Integrated Photonics based on Silicon Nitride

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Collaborators:

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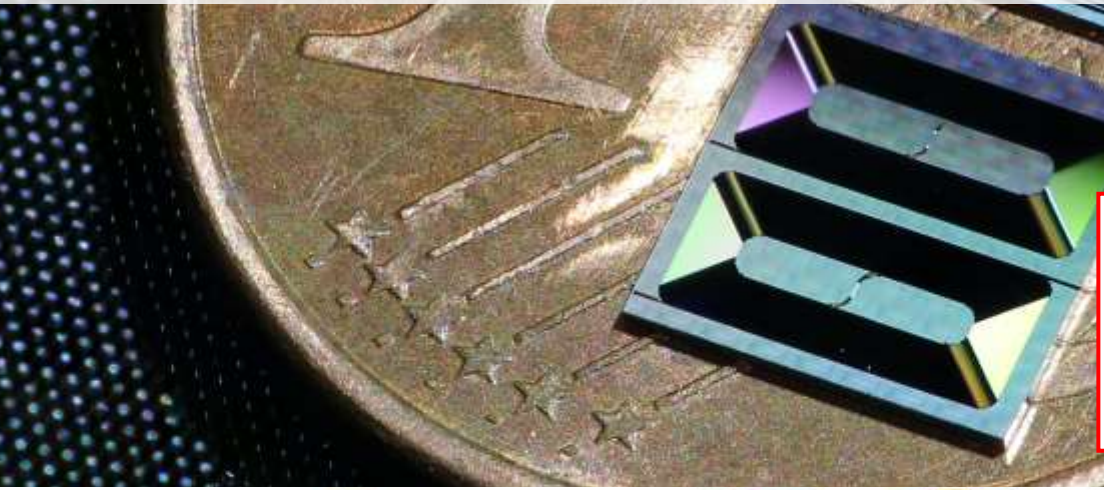
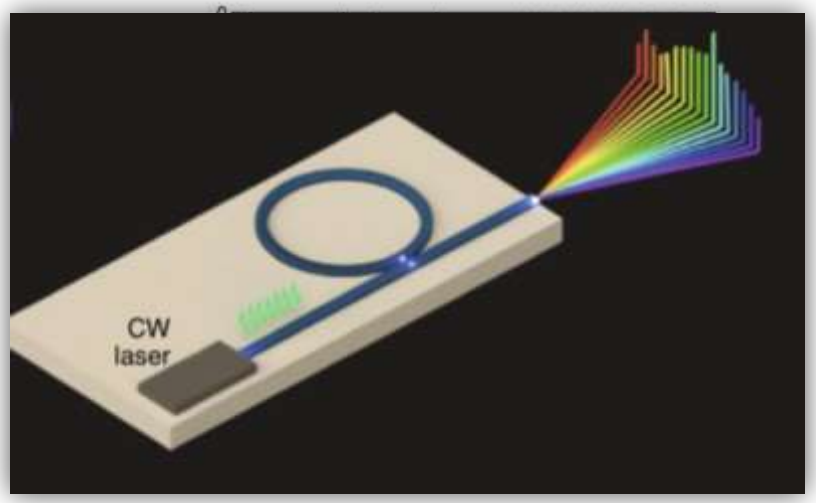


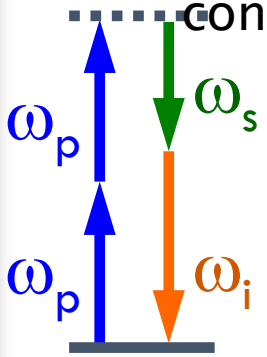
Disclosure: Co-founder & equity holder of LIGENTEC

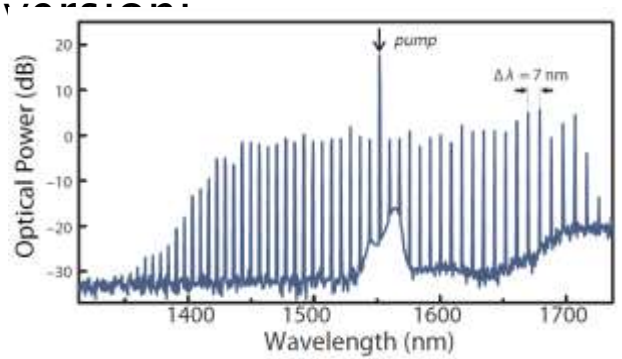
AFOSR esa MARIE CURIE ACTIONS BRIDGING THE GAP DARPA POWERED BY IDEAS FNSNF FONDS NATIONAL SUISSE SCHWEIZERISCHER NATIONALFONDS FONDO NAZIONALE SVIZZERO SWISS NATIONAL SCIENCE FOUNDATION cQOM SEVENTH FRAMEWORK PROGRAMME OMT

Kerr combs: Parametric interactions



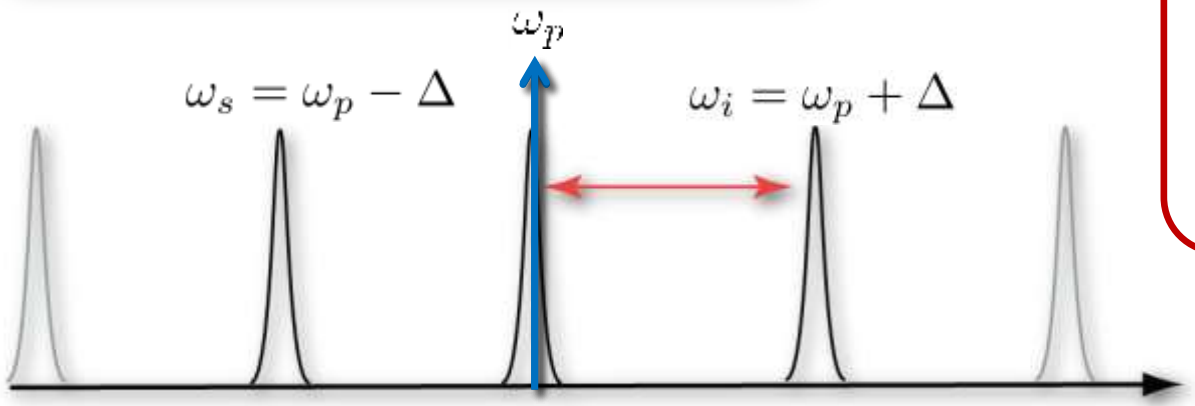
Parametric frequency conversion:



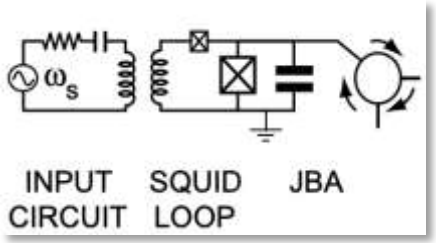


$$\hat{H}_{\text{kerr}} = \hbar g : \hat{a}_i^{\dagger}\hat{a}_s^{\dagger}\hat{a}_p\hat{a}_p :$$

$$g = \frac{\hbar\omega_0^{\,2} c n_2}{n_0^{\,2} V_{\text{eff}}}$$



$$P_{\text{th}} = \frac{\kappa^2 \hbar\omega_0}{8\eta g_0} \propto \frac{V_{\text{eff,nl}}}{Q^2}$$

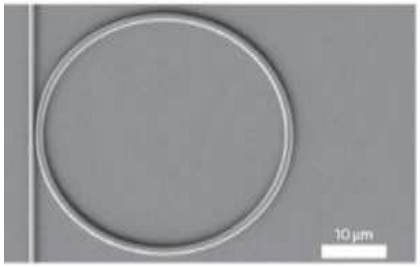


Josephson Bifurcation Amplifier for Quantum Measurement
- Siddiqi, et al. Devoret Phys. Rev. Lett. 2004
- C. Eichler, et al. A. Wallraff Phys. Rev. Lett. 113, 2014
- B. Yurke, et al. Phys. Rev. A 1989

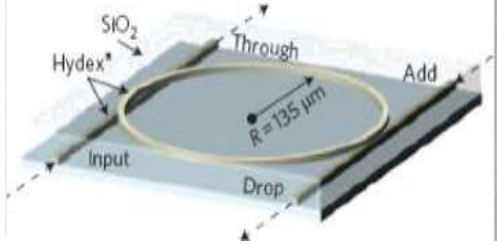
Del Haye,Schliesser,Wilkins, Holzwarth,TJK, *Nature*, 2007
EU & US Patent application
TJK, Gaea, Lipson, Gorodetsky, et al., *Science* 2011

Microresonator platforms for frequency combs

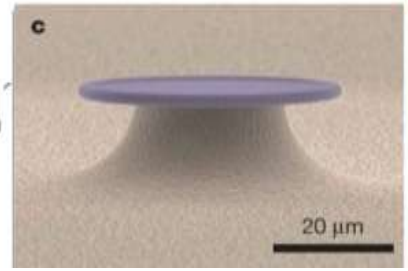
Silicon Nitride (Columbia, Purdue, EPFL, UCLA, NIST, ..)



Hydex
(INRS, Melbourne)

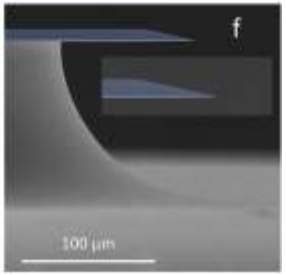


Fused Silica
(NIST, Caltech,)

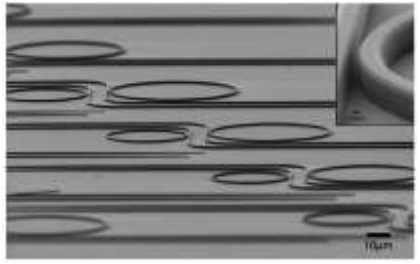


CaF_2 , MgF_2
(JPL, OEWaves, RQC, EPFL)

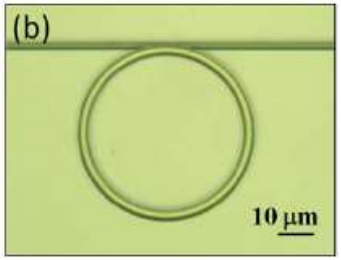
Silica Disks
(Caltech, NIST)



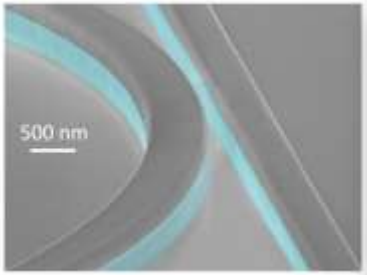
Diamond
(Harvard)



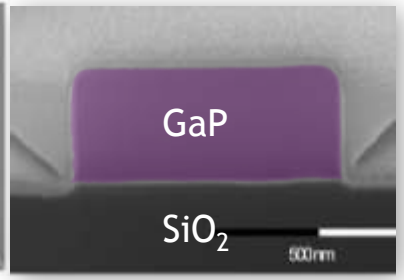
AlN
(Yale)



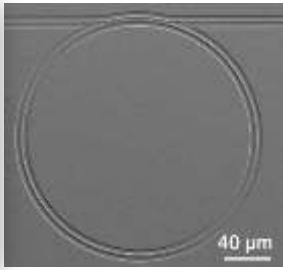
AlGaAs
(DTU)



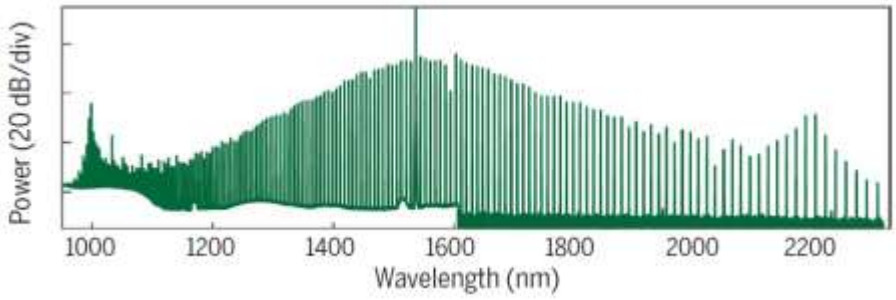
GaP
(IBM Zurich)



$LiNbO_3$
(Rochester, Caltech



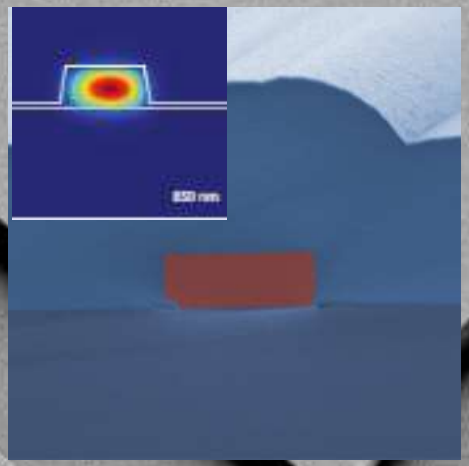
Razzari et al., Nature Phot., 41 (2010)
Levy et al., Nature Phot., 37 (2010)
Savchenkov et al., PRL, 93902 (2008)
Jung et al., Opt.Lett., 2810 (2013)
Hausmann et al., Nature Phot., 369 (201
Li et al., PRL, 233901 (2012)
Pu et al., Optica (2015)
Obrzud, Nat. Photon. (2017)
Wilson et al. Nat. Phot (2018)
Y. He OL (2019)



Ultrahigh rep-rate (> 100 GHz)
Large/Octave bandwidth solitons

Bulk silica/ saphi
(CSEM, MPQ)

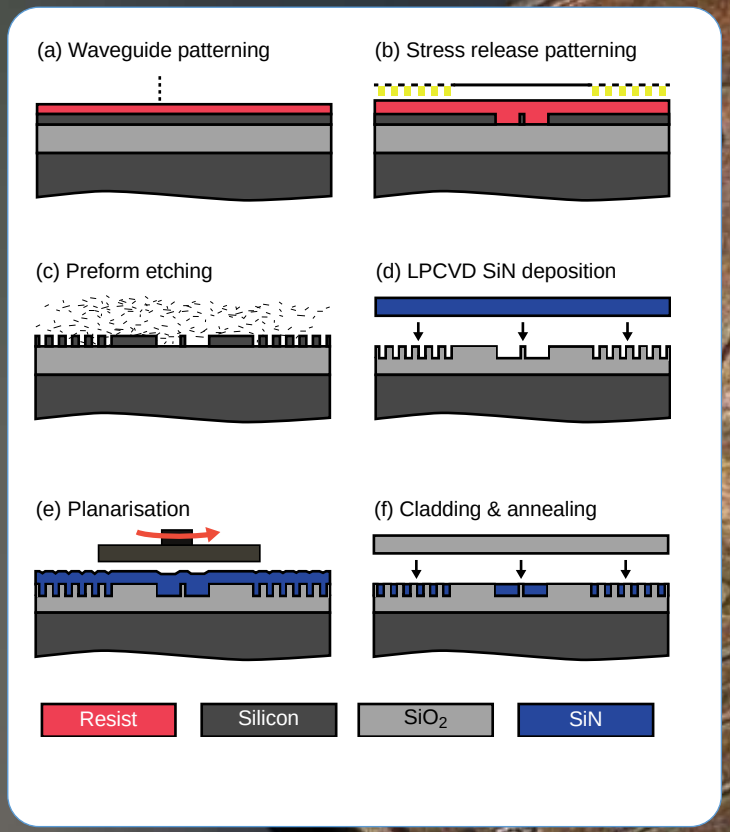
Photonic chip based frequency comb



- No two photon absorption
- Low Raman and SBS gain
- High power handling (> 10 Watt CW)
- High effective nonlinearity
- Space compatible material
- Transparency window visible-mid IR

V,. Brasch et al Science 2016
TJK et al. Science 2018

Ultra low loss photonic nonlinear integrated circuits

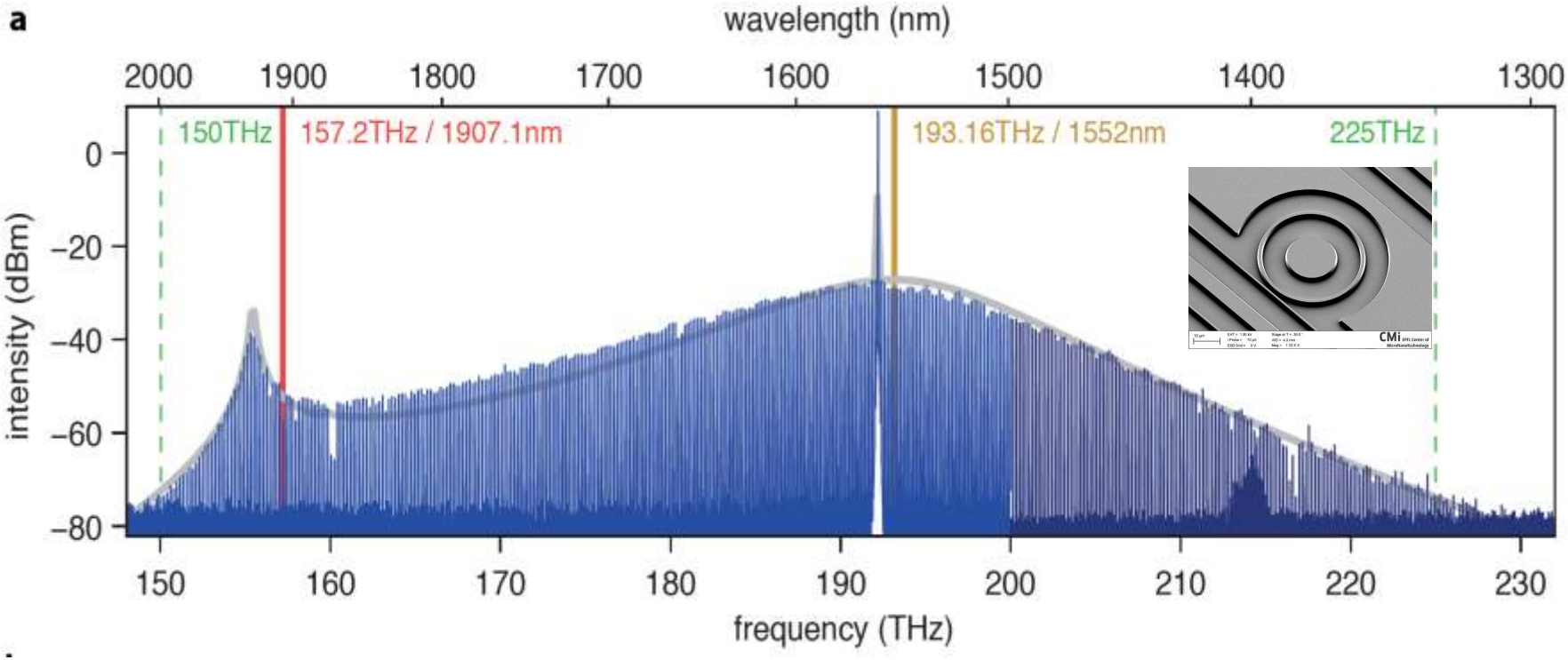


- 1 m long waveguide with 2.4 dB/m loss , occupying a footprint of 6.6 mm^2

J. Liu et al. Nat. Comm. (2021)

Soliton Cherenkov Radiation on a photonic chip

Experimental spectrum and simulation



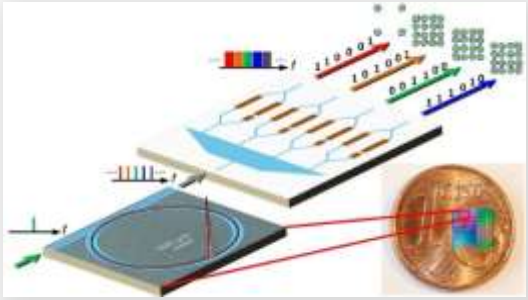
$$\frac{\partial A(\phi,t)}{\partial t} = -\left(\frac{\kappa}{2} + i\cdot(\omega_0 - \omega_p)\right)A + i\cdot D\cdot A + i\cdot\hat{s}\cdot g\cdot\left\{(1-f_R)|A|^2 + f_R h_R(2\pi t/t_R)\otimes|A|^2\right\}A + \sqrt{\kappa_{ex}}\cdot s_{in}$$

Thermal effects — Soliton Cherenkov dispersive wave — Raman effect

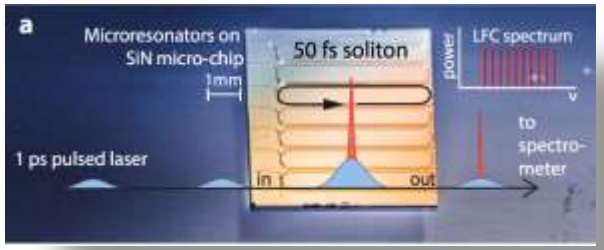
V. Brasch, et al. ***Science*** 2016

Recent highlighted applications

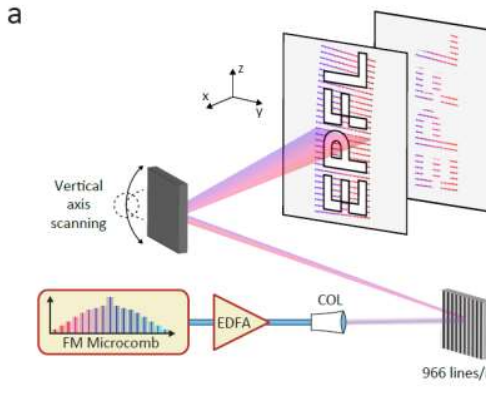
Massively Parallel Telecom
(**P. Marin-Palomo, TJK&Koos, Nature (2017)**)

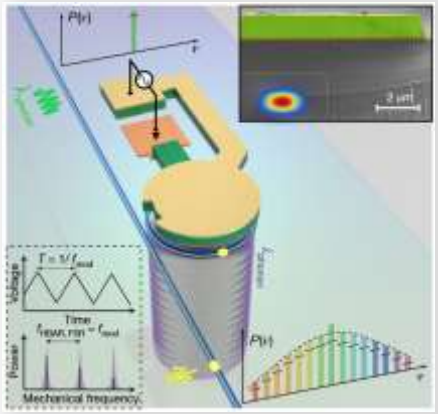


Astrophysical spectrometer calibration
(**Obruz, et al. TJK& Herr (2019)**)

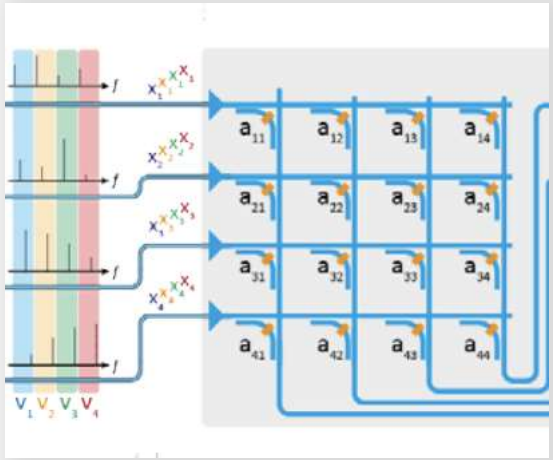


Massively Parallel Coherent LiDAR
(**J. Riemensberger, TJK Nature (2020)**)





Piezo-electric soliton microcomb control
(**J. Liu, TJK Nature (2020)**)

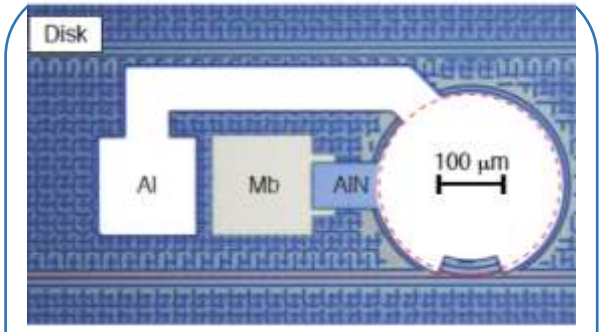


Neuromorphic
(**J. Liu, TJK, Pernice,.. Nature (2021)**)

Integrated turnkey soliton microcomb
(**B. Shen, TJK, Vahala, Bowers Nature (2020)**)

Si_3N_4 as Hybrid Nonlinear Integrated Platform

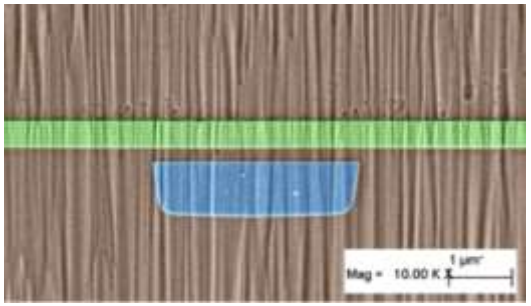
Modulation



Bhave & TJK, Nature 2020

EO-Modulation

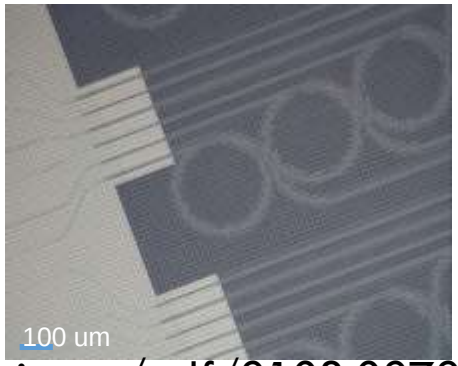
Integration with Lithium Niobate



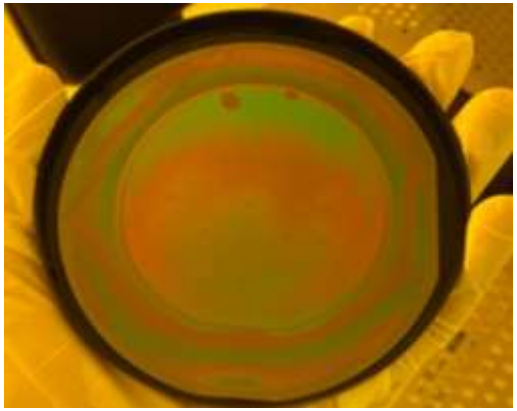
IBM&EPFL, unpublished

Amplification

III-V Heterogenous integration



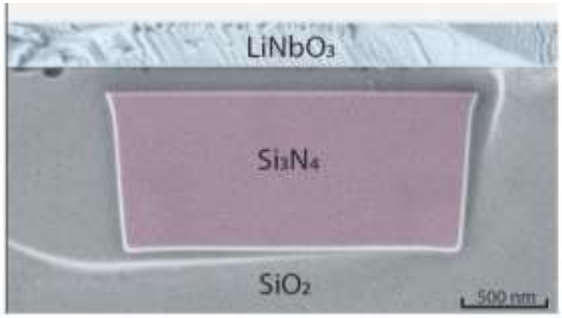
arxiv.org/pdf/2103.02725

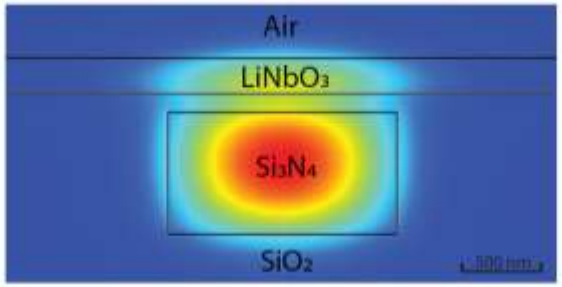


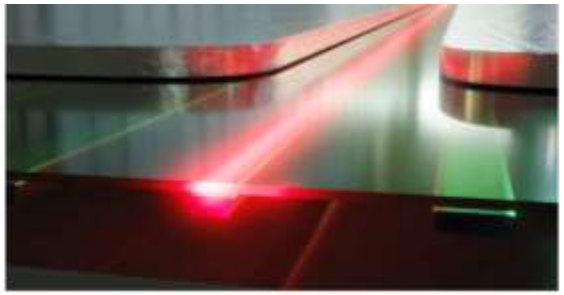
Amplification

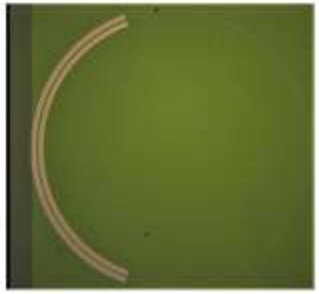
Integration with Erbium doping

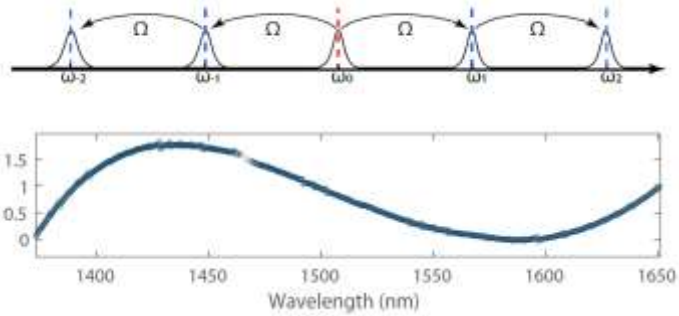
Heterogenous integration of Lithium Niobate on SiN (with IBM Zurich, Paul Seidler)

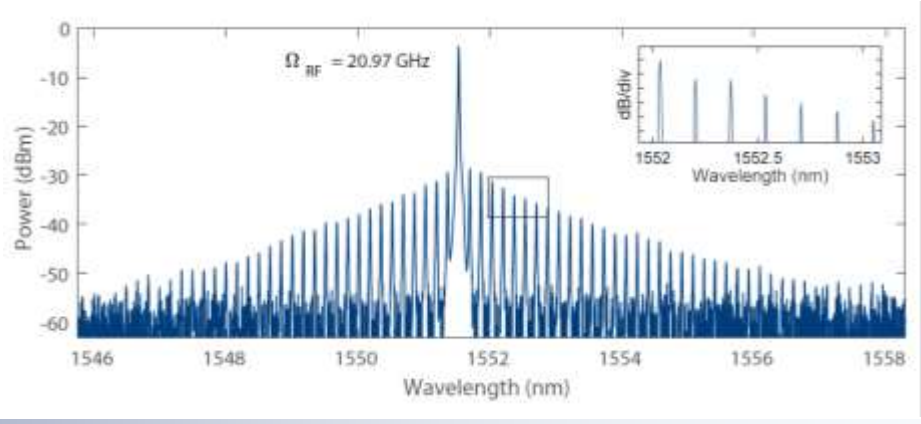




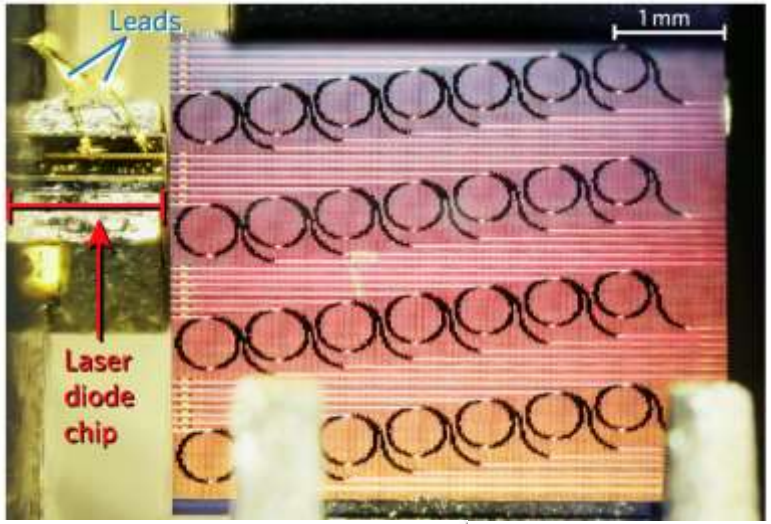


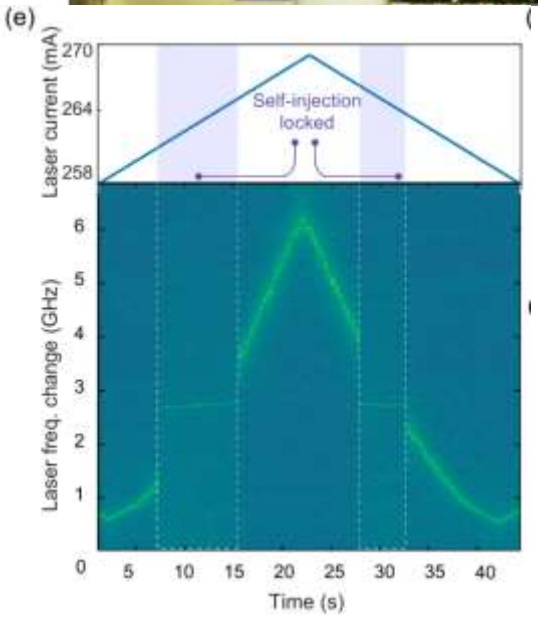






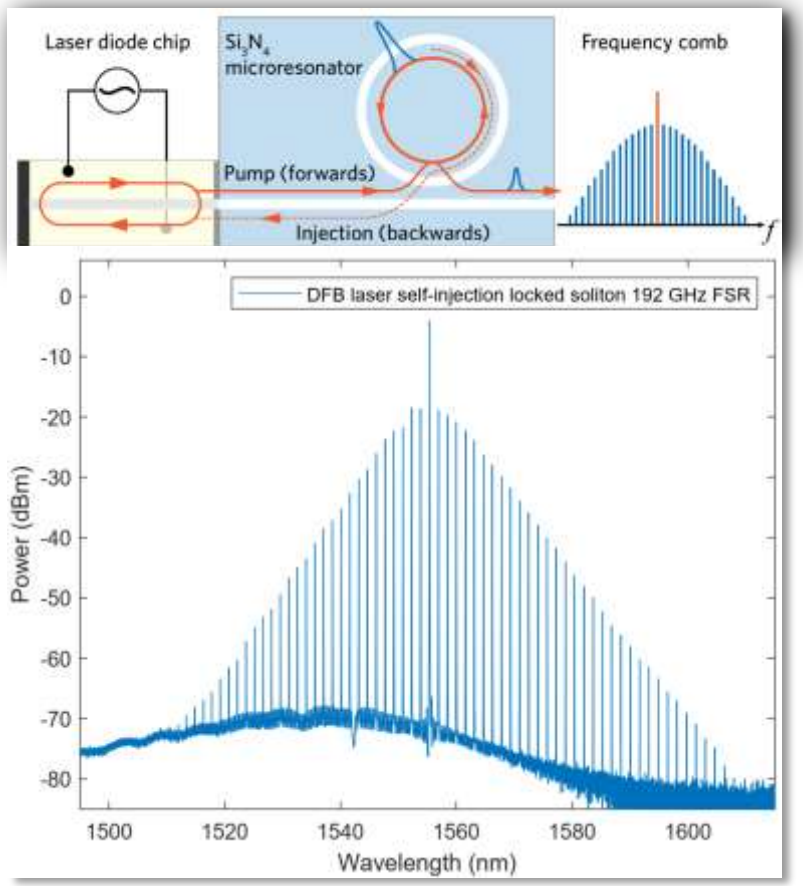
Hybrid integration: Self injection locked DKS





$$\Delta\omega_{\text{lock}} \approx r\sqrt{1+\alpha_g^2}\,\frac{\omega}{Q_{\text{LD}}}$$

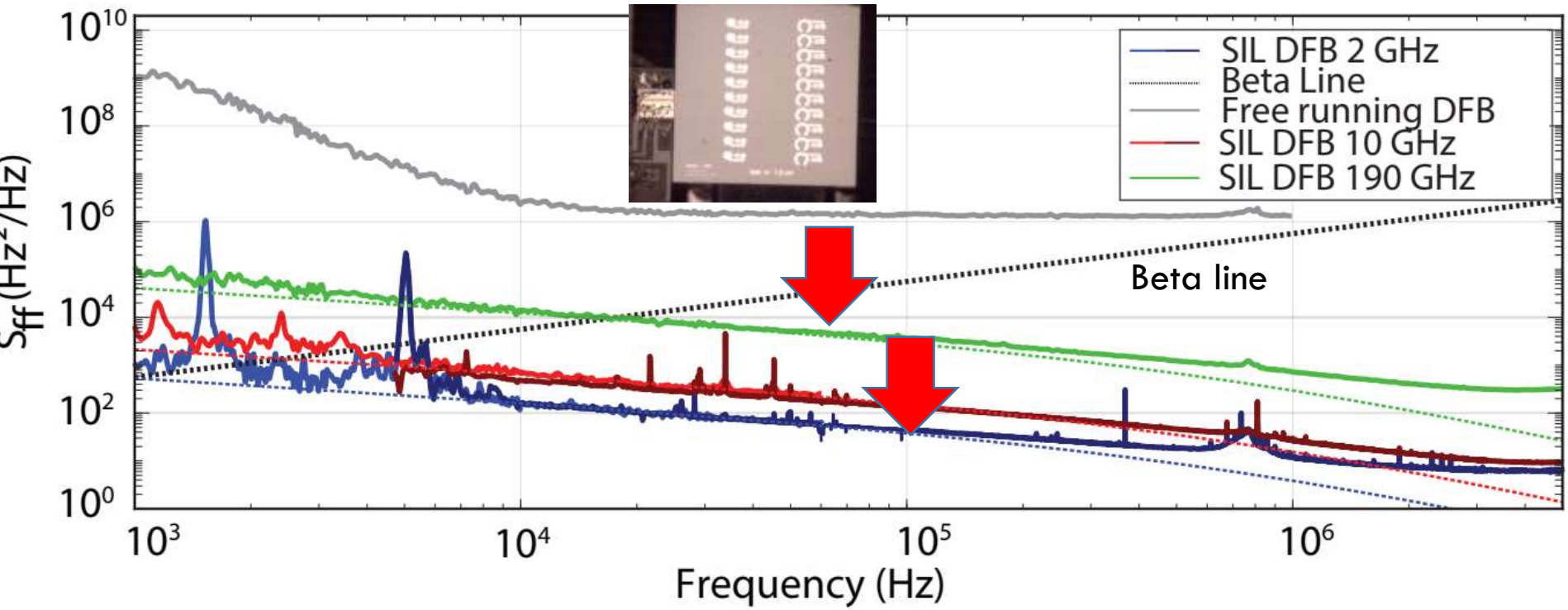
$$\delta\omega \approx \delta\omega_{\text{free}}\,\frac{Q_{\text{LD}}^2}{Q^2}\,\frac{1}{16r^2(1+\alpha_g^2)}$$



A. Raja et al. TJK , *Nat. Comm.* 2019

Related work: Lipson group, *Nature* 2018
Gorodetsky group *Nat. Photon* 2018

Performance of Si_3N_4-AlN integrated Lasers

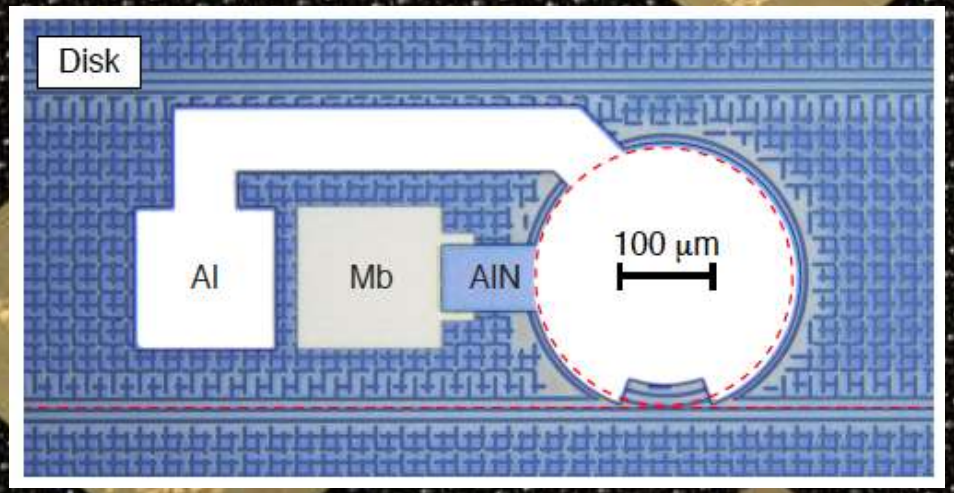


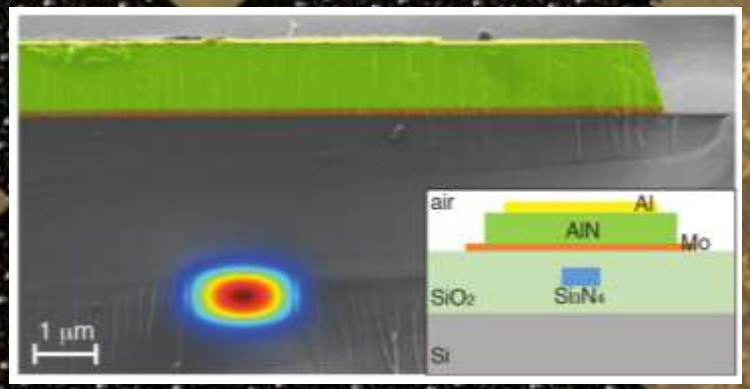
- Noise is limited by **thermorefractive noise**
- Increasing the cavity size decreases the phase noise due to thermodynamical noise
- 2 kHz rms linewidth (from betaline)

$$\langle \delta T^2 \rangle = \frac{k_B T^2}{\rho C V}$$

(arXiv, 2021)

Piezomechanical control on a chip

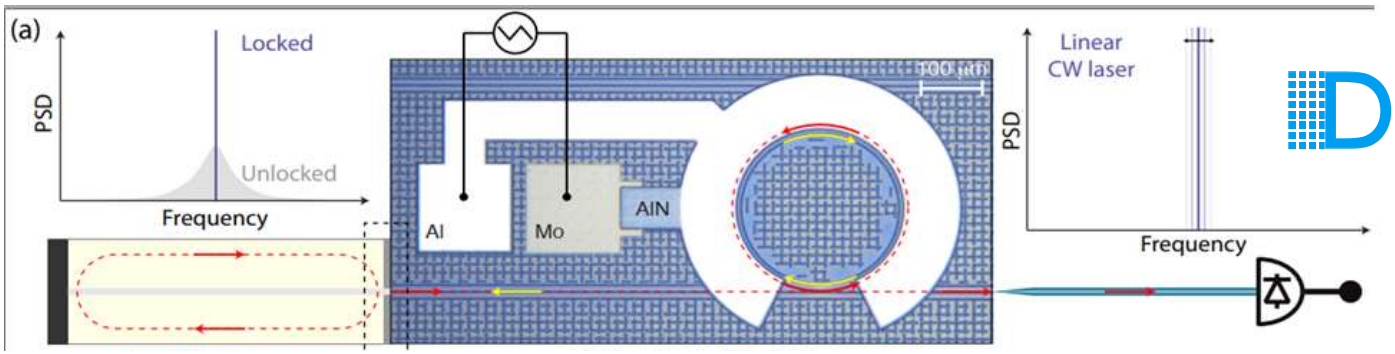


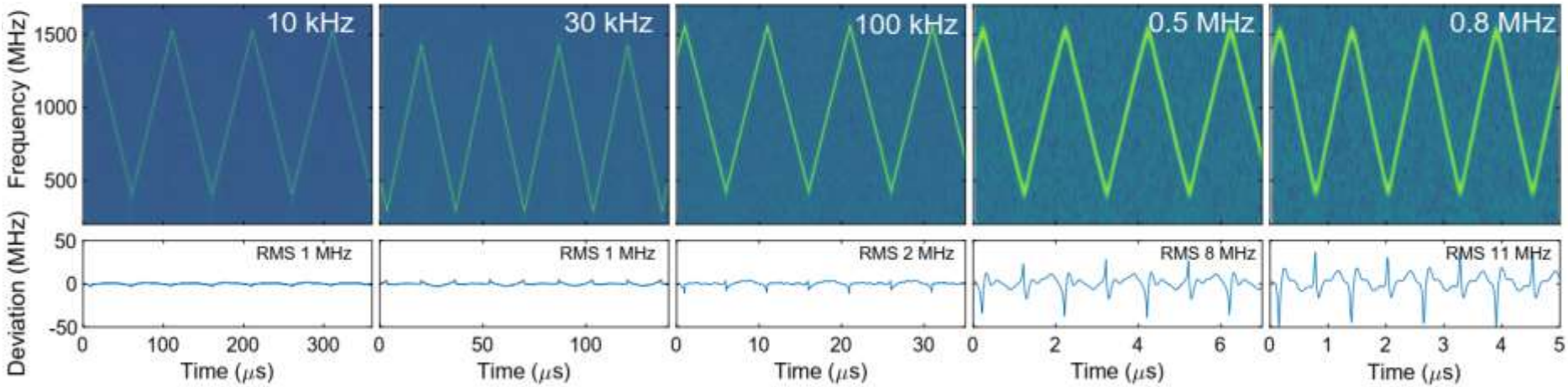


Tian et al., TJK & Bhave ***Nat. Commum.*** 11, 3073 (2020)

J. Liu et al Bhave & TJK, ***Nature*** (2020)

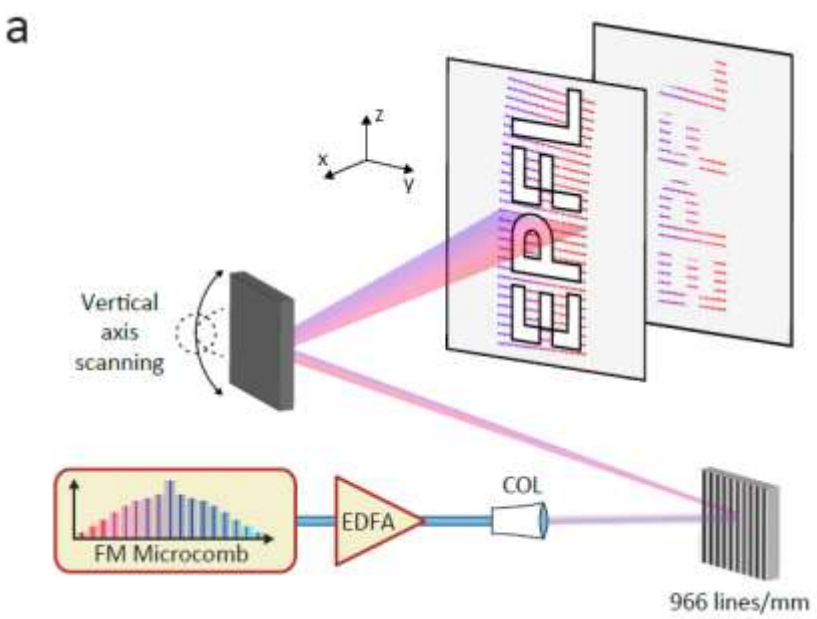
Ultrafast and linear chirping on chip

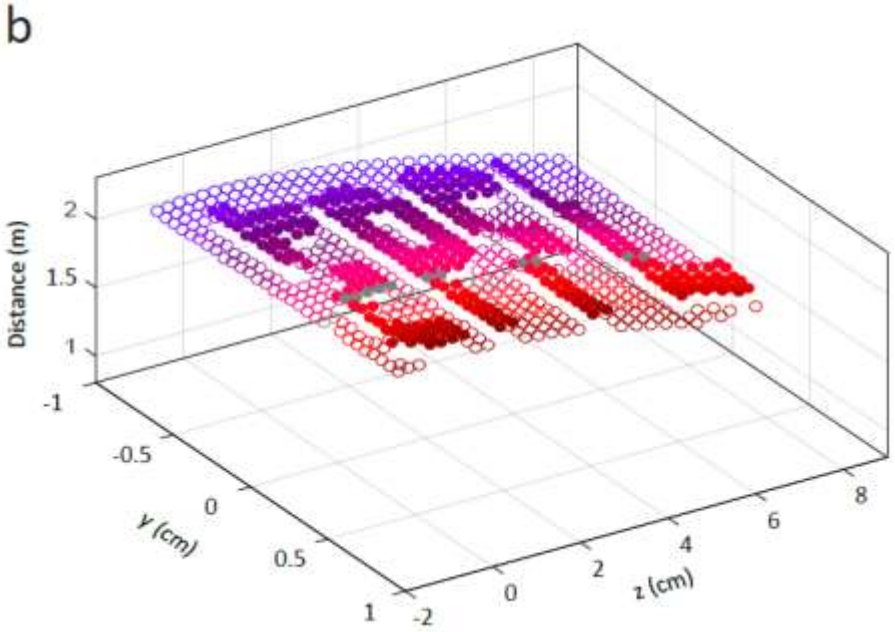


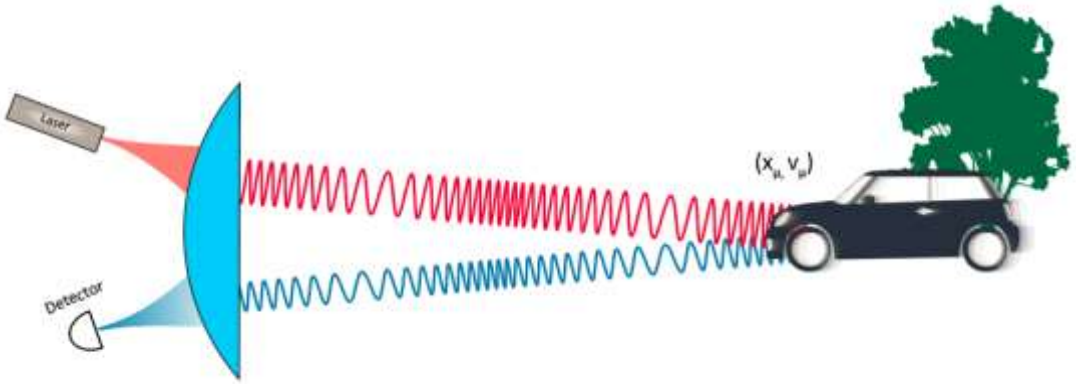


- **MHz Bandwidth tuning with 1 GHz chirp amplitude**
- **Without any active linearization**
- **Extendable to 10 GHz amplitude and > 1 GHz bandwidth**

Massively Parallel LiDAR

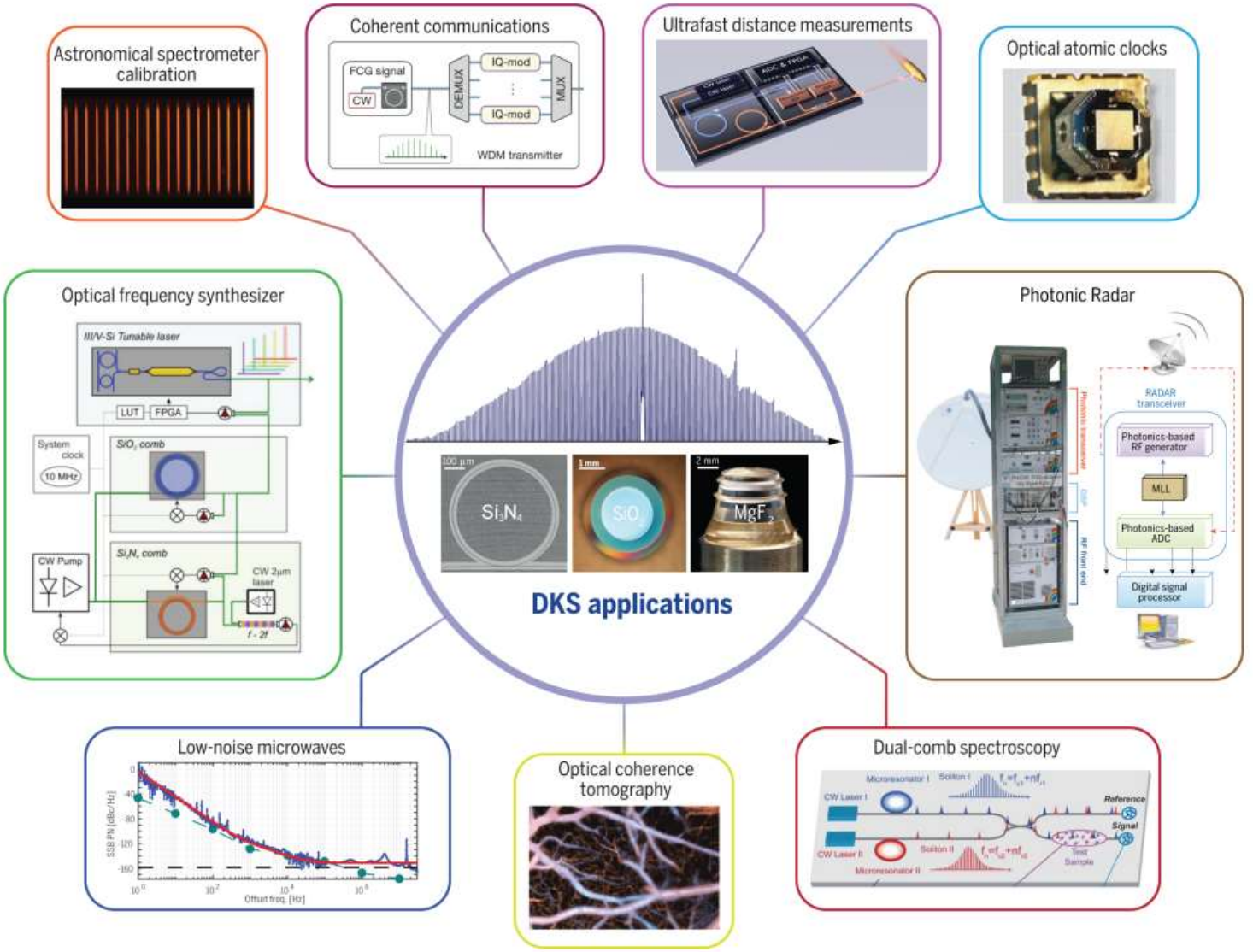






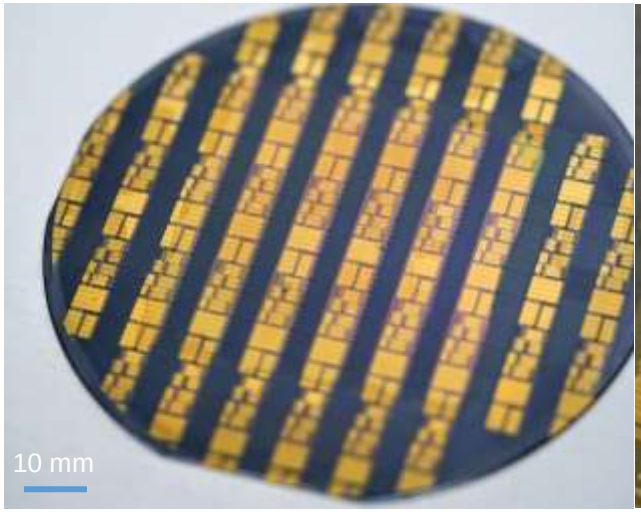
Riemensberger et al. TJK Nature (2020)

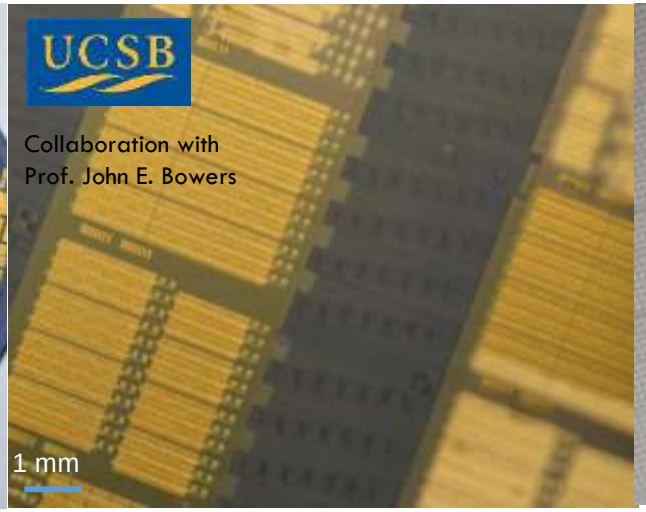
Soliton-based Frequency Comb Applications

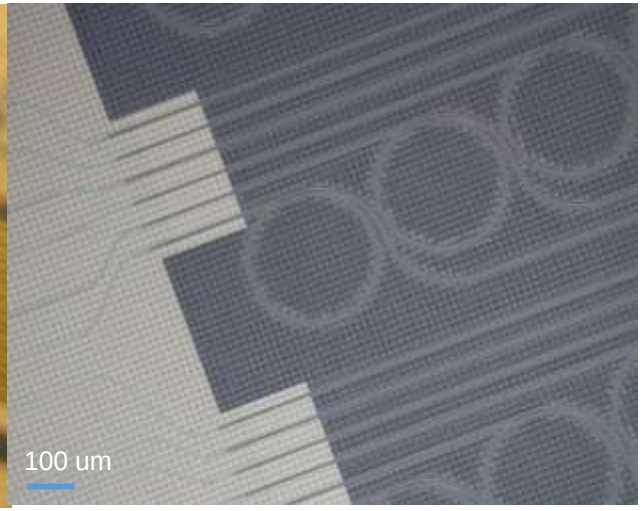


TJK Gaeta, Lipson, Gorodetsky, **Science** 361.6402 (2018)

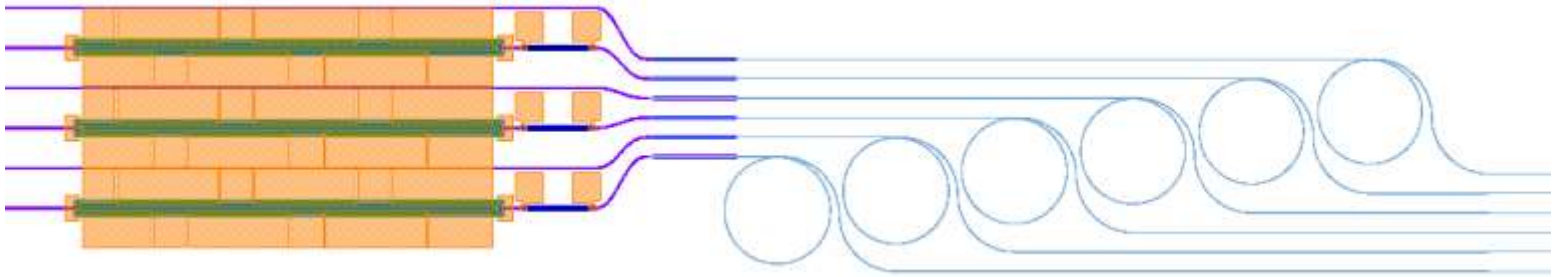
Wafer compatible frequency combs







HR coated facet | InP/Si DFB laser | Phase tuner | Si-SiN taper | SiN high-Q resonator | Comb output

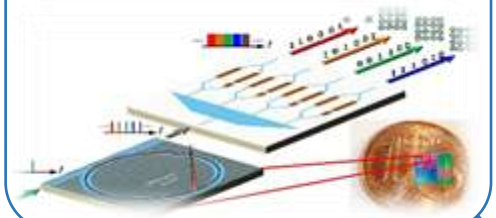


- First wafer scale frequency comb compatible with Intel Foundry processing

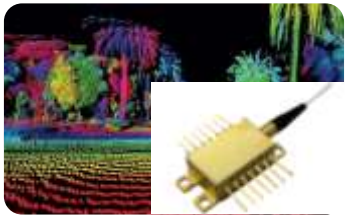
TJK & Bowers, ***Science*** (in press)

Ultra low loss Si_3N_4 integrated photonics enabled products

Microcombs sources

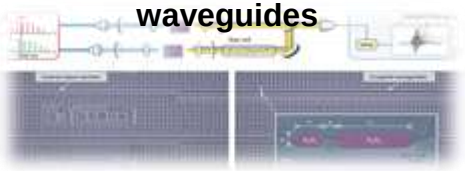


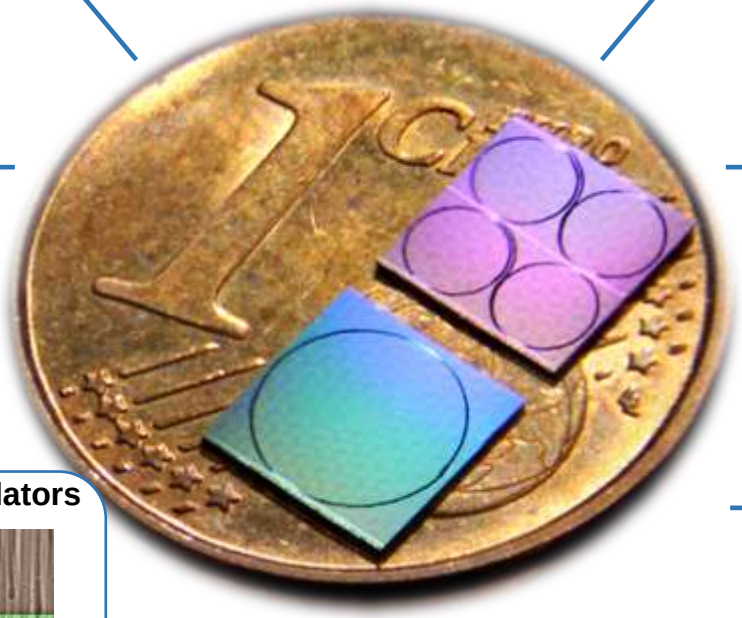
FMCW laser 1550 nm



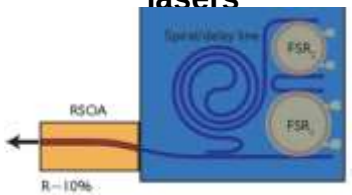
Frequency agile lasers at custom visible wavelength (950,

Mid IR supercontinuum waveguides



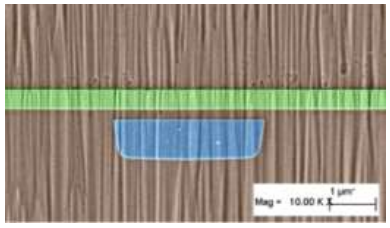


Discretely tunable Vernier lasers



Submounted lasers, combs

Integrated LiNbO3 modulators



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Thank you for your attention