Hybrid Integrated Photonics for Coherent LiDAR

Anton Lukashchuk, EPIC meeting, ESA, 13 Sept

EPFL

Technology development @ EPFL

Milestones & achievements

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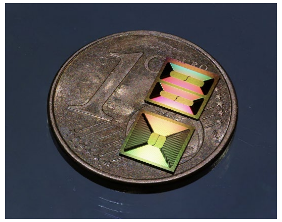
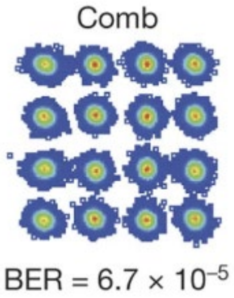
enlightra

DEEPLight

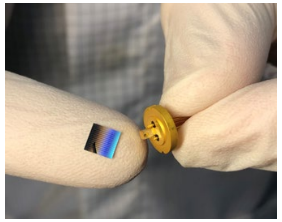
2016
Development of **ultra-low loss SiN platform**[1]



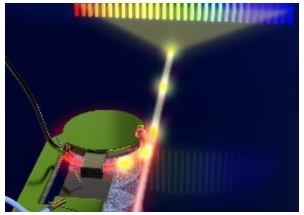
2017
Demonstration of **telecom applications**[2] and **hybrid integrated SIL laser**[3]



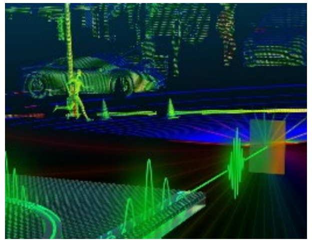
2018
First **fully integrated optical frequency comb**[3]



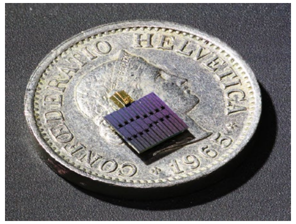
2018 – 2019
Development of **piezoelectric actuators** monolithically integrated with SiN PICS[4, 5]



2020
Demonstration of **frequency-agile optical frequency comb**[6-7] **and comb-based FMCW LiDAR**[6-8]



2021
Development of **frequency-agile laser**[9]



2022
Industrialization of frequency-agile lasers: **RSOAs & PZT actuators**

Blue laser[10]

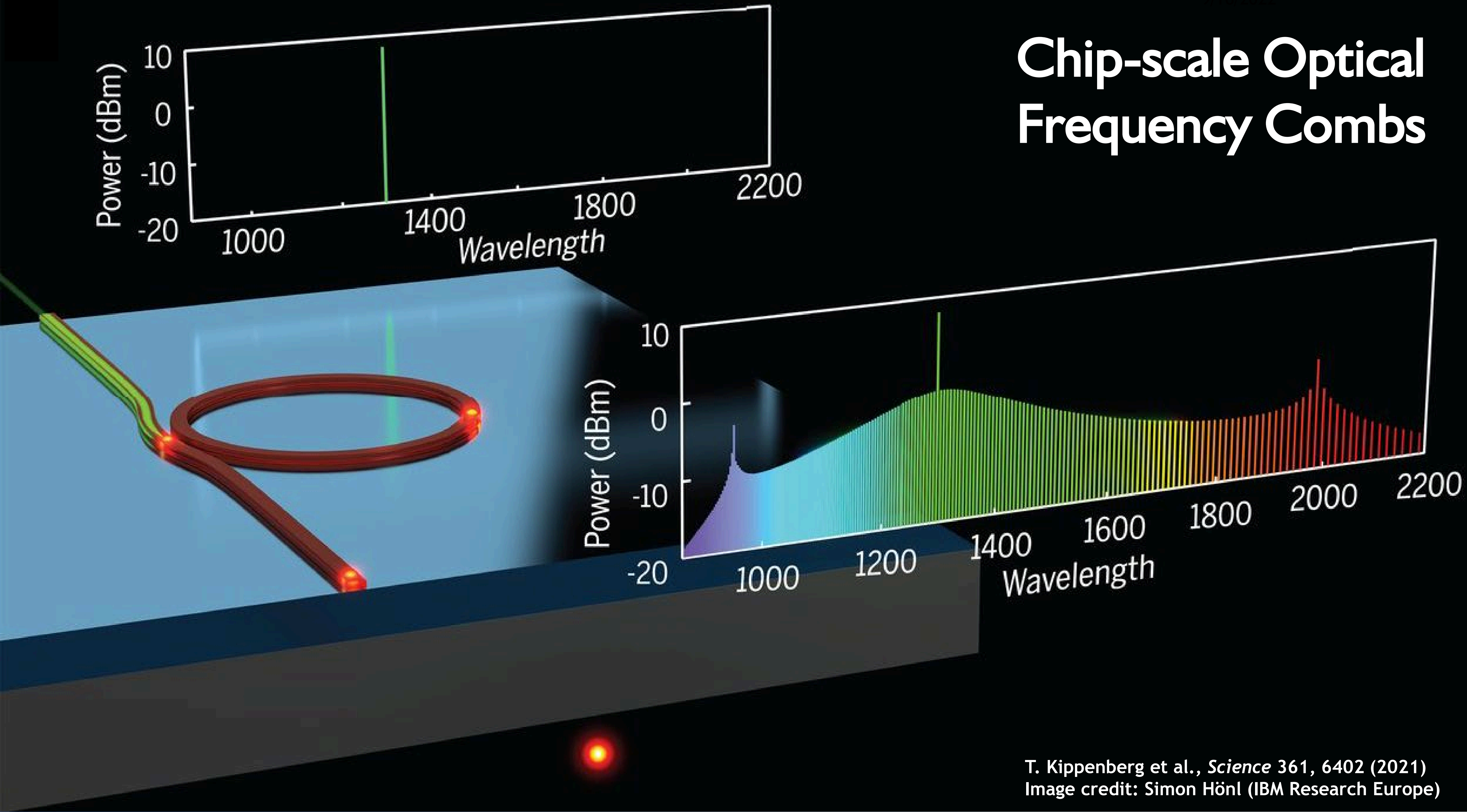
Demonstration of **thin-film SiN platform**

Development of **LNOI platform**

Electro-optical hybrid integration

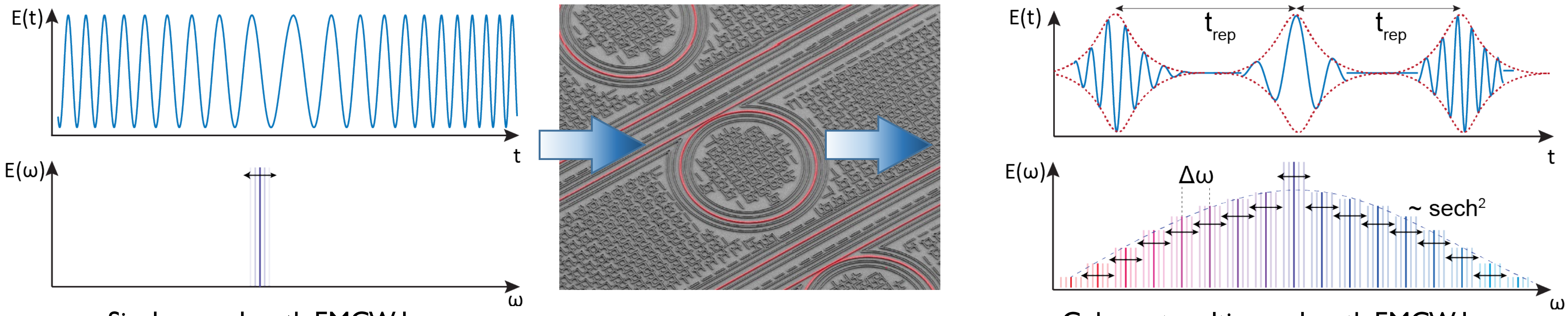
[1] M. Pfieffer et al. Optica 3(1) (2016)
[2] P. Marin-Palomo et al. Nature 546 (2017)
[3] A. Raja et al. Nature comm. 10(1) (2019)
[4] H. Tian et al. Nature comm. 11(1) (2020)
[5] J. Liu et al. Nature 583(7816) (2020)
[6] A. Voloshin et al. Nature comm. 12(1) (2021)
[7] J. Liu et al. Nature comm. 12(1) (2021)
[8] J. Riemensberger et al. Nature 581(7807) (2020)
[9] G. Lihachev et al. Nature comm. 13(1) (2022)
[10] A. Siddharth APL Photonics 7(046108) (2022)

Chip-scale Optical Frequency Combs



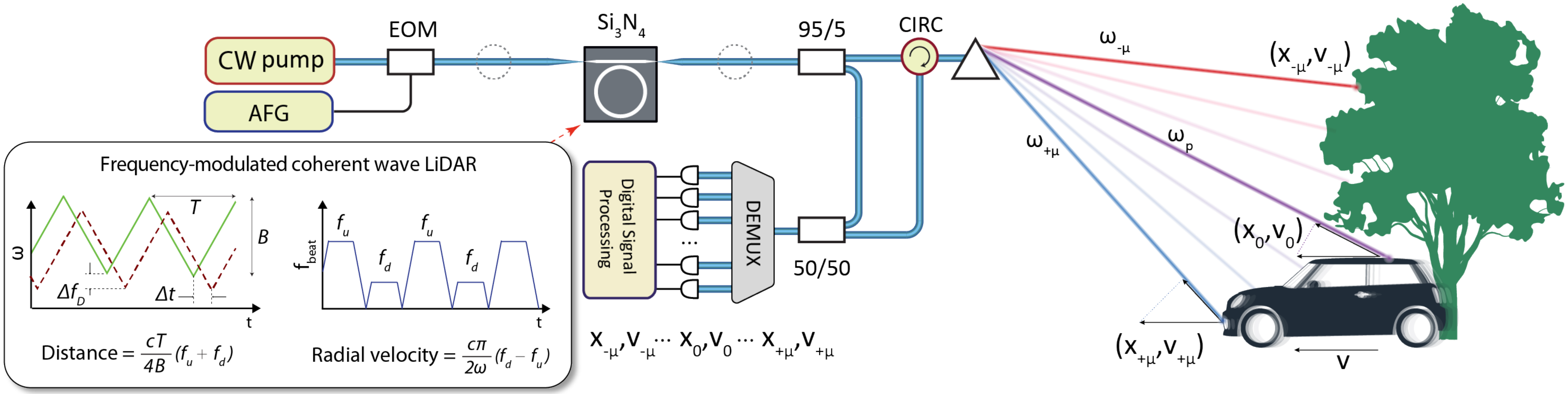
T. Kippenberg et al., *Science* 361, 6402 (2021)
Image credit: Simon Hönl (IBM Research Europe)

Massively parallel coherent laser ranging using soliton microcombs

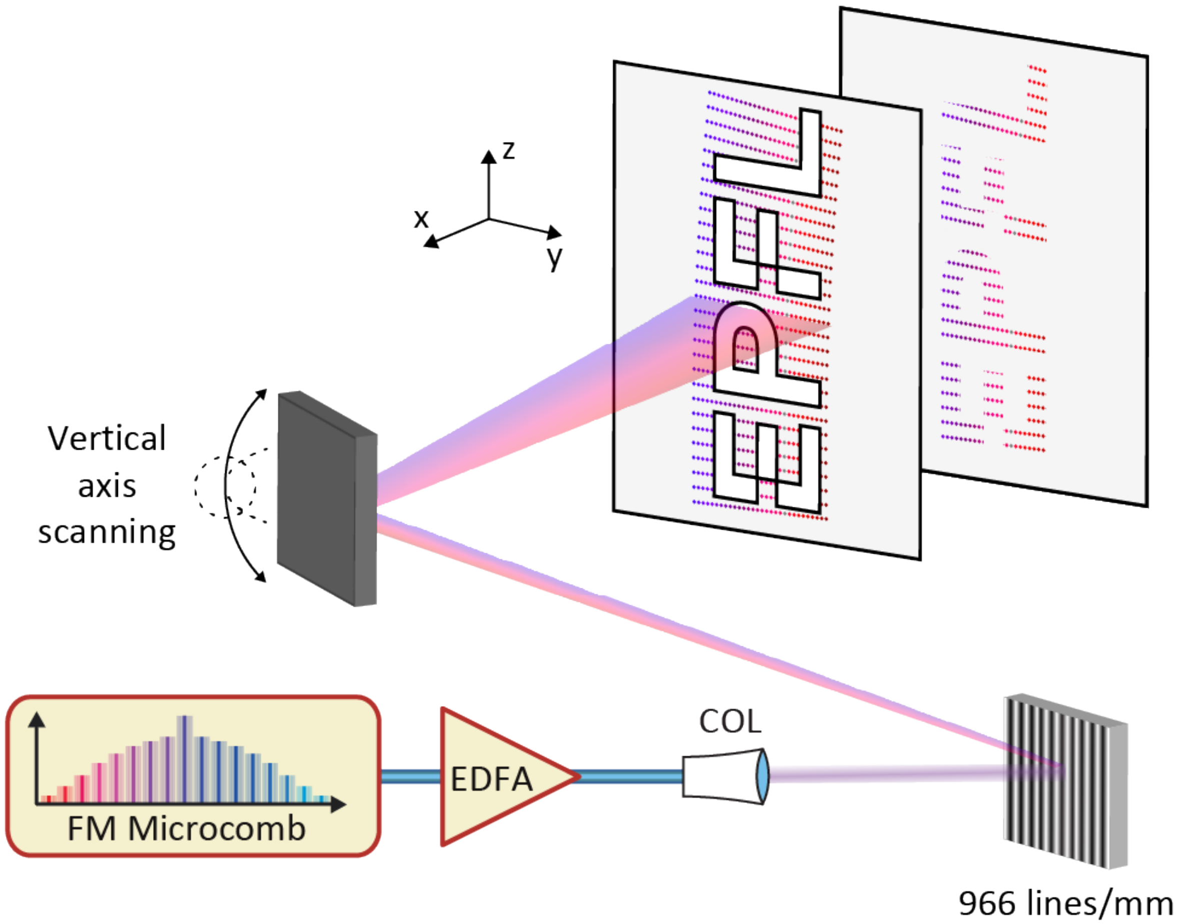


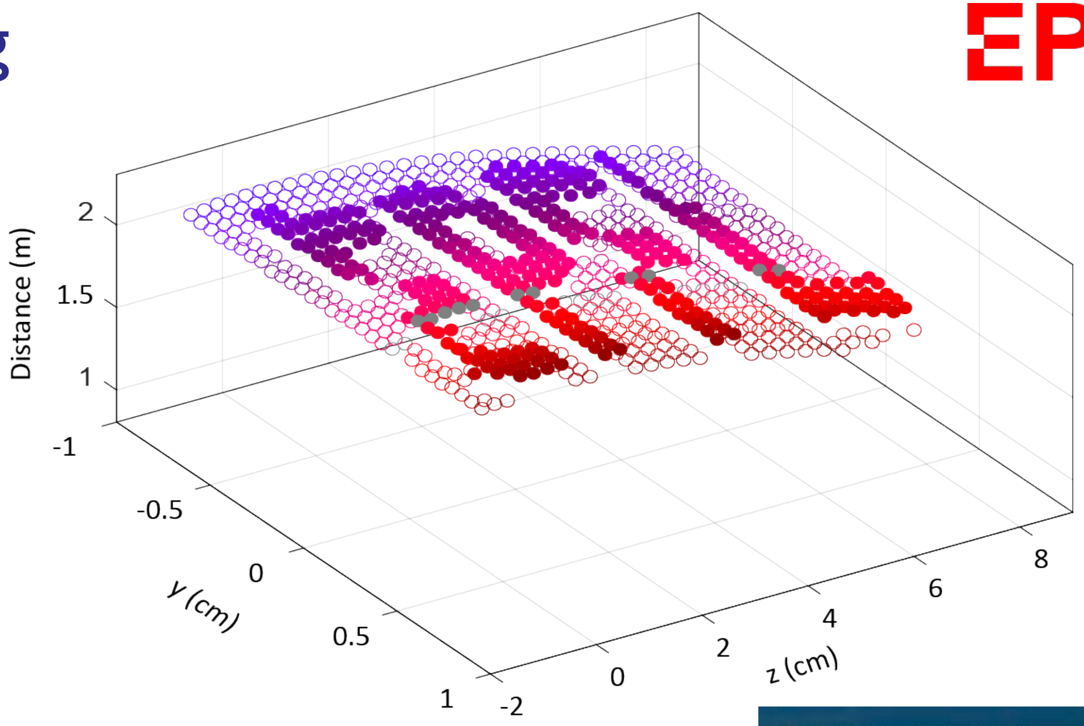
Single-wavelength FMCW laser

Coherent multi-wavelength FMCW laser



Massively parallel coherent laser ranging

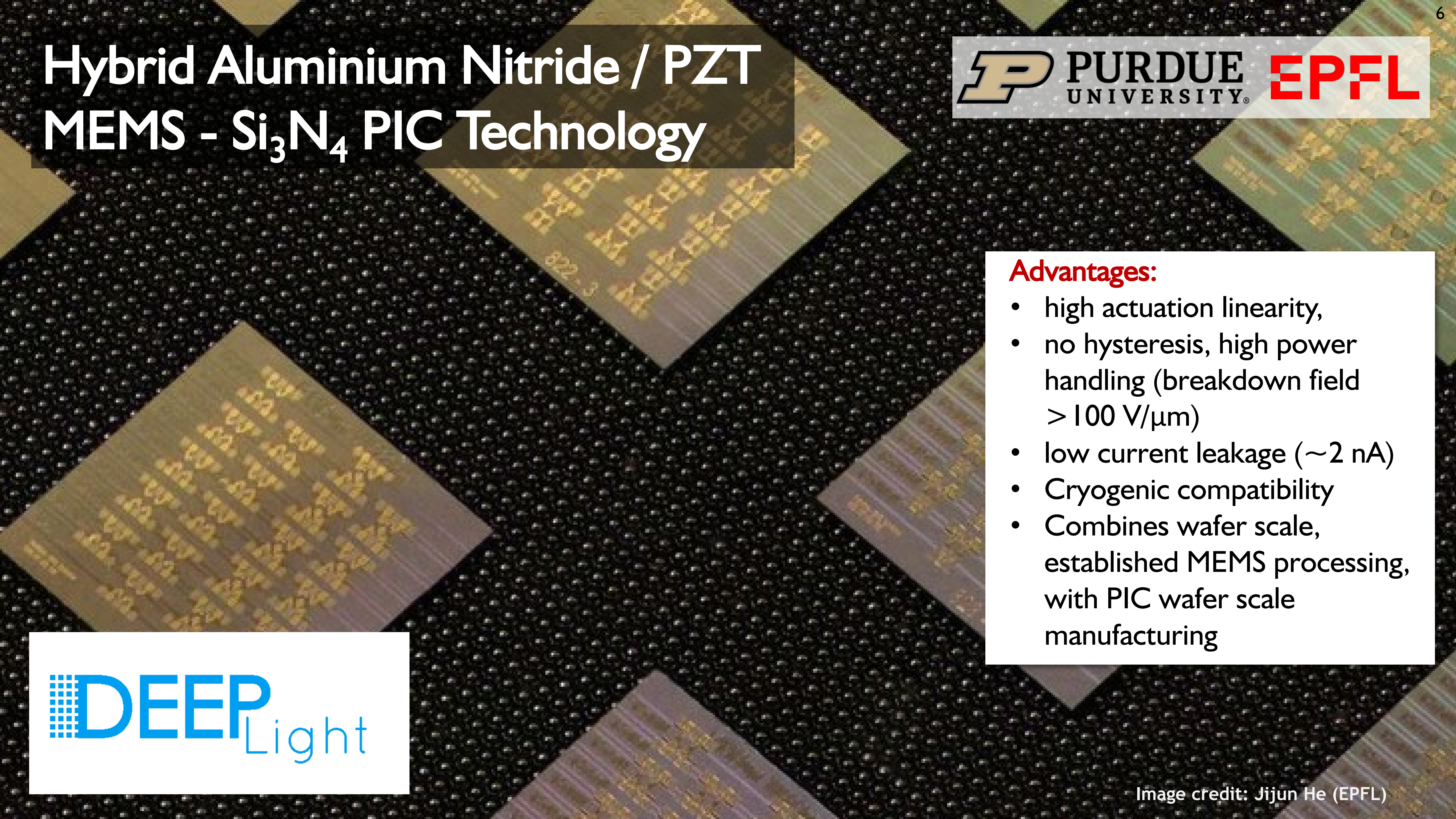




Cover article of Nature issue 14th May 2020

J. Riemensberger et al, Nature 581, 164 (2020)

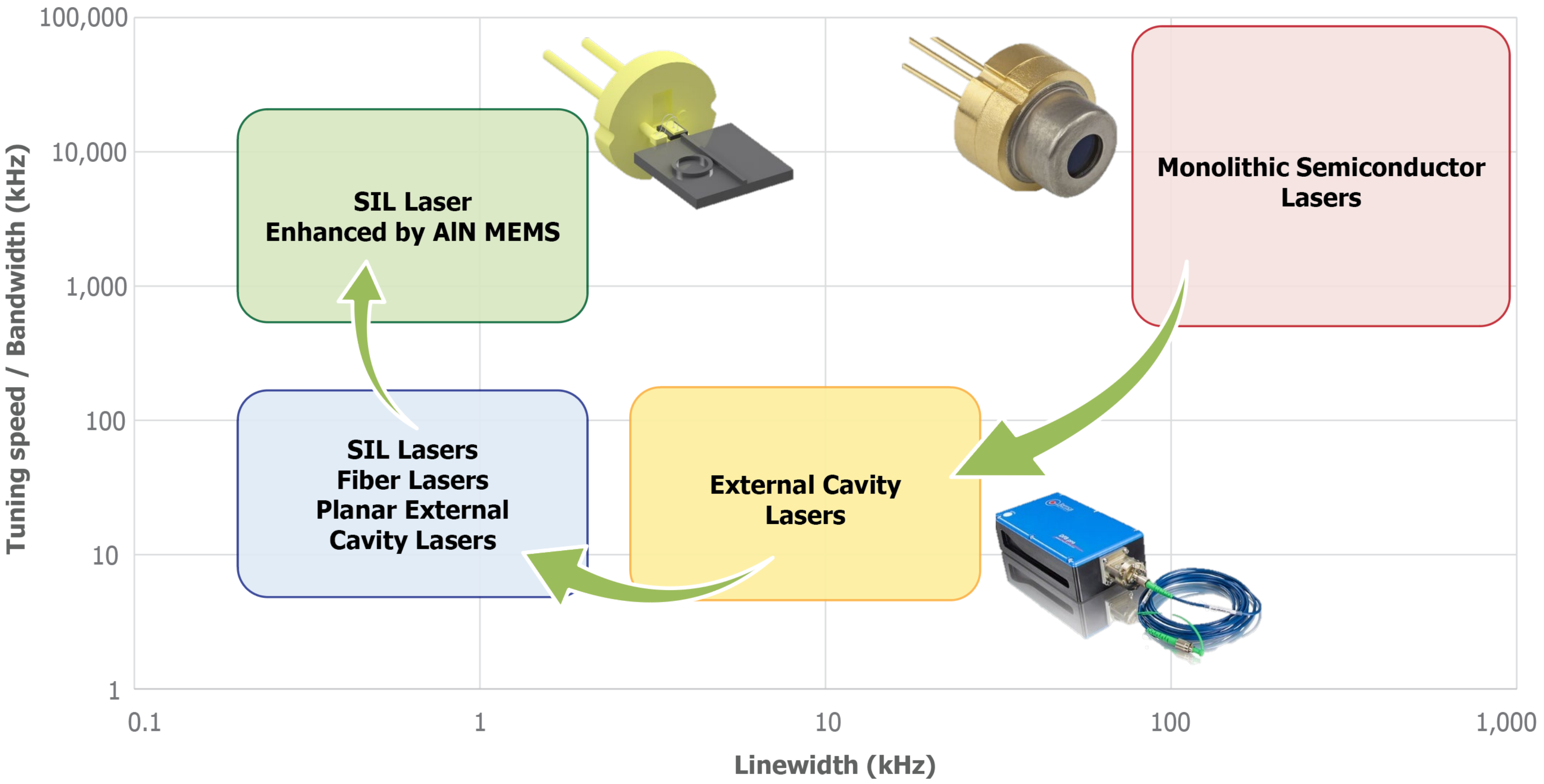
Hybrid Aluminium Nitride / PZT MEMS - Si_3N_4 PIC Technology



Advantages:

- high actuation linearity,
- no hysteresis, high power handling (breakdown field >100 V/µm)
- low current leakage (~2 nA)
- Cryogenic compatibility
- Combines wafer scale, established MEMS processing, with PIC wafer scale manufacturing

Eliminating the **trade-off** between **tunability** and **narrow linewidth** lasing



Piprek, Joachim, and John E. Bowers. "Analog modulation of semiconductor lasers." Vol. 234, Cambridge Univ. Press (2002)
Mroziewicz, B. "External cavity wavelength tunable semiconductor lasers - a review." *Opto-Electronics Review*, 16.4 (2008)
Zorabedian, Paul. "Tunable external-cavity semiconductor lasers." *Tunable Lasers Handbook*. Academic Press, 349-442 (1995)
Liang, W., et al. "Ultralow noise miniature external cavity semiconductor laser." *Nature communications* 6.1 (2015)
Numata, Kenji, et al. "Performance of planar-waveguide external cavity laser for precision measurements." *Optics Express* 18.22 (2010)

Self-injection locking of semiconductor laser diodes

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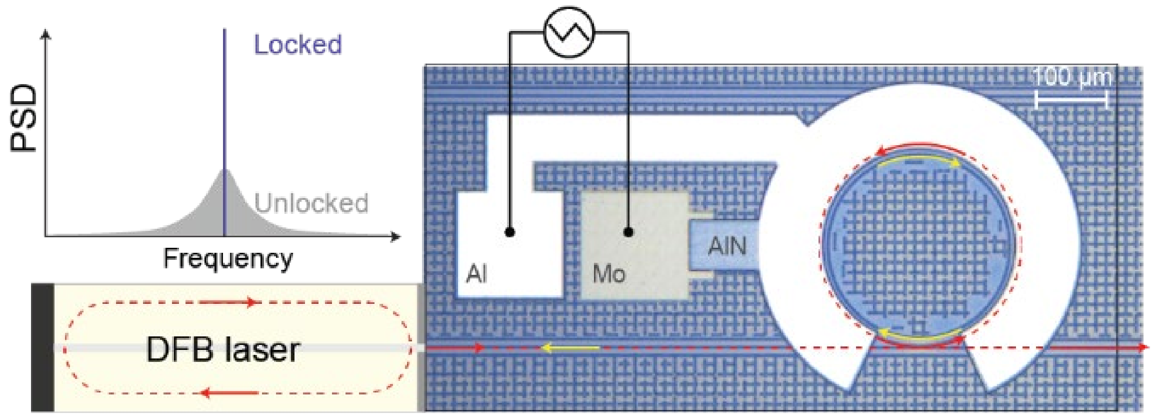
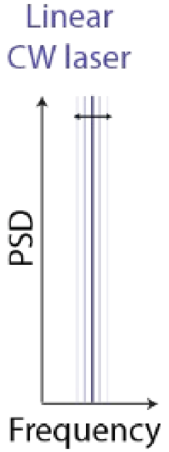
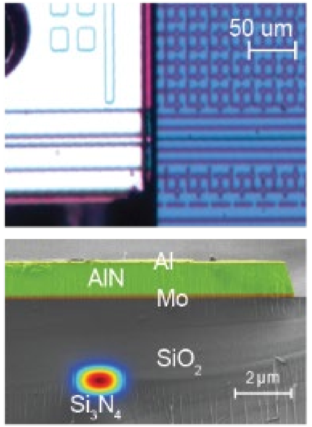
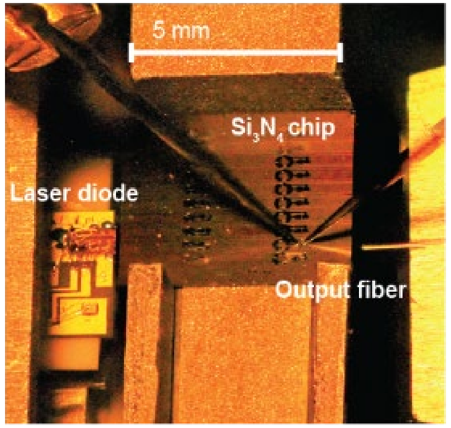


Si_3N_4 photonic chip







Self-injection locking bandwidth:

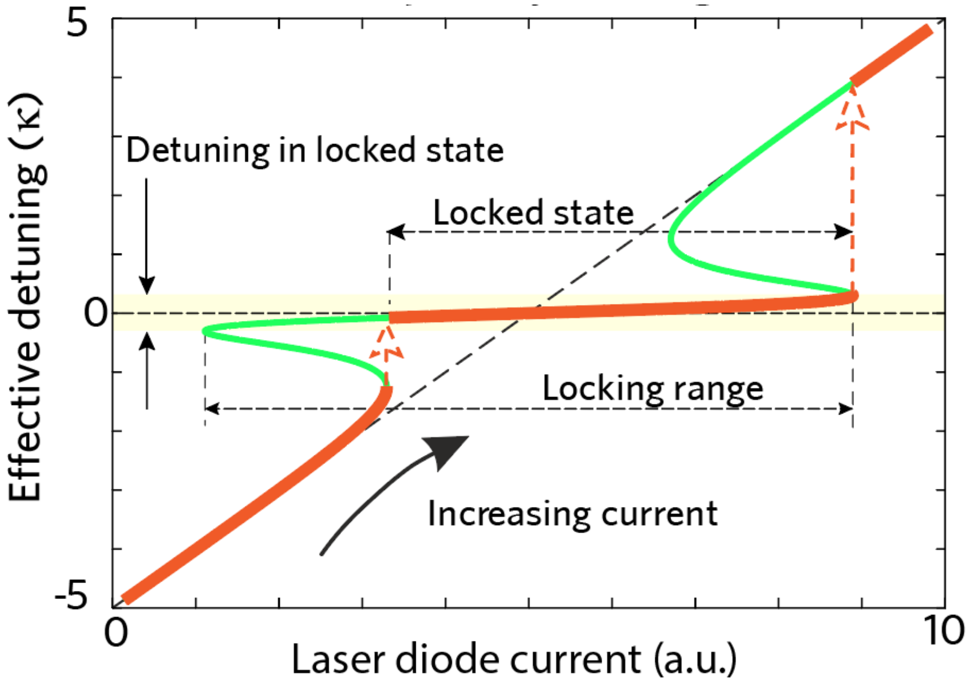
$$\frac{\Delta\omega_{lock}}{\omega} \approx \sqrt{1+\alpha_g^2}\frac{\Gamma_m}{Q_d}$$

Assuming strong backreflection Γ_m

Laser linewidth reduction:

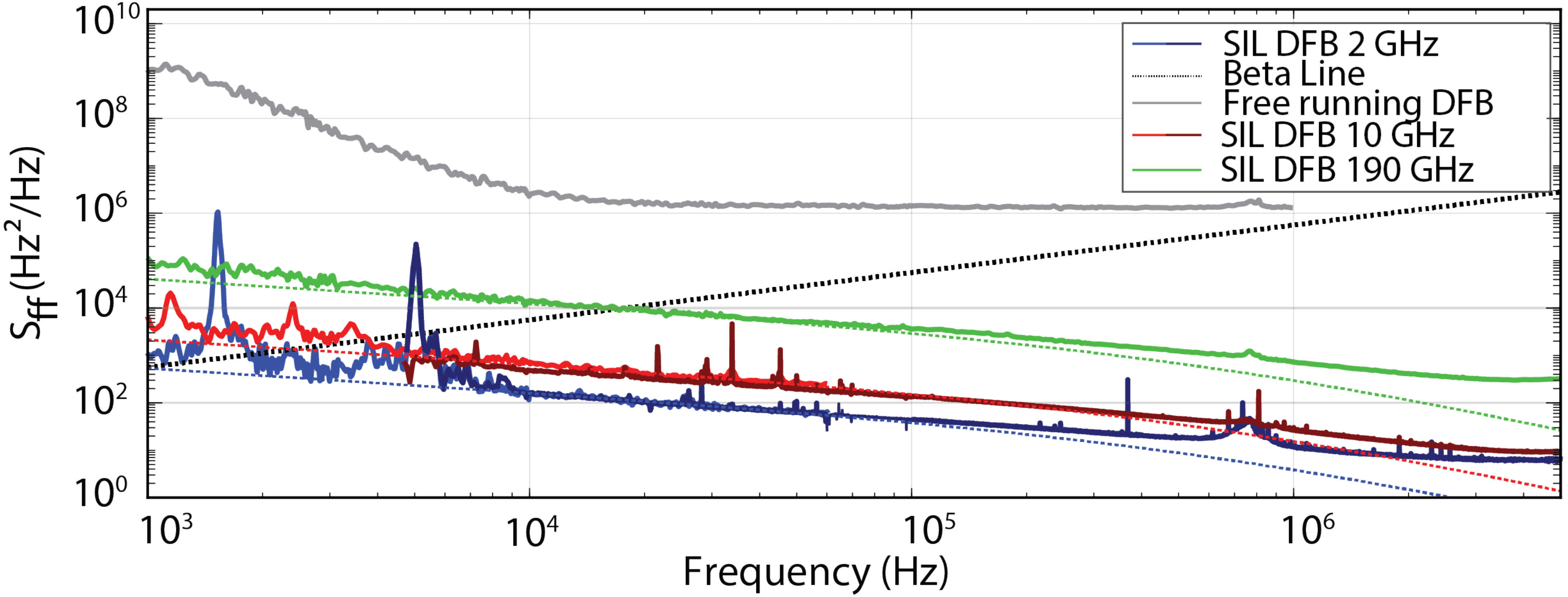
$$\frac{\delta\omega}{\delta\omega_{free}} \approx \frac{Q_d^2}{Q_m^2}\frac{1}{16\Gamma_m^2(1+\alpha_g^2)}$$

Assuming white frequency noise



W. Liang et al. *Optics letters* 35.16 (2010); N. M. Kondratiev et al. *Optics Express* 25.23 (2017);

Frequency noise of Photonic Damascene SIL



- Frequency noise limited by thermo-refractive noise of high confinement microresonator
- Lorentzian linewidth: 600 Hz (190 GHz), 40 Hz (10 GHz), 25 Hz (2 GHz)

Core Technology: Piezoelectric MEMS actuators

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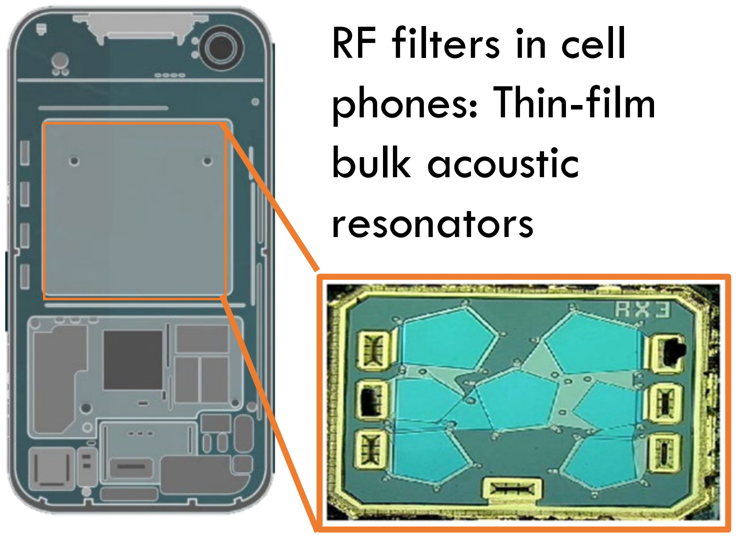
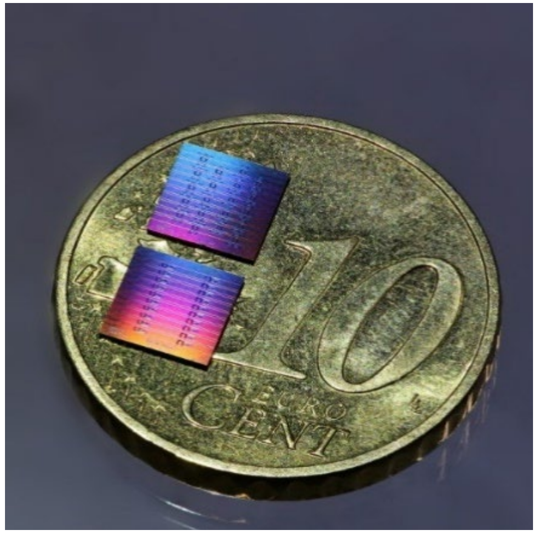
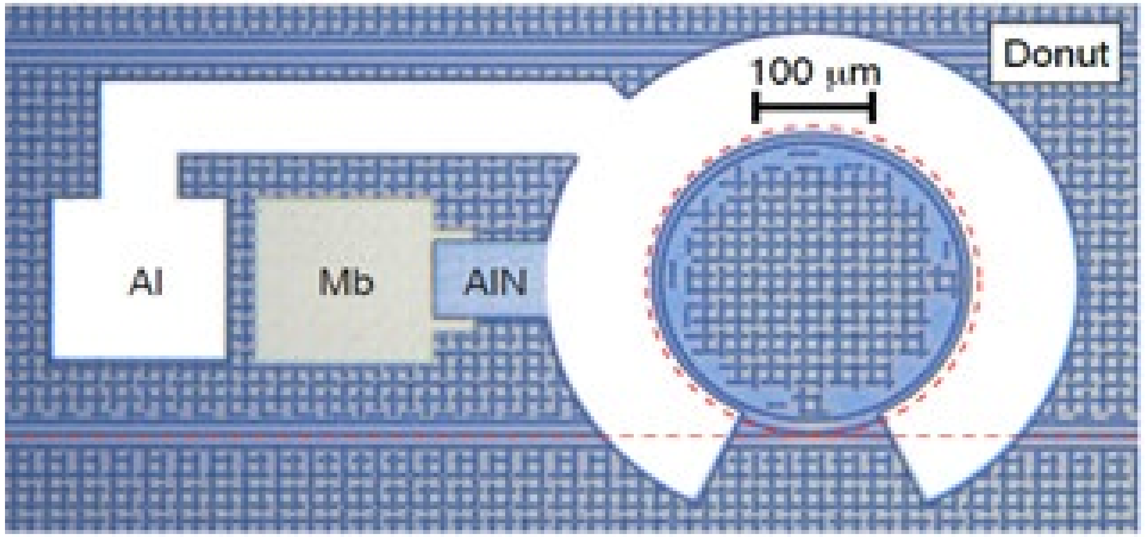


RF filters in cell phones: Thin-film bulk acoustic resonators





Proven MEMS technology based on piezo-electric materials AlN, PZT

- Available foundry processes (BEOL process)
- Monolithic integration
- Compatible with Si_3N_4 PIC
- Highly linear, no hysteresis, low power

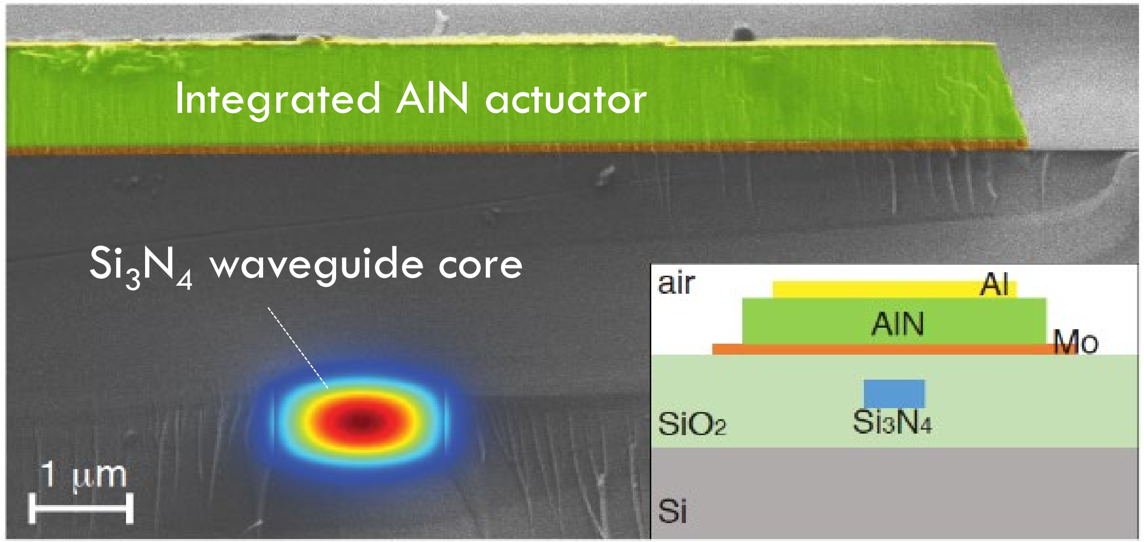
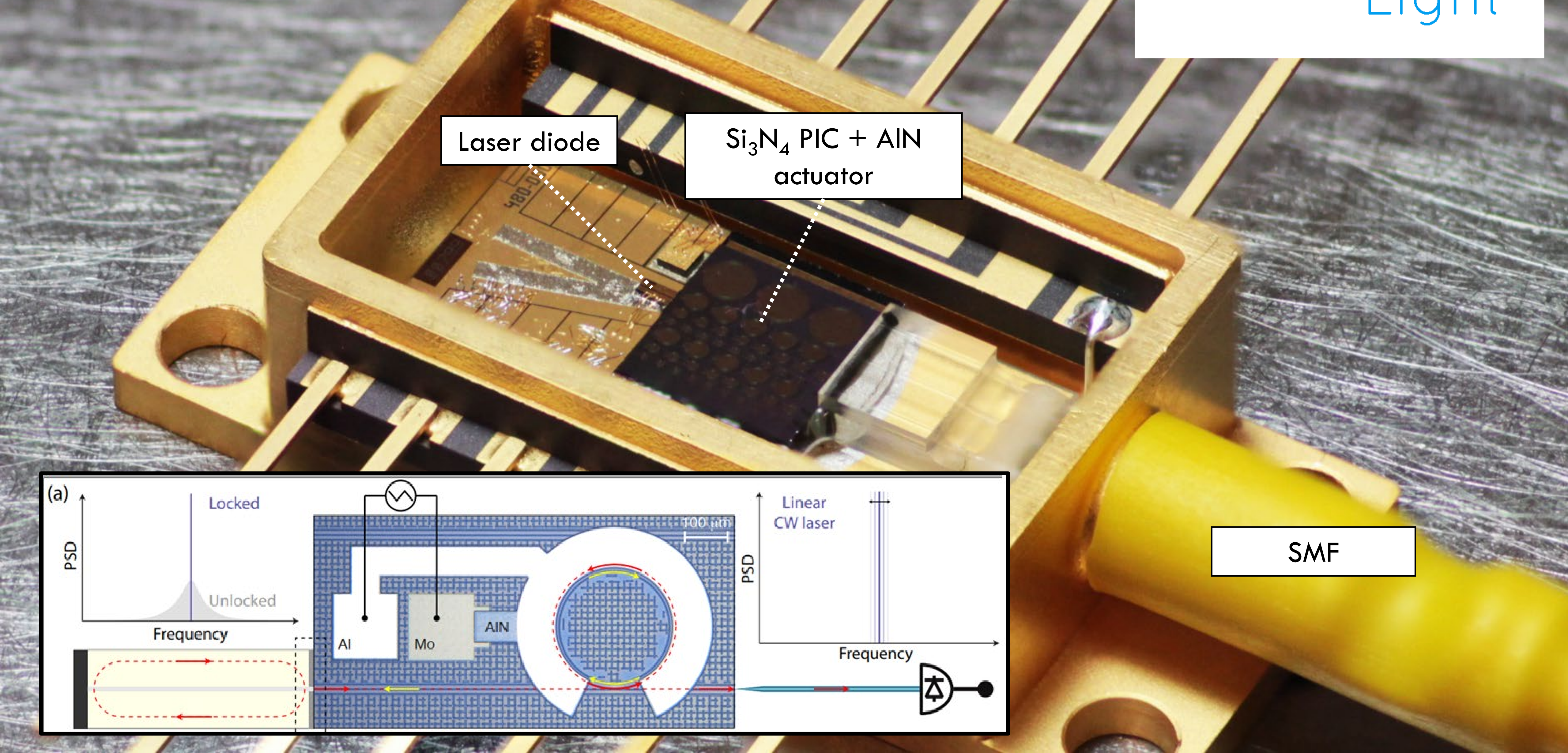
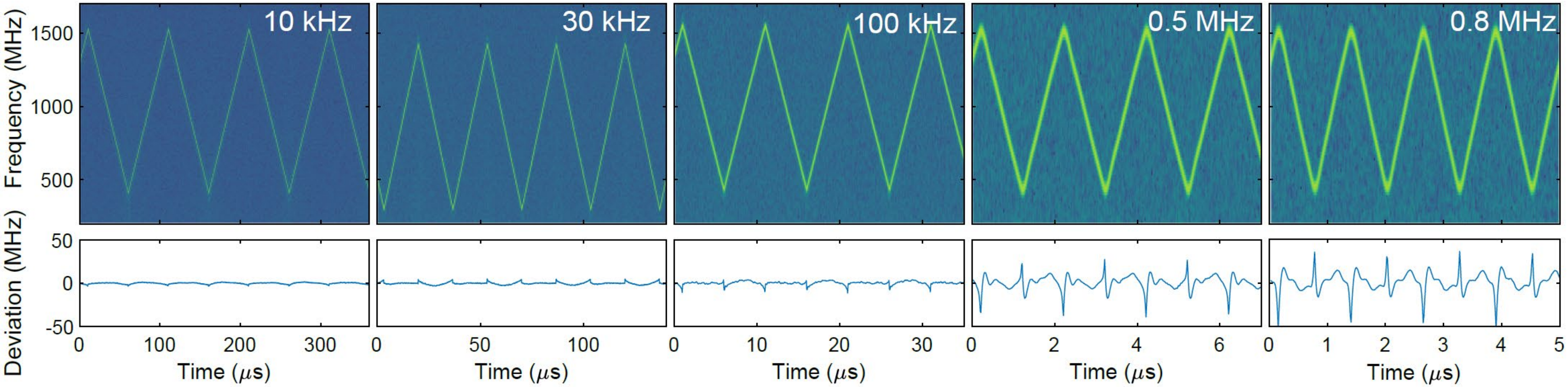


Image: D. Malinaik, 'The Future of RF Filtering in a 5G World', Jan. 14, 2019, www.mwrf.com

Technology Demonstrators

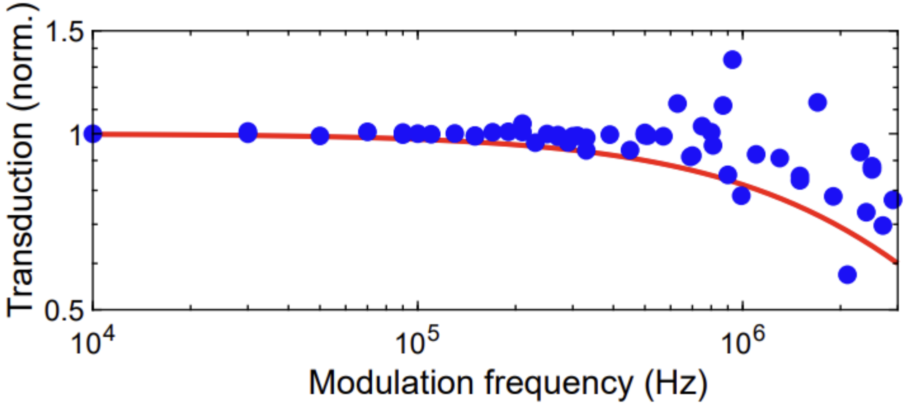


Performance of Frequency-Agile SIL Lasers



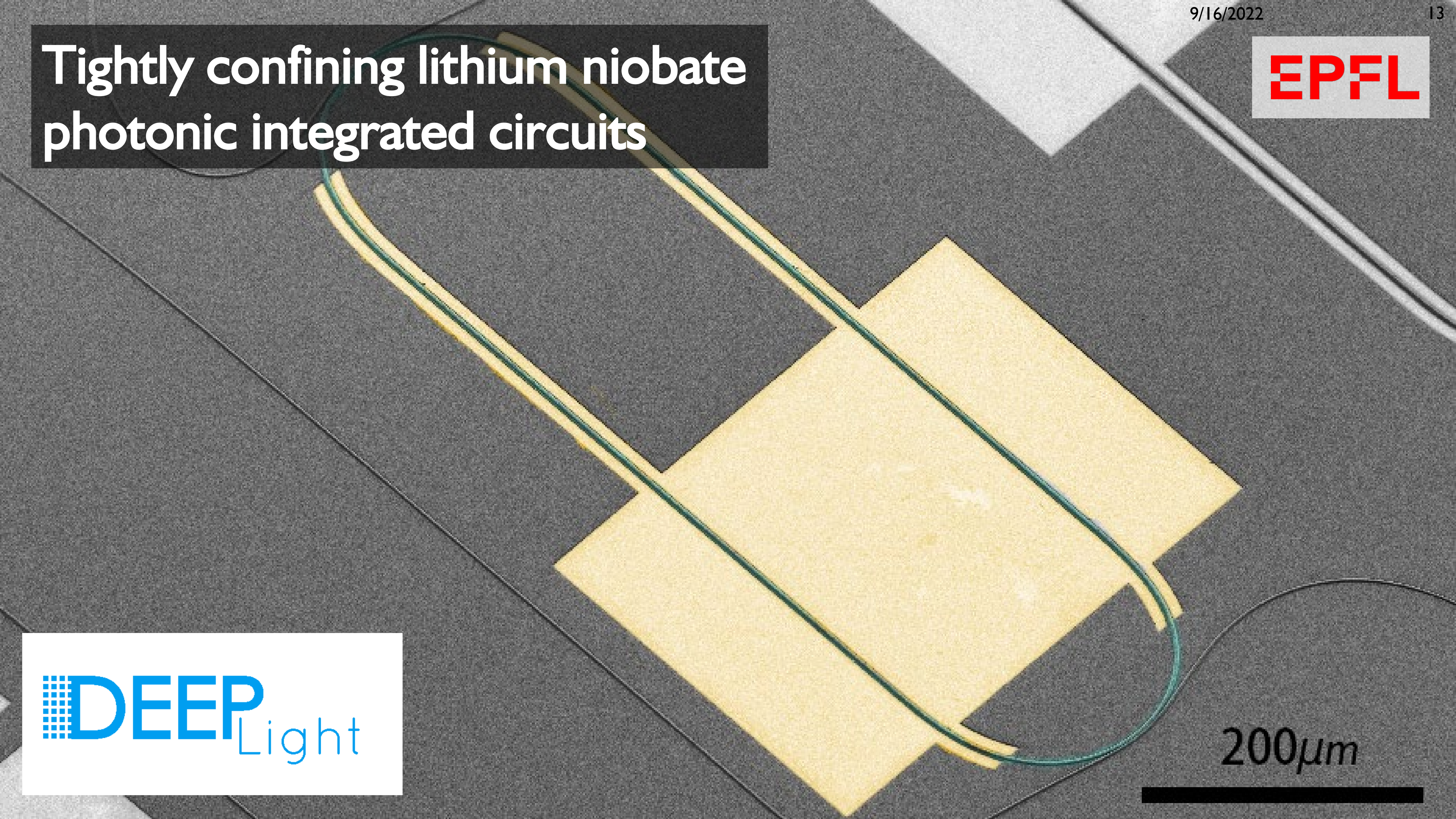
AlN actuators:
- > 1 GHz tuning at 1 MHz sweep rate, tuning efficiency ~ **20 MHz/V**
- Frequency actuation bandwidth: > **10 MHz**
- Flat frequency actuation bandwidth: >**0.8 MHz** (RMS nonlinearity < **0.1%** @ 10 kHz sweep rate)

PZT actuators:
- > 1 GHz tuning at 100 kHz sweep rate, tuning efficiency ~ **400 MHz/V**
- Frequency actuation bandwidth: > **1 MHz**
- RMS nonlinearity < **0.3%** @ 10 kHz sweep rate (for 90% of sweep)



Lihachev et al., Nature Comm (2022)

Tightly confining lithium niobate photonic integrated circuits



Ultra-low loss thin film lithium niobate photonics

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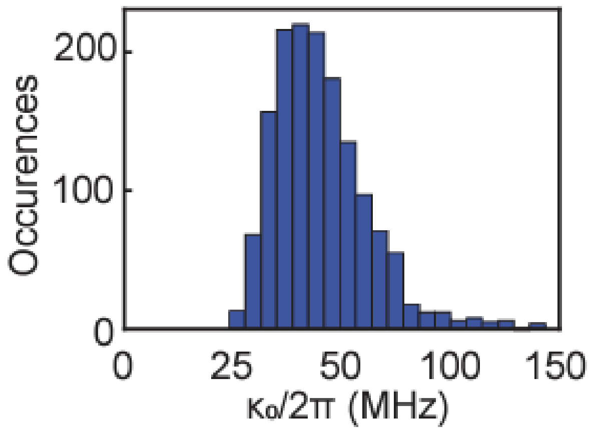
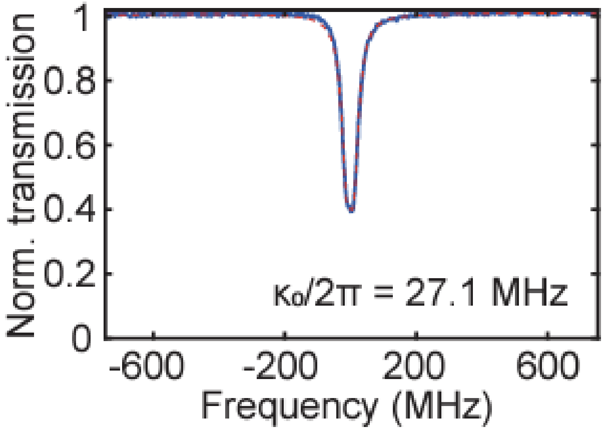
Lithium Niobate was once hailed as the "Silicon of Photonics"…

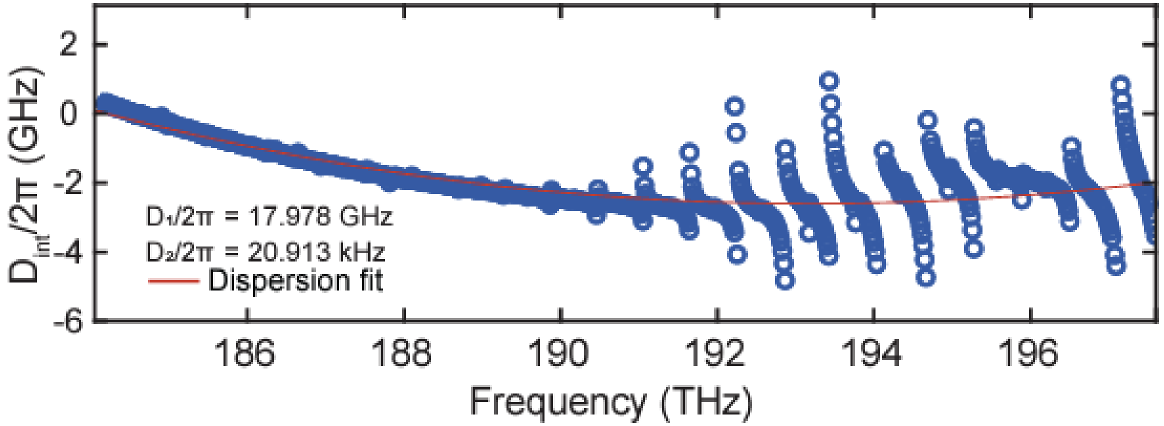
Strong electro-optical **nonlinearity** for ultrafast modulators & datacenter applications

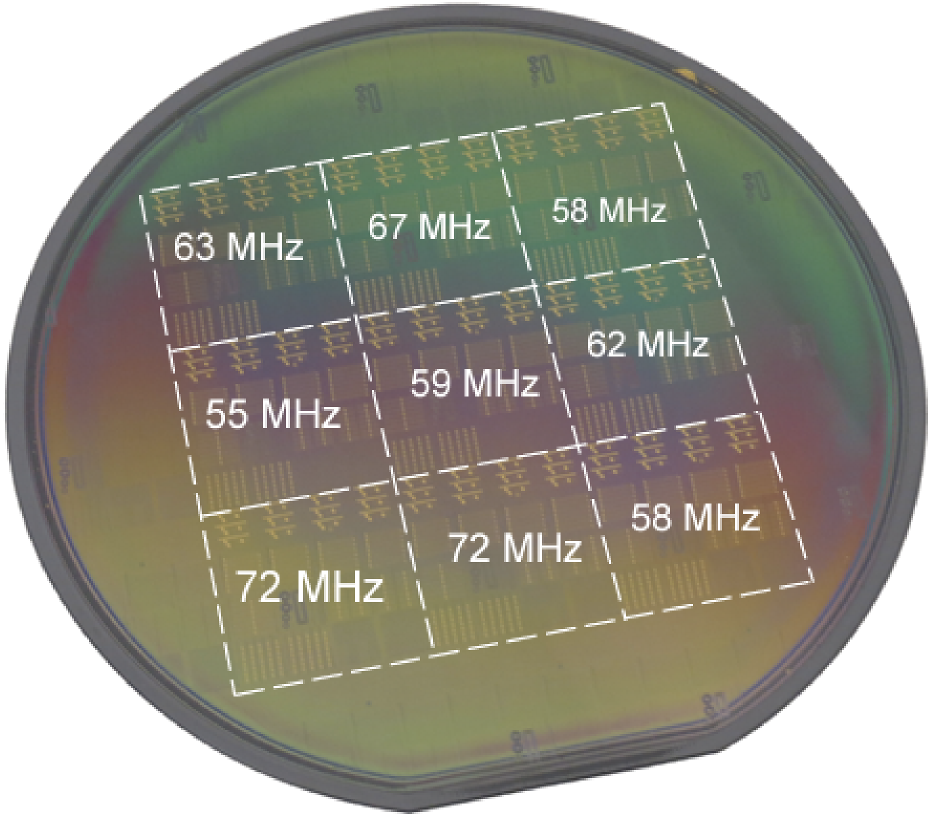
Wafer-scale fabrication process:

- Optical propagation loss < 0.12 dB/cm across full wafer
- Best propagation loss < 0.05 dB/cm

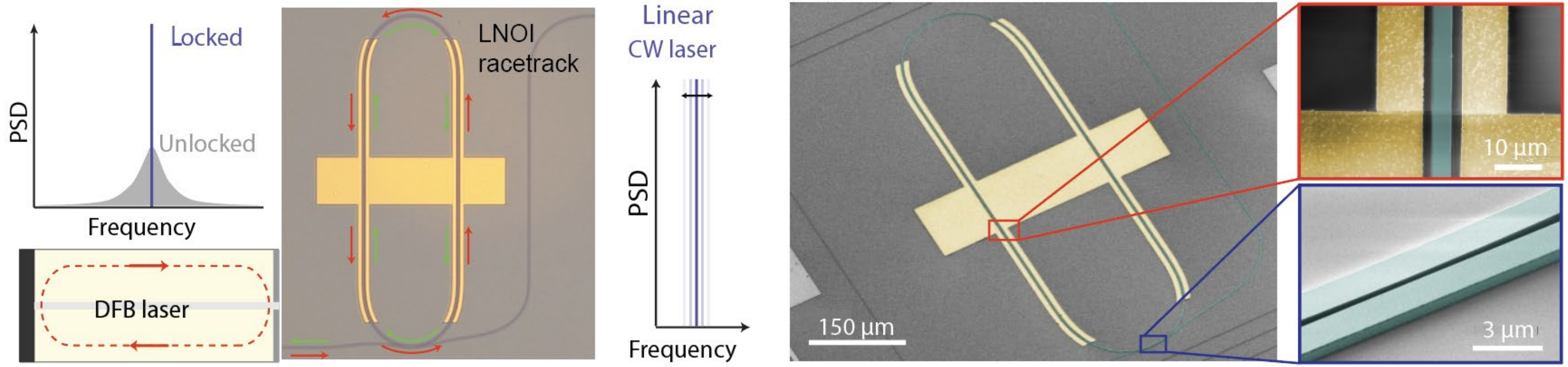


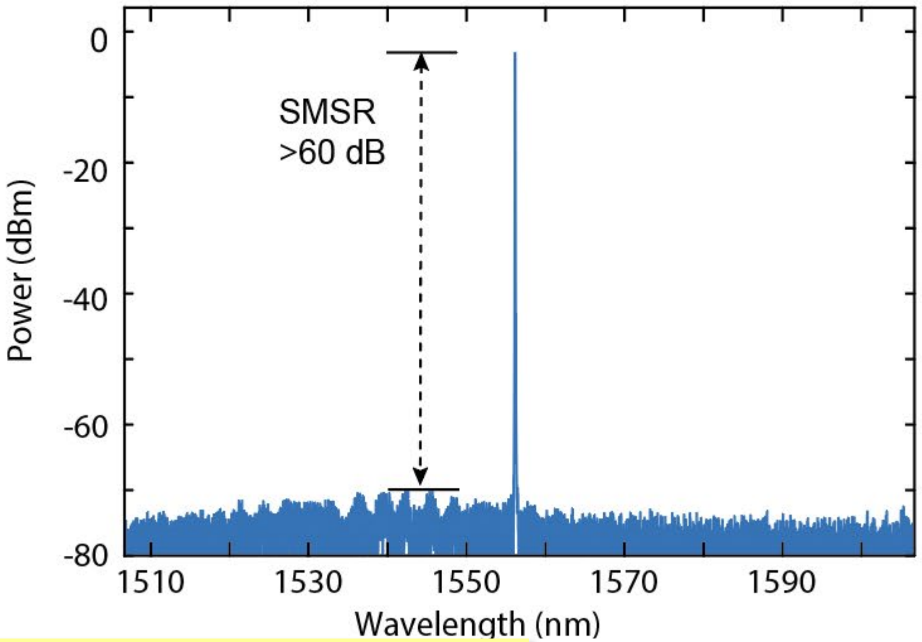


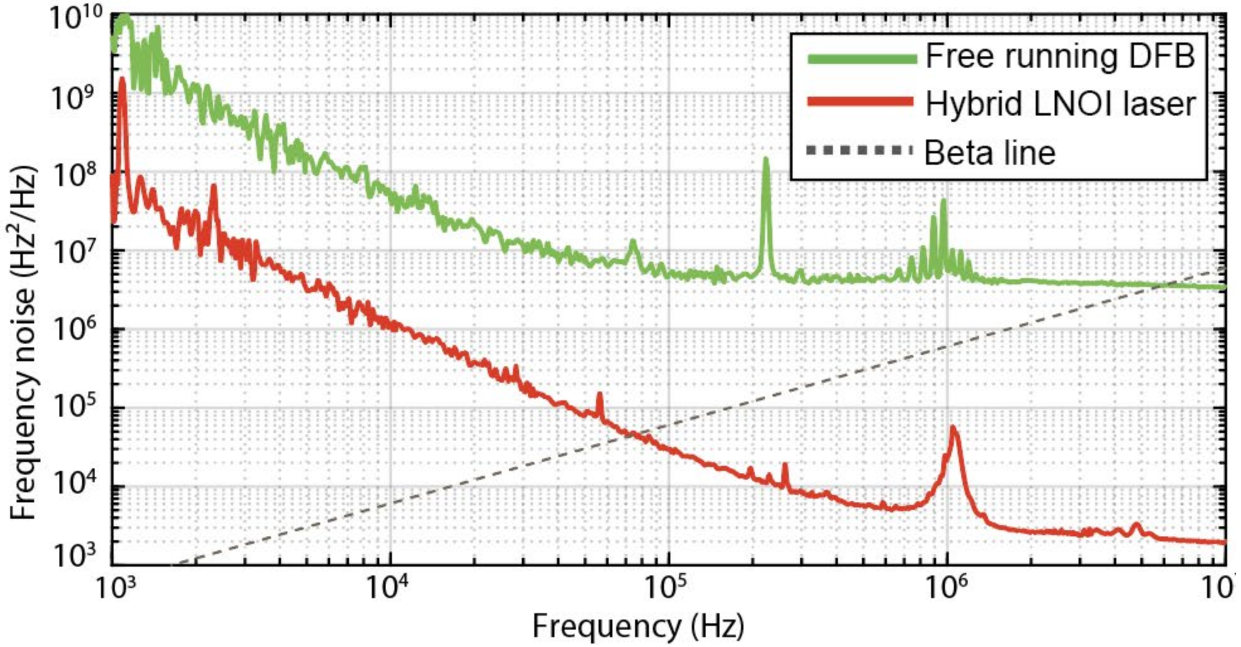




Self-injection locked lasers based on LNOI

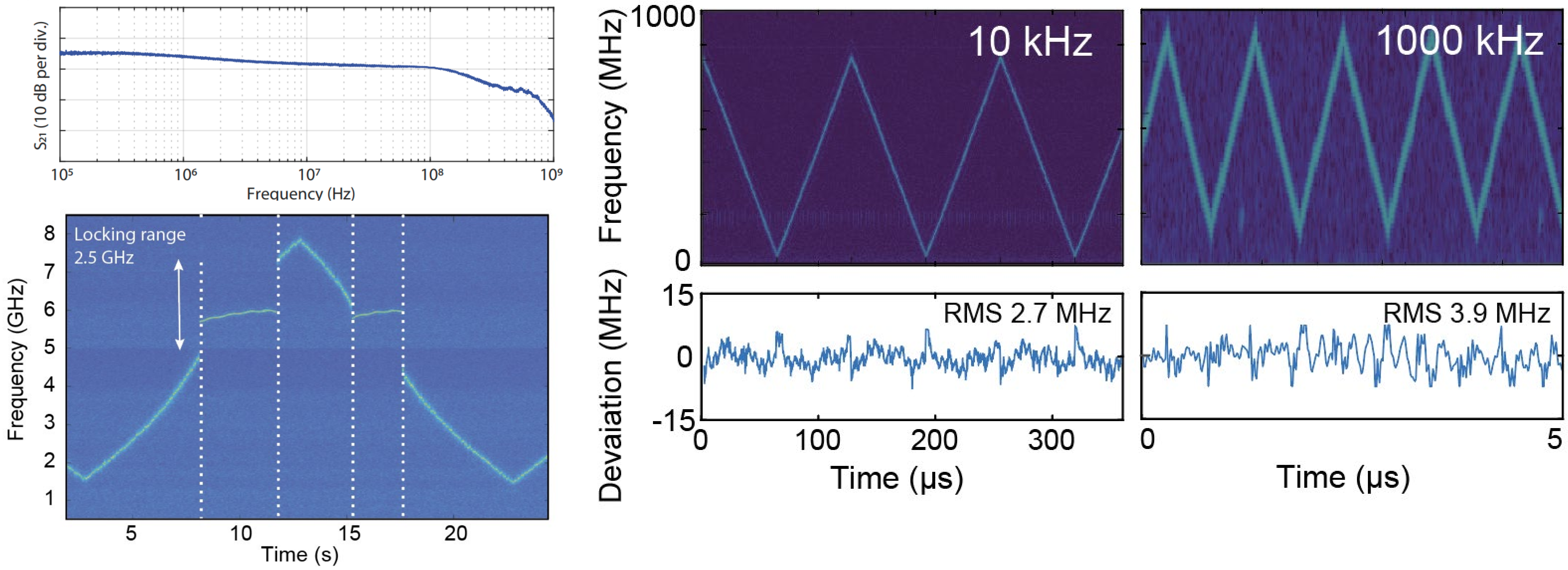






Z. Li, et al., arXiv:2208.05556 (2022)

Frequency-agile operation of LNOI laser



Frequency-agile operation of self-injection locked laser:

- Locking range > 2.5 GHz, > 10 kHz intrinsic optical laser linewidth
- Linear chirping at MHz rates w/o predistortion (RMS < 0.5%) at CMOS compatible voltages (950 MHz/V)

Z. Li, et al., arXiv:2208.05556 (2022)

Thank you for your attention!

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DEEP Light

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