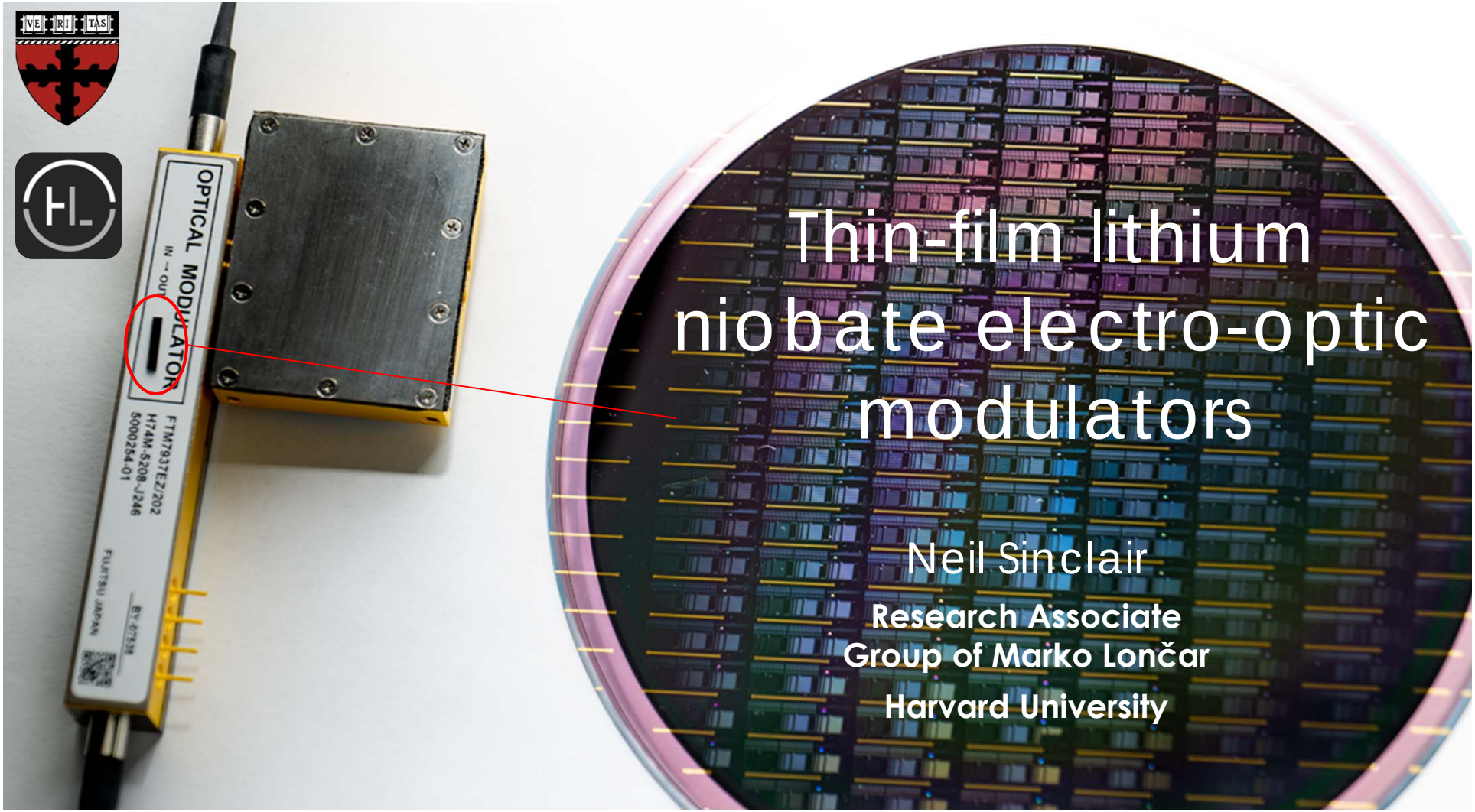


# Thin-film lithium niobate electro-optic modulators

Neil Sinclair

**Research Associate**
**Group of Marko Lončar**
**Harvard University**

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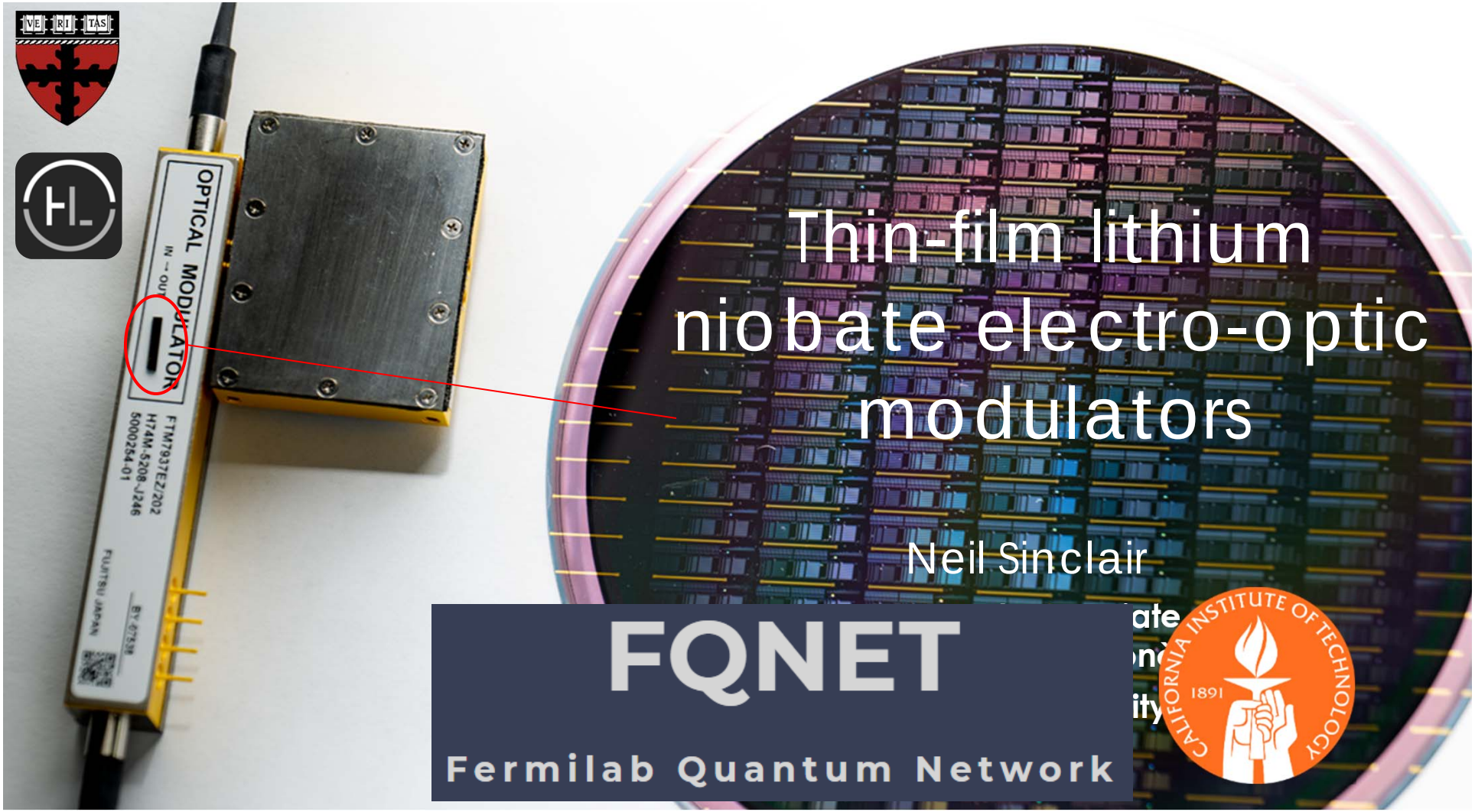



# Thin-film lithium niobate electro-optic modulators

Neil Sinclair

FQNET

Fermilab Quantum Network

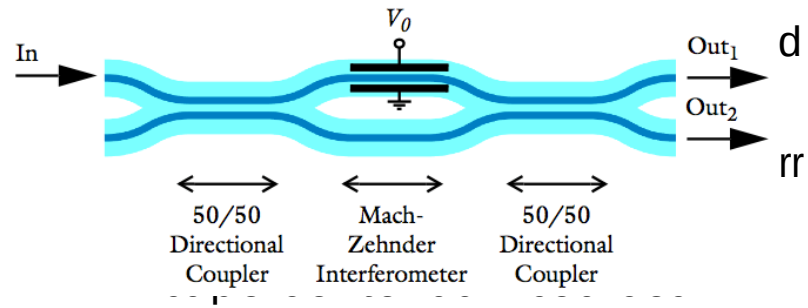
# Lithium Niobate

| High refractive index ~ 2.2 | Large diagonal $\chi^{(2)}$ nonlinearity ~ 30 pm/V | Wide transparency window (0.4 – 5.5 µm) |
|---|---|---|

$$P = \varepsilon_0 \chi E + \boldsymbol{\varepsilon_0 \chi^{(2)} E^2} + \varepsilon_0 \boldsymbol{\chi^{(3)} E^3} + \cdots$$

$\boldsymbol{\chi^{(2)}}$ is essential for:

- low-loss, highly linear, electro-optic (EO) modulation
- EO frequency comb generation
- frequency conversion (e.g. second harmonic generation)




**The problem:** Lithium Niobate is inert & hard to etch, therefore waveguides are defined by ion-indiffusion or proton exchange.

⇒ small index contrast between core and cladding (~ 0.02)

⇒ devices are bulky, non-scalable, expensive and require large driving voltage!

Ion-diffused core

Intact LN cladding

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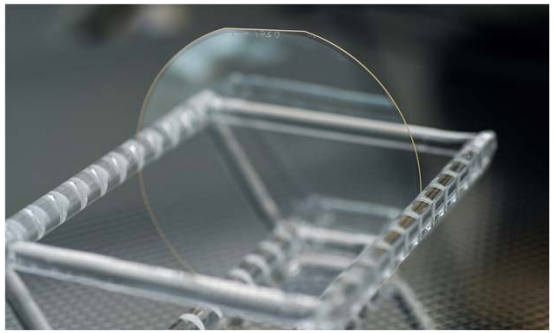
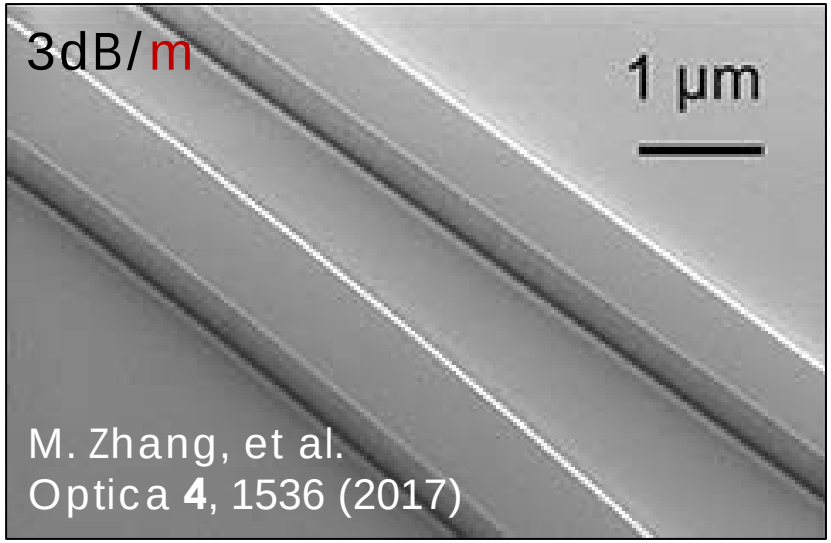
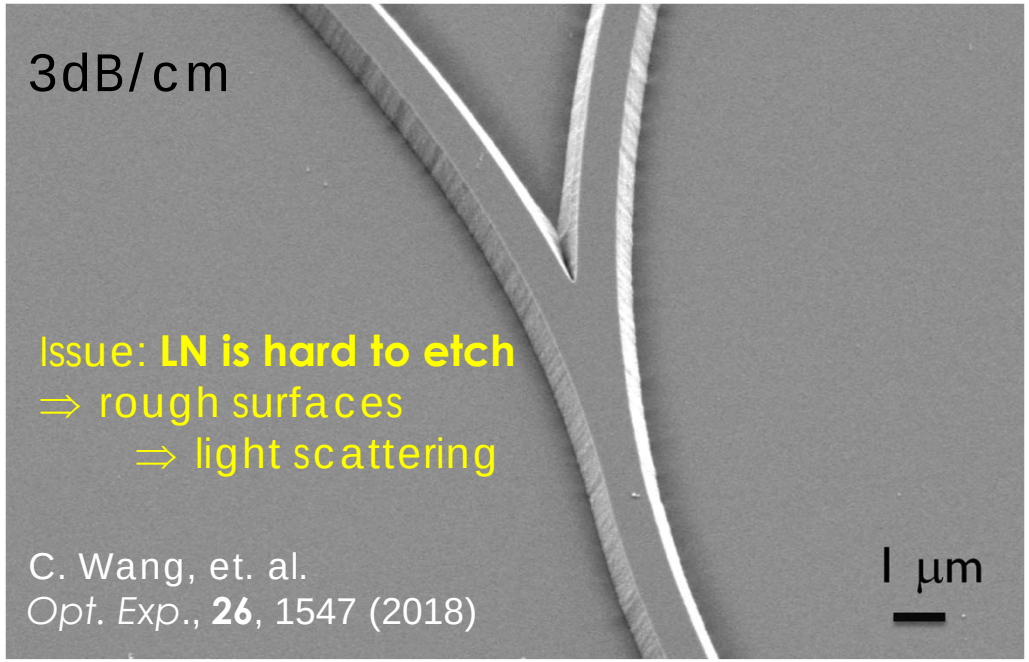
# Approach

- Thin LN film on insulator wafers produced by NanoLN company, using smart cut process.

- Device fabrication
  - e-beam lithography
  - reactive ion etching of LN
  - metal evaporation (contacts)
  - $SIO_2$ deposition (top cladding)




Optimized etch!
⇒ Smooth sidewalls
⇒ Low loss!

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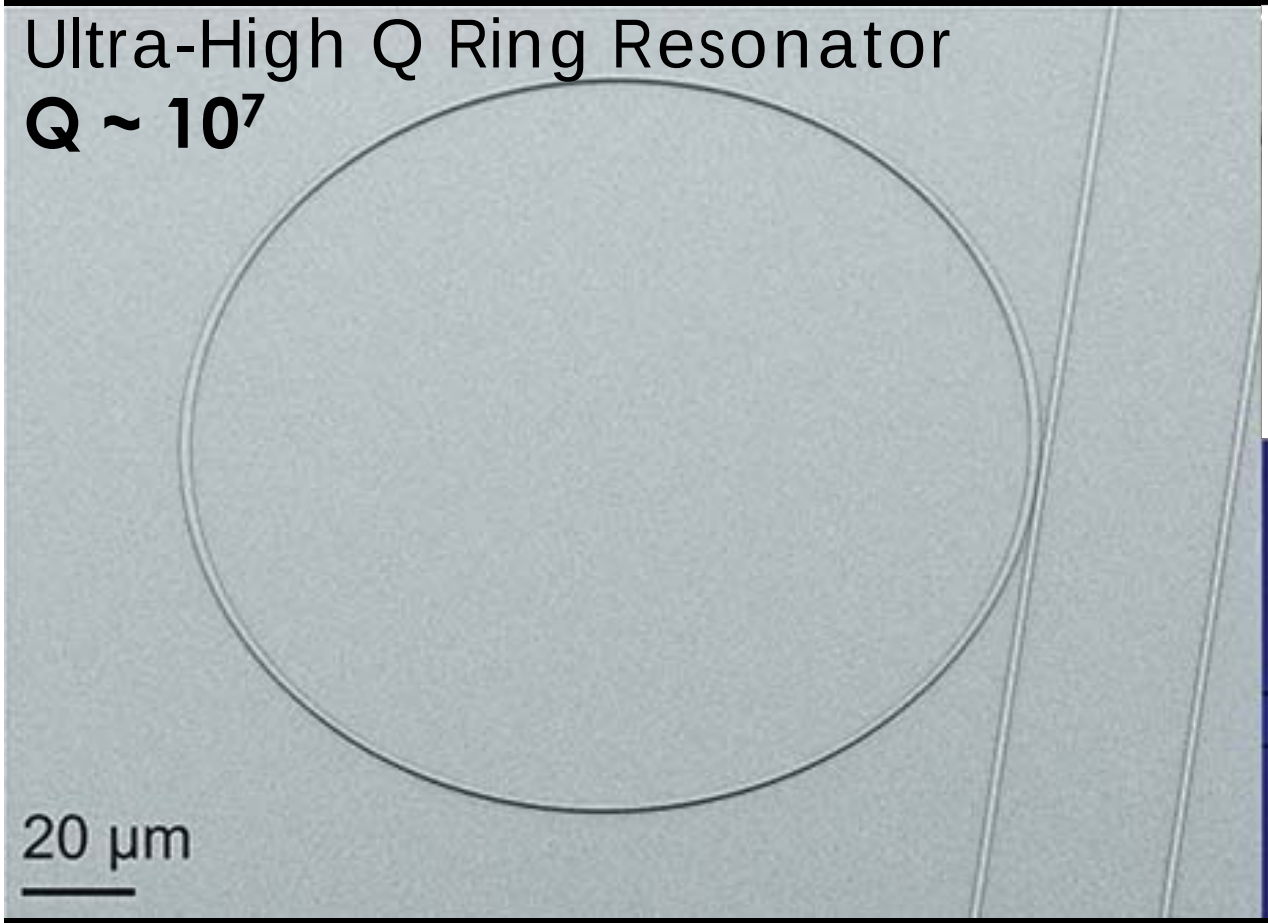
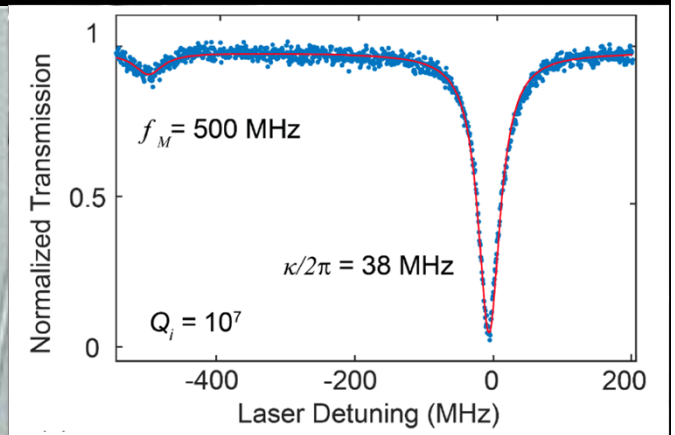
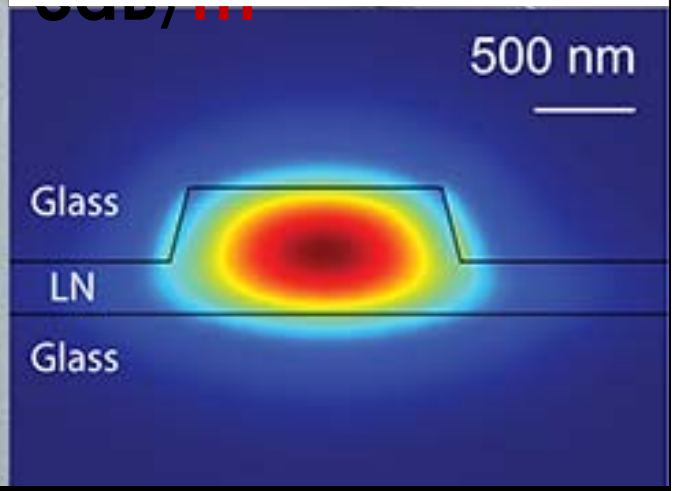
# Ultra-High Q LN Cavities!




$\lambda = 1.55\ \mu m$:
cavity Q ~ 10,000,000
waveguide loss ~ 0.03 dB/cm

M. Zhang, et al. *Optica*, **4**, 1536 (2017)

$\lambda = 630\ nm$:
cavity Q ~ 11,000,000
waveguide loss ~ 0.06 dB/cm

B. Desiatov et al, *Optica*, **6** 380 (2019)

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# Vision: Integrated Lithium Niobate Photonics

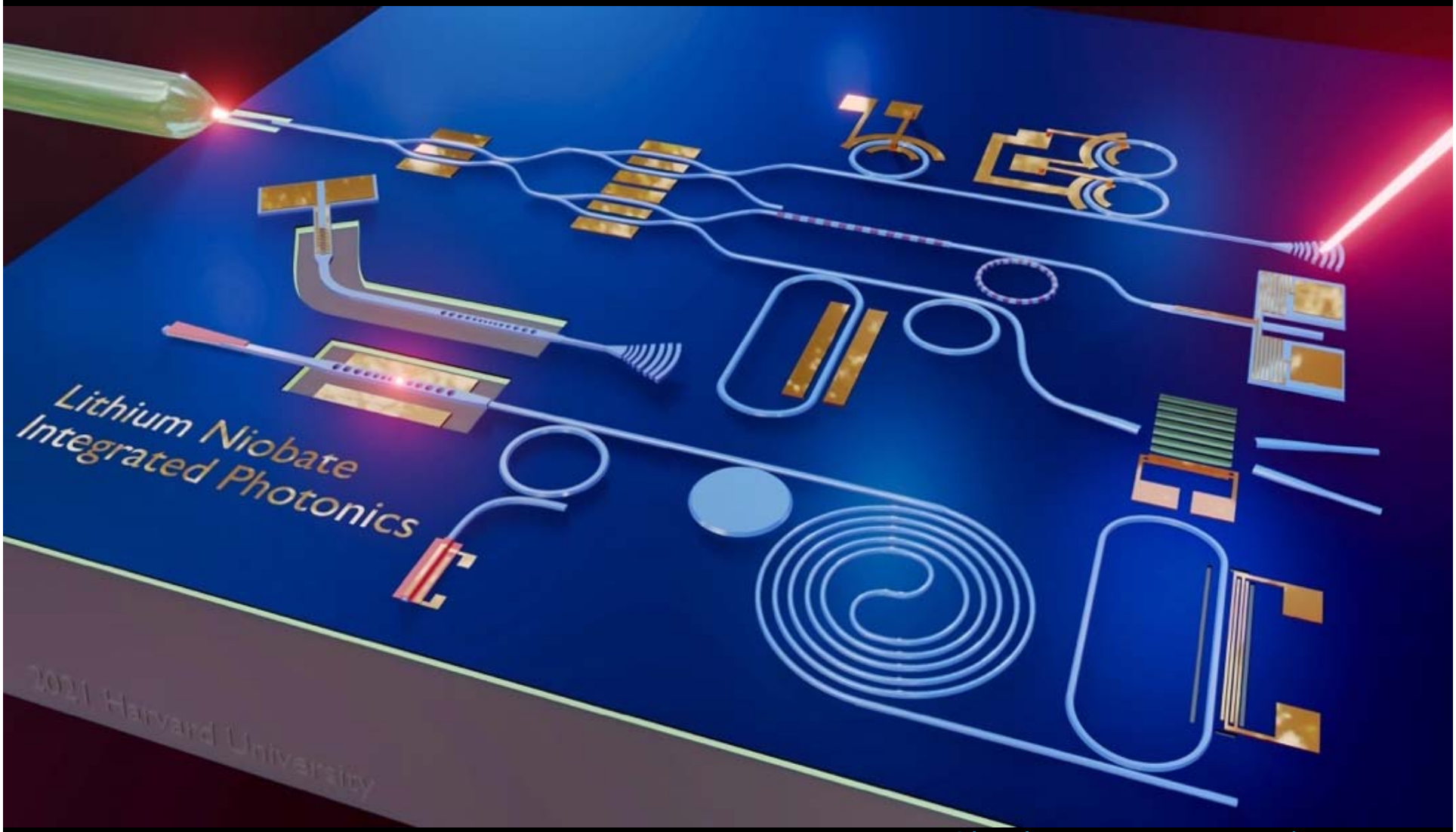


Image credit: Linbo Shao

Check out our recent review paper:
Zhu et al., *Adv. Opt. Photonics* **13**, 242 (2021)

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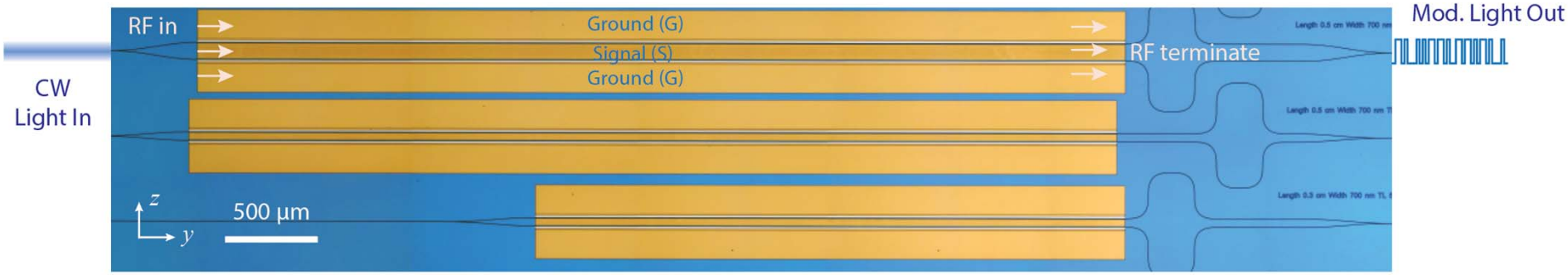
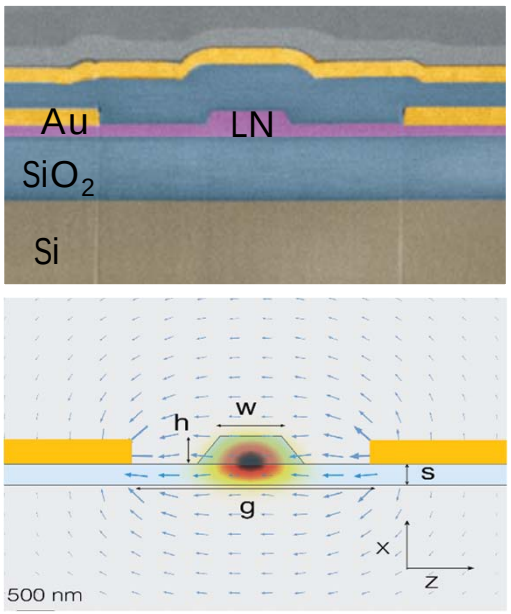
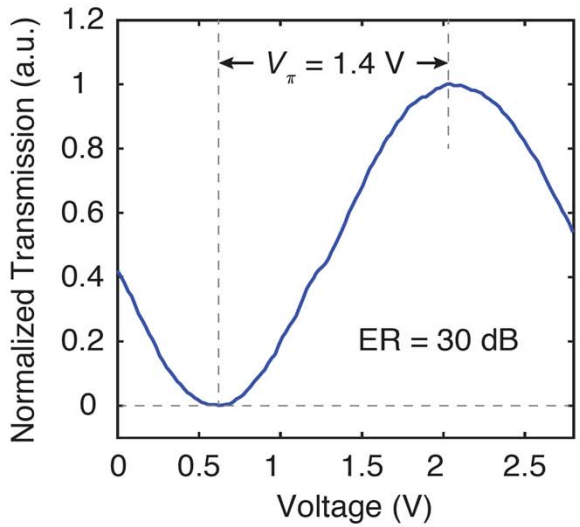
# (travelling wave) Integrated LN Electro-Optic Modulators




Good overlap between microwave & optical fields

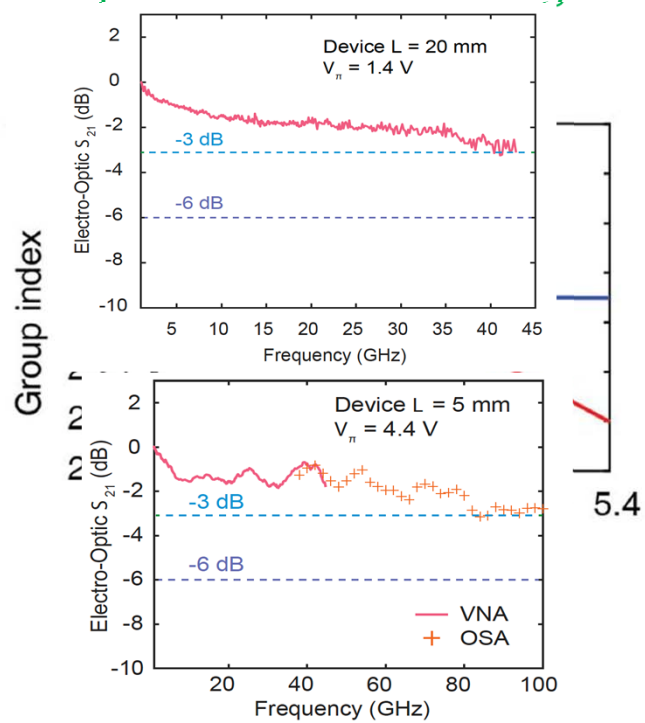



Good EO efficiency
$V\pi L$ = 2.8 Vcm



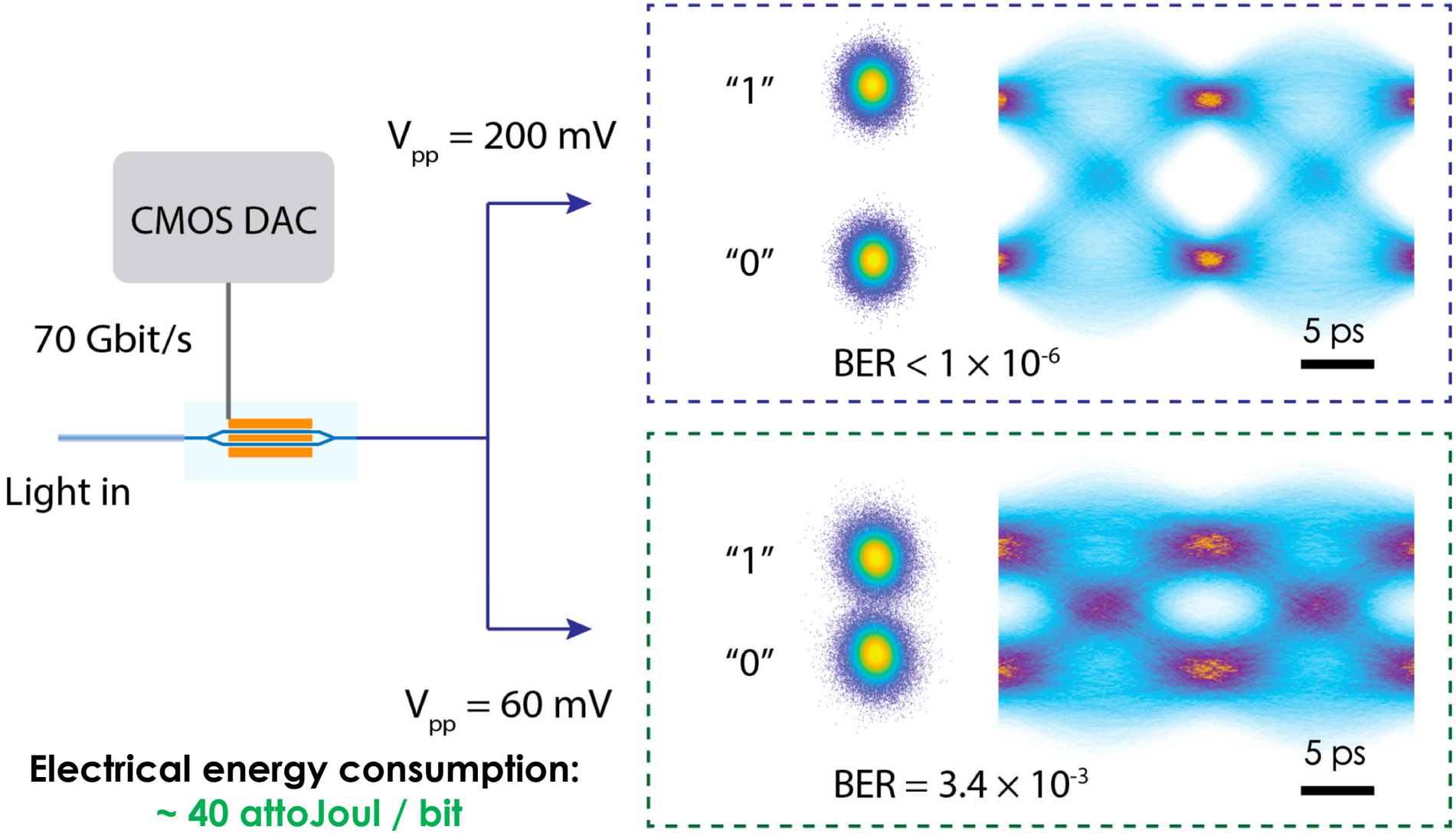

EO bandwidth > 100 GHz
(limited by microwave loss)

Matched group velocity of optical & microwave signals




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

# CMOS Driven Modulator

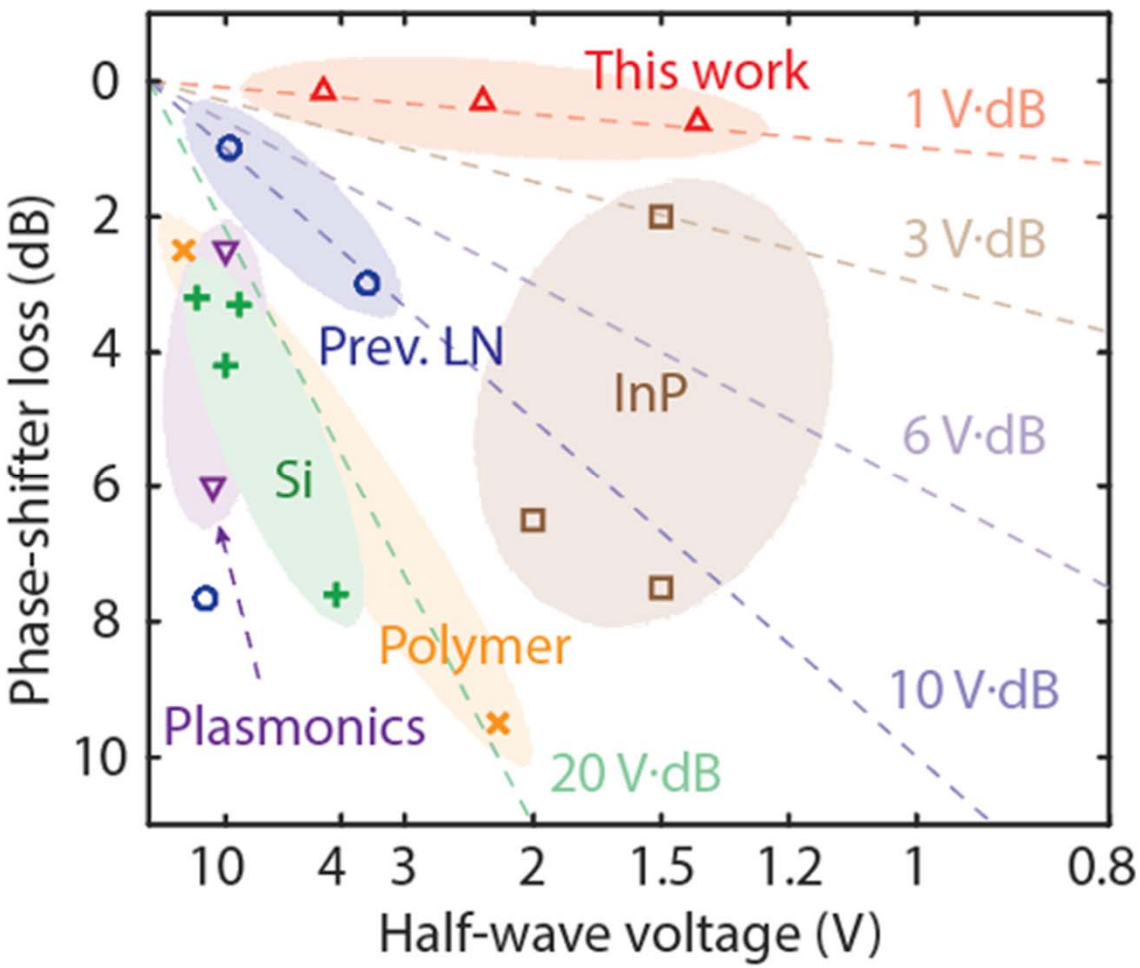



**Electrical energy consumption:**
**~ 40 attoJoul / bit**

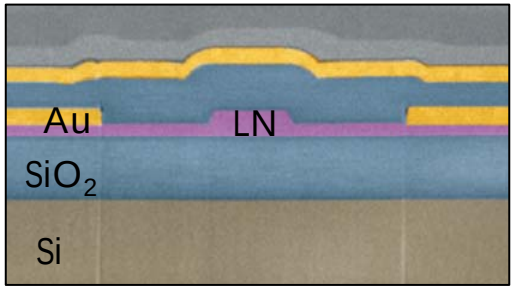
C. Wang, M. Zhang et al, *Nature*, **562**, 101 (2018)

with Nokia Bell Labs (Peter Winzer & team)

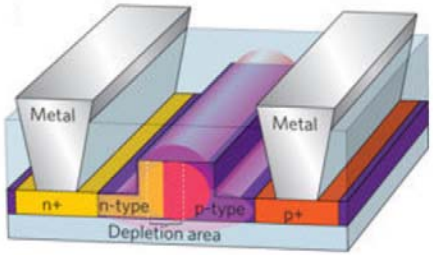
# Comparison with Integrated Modulators



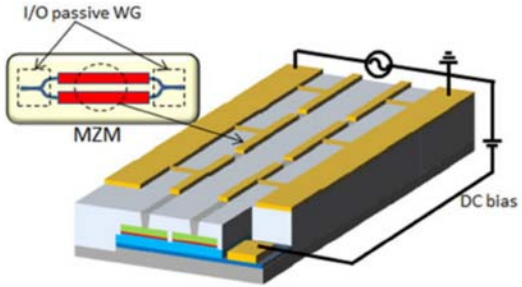

**Integrated LN modulator**




Silicon Photonics
Nature Photonics 4, 518 (2010)




InP Photonics
JLT, 35, 1450 (2017)

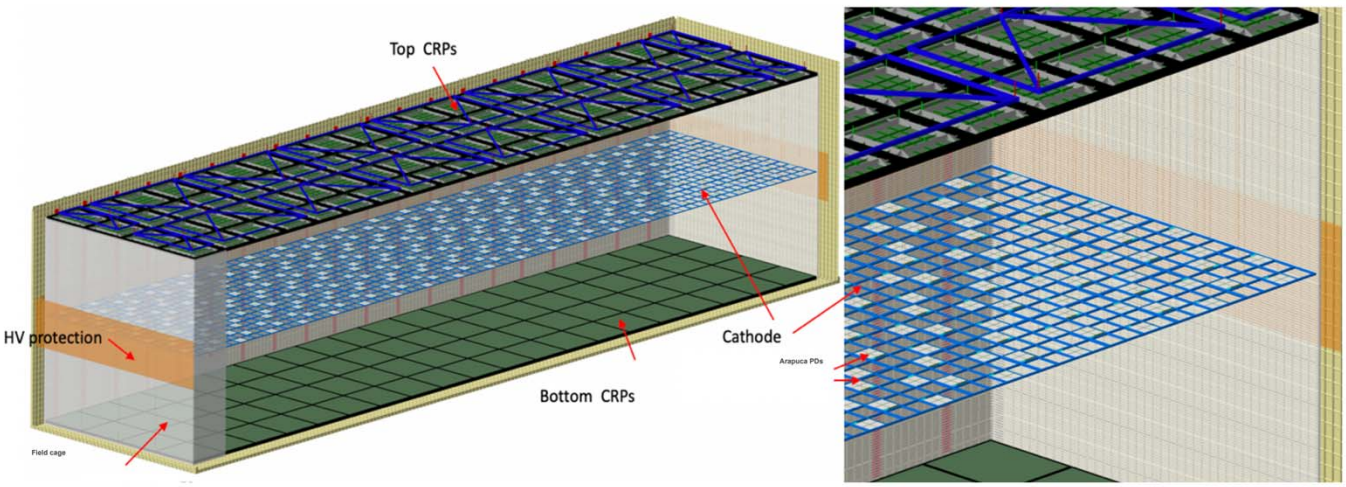



C. Wang, M. Zhang et al, *Nature*, **562**, 101 (2018)

# Collaboration with DUNE

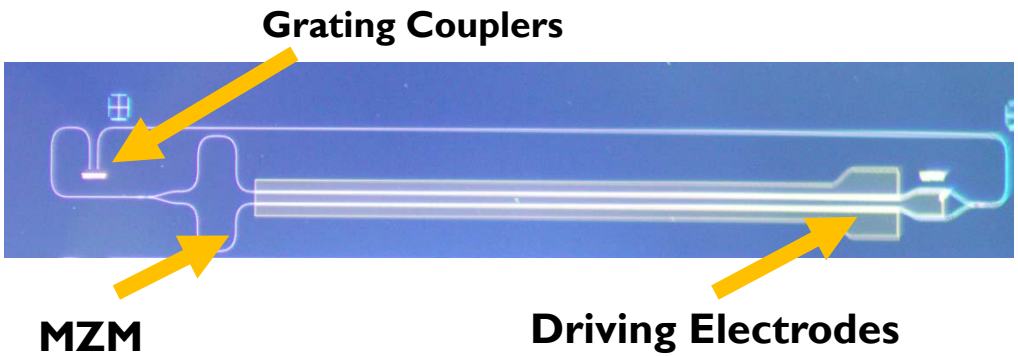
- Goal: remove signals from HV (300 kV) plane at lower power cost
  - Use optical carrier to transmit signals via fiber
  - Liquid Ar low temperature operation (-186 C)

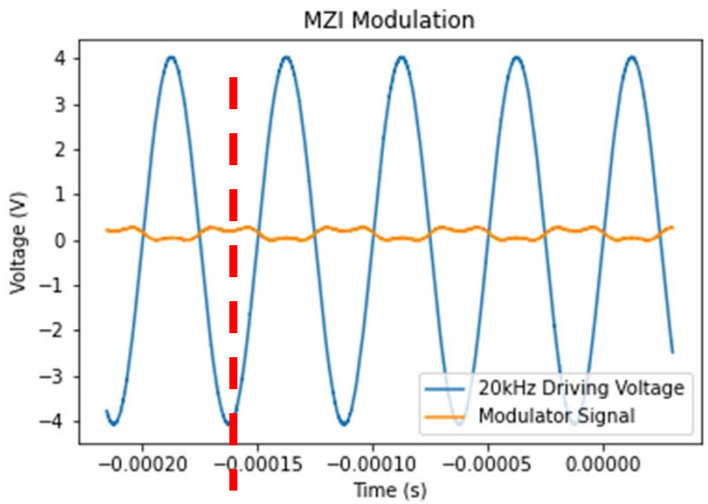
- **Analog Encoding**
  - 1V pulse, 80 ns rise time, 1-2 μs decay times
- **Digital Encoding**
  - 60 MB/s

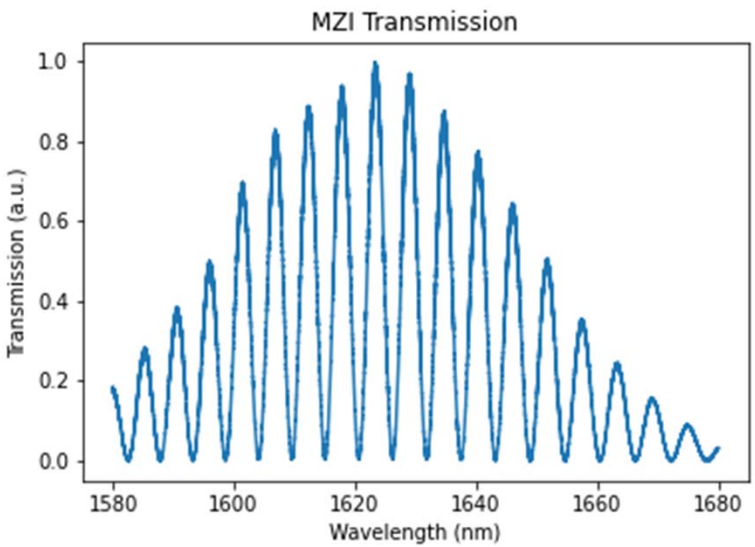


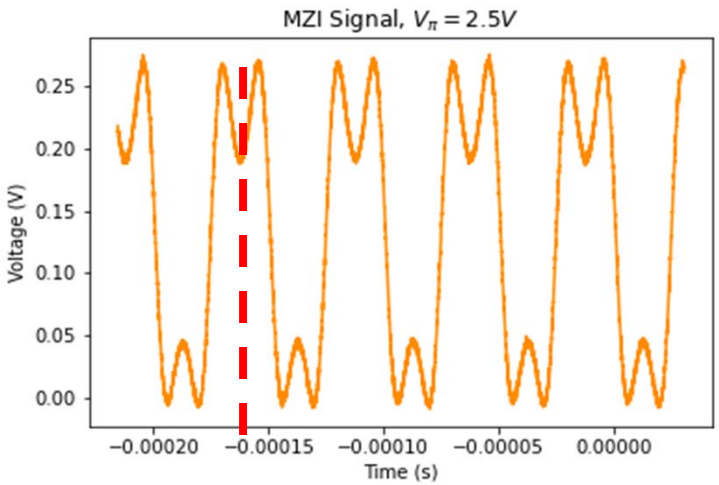

Segreto, E. & Cavanna, F. , Vertical Drift Technical Review (2021)

# M-Z Modulator Specifications



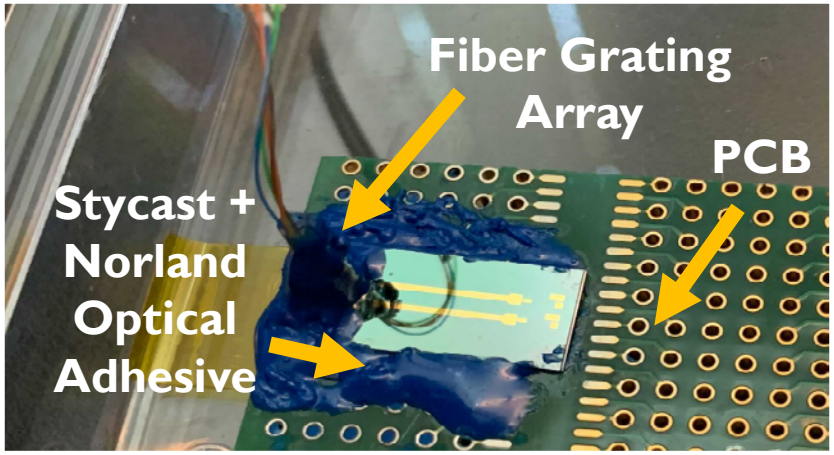

~180 pm FSR

**Vπ = 2.5 V**

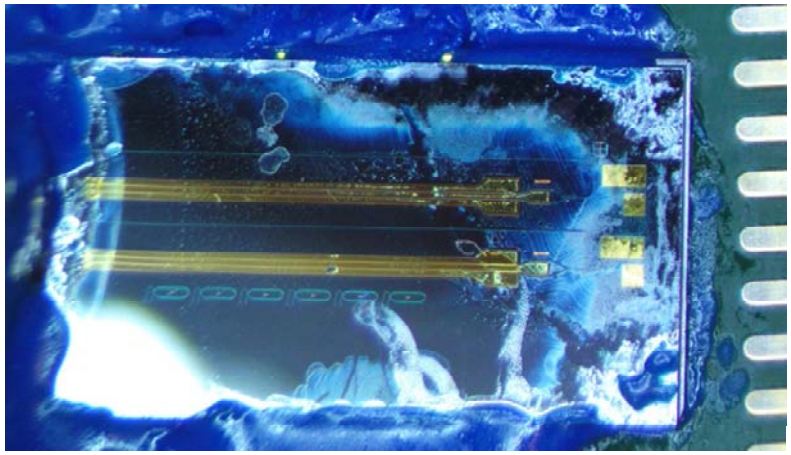
# Liquid Nitrogen Dunk Testing

- Glue fiber array onto device, submerge into liquid nitrogen and see if transmission OK
- Modulator works down to 50 mK
- Norland Optical Adhesive + Stycast Epoxy
  - 5 dB/coupler loss at RT
  - 45 dB loss in Liquid Nitrogen T ☹
  - ***Reversible on warm-up***
- Ongoing Measurements:
  - Optical characterization of thermal-optic and mechanical drift

**Fiber array glued to modulator**




**Zoom of device**



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Dr. David Barton
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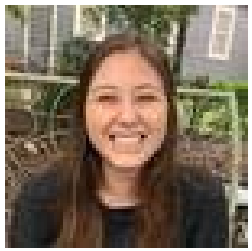
Eric Puma (G4)
Rebecca Cheng (G3)
Yaowen Hu (G3)
CJ Xin (G3)
Soumya Ghosh (G3)
Amirhassan Shams-Ansari (G3)
**Hanna Warner (G1)**
Lingyan He (-> HyperLight)
Tianhao Ren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**Caltech**
Maria Spiropulu

**HyperLight**