Scalable infrastructure for Sr optical clocks with integrated photonics

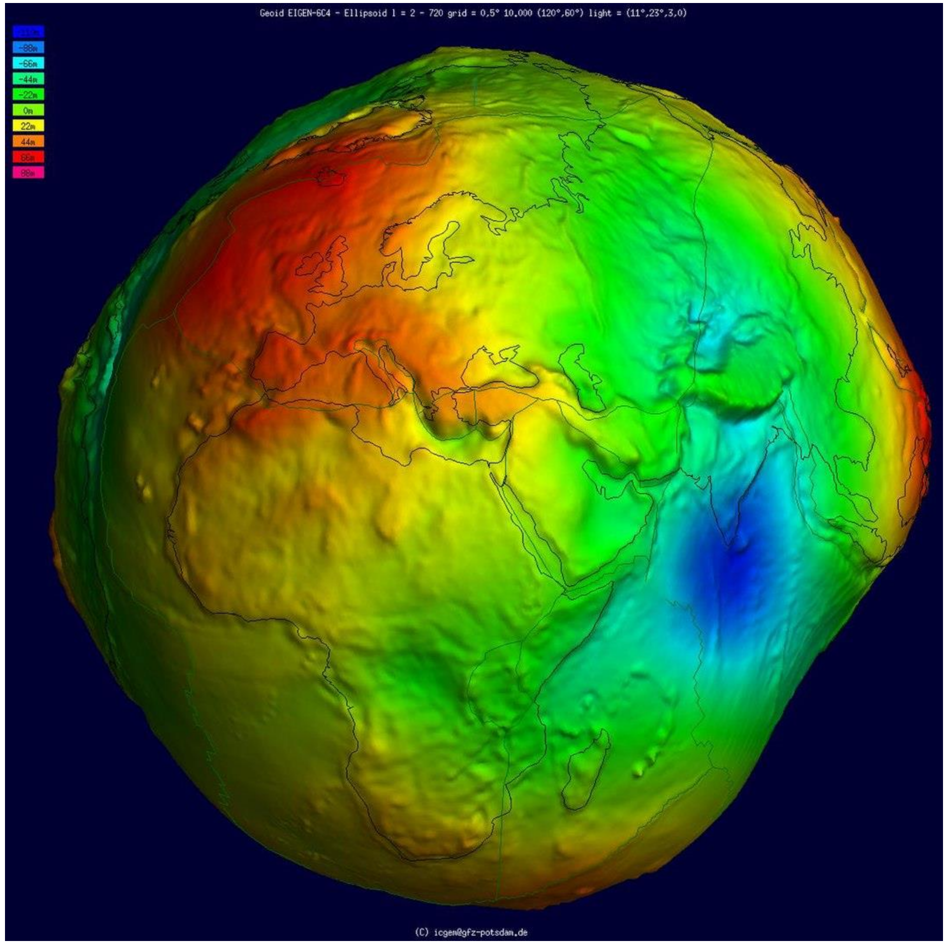
9th FSM, Kingscliff, Australia, October 2023

Scott Papp
Quantum and Nonlinear Nanophotonic Systems (QNS)

Funding: DARPA (QuASAR, PULSE, DODOS, ACES, DRINQS, PIPES, A-PhI, LUMOS, QuICC, NaPSAC), AFOSR, AFRL, NASA, JPL, ARPA-e, NSF, NIST

National Institute of Standards and Technology
U.S. Department of Commerce

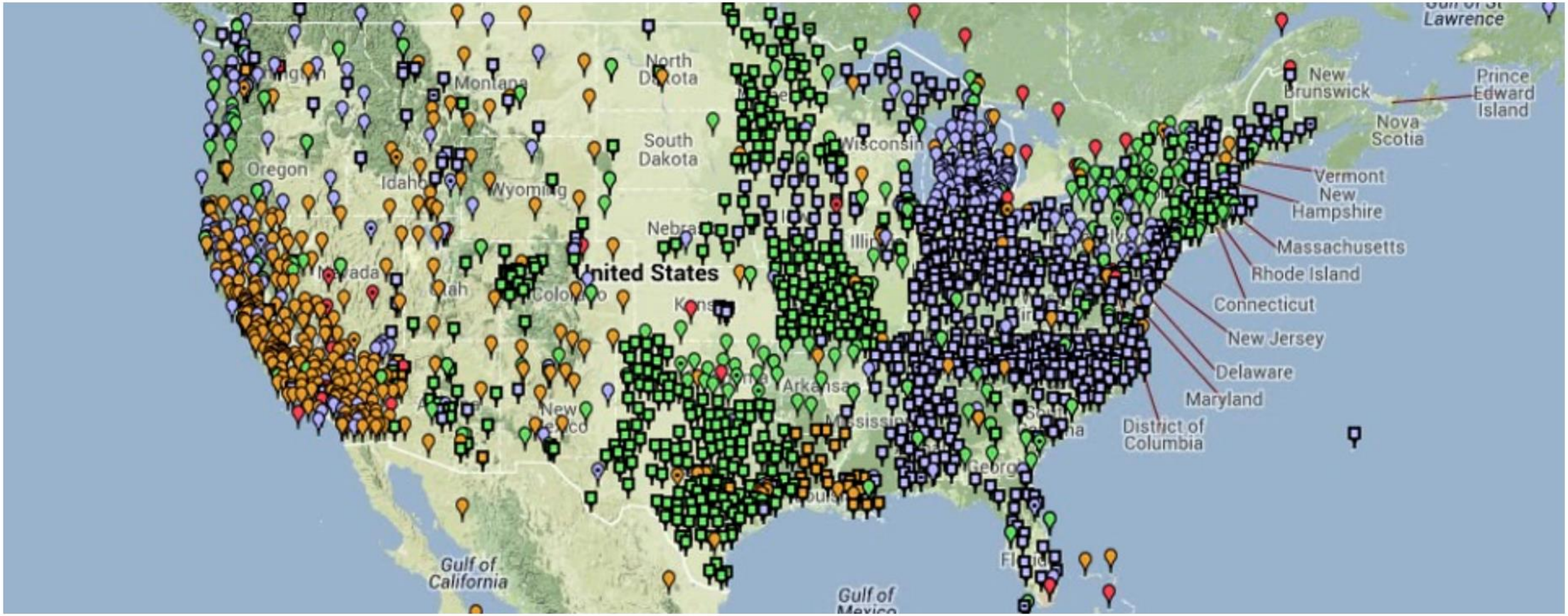
Geodesy



Barthelmes *et al* International Centre for Global Earth Models (ICGEM)

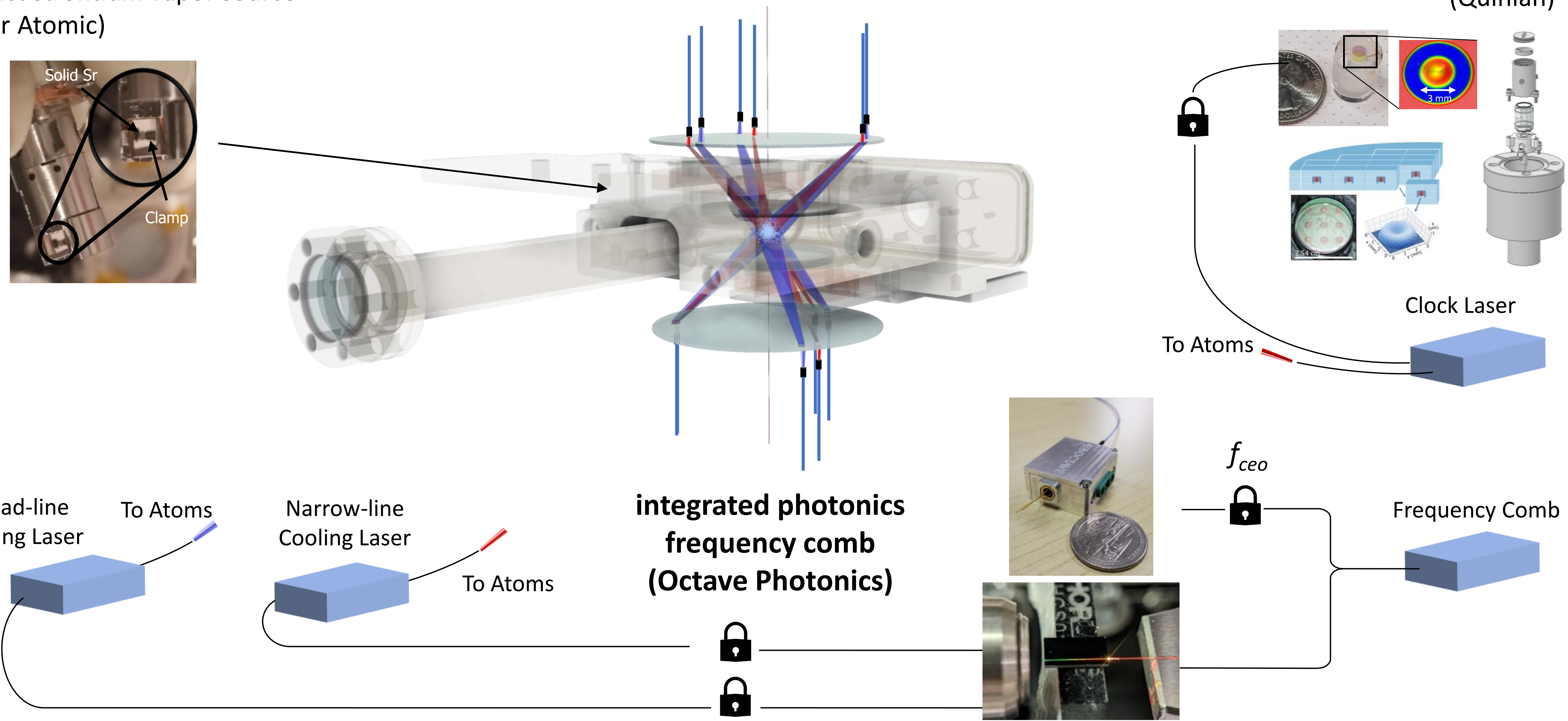
$$\frac{\delta f}{f} = 10^{-18} \rightarrow 1 \text{ cm height resolution}$$

Geodesy stations



https://oceanservice.noaa.gov/education/tutorial_geodesy/geo08_spatref.html

Scalable infrastructure for Sr clocks



compact strontium vapor source
(Vector Atomic)

atom-photonic Interface

Micro Fabry-Perot Cavity
(Quinlan)

Clock Laser

To Atoms

Broad-line
Cooling Laser

To Atoms

Narrow-line
Cooling Laser

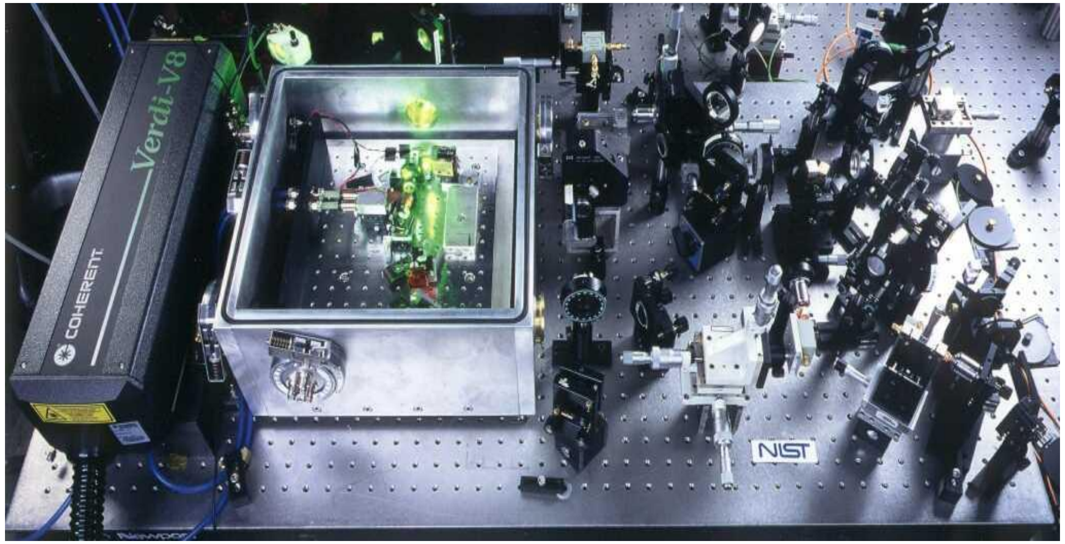
To Atoms

**integrated photonics
frequency comb
(Octave Photonics)**

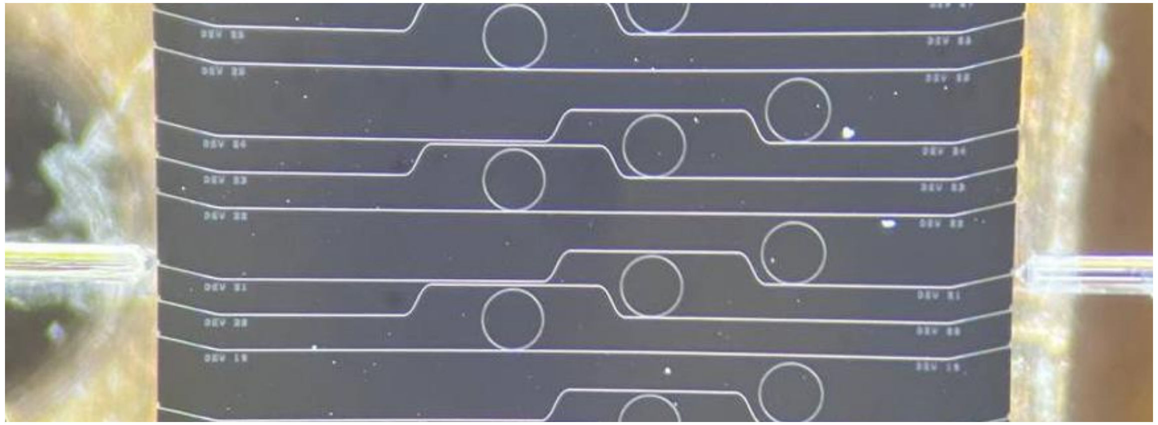
Frequency Comb

Integrating frequency combs

NIST tabletop frequency comb



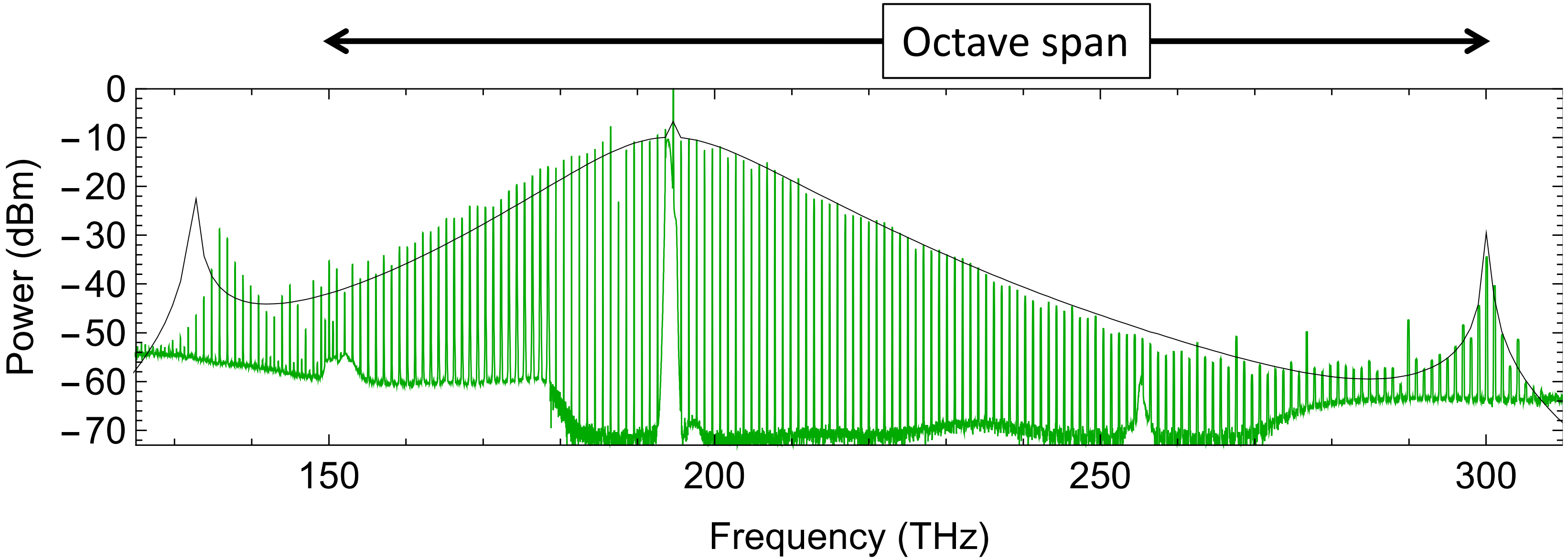
NIST microcombs

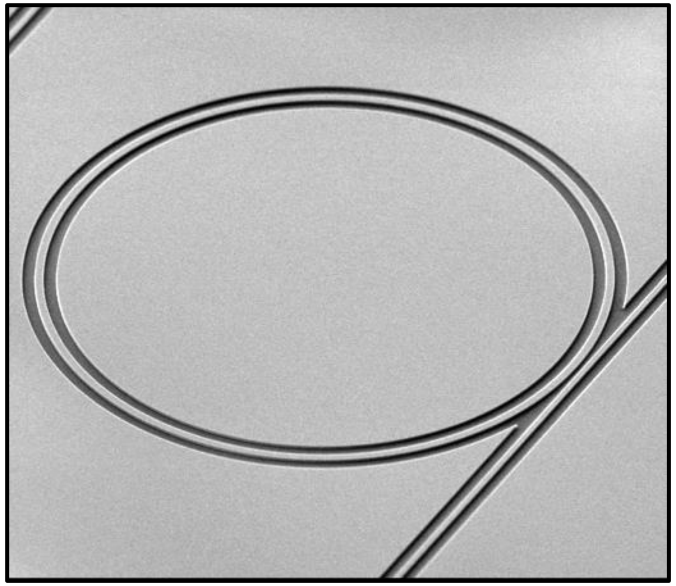


Soliton microcombs

$$\frac{\partial\psi}{\partial\tau} = -(1+i\alpha)\psi + i|\psi|^2\psi - i\frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F$$

Size **Dissipation** and detuning Kerr nonlinearity Dispersion Pump

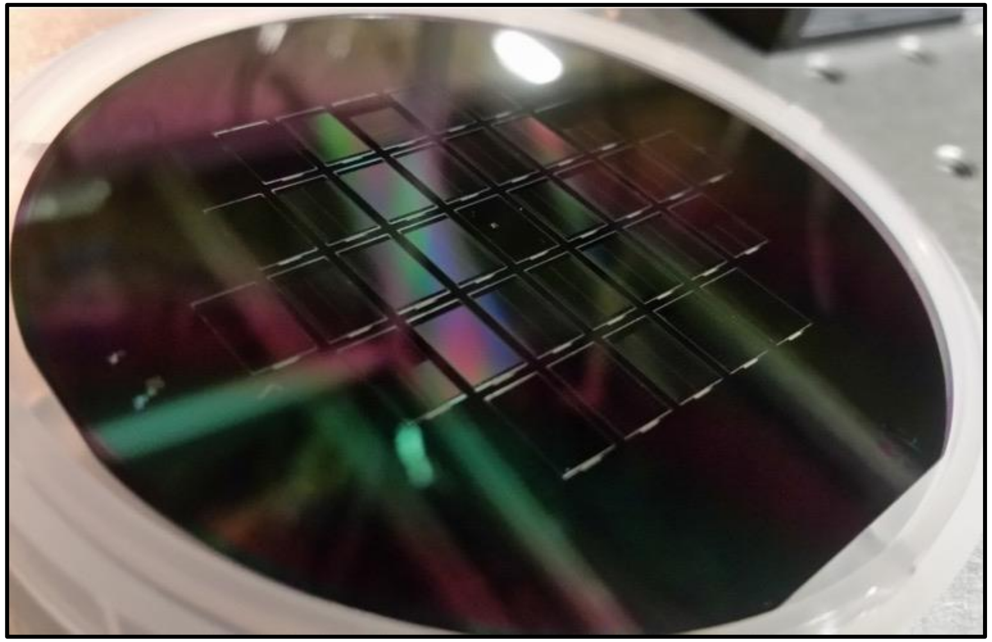




Kartik Srinivasan

Spencer et al. Nature 2018; Briles et al. Opt. Lett. 2018; Stone et al. PRL 2018

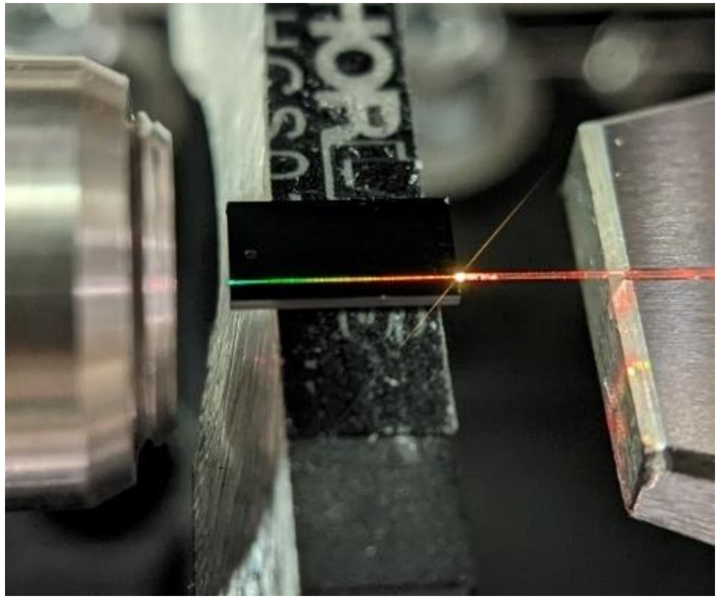
Tantala (Ta_2O_5) integrated photonics

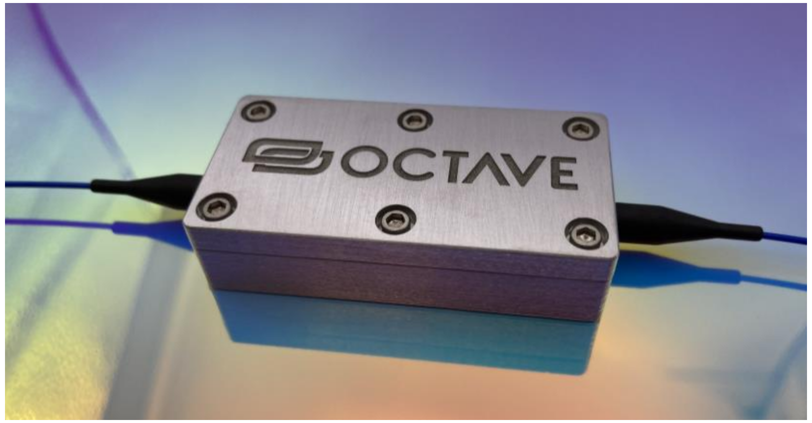


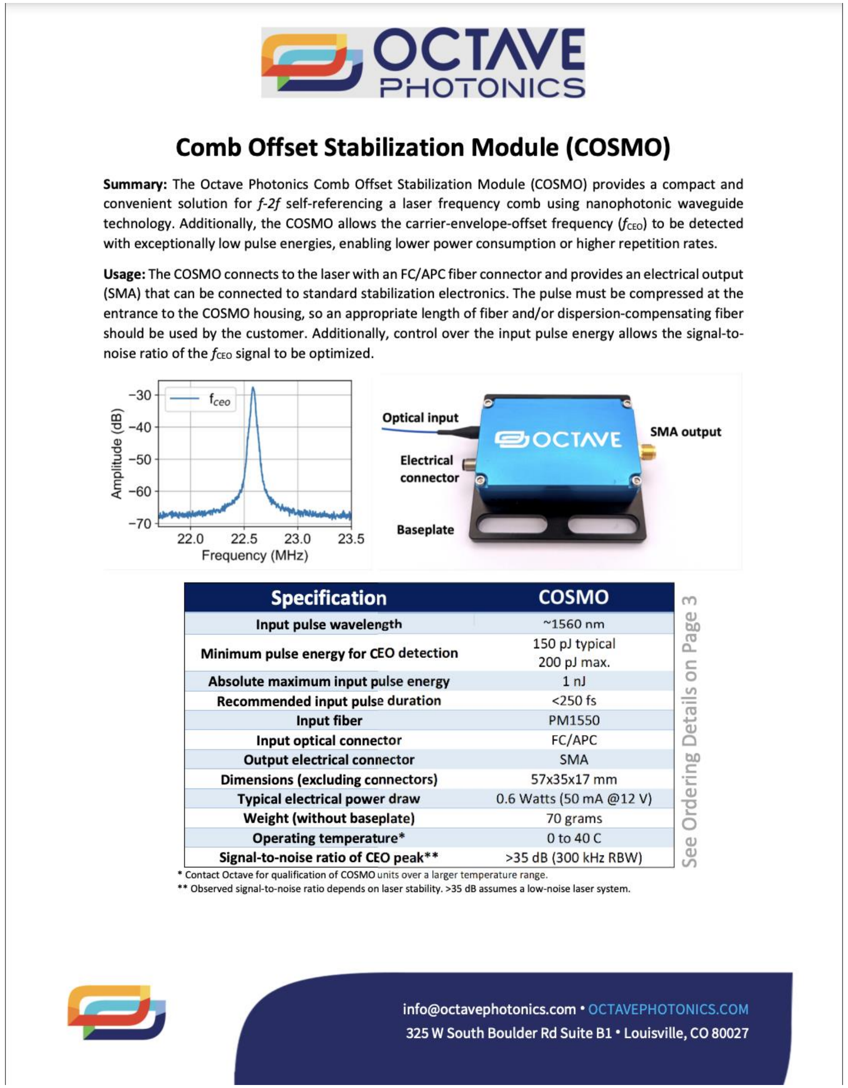
- High *Q*
- Full wafer process
- Visible to SWIR wavelength range
- Versatile integrated nonlinear photonics
- Spin-off: Octave Photonics

H. Jung et al. Optica 2020; J. Black et al. Opt Lett 2020; D. Carlson et al. AVFOP 2019

Integrated photonics modules







OCTAVE PHOTONICS

Comb Offset Stabilization Module (COSMO)

Summary: The Octave Photonics Comb Offset Stabilization Module (COSMO) provides a compact and convenient solution for *f-2f* self-referencing a laser frequency comb using nanophotonic waveguide technology. Additionally, the COSMO allows the carrier-envelope-offset frequency (f_{CEO}) to be detected with exceptionally low pulse energies, enabling lower power consumption or higher repetition rates.

Usage: The COSMO connects to the laser with an FC/APC fiber connector and provides an electrical output (SMA) that can be connected to standard stabilization electronics. The pulse must be compressed at the entrance to the COSMO housing, so an appropriate length of fiber and/or dispersion-compensating fiber should be used by the customer. Additionally, control over the input pulse energy allows the signal-to-noise ratio of the f_{CEO} signal to be optimized.

Specification	COSMO
Input pulse wavelength	~1560 nm
Minimum pulse energy for CEO detection	150 pJ typical 200 pJ max.
Absolute maximum input pulse energy	1 nJ
Recommended input pulse duration	<250 fs
Input fiber	PM1550
Input optical connector	FC/APC
Output electrical connector	SMA
Dimensions (excluding connectors)	57x35x17 mm
Typical electrical power draw	0.6 Watts (50 mA @12 V)
Weight (without baseplate)	70 grams
Operating temperature*	0 to 40 C
Signal-to-noise ratio of CEO peak**	>35 dB (300 kHz RBW)

See Ordering Details on Page 3

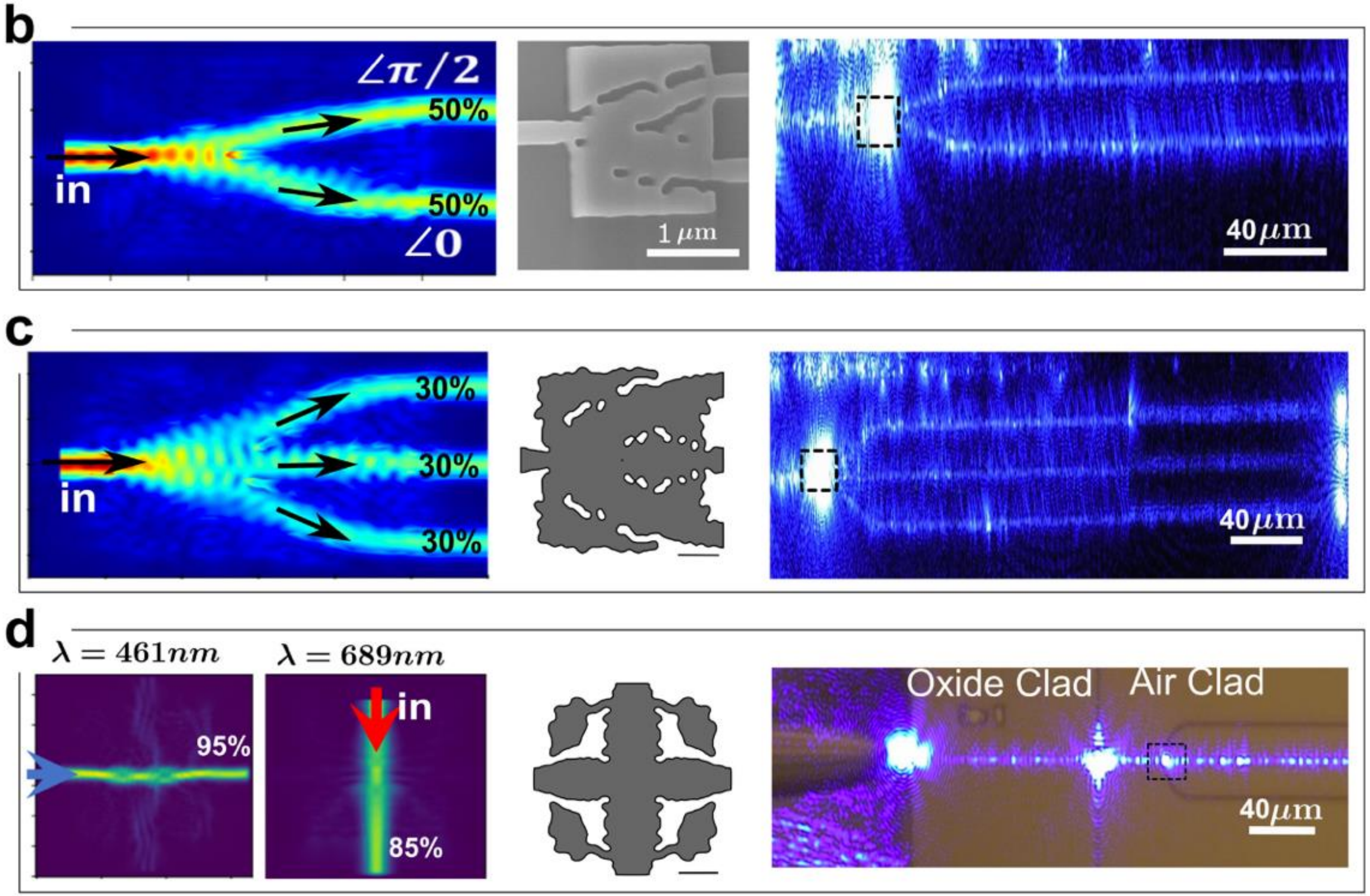
* Contact Octave for qualification of COSMO units over a larger temperature range.

** Observed signal-to-noise ratio depends on laser stability. >35 dB assumes a low-noise laser system.

info@octavephotonics.com • OCTAVEPHOTONICS.COM
325 W South Boulder Rd Suite B1 • Louisville, CO 80027

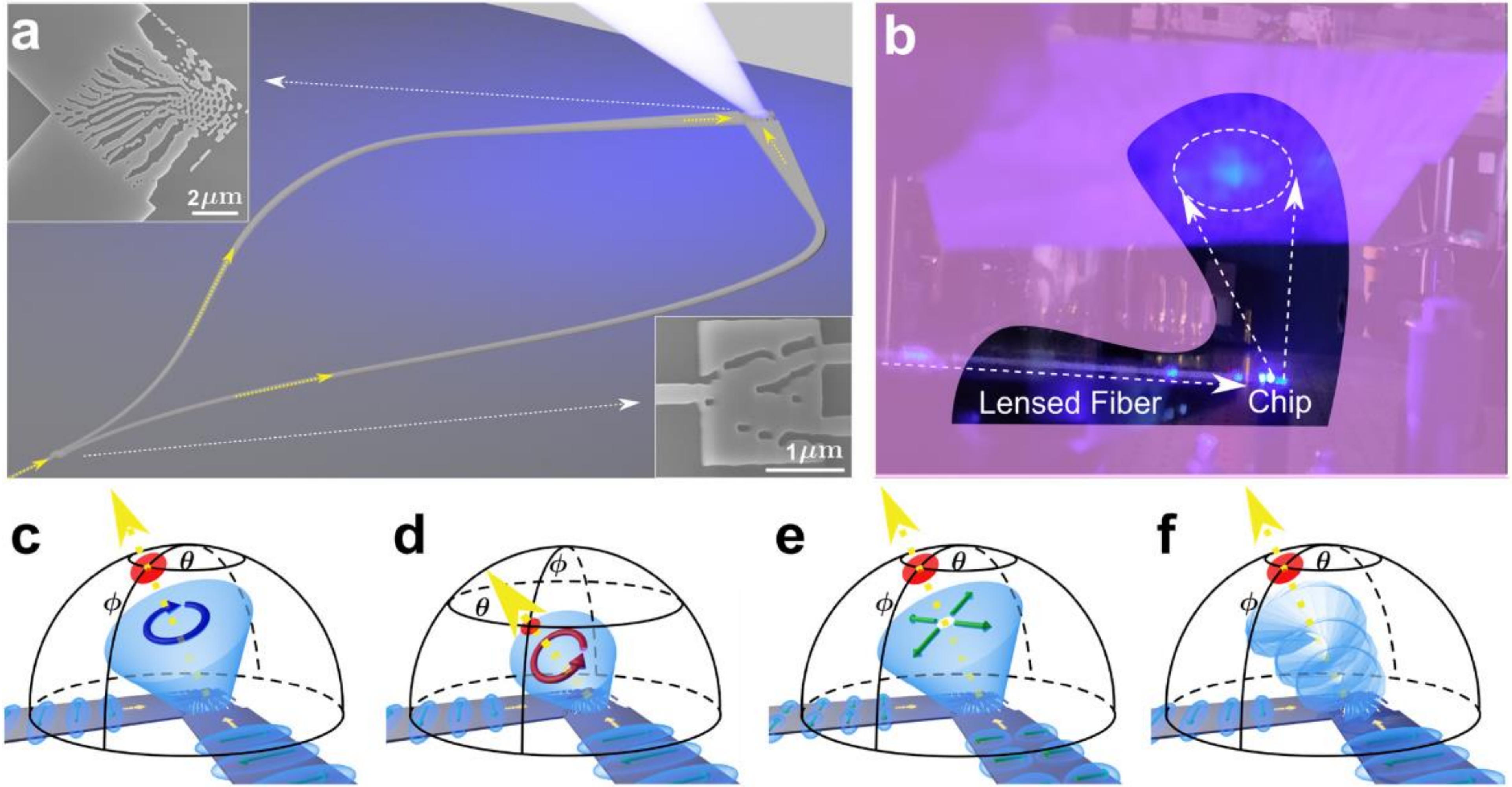
Visible integrated photonics with tantala

Loss < 2 dB/cm from blue to SWIR



Spektor et al. Optica 2023

Circular polarization grating coupler

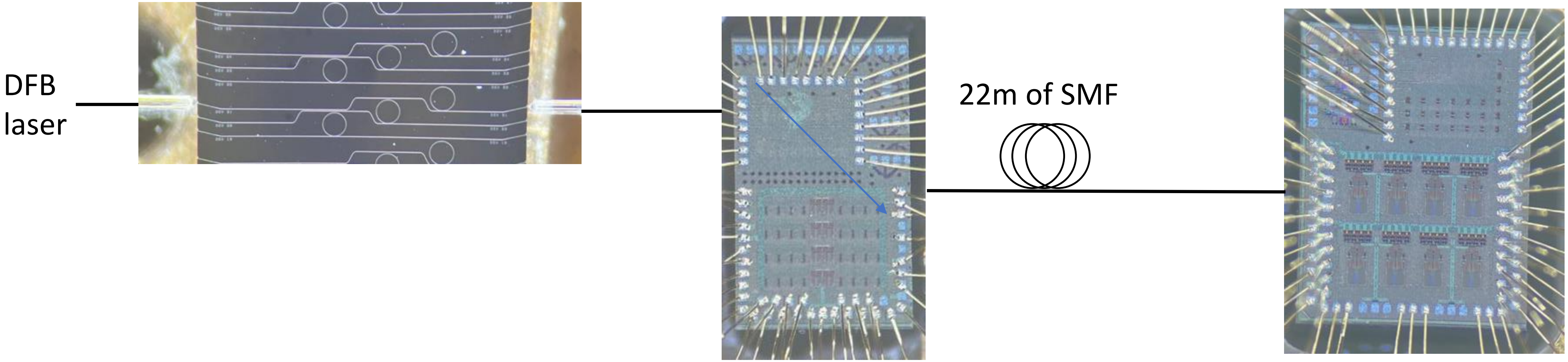


Spektor et al. Optica 2023

Microcombs & Si photonics/electronics

NIST-B fab

GlobalFoundries 45CLO



Microcomb

32channel transceiver

32channel receiver

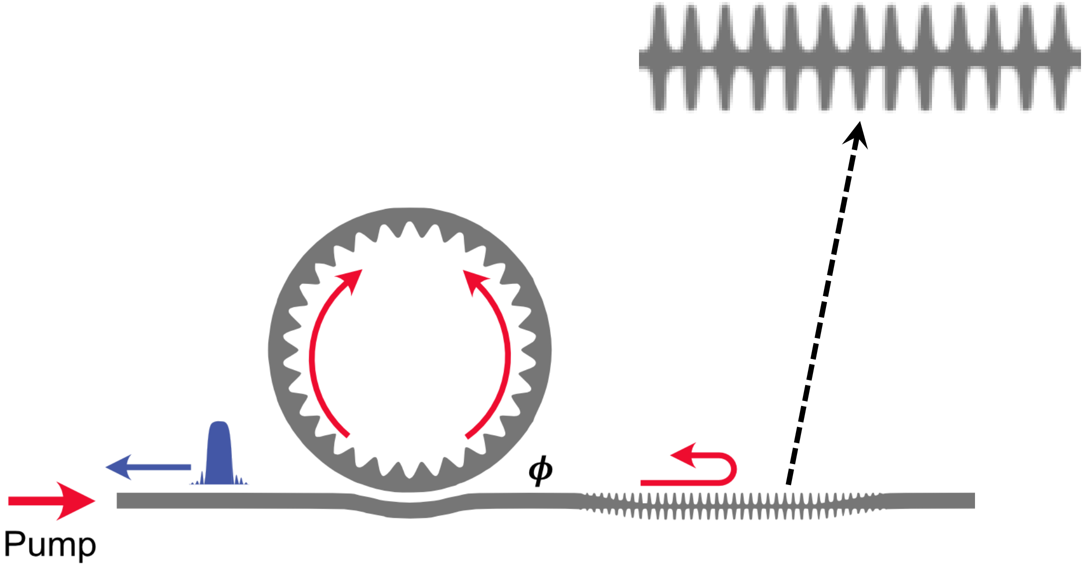
10 Tb/s data link →

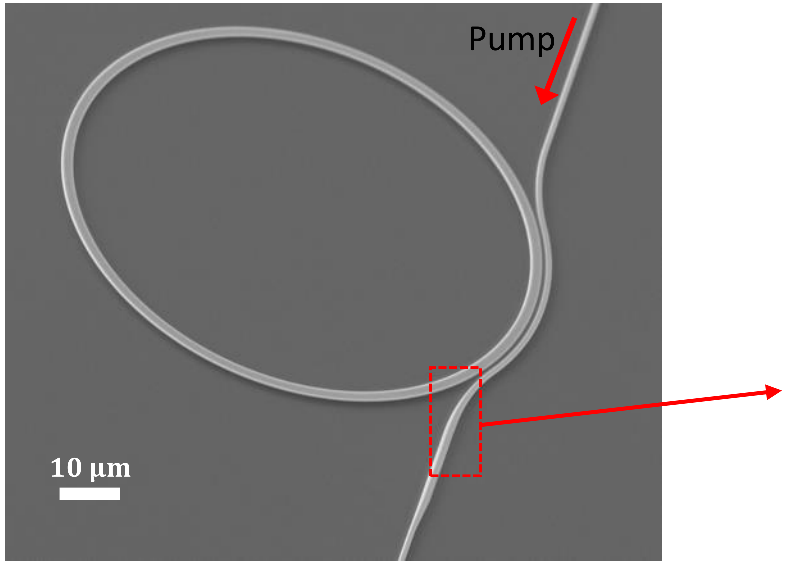
Needed for data centers and next-gen computing

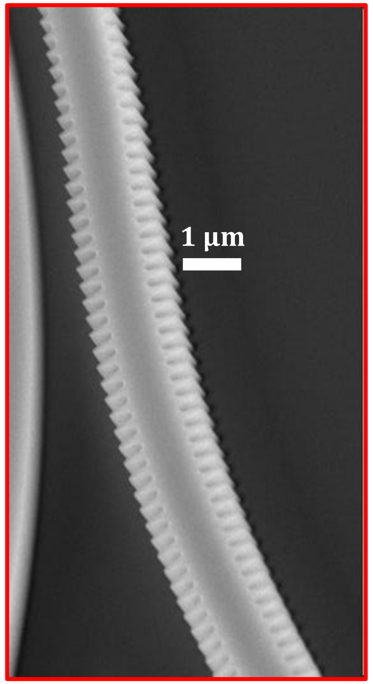
Collaboration: UPenn, NIST, Stanford, UCF

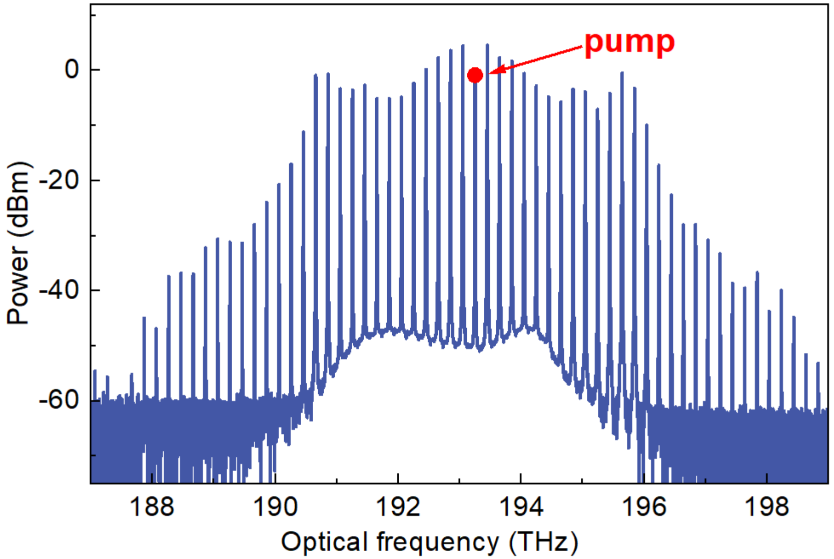
Nanophotonic microcombs

A photonic crystal reflector for “pump recycling”





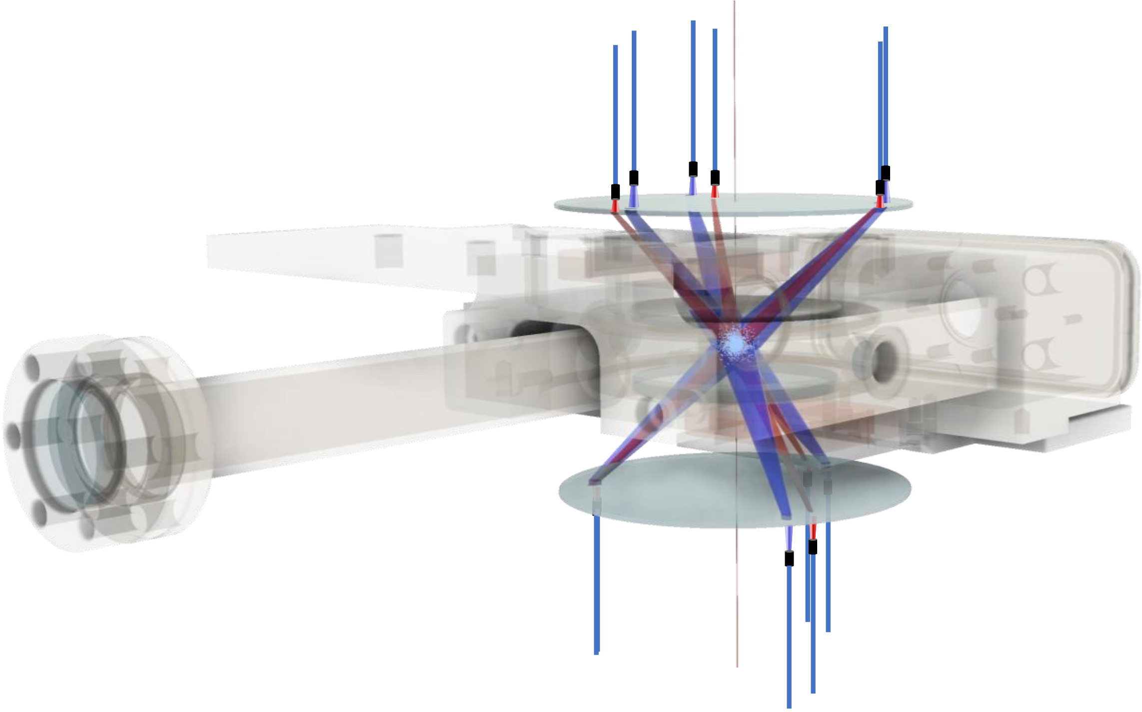




S. P. Yu et al. Nature Photonics 2021
S. P. Yu et al. Nature Communication 2022
E. Lucas et al. Nature Photonics 2023

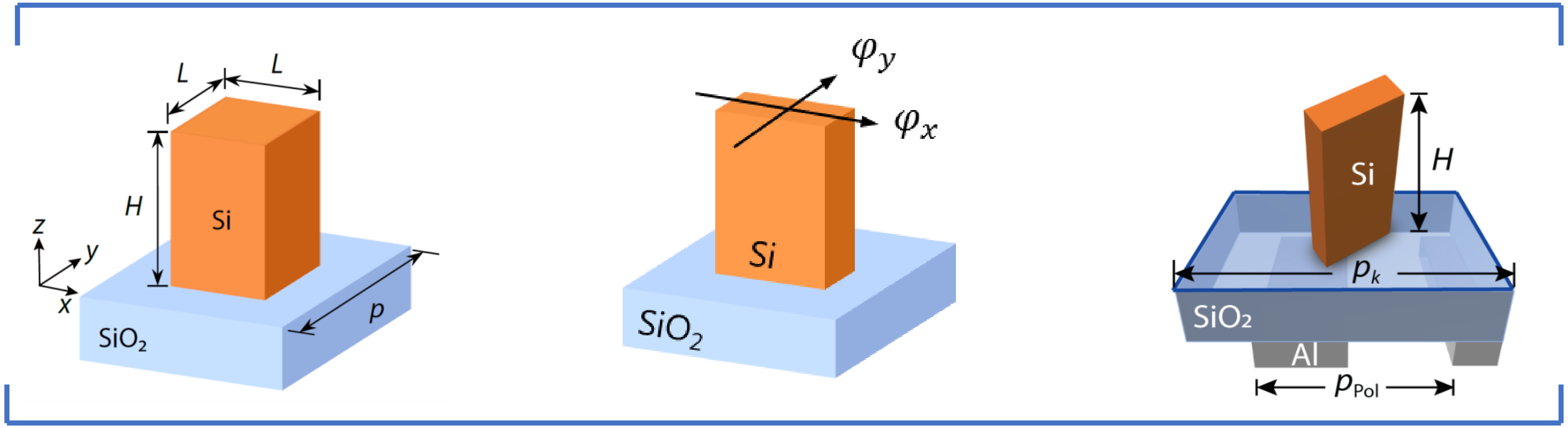
Scalable infrastructure for Sr clocks

metasurface optics:
atom-photonic interface



Metasurface optics

Propagation phase



Input = $\begin{pmatrix}1\\0\end{pmatrix}$

$\phi_x = \phi_y + \pi/2$ (QWP)

$\phi_x = \phi_y + \pi$ (HWP)

Output :	$\begin{pmatrix}1\\0\end{pmatrix} e^{i\phi}$	$\begin{pmatrix}1\\i\end{pmatrix} e^{i\phi_x}$	$\begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}\cos 2\theta & \sin 2\theta\\ \sin 2\theta & -\cos 2\theta\end{pmatrix} e^{i\phi_x}$	$\begin{pmatrix}1\\0\end{pmatrix} e^{i\phi_x}\cos 2\theta$
Control of :	Phase	Ellipticity and phase	Polarization and phase	Amplitude and phase

Metasurface optics

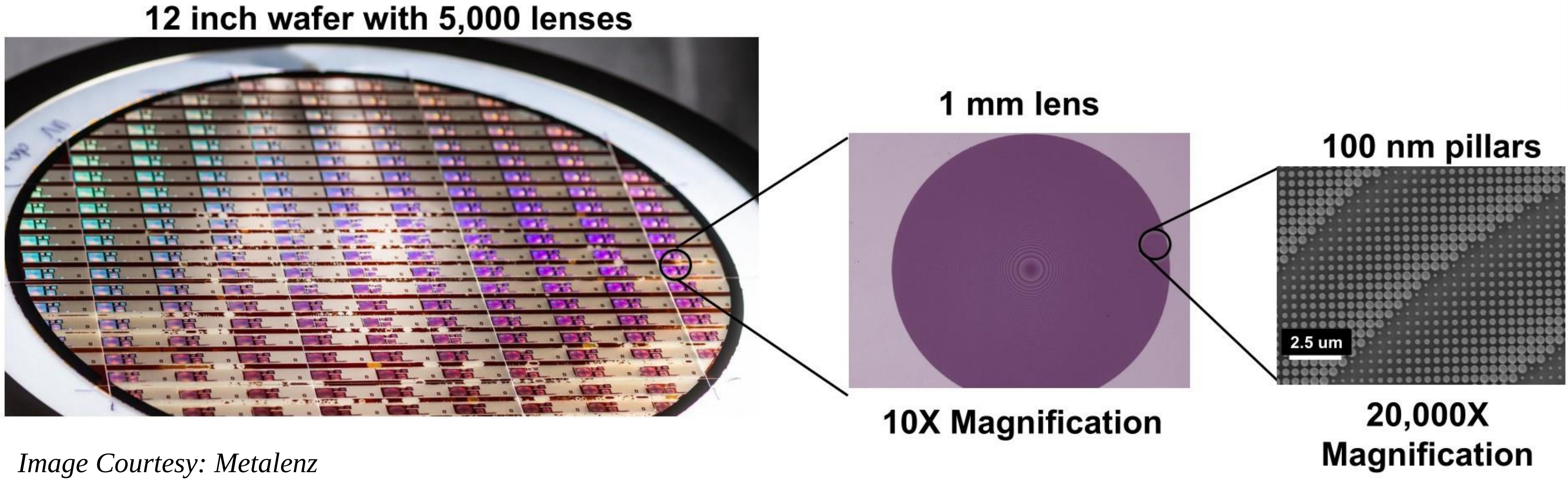
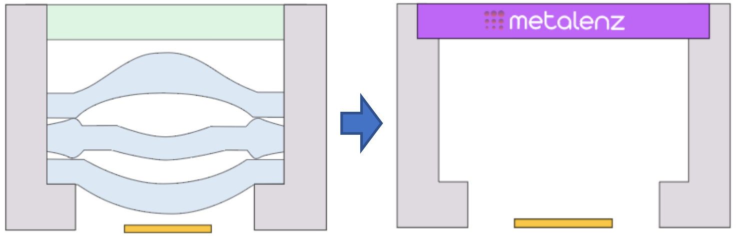
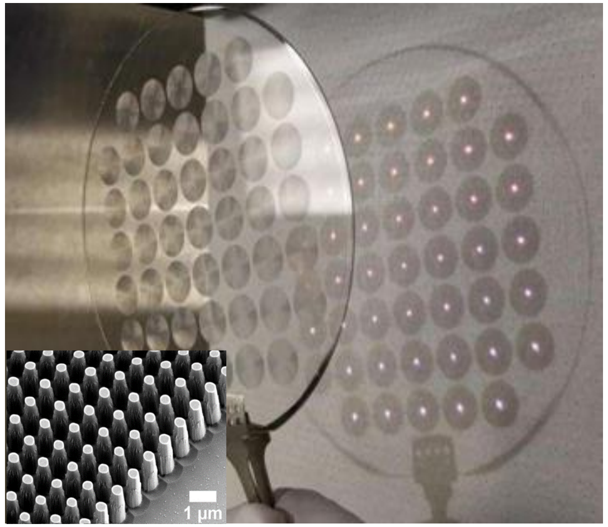


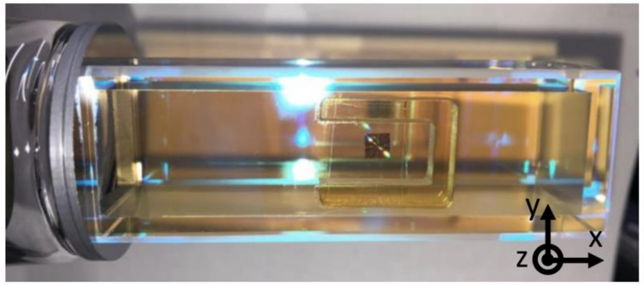
Image Courtesy: Metalenz

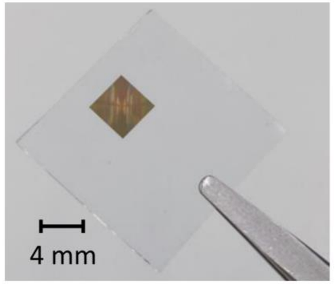


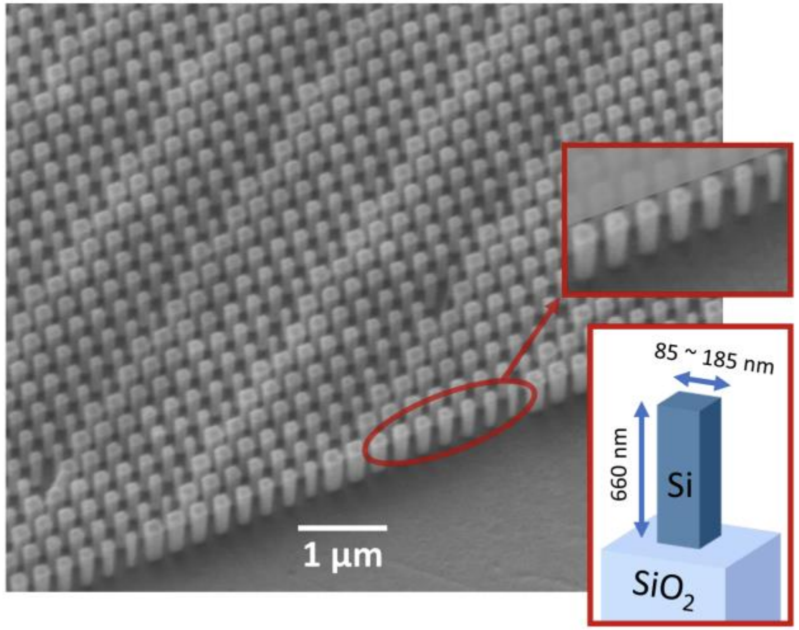


Nano Lett. **19**, 8673 (2019)

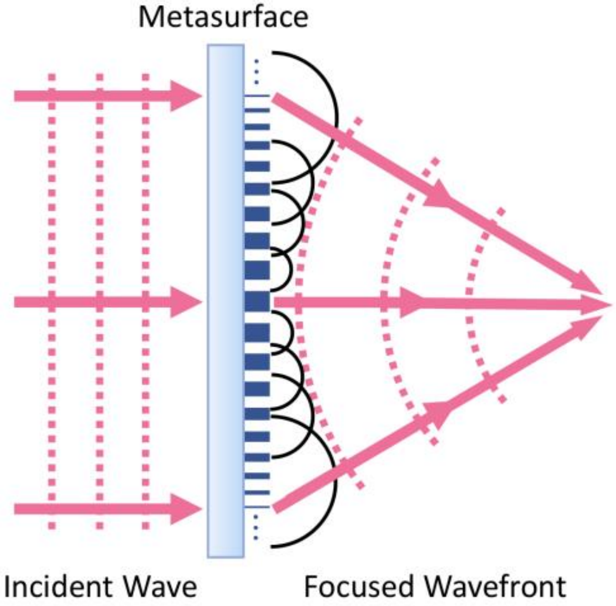
Pilot experiment: Rb single-atom trapping





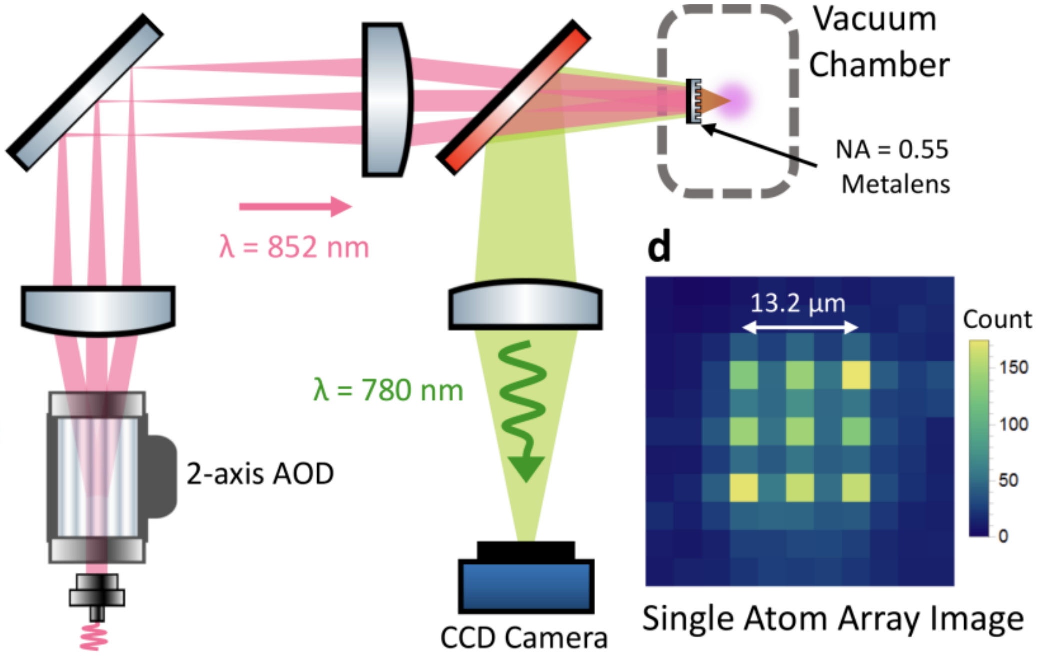


metasurface
amorphous silicon on fused silica



metasurface lens
concept

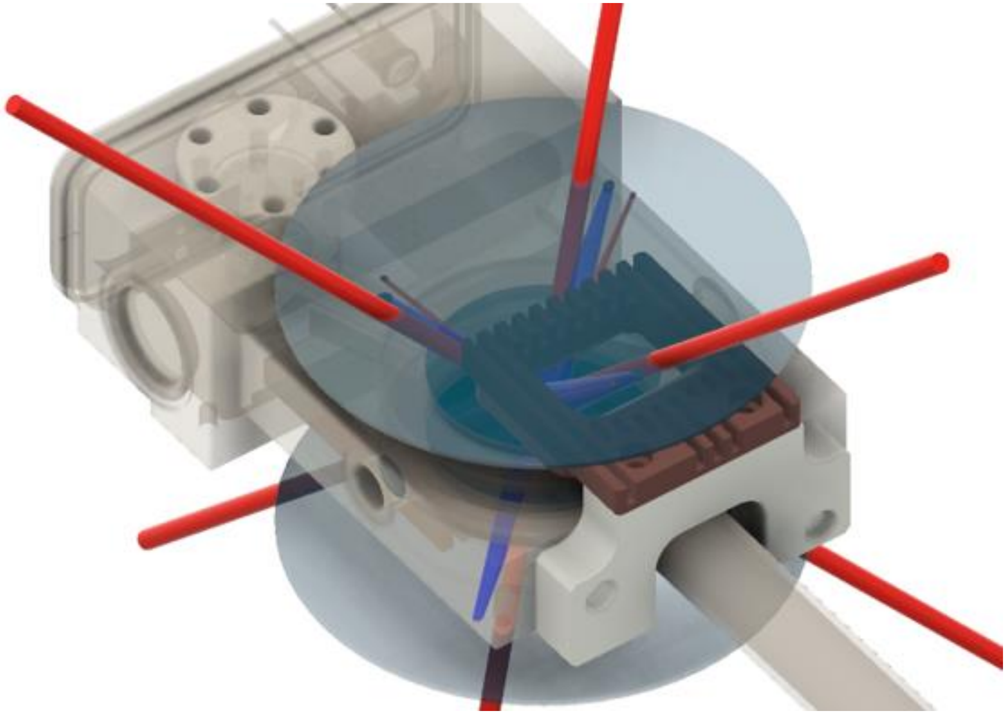
Atom trapping configuration for
single-atom array creation and imaging

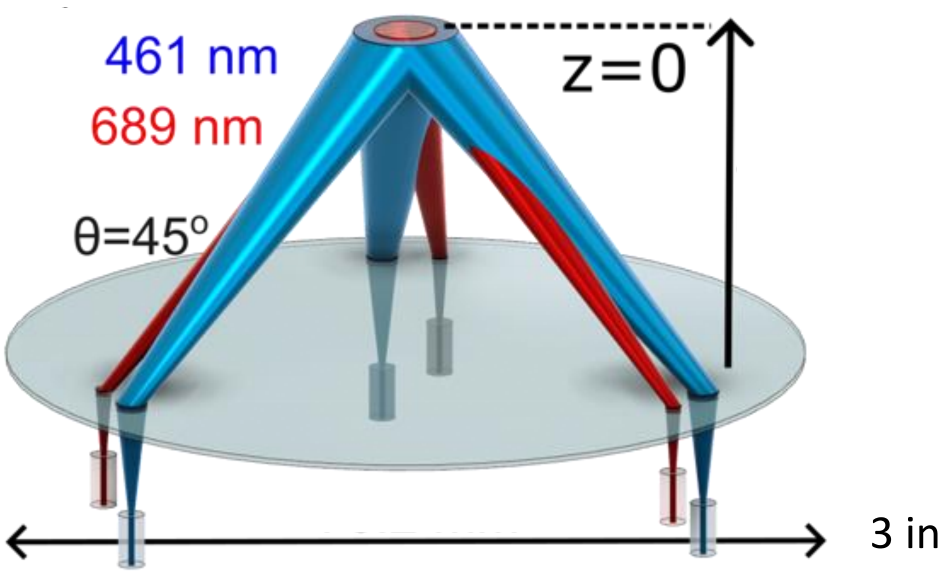


Single Atom Array Image

T. W. Hsu et al. PRX Quantum 2022

MS optics system for Sr

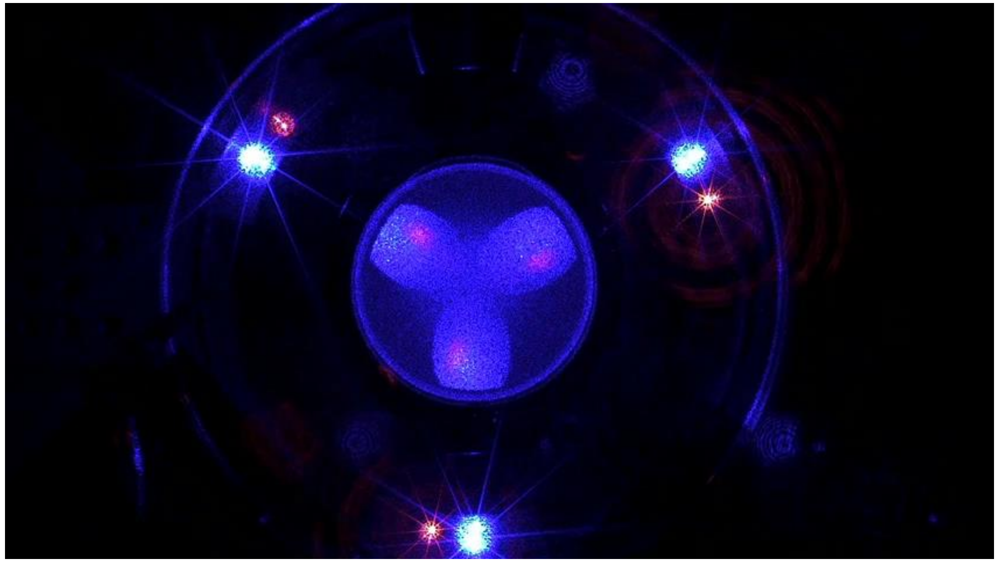




Metasurface	η_{MS} (%)	DOCP (%)
Blue	45 ∓ 2	92
Red	49 ∓ 2	96

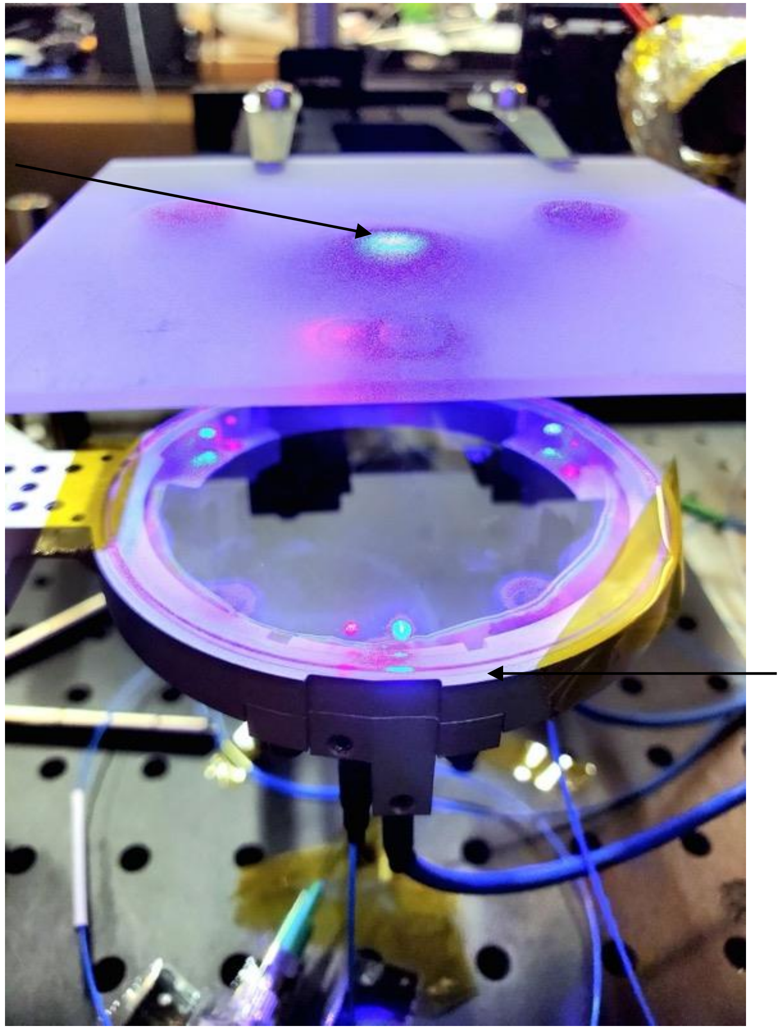
Sr MS system: Optical assembly and test

Field of view: 101.6 mm



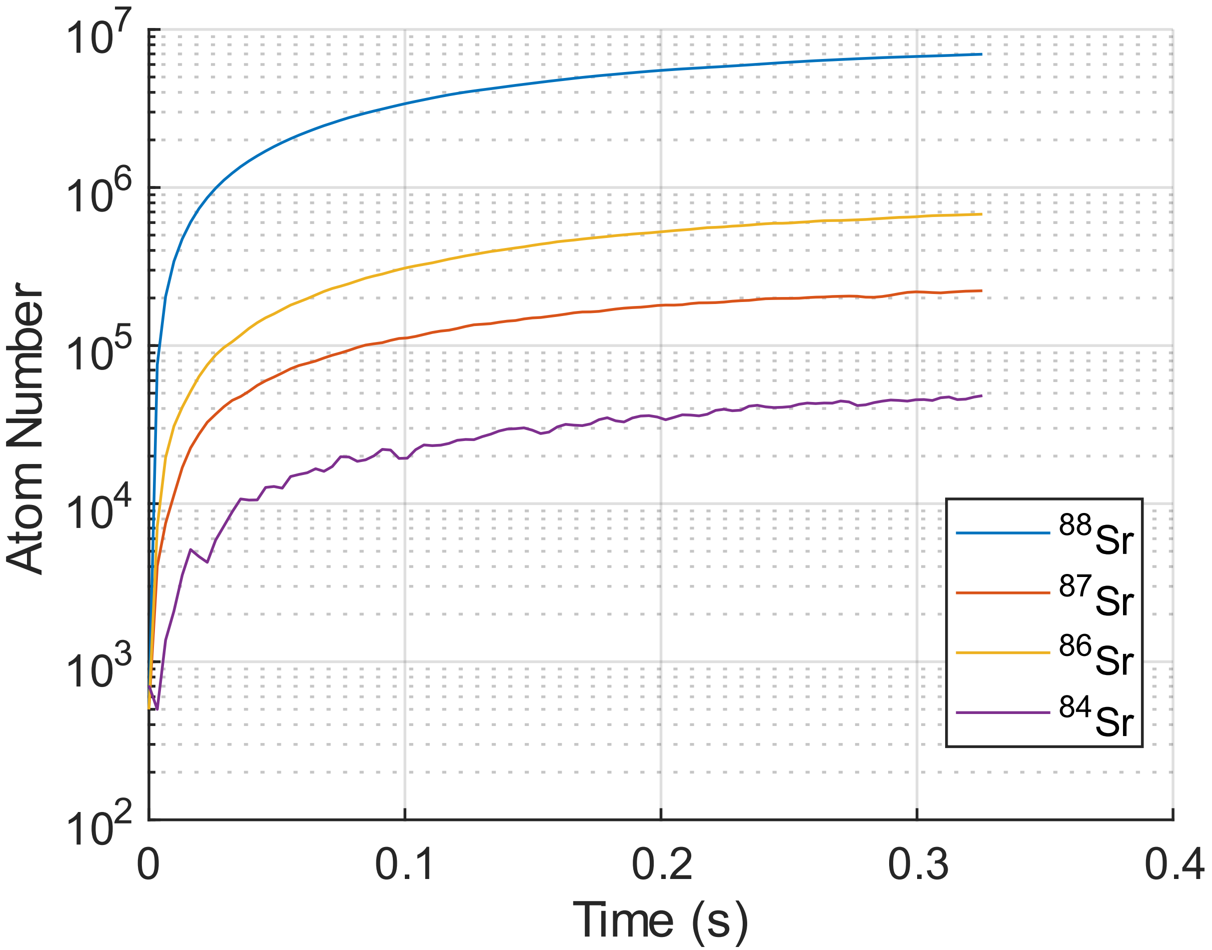
55.9 mm

461 nm and 689 nm beams

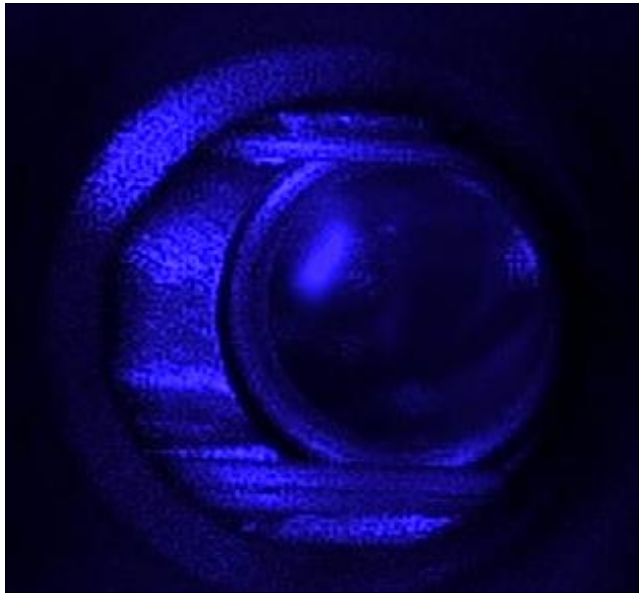


Custom designed Photonics holder

Breakthrough #1: Broad line trapping

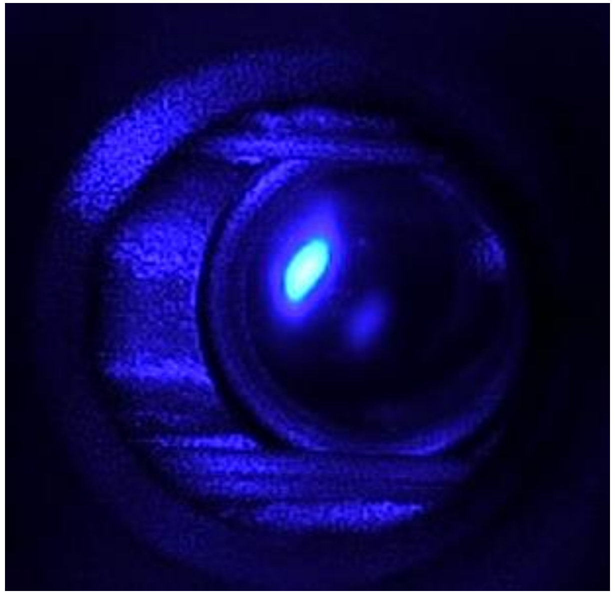


^{87}Sr



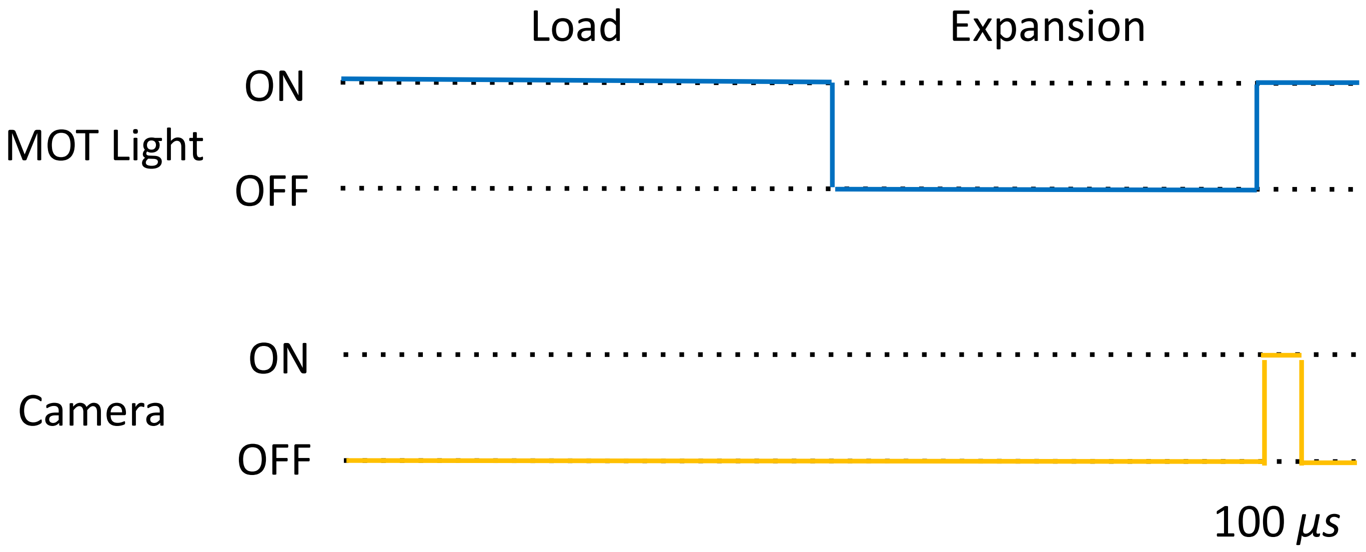
3×10^5 atoms

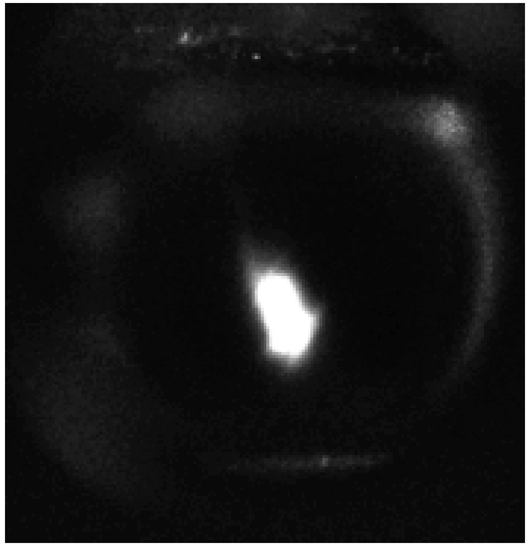
^{88}Sr



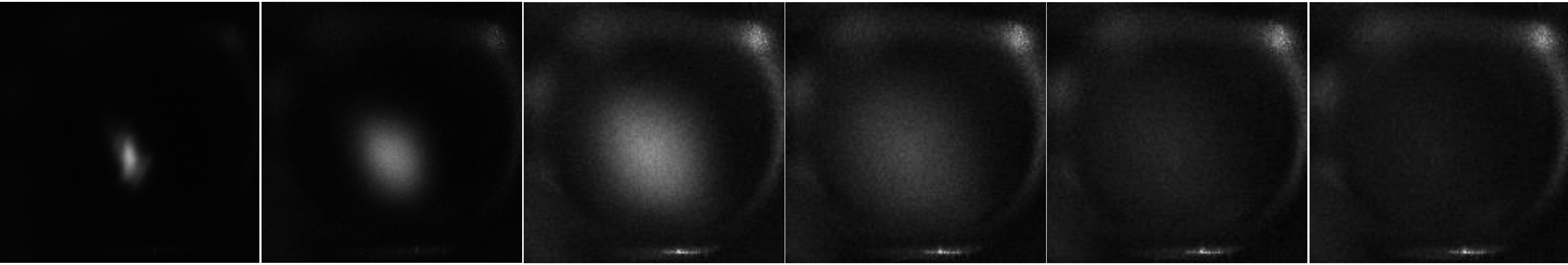
8×10^6 atoms

Time of Flight – MOT Temperature



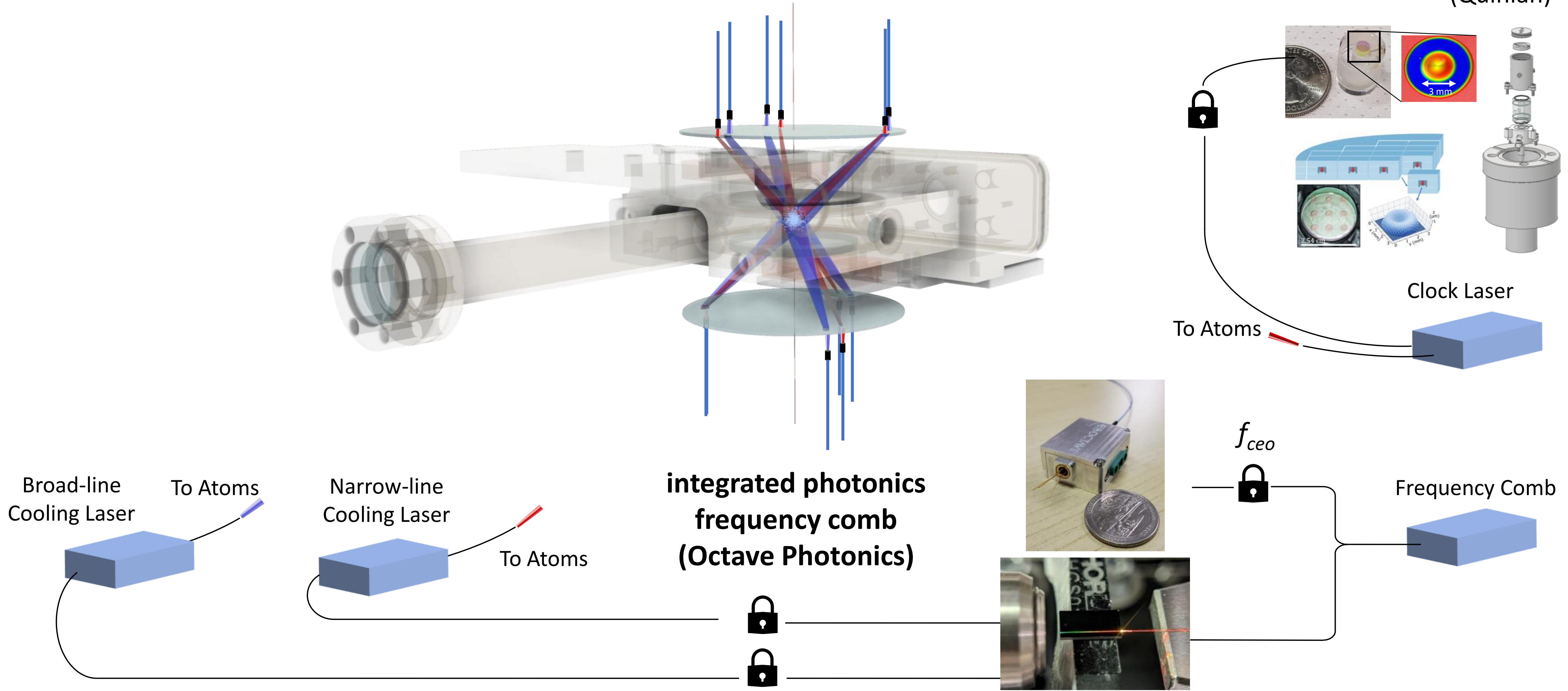


T = 1.7 mK



0 ms
1 ms
2 ms
3 ms
4 ms
5 ms

Scalable infrastructure for Sr clocks



atom-photonic Interface

Micro Fabry-Perot Cavity (Quinlan)

Clock Laser

To Atoms

f_{ceo}

Frequency Comb

Broad-line Cooling Laser

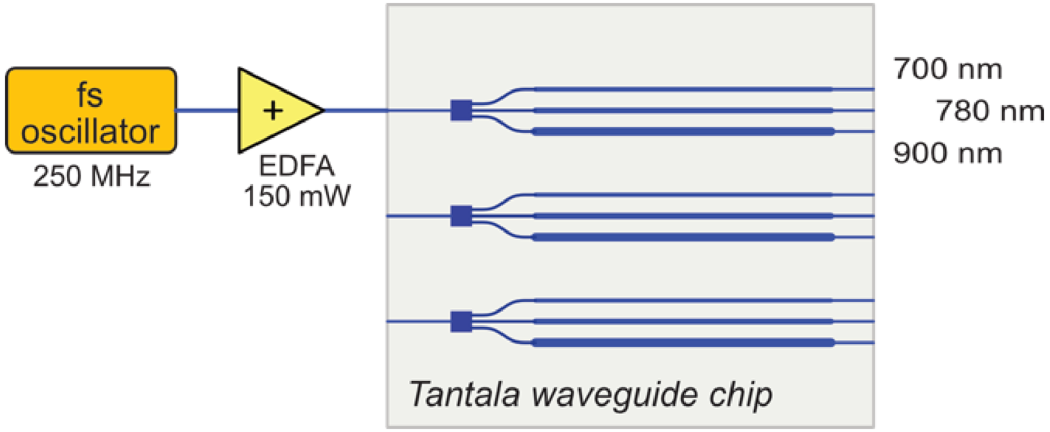
To Atoms

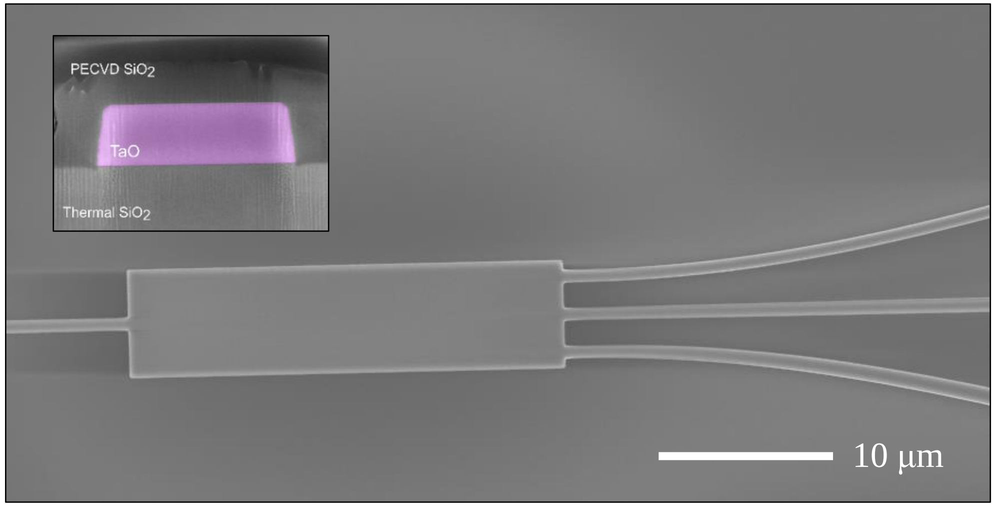
Narrow-line Cooling Laser

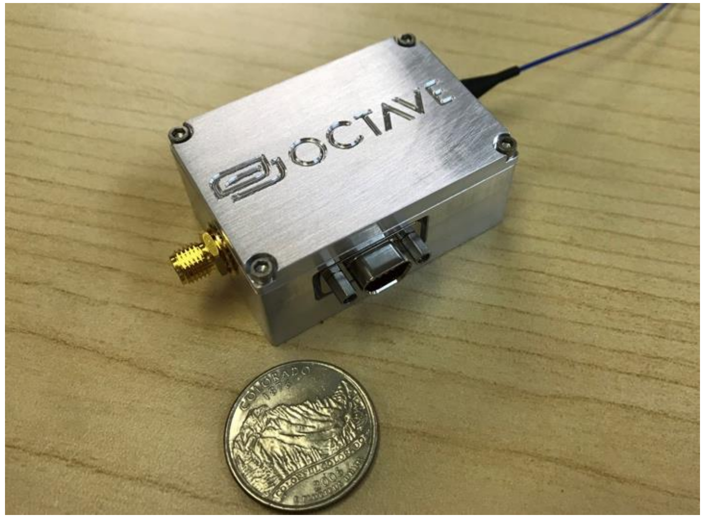
To Atoms

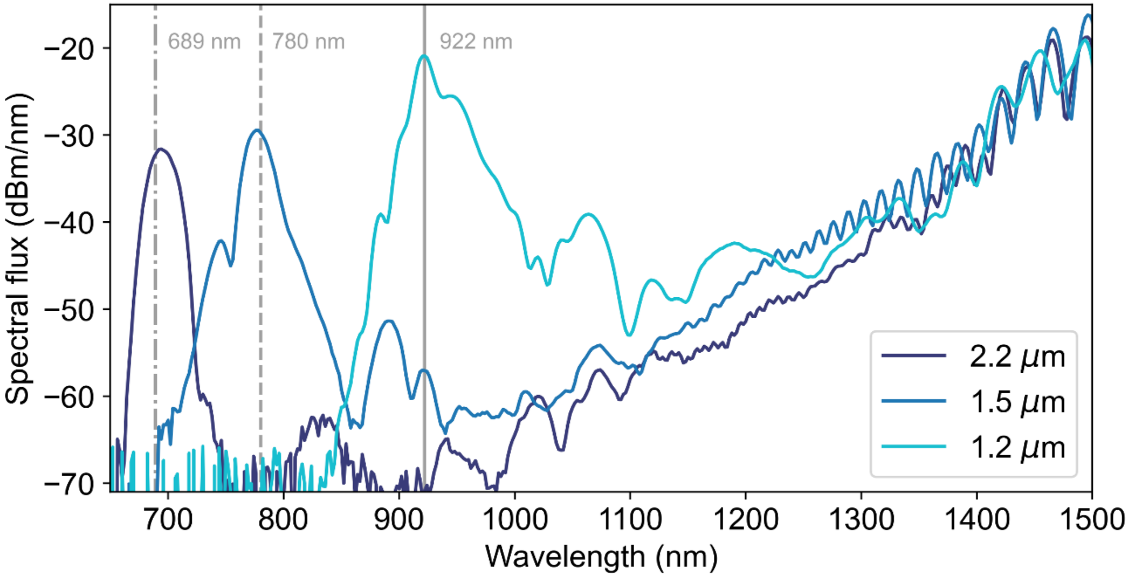
integrated photonics frequency comb (Octave Photonics)

Laser stabilization with waveguides



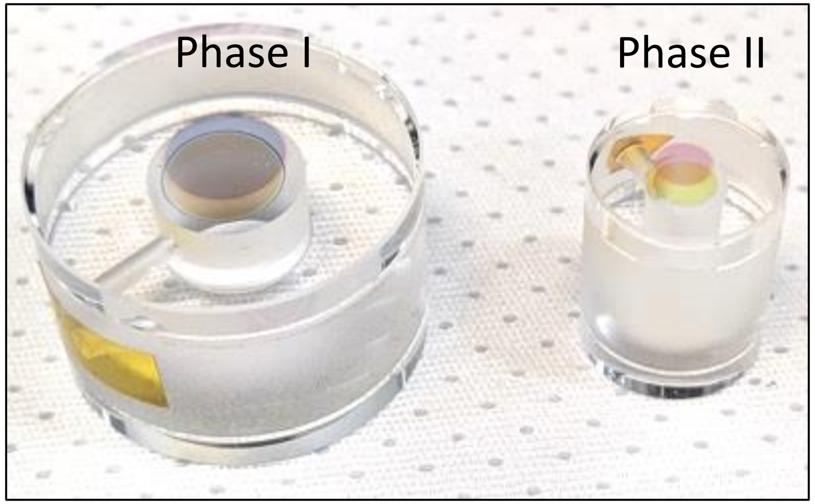




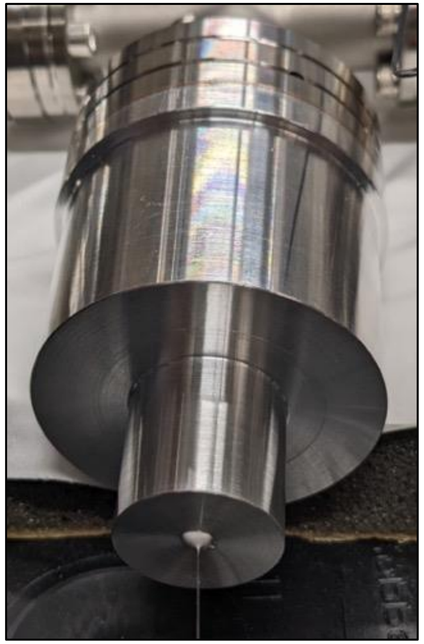


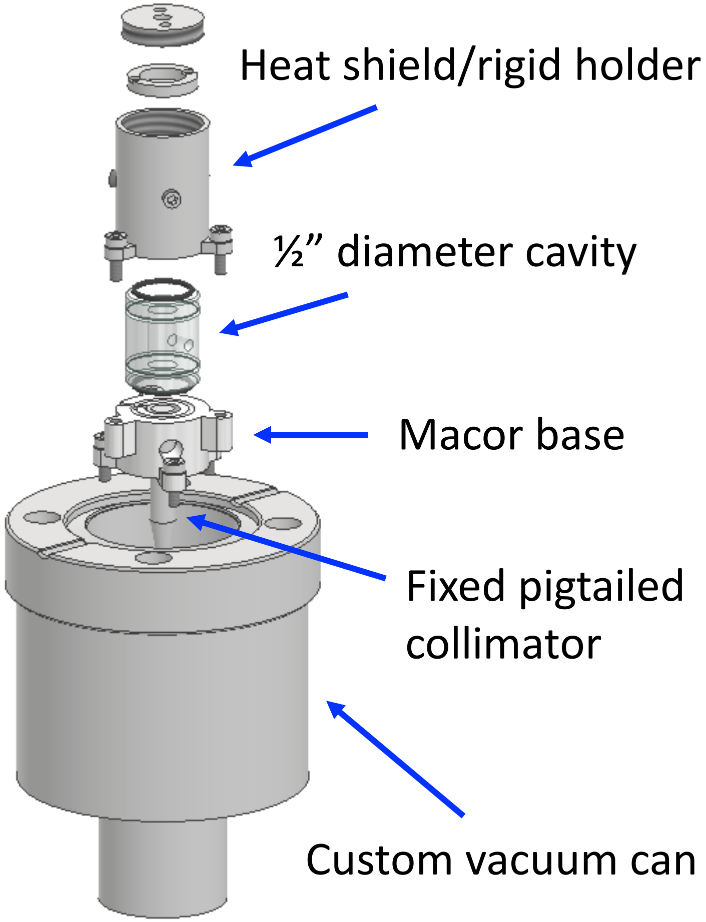
Chip-scale clock lasers

Frank Quinlan



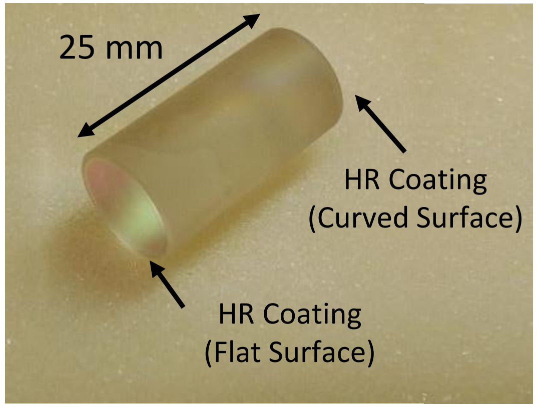
Compact vacuum Can

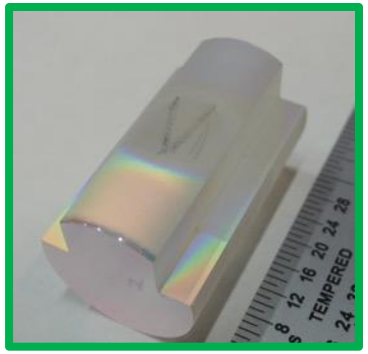


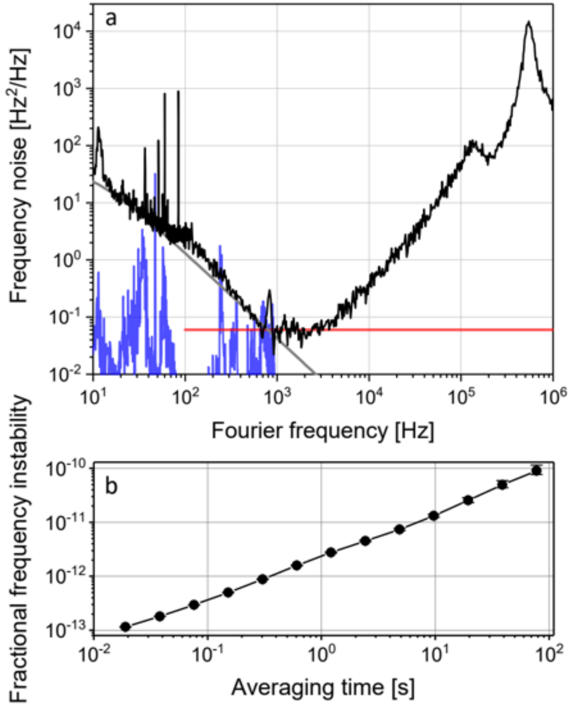


Chip-scale clock lasers

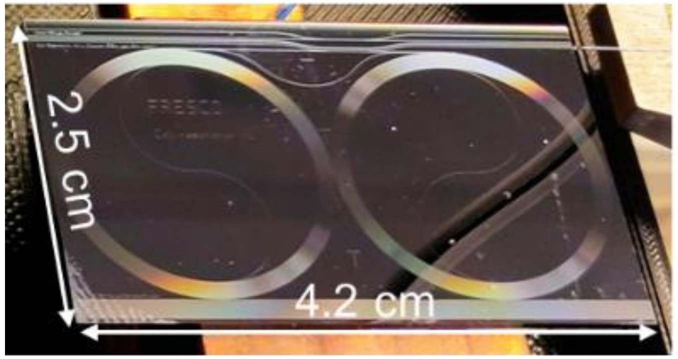
Scott Papp group, NIST
Q = 5 billion
Thermal-noise limited performance
~30 Hz linewidth & ~1 kHz/s drift

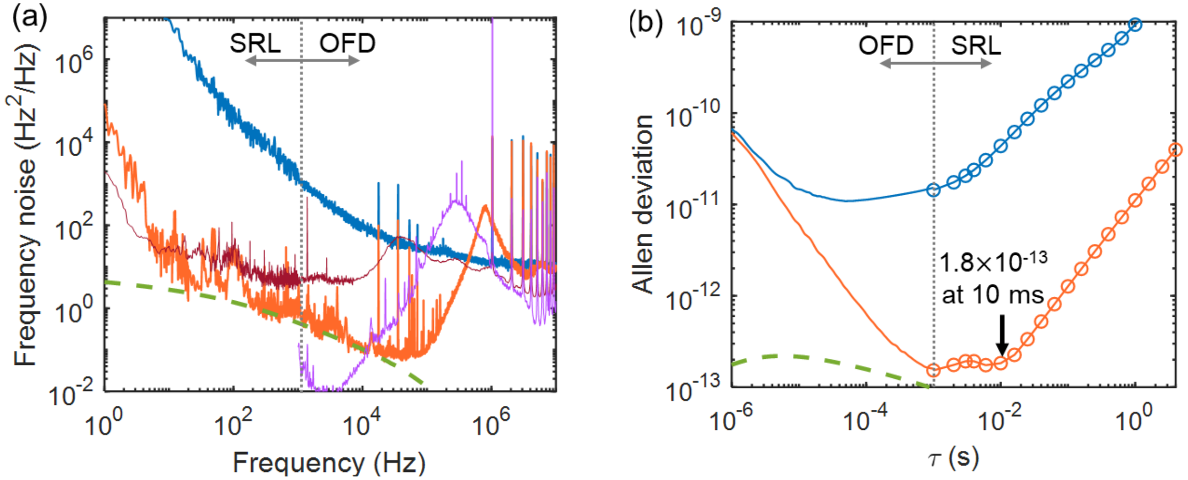






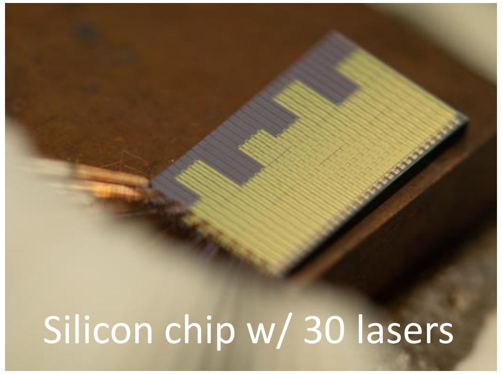
Dan Blumenthal (UCSB) **/ SP collaboration**
Q = 720 million
Thermal-noise limited performance
~30 Hz linewidth & ~1 kHz/s drift

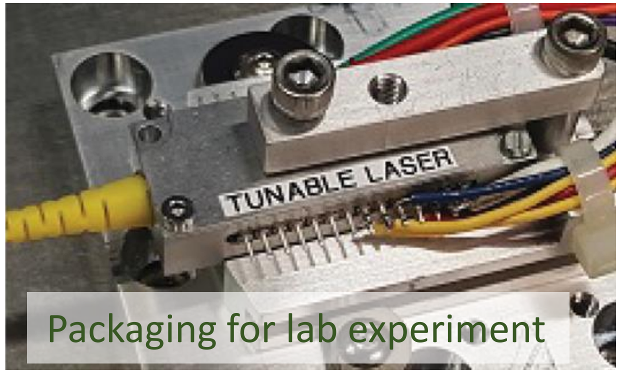




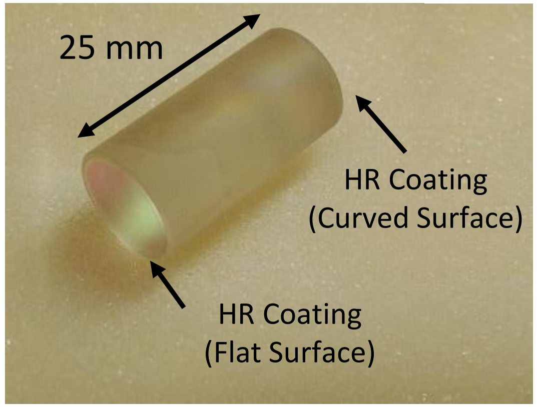
Heterogeneously integrated clock laser

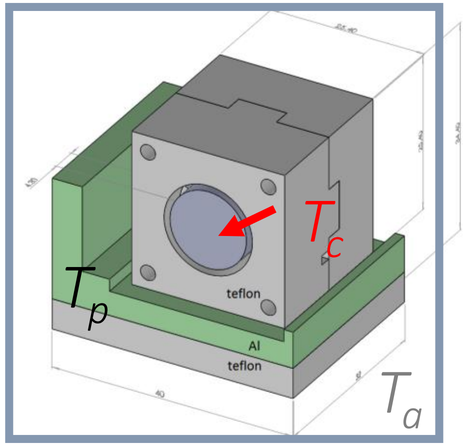
UCSB III/V-Si tunable laser + NIST photonic resonator

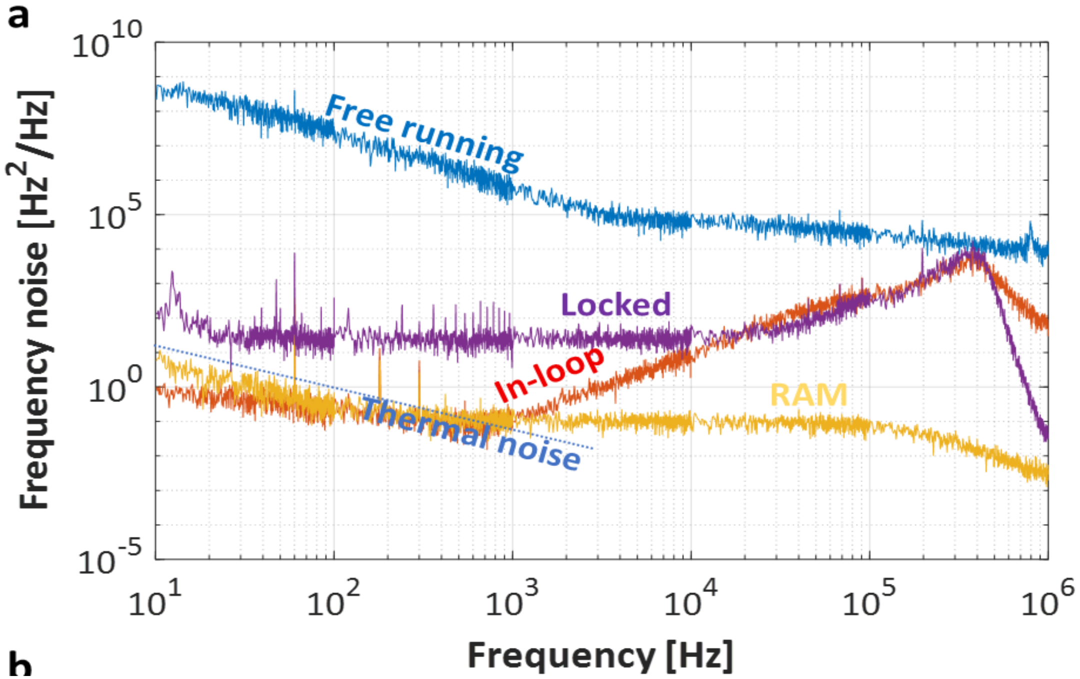

Silicon chip w/ 30 lasers



Packaging for lab experiment



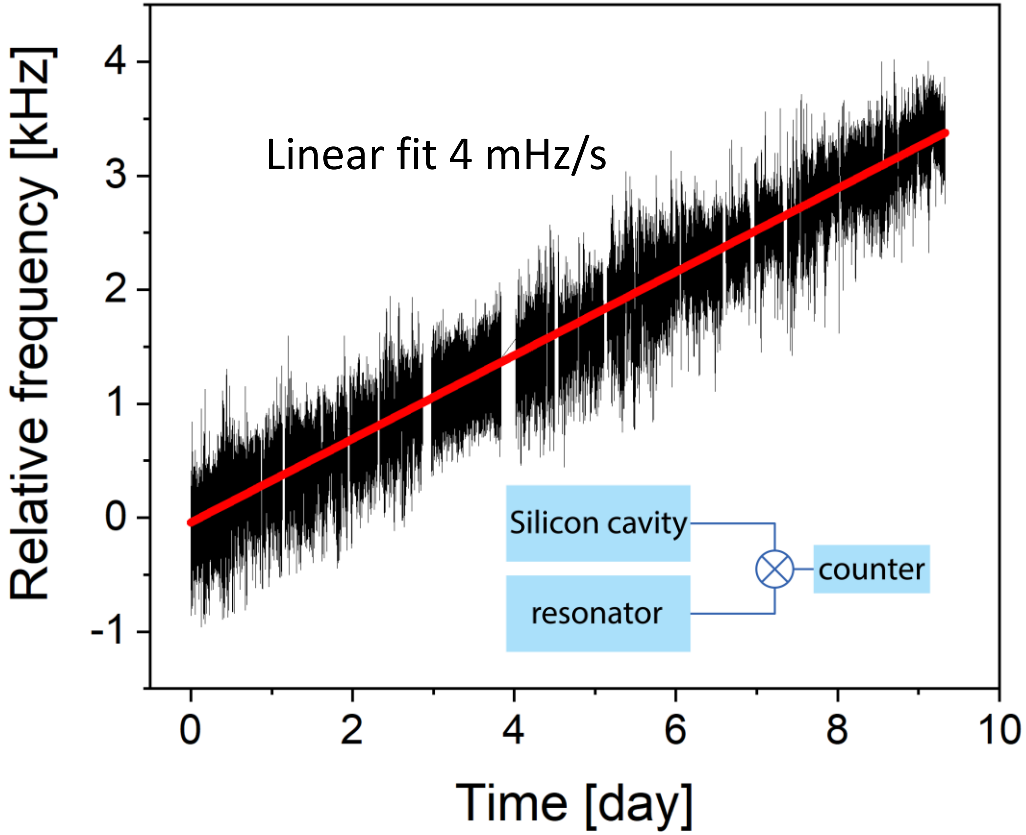




L. Stern et al. Opt. Lett. 2020

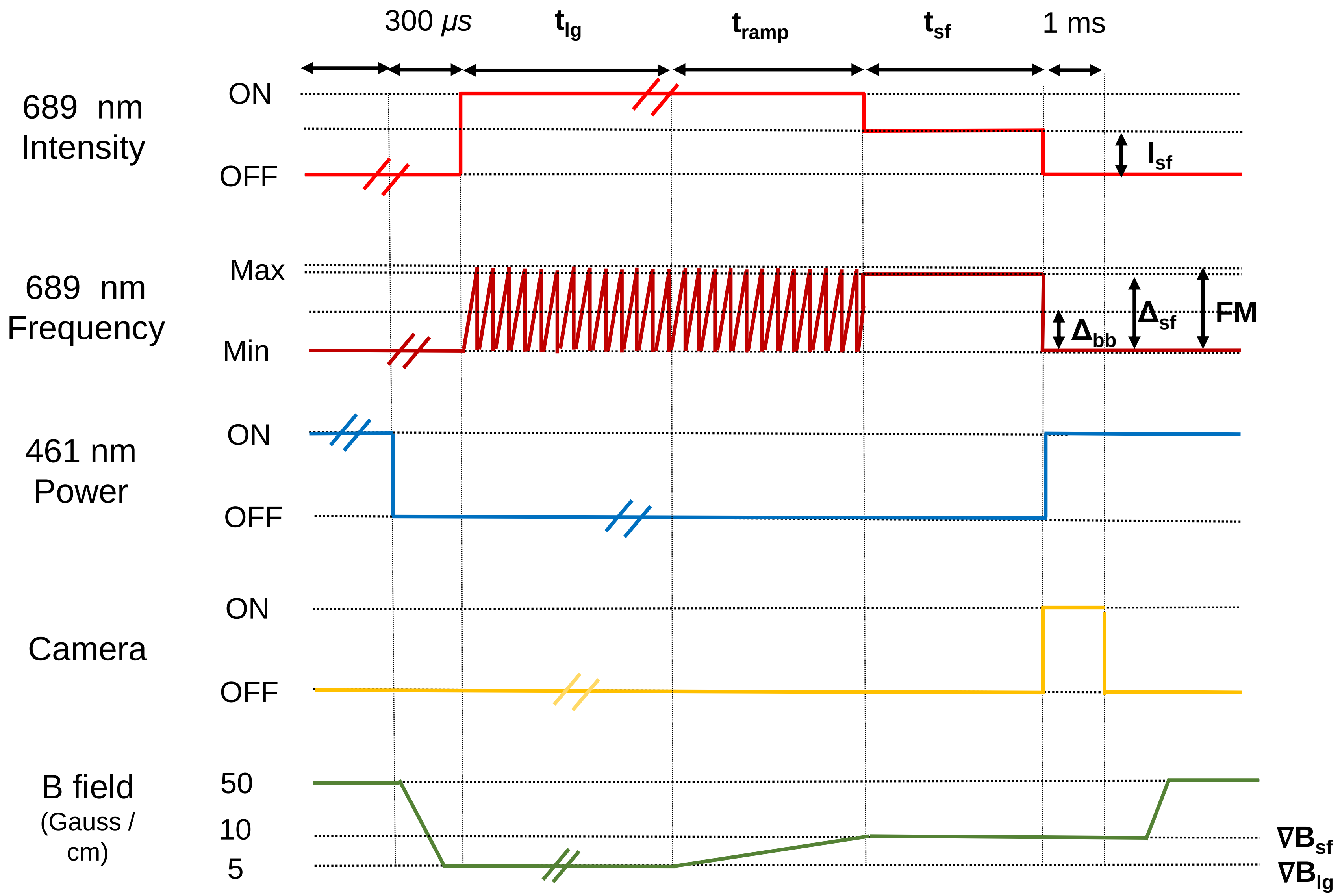
Ultralow drift at low temperature

NIST (+ JILA for measurement support)



Collaboration: Wei Zhang, Andrey Matsko JPL

Narrow Line MOT Sequence

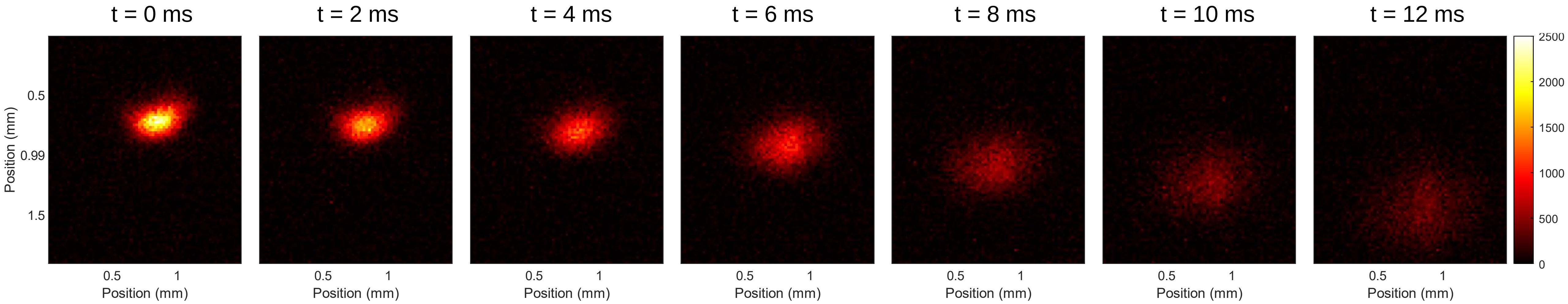


Variables:

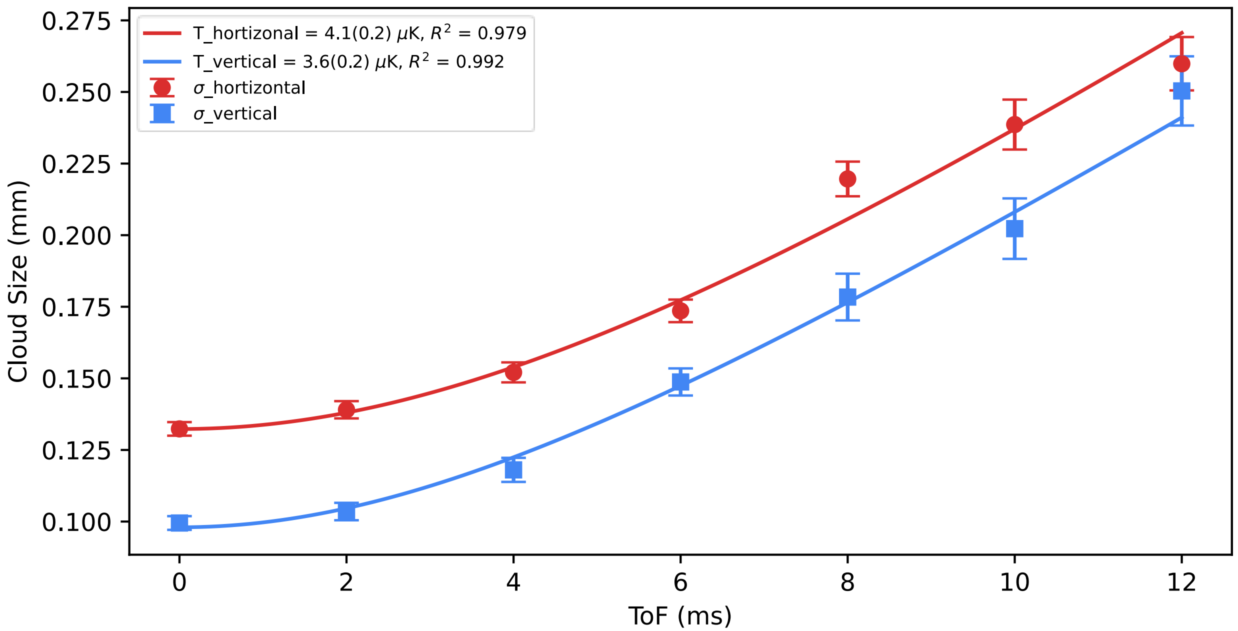
- t_{lg} – time low gradient
- t_{ramp} – time B gradient ramp
- t_{sf} – time single frequency cooling
- I_{sf} – 689 nm intensity single frequency cooling
- Δ_{sf} – 689 nm single frequency detuning
- **FM** – 689 nm frequency modulation during broadband cooling
- Δ_{sf} – 689 nm single frequency detuning
- Δ_{bb} – 689 nm center frequency detuning during broadband cooling
- ∇B_{lg} – magnetic field gradient low point
- ∇B_{sf} – magnetic field gradient at single frequency cooling

Controlled with Argent
Ludlow group, NIST

Breakthrough #2: Narrow line trapping

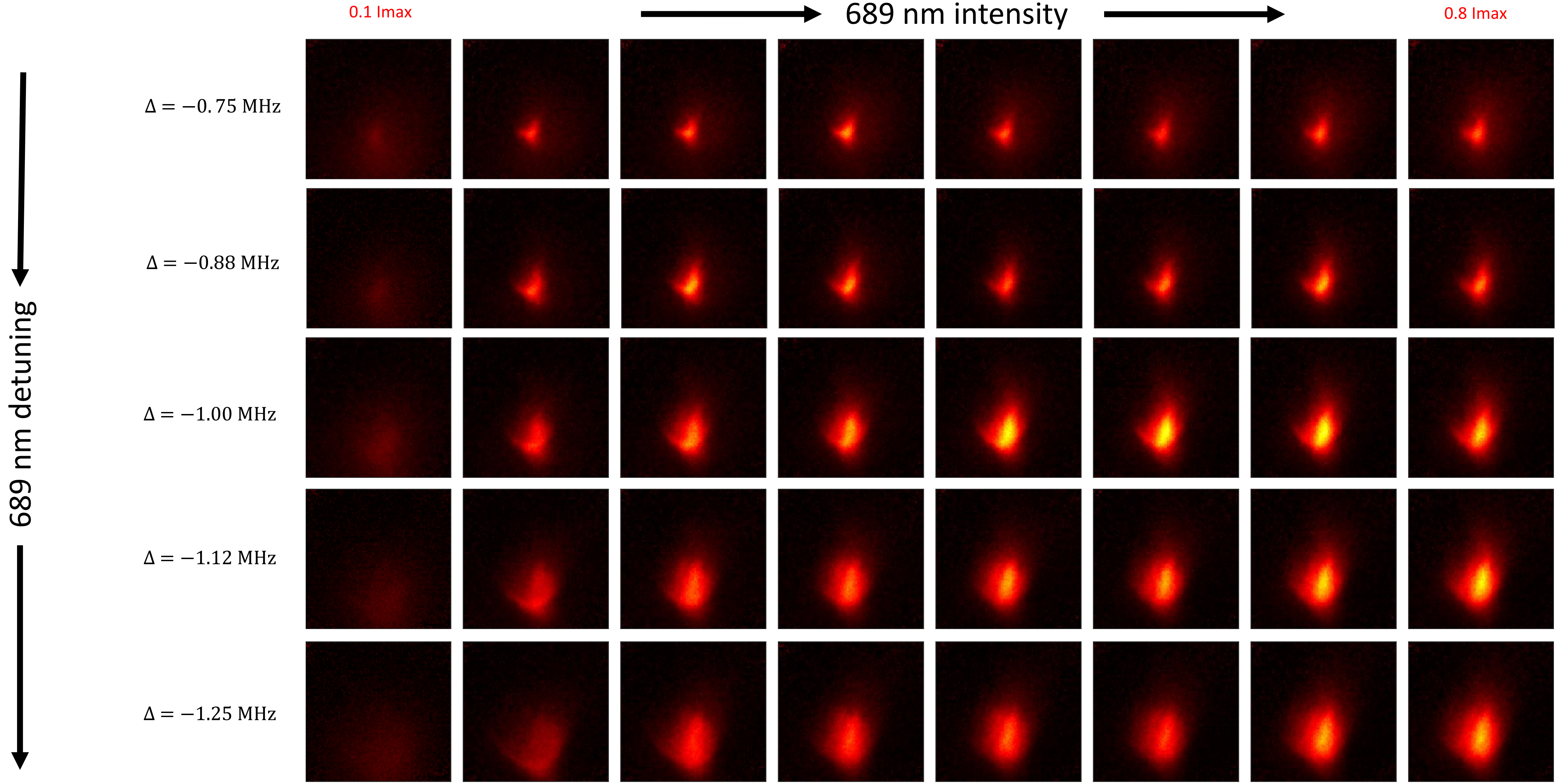


$s_{\text{final}} = 57$
$\Delta = 670\ \text{kHz}$



$T = 4\ \mu\text{K}$

MOT dependence on Δ and s



0.1 Imax → 689 nm intensity → 0.8 Imax

689 nm detuning

$\Delta = -0.75\ \mathrm{MHz}$

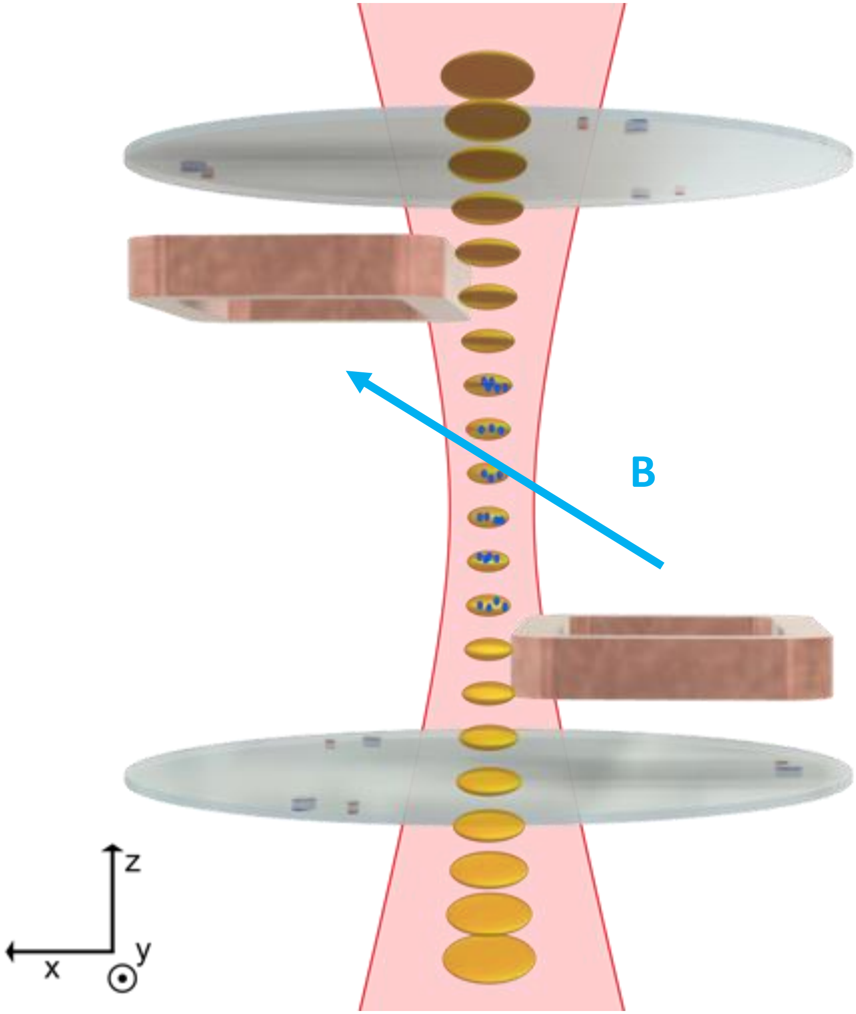
$\Delta = -0.88\ \mathrm{MHz}$

$\Delta = -1.00\ \mathrm{MHz}$

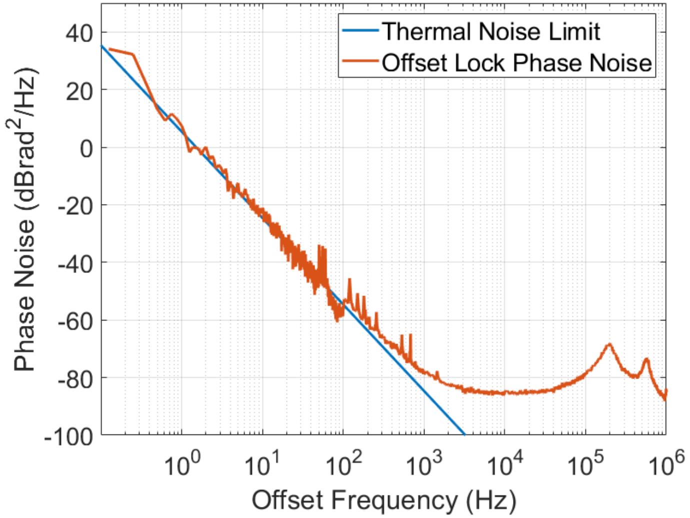
$\Delta = -1.12\ \mathrm{MHz}$

$\Delta = -1.25\ \mathrm{MHz}$

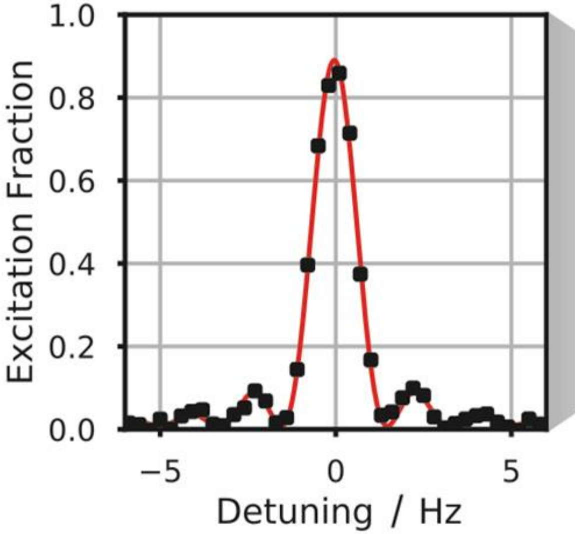
In progress: lattice trapping



Frank's clock laser

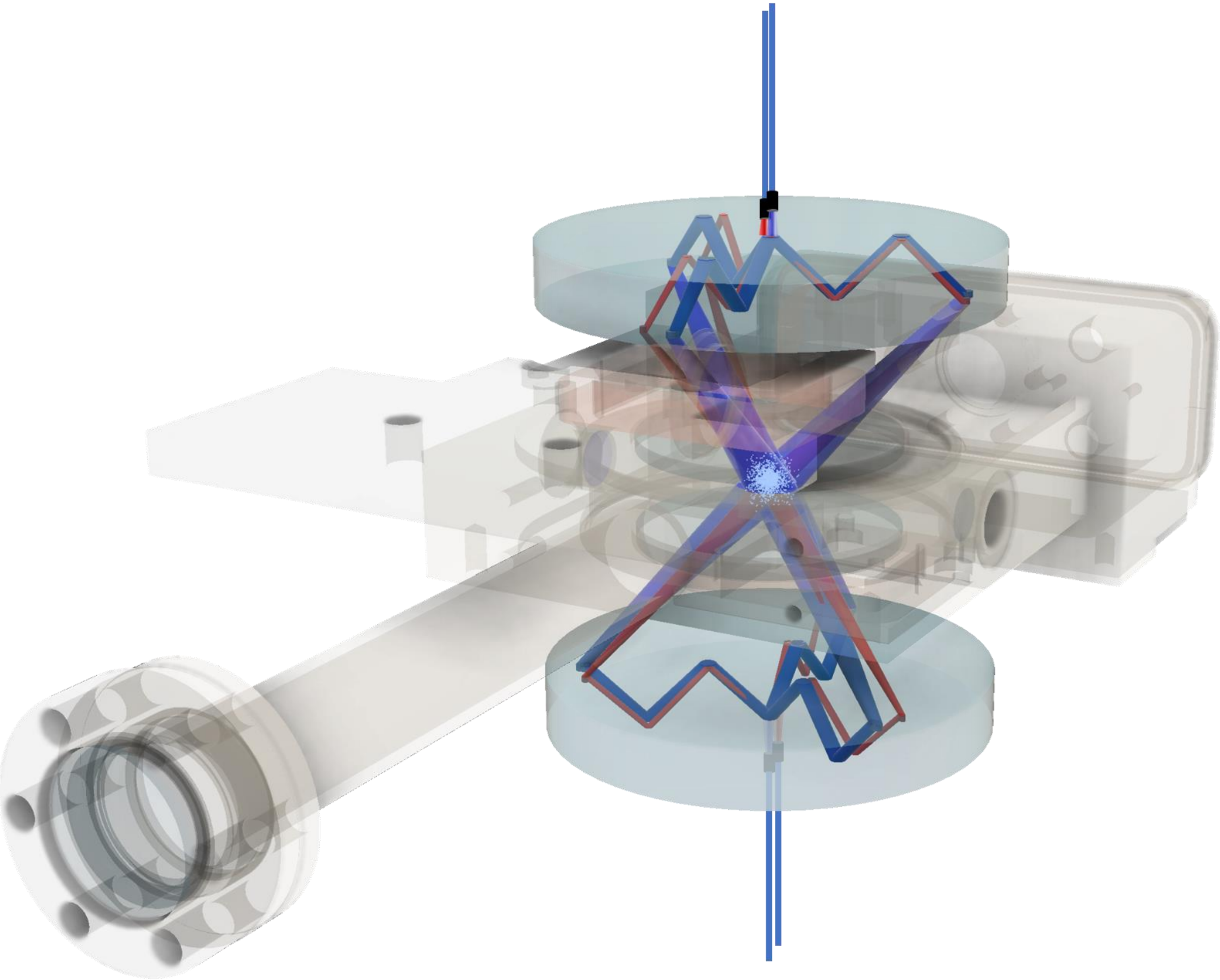


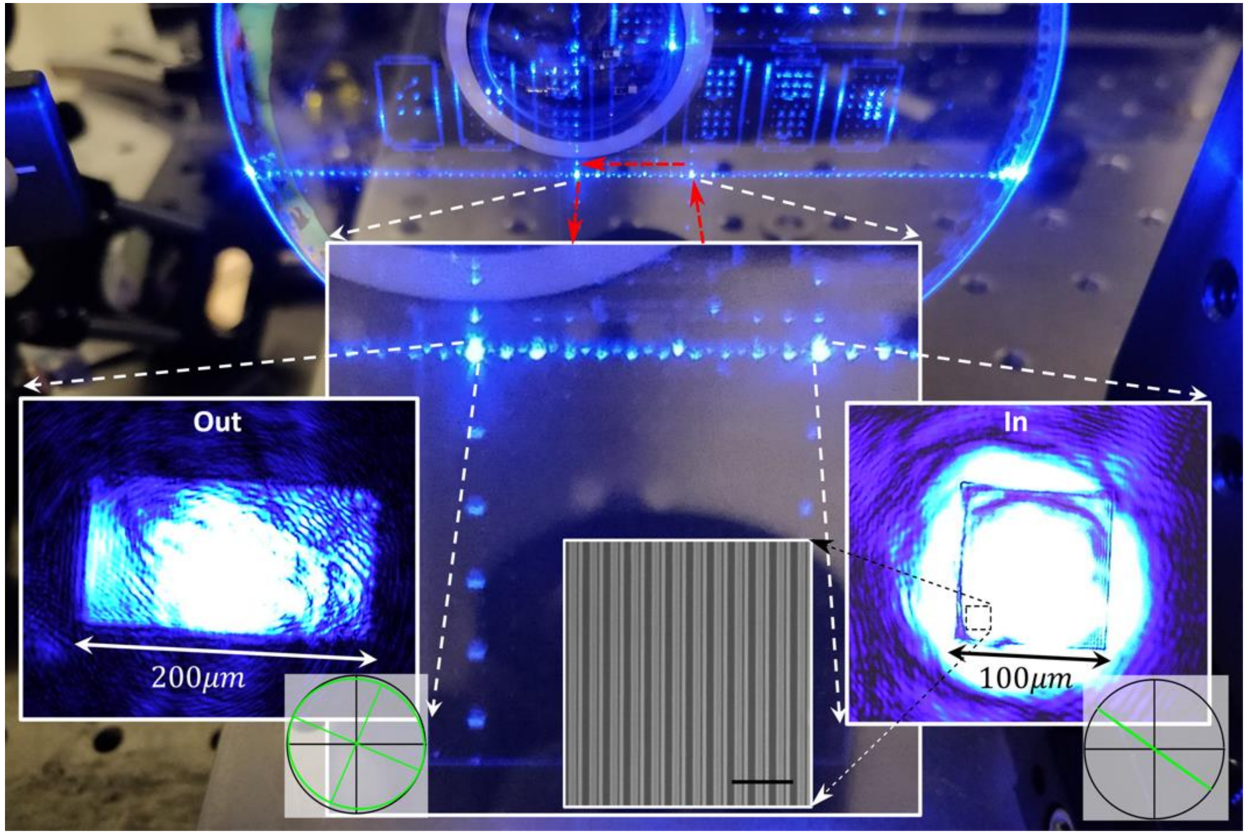
Clock transition search



Bothwell *et al* Metrologia 2019

Further metasurface integration





DARPA A-PhI program

Boulder, CO
Scott Papp (PI)
Frank Quinlan
Scott Diddams
Cindy Regal

- Sr experiments with photonics
- Optical frequency divider combs
- Optical reference cavity

Marty Boyd
Jamil Abo-Shaeer

- Atomic source: Design, fabrication, and testing
- System integration
    - Phase 1 laser cooling
    - Phase 2 deliverable construction and testing.

Gaithersburg, MD
Amit Agrawal
Vladimir Aksyuk
(Kartik Srinivasan)

- Photonic system for atomic interface: Design, fabrication, testing
- Photonic interface for reference cavity: Design, fabrication

Yale University

Peter Rakich
- Micro FP cavity design/fab/test

Caltech

Kerry Vahala
- 10 GHz photonic oscillator

UCSB

John Bowers
- SHG for clock laser

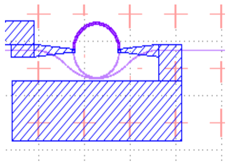
Heterogeneous laser integration for visible

SOA and WG-facet laser-mirror

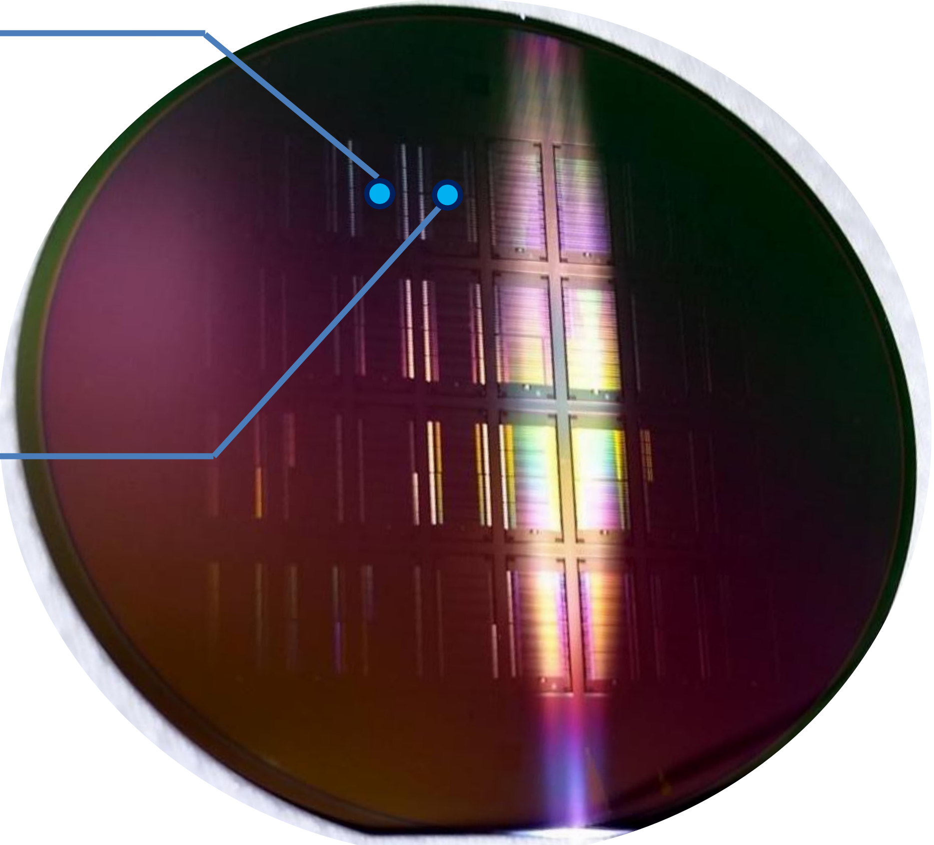
Design Angled facets for 570 nm TaO at 980 nm wavelength

Chip 1

LM+PhCRR laser cavity

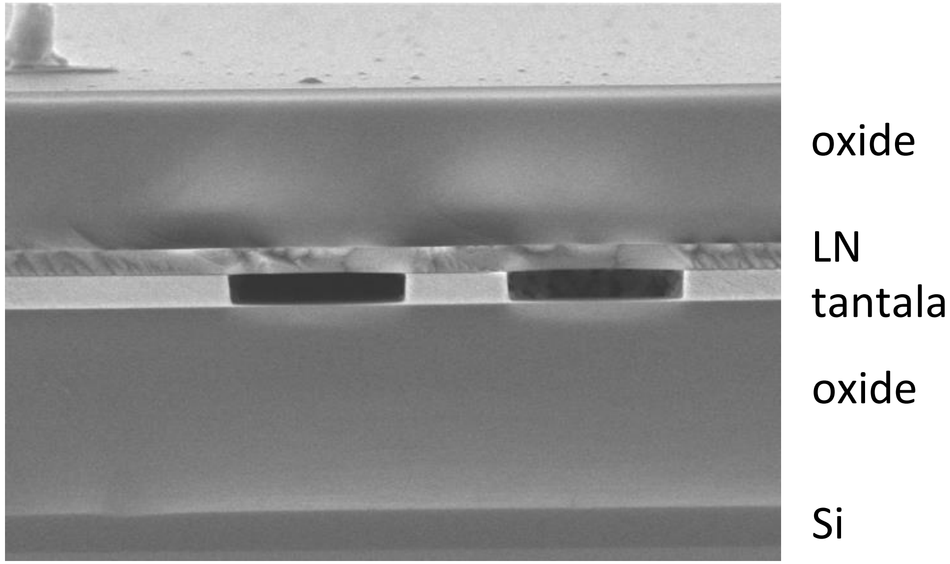


Chip 2



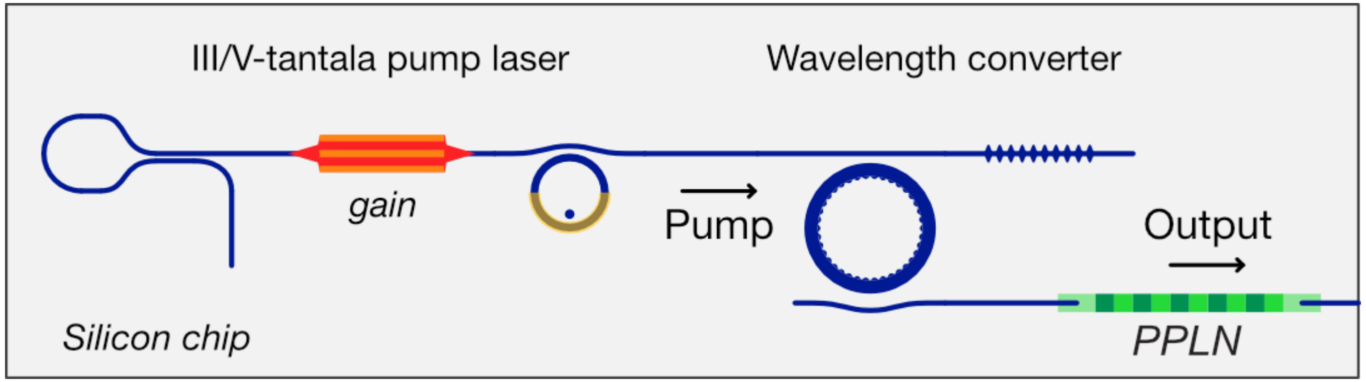
full wafer laser epi layer

III/V-tantala integrated laser + nonlinear optics platform (NIST-Boulder)

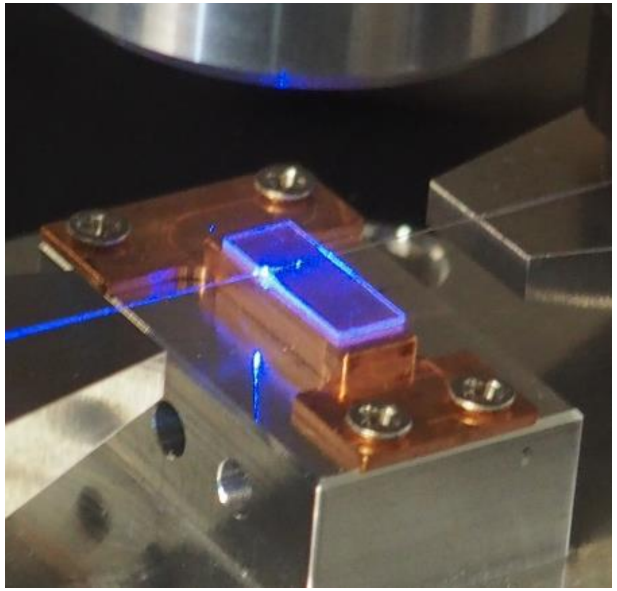


50 mm^2 LN chip areas

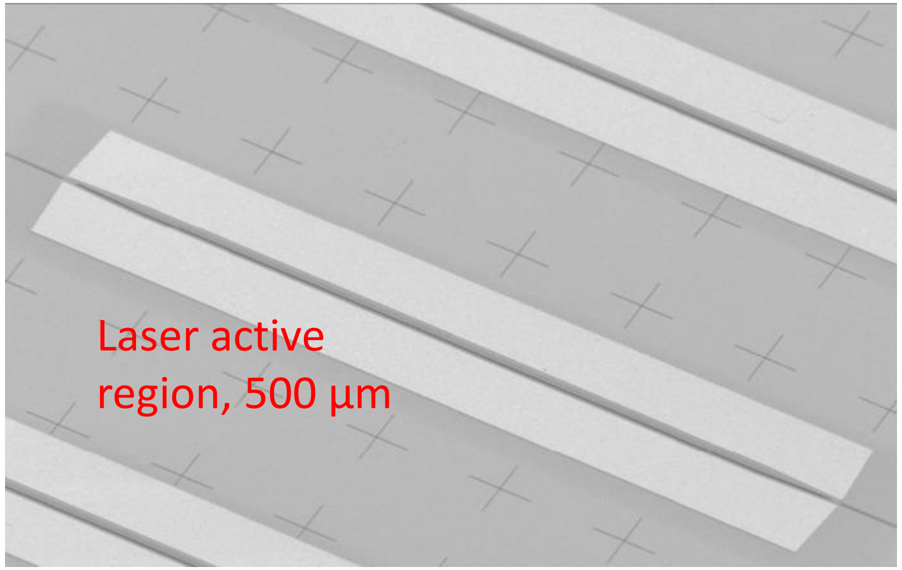
Heterogeneous laser integration for visible



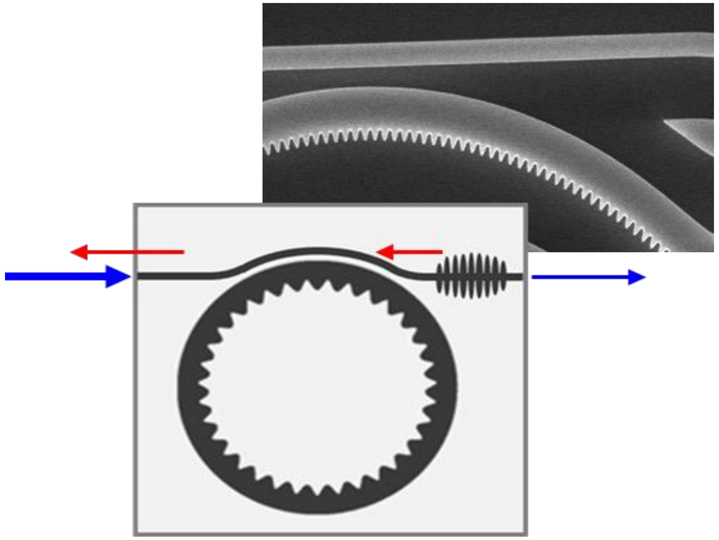
Waveguide PPLN (Stanford)



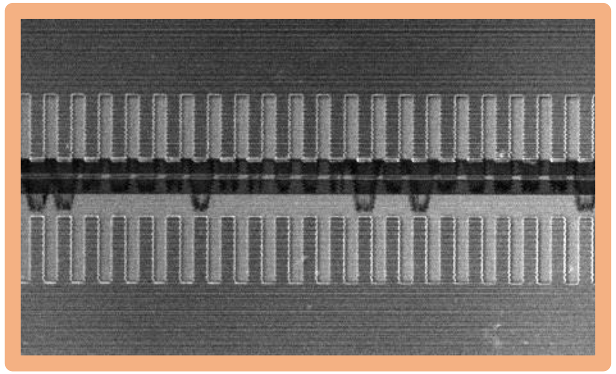
III/V tantala laser (NIST)



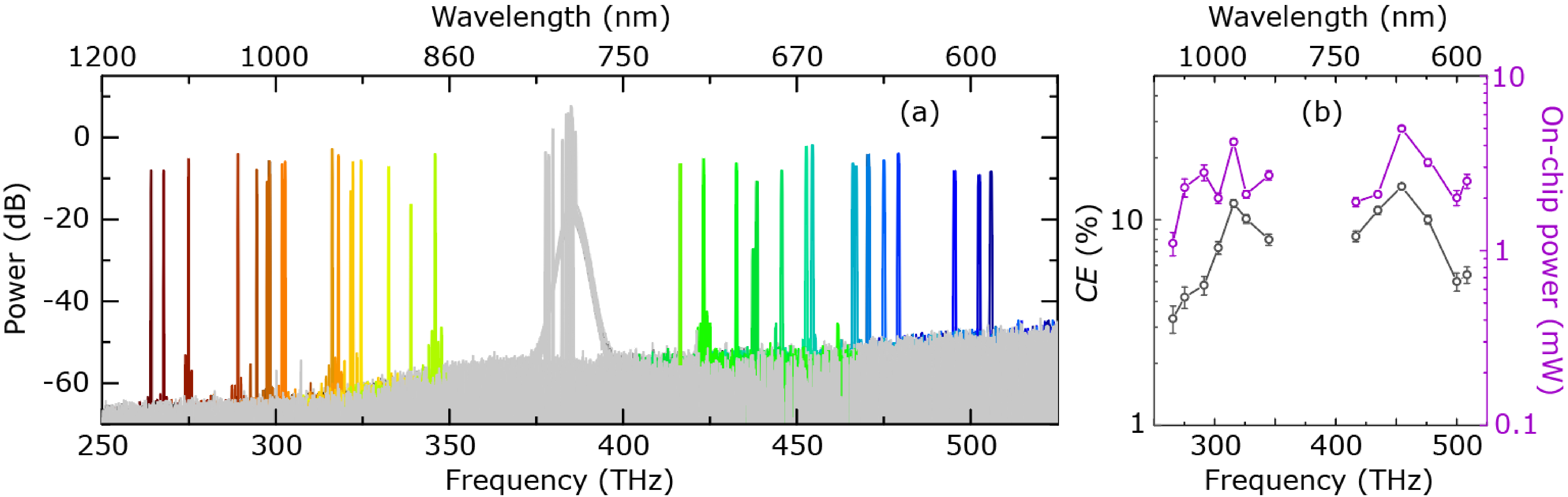
Tantala OPO (NIST and Octave)



Waveguide PPLN (Colorado)



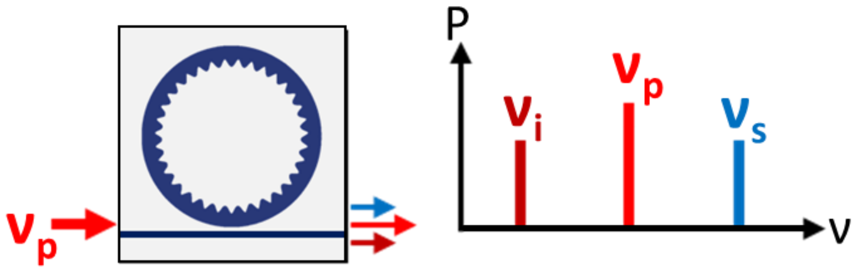
Visible OPO lasers

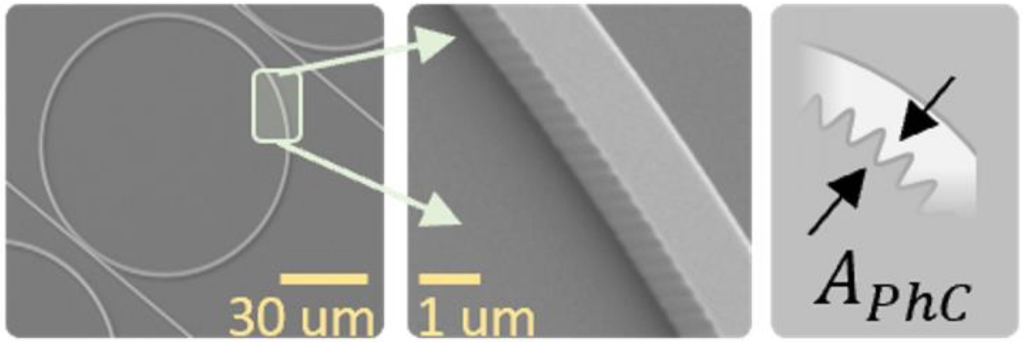


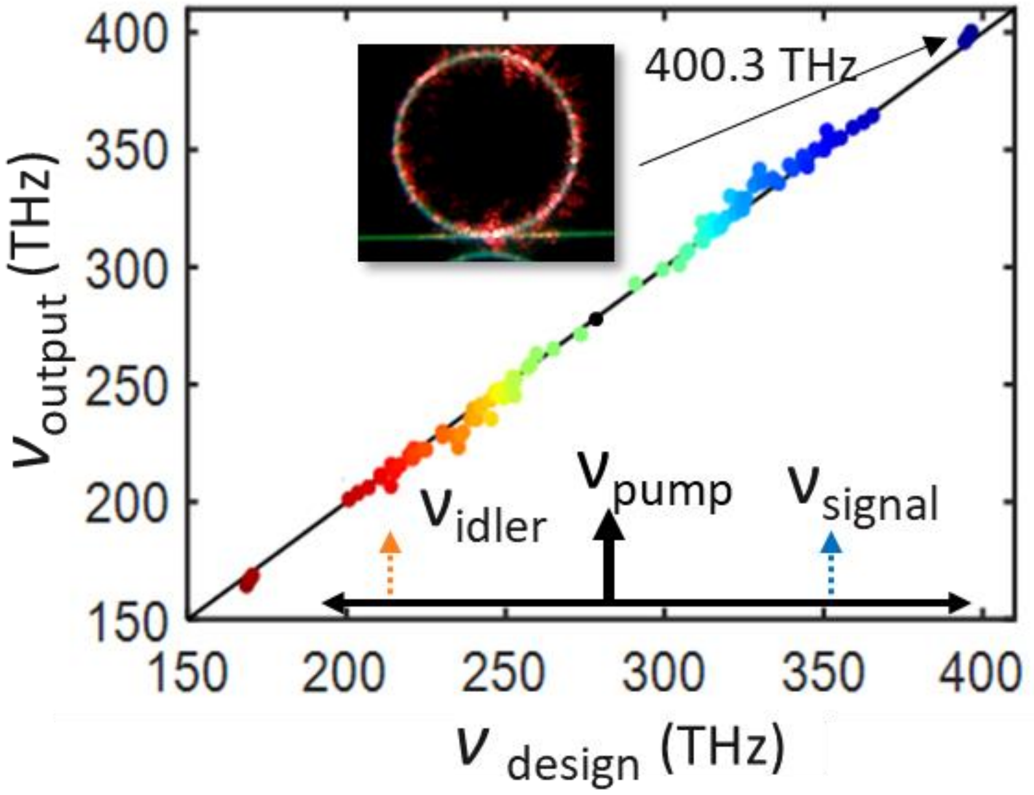
K. Srinivasan, 2022

Visible OPO lasers

Wavelength *by* design.







J. Black and S. Papp, 2023

DARPA LUMOS program

NIST

CU NIST

Boulder, CO
Scott Papp (PI)
Jennifer Black
Rich Mirin
Nima Nader
Scott Diddams

- nonlinear wavelength converter
- integrated pump laser
- Lithium niobate poling in Boulder

Stanford University

Jelena Vuckovic
Amir Safavi-Naeini

- inverse design of photonics
- nonlinear wavelength converter
- optical isolation
- lithium niobate for modulation and SHG

UNIVERSITY OF MARYLAND

NIST

Gaithersburg, MD
Kartik Srinivasan

- nonlinear wavelength converter
- Phase 3 application: heterogeneous quantum network

OCTAVE PHOTONICS

Louisville, CO

David Carlson
Zach Newman

- Preliminary PDK on tantala platform
- Tantala passives and nonlinear fabrication
- Lithium niobate bonding and fab

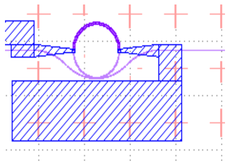
Integrated photonics for quantum

SOA and
WG-facet
laser-mirror

Design Angled facets for 570 nm TaO at 980 nm wavelength

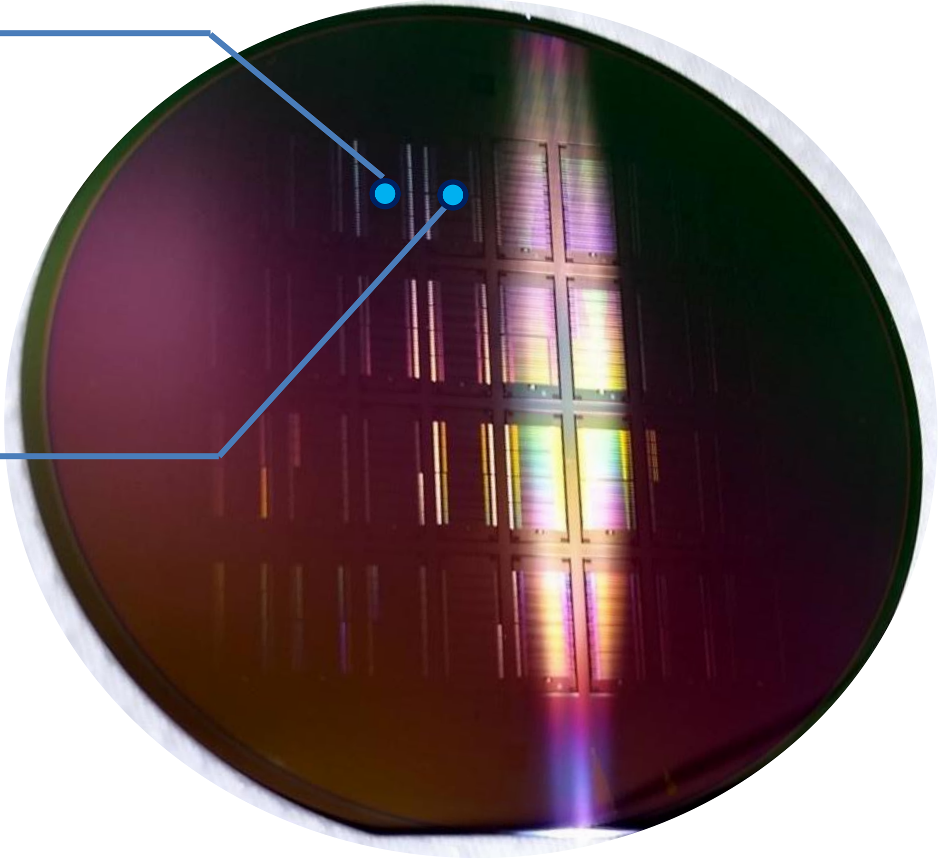
Chip 1

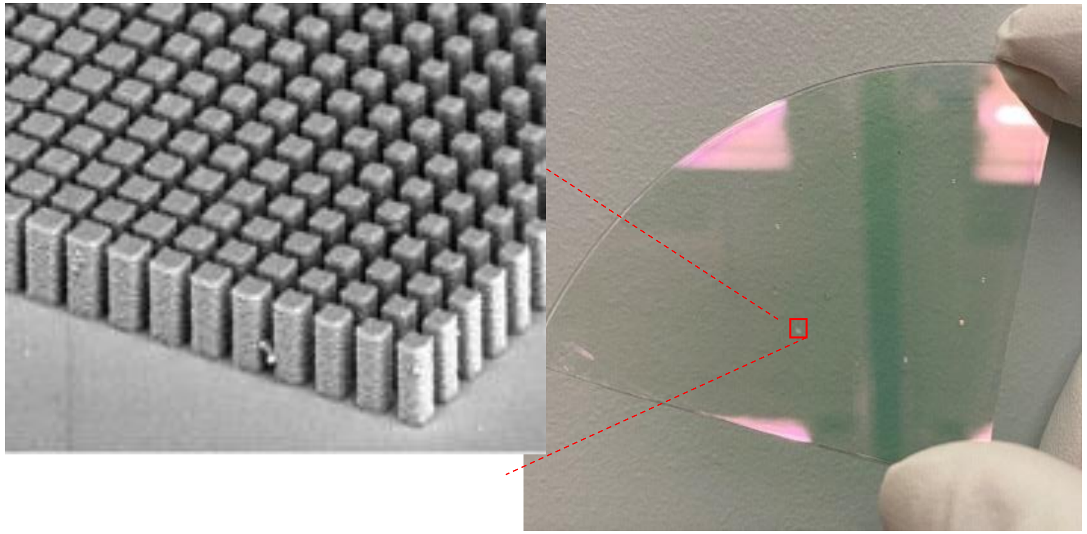
LM+PhCRR laser cavity

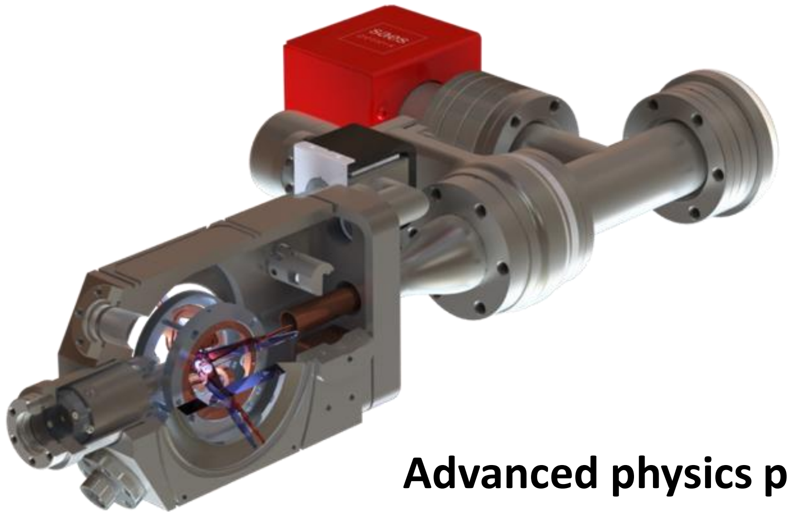


Chip 2

NIST integrated photonics

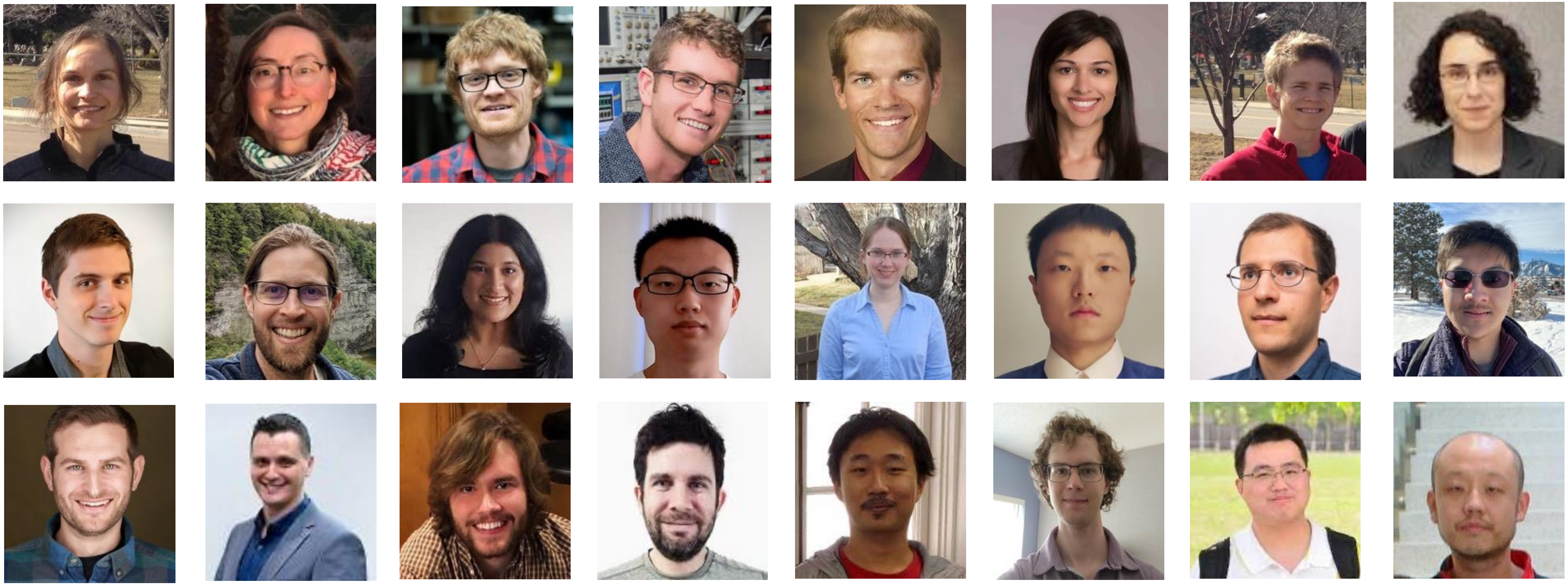






Advanced physics packaging (Vector Atomic)

QNS Group at NIST-B



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NIST Collaborators: Agrawal, Aksyuk, Diddams, Kitching, Hummon, Mirin, Nader, Stanton, Newbury, Srinivasan, Westly, …