



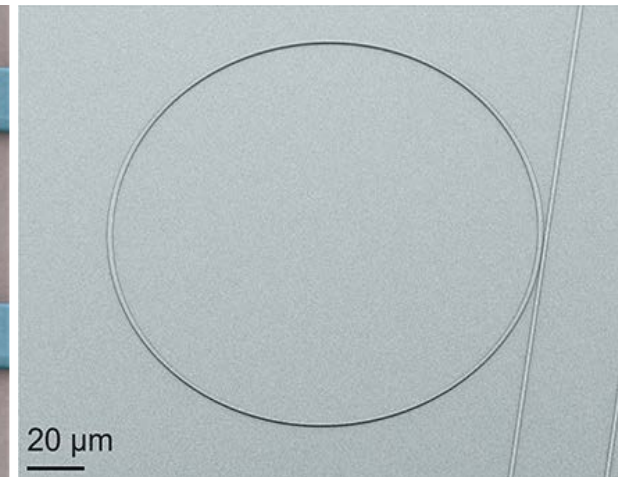
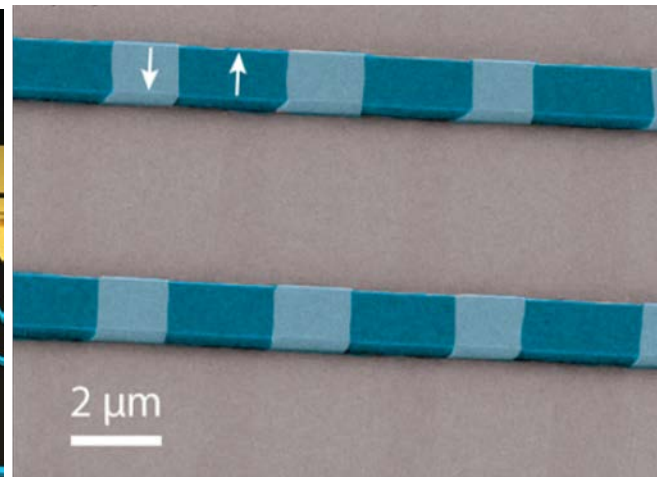
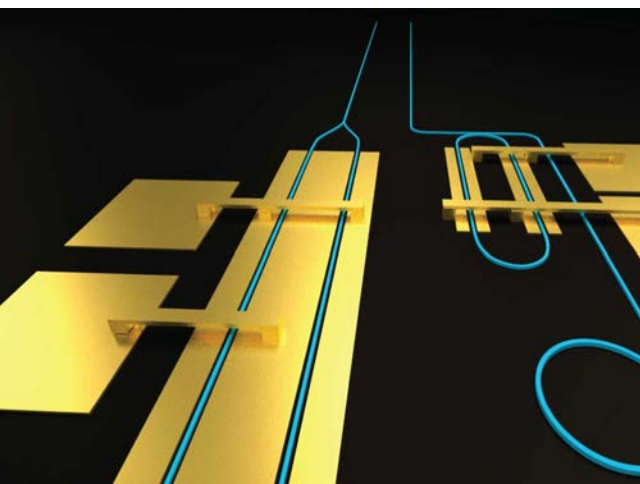
# Integrated LiNbO<sub>3</sub> Photonics

Marko Lončar

John. A. Paulson School of Engineering and Applied Sciences  
Harvard University

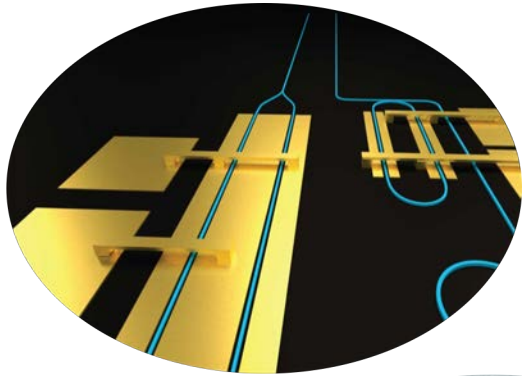
29 Oxford Street, Pierce Hall 107C, Cambridge, MA 02138  
loncar@seas.harvard.edu; <http://nano-optics.seas.harvard.edu>

**Slides can be downloaded at:**

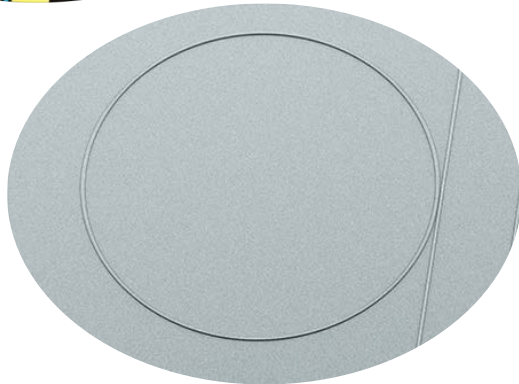




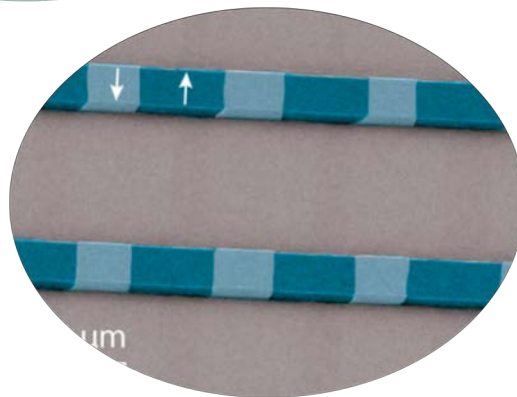
# Topics to be discussed today...



**High-speed & low drive voltage  
electro-optic modulators**



**Ultra-high Q cavities & applications**



**Nonlinear optics with LN  
waveguides**

# Energy-Efficient Communication

Long-Haul Telecomm



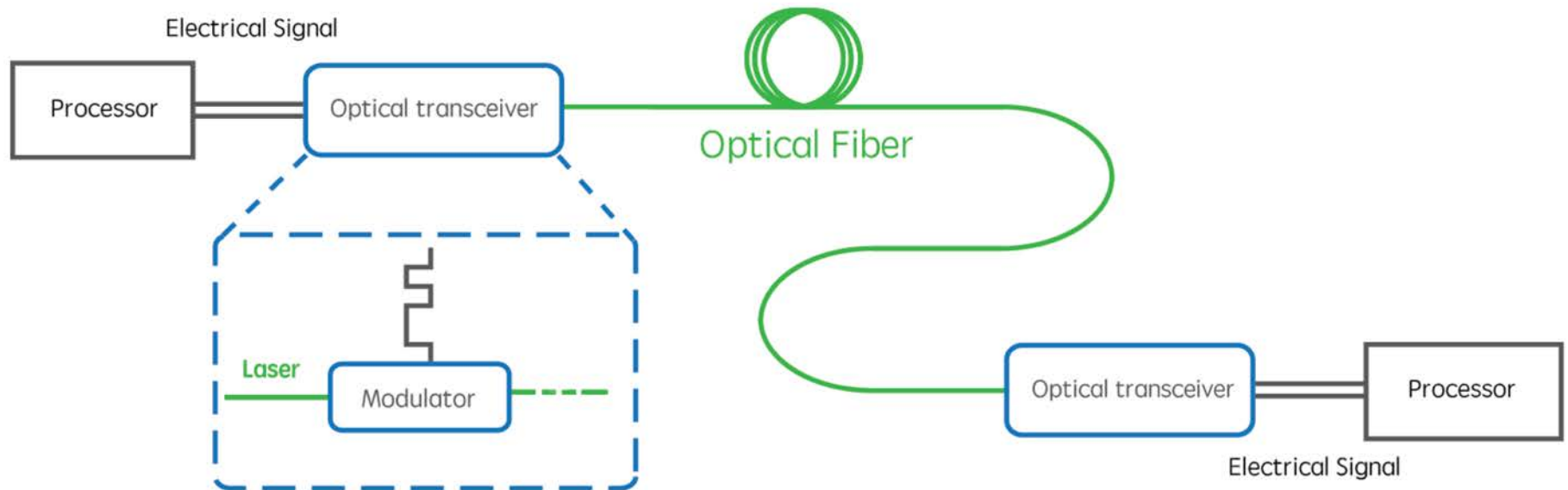
Datacomm and High-Performance Computing



Wireless Communication



## Electro-Optic Modulators : The Critical Component

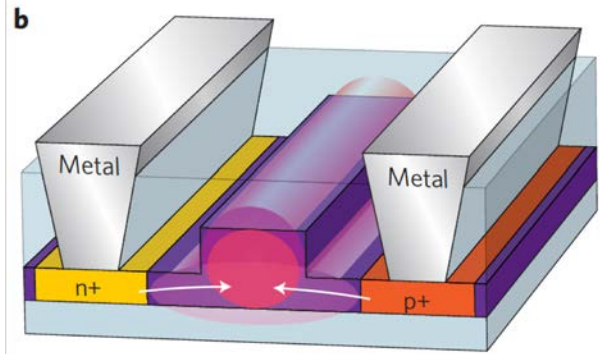




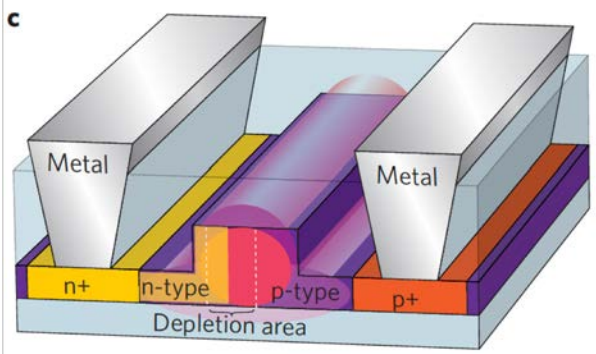
# Si Photonics Modulator

## Carrier dispersion is used to control the refractive index using external voltage!

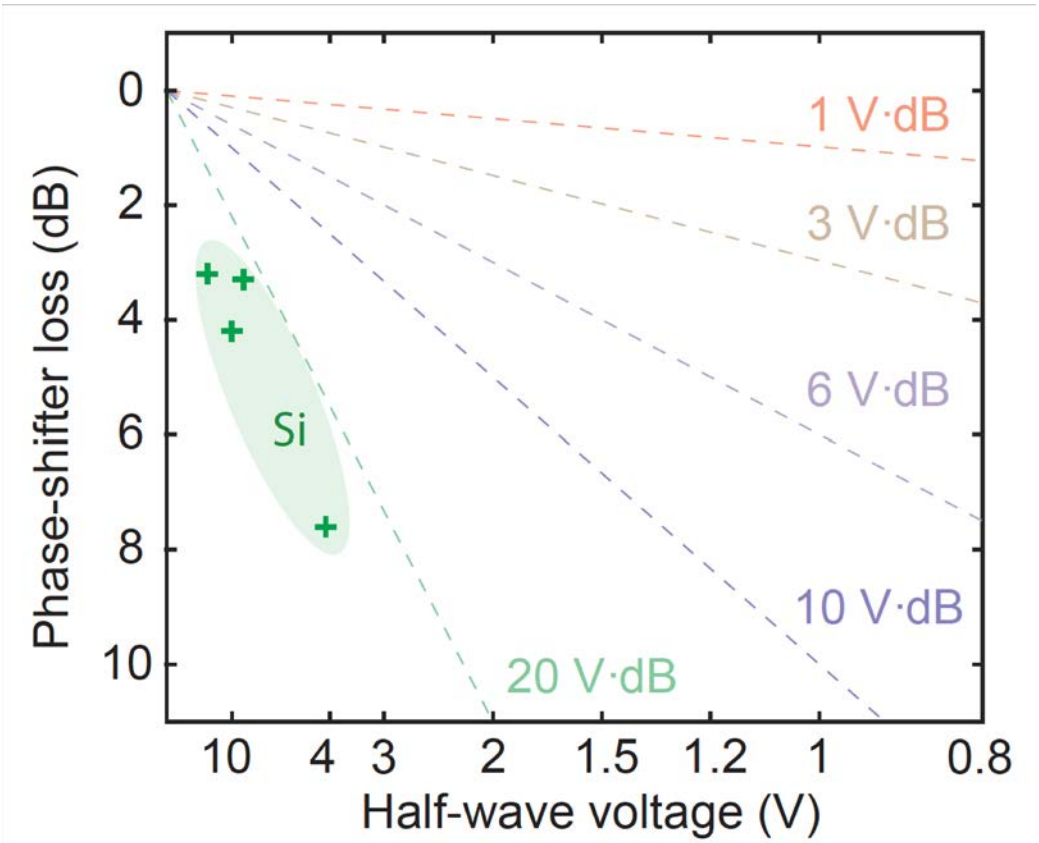
- carriers can be injected (or swept away) to change refractive index
- this results in changes of **real (n)** and **imaginary (k)** part of refractive index, resulting in **phase change** of optical signal + **additional loss!**
- **drawback: carrier absorption introduces significant losses**



Carrier injection



Carrier depletion



# Lithium Niobate Modulators

the workhorse of optoelectronics!

Pockel's effect is used in non-centro-symmetric materials, with second order nonlinearity (e.g. lithium-niobate,  $\text{LiNbO}_3$ )

- applied electric field changes refractive index (Pockel's effect)

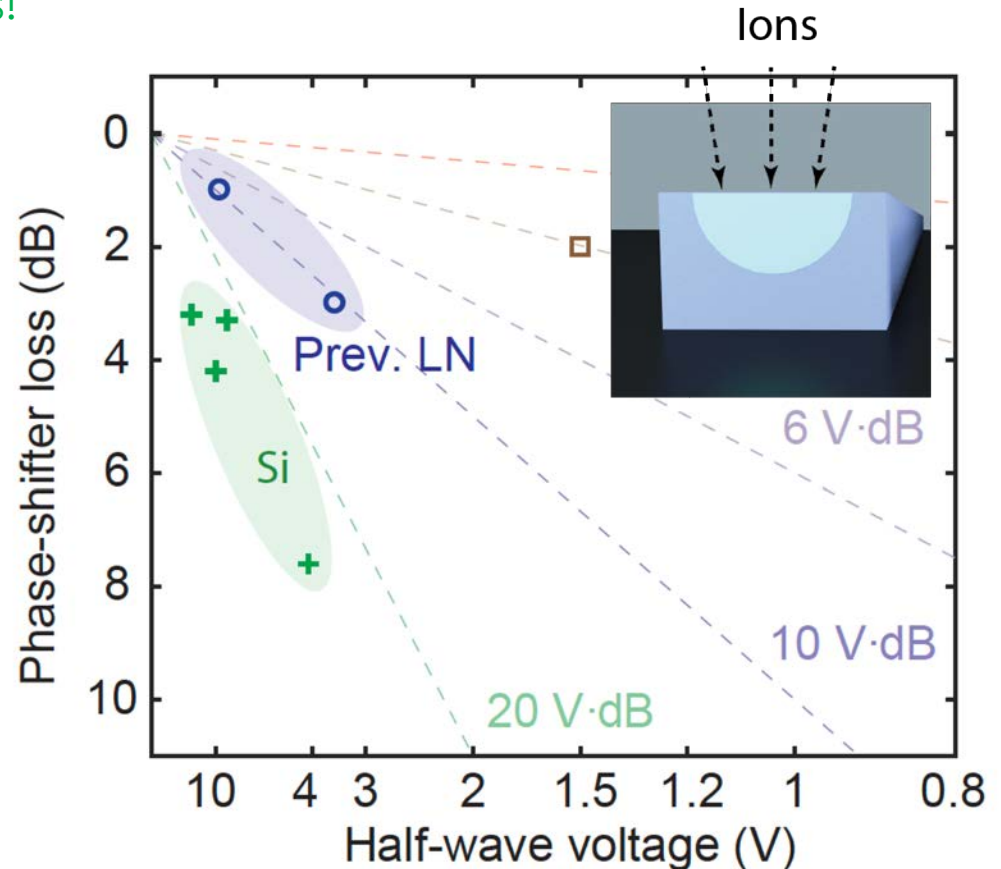
$$P = \epsilon_0 \chi E + \epsilon_0 \chi^{(2)} E^2 + \epsilon_0 \chi^{(3)} E^3 + \dots$$

- and there are no additional losses!

Conventional LN modulators are bulky & discrete components;

Waveguides defined by ion-diffusion or proton exchange

- ✗ small index contrast ( $\sim 0.02$ )
- ✗ large driving voltage ( $\sim 5\text{V}$ ) => amplifiers needed
- ✗ large energy consumption per transmitted bit
- ✗ limited bandwidth ( $\sim 35\text{GHz}$ ) due to mismatch between microwave and optical velocities



# Lithium Niobate Modulators

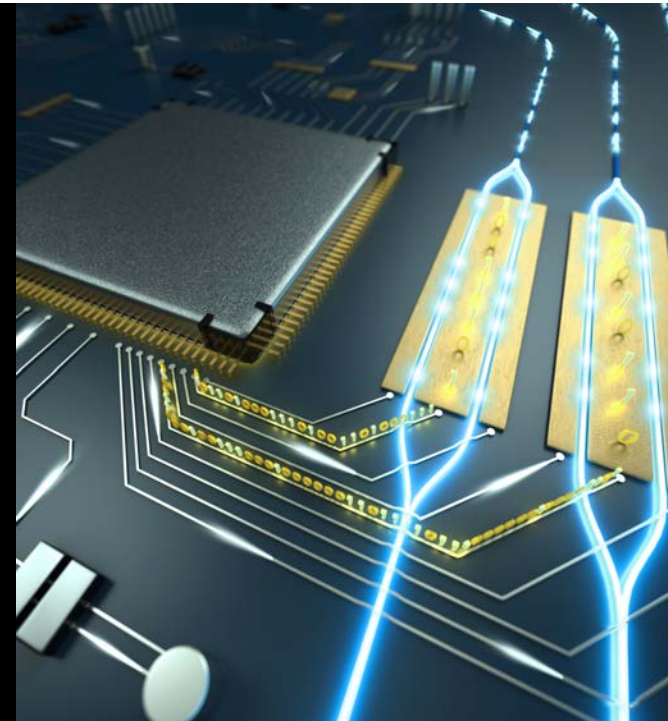
the workhorse of optoelectronics!

Pockel's effect is used in non-centro-symmetric materials, with second order nonlinearity (e.g. lithium-niobate,  $\text{LiNbO}_3$ )

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

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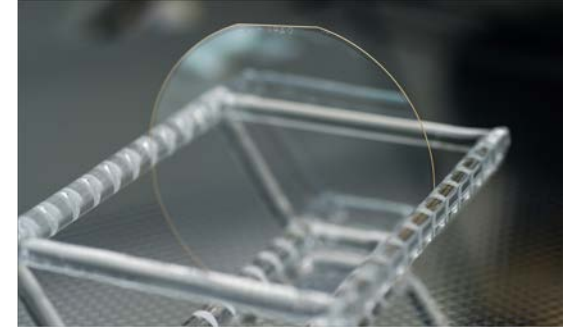
## Goal: Integrated LN modulator!

Waveguides defined by etching thin LN films

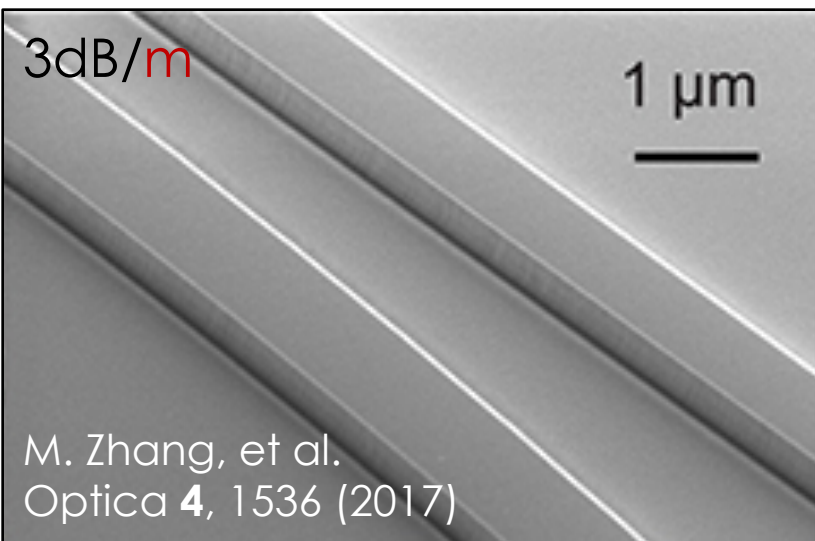
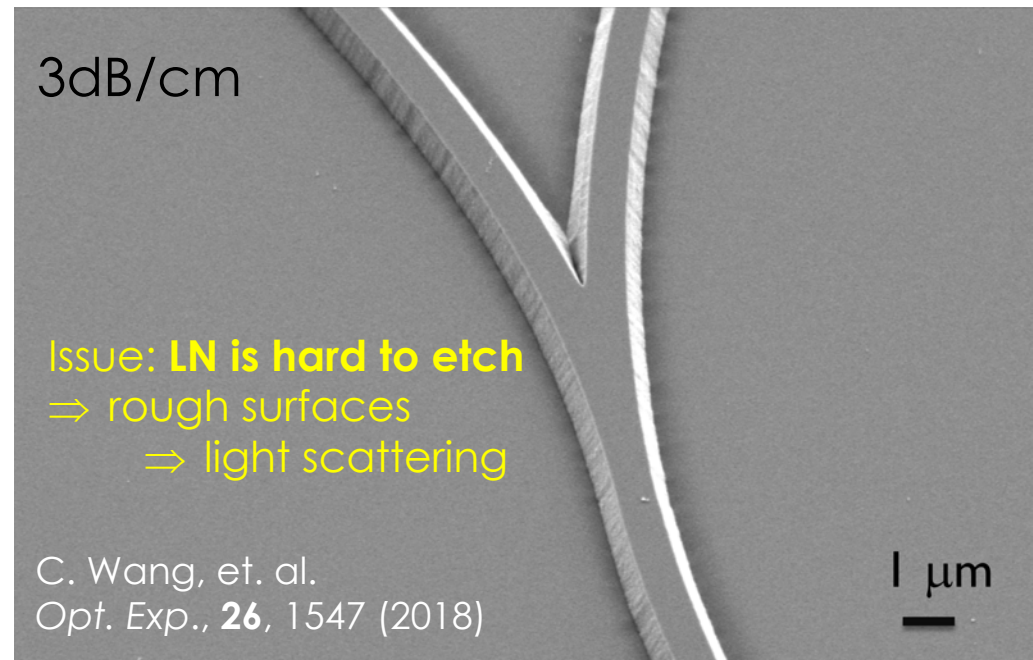
- ✓ large index contrast ( $\sim 0.7$  for oxide cladded devices)
- ✓ enhanced electro-optic (EO) response
- ✓ driving voltage reduced to  $< 1$  V
  - ⇒ can be driven by CMOS circuitry without amplifiers!
  - ⇒ low energy consumption per transmitted bit
- ✓ increased EO bandwidth ( $> 100$  GHz)
- ✓ reduced cost

# Approach

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



- Devices fabrication
  - e-beam lithography
  - reactive ion etching of LN
  - metal evaporation (contacts)
  - SiO<sub>2</sub> deposition (top cladding)

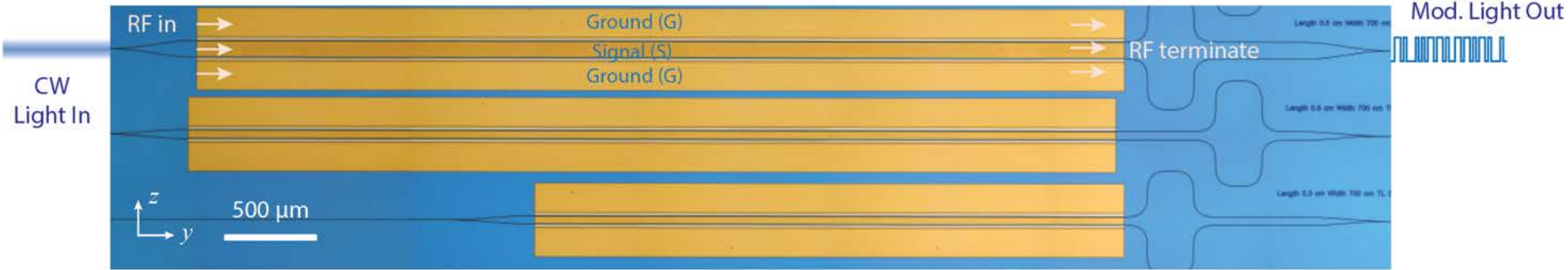


Optimized etch!  
⇒ Smooth sidewalls  
⇒ Low loss!



(travelling wave)

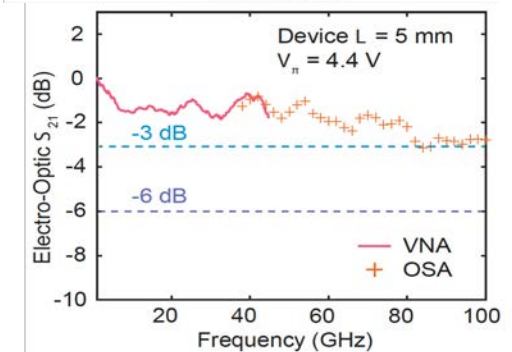
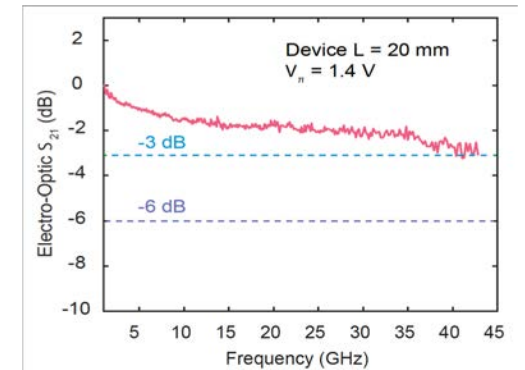
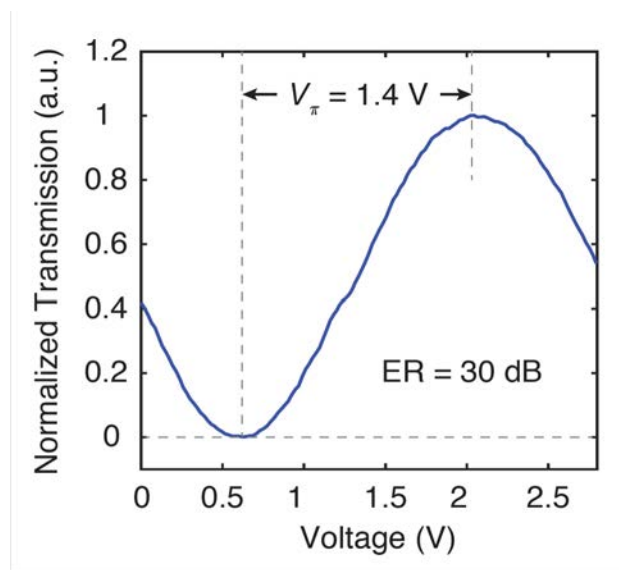
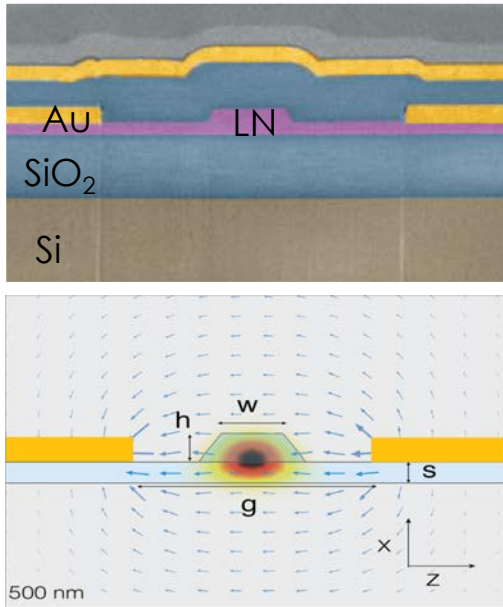
# Integrated LN Electro-Optic Modulators



Good overlap between microwave & optical fields

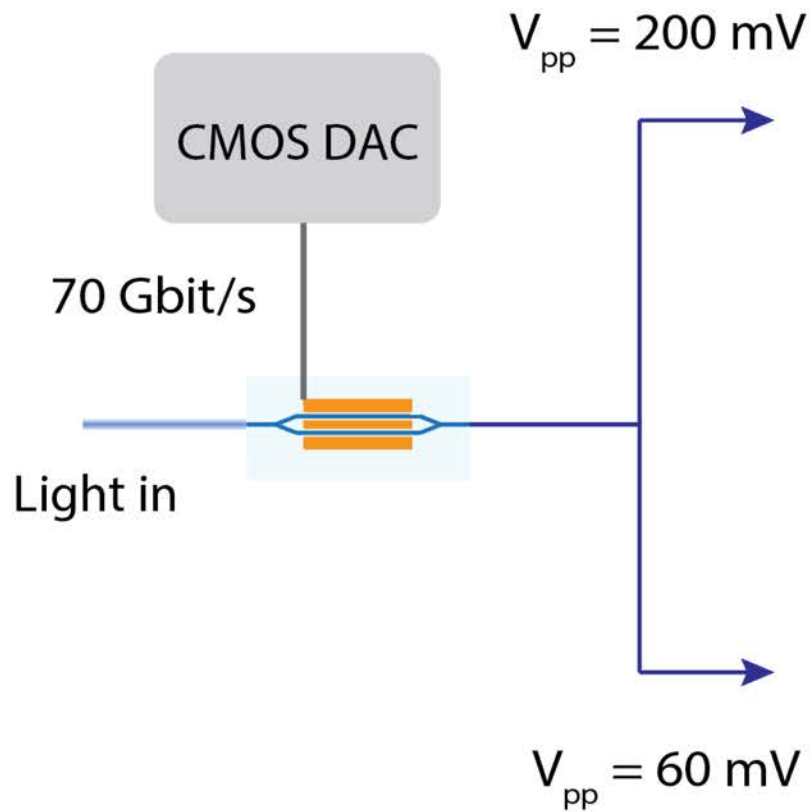
Good EO efficiency  
 $V\pi L = 2.8 \text{ Vcm}$

EO bandwidth > 100 GHz  
(limited by microwave loss)

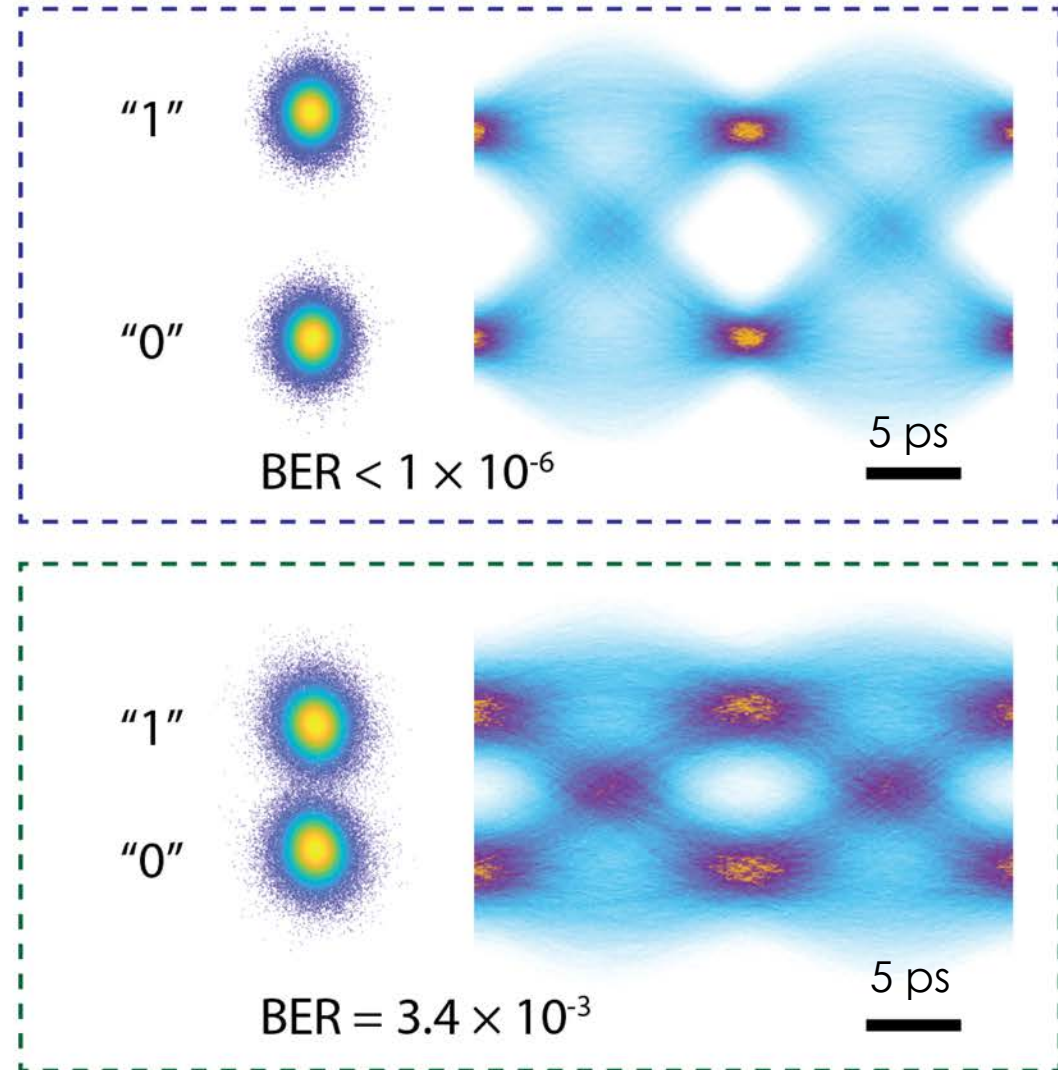




# CMOS Driven Modulator!

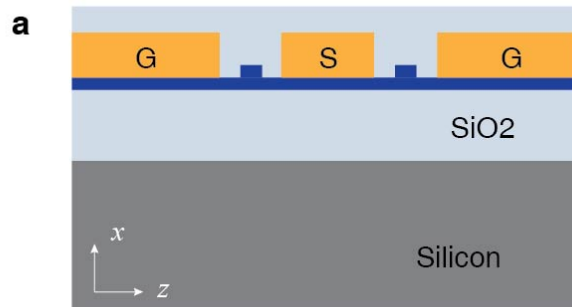
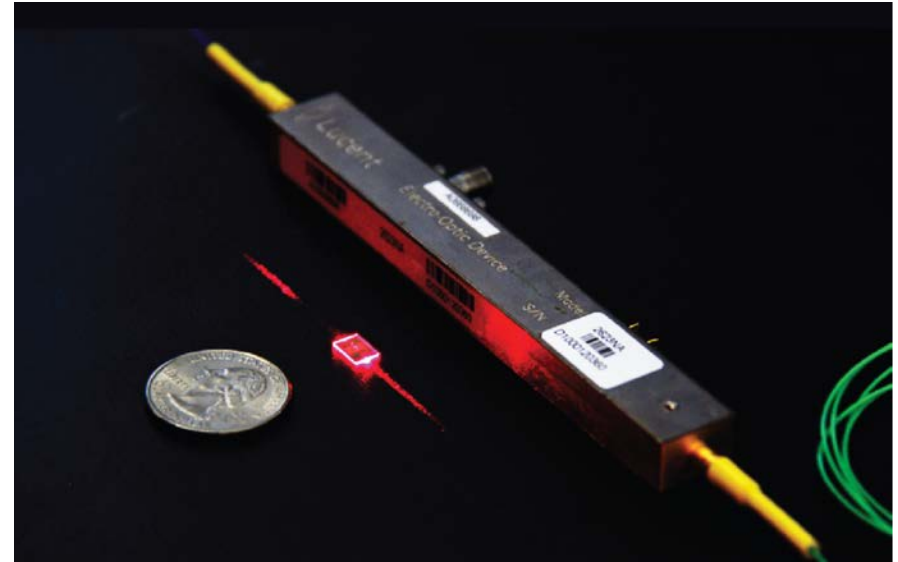
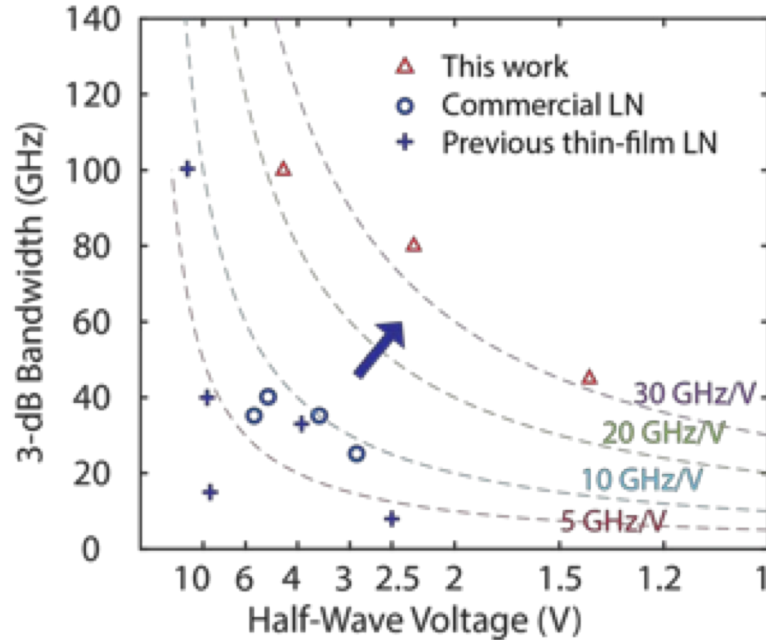


**Electrical energy consumption:**  
**~ 40 attoJoul / bit !!!**

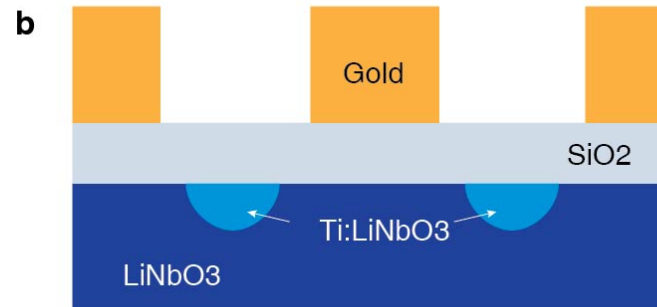




# Comparison with Traditional LN Modulators



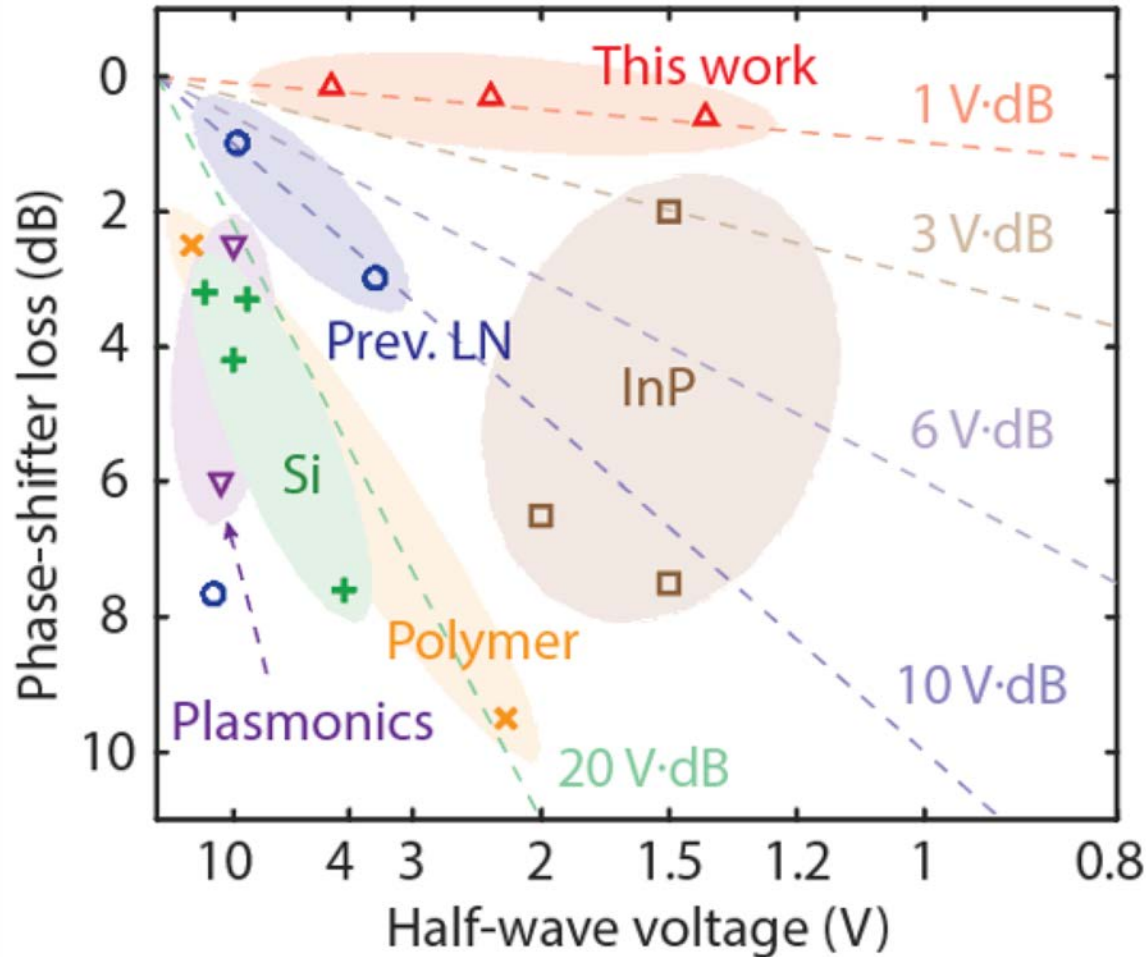
Integrated LN modulator



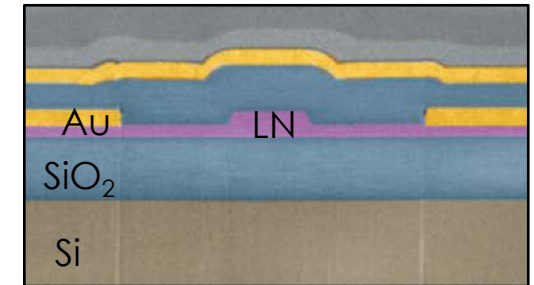
Conventional LN modulator



# Comparison with Integrated Modulators

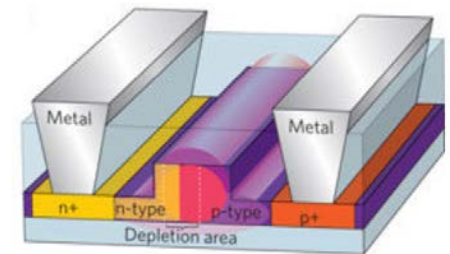


## Integrated LN modulator



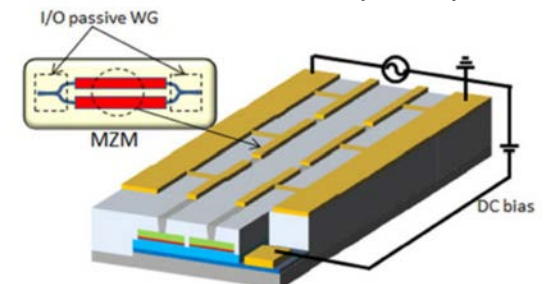
## Silicon Photonics

Nature Photonics 4, 518 (2010)



## InP Photonics

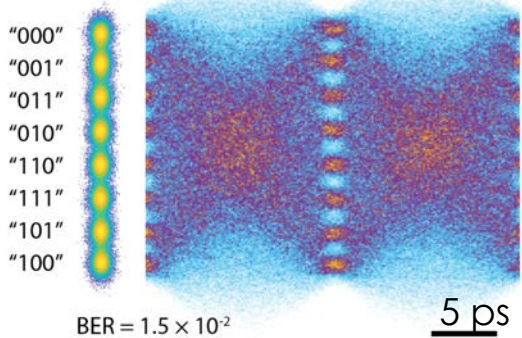
JLT, 35, 1450 (2017)



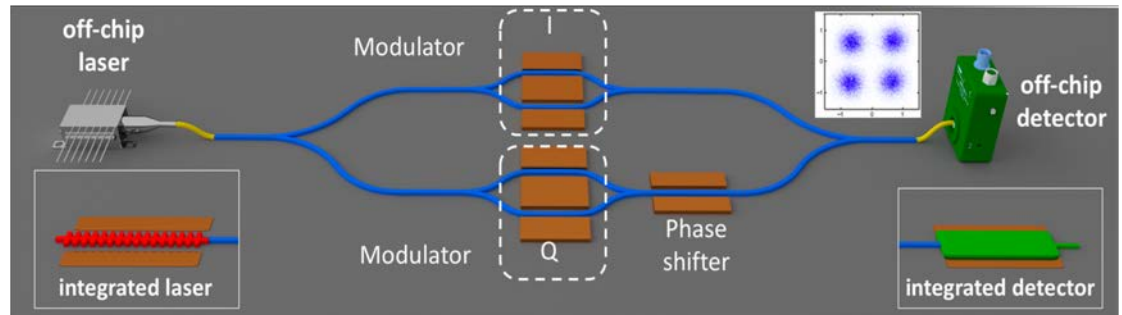
# Even Higher Data Rates?

## Coherent communication with complex modulation formats !

Current: 8-ASK format  
70 Gbaud  $\leftrightarrow$  210 Gbit/s



Next: IQ Modulator & QAM-64  
with dual polarization, > 1 Tbit/s per wavelength



low insertion loss is essential !

C. Wang, M. Zhang et al, *Nature*, **562**, 101 (2018)  
with Nokia Bell Labs (Peter Winzer & team)

## On-chip wavelength division multiplexing with frequency combs

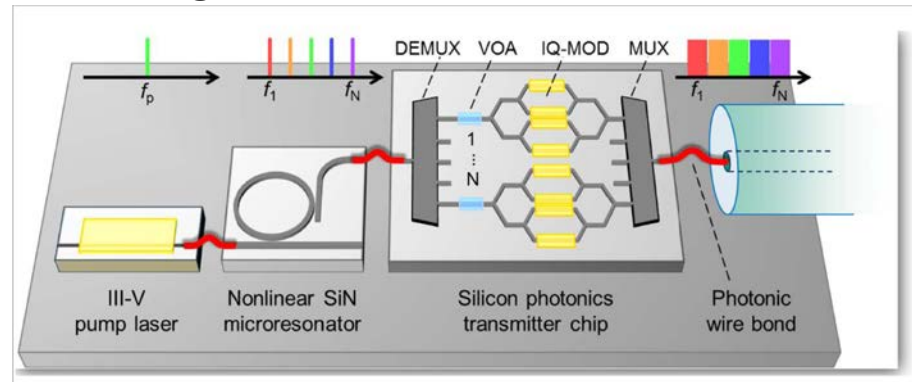
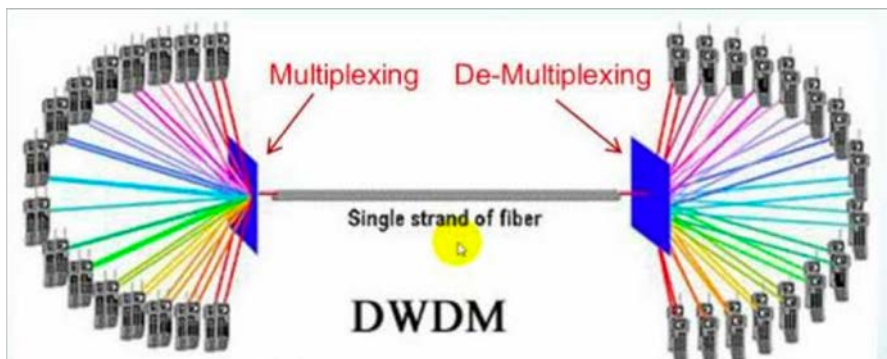
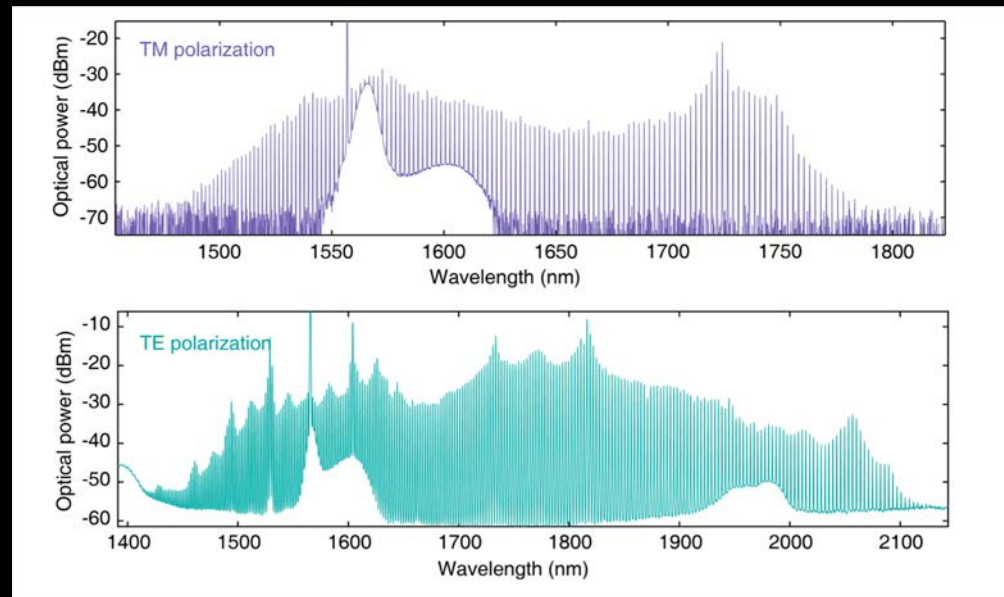
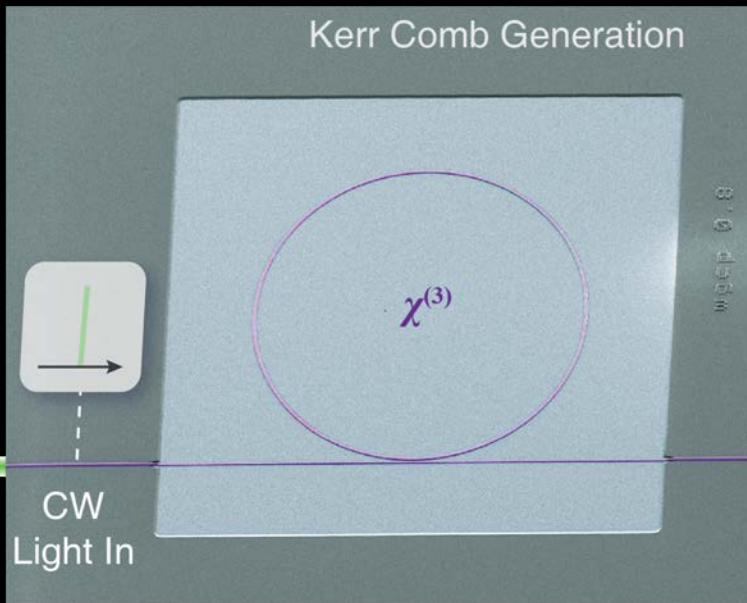


Photo: C. Koos & T. Kippenberg

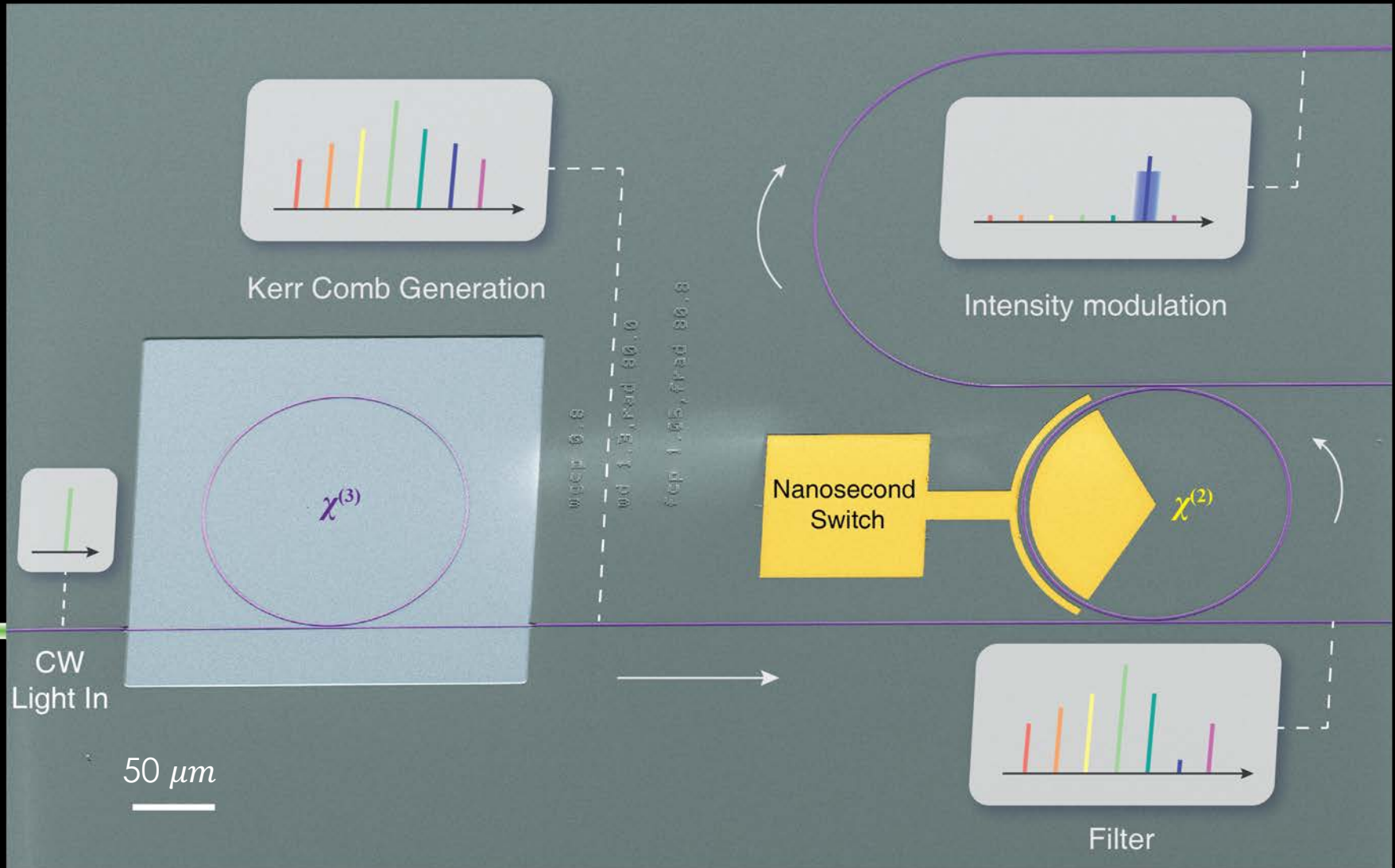
# Kerr ( $\chi^3$ ) Frequency Comb

- **Kerr frequency comb** spanning 2/3 of an octave in dispersion-engineered rings
- Pump: 100 mW in a waveguide, 100 W in the ring !

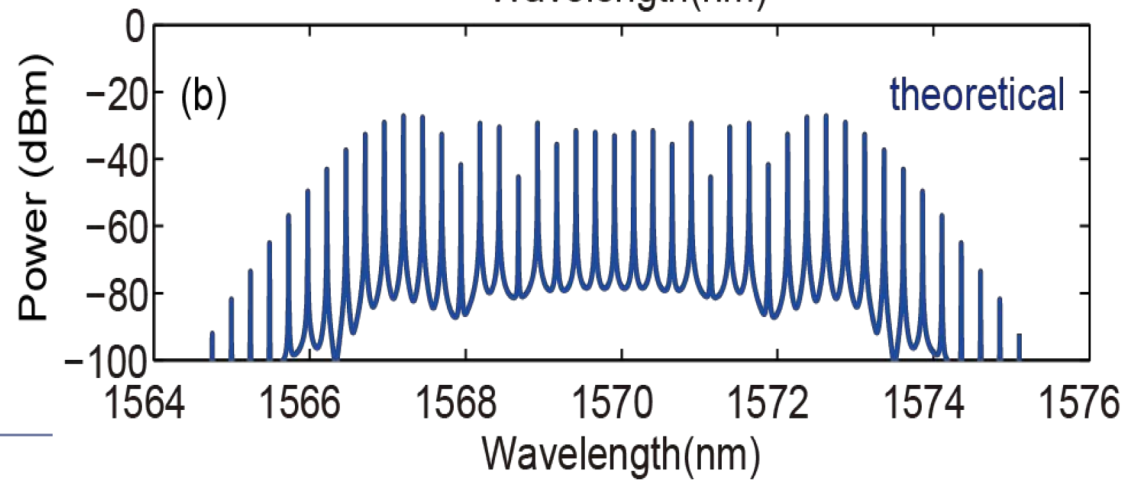
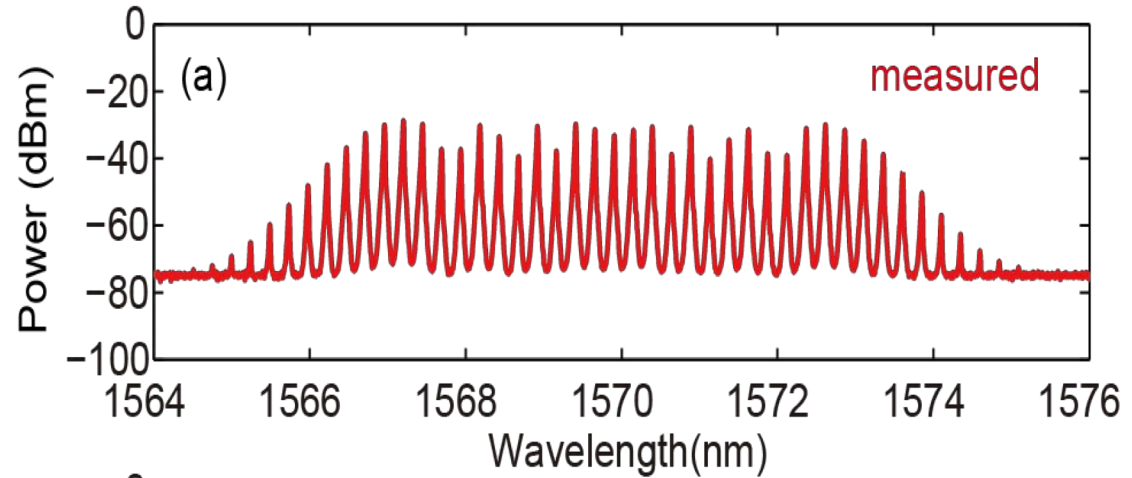
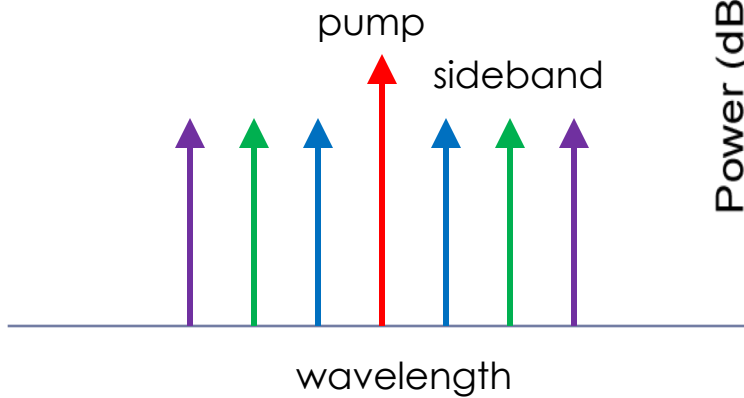
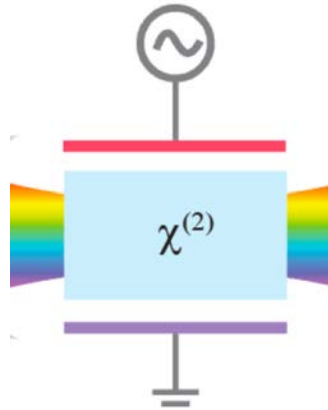




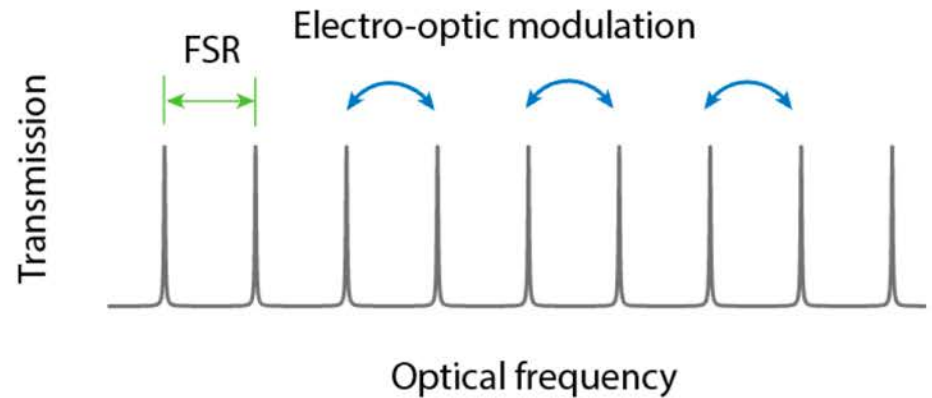
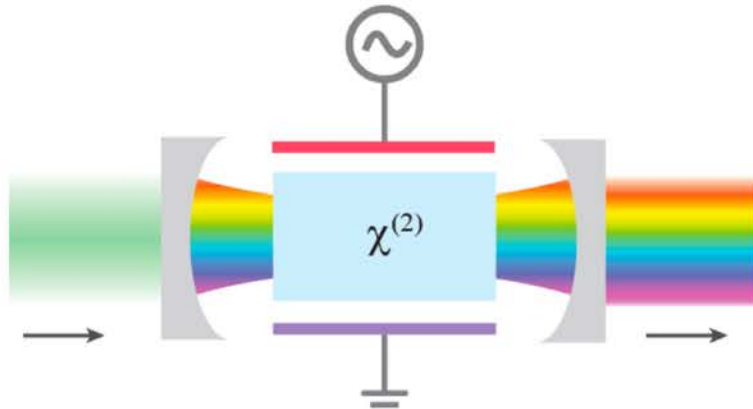
# LN Integration comb + filter + modulator



# Electro-Optic ( $\chi^2$ ) Frequency Comb

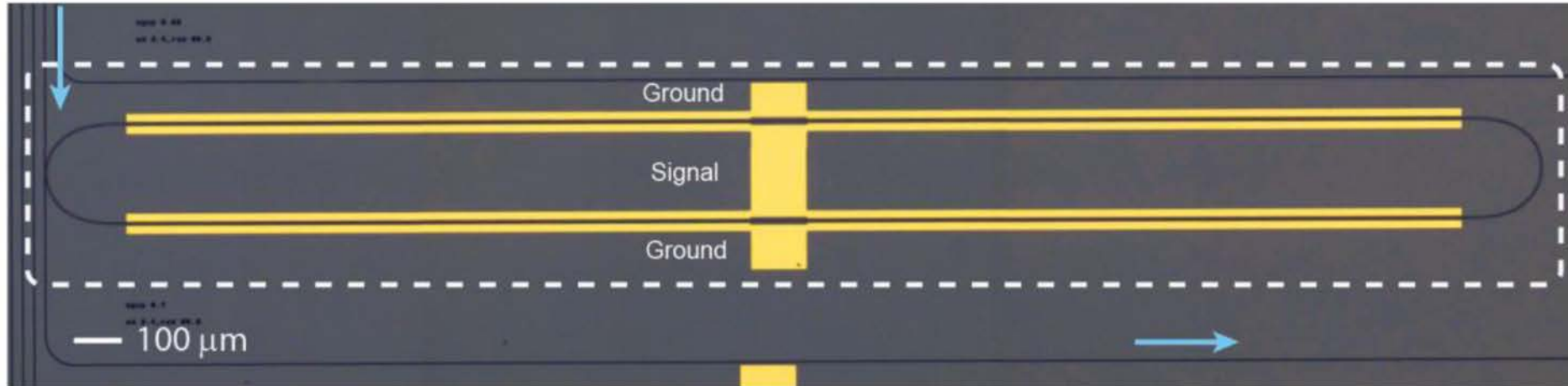


# Electro-Optic ( $\chi^2$ ) Frequency Comb



## The Idea:

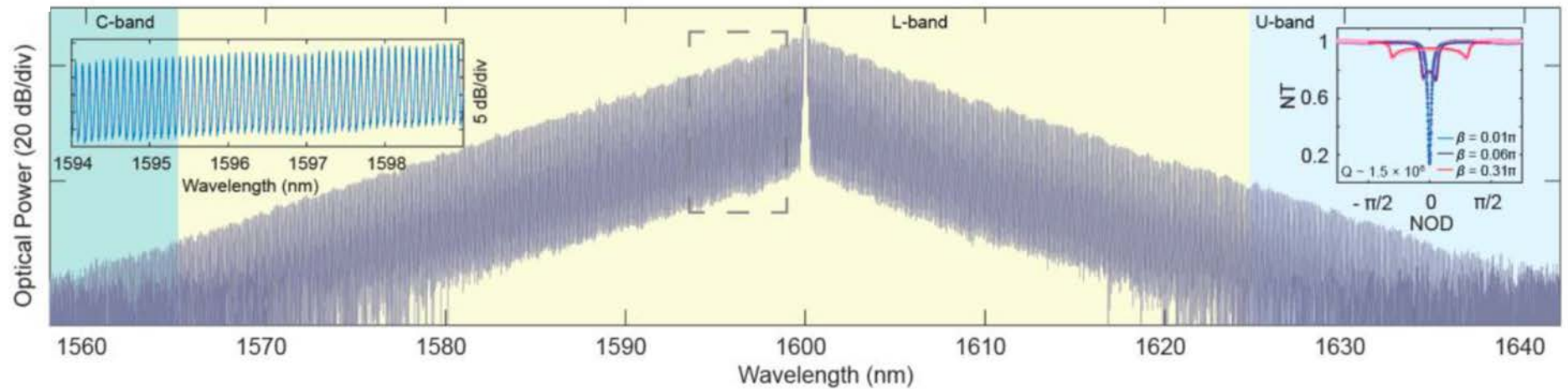
use the cavity to enhance the sideband generation process when **cavity FSR** matches the **modulation frequency**



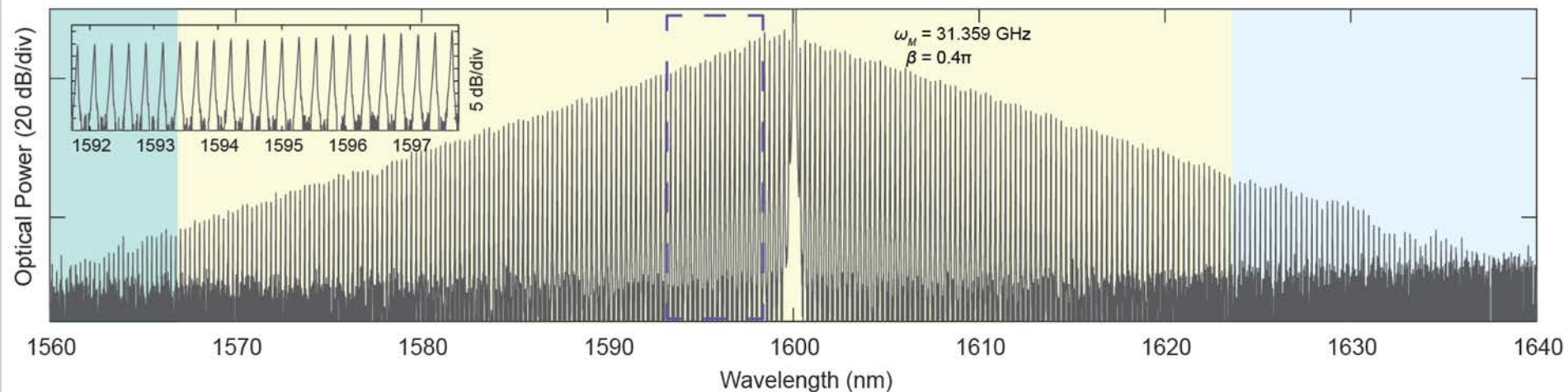


# Electro-Optic ( $\chi^2$ ) Frequency Comb

**10 GHz EO Comb:** FSR = 10 GHz, RF drive = 10 GHz



**30 GHz EO Comb:** FSR = 10 GHz, RF drive = 30 GHz



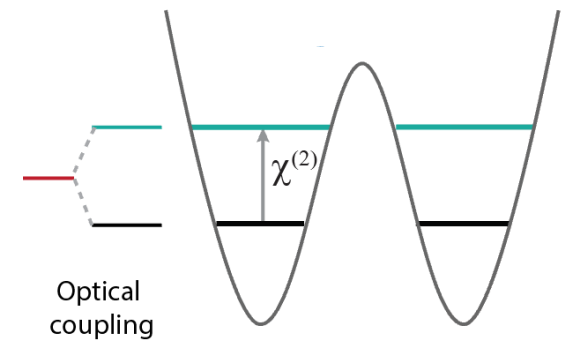
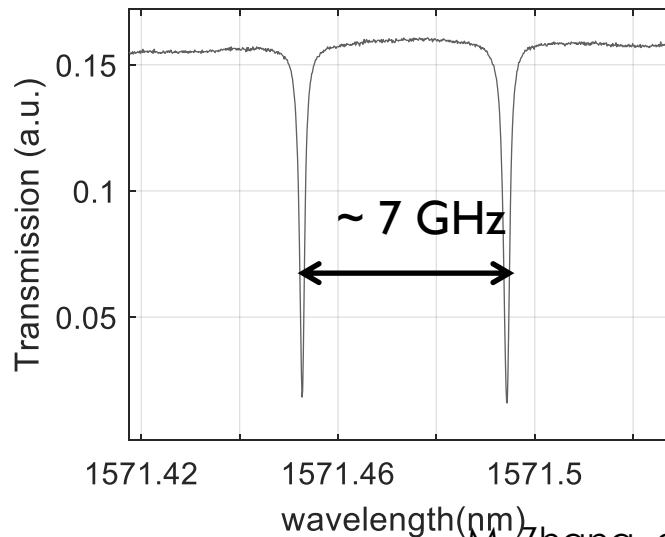
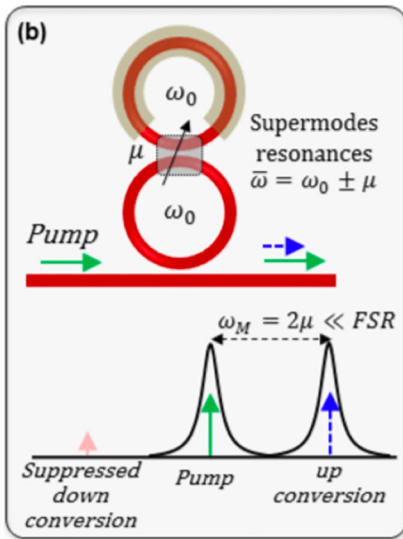
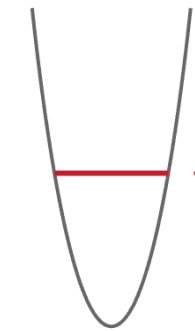
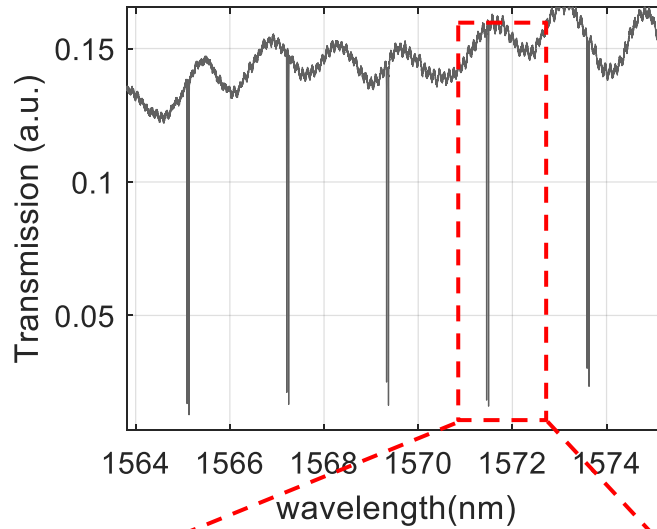
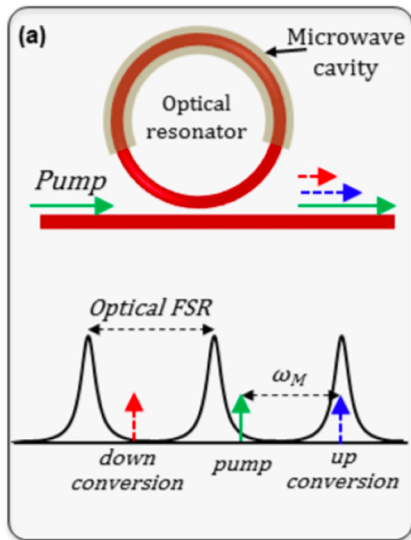


HARVARD

John A. Paulson  
School of Engineering  
and Applied Sciences

# Towards On-Chip Quantum Transducers

## Coherent Microwave $\leftrightarrow$ Optical Conversion

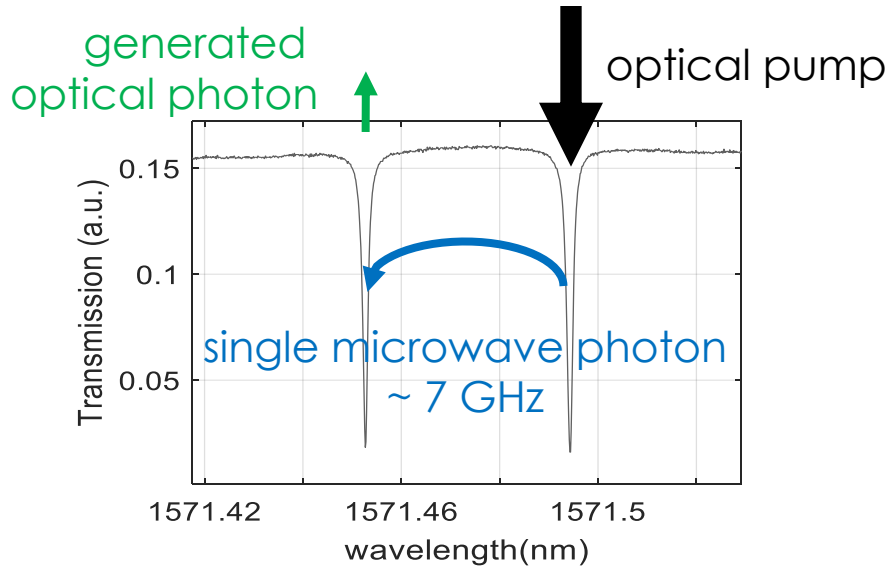
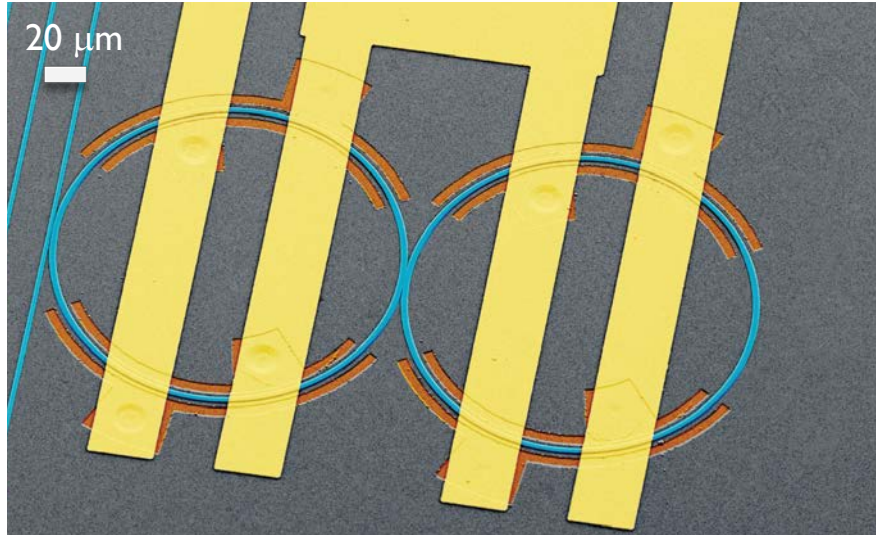


M. Zhang, et al. *Nature Photonics*, **13**, 36 (2019)

M. Soltani et al, *PRA* **96**, 043808 (2017)

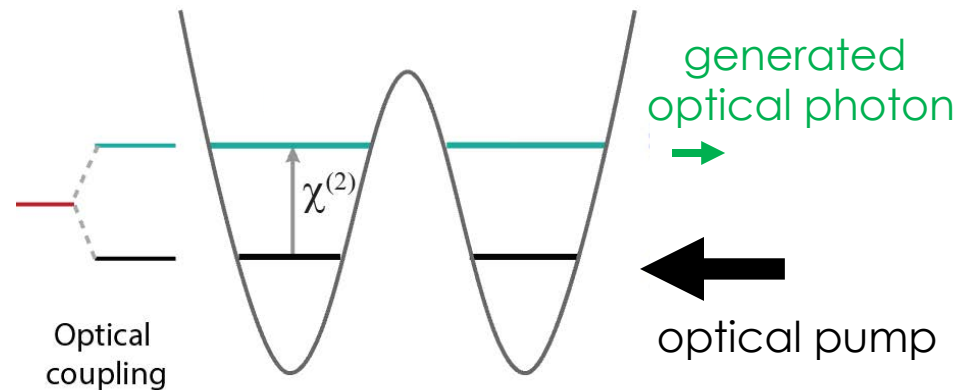
# Towards On-Chip Quantum Transducers

## Coherent Microwave $\leftrightarrow$ Optical Conversion



$$C = \frac{4ng^2}{\gamma_{\text{mw}}\gamma_{\text{opt}}}$$

Within reach	Improved system
$g/2\pi = 10\text{kHz}$	30 kHz
$\gamma_{\text{opt}}/2\pi = 80$ MHz	30 MHz
$\gamma_{\text{mw}}/2\pi = 700$ kHz	7 kHz
$n_{C=1} = 140,000$	60
$P_{\text{opt},c=1} = n\hbar\omega\gamma_{\text{opt}}$ $= 7 \mu\text{W}$	1 nW

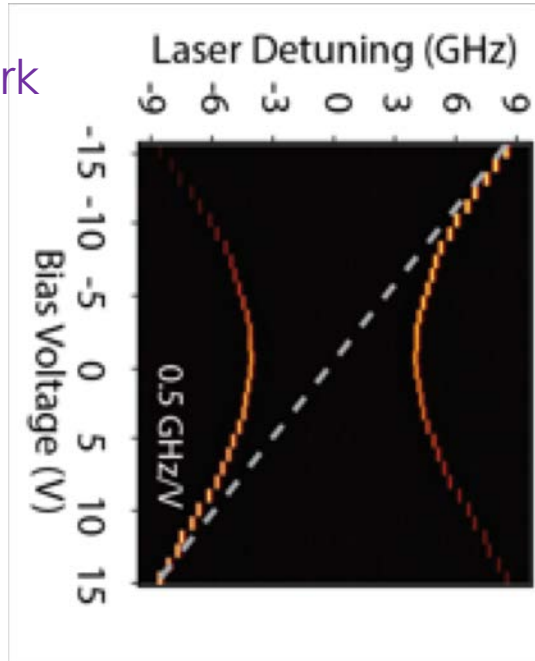




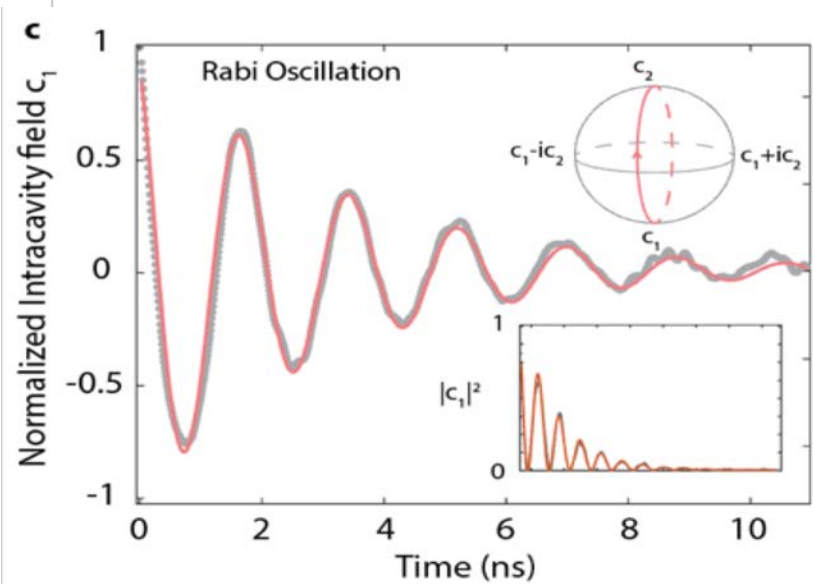
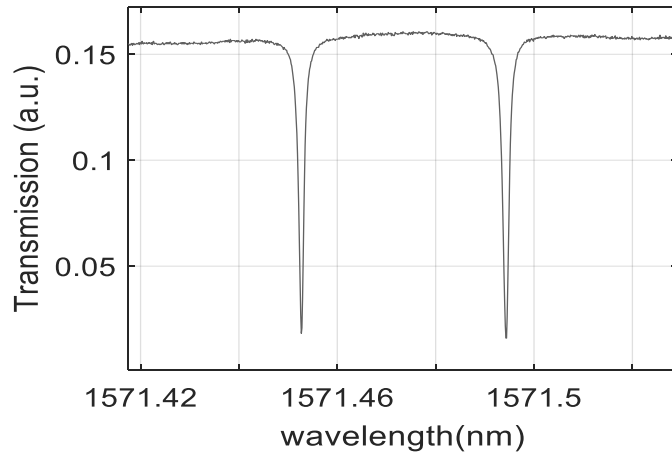
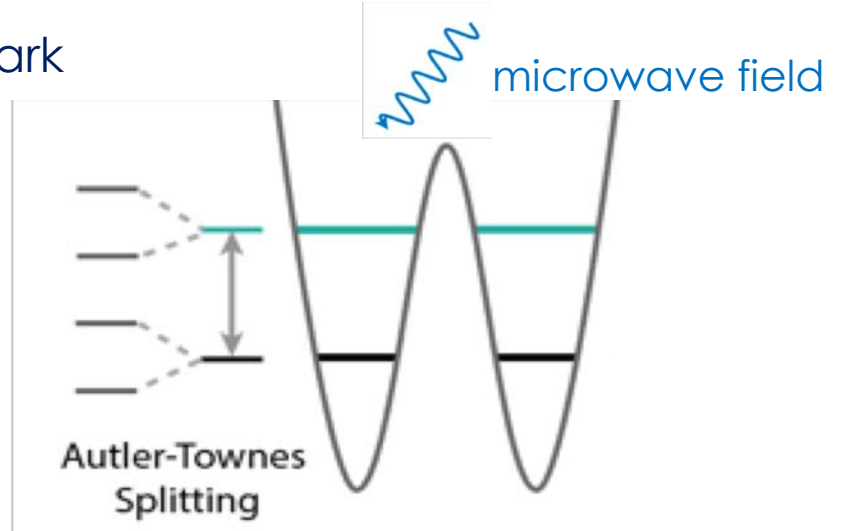
# Towards On-Chip Quantum Transducers

## Coherent Microwave $\leftrightarrow$ Optical Conversion

DC Stark

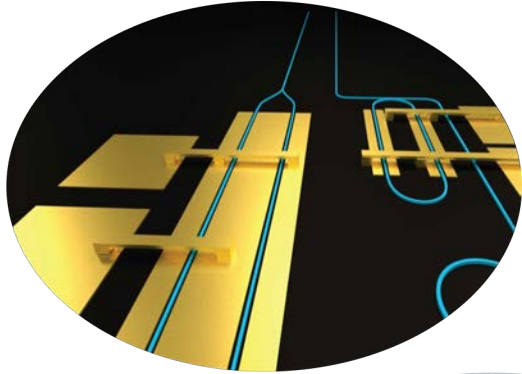


AC Stark





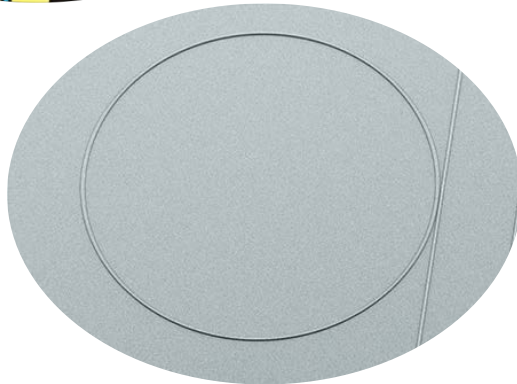
# Outline



## High-speed & low drive voltage electro-optic modulators



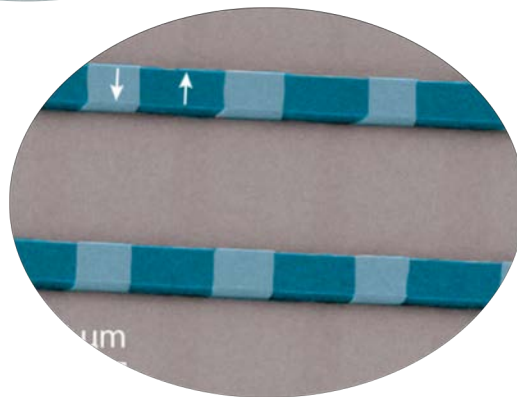
- C. Wang, et al, *Nature*, **562**, 101 (2018)
- C. Wang, et. al. *Opt. Exp.*, **26**, 1547 (2018)
- M. Zhang, et al. arXiv:1809.08636 (2018)



## Ultra-high Q cavities & applications



- M. Zhang, et al. *Optica*, **4**, 1536 (2017)
- M. Zhang, et al. *Nature Photonics*, **13**, 36 (2019)
- C. Wang, et al. arXiv:1809.08637 (2018)



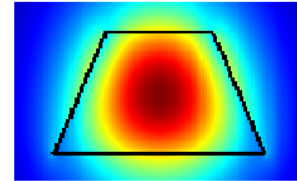
## Nonlinear optics with LN waveguides: $\chi^2$ and $\chi^3$

**Modal phase matching:** the same effective mode indices for all waves

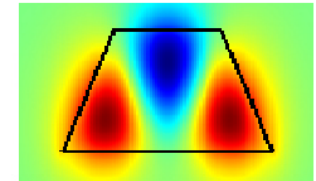
C. Wang, et al. *Opt. Express*, **25**, 6963 (2017)

C. Wang, et al, *Opt. Express*, **22**, 30924 (2014)

1550nm, TE<sub>1</sub> mode



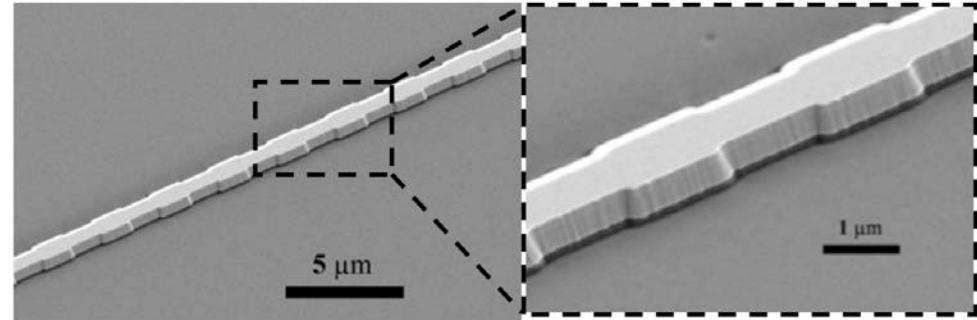
775nm, TE<sub>3</sub> mode



**Periodically grooved waveguide**

introduces additional momentum to compensate for the phase mismatch:

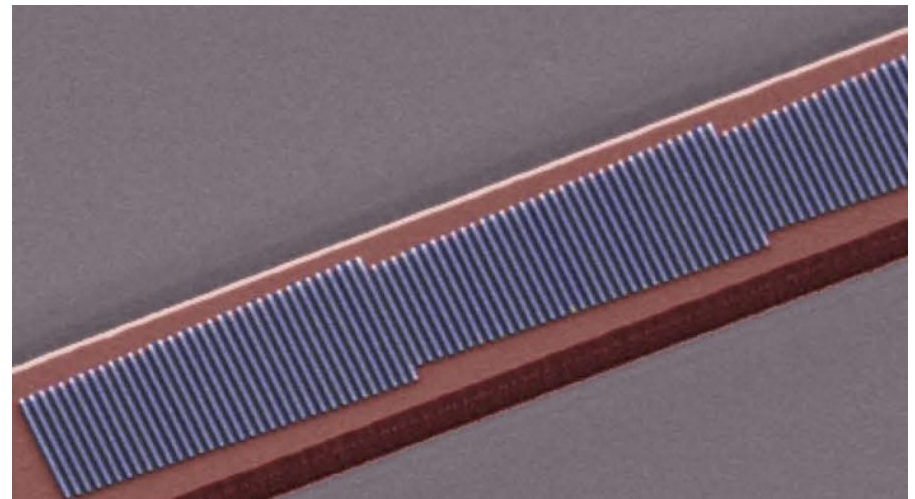
C. Wang, et al. *Opt. Express*, **25**, 6963 (2017)



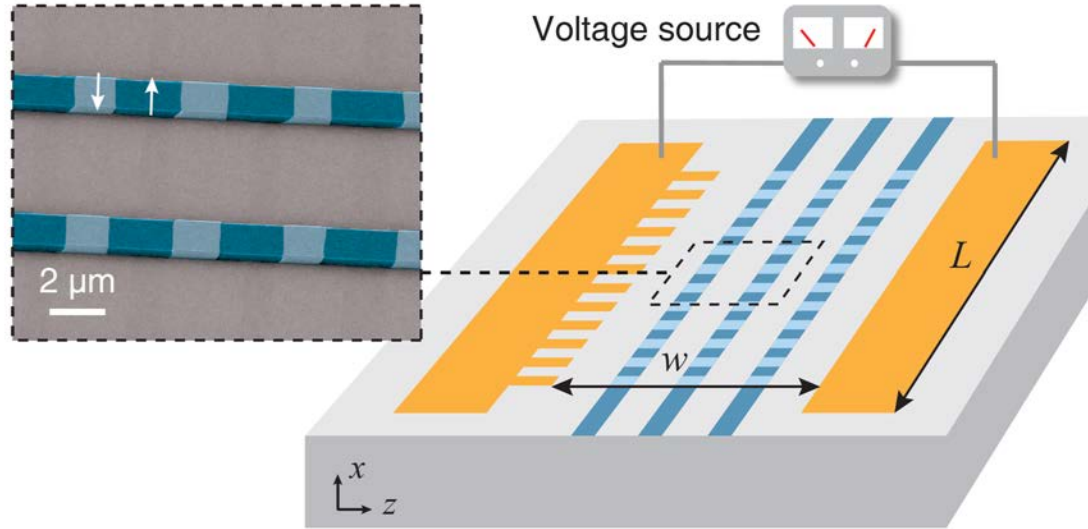
**Gradient metasurface** manipulates the photon momentum during SHG process

⇒ **Phase-matching-free** SHG.

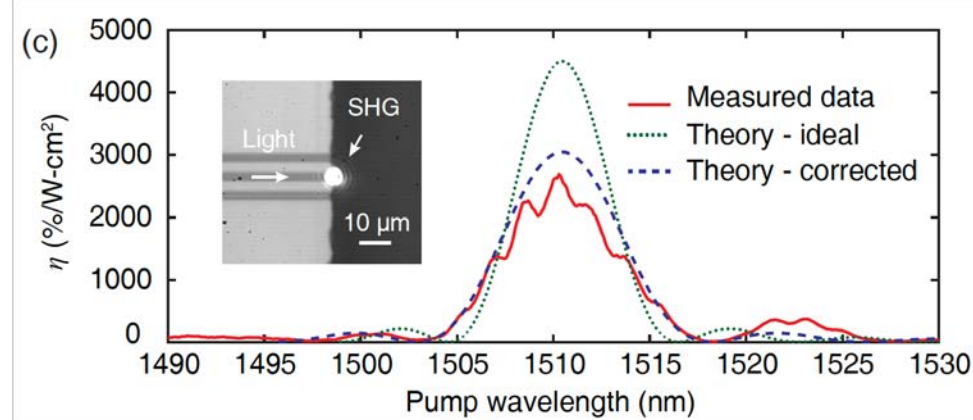
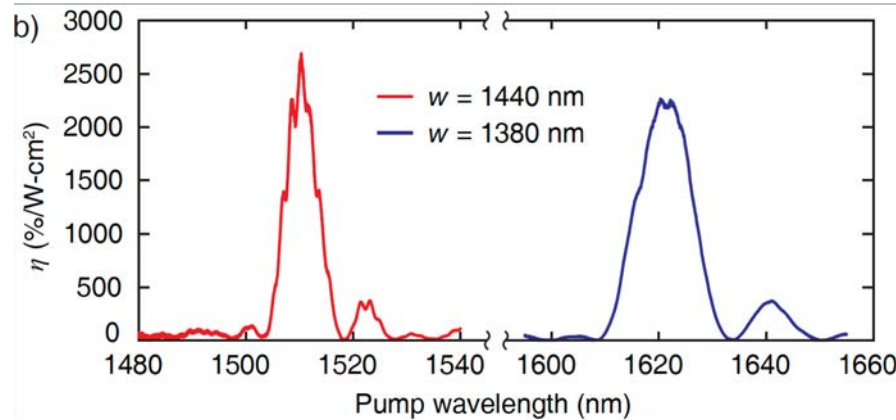
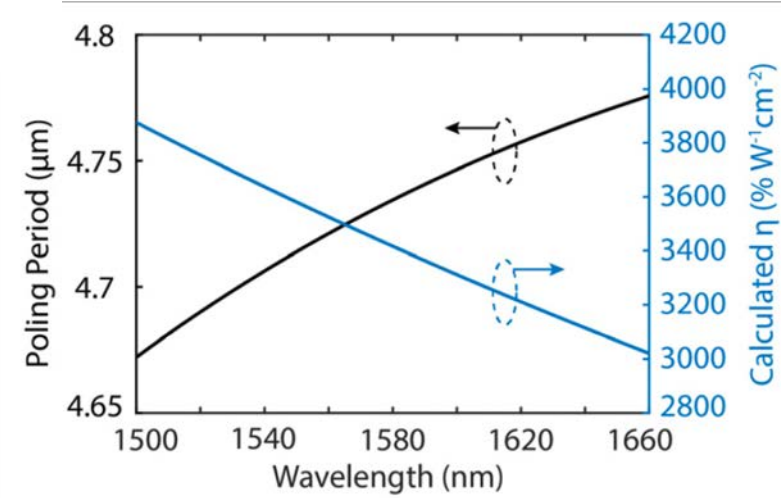
C. Wang, et al. *Nature Comm.*, **8**, 2098 (2017)



# Second harmonic generation with Periodically Polled Thin-Film LN



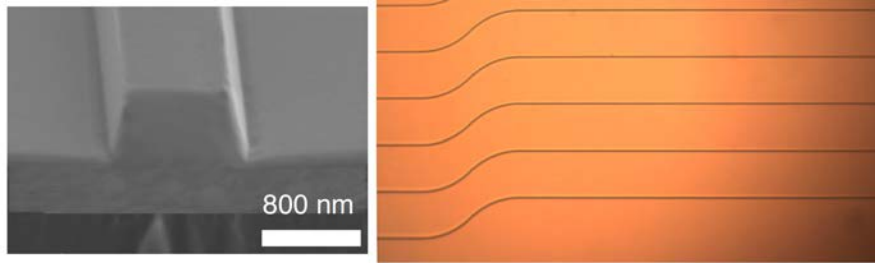
Record-high conversion efficiency!



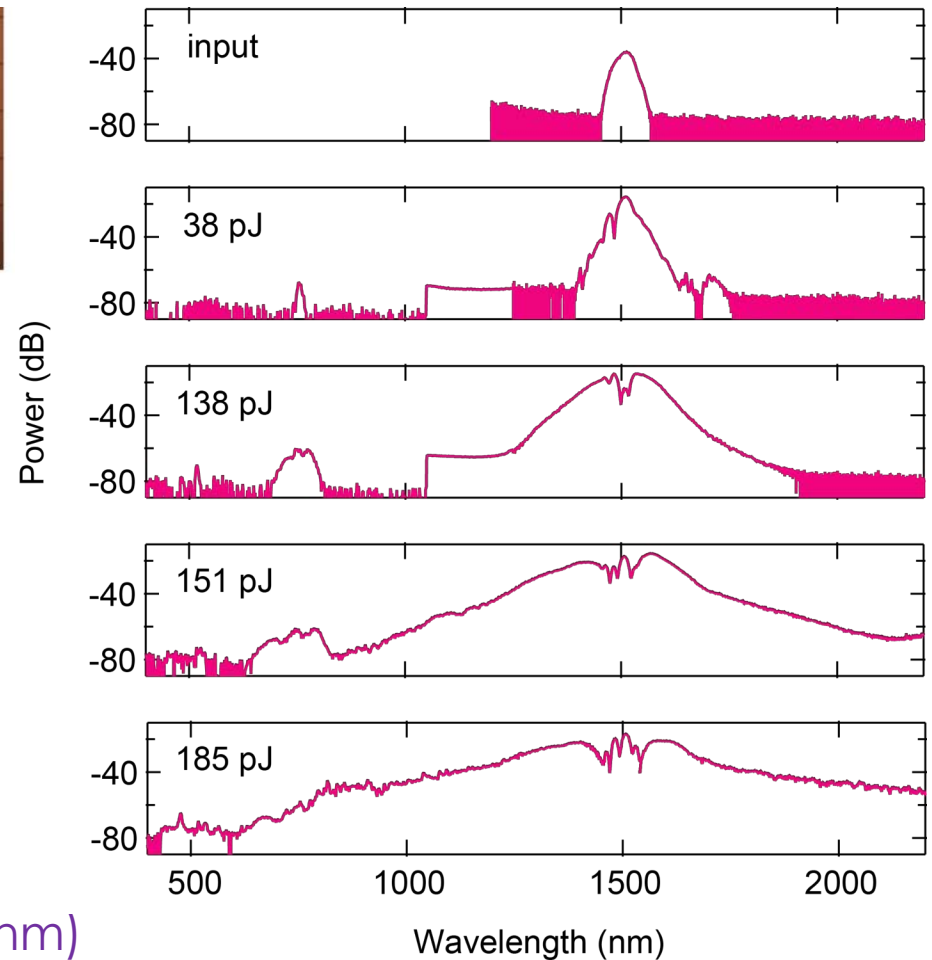
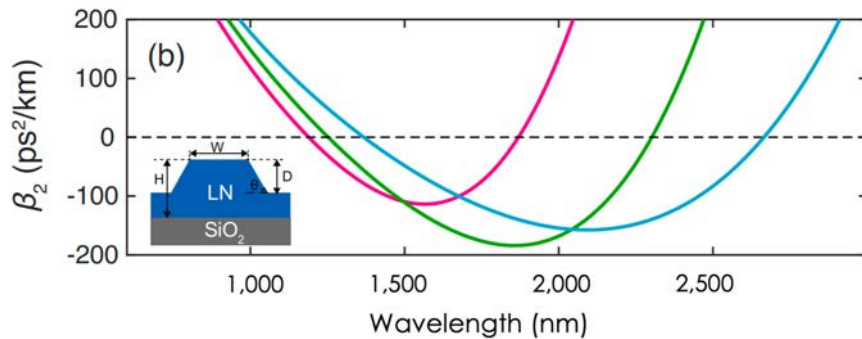
Evidence of pump-depletion observed => efficient frequency conversion!



# Supercontinuum Generation



Anomalous dispersion



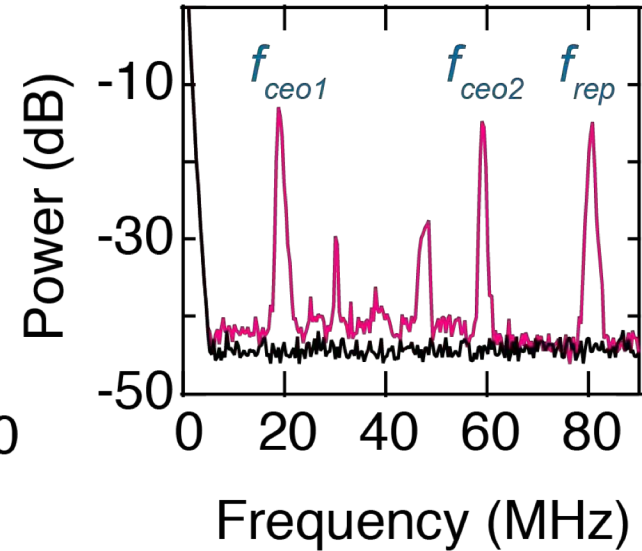
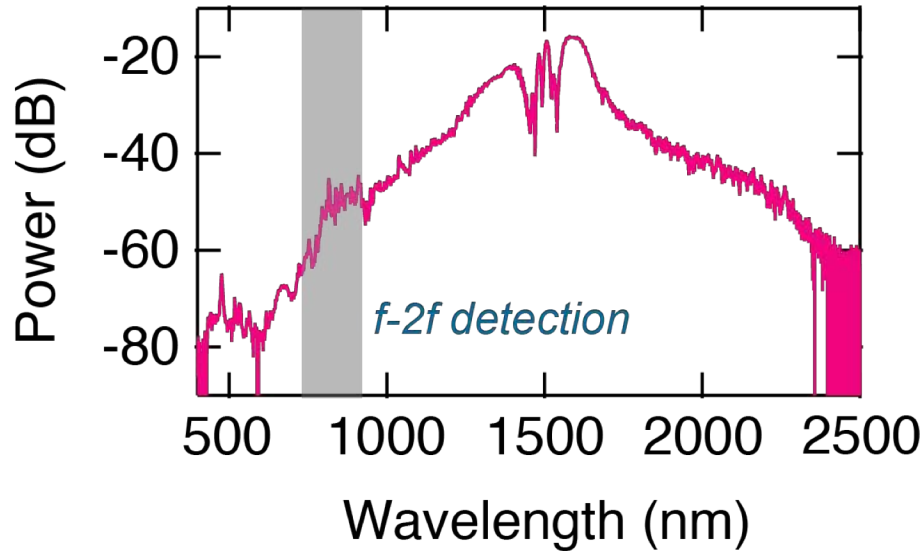
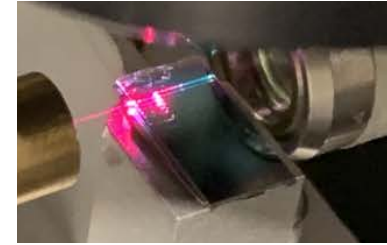
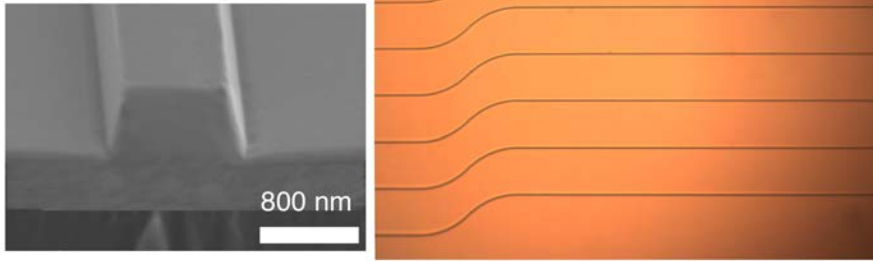
**Result:** 2.6 octave spanning (400-2400 nm) when 185-pJ pulse energy used

**Dimensions :** 800 × 800 nm, etch depth 450 nm, 0.5-cm length

**Pump:** 1500 nm, 160 fs pulse, 80-MHz rep rate



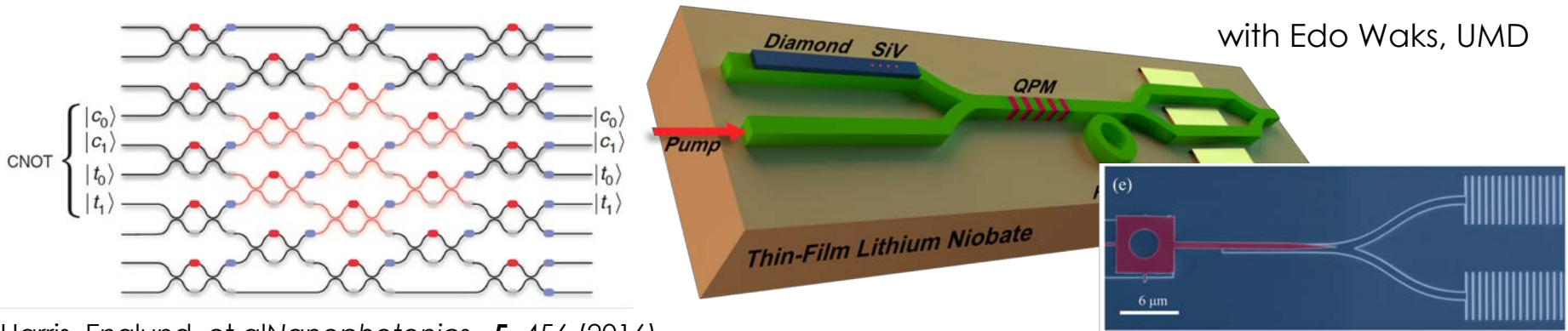
# Supercontinuum Generation



- Direct  $f_{CEO}$  detection in a single LN waveguide
- 30-dB signal-to-noise ratio of  $f_{CEO}$  beat-note

# Summary & Outlook

- ✓ **Low-loss integrated lithium-niobate photonics platform developed**
  - waveguide loss: 0.03 dB/cm; cavity Q: 10,000,000
- ✓ **Efficient, fast and integrated modulator for complex modulation formats**
  - $V_{\pi} \sim 1$  V; bandwidth > 100 GHz; on-chip insertion loss < 0.5dB; rates > 200 Gbps
  - fiber-to-fiber insertion loss as low as 3dB
- ✓ **Electro-optic (and Kerr) frequency combs be co-integrated with filters & modulators *on the same chip* for higher data rates**
  - 30 GHz EO comb spanning ~ 100 nm



with Edo Waks, UMD

Harris, Englund, et al *Nanophotonics*, **5**, 456 (2016)

S. Aghaeimeibodi, *APL*, **113**, 221102 (2018)

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

C. Wang, et. al. *Opt. Exp.*, **26**, 1547 (2018)

C. Wang, et al. arXiv:1809.08637 (2018)

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M. Zhang, et al. *Nature Photonics*, **13**, 36 (2019)

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

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