Fiber based high power lasers for quantum computing applications

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OUTLINE

- A shared lab for low noise high power fiber laser investigation & development
- Introduction: high power (HP) fiber based single frequency low noise lasers
- Neutral atom quantum processors : a brief overview
- Examples of IR, NIR, and VIS laser sources for neutral atom quantum processors
- Conclusions & outlook

INSTITUT d'OPTIQUE GRADUATE SCHOOL

A SHARED LAB FOR HIGH POWER LOW NOISE LASERS

cnrs

université de BORDEAUX

Created in 2010
>35 employees

>800 lasers delivered

2 Academics
& 2 Industrial staff
+Ph.D/postdocs

- Academic/industry partnership since 2014
- Shared governance /PI agreement
- Common roadmap for research&innovation
- Fast pathway from lab to industrial systems

LAPHIA Centre d'excellence de l'université de Bordeaux

INVESTISSEMENTS D'AVENIR

LabCom ANR

Agence Nationale de la Recherche ANR

anrt association nationale recherche technologie

FUI PROJET SÉLECTIONNÉ

RÉGION Nouvelle-Aquitaine

European Commission

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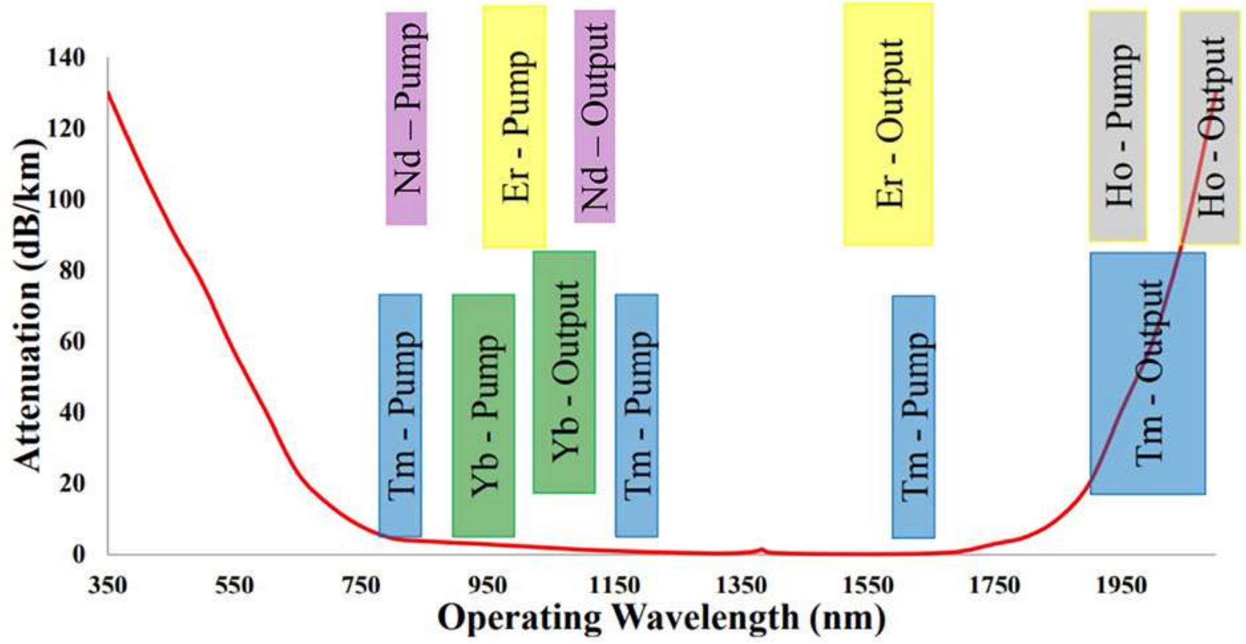
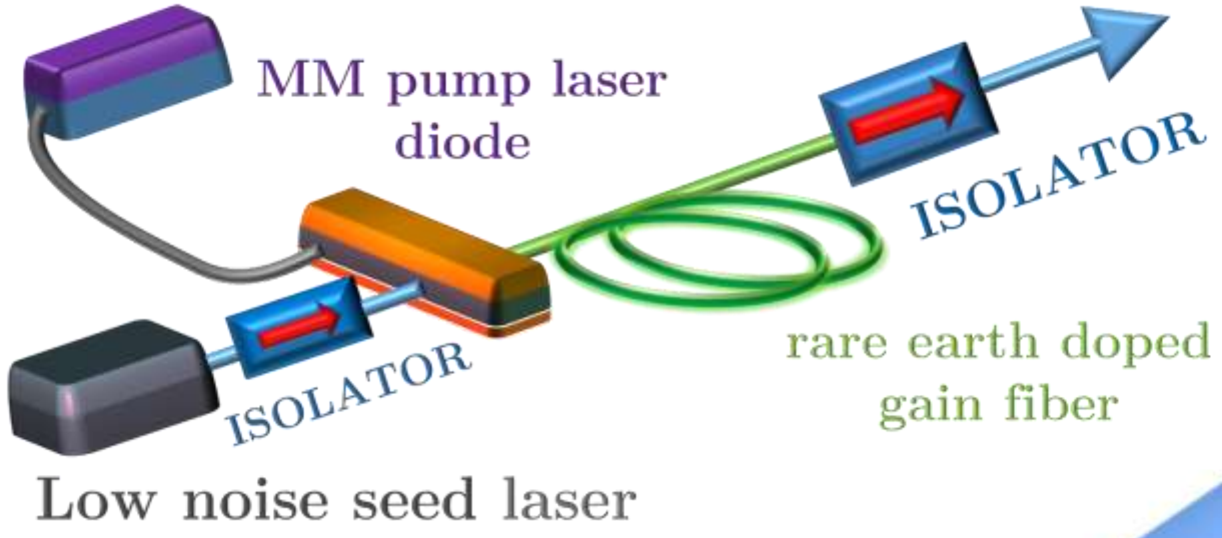
WHY FIBERS BASED LASER FOR SINGLE FREQ. LOW NOISE LASERS?

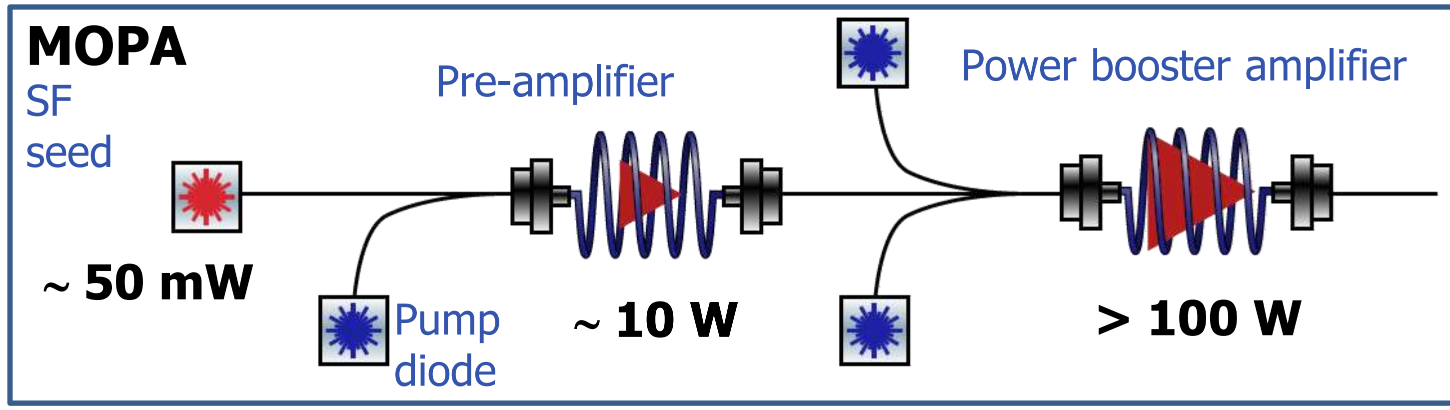
- ✓ Wide emission bandwidth w/rare earth doping in glass host (Nd, Yb, Er/Yb, Tm…..)
- ✓ High-gain by multi-stage Master Oscillator Power Amplifier (MOPA) configuration
- ✓ Simple power scaling (with some limitations)
- ✓ Low noise SF seed lasers available (fiber DFB, ECLD, DBR…)
- ✓ Large variety of PM fibers core sizes, doping levels and …..
- ✓ Rugged and compact with good heat dissipation





POWER SCALING OF SINGLE FREQUENCY LASERS

MOPA

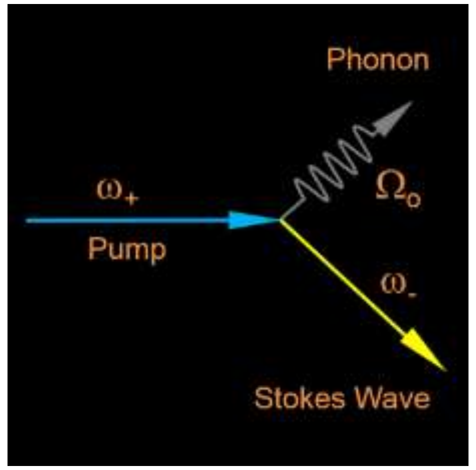


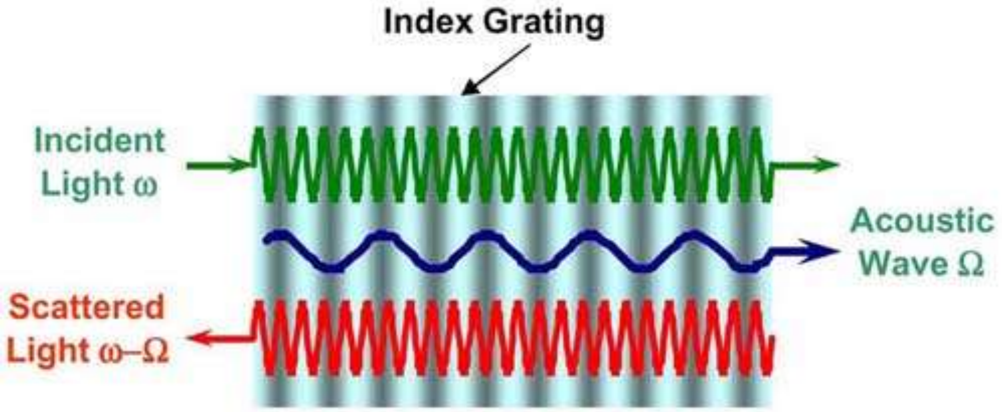
Limitations :
Stimulated Brillouin Scattering (**SBS**)
Transverse Mode Instabilities (**TMI**)

- **SBS** Related to long lengths & high intensity in small core
- Backward wave (output depletion and system damage)

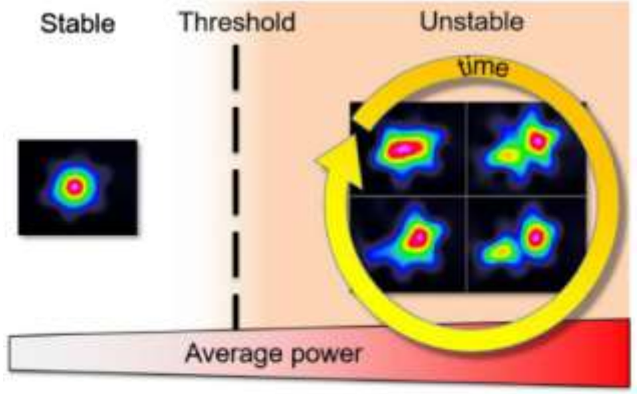
$$P_{th,SBS} = \kappa \frac{A_{eff}}{g_B L_{eff}}$$

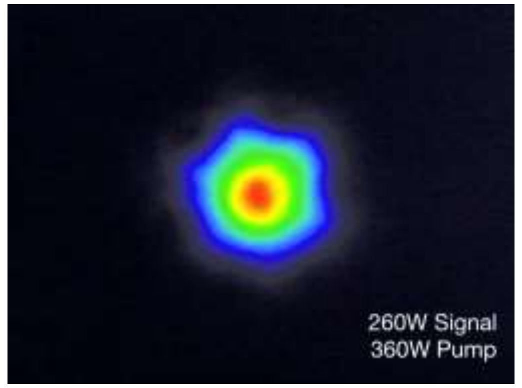
- Mitigation: **shorter fiber lengths** + **larger cores** =>
  highly doped Large Mode Area (LMA) fibers





- **TMI** Related to the thermal load in the doped fiber& mode confinement
- Highly sensitive to photodarkening
- Mitigation : **lower doping+optimized glass host+better mode confinement**

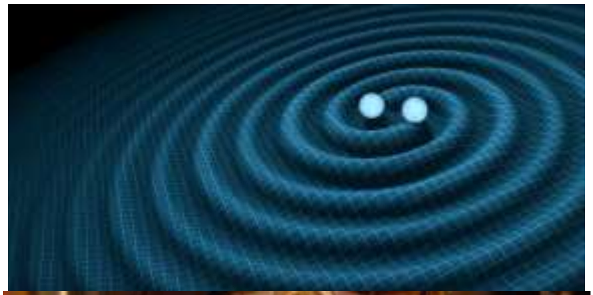




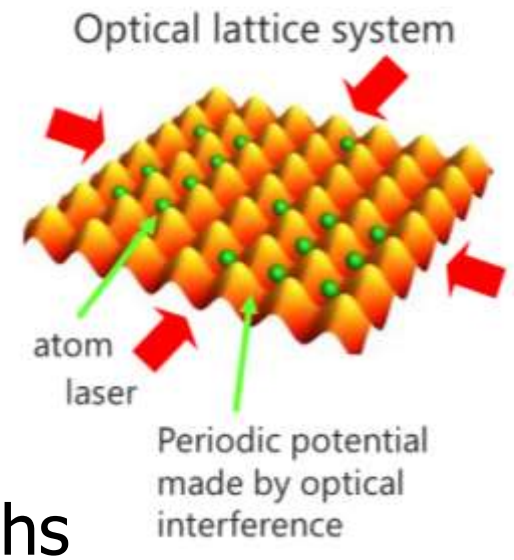
TMI investigated by several teams with special focus by the Jena group (Jauregui, Tünnermann, Limpert)

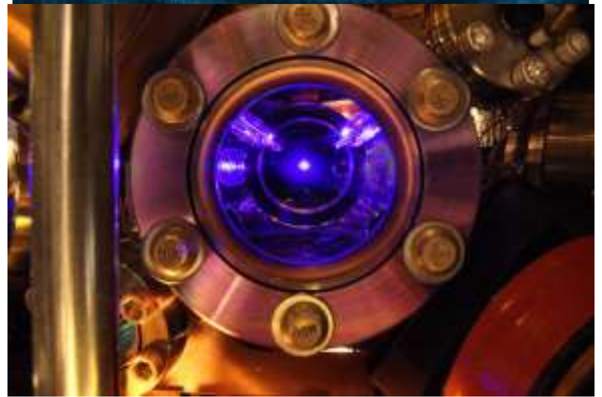
Jauregui et al *Nature Photon* **7**, 861–867 (2013). Eidam et al, Opt. Express **19**, 13218-13224 (2011)

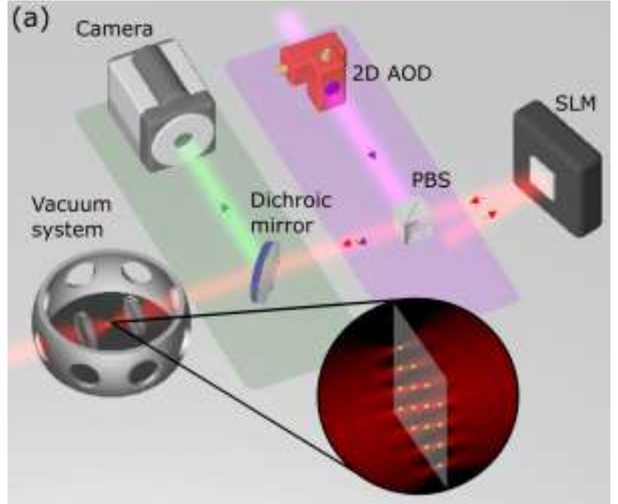
HIGH POWER LOW NOISE
LASER APPLICATIONS

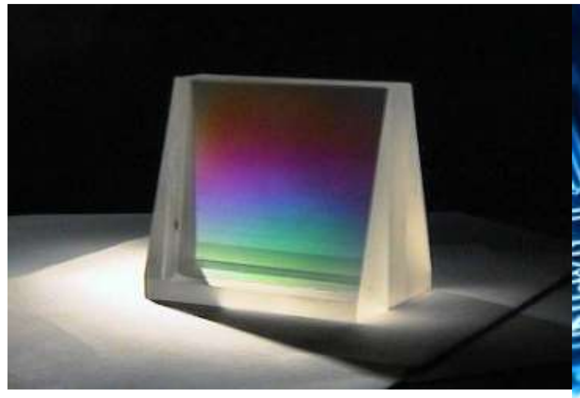


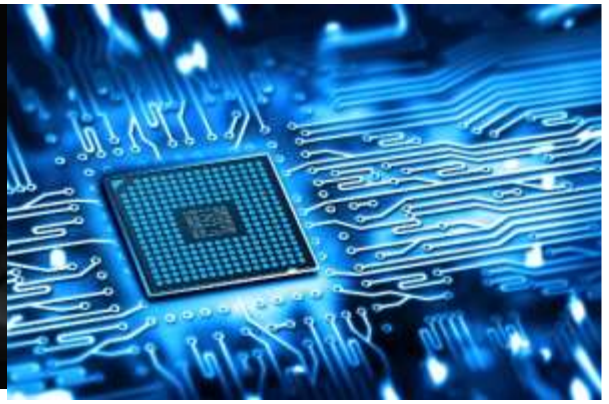
- ✓ Gravitational Wave Detectors
- ✓ Atomic physics (laser cooling, optical lattices,..)
- ✓ Frequency metrology (cold optical clocks, atom interferometers..)
- ✓ Neutral atoms-based quantum computing/simulators (many wavelengths 1064nm, 1013nm, 820nm, 813nm, 780nm, 420nm, 317nm…)
- ✓ High resolution 3D lithography
- ✓ Industrial metrology (semiconductor inspection, holography VIS & DUV by frequency conversion)











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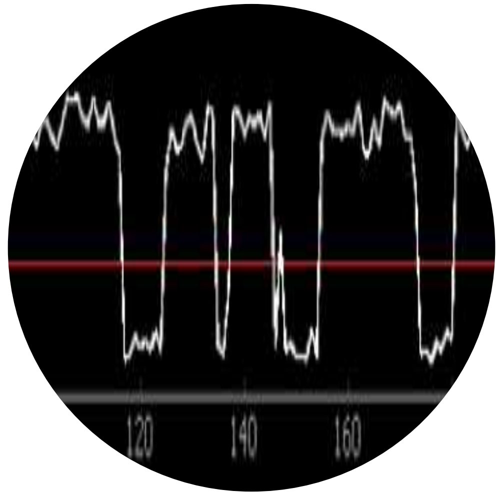
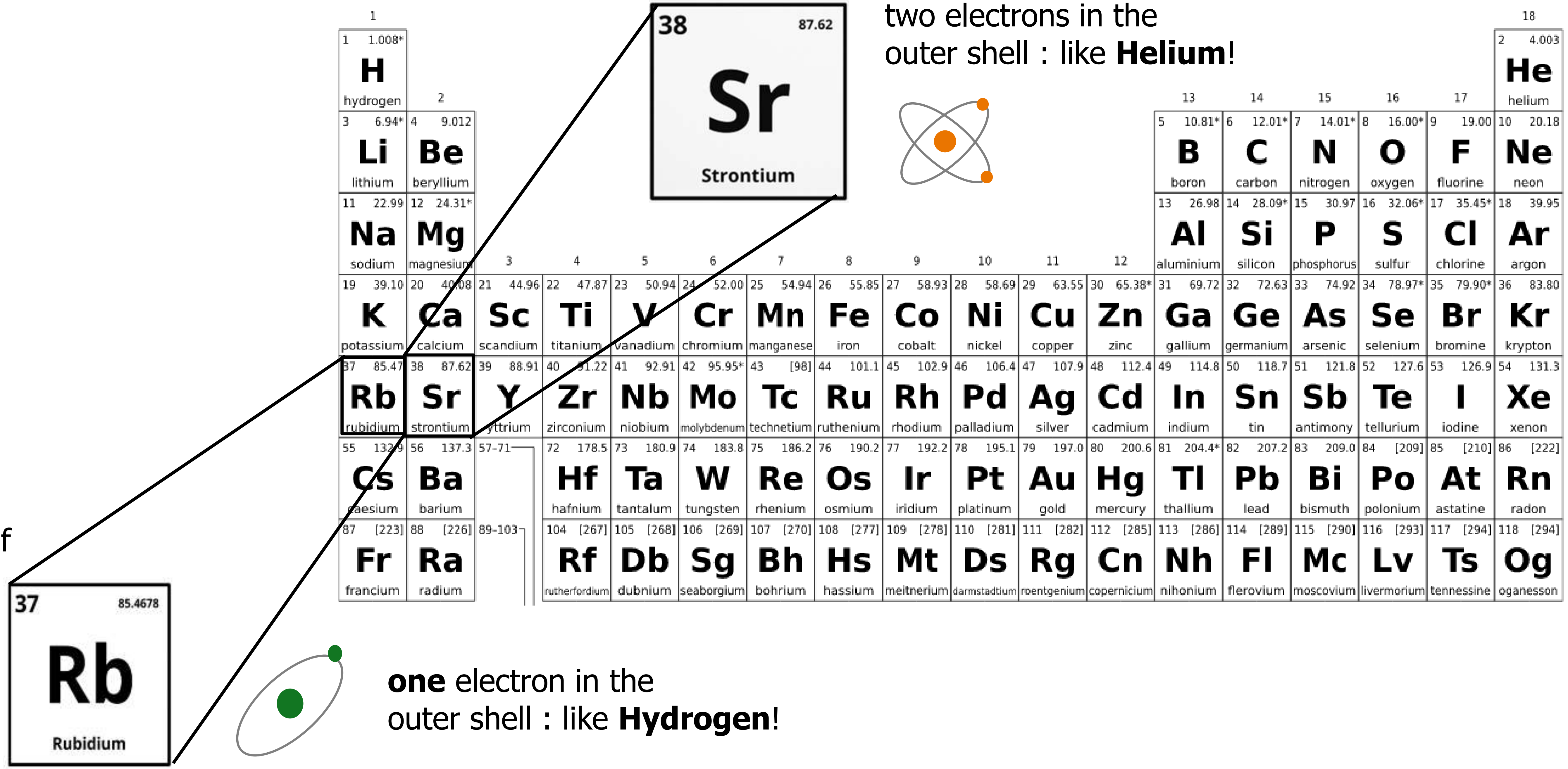
NEUTRAL ATOM QUANTUM PROCESSORS

Atoms act as qubits



Qubits are encoded into two of the many electronic states of neutral atoms.

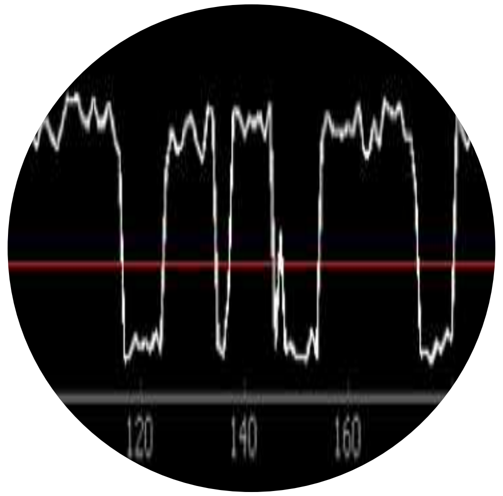


two electrons in the outer shell : like **Helium**!

one electron in the outer shell : like **Hydrogen**!

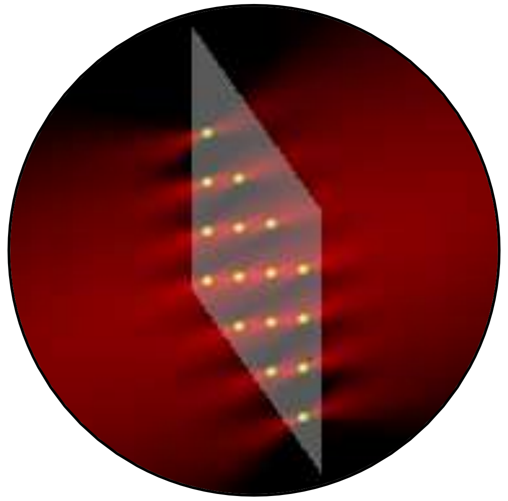
NEUTRAL ATOM QUANTUM PROCESSORS

Atoms act as qubits



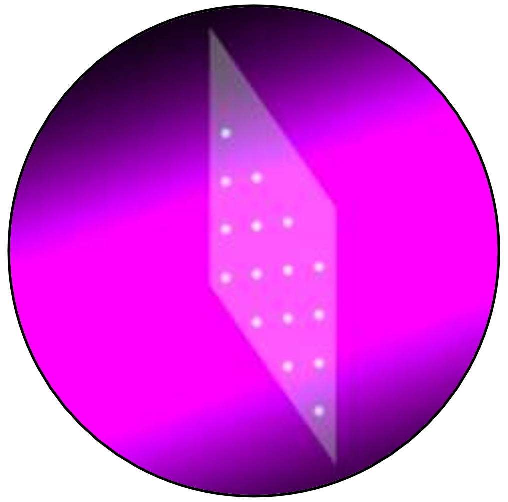
Qubits are encoded into two of the many electronic states of neutral atoms.

Qbits register made with optical tweezers



The register is prepared using **laser cooling and trapping** techniques

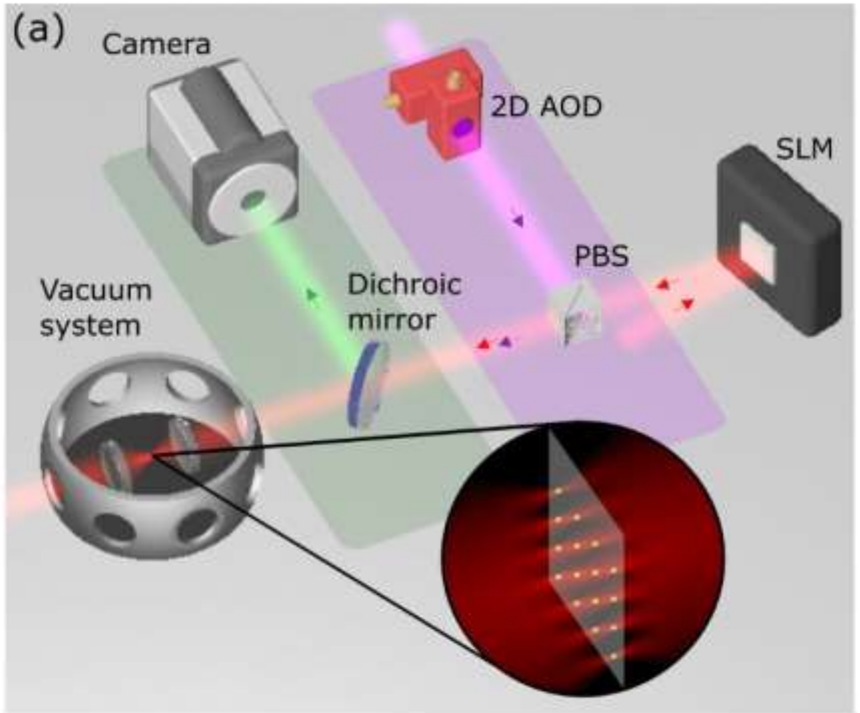
Processing using laser fields

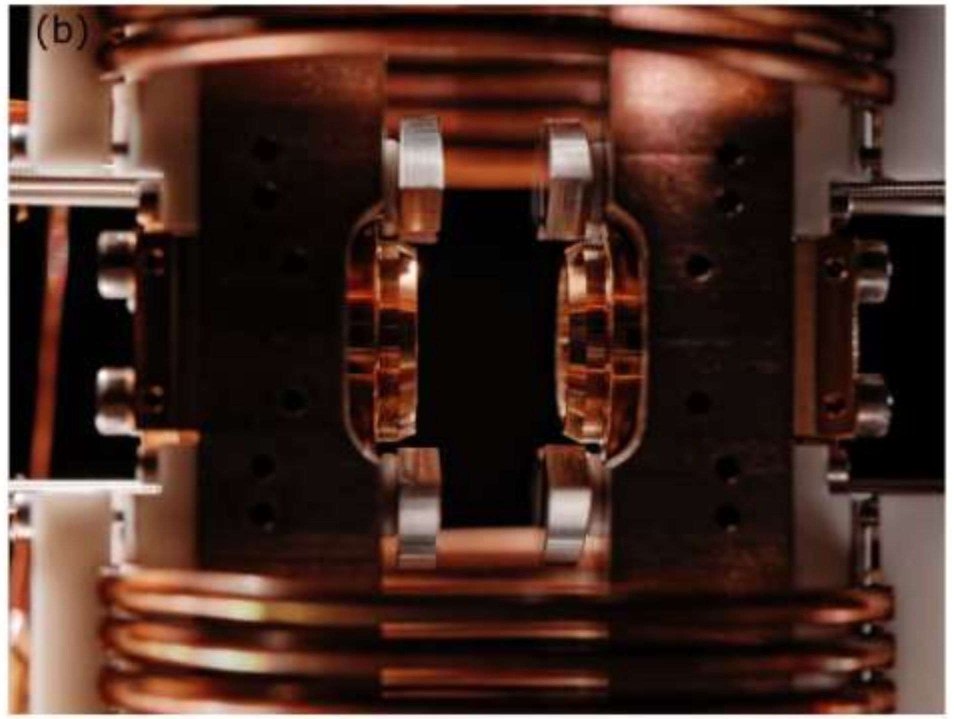


Laser fields are used to manipulate the internal degree of freedom

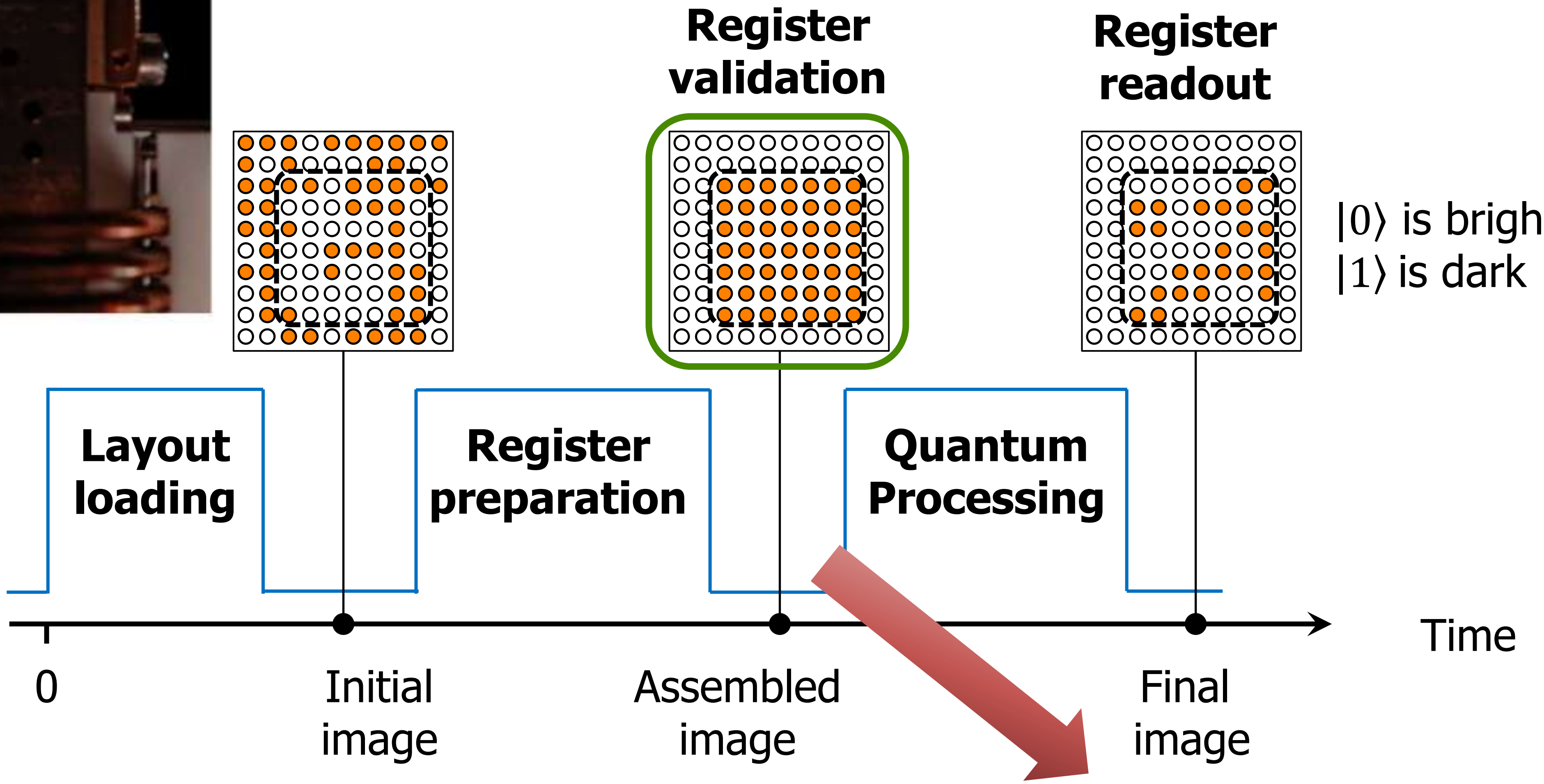
***courtesy of Adrien Signoles deputy CTO Pasqal**

RB NEUTRAL ATOM QUANTUM PROCESSORS





- Processing cycles



Register validation

Register readout

|0⟩ is bright
|1⟩ is dark

Layout loading

Register preparation

Quantum Processing

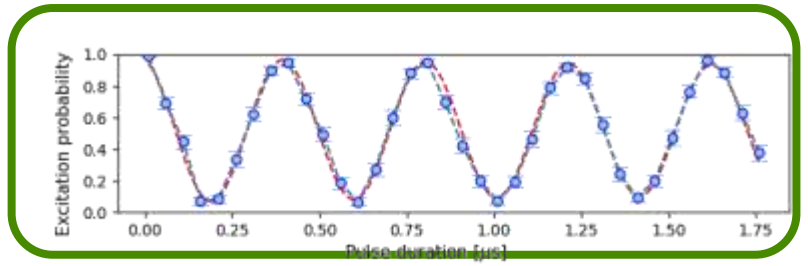
Time

0

Initial image

Assembled image

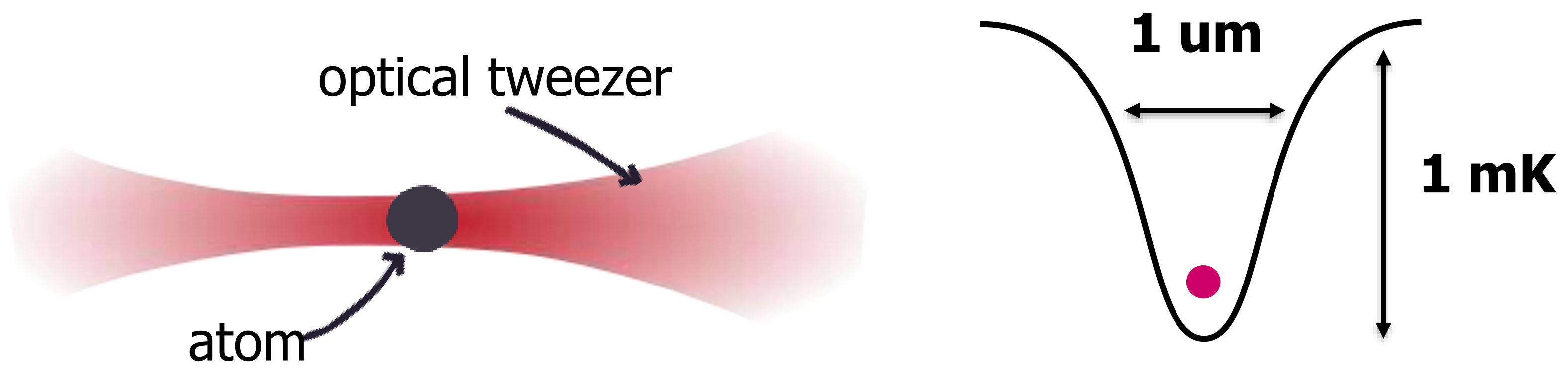
Final image



PASQAL

***courtesy of Adrien Signoles deputy CTO Pasqal**

TRAPPING ATOMS IN OPTICAL TWEEZERS



Single atoms in optical tweezers

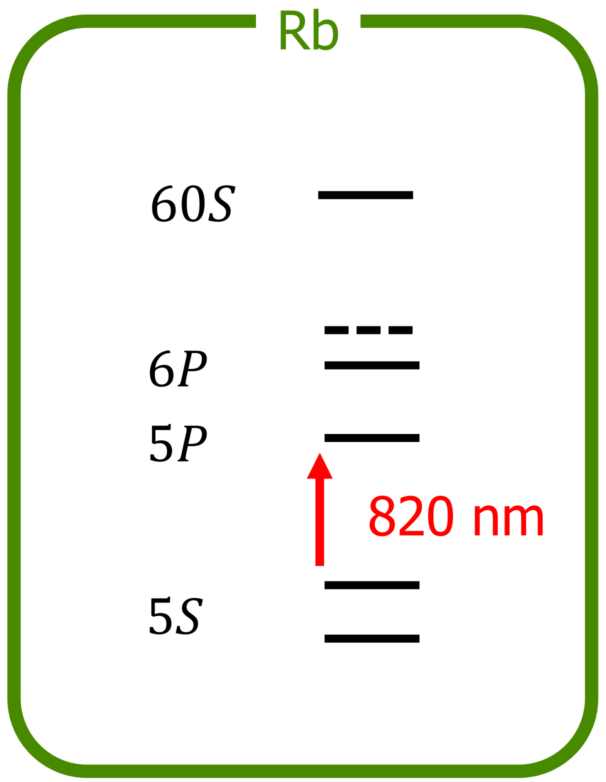
- Optical tweezer=tightly focused 1 µm beam
- Light-assisted collisions 1 atom per trapl

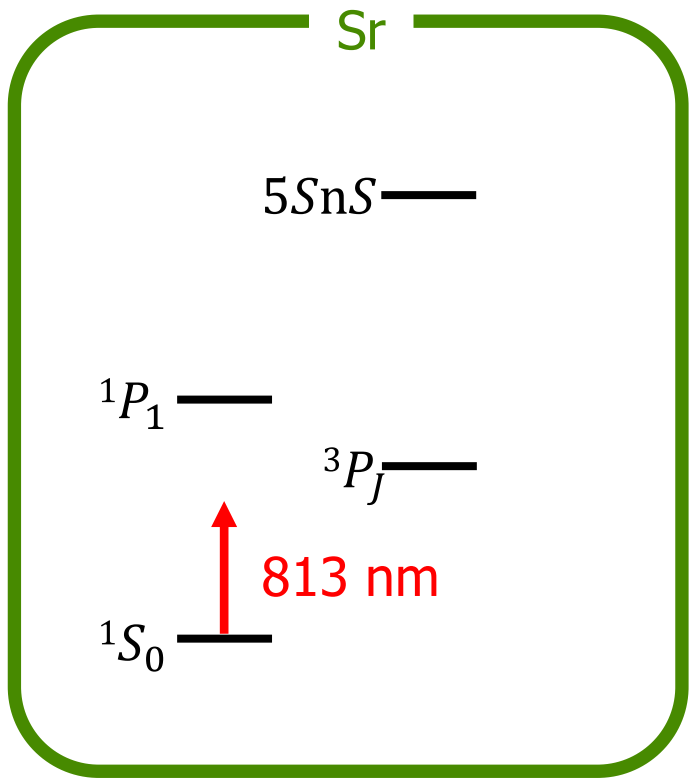
Trapping Rb atoms

- red-detuned light from D1 (795nm)&D2 (780nm)
- A bit of flexibility on the wavelength… 820 nm.

Trapping Sr atoms

- 2 electron atoms: singlet and triplet states
- Magic wavelength @ 813 nm for the $^1S_0$ and $^3P_1$

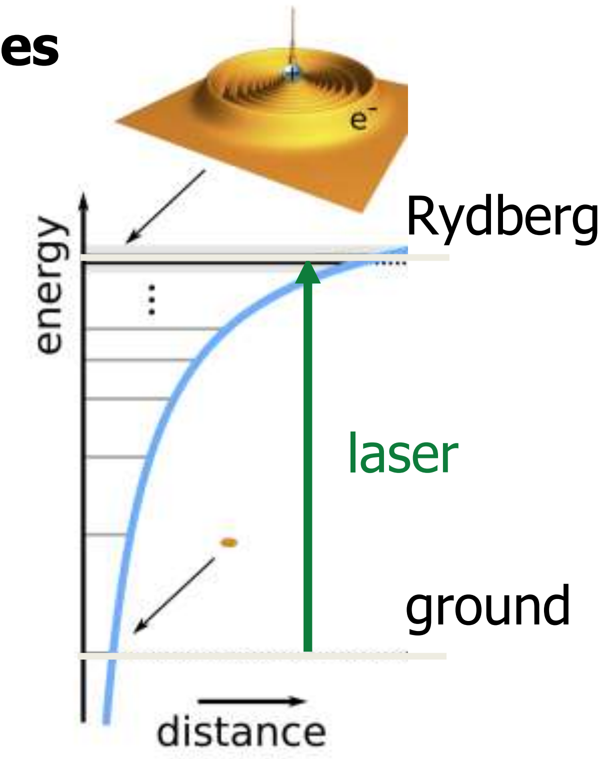




ENTANGLING ATOMIC QUBITS

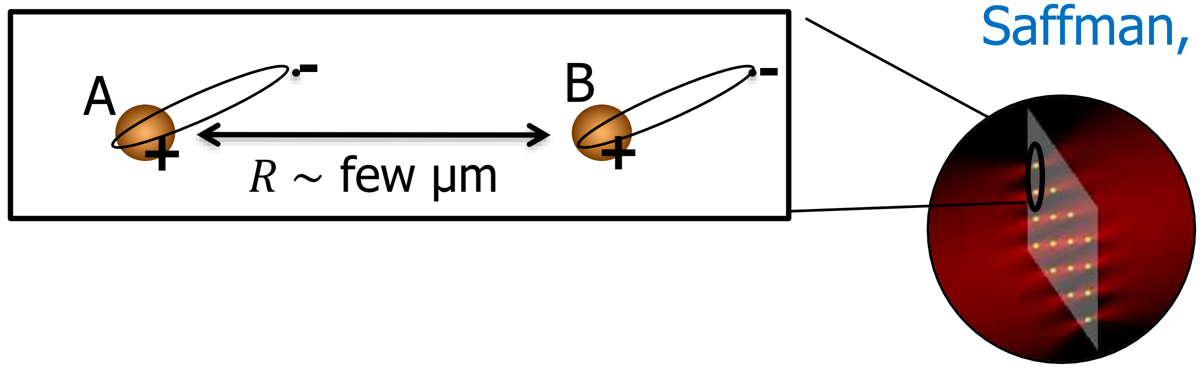
- **Rydberg states : highly excited states**
- **Atoms act as electric dipoles**

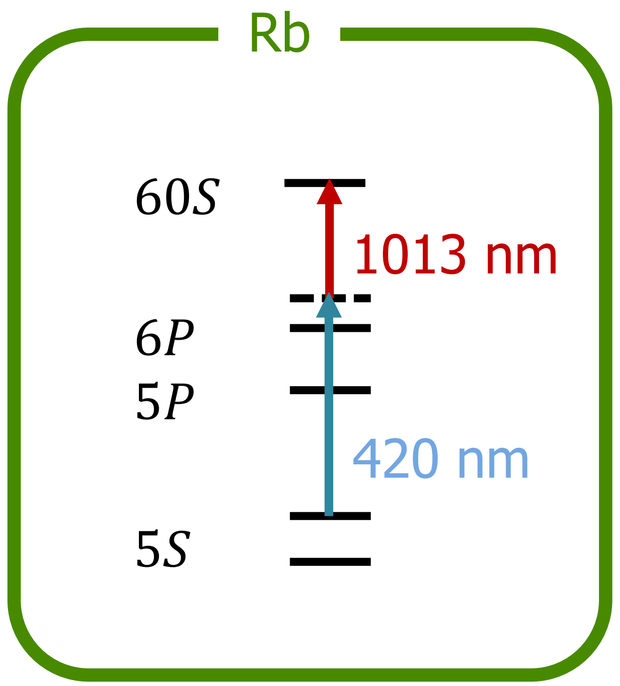
➢ **dipole-dipole interactions generate entanglement**

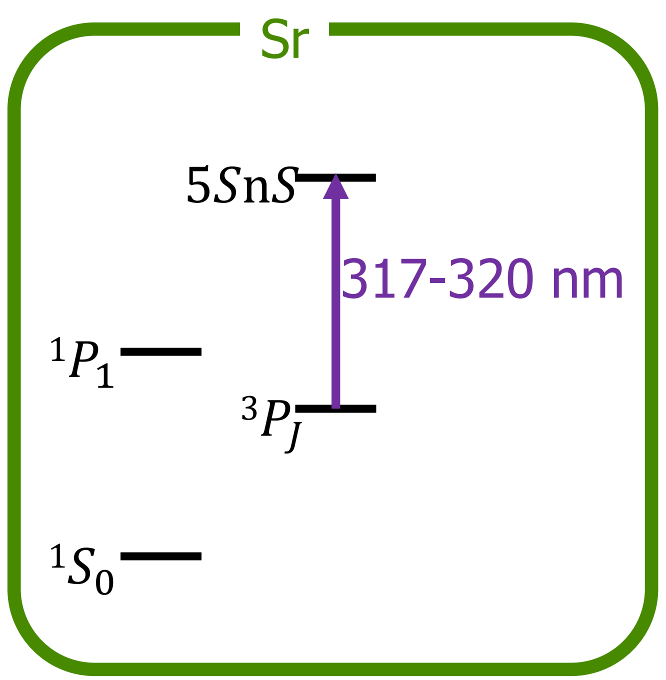


Morgado, Withlock, AVS Quantum Sci. (2021)

Jaksch et al., PRA (2000)
Saffman, RMP (2010)







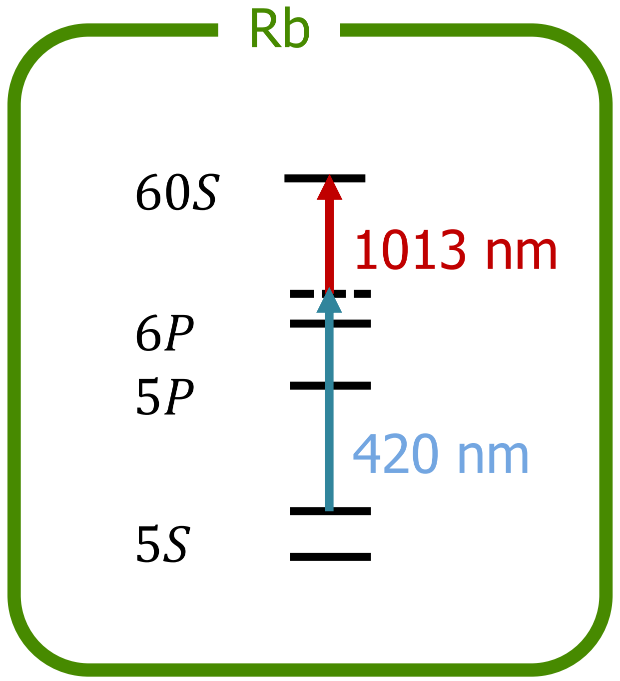
QPU TOWARDS RELIABLE SYSTEMS

PASQAL's current setup

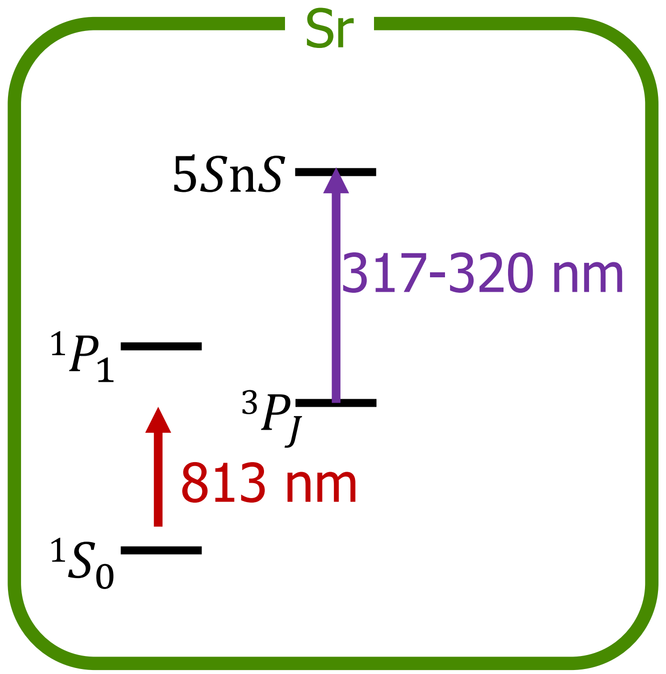
***courtesy of Adrien Signoles deputy CTO Pasqal**

QPU LASER REQUIREMENTS

Rydberg 1013nm >40W
Rydberg 420 nm >2 W
Trapping 820nm >5W
Cooling 780nm >1W



Rydberg 318nm >2W
Trapping 813nm >5W
Cooling 461nm >2W



Robust, high power, tunable, good beam quality …

Low intensity noise, power stable, wide locking bandwidth…

Metrological grade systems : laser linewidth <10-100kHz (NIR/VIS/UV)

Long term frequency stability (frequency combs, cavities, fiber interferometers…..)

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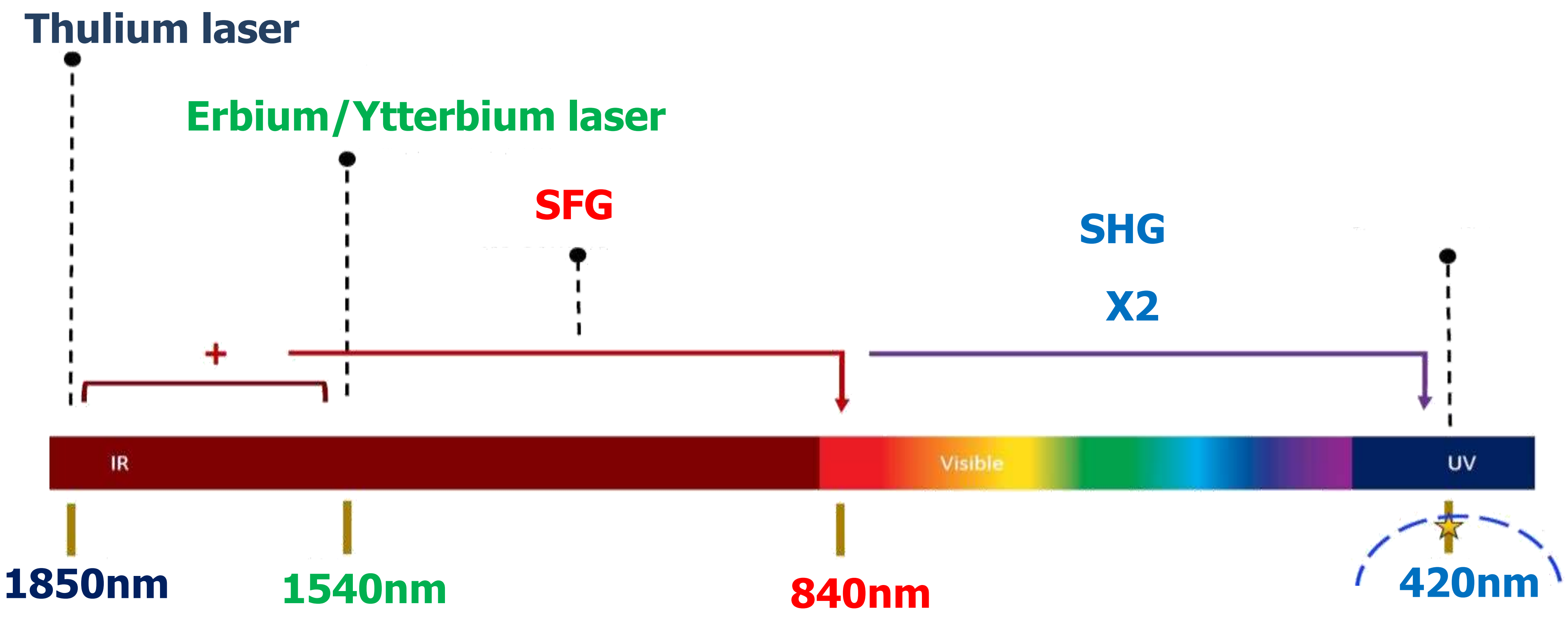
HOW WE CREATE SUCH WAVELENGTHS?

- ✓ Fiber lasers systems are good candidates : robust industrial grade high power…
- ✓ MOPA set-up & good seed laser (linewidth, intensity noise, control bandwidth….)
- ✓ Only IR wavelengths >1000nm w/ rare Earth doped fibers
- ✓ We need SGF/SHG to reach NIR, VIS and UV

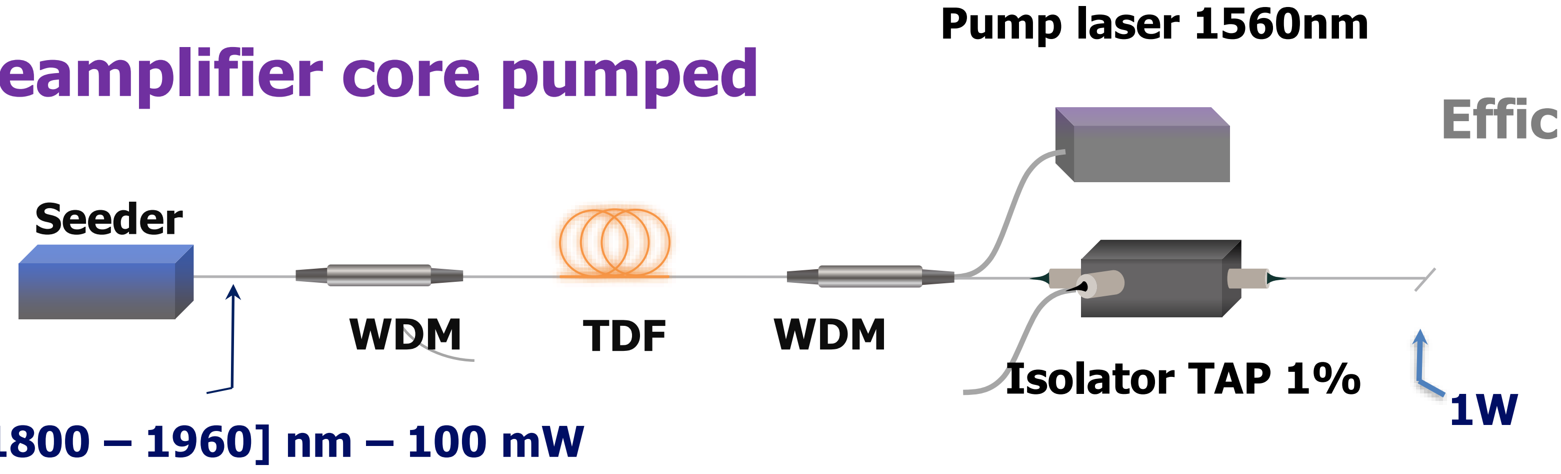


i-demo
NEXT-WAVE
QPU

HP THULIUM FIBER LASER AROUND 1850NM

Very little investigation < 1900nm with an all-fiber configuration

Preamplifier core pumped



Pump laser 1560nm

Seeder

WDM

TDF

WDM

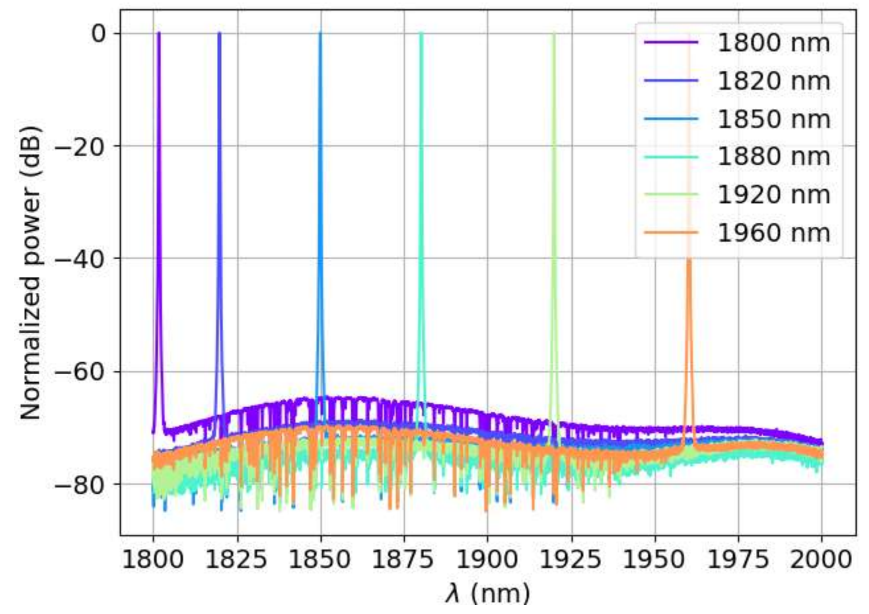
Isolator TAP 1%

1W

[1800 – 1960] nm – 100 mW

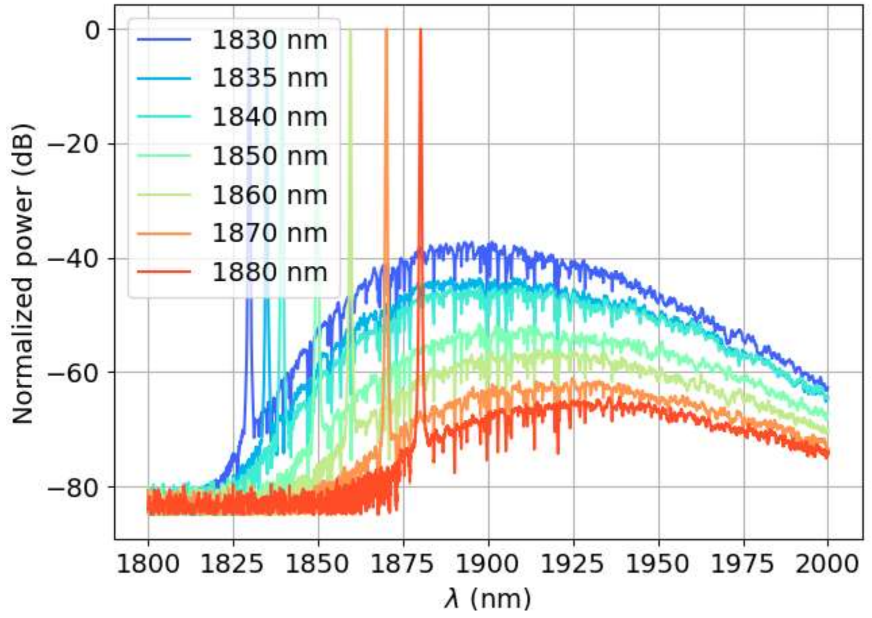
Efficiency ~50%

Tunable 1800-1960nm



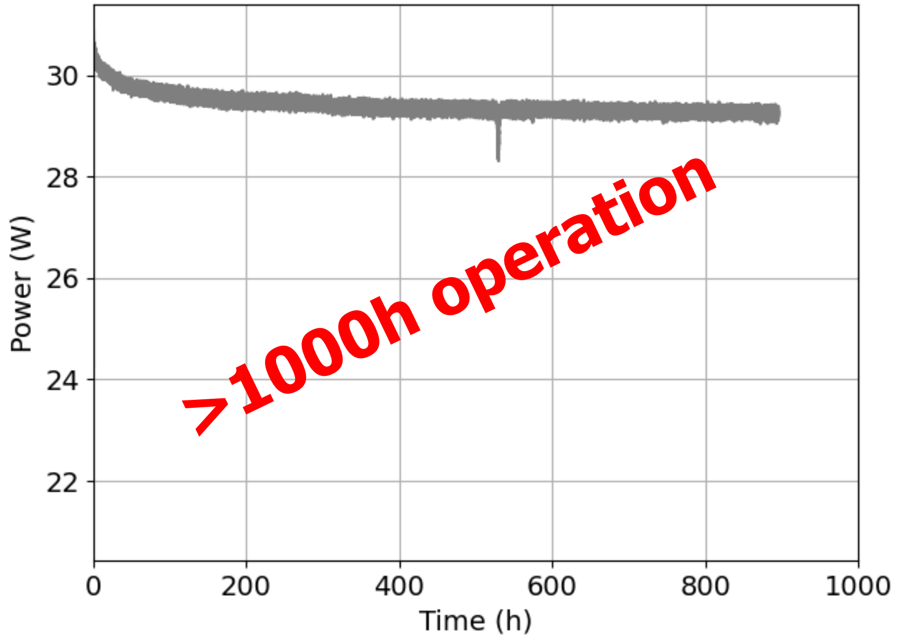
Main amplifier

Tunable 1830-1880nm



OSNR>40dB (0.1nm)

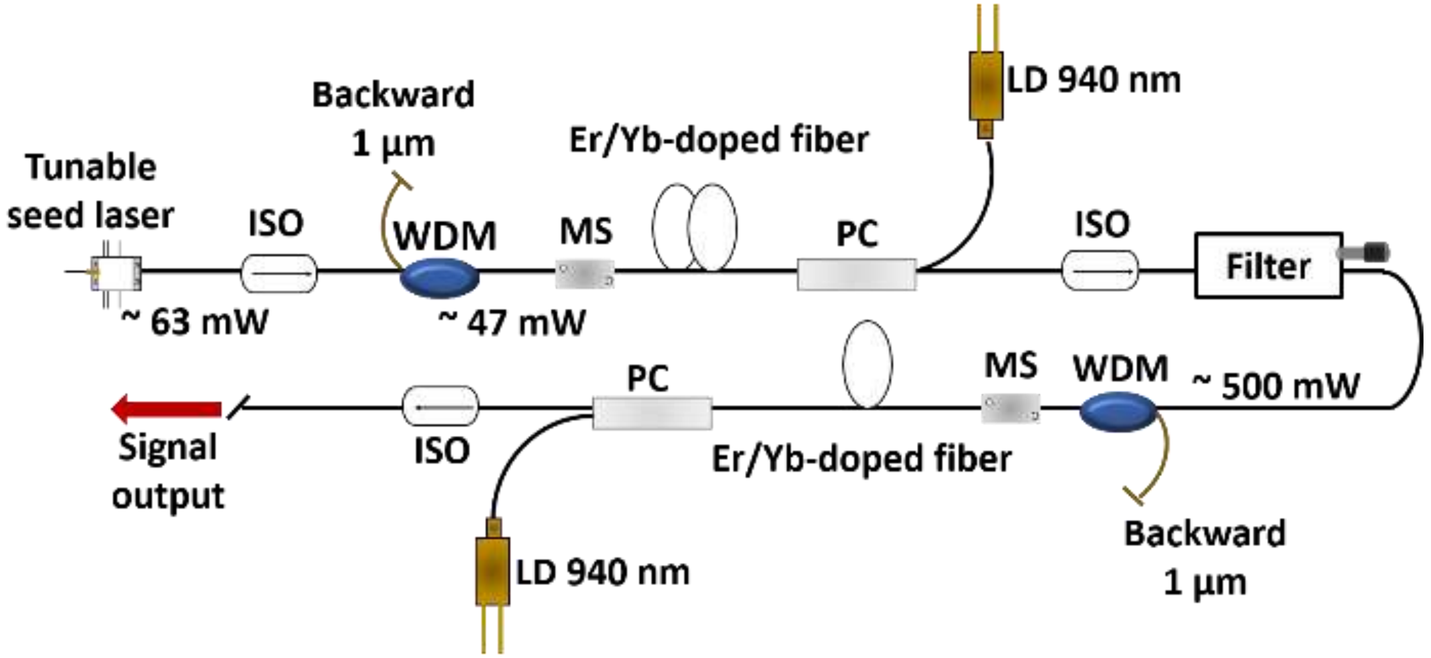
About 30W long term stable

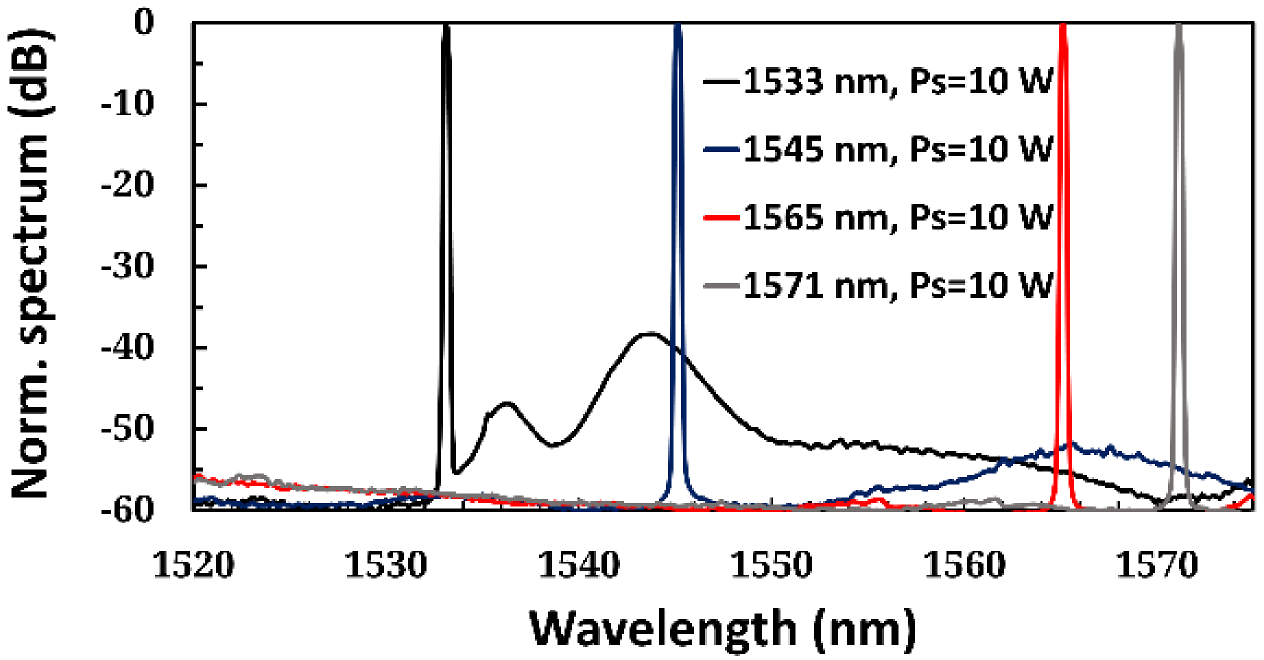


>1000h operation

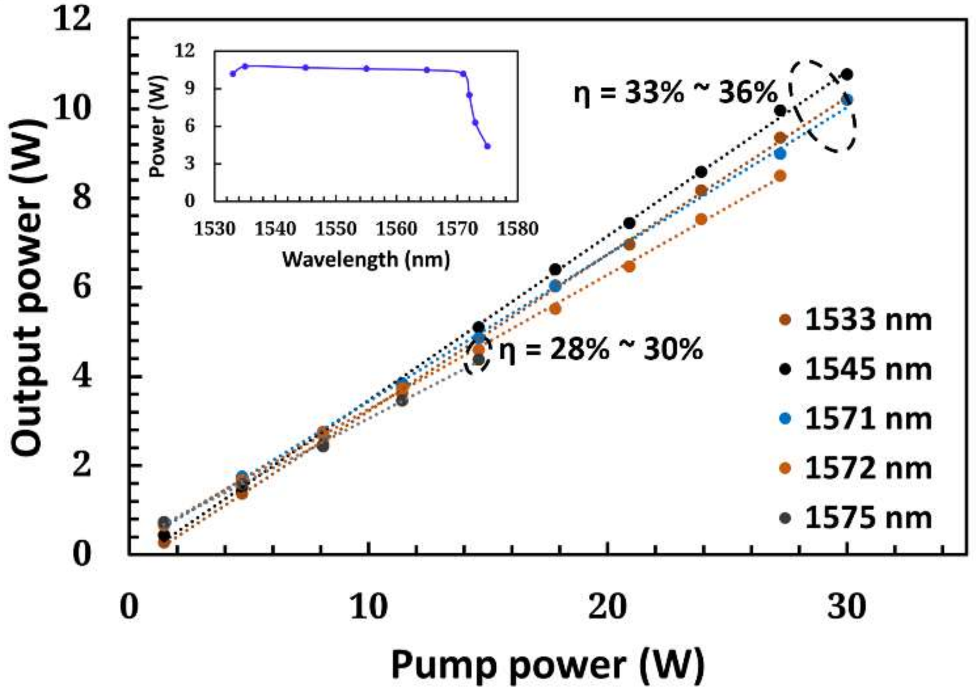
10 W Tunable low noise Er/Yb laser system

Tunable >10W, all-fiber configuration

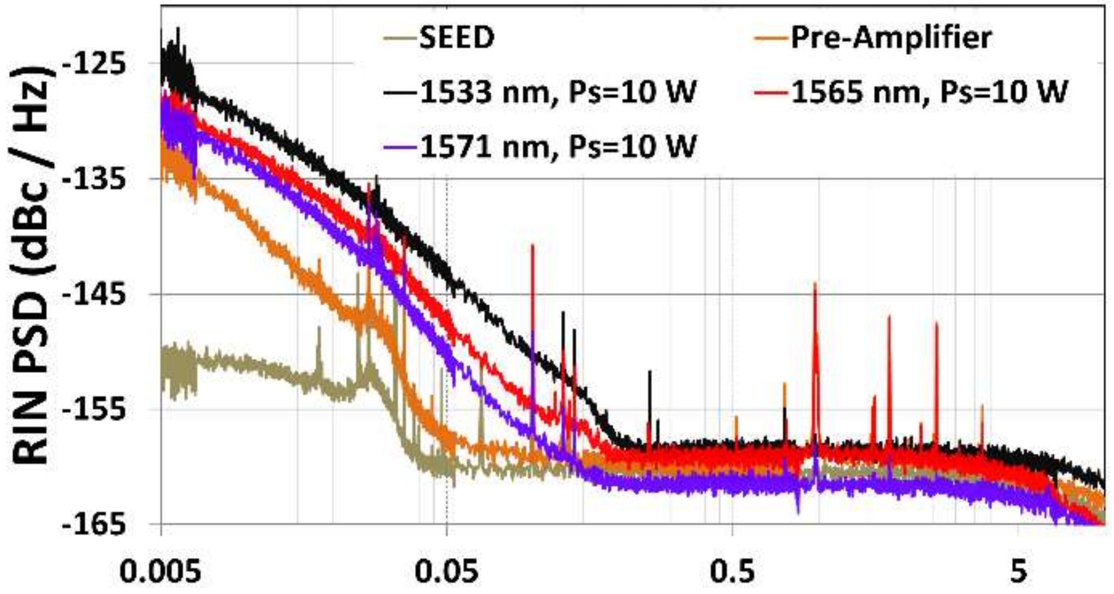




>35nm tunability, good efficiency >30%



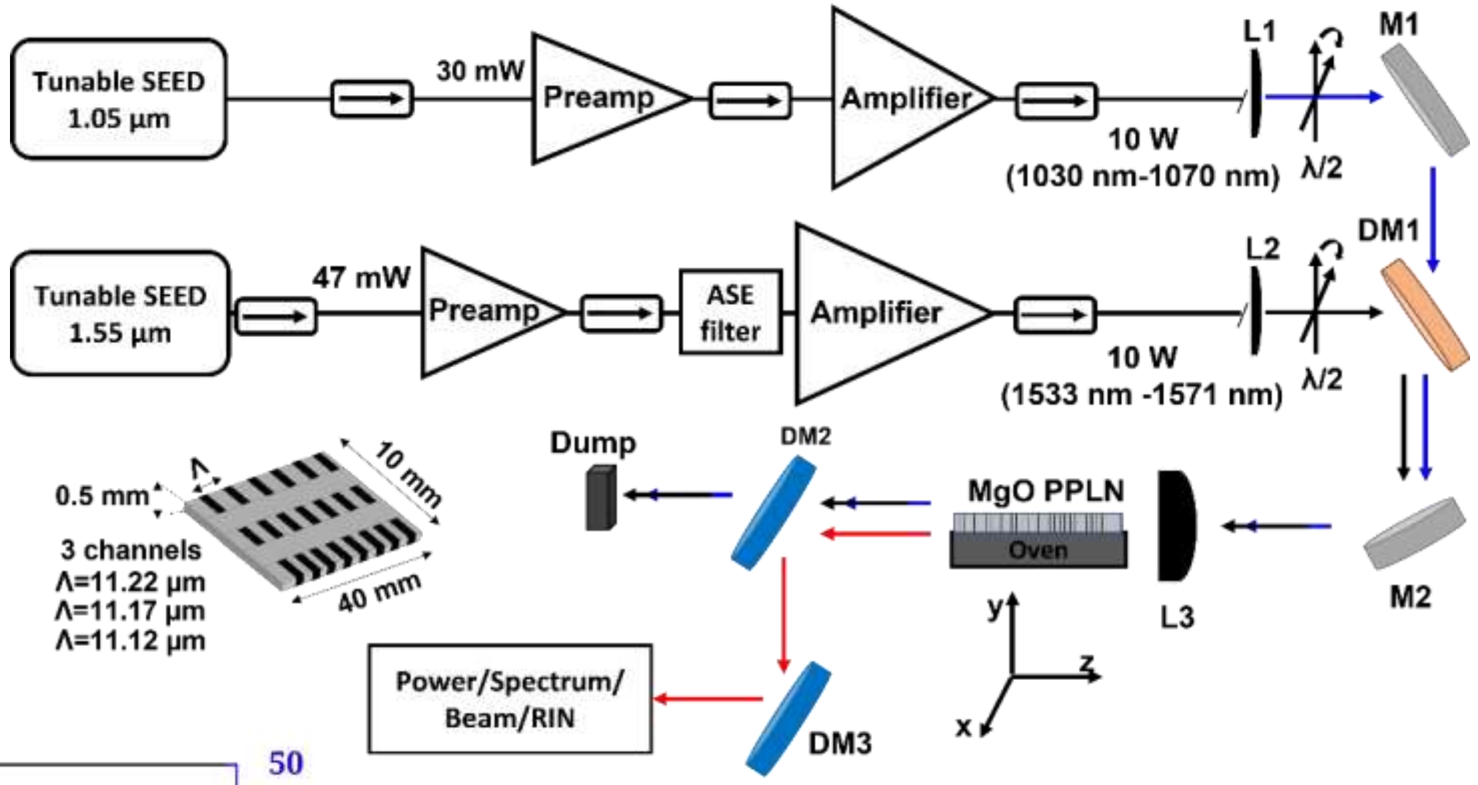
Low intensity noise



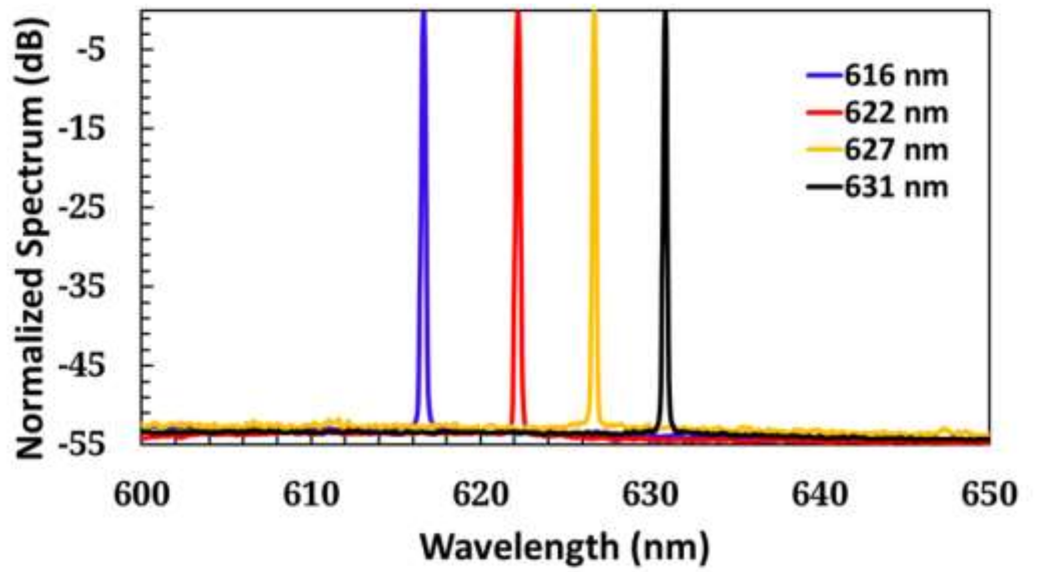
Darwich et al, "Ultra low-intensity noise, 10 W all-fiber single frequency tunable laser system around 1550 nm," Appl. Opt. **60**, 8550-8555 (2021)

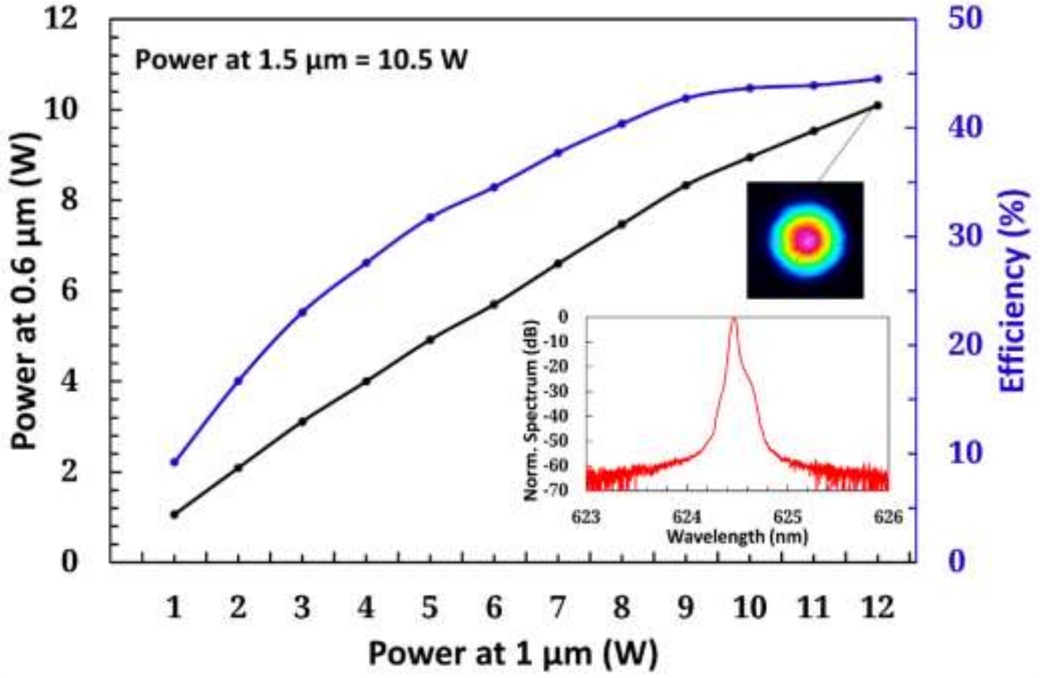
LOW NOISE HP RED/ORANGE TUNABLE LASER SOURCE

Both lasers tunable >10W



15 nm tunability limited by PPLN





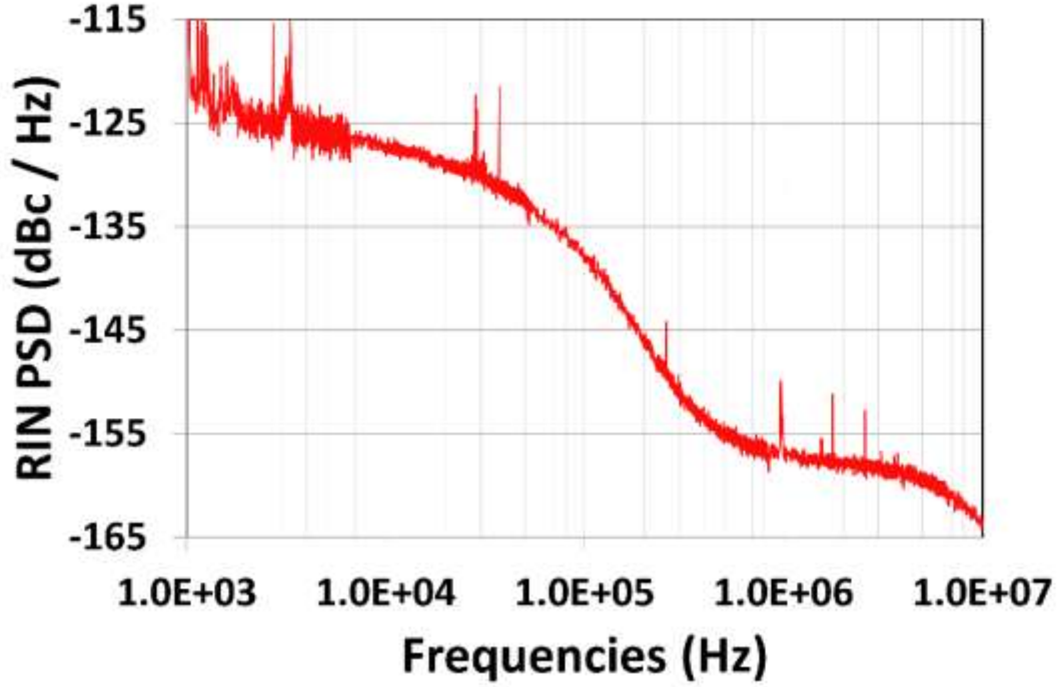
Good beam quality

>10W of VIS rad.

>60dB S/N

>40% efficiency

Low RIN



Darwich et al "High power ultralow-intensity noise continuous wave laser tunable from orange to red," Opt. Express **30**, 12867-12877 (2022).

High Power laser for Rb Rydberg atoms

Motivations

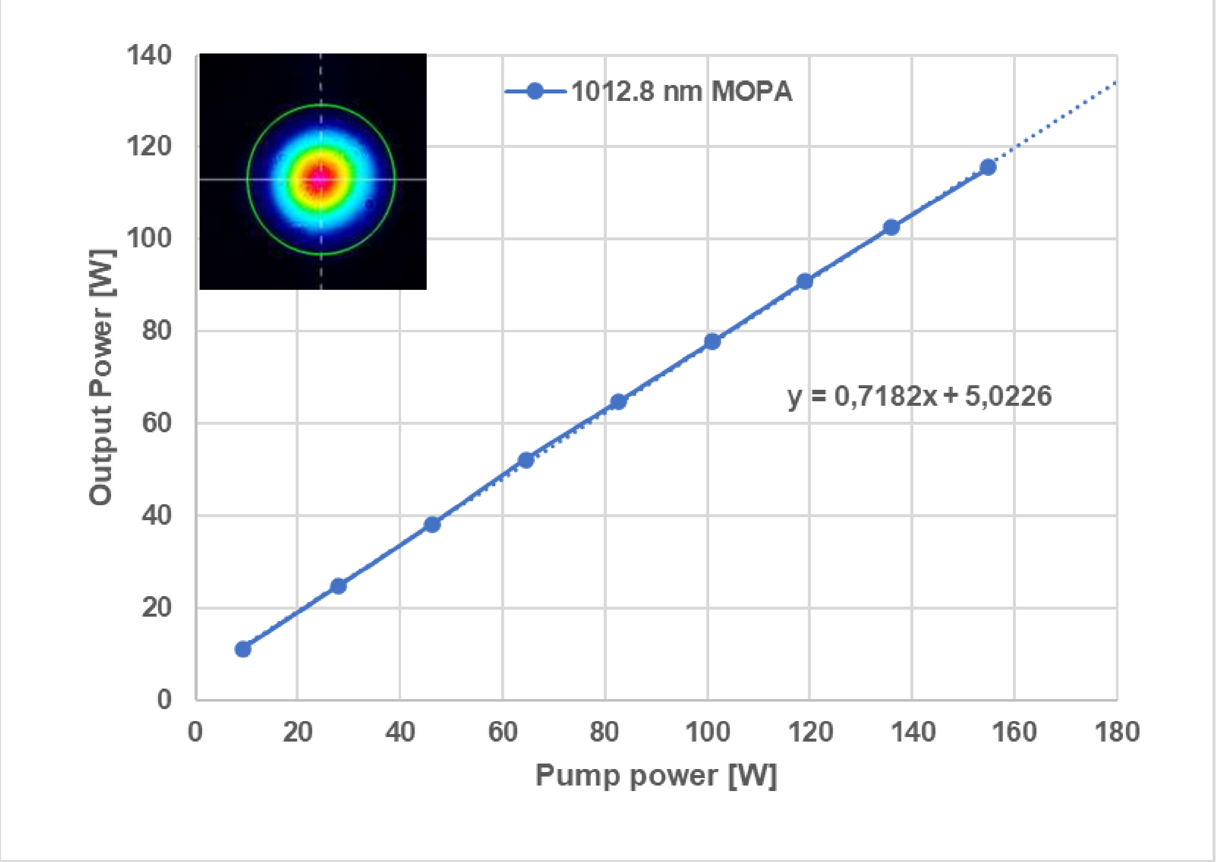
- **Rb Rydberg atoms (1012nm-1016nm)**
- **Mercury atom laser cooling (1014.8nm)**

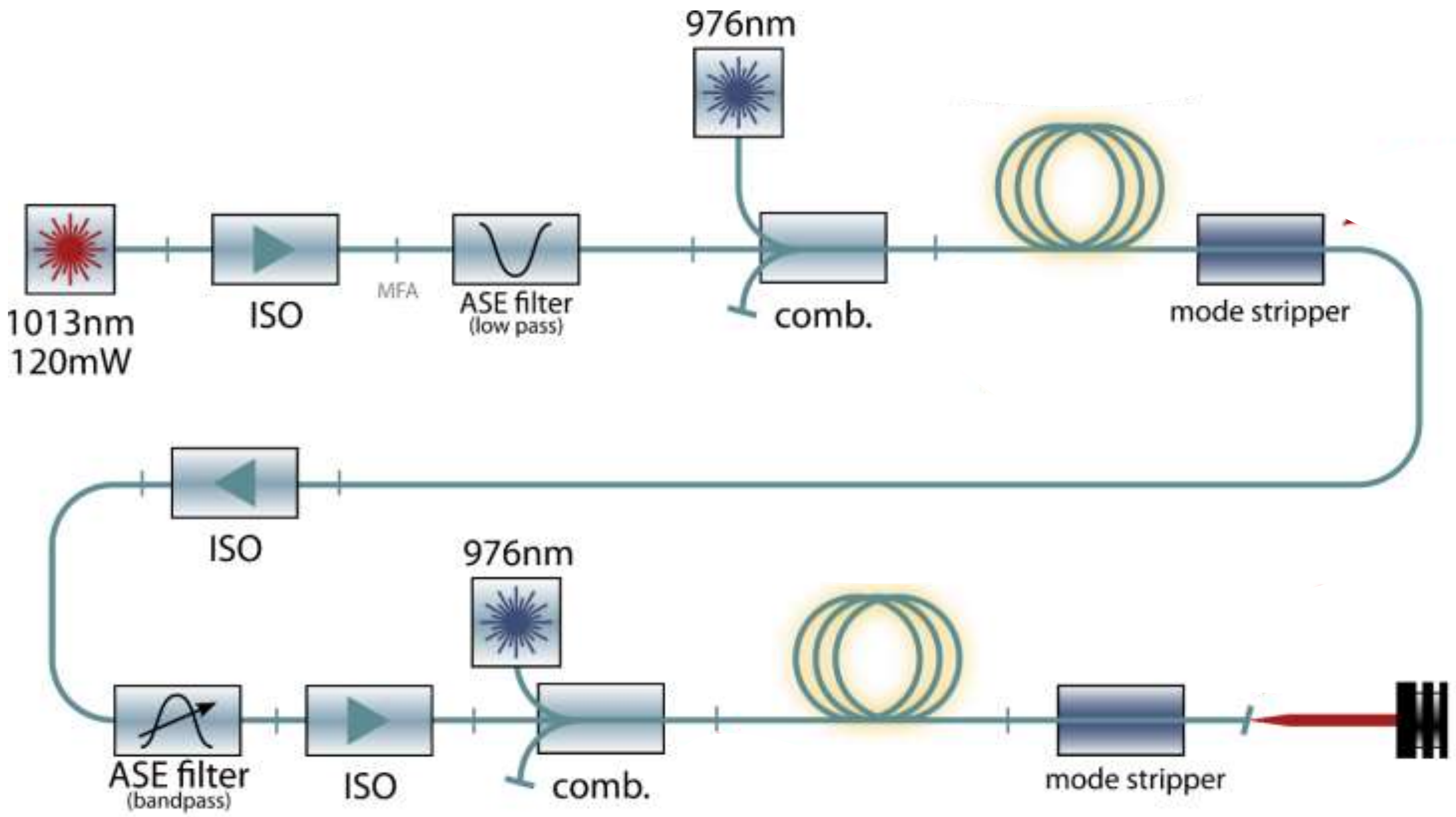
High power >115W

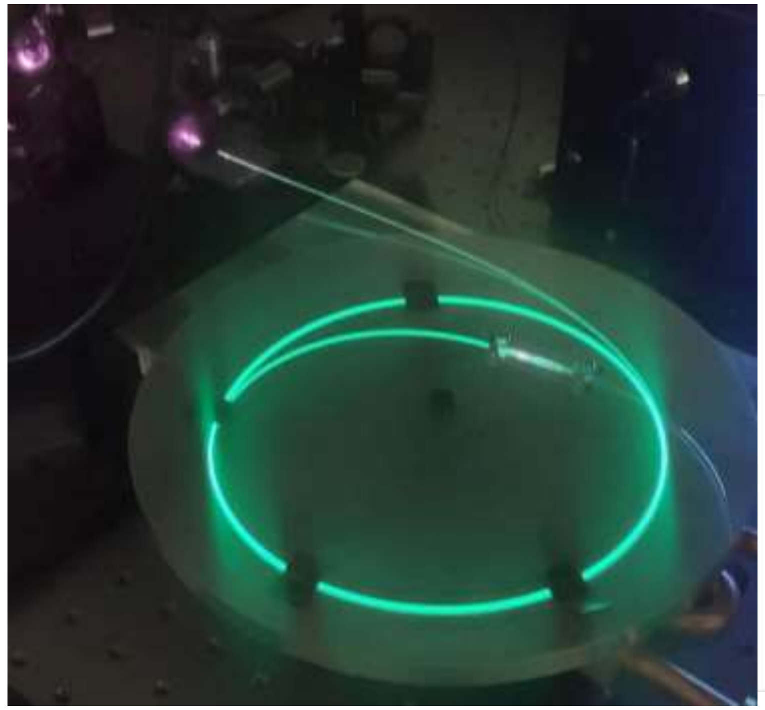
High efficiency >70%

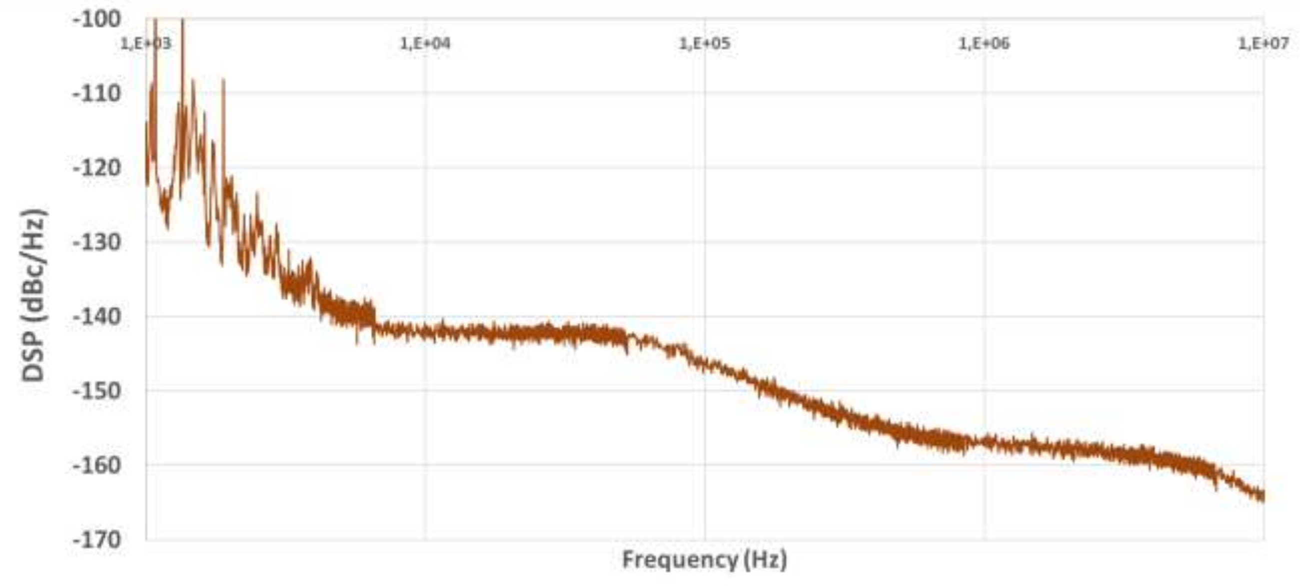
OSNR >50dB

Very low RIN







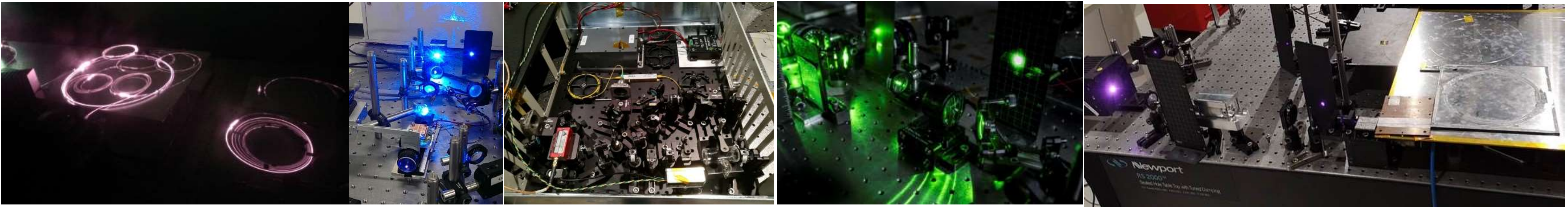


Seminal work by Gouhier et al, “Low-noise single-frequency 50 W fiber laser operating at 1013 nm”, Laser Physics Letters, **16**, 045103 (2019)

CONCLUSIONS&OUTLOOK

- Neutral atom quantum computing&simulators requires ultra-reliable low noise HP lasers
- Several wavelength in the NIR/VIS & UV are necessary for Rb, Sr&Yb QPUs
- Fiber technology w/ non-linear optics is a potential solution
- High-power waveguides and cavity assisted SHG/SFG can lower the power requirements
- T&F metrology techniques&methods are valuable for QPU laser systems
  - Phase /frequency stabilization techniques, RIN control (noise eater)
  - Reliable compact & robust frequency references (cavities, fiber interf., atomic/mol. transitions)
  - Characterization & measurements methods…

The end



Thank-you

Post-doc positions available @LP2N