Lithium Niobate Photonics for High Speed and Low Loss Data Links

Cheng Wang（王骋）

Assistant Professor

Department of Electrical Engineering

City University of Hong Kong

https://www.cityu.edu.hk/~cwang cwang257@cityu.edu.hk

Lithium niobate (LN)

Electronics/ Microwave →  → Optics

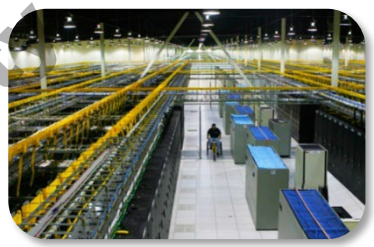
LN modulator

Large diagonal $\chi^{(2)}$ nonlinearity ~ 30 pm/V

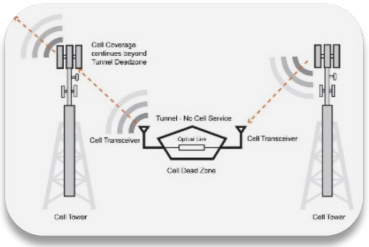
Low optical loss ~ 0.001 dB/cm

Wide transparency window (0.4 – 5.5 μm)

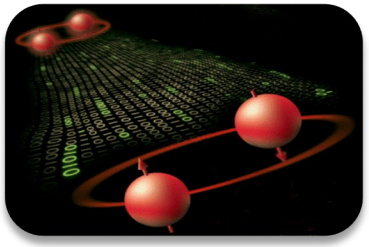
Telecommunications



Data centers/ HPC

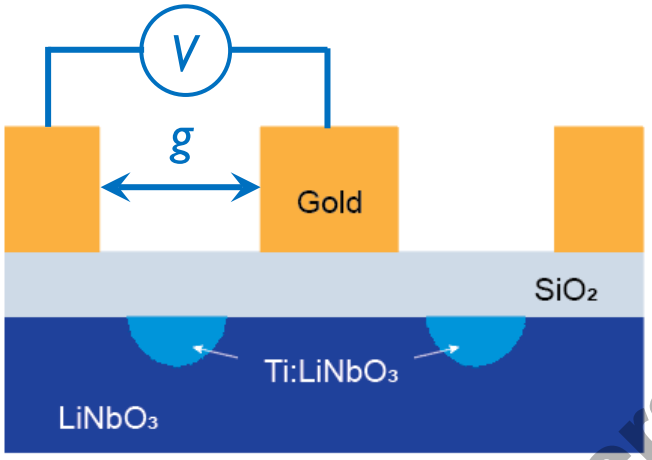


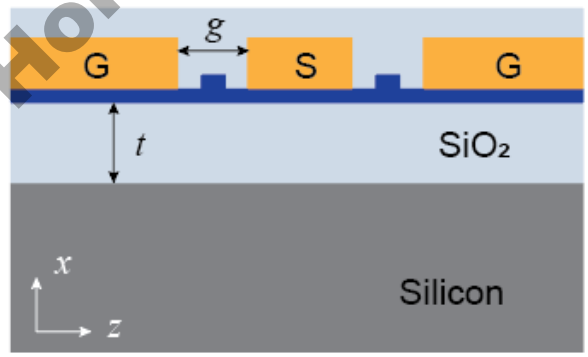
Microwave photonics



Quantum/nonlinear photonics

Bulk vs. thin-film LN devices





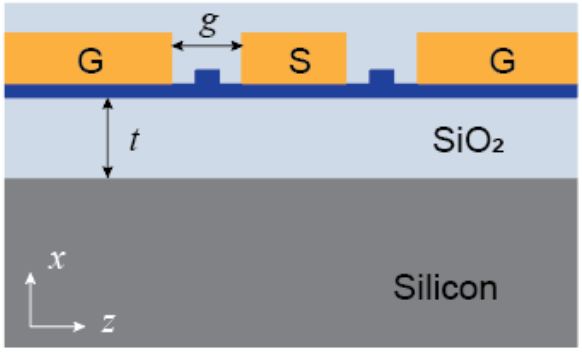
Bulk ($Ti:LiNbO_3$) devices:

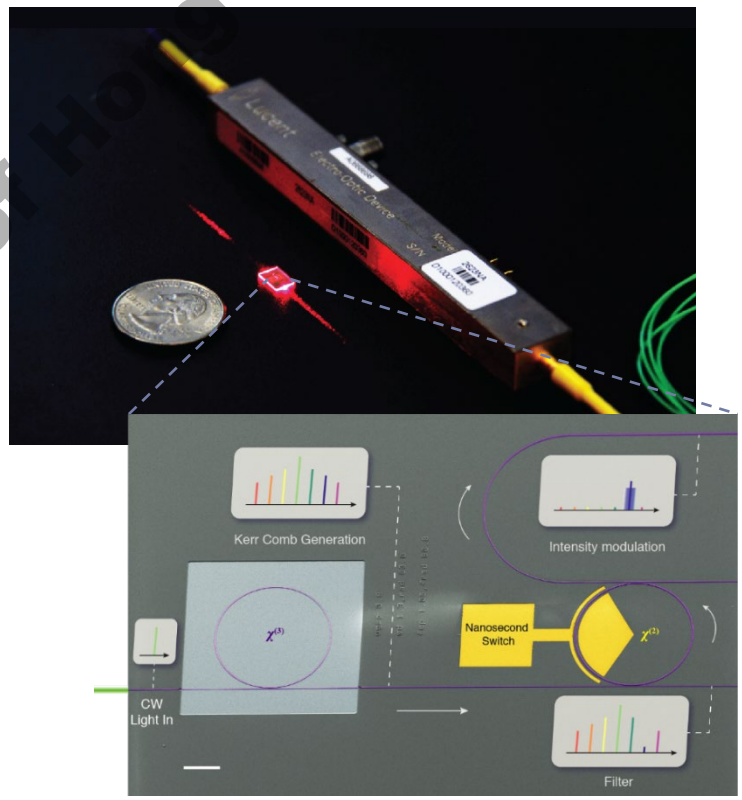
- $\Delta n \sim 0.02$ (mode size ~ 10 μm)
- Bending radius ~ cm scale
- EO efficiency limited by large gap *g*

Thin-film LN devices:

- Single-crystal LN on SiO_2 (LNOI)
- Submicron light confinement
- Bending radius ~ 50 μm
- Much better EO/nonlinear efficiency

Smaller but more efficient





Thin-film LN devices:

- Single-crystal LN on SiO_2 (LNOI)
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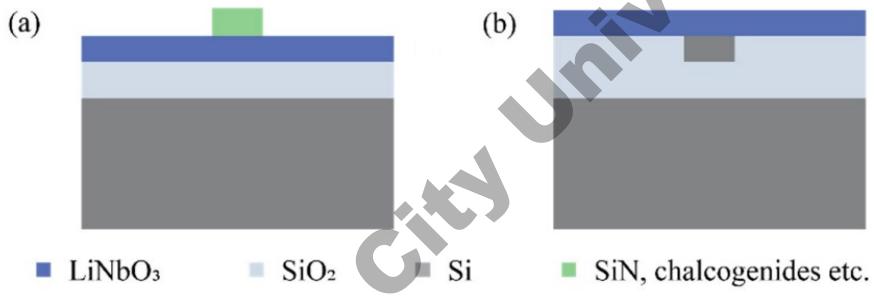
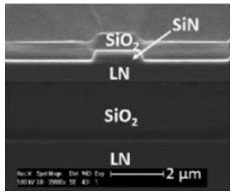
C. Wang & M. Zhang et al.
Nat. Commun. **10**, 978 (2019)

LNOI (lithium niobate on insulator)

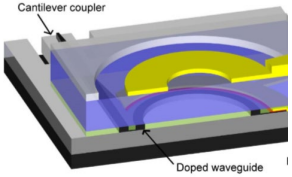
Monolithic approach:

- Non-trivial dry etching
- Take full advantage of the material property, low-loss (once figured)





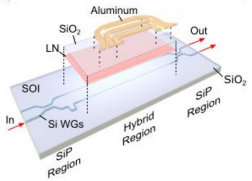
UCSB



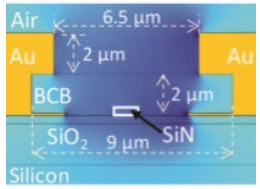
OSU

Heterogeneous approach:

- No need for dry etching LN
- Potential compatibility with standard foundry processes

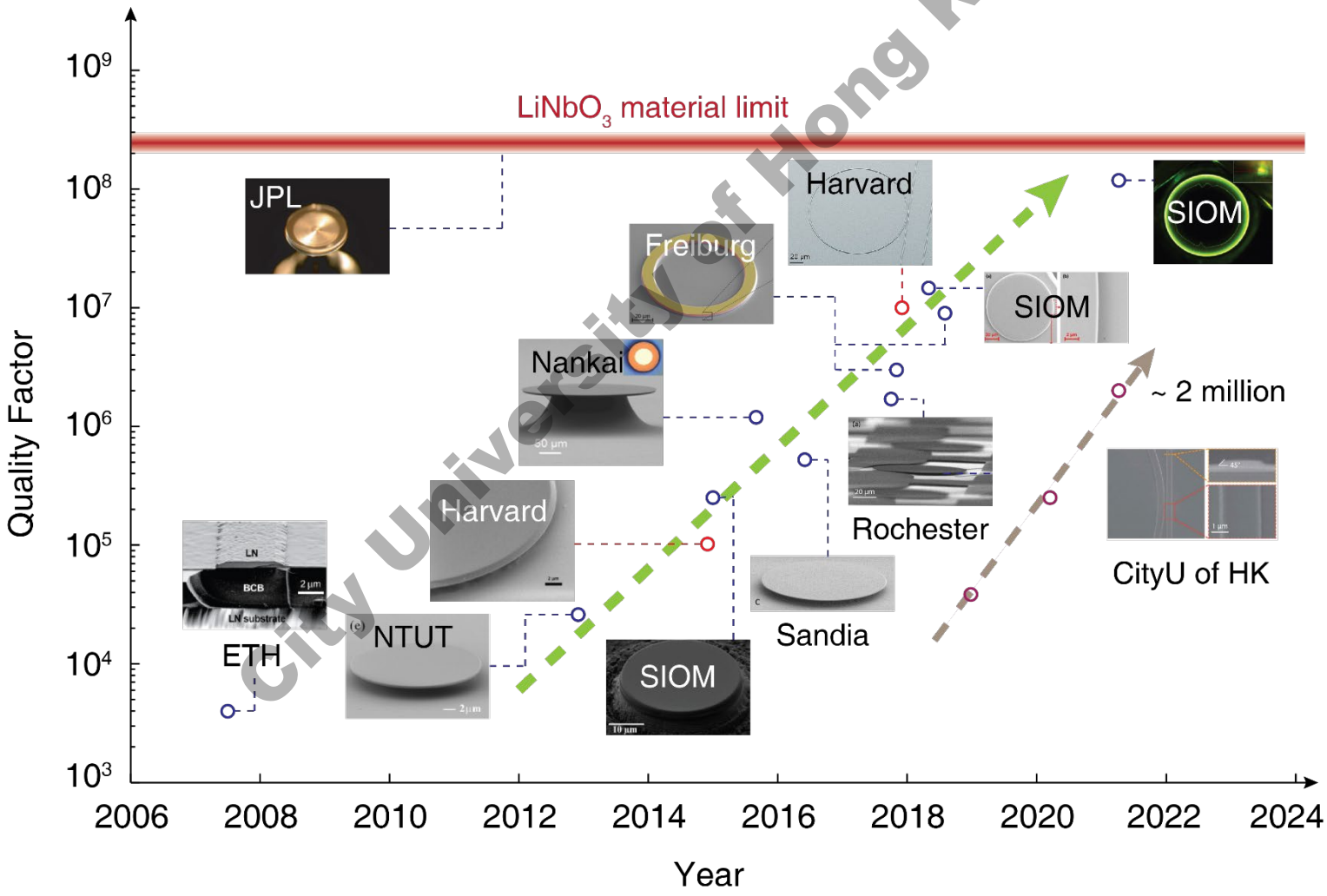


UCSD

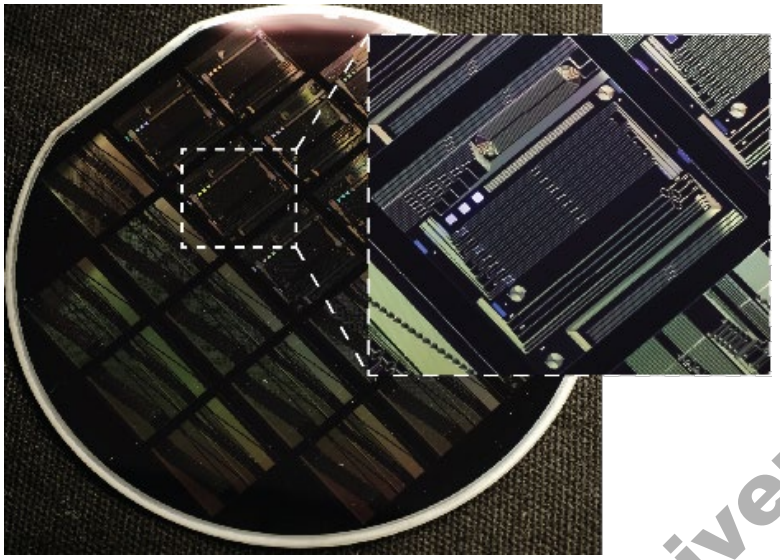


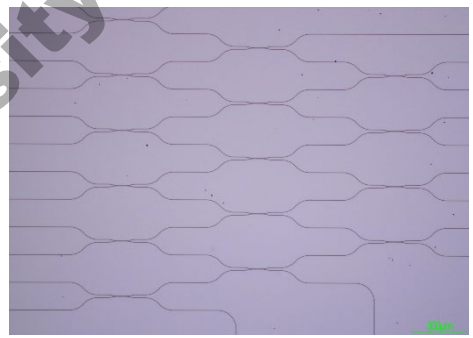
CREOL

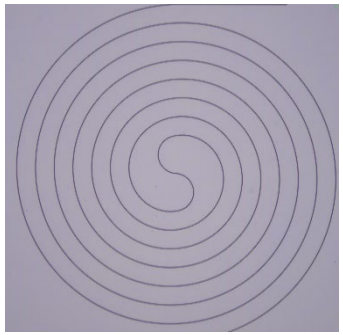
Dry-etched LN resonators



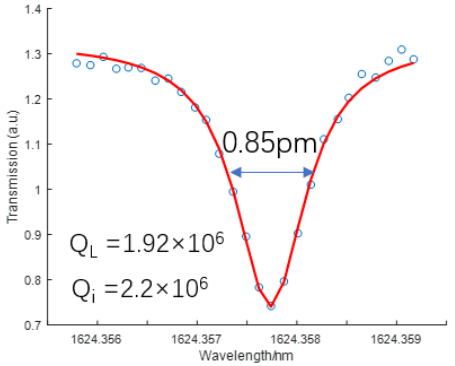
Wafer-scale LN processes



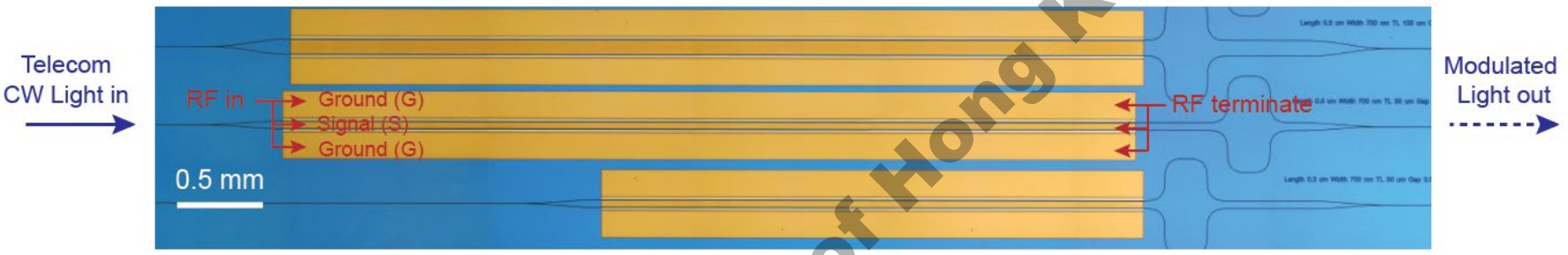


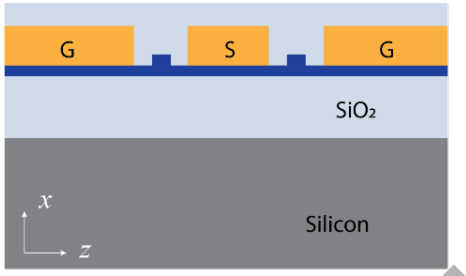


- 4-inch LNOI wafer process using UV Stepper (at HKUST and CityU)
- 6 inch readily possible
- Q factors ~ 2 million (loss ~ 0.2 dB/cm) across the wafer

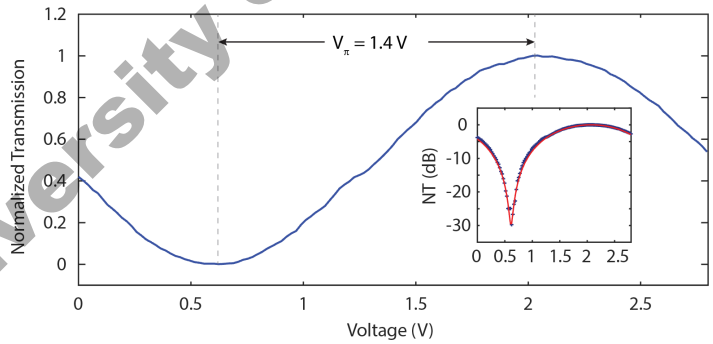


EO modulators based on LNOI





Integrated LN modulator



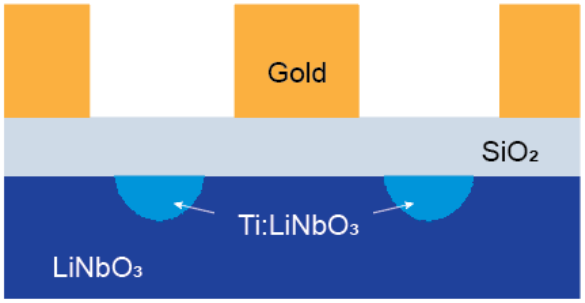
V_π = 1.4 V

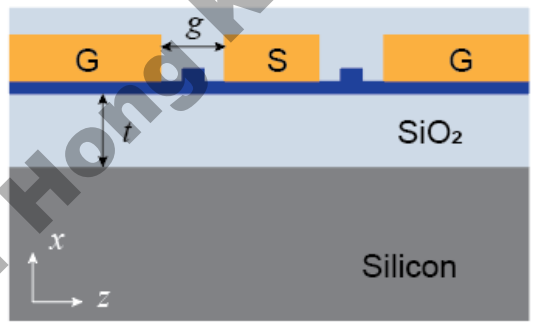
ER = 30 dB

- Co-propagating RF transmission line and optical MZI
- Voltage-length product ~ 2 V·cm (Conventional LN MZM ~ 20 V·cm)
- 2 cm → 1 V (CMOS level)
- E/O bandwidth dependent on velocity matching & RF loss

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

RF/optic velocity matching





Bulk LN modulators:

$\varepsilon_{RF} = 28, \varepsilon_{opt} = 5$

$v_p(RF) << v_g(opt)$

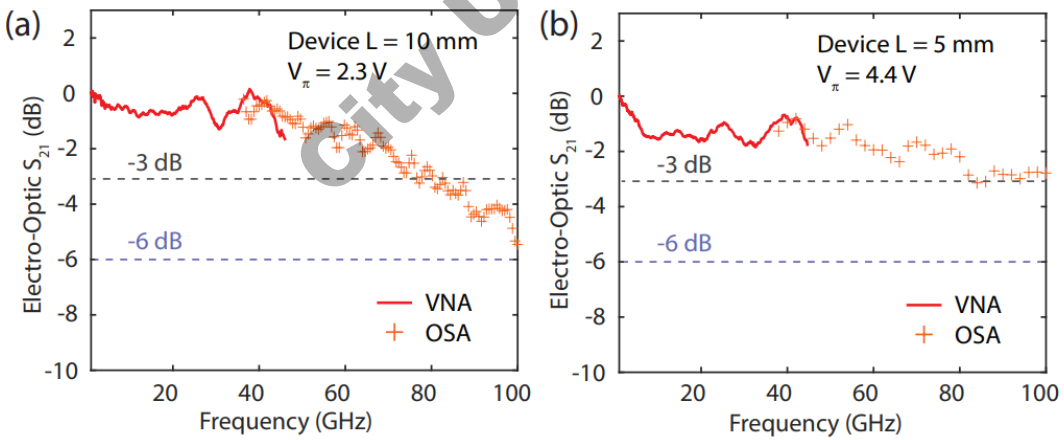
Buffer oxide layer for velocity matching

Thin-film LN devices:

$v_p(RF) \approx v_g(opt)$

RF field mostly in buried oxide ($\varepsilon_r = 4$)

Velocity matching readily achievable!

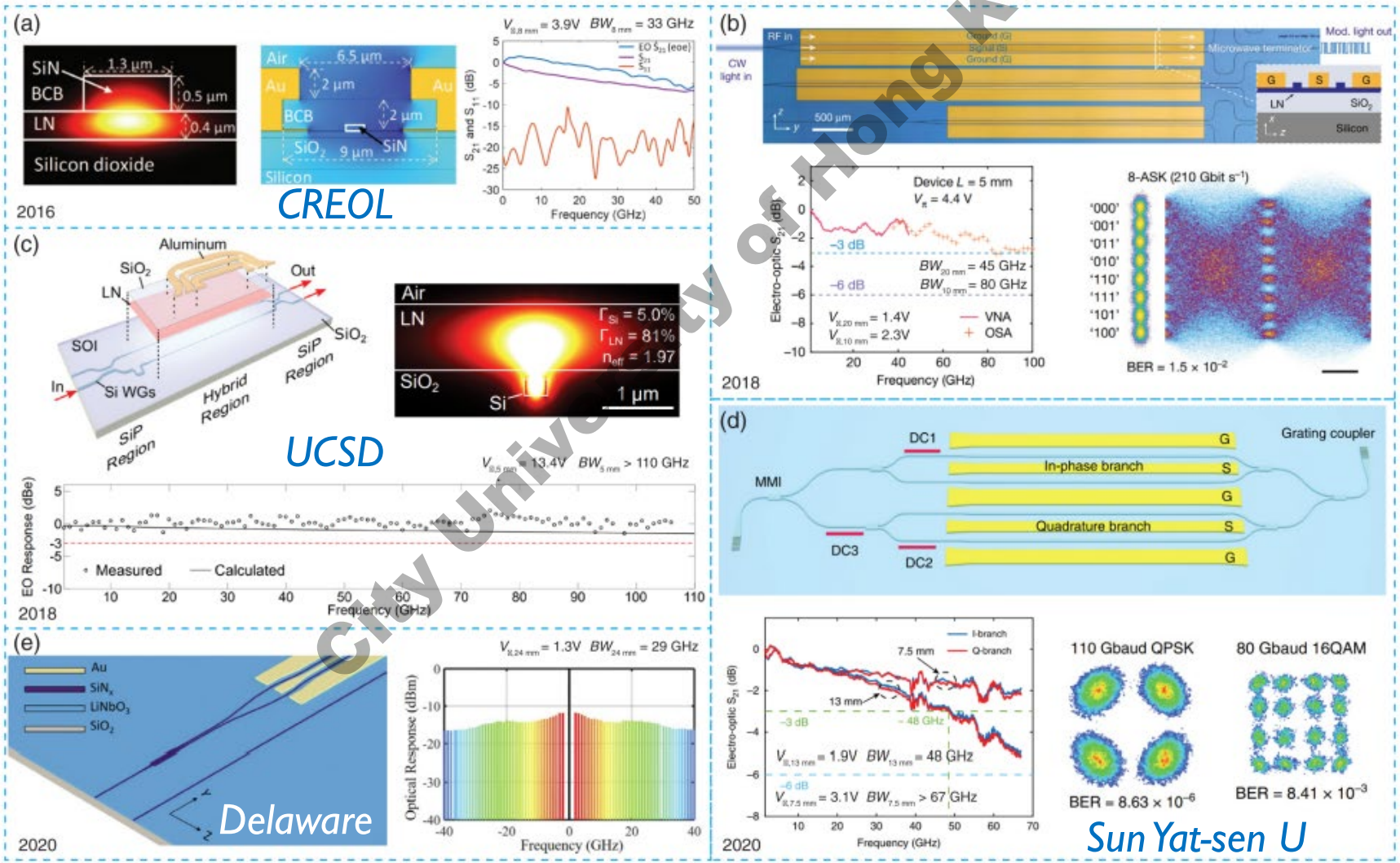


2.3 V 80 GHz

4.4 V 100 GHz

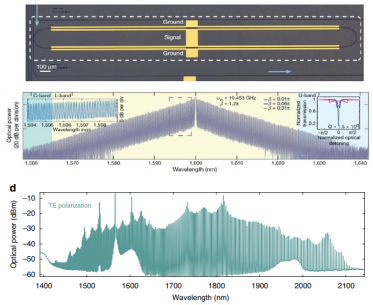
C. Wang & M. Zhang et al. Nature **562**, 101-104 (2018).

LNOI-based EO modulators

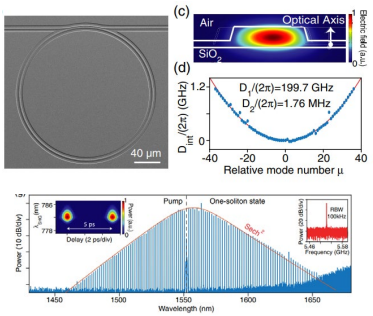


Functional LNOI photonic devices

Kerr/EO comb generator

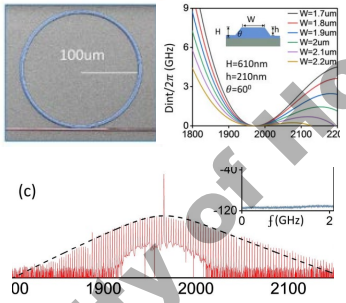


Harvard

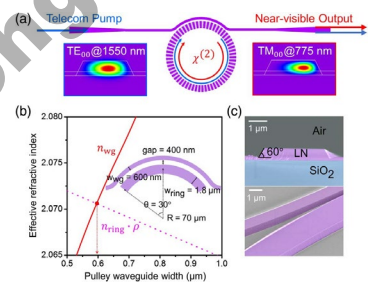


Rochester/Caltech

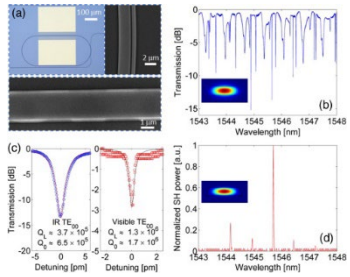
Efficient wavelength converter



Yale

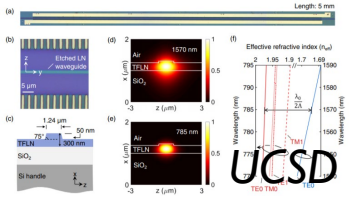


Yale

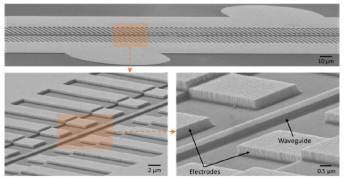


Stevens

Photon pair generator

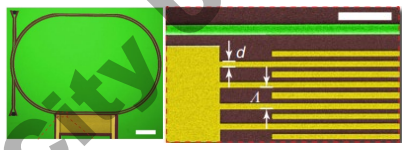


UCSD

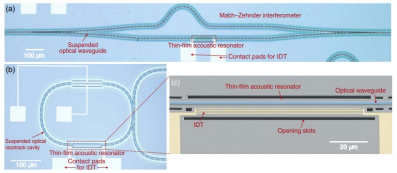


Rochester

Acousto-optic modulator

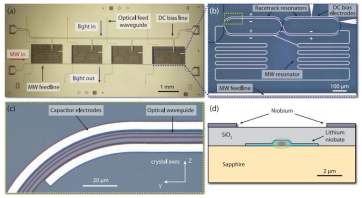


CUHK

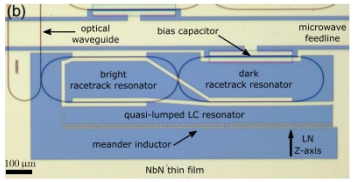


Harvard

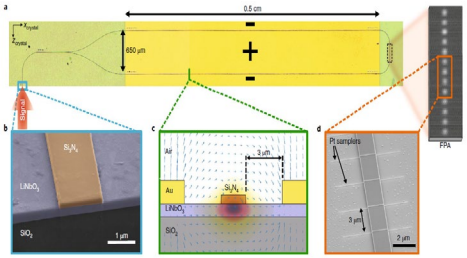
Microwave-to-photon convertor



Stanford



Spectrometer

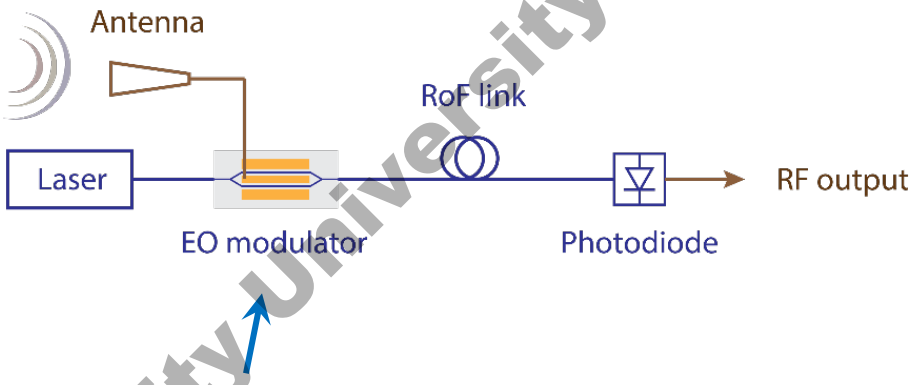


ETH

Towards LNOI photonic integrated circuits

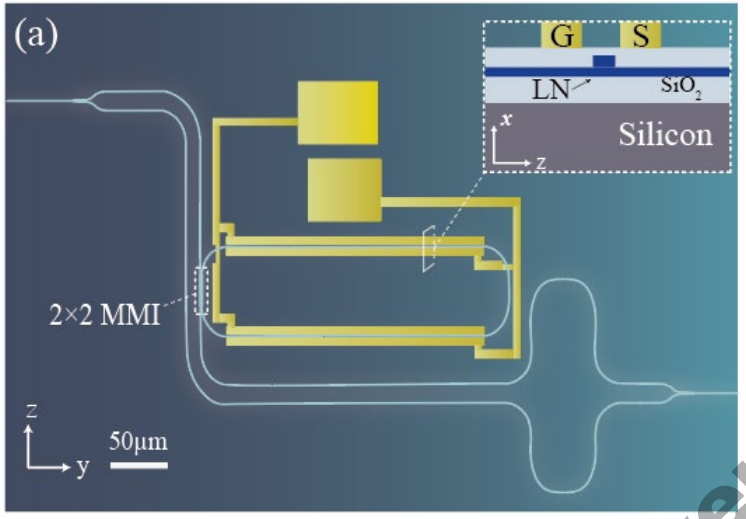
- Microwave photonics:
  - "the use of optical devices and techniques to generate, manipulate, transport and measure high-speed RF signals"
  - e.g. radio over fiber (RoF) link

D. Marpaung et al. Nat. Photonics **13**, 80–90 (2019)

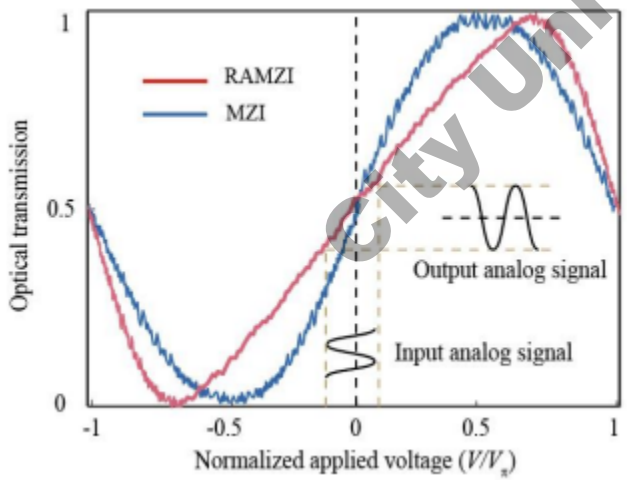


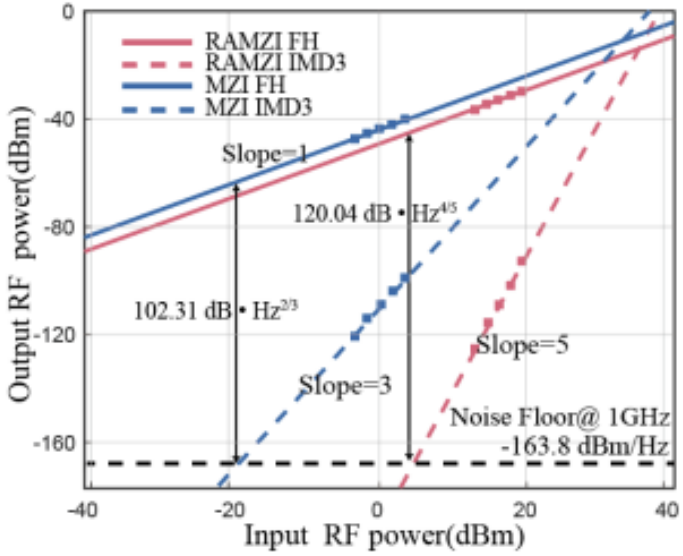
Key: a modulator with highly linear EO response to faithfully convert microwave signals into optics

Linearized EO modulators



- Ring-assisted MZI modulator with high linearity for RF-photonic applications
- Measured spurious-free dynamic range (SFDR) ~ 120 dB·Hz$^{4/5}$
- 18-dB improvement over reference MZI

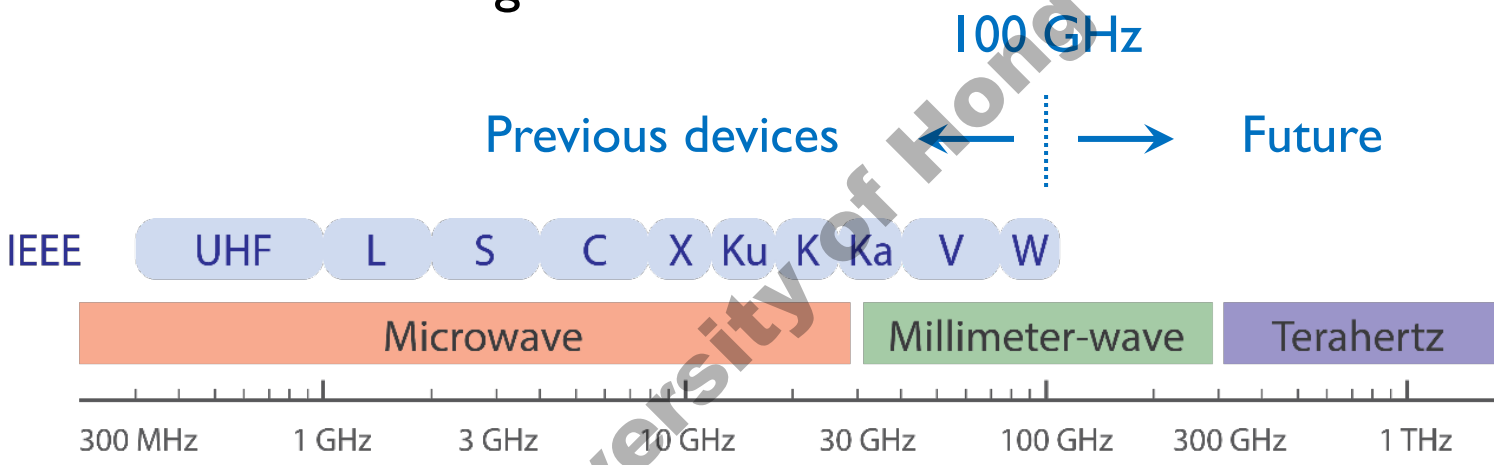




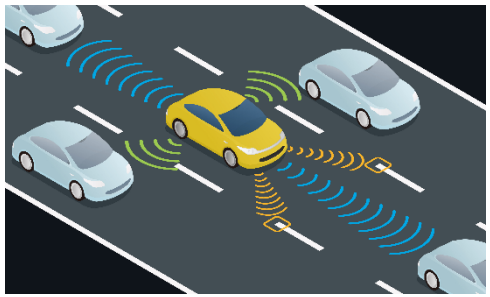
H. Feng, K. Zhang et al. & C. Wang, arXiv:2202.12739.

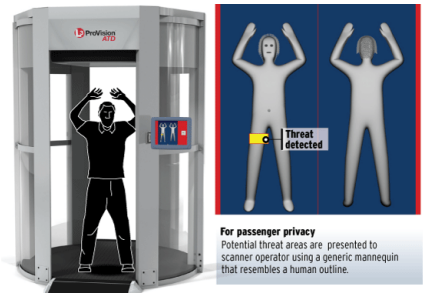
Millimeter-wave photonics

- Can LN modulators go even faster?



Millimeter-wave (mmW) photonics:

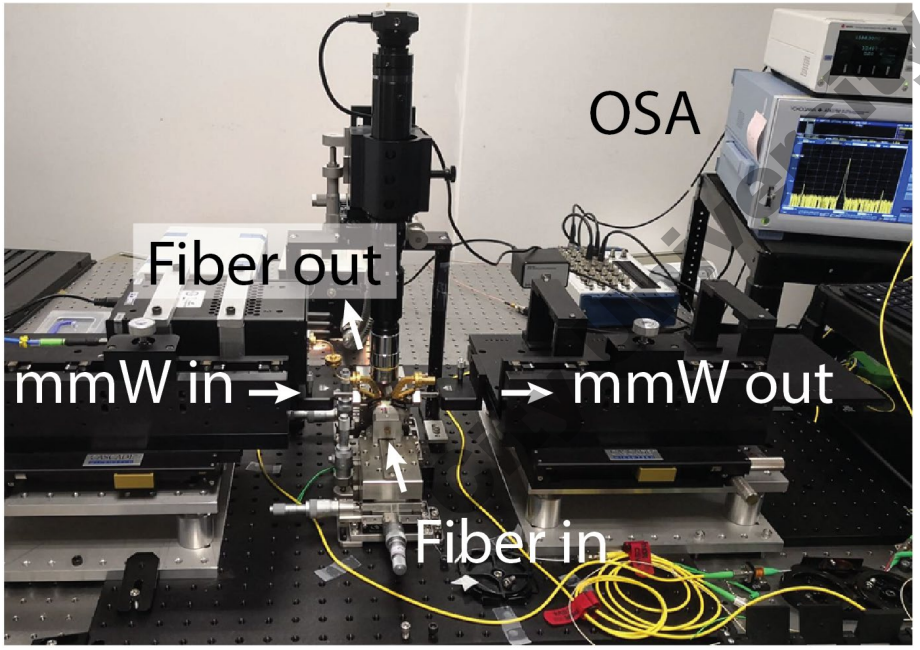


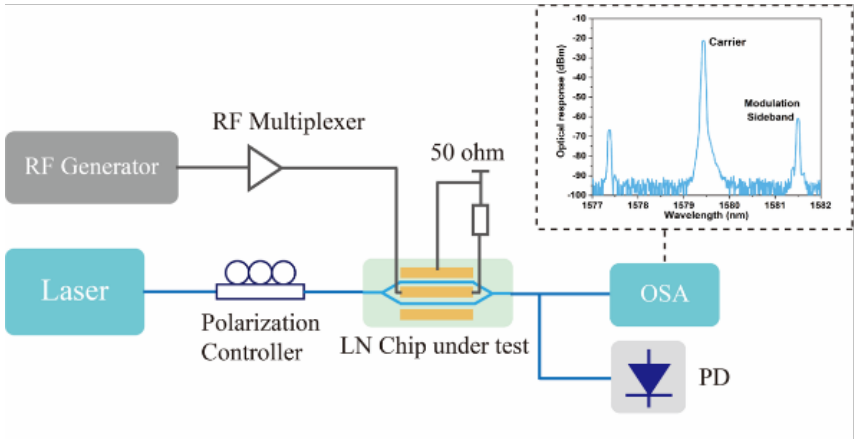


Sources: U.S. Transportation Security Agency, LiveScience.com, L-3 Security & Detection Systems, CNN

EO measurement at mmW frequencies

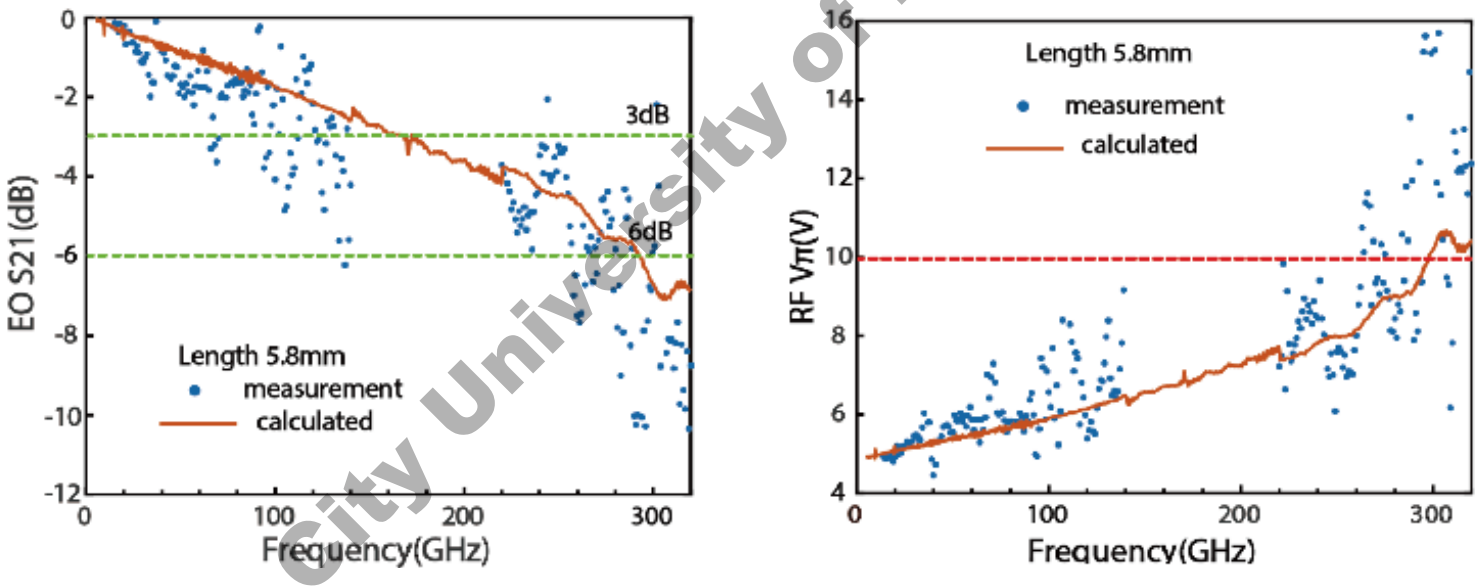
- In-house measurement setup at State Key Lab of THz and Millimeter waves
- Electro-optic responses measured at frequencies up to 330 GHz
- Sideband-to-carrier ratio vs. frequency measured using OSA





EO measurement at mmW frequencies

- 3-dB bandwidth of 175 GHz and 6-dB bandwidth of 295 GHz (5.8 mm)
- RF V_π = 6.3 V at 250 GHz (10.8 mm)



····· Direct EO measurement

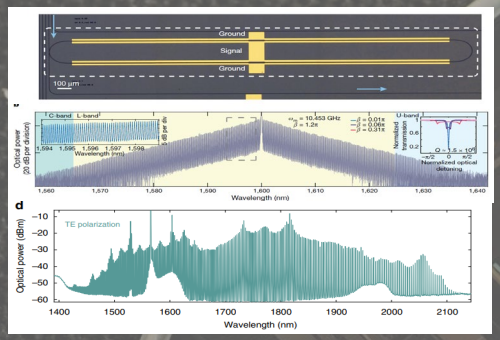
—— Calculated based on real EE measurement

Y. Zhang et al. manuscript in preparation

*Device fabrication courtesy to Dr. Linbo Shao

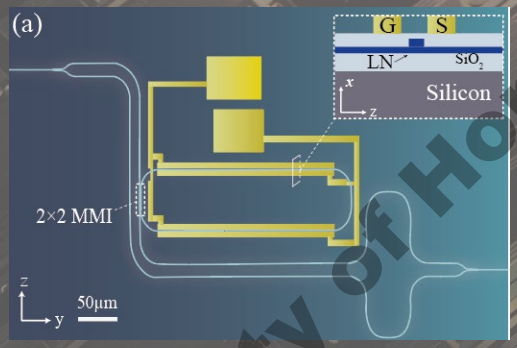
Future of LNOI photonics

City University of Hong Kong
Department of Electrical Engineering
Nanophotonics Group



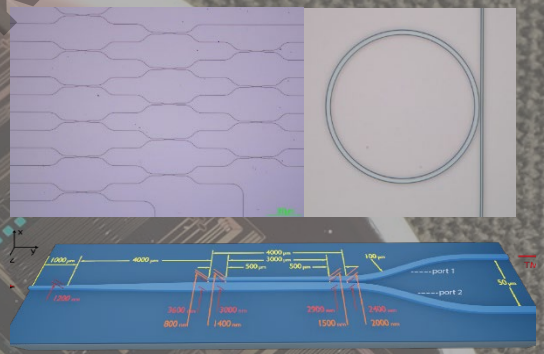
Frequency comb sources

Nature **568**, 373–377 (2018)
Nat. Commun. **10**, 978 (2019)



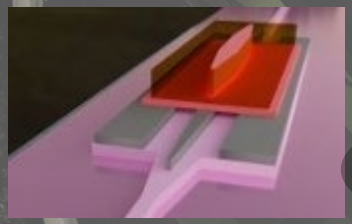
High-performance modulators

Nature **562**, 101-104 (2018)
arXiv:2202.12739



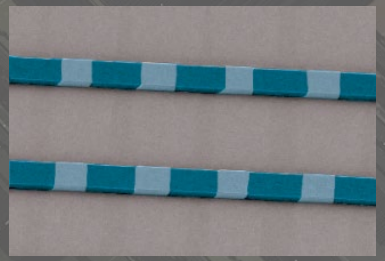
Low-loss passive components

Optica **4**, 1536-1537 (2017)
Photonics Res. **9**, 2319-2324 (2021)



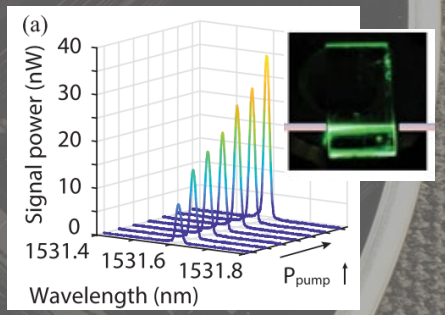
Heterogeneous integrated lasers/detectors

- Ghent/IMEC/Stanford
- SYSU
- Harvard/HyperLight/ Freeform Photonics)



Quantum light sources/ nonlinear photonics

Optica 5, 1438-1441 (2018).



Er:LNOI amplifiers

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City University
of Hong Kong
Department of Electrical Engineering
Nanophotonics
Group
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