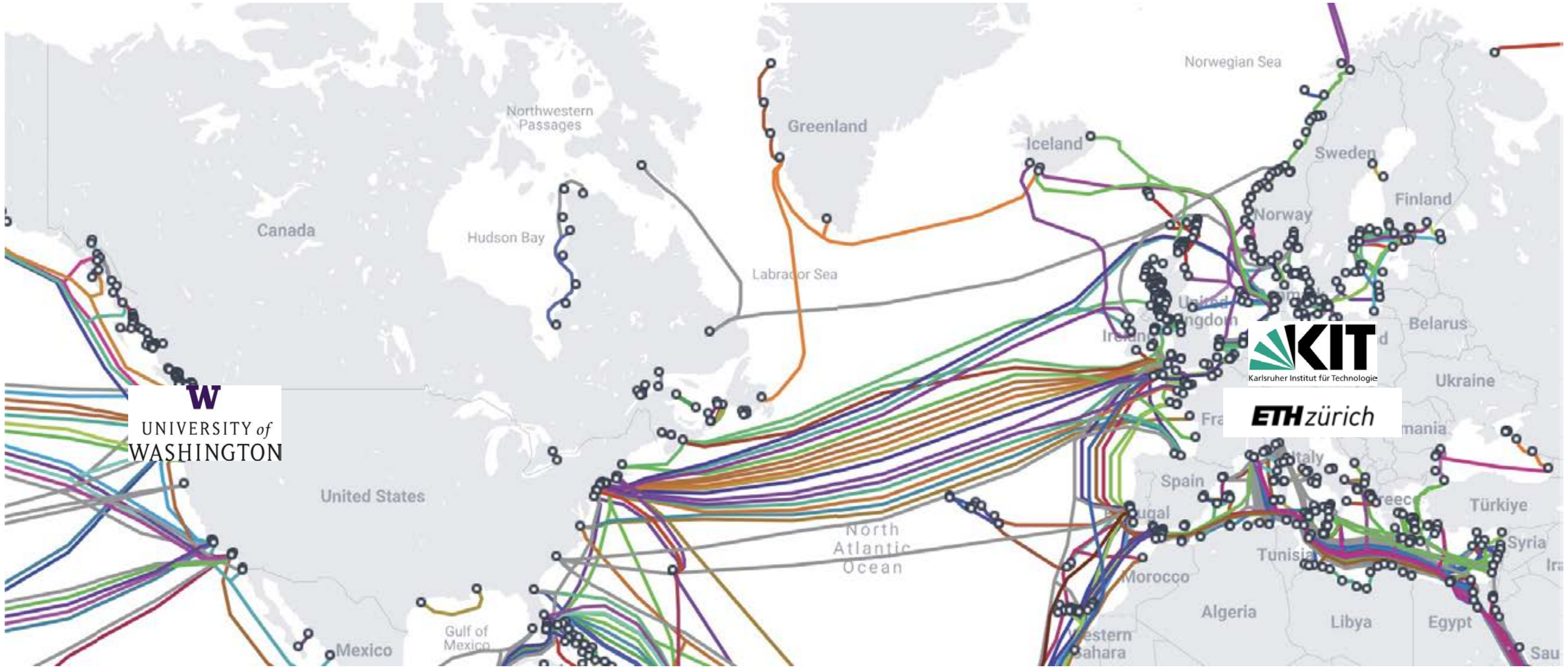
Depends on:
EO coefficient (r_{33})
Refractive index (n); n_e is index parallel to r_{33}

Hyperpolarizability (individual-molecule performance)

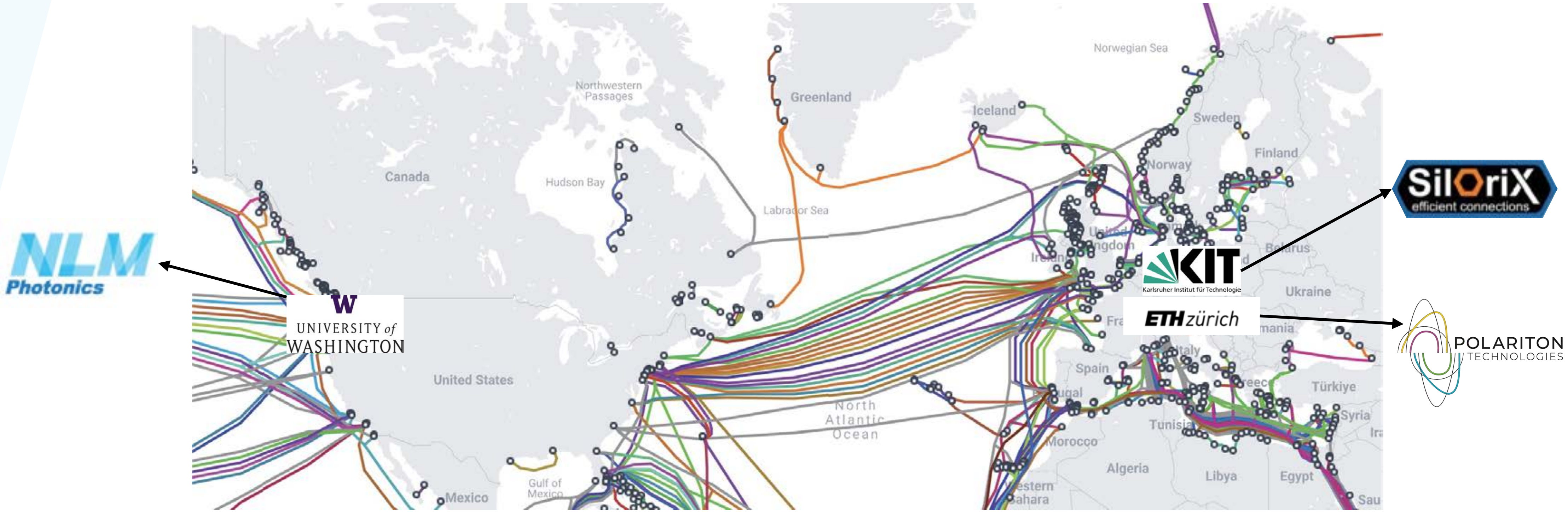
How effectively many molecules work together in a material
Depends on:
Density (ρ_N)
Parallel alignment of dipoles $\langle \cos^3\theta \rangle$

Local-field factors (depend on dielectric response)

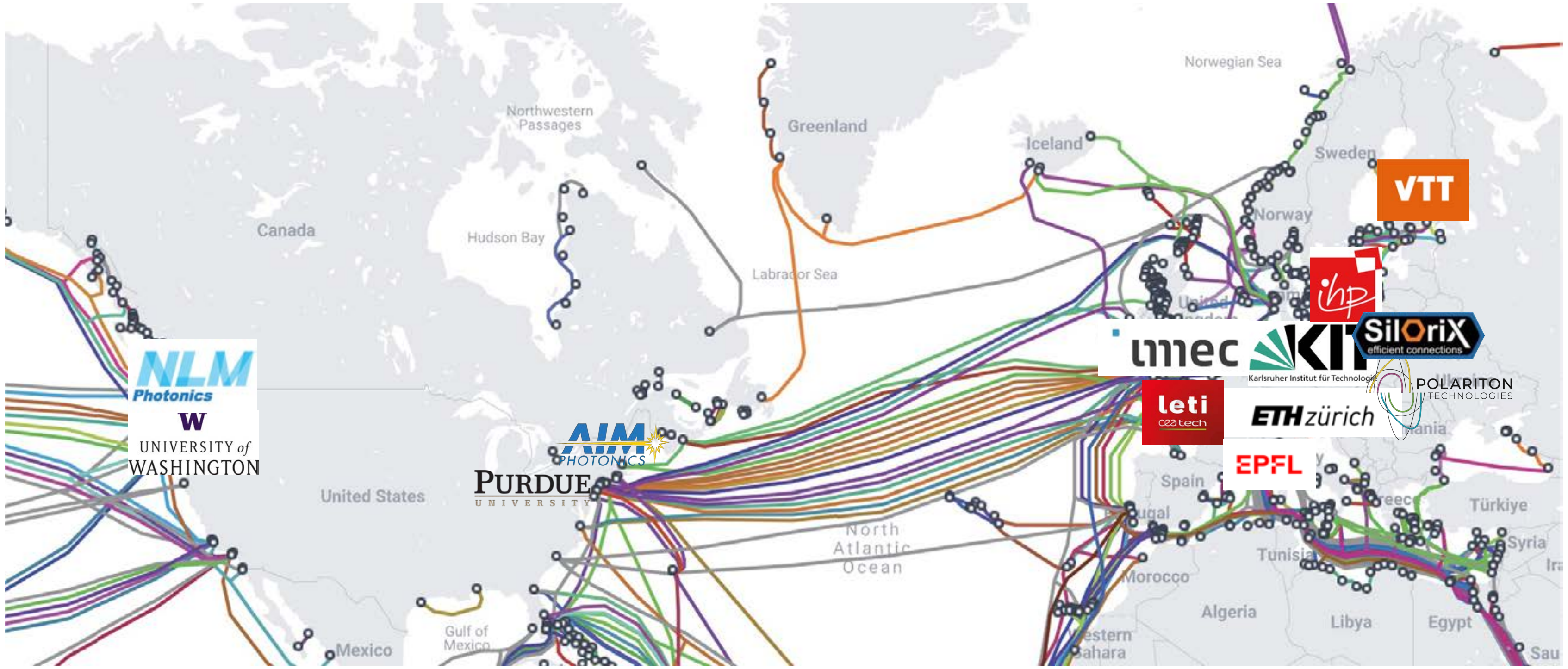
How did we get here? Transatlantic Partnerships



...and commercialization...



...and growth



(not exhaustive)

Developing better OEO materials

A. F. Tillack and B. Robinson, *JOSA B* **2016**, doi: 10.1364/josab.33.00e121
W. Heni et al. *ACS Photonics* **2017**, doi: 10.1364/oe.25.002627
H. Xu et al. *Chemistry of Materials* **2020**, doi:10.1021/acs.chemmater.9b03725
L. E. Johnson, et al. *Proc. SPIE* **2021**, doi: 10.1117/12.2594939
L. E. Johnson, et al. *Proc. SPIE* **2021**, doi: 10.1117/12.2595638
H. Xu, et al. *et al. Materials Horizons* **2021**, doi: 10.1039/d1mh01206a

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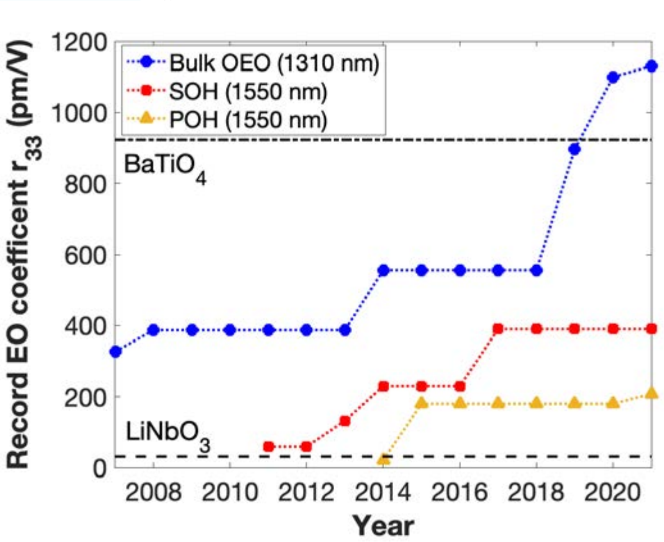
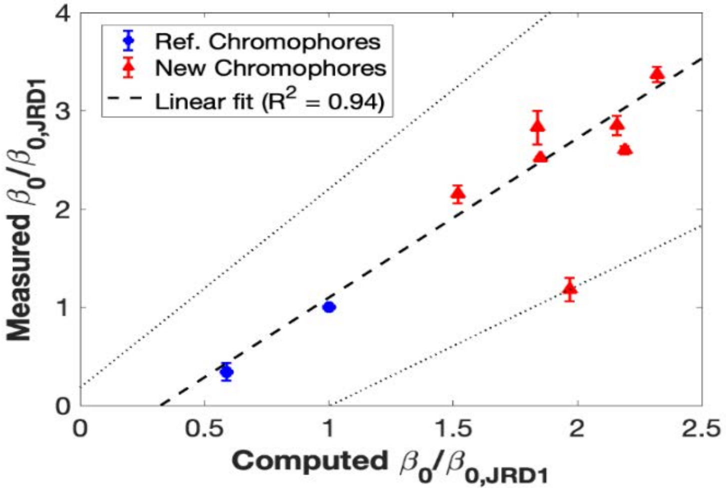
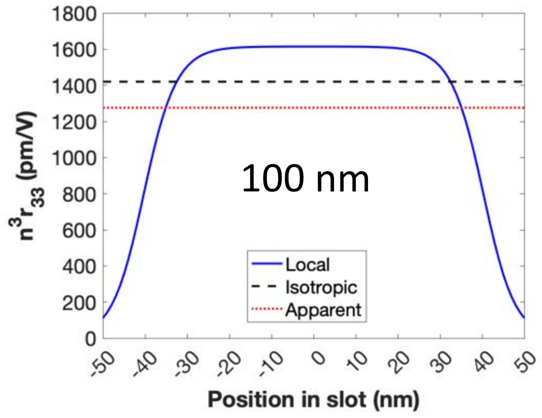
Performance comes from...

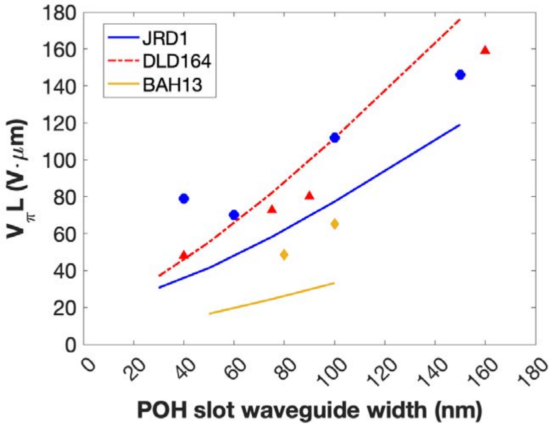


Higher hyperpolarizability

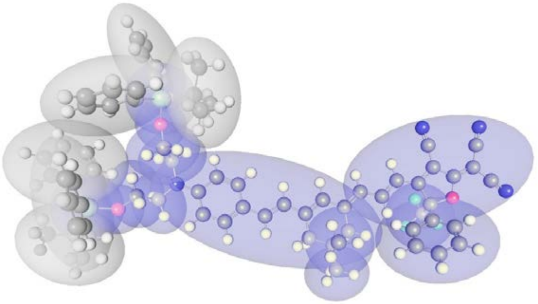


Understanding interfacial effects

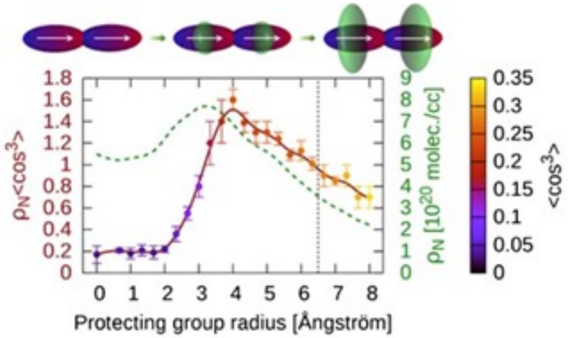




Higher chromophore concentration

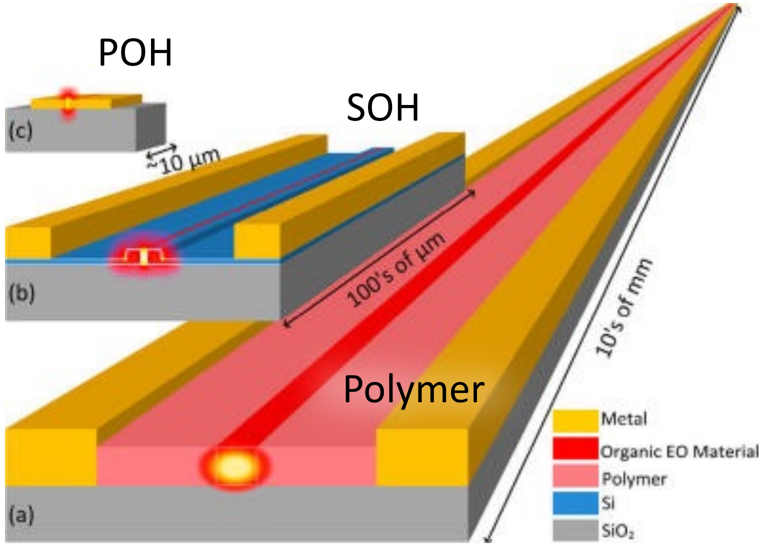


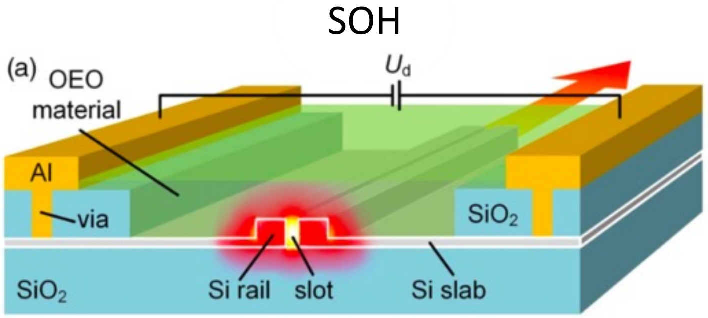
Improved ordering



Silicon Organic Hybrid (SOH) technology

- High compatibility with existing silicon photonics processes
  - No complex epitaxy or ion etch
  - Noble metal free
  - Accessible critical dimensions ~ 100 nm
- Slot waveguide based designs utilizing large Pockels response
  - MZIs with $V_\pi L$ ~ 500 V-µm
  - Athermal resonant modulators
- Facile OEO integration:
  - Oxide trench etch
  - Solution-processed advanced packaging step
  - Localized on-chip encapsulation
- Competitive device performance:
  - $V_\pi < 1$ V possible
  - Insertion loss < 1 dB/phaseshifter demonstrated
  - Bandwidth up to 60-100 GHz demonstrated, higher possible





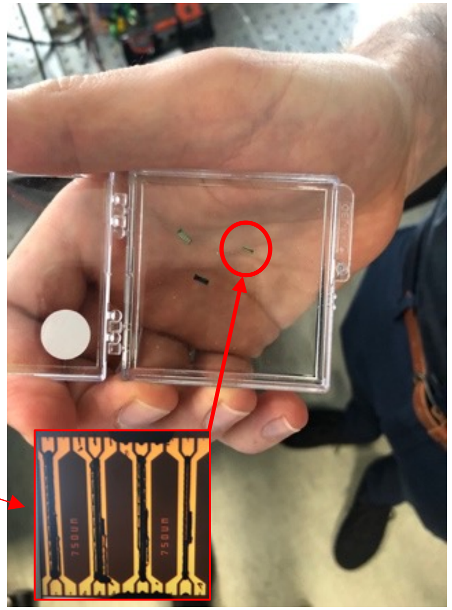
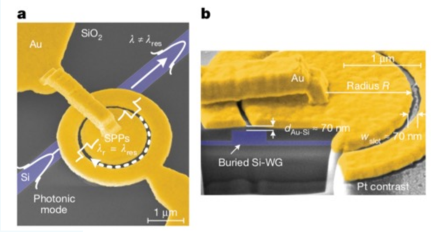


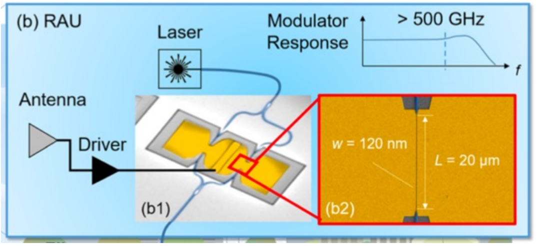
Photo: Gerard Zytnicki

C. Kieninger et al. *Optics Express* **2020**. doi:10.1364/oe.390315
C. Kieninger et al. *Optica* **2018**, doi: 10.1364/OPTICA.5.000739

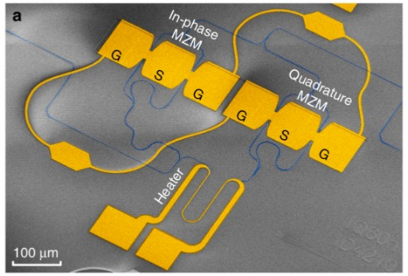
Plasmonic-Organic Hybrid (POH) technology



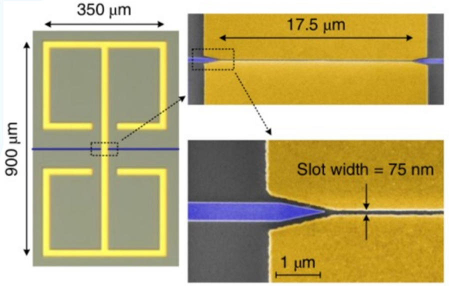
High-efficiency microscale POH ring resonator (1)



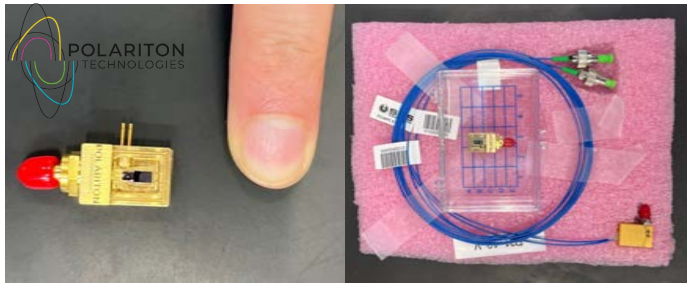
500+ GHz POH MZI (3)



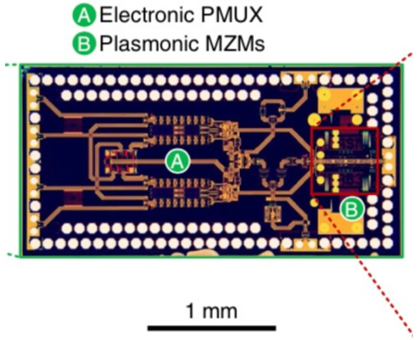
sub-100 aJ/bit IQ modulator (5)



60 GHz, sub-mm plasmonic mixer/antenna (2)



Commercial prototype 110+ GHz POH modulator from Polariton (4)



Integrated POH-BiCMOS transmitter (6)

Advantages of POH technology:

Ultra-small $V_{\pi}L$ (< 50 V-µm)

- Tight confinement + effective index of plasmonic mode
- Can be further improved with higher-performance materials

Ultra-large bandwidth (> 500GHz)

- Flat frequency response
- SFDR competitive with III-V based solutions

Crosslinked materials can survive space-relevant conditions

1) C. Haffner et al., Low-loss plasmon-assisted electro-optic modulator. *Nature* **2017**, 556, 483-486.
2) Y. Salamin et al. Microwave plasmonic mixer in a transparent fibre–wireless link. *Nature Photonics* **2018**, 12, 749-753. doi:10.1038/s41566-018-0281-6
3) M. Burla et al. 500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics. *APL Photonics* **2019**, 4. doi:10.1063/1.5086868
4) http://www.polariton.ch
5) W. Heni et al. Plasmonic IQ modulators with attojoule per bit electrical energy consumption. *Nature Communications* **2019**, 10. doi:10.1038/s41467-019-09724-7
6) U. Koch et al. A monolithic bipolar CMOS electronic–plasmonic high-speed transmitter. *Nature Electronics* **2020**. doi:10.1038/s41928-020-0417-9

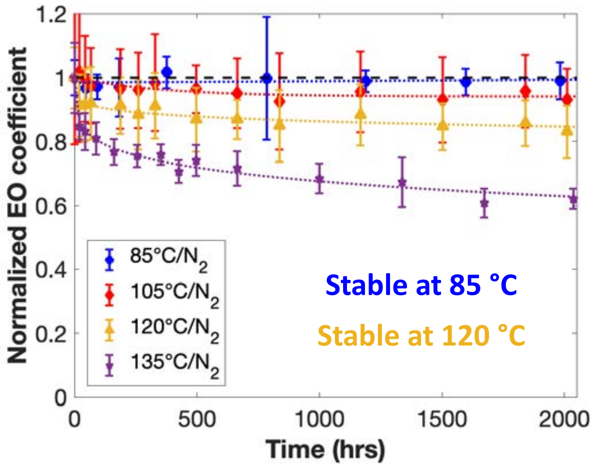
Engineering for thermal stability

Precursors

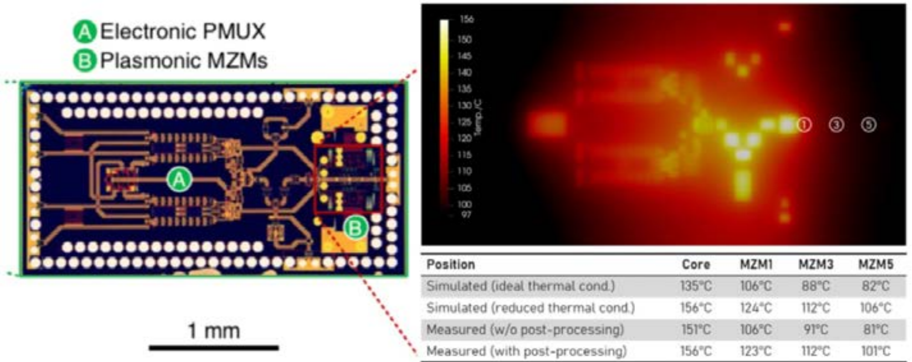
Poling + Crosslinking

Stable, high-performance material

High-temperature storage stability
(Telcordia GR-468 CORE)



Monolithic integration can get hot!



Position	Core	MZM1	MZM3	MZM5
Simulated (ideal thermal cond.)	135°C	106°C	88°C	82°C
Simulated (reduced thermal cond.)	156°C	124°C	112°C	106°C
Measured (w/o post-processing)	151°C	106°C	91°C	81°C
Measured (with post-processing)	156°C	123°C	112°C	101°C

82-124°C at MZIs!

- *Historical* Challenge – hard to get high EO performance and high temperature stability
- Multiple approaches (high T_g thermoplastics, crosslinked thermoset plastics) have demonstrated > 85°C long-term stability
- NLM approach – binary crosslinked organic glasses – form polymers in-situ during processing, projected > 11 year t_{80} at 120°C for HLD after initial burn-in, in absence of water or oxygen
- Operation demonstrated in devices using HLD at 120°C

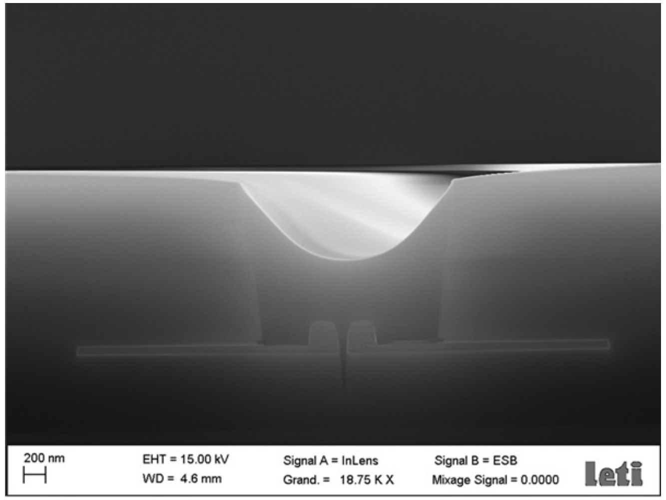
Data from S. R. Hammond et al, *Proc. SPIE* **2022**, doi: 10.1117/12.2622099
Upper right: U. Koch et al.. *Nature Electronics* **2020**. doi:10.1038/s41928-020-0417-9

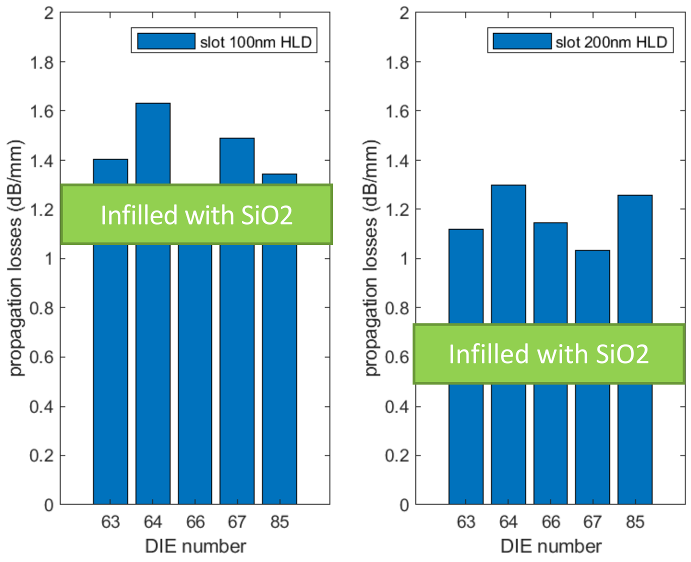
Fab process development

Slot waveguides and oxide open

OEO infill

Optical loss measurements





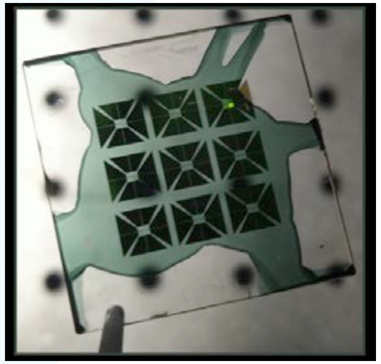
Data from Dr. Yohan Désières (CEA-LETI) and team
100 and 200 nm slot waveguides fabricated on 300nm line
Initial demo on passive devices

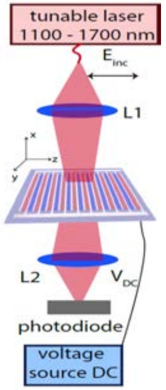
Slot width =100nm Slot width = 200nm

HLD infilling

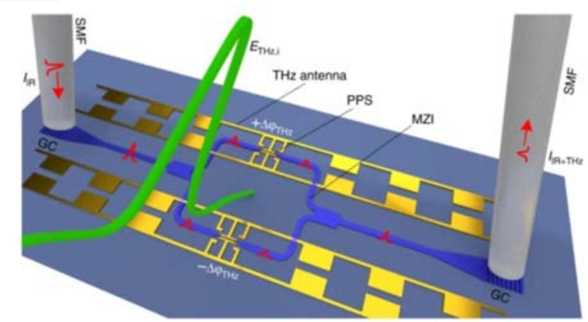
What's next?

New device architectures and additional platforms (SiN, III-V semiconductors)





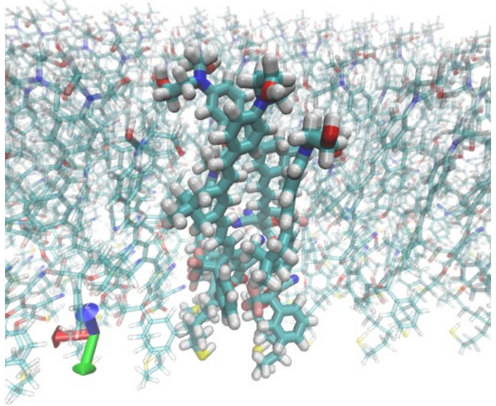
SLM

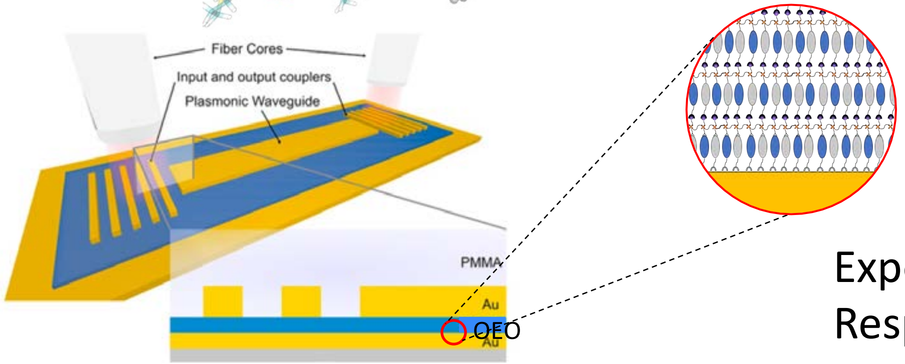


THz

I.-C. Benea-Chelmus et al, Nat. Commun. **2021,** doi: 10.1038/s41467-021-26035-y
Y. Salamin, et. al. Nat. Commun. 2019, doi: 10.1038/s41467-019-13490-x

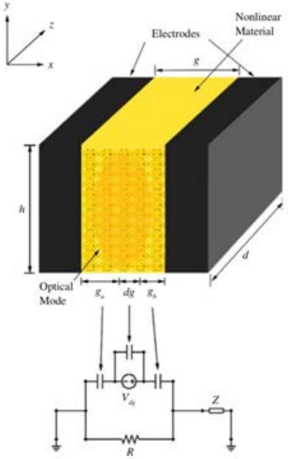
Wafer-scale deterministic assembly (sequential synthesis)





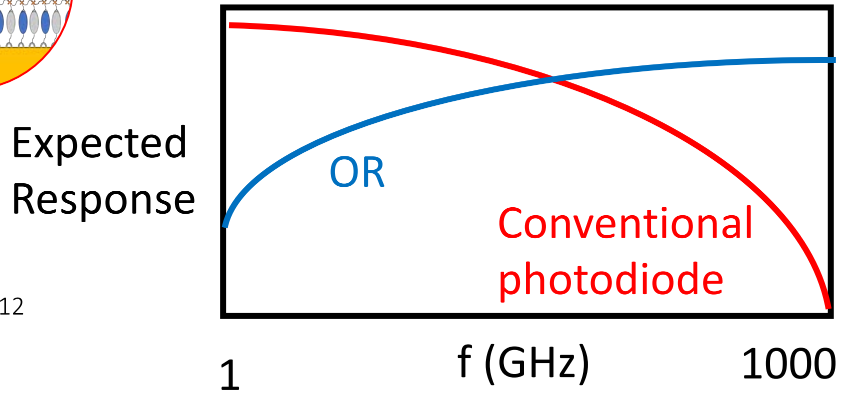
L. R. Dalton, et. al. APL Materials 2023, doi: 10.1063/5.0145212

Optical rectification-based detection



T. Baehr-Jones, J. Witzens, M. Hochberg, *IEEE Journal of Quantum Electronics* **2010** doi:10.1109/jqe.2010.2055838

C. Cox, E. Wooten, J. Lightwave Technology **2021**, doi: 10.1109/jlt.2021.3118968



Acknowledgements

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Dir. Process Development

Dr. Stephanie Benight

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- Dr. Andreas Tillack

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- Dr. Claudia Hoessbacher

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- Dr. David Moor

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- Dr. Yovan de Coene

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Dr. Christian Haffner (imec)

Prof. Ileana-Cristina Benea-Chelmus (EPFL)

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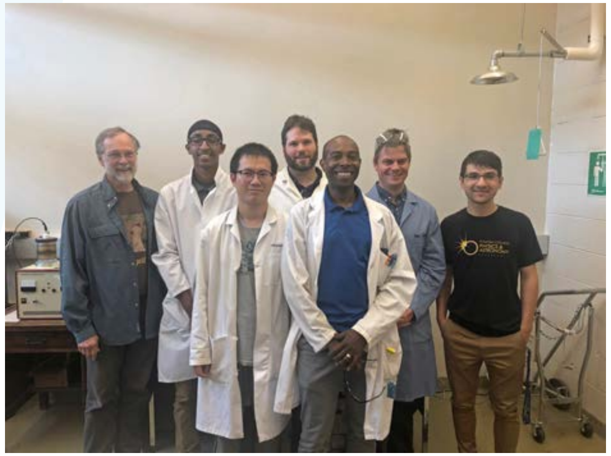
Thanks!

NLM Photonics Team



Robinson/Dalton group in 2019

University of Washington