New Opportunities with Old Optical Materials

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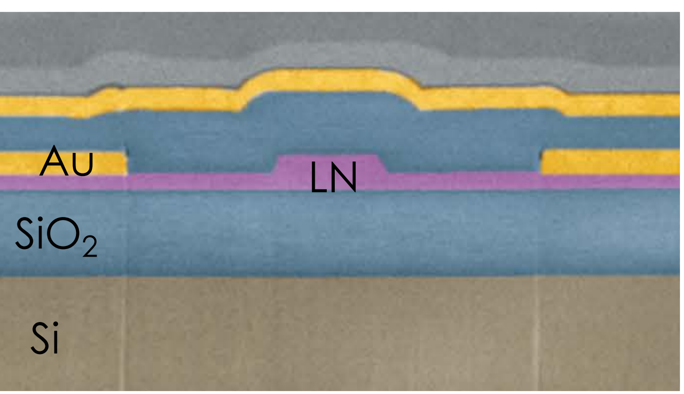

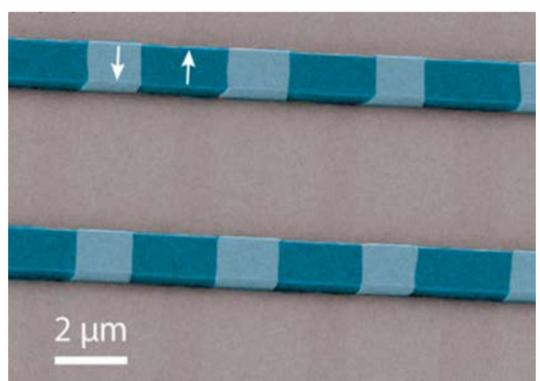

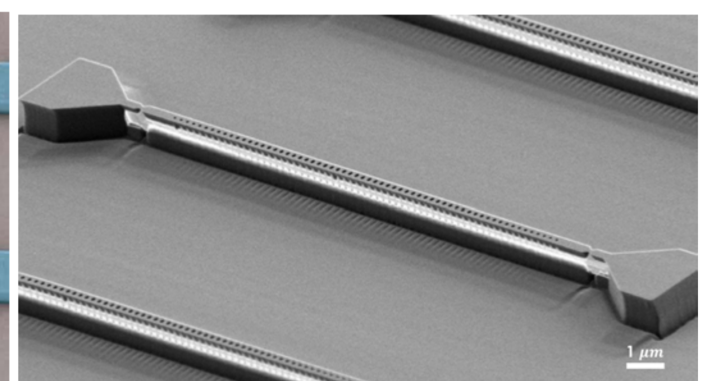

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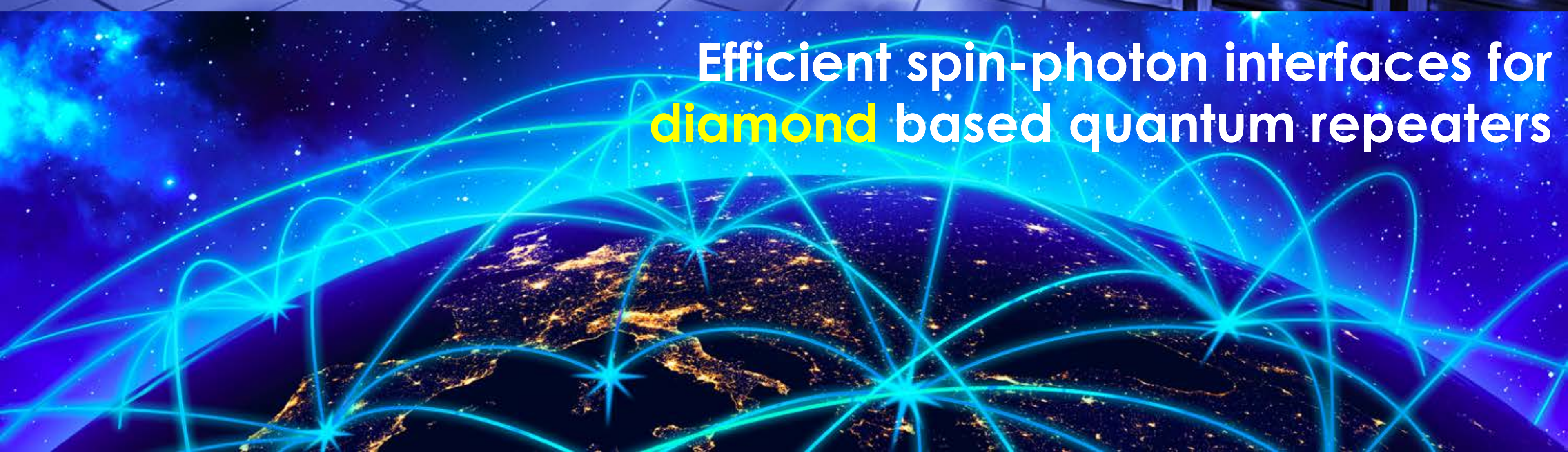
Topics to be discussed today...

Nanostructured $LiNbO_3$
for efficient optical interconnects



Efficient spin-photon interfaces for
diamond based quantum repeaters

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Lithium Niobate

High refractive index ~ 2.2

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

Wide transparency window (0.4 – 5.5 μm)

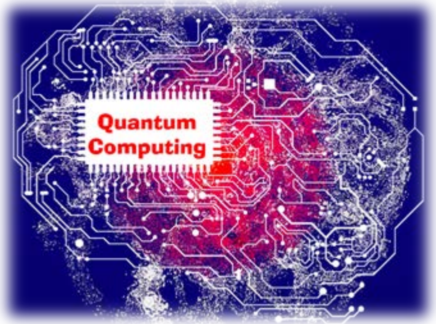
$$P = \varepsilon_0 \chi E + \boldsymbol{\varepsilon_0 \chi^{(2)} E^2} + \varepsilon_0 \boldsymbol{\chi^{(3)} E^3} + \cdots$$

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

- low-loss, highly linear, electro-optic modulators
- efficient electro-optic frequency combs
- frequency converters & entangled photon pair sources

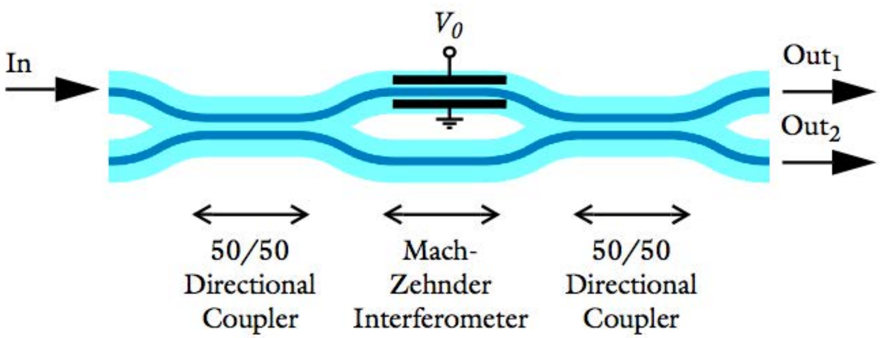
When combined with its $\chi^{(3)}$ it becomes possible to realize locked & self-referenced Kerr frequency combs, with applications in:

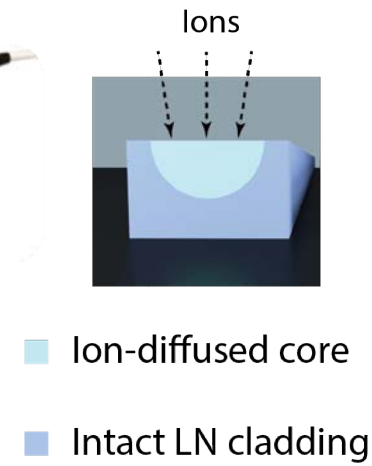
- spectroscopy
- precision measurements
- …



Lithium-Niobate Modulators

the workhorse of optoelectronics!





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!
  - ⇒ expensive and power hungry amplifiers are needed
  - ⇒ large energy consumption per transmitted bit

The solution is simple… ☺

Figure out how to etch lithium niobate properly to realize ultra-low loss, highly integrated, lithium niobate photonics platform!

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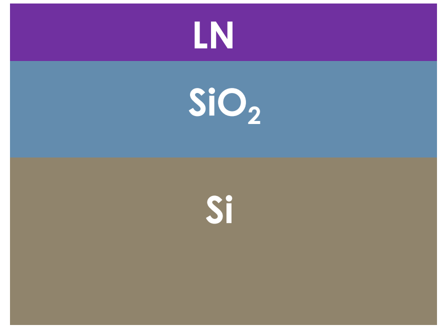
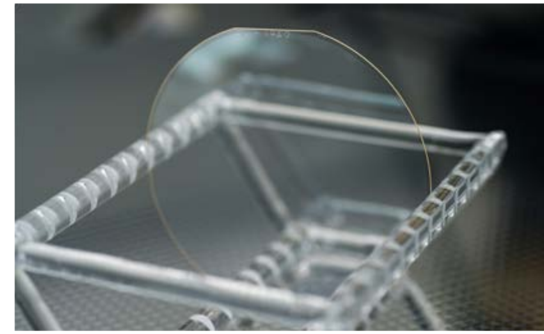
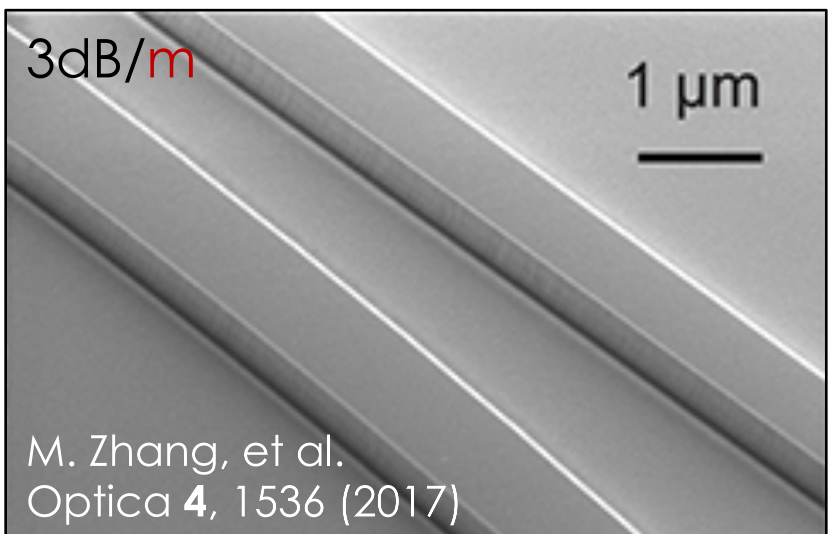
Approach

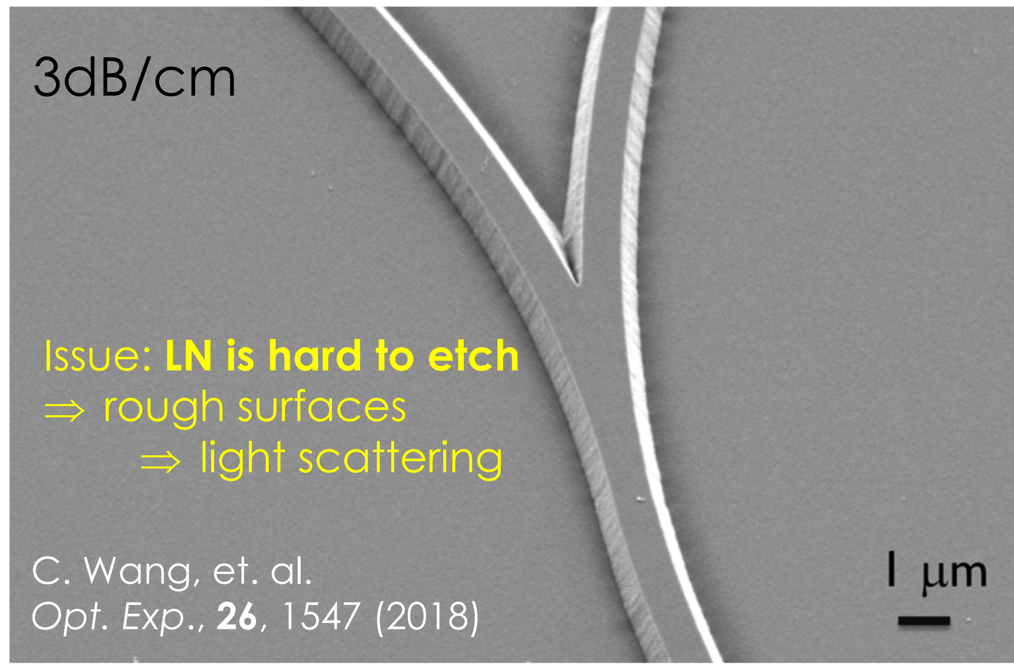
- Thin LN film on insulator wafers produced by NanoLN company, using smart cut process.





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





Optimized etch!
⇒ Smooth sidewalls
⇒ Low loss!

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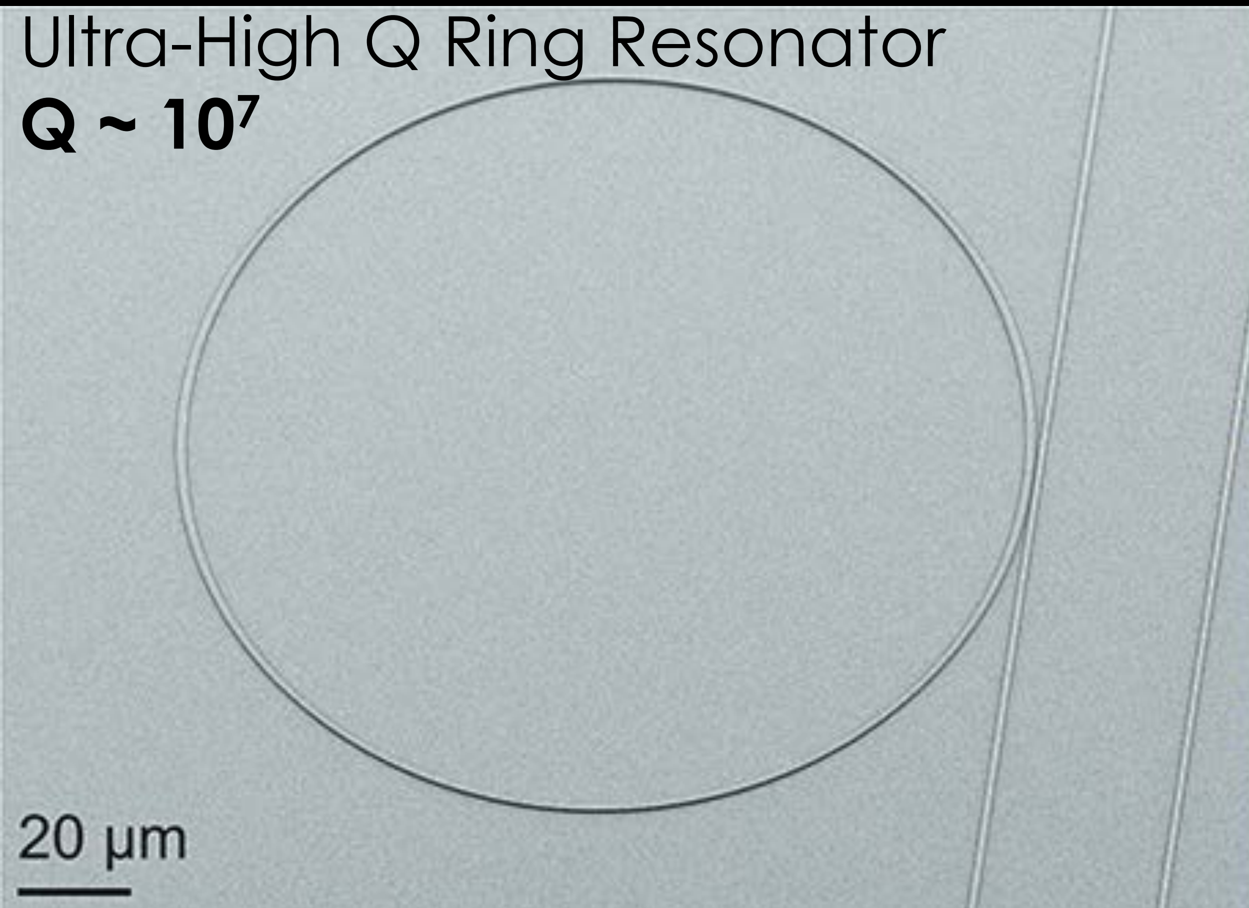
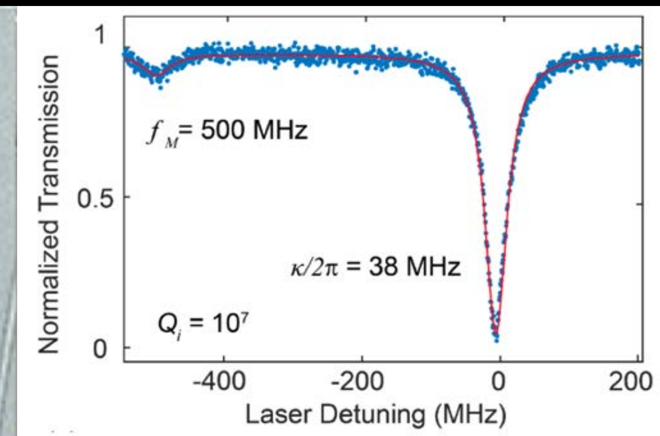
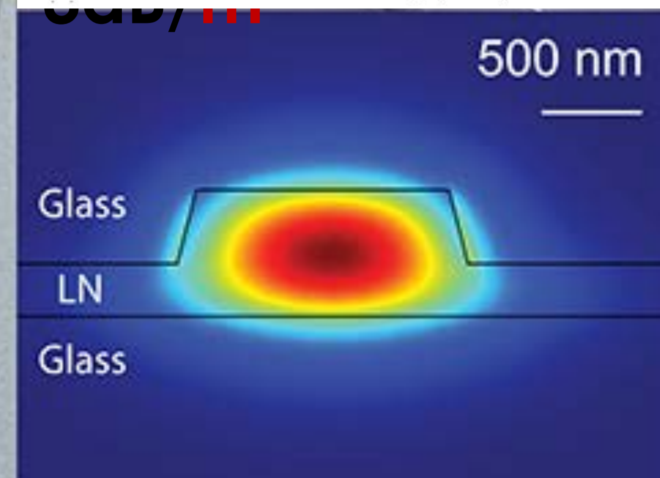
another way to think about low loss:

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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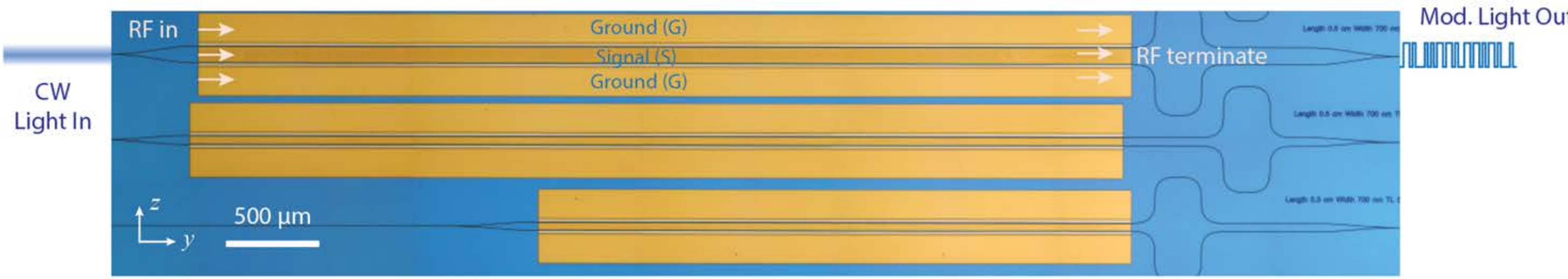
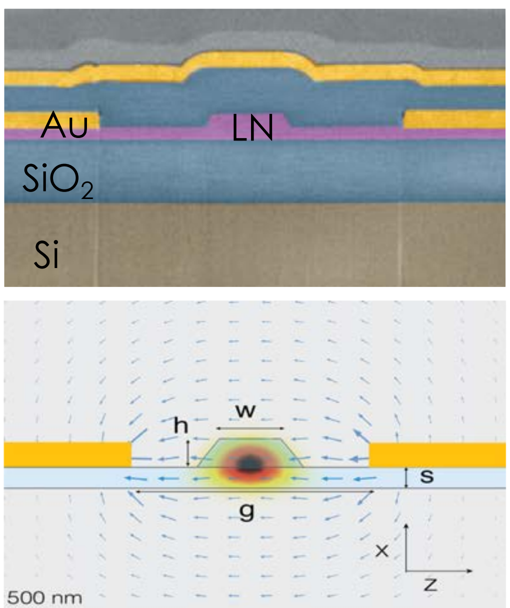
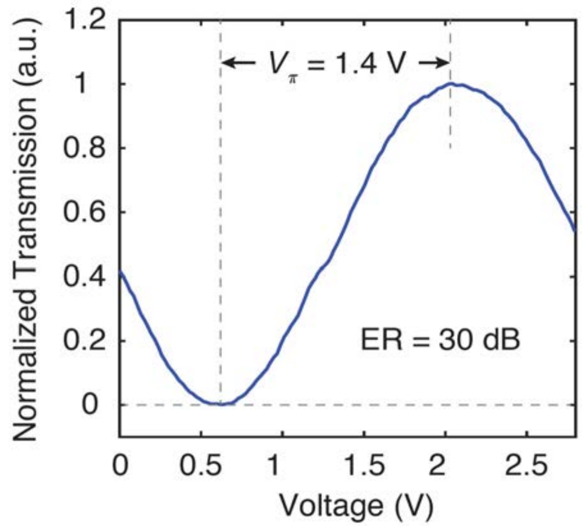
(travelling wave)
Integrated LN Electro-Optic Modulators



Good overlap between microwave & optical fields

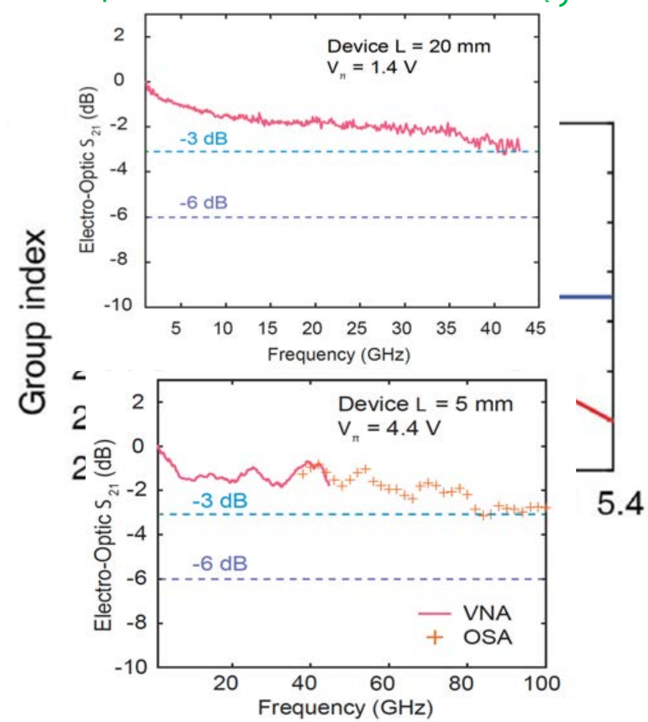


Good EO efficiency
$V\pi L$ = 2.8 Vcm



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)

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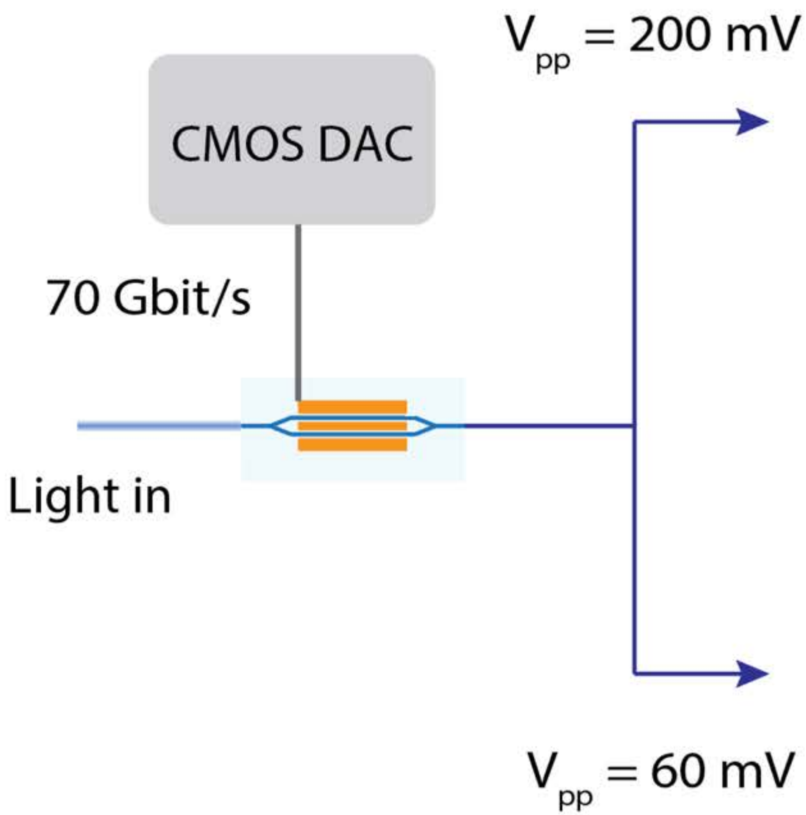
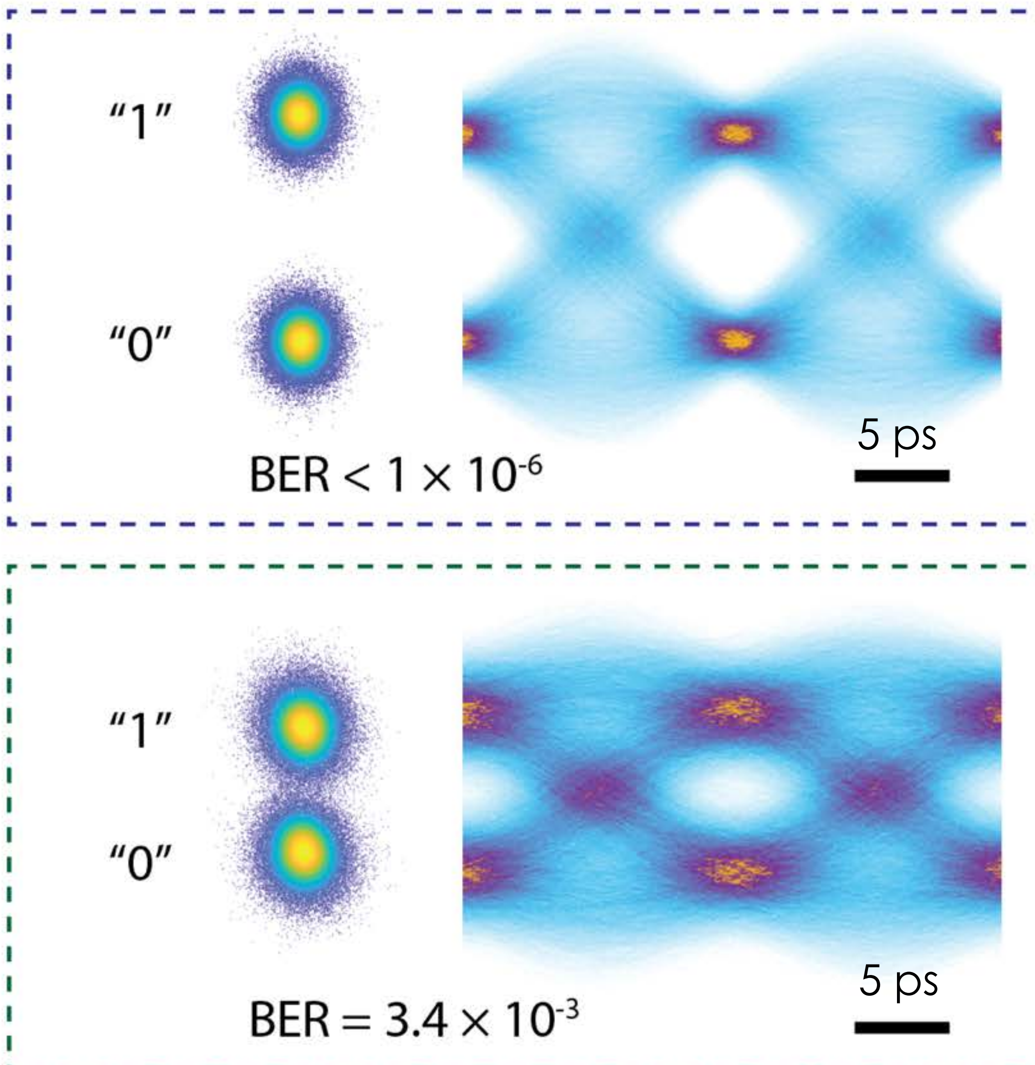
CMOS Driven Modulator!



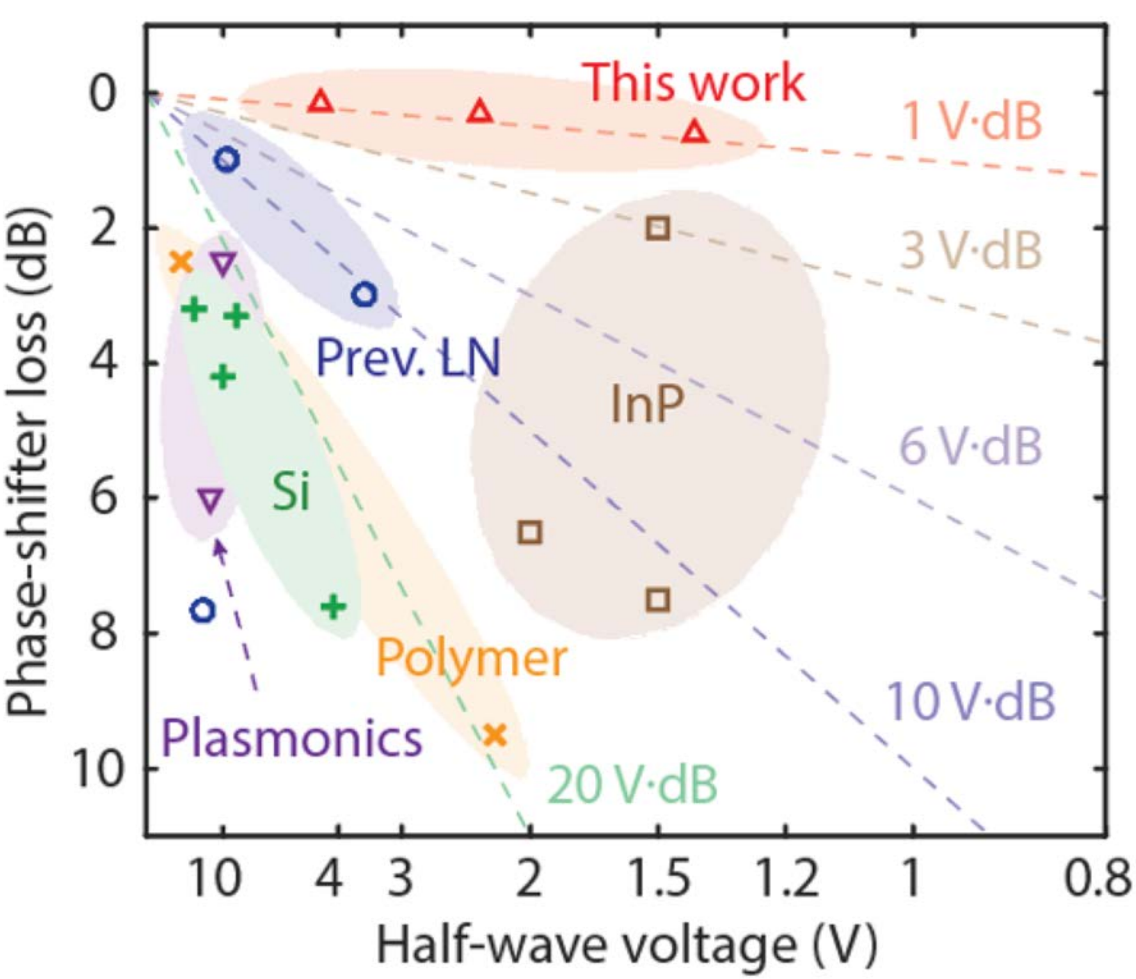


Electrical energy consumption:
~ 40 attoJoul / bit !!!

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

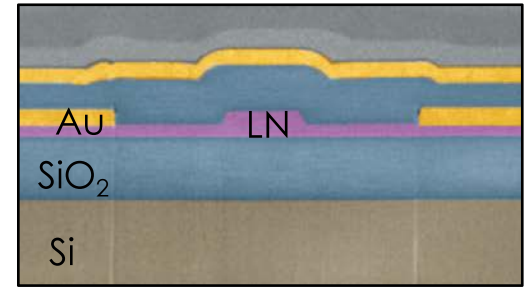
with Nokia Bell Labs (Peter Winzer & team)

Comparison with Integrated Modulators



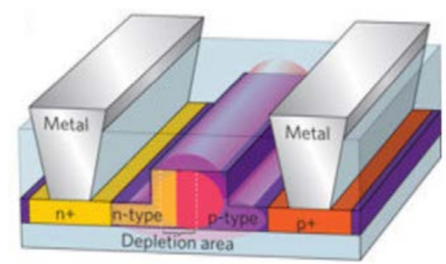
C. Wang, M. Zhang et al, *Nature*, **562**, 101 (2018)

Integrated LN modulator



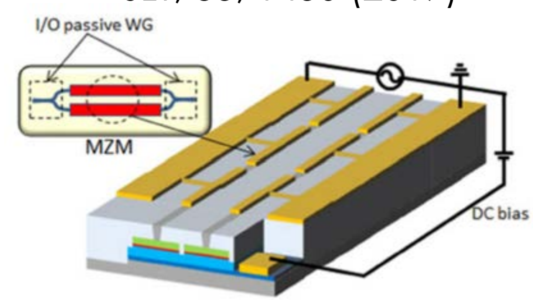
Silicon Photonics

Nature Photonics 4, 518 (2010)



InP Photonics

JLT, 35, 1450 (2017)



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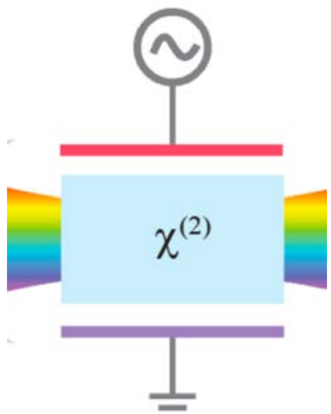
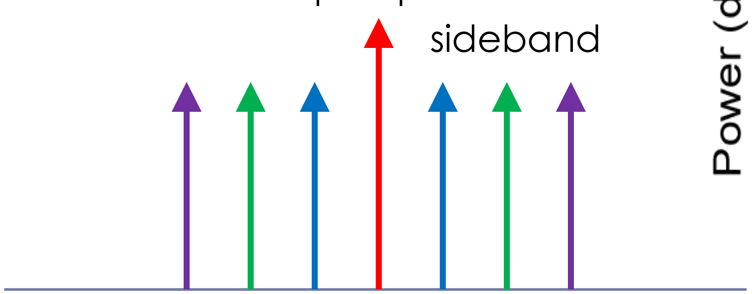
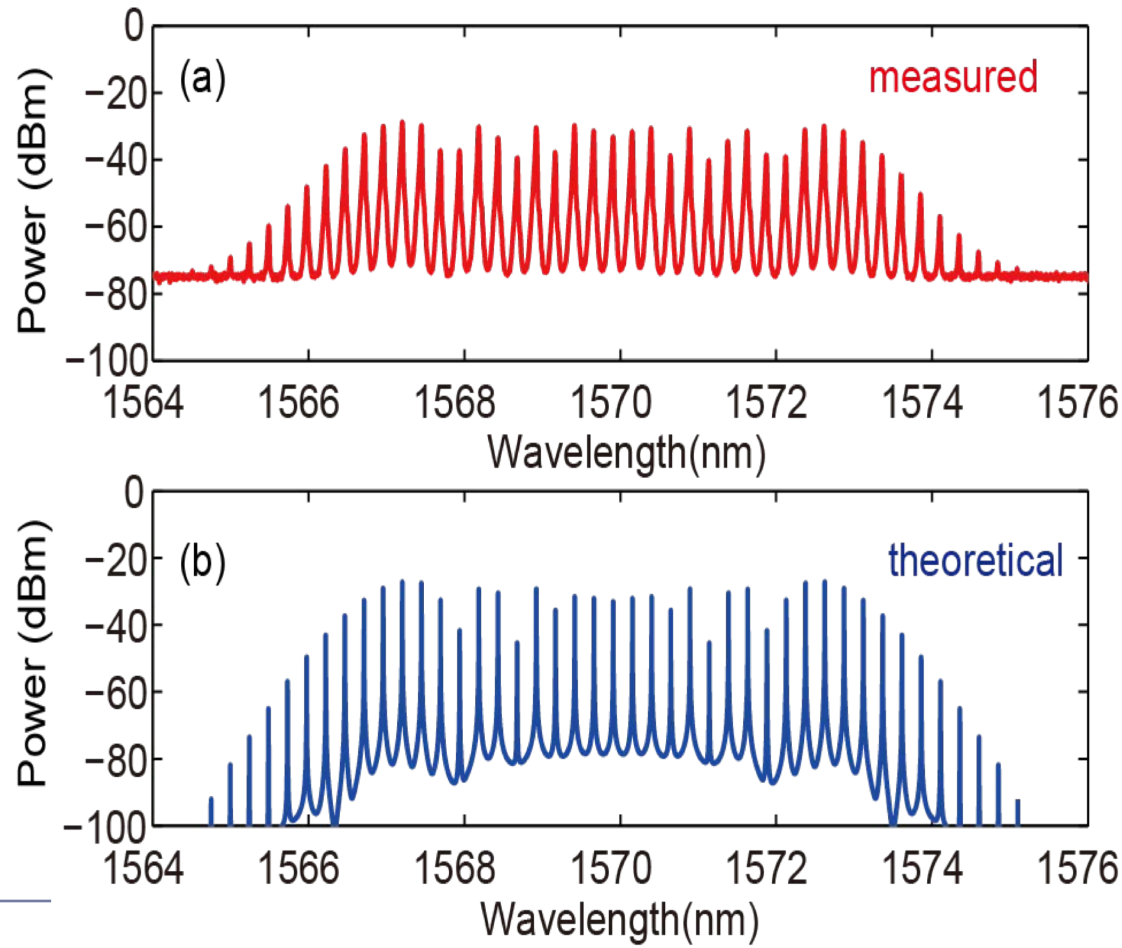
Electro-Optic (χ^2) Frequency Comb

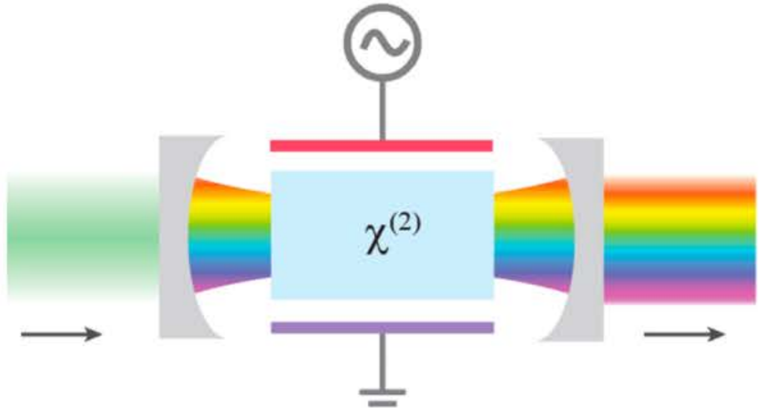


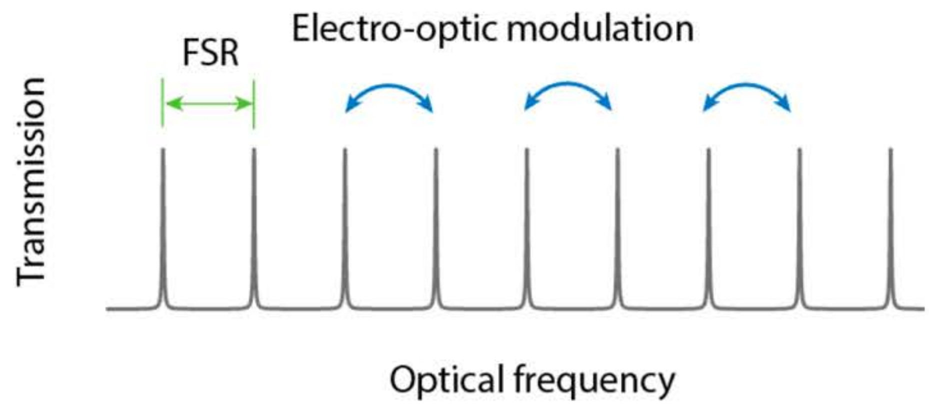




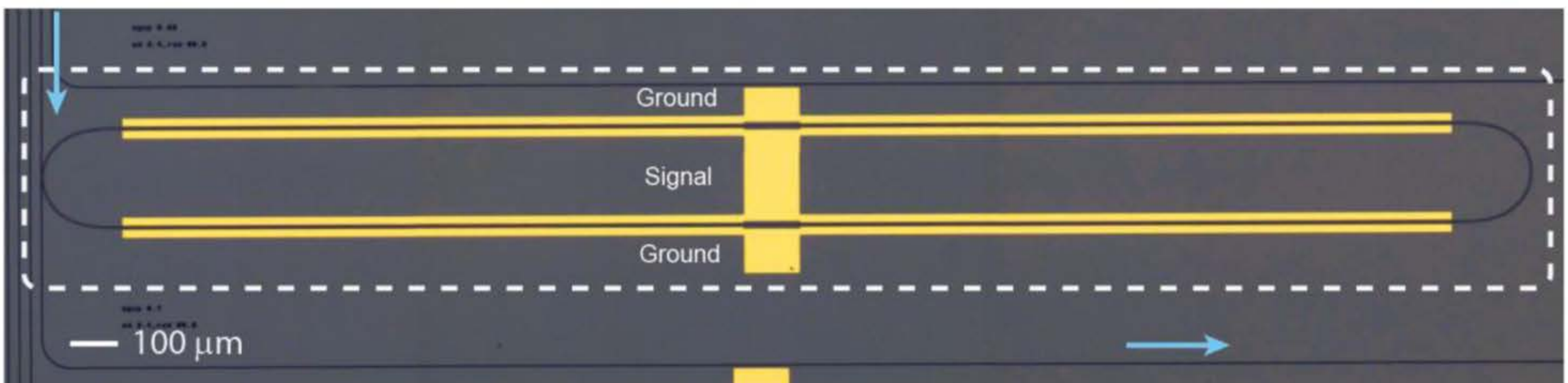
T. Ren, et al, *Phot. Tech. Lett.*, DOI: 10.1109/LPT.2019.2911876 (2019)

Electro-Optic (χ^2) Frequency Comb





The Idea:
use the cavity to enhance the sideband generation process
when cavity FSR matches the modulation frequency



M. Zhang, et al. *Nature*, **568**, 373 (2019)

with Joe Kahn, Stanford

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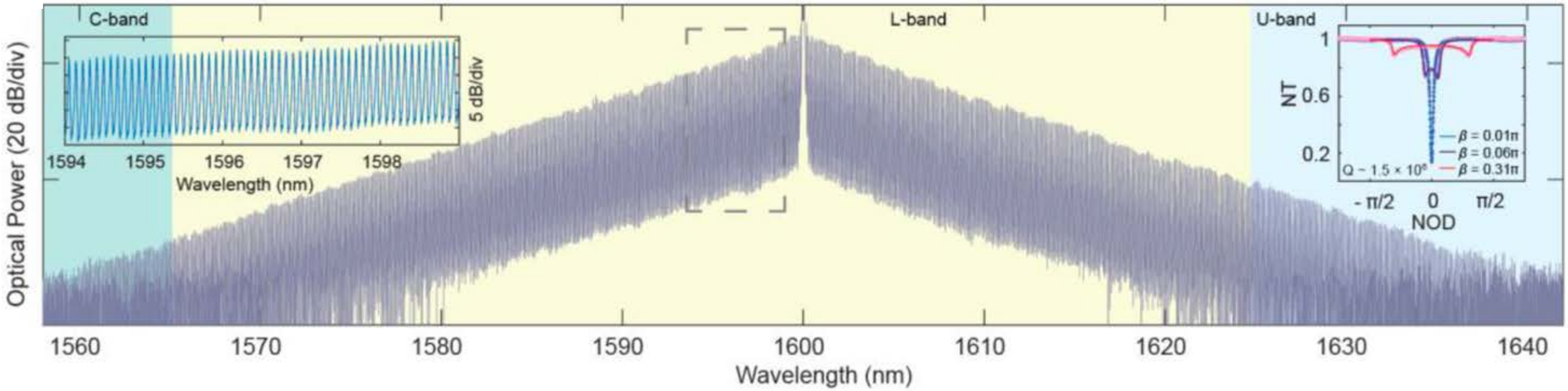
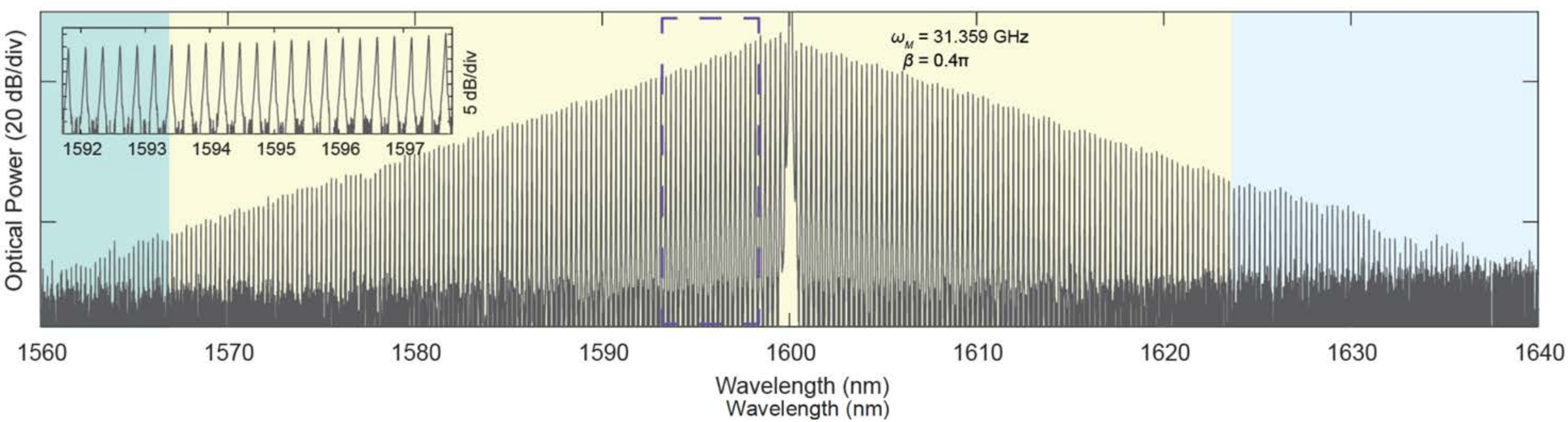
Electro-Optic (χ^2) Frequency Comb

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



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



M. Zhang, et al. *Nature*, **568**, 373 (2019)

with Joe Kahn, Stanford

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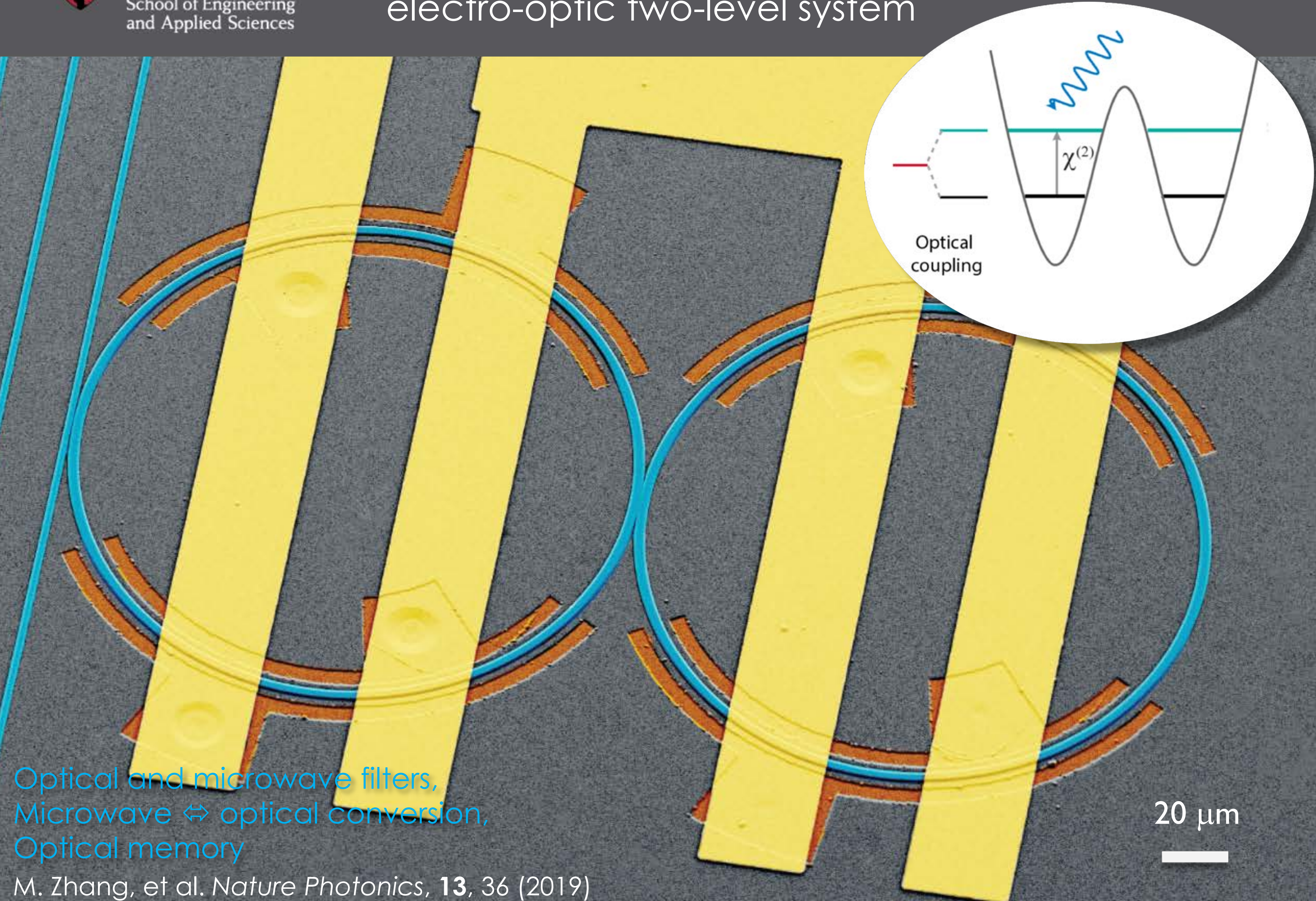
Photonic Molecule
electro-optic two-level system



Optical and microwave filters,
Microwave ⇔ optical conversion,
Optical memory

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

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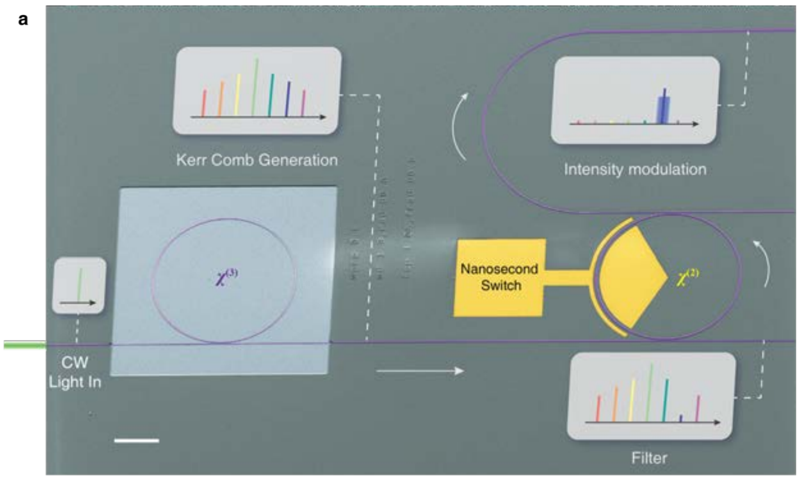
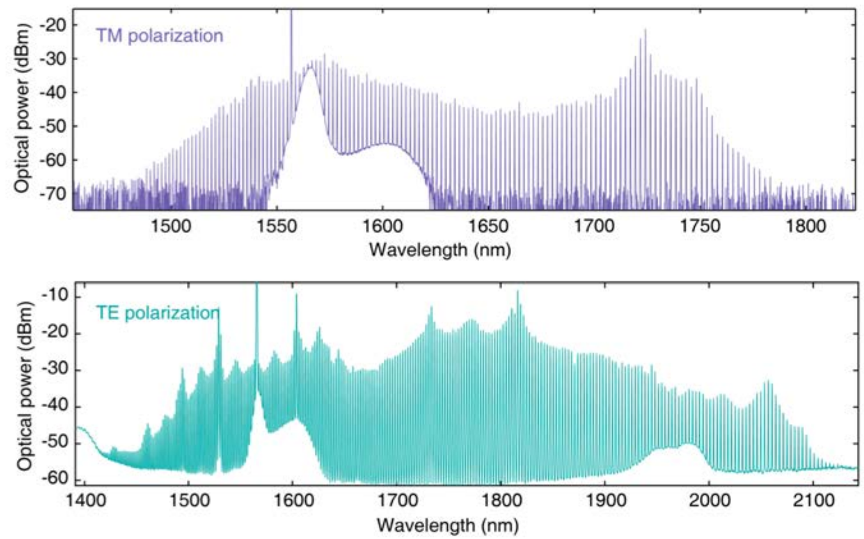
Integrated Lithium Niobate Photonics
χ^3 Frequency Combs & Supercontinuum

Kerr frequency combs integrated with filters, modulators, etc

- Spans 2/3 of an octave for 100 mW in a waveguide (100 W in the ring !)

a

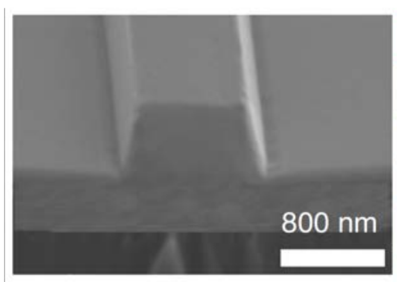


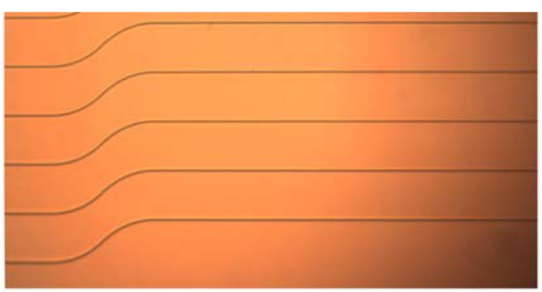


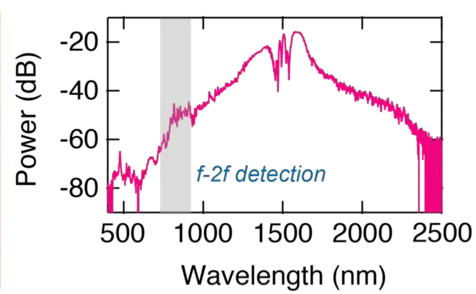
C. Wang, *Nature Comm.*, **10**, 978 (2019)

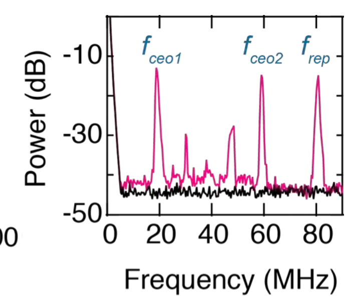
2.6 octave spanning supercontinuum source (185-pJ pulse energy used)

- Direct f_{CEO} detection with 30-dB signal-to-noise ratio









M. J. Yu, *Optics Letters*, **44**, 1222 (2019)

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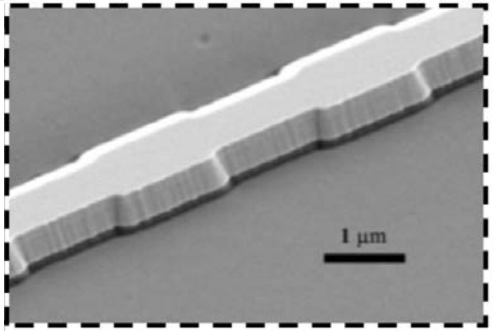
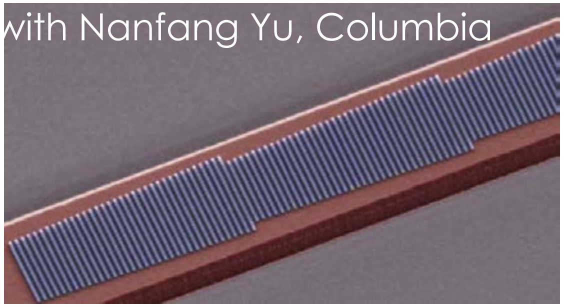
Integrated Lithium Niobate Photonics
Efficient Nonlinear Frequency Conversion



Periodically grooved waveguide introduces additional momentum to compensate for the phase mismatch:

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



Gradient metasurface manipulates the photon momentum during SHG process

⇒ **Phase-matching-free** SHG.

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

Periodically poled thin film lithium niobate

⇒ Very efficient three-wave mixing processes

⇒ 20-fold increase in second harmonic generation (SHG) compared to state of the art. (3000 %/W-cm^2)

⇒ Ideally suited for realization of OPOs, quantum frequency converters, photon pair sources, etc.

C. Wang, *Optica*, **5**, 1438 (2018)

Englund Group, MIT

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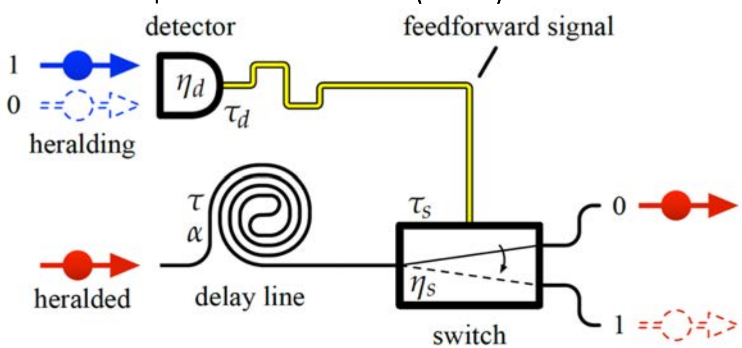
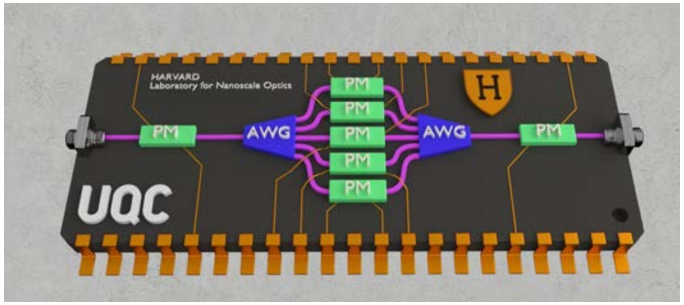
Ongoing work:
Photonic Computing with LN

Photonic computation

- **Quantum**:
  - path-encoded qubits
  - frequency- and time-bin encoded qubits.
- **Classical** (e.g. neuromorphic): a few photon optical nonlinearities (chi-2, photorefractive…)

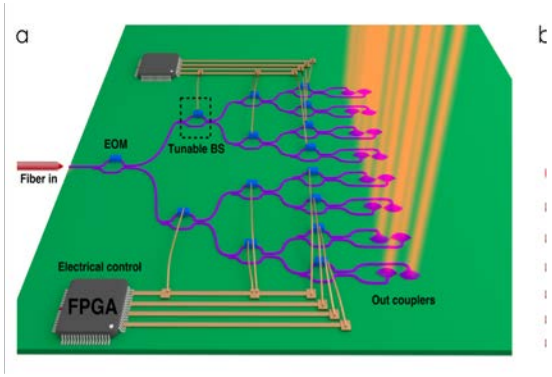
O'Brien & Thompson, *IEEE JSTQE* (2016)



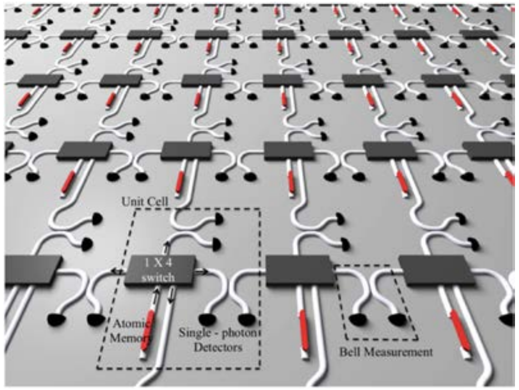


Fast photonic switch fabric:

Delivery of control signals to trapped atom and ion quantum computers, beam steering, LIDAR, etc

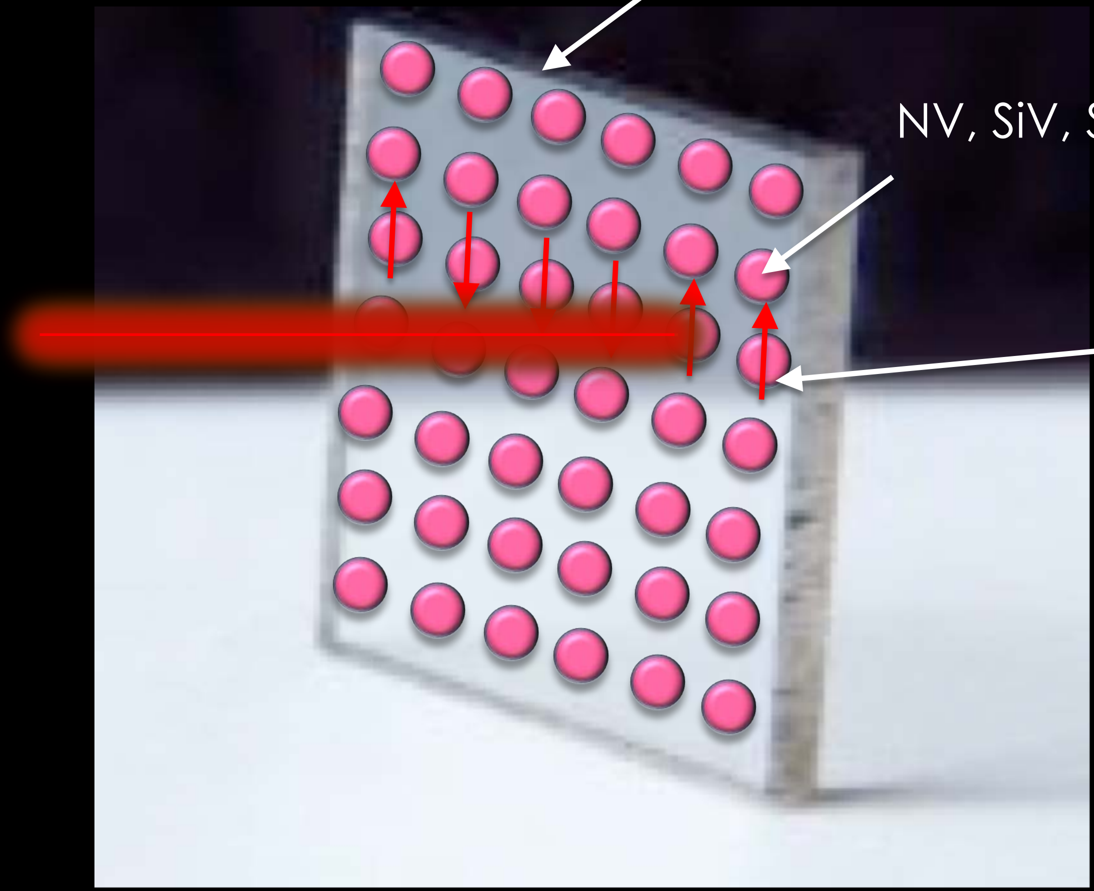


Hybrid quantum photonics combines quantum memories (e.g. diamond), shown in red, with LN photonics



Englund group, MIT

Color center ⇔ atomic scale, optically addressable, memory!



Quantum Cloud

An unprecedented **distributed computational resource** based on a network of quantum computers, quantum sensors, and atomic clocks interfaced via secure quantum internet.

Requirements:

- ✓ Long lived quantum memory ⇔ information is stored while entanglement is distributed
- X Indistinguishable photons ⇔ good optical coherence
- X Fast emission and excellent photon collection ⇔ high entanglement rates
- X Low photon propagation losses ⇔ high entanglement rates

R. Hanson, Delft

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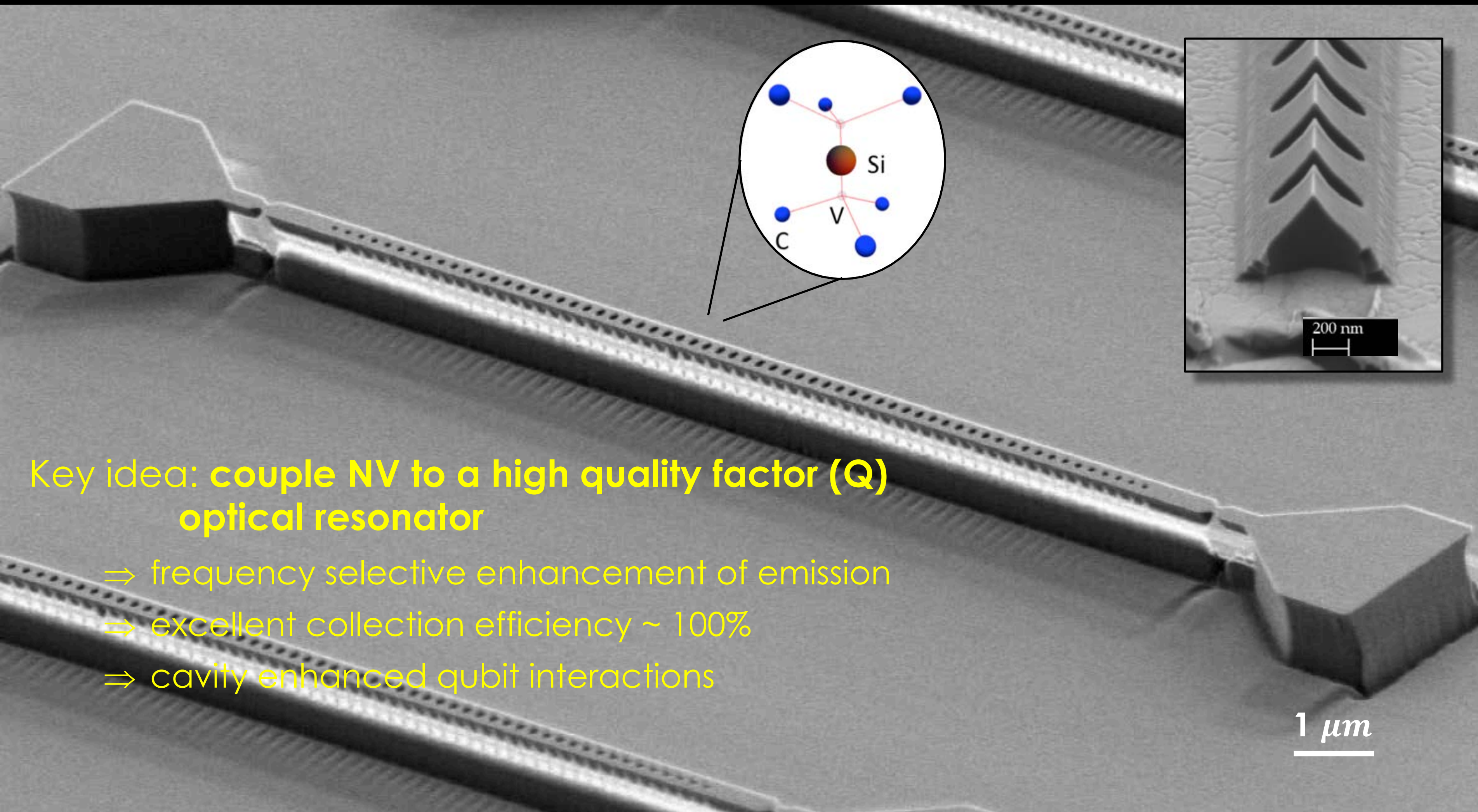
Cavity: Efficient Spin-Photon Interface



Key idea: **couple NV to a high quality factor (Q) optical resonator**

⇒ frequency selective enhancement of emission

⇒ excellent collection efficiency ~ 100%

⇒ cavity enhanced qubit interactions

Monolithic, all diamond approach – devices carved inside bulk diamond crystal

M.J. Burek, *Nature Comm.*, **5**, 5718 (2014)

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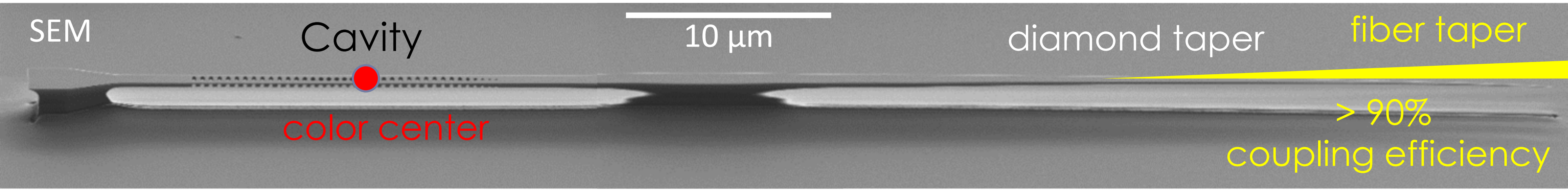
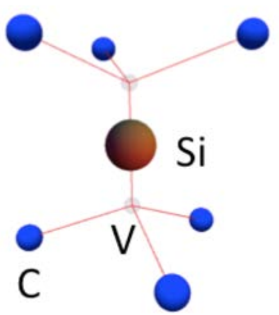
State of The Art

Monolithic, all diamond nanocavity, carved inside bulk diamond crystal



M. Burek, et al, *Phys. Rev. Appl.*, **8**, 024026 (2017).



Silicon-Vacancy color center (SiV):

✓ symmetric => no permanent dipole;
less sensitive to charge fluctuations at surfaces.

✓ strong zero-phonon line emission (> 70%)

✓ spin coherence ~ 10 ms @ 100 mK
(with dynamical decoupling)

Cooperativity:
$C=4g^2/\kappa\gamma$

2016: C ~ 1
2017: C ~ 5
2018: C ~ 20
2019: C ~ 40

Using this platform, we demonstrated:

- **Photon number router & single photon switch with a memory:** control pulse causes signal pulse to be transmitted or reflected;
  A. Sipahigil, et al, *Science*, **354**, 847 (2016)
- **Cavity mediated Interactions between spins** embedded inside the same cavity
  R. Evans, et al, *Science* (2018)

Strain Tuning of SiV Spin Emission

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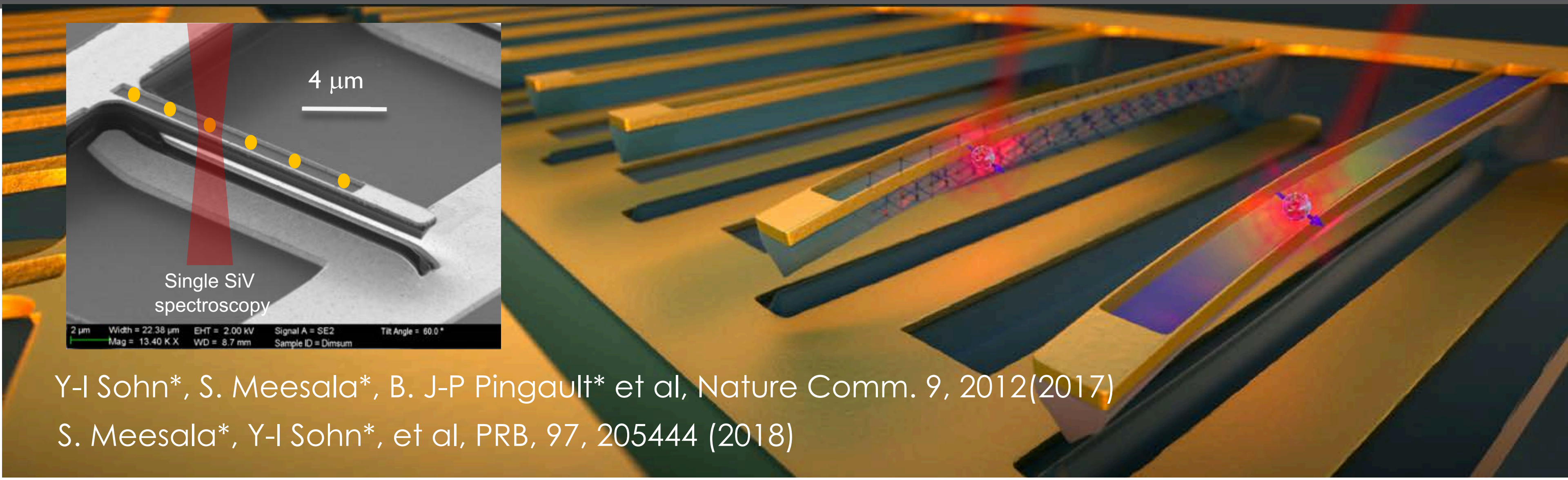
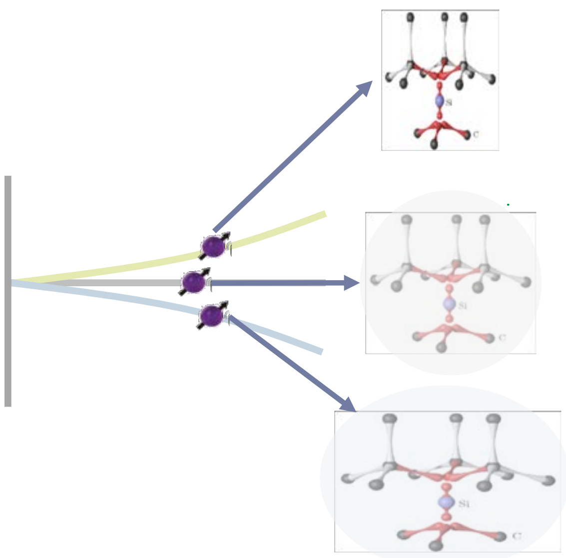
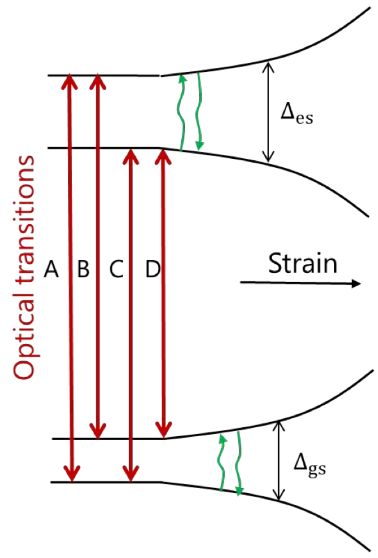
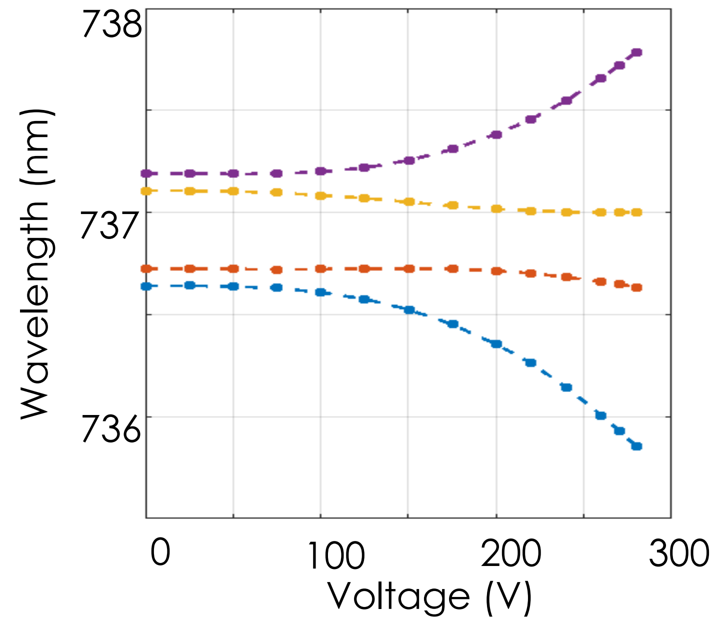


Y-I Sohn*, S. Meesala*, B. J-P Pingault* et al, Nature Comm. 9, 2012(2017)

S. Meesala*, Y-I Sohn*, et al, PRB, 97, 205444 (2018)



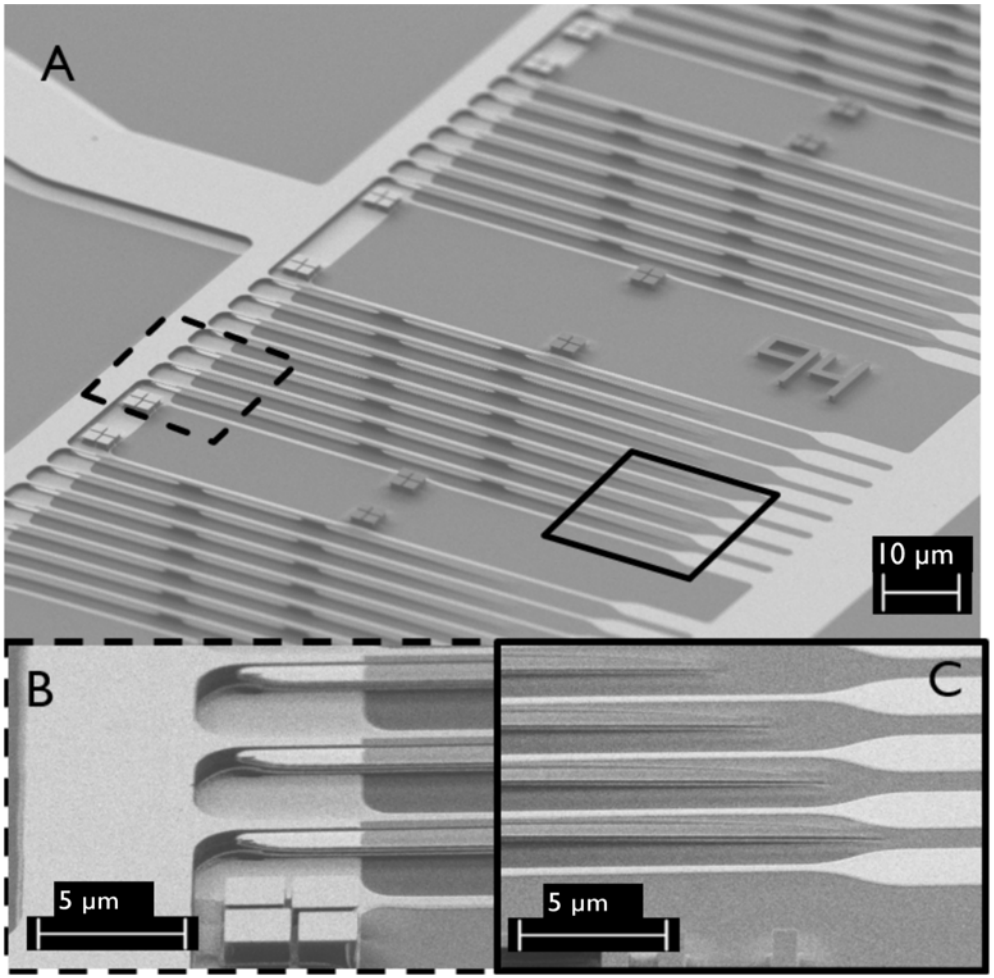




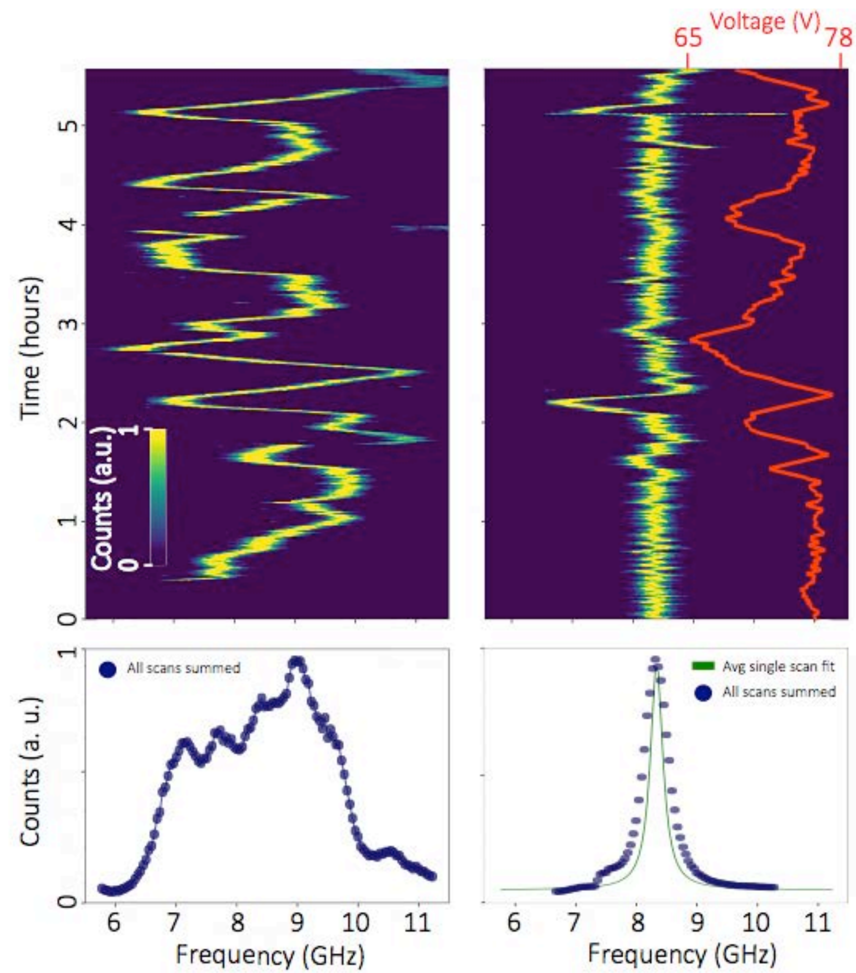
Strain stretches orbitals of SiV→ shifts energy levels

Strain Control + Efficient Collection

NEMS for strain control + efficient fiber collection



feedback OFF feedback ON



B. Machielse, et al, arXiv:1901.09103 (2018)

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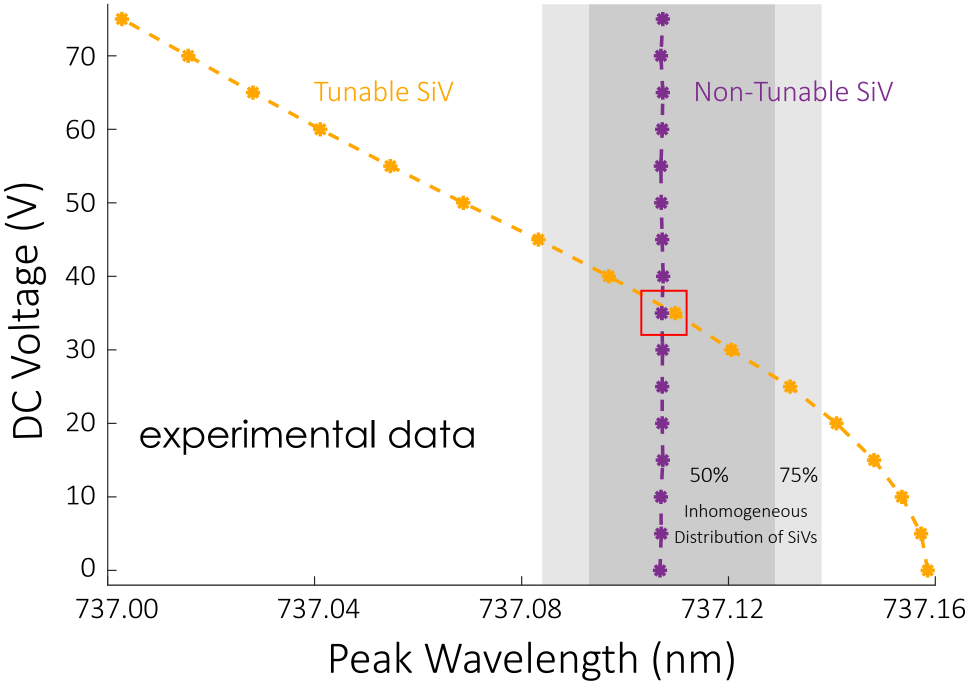
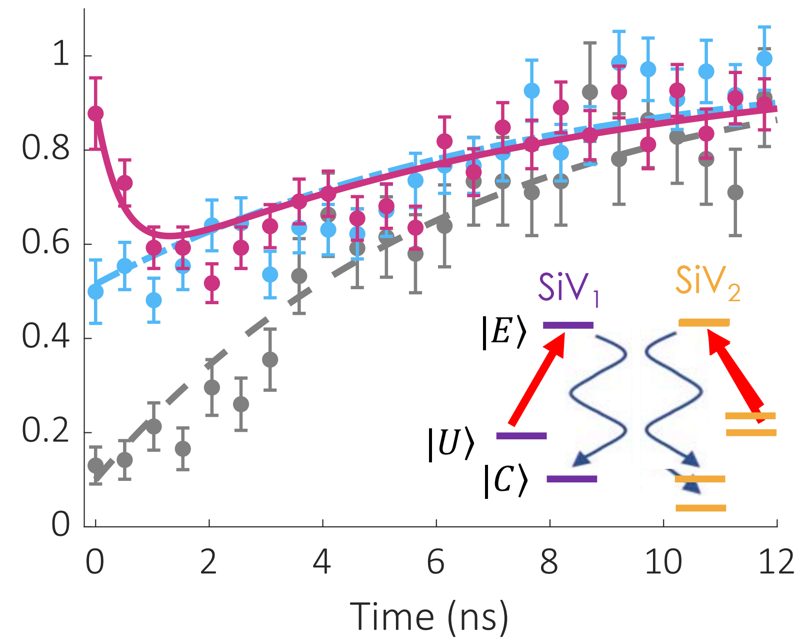
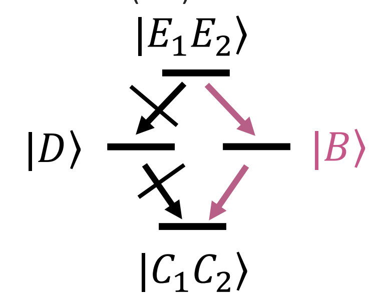
Entangled SiVs & Super-Radiance







- new tuning knob demonstrated to overcome inhomogeneous broadening
- relies on resonant interactions between SiVs:

  ⇒ faster rates @ lower powers + longer coherence than off-resonant (Raman) interactions
- framework for novel spin-phonon interfaces!

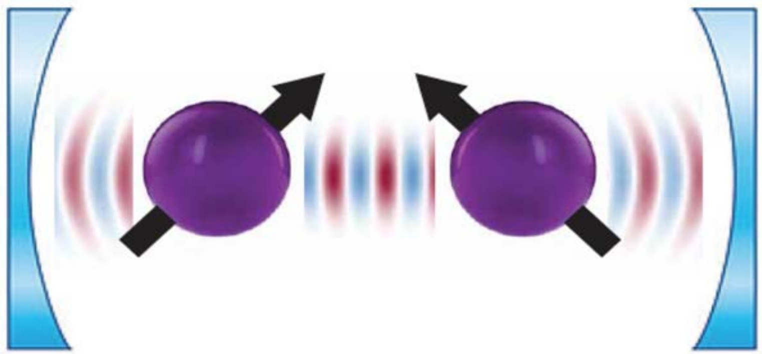
$$|B\rangle = \frac{1}{\sqrt{2}}(|E_1C_2\rangle + |C_1E_2\rangle)$$

$$|D\rangle = \frac{1}{\sqrt{2}}(|E_1C_2\rangle - |C_1E_2\rangle)$$

B. Machielse, et al, arXiv:1901.09103 (2018)

Qubit Interactions

Quantum Photonics
efficient photon-mediated qubit interactions

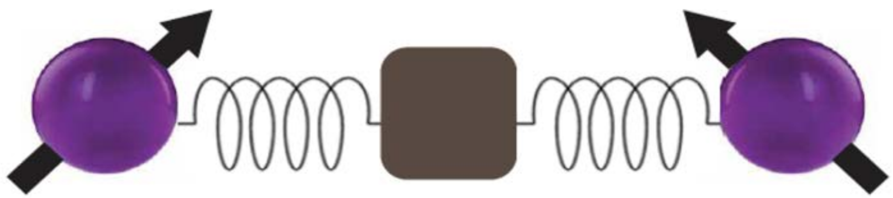


Key idea: couple color centers to optical cavities fabricated in diamond;

⇒ Large, frequency selective, enhancement of emission!

⇒ Excellent collection efficiency of emitted photons, approaching 100%!

Quantum Phononics
vibration-mediated qubit interactions



Key idea: couple color centers to mechanical resonators fabricated in diamond;

⇒ Leverage large strain susceptibility to realize quantum gates

Spin-Phonon cooperativity:

$$C = \frac{4g^2}{(n_{th}+1)\kappa_m \gamma}$$

g: single spin-phonon coupling rate
n_{th}: number of thermal phonons
κ_m: mechanical damping rate
γ: spin dephasing rate

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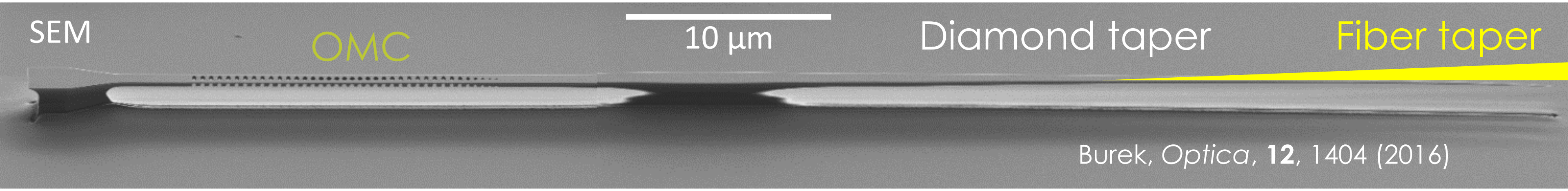
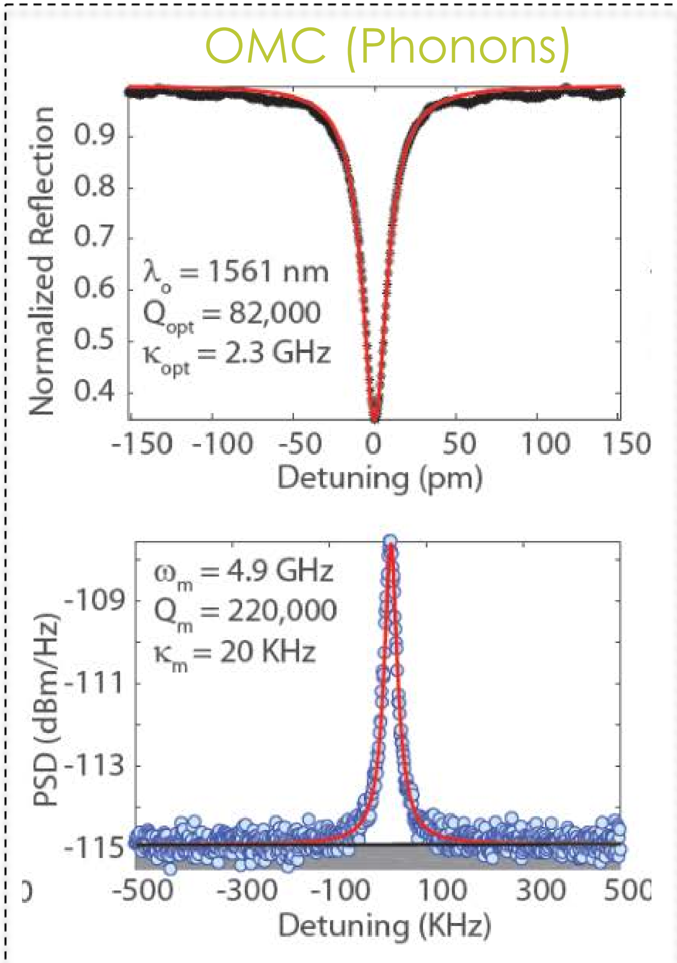
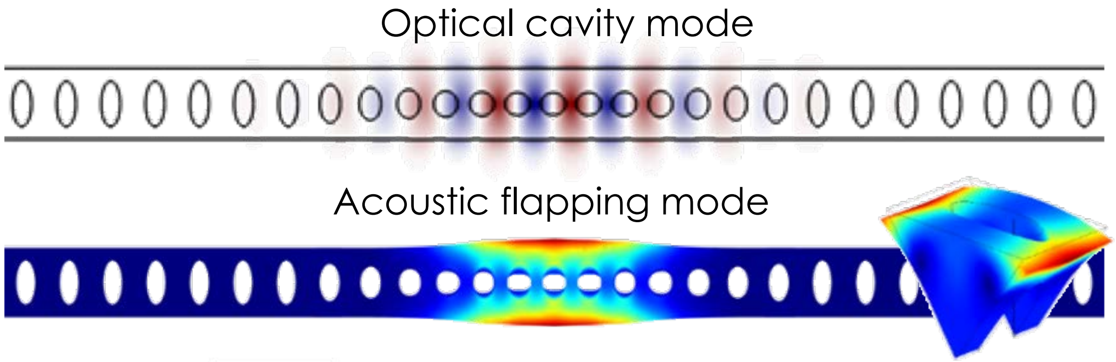
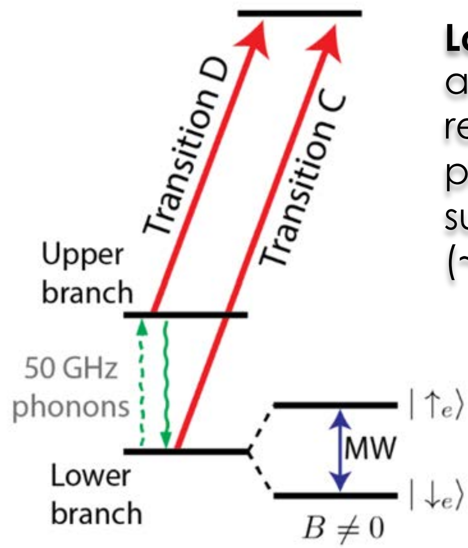
Towards Coherent Spin-Phonon Interface

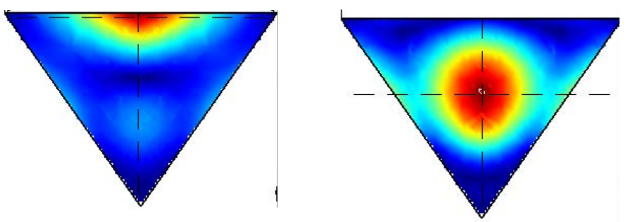




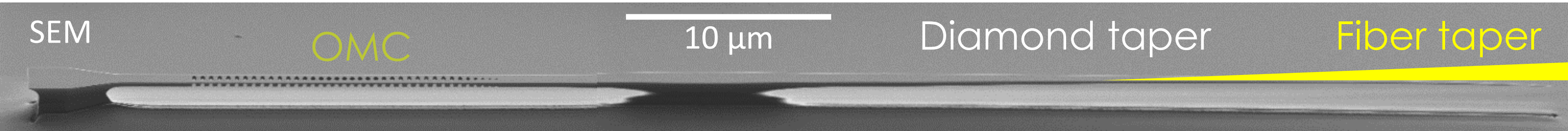




Large *g* due to wavelength-scale acoustic mode volumes (~ 1 μm^3) resulting in large strain-fields per phonon (~10^{-8}) with high strain susceptibility of the SiV ground state (~1000 THz/strain).

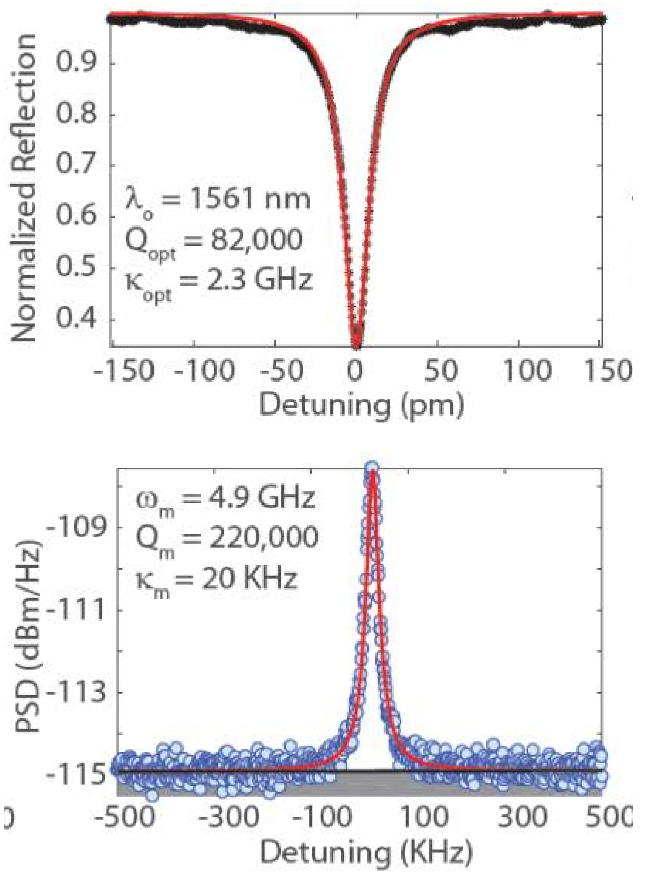


Towards Coherent Spin-Phonon Interface

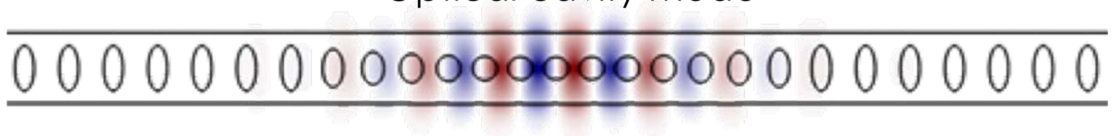


Burek, *Optica*, **12**, 1404 (2016)

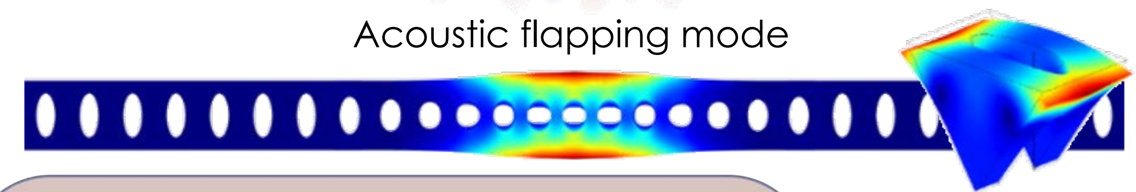
OMC (Phonons)



Optical cavity mode



Acoustic flapping mode



At 4 K: C ~ 1

$g \sim 1$ MHz (from simul

$$n_{th} = \frac{k_B T}{\hbar\omega_m} \sim 20$$

$\kappa_m = \omega_{m,} / Q_m \sim 20$ kH

$\gamma \sim 4$ MHz

$\Rightarrow C \sim 1$

At 100 mK: C >> 1

$g \sim 1$ MHz (from simulations)

$$n_{th} = \frac{k_B T}{\hbar\omega_m} << 1$$

$\kappa_m = \omega_{m,} / Q_m << 20$ kHz (expected)

$\gamma < 100$ Hz (Sukachev et al, arXiv 2017)

$\Rightarrow C >> 1$

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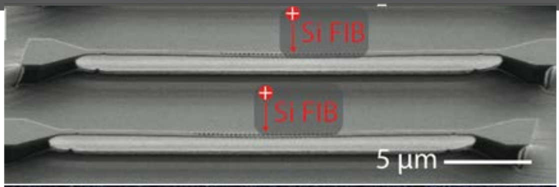
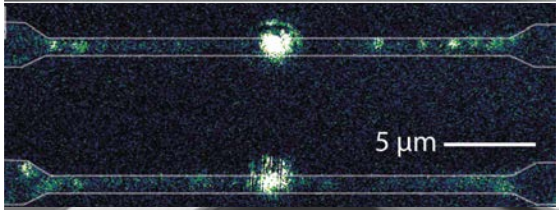
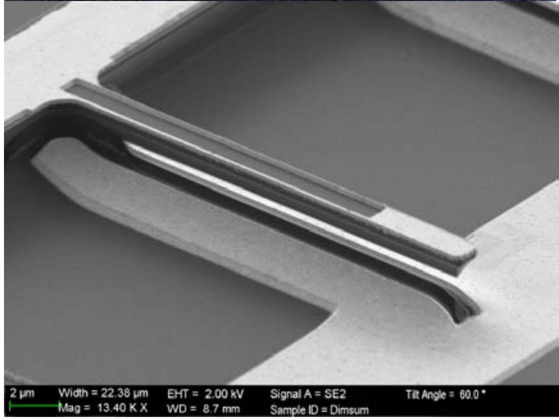
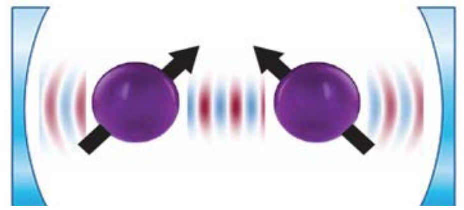
Diamond - Summary

- Developed angled-etching technique for diamond and used it to realize high Q cavities in bulk crystals
  M.J. Burek, et al, *Nature Comm.*, **5**, 5718 (2014)
- Efficient spin-photon interfaces demonstrated
  M. Burek, et al, *Phys. Rev. Appl.*, **8,** 024026 (2017)
- Developed approaches to increase spin-coherence using strain
  S. Meesala, et al, PRB 97, 205444 (2018)
  Y-I Sohn, et al, *Nature Comm*. 9, 2012, (2017)
- Strain-tuning used to overcome inhomogeneous broadening & spectral diffusion
  B. Machielse, et al, arXiv:1901.09103 (2018)
- Cavity and waveguide mediated mediated spin-spin interactions
  R. Evans, et al, *Science* (2018)
  A. Sipahigil, et al, *Science*, **354**, 847 (2016)
  B. Machielse, et al, arXiv:1901.09103 (2018)
- Exploring coherent spin-phonon interfaces
- Still looking for the ideal color center with excellent spin and optical coherence at the same time…









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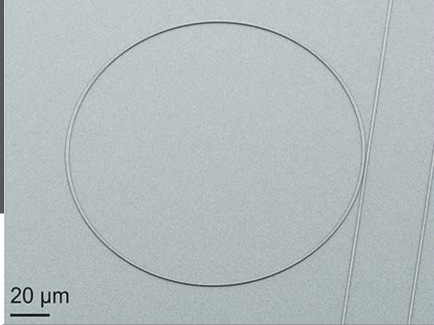
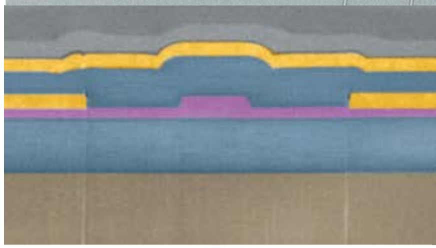
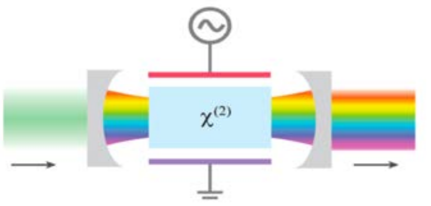
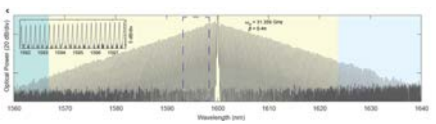
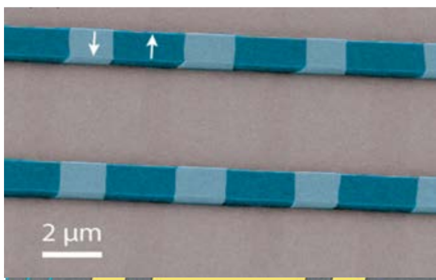
$LiNbO_3$ - Summary

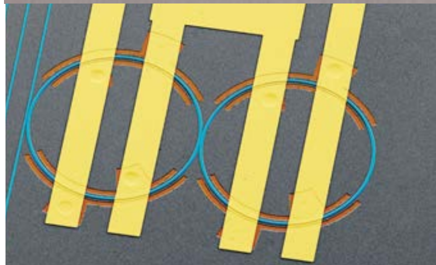












✓ **Low-loss integrated lithium-niobate photonics platform developed**
- M. Zhang, et al. Optica, **4**, 1536 (2017) (telecom)
- B. Desiatov et al, *Optica*, **6** 380 (2019) (visible)

✓ **Efficient, fast and integrated modulators with** $V_\pi \sim 1$ V, bandwidth > 100 GHz, data rates > 200 Gbps, on-chip insertion loss < 0.5dB; fiber-fiber insertion loss < 3.4 dB
- C. Wang, et al, *Nature*, **562**, 101 (2018)
- C. Wang, et. al. *Opt. Exp.*, **26**, 1547 (2018)
- L. He, et al, *Optics Letters*, **44**, 2314 (2019)

✓ **Electro-optic frequency combs, both with and without cavity demonstrated**
- M. Zhang, et al, *Nature*, **568**, 373 (2019)
- T. Ren, et al, *Phot. Tech. Lett., DOI:* (2019)

✓ **Kerr frequency comb** (2/3 of an octave) **and supercontinuum source** (2.6 octaves)
- C. Wang, et al. *Nature Communications*, **10**, 978 (2019)
- M. J. Yu, B. Desitov, et al, *Optics Letters*, **44**, 1222 (2019)

✓ **Thin Film Periodically Poled LN (TFPPLN) offering > 20-fold higher efficiency**
- C. Wang, et al, *Optica*, **5**, 1438 (2018)

✓ **Programmable photonic molecule for** coherent microwave ⇔ optical transduction
- M. Zhang, et al. *Nature Photonics*, **13**, 36 (2019)

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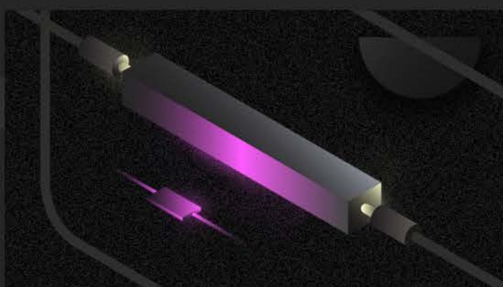
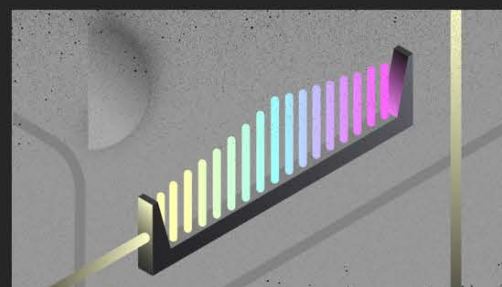
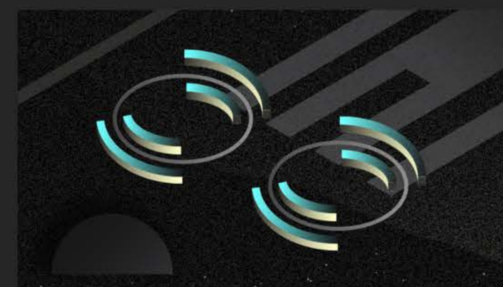
We design and produce integrated optical circuits with the potential to reshape the world's relationship with optical data.







A COLOSSAL SMALL-SCALE BREAKTHROUGH.

We've invented unique processes and designs for fabricating integrated, chip-scale Lithium Niobate (LN) modulators with extremely low signal loss

PROVEN TRANSFORMATIVE.

Our technology was developed from research at Harvard University where it inspired multiple publications in the journal Nature.

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Our low-loss integrated lithium niobate circuits are enabling novel functionalities from communication to spectroscopy.