ADVANCES IN LASERS FOR SPACE-BASED SENSING

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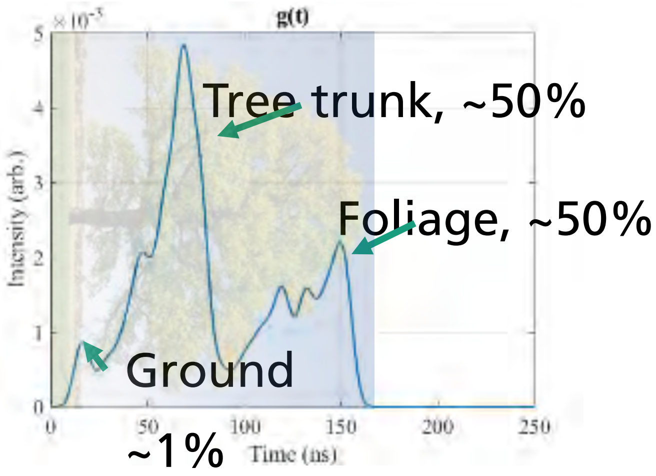
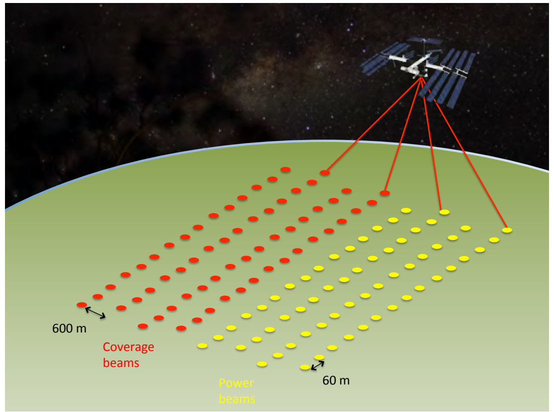
Fraunhofer Centre for Applied Photonics

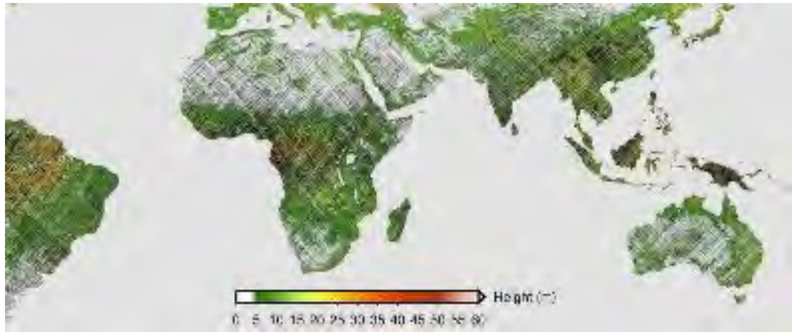
- Founded in 2012 in Glasgow, Scotland, UK
  - Non-for-profit RTO
  - Part of the Fraunhofer network
- 65 staff including 25 PhD/EngD students
- Supporting industry
  - Contract R&D
  - Innovations in photonics
  - >100 funded company partners
- Two Business Units
  - Laser and Laser Systems
  - Quantum Technologies

GLAMIS - Overview

- Global Lidar Altimetry Mission presents a three-fold challenge in terms of source development:
  - Laser pulse power is required to be strong enough to penetrate atmosphere and high degree of foliage cover to detect ground level.
  - Laser pulses need to be repetitive enough to take sufficient data points when coupled to satellite motion.
  - Lasers need to be of relevant efficiency and scale to present multiple parallel recording points.
- Solid-state lasers provide means to achieve this but sacrifice SWaP considerations.

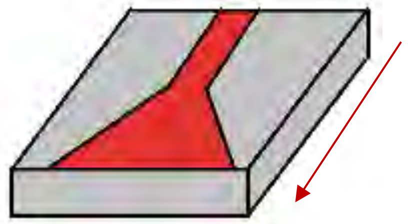


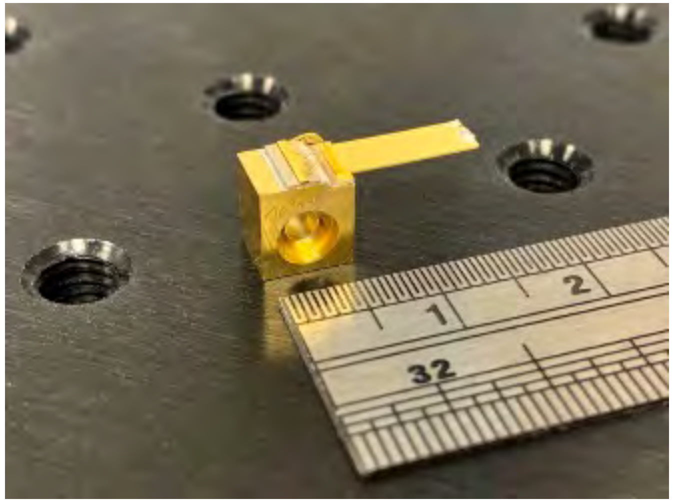




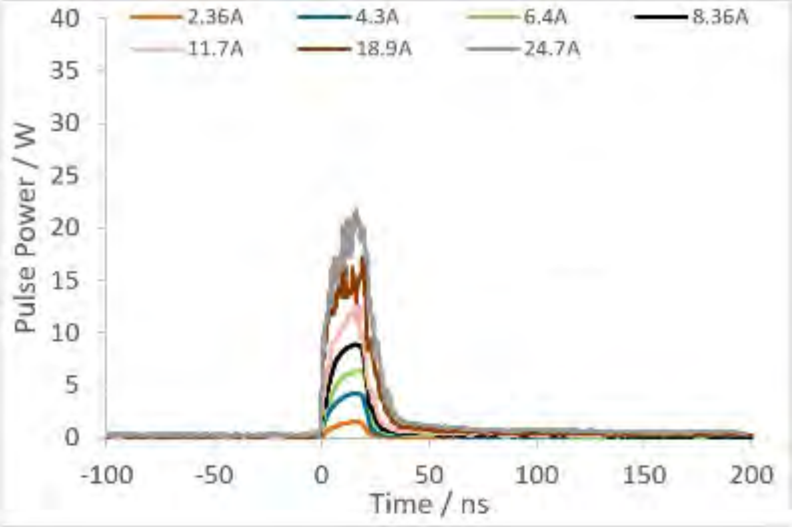
GLAMIS – Source development

- Aim to use small form factor and high efficiency diode laser sources.
- **Tapered diodes** can provide high optical powers > 3 W c/w whilst maintaining good beam quality.
- LiDAR operation in pulse train mode to allow for more modest peak powers.





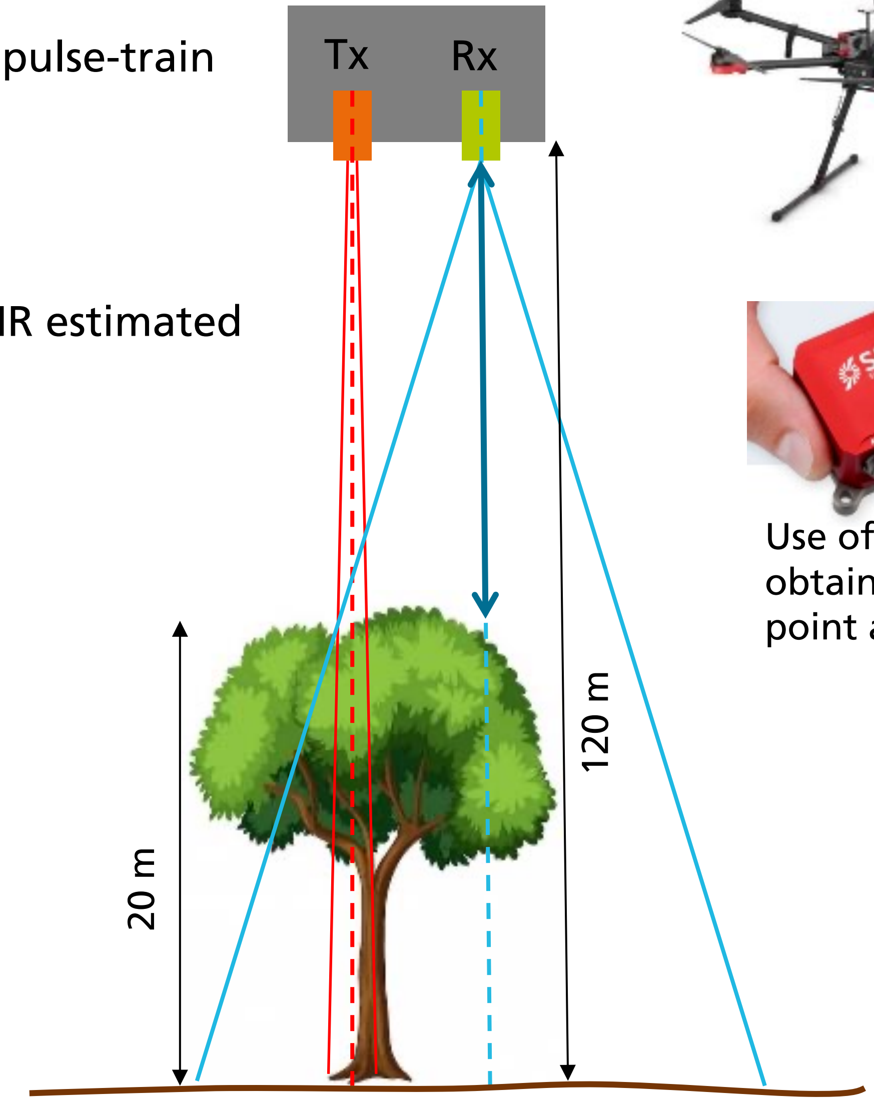
- Proof of operation at powers beyond **20 W** peak over a duration of **20 ns** and a pulse repetition rate of **1 MHz**.
- **850 nm** spectral region in compromise between atmospheric transmission and single photon detector sensitivity.
- ~ **1 GHz** optical bandwidth when utilised in a MOPA configuration.



GLAMIS – Drone demonstrator phase

- Build a LiDAR unit that will demonstrate the viability of the pulse-train approach and prove simulation results
  - Confirm the background noise estimation from model
  - Pulse train LiDAR results in real environment
- LiDAR unit parameters have been 'scaled down' to match SNR estimated for the space application

Parameter	Satellite	UAV
Footprint diameter	30 m	12.6 cm
Telescope diameter	58 cm	3-5 cm
Altitude	500 km	120 m
Atmospheric transmission	0.8	~1
Surface reflectance	40%	40%
Detector efficiency	58%	15-20%
Optical efficiency	70%	70%
Wavelength	~ 850 nm	808 nm
Pulse length	~ 10 ns	Options: 10ns; 20ns; 30ns
Energy/pulse ground	107 nJ	6.4 pJ
Signal photons per laser shot	0.012	0.014
Dark count photons per laser shot	8x10^{-4} photons	3x10^{-4} photons
Day background	542 photons	766 photons
Night background	1.4x10^{-3} photons	1.9x10^{-3} photons



Use of IMU to obtain high point accuracy

UK SPACE AGENCY

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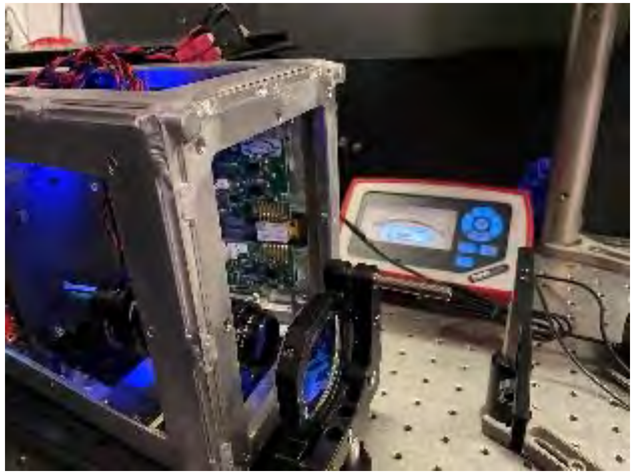
GLAMIS – Drone demonstrator phase

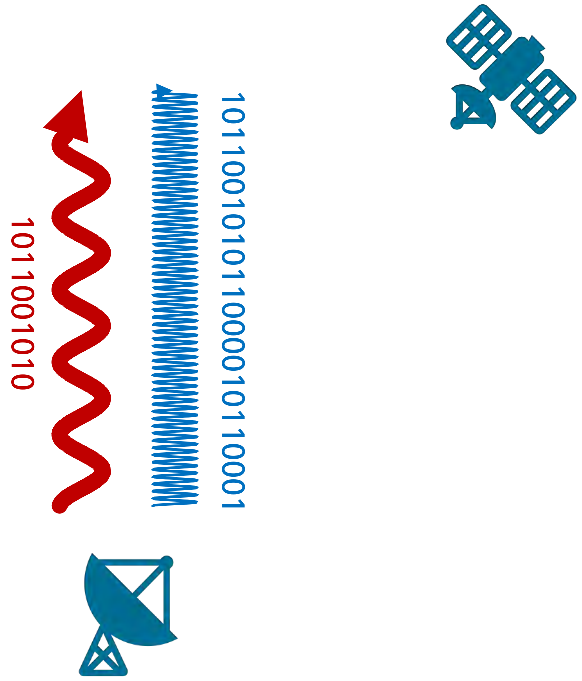
- Transmitter telescope – Beam expander
  - Laser diode (808 nm) triggered by Red-Pitaya board at 1 MHz
  - Collimated beam (0.45 mrad divergence angle)
  - Absorptive ND filter to match required SNR
- Receiver telescope
  - Bandpass filter (5 nm bandwidth)
  - Single photon detector with photon detection efficiency of 20%
- Home-made time tagger with FPGA board – Red Pitaya
  - Decode the UTC, geolocation and Euler angle (Roll/pitch/yaw) data from the GNSS/IMU module
  - Process the measured timestamps from TCSPC (20 ps timing resolution)
  - Integrate and log the TCSPC and GNSS/IMU data into an on-board SD card
  - Synchronise TCSPC with the PPS of the GNSS/IMU module.

➢ LiDAR unit is currently being classified as Class 1

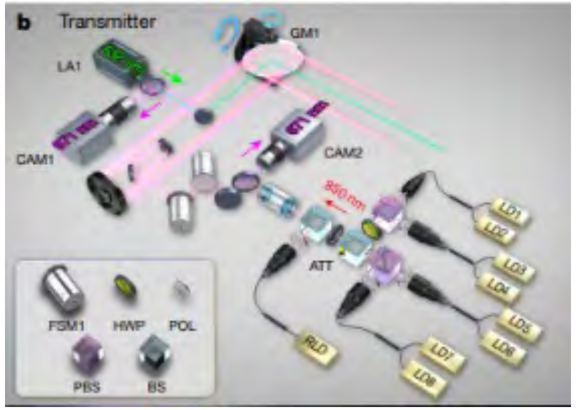
➢ Flight test will start mid-April



Characterisation of Faint-Pulse-Sources for QKD
Motivation



- Aim is secure quantum communication on a global scale:
- Ground based QKD channels
  - Currently limited to 100’ds of km
  - Quantum repeaters not viable technology yet
- Satellite based QKD combined with free space laser communication
  - Can overcome this limit
  - Compatible with small satellite environments (transmitter/receiver optics)
  - Potential to provide necessary bandwidth
    - Key-exchange in single overpass
    - Longer keys, higher security / More keys (GHz)



MICIUS Mission
Decoy state BB84 protocol
8 fibre-based laser diodes
850 nm, 100 MHz, 0.2ns
kHz-key-rate
Up to 1200 km distance

S. K. Liao *et al.*, *Nature*, vol. 549, no. 7670, pp. 43–47, Sep. 2017, doi: 10.1038/nature23655

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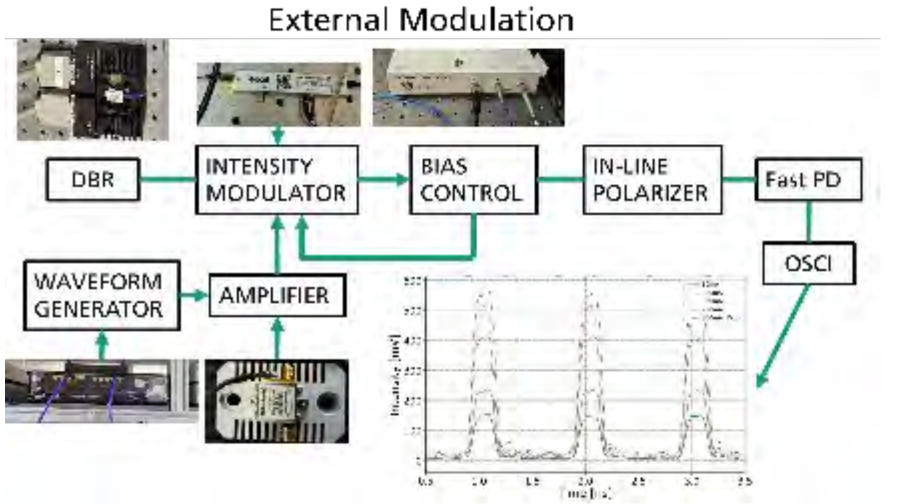
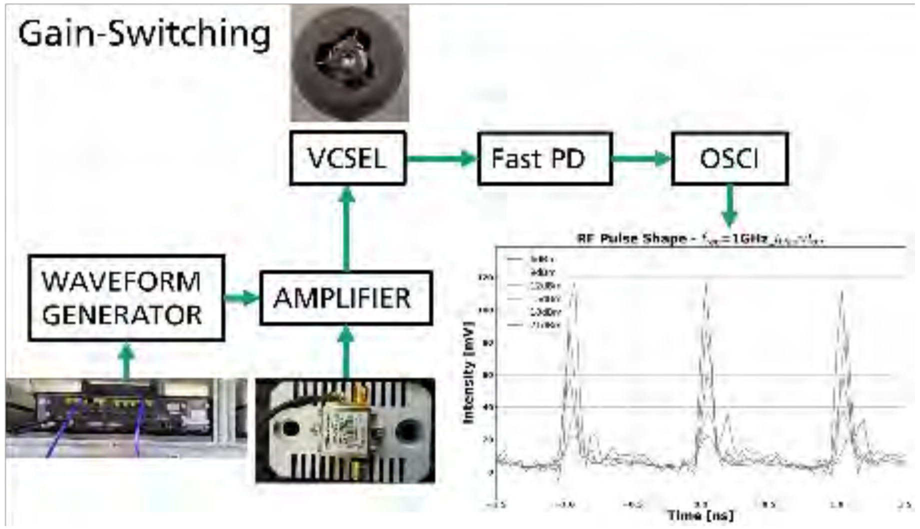
2) Arqit Quantum Inc., London, United Kingdom

Motivation

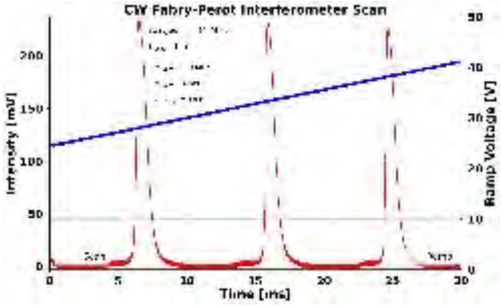
- Requirement of suitable **faint pulse sources** for the transmission of the quantum key
  - Compact, low SWaP systems suitable for satellite environments
  - Commercially available (COTS)
  - Operation near 850 nm
  - Direct modulation bandwidth > 1 GHz
    - Difficult to achieve in commercial laser diodes architectures.
- Investigation of two different approaches
  - Externally modulated DFB lasers
  - Gain-switched VCSELs

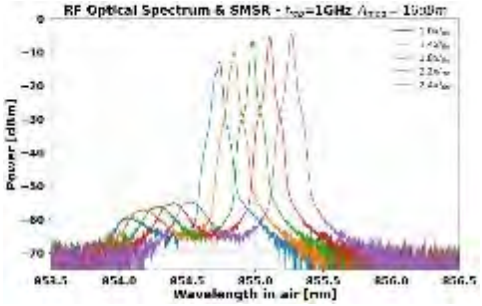


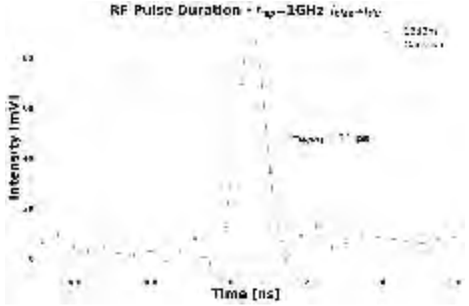


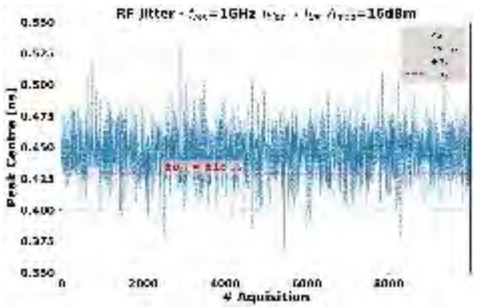
Investigated parameters

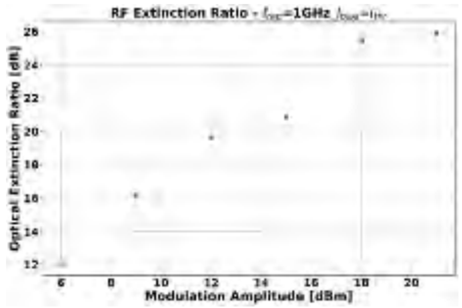
- Single frequency operation
- Single spatial mode & SMSR
- Output power stability
- Polarisation stability: PER & DOP
- Pulse duration: τ_{FWHM}
- Optical Extinction Ratio: ER
- Pulse-to-pulse characteristics
  - Jitter
  - Amplitude
  - Pulse-to-pulse coherence:

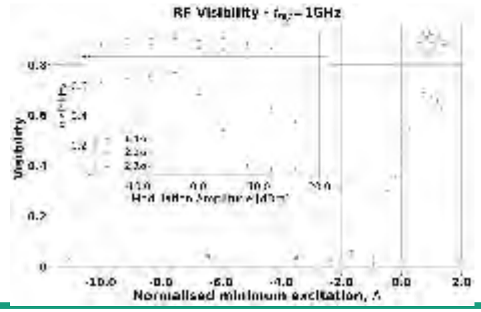












- External modulation
  - Commercially more mature
  - Expensive, larger footprint, higher power requirements
  - Challenges of maintaining ER, PER, DOP at high repetition rates
- Gain-switched VCSELs
  - High performance maintained in the low GHz regime up to 3 GHz:
  - Supply chain (quality, repeatability)
  - Multiple lasers required in
  - Bandwidth limited by ESD protection diode

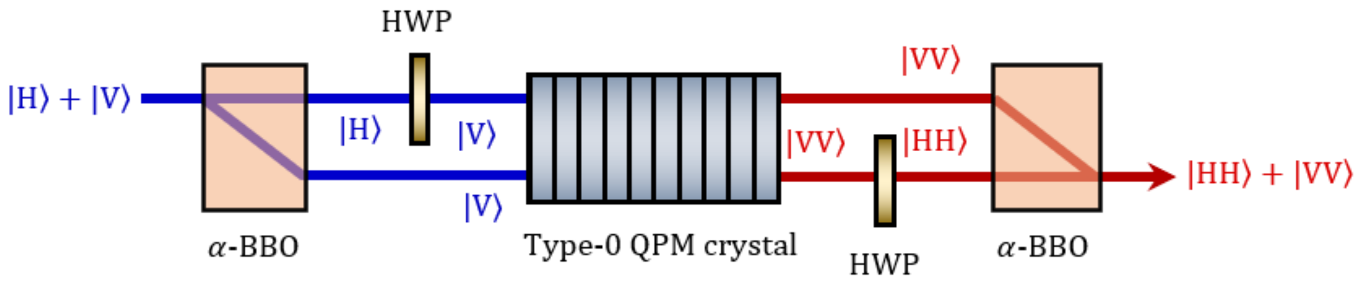
Entangled Photon Sources for Satellite Quantum Communications

- **NextSTEPS (Next Generations Space Entangled Photon Source):** Development of a miniaturized polarization entangled photon pair source for the application to satellite mediated quantum communications.

- Collaboration with Craft Prospect and Alter Technology

- Spontaneous parametric down-conversion sources with typical photon-pair detection of > 500,000 pairs/s for 1 mW of pump power, and heralding efficiencies of ~ 20%.

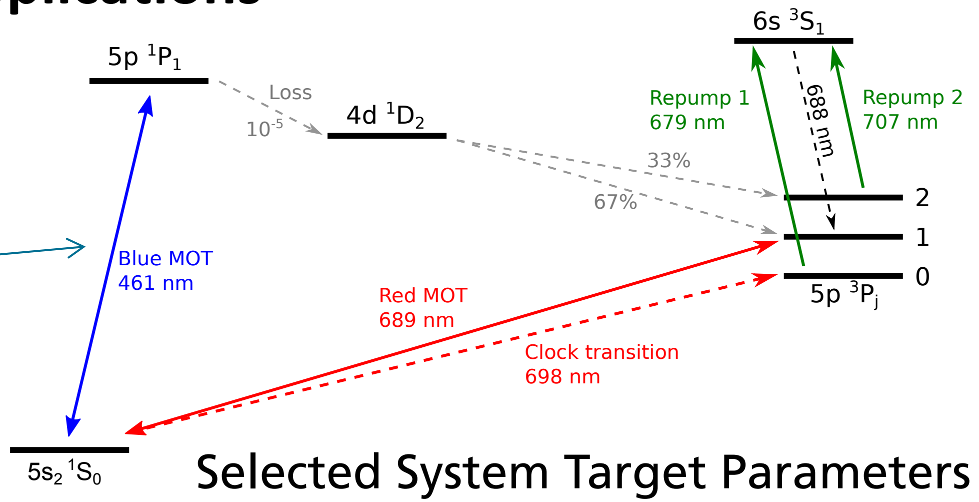
- Source designs with higher functional stability and non-critical alignment tolerances.



CRAFT PROSPECT ALTER Fraunhofer UK

Engineering SDL systems for single-frequency applications
Motivation

- Development of a stable laser for 1st Stage Strontium cooling
- Direct emission in the blue not available
- Based on a Semiconductor Disk Laser (SDL)
  - Fundamental operation in the near IR
    - $f_{922\ nm}$ = 325.2520 THz (NPL, PTB)
  - Intra-cavity second harmonic generation

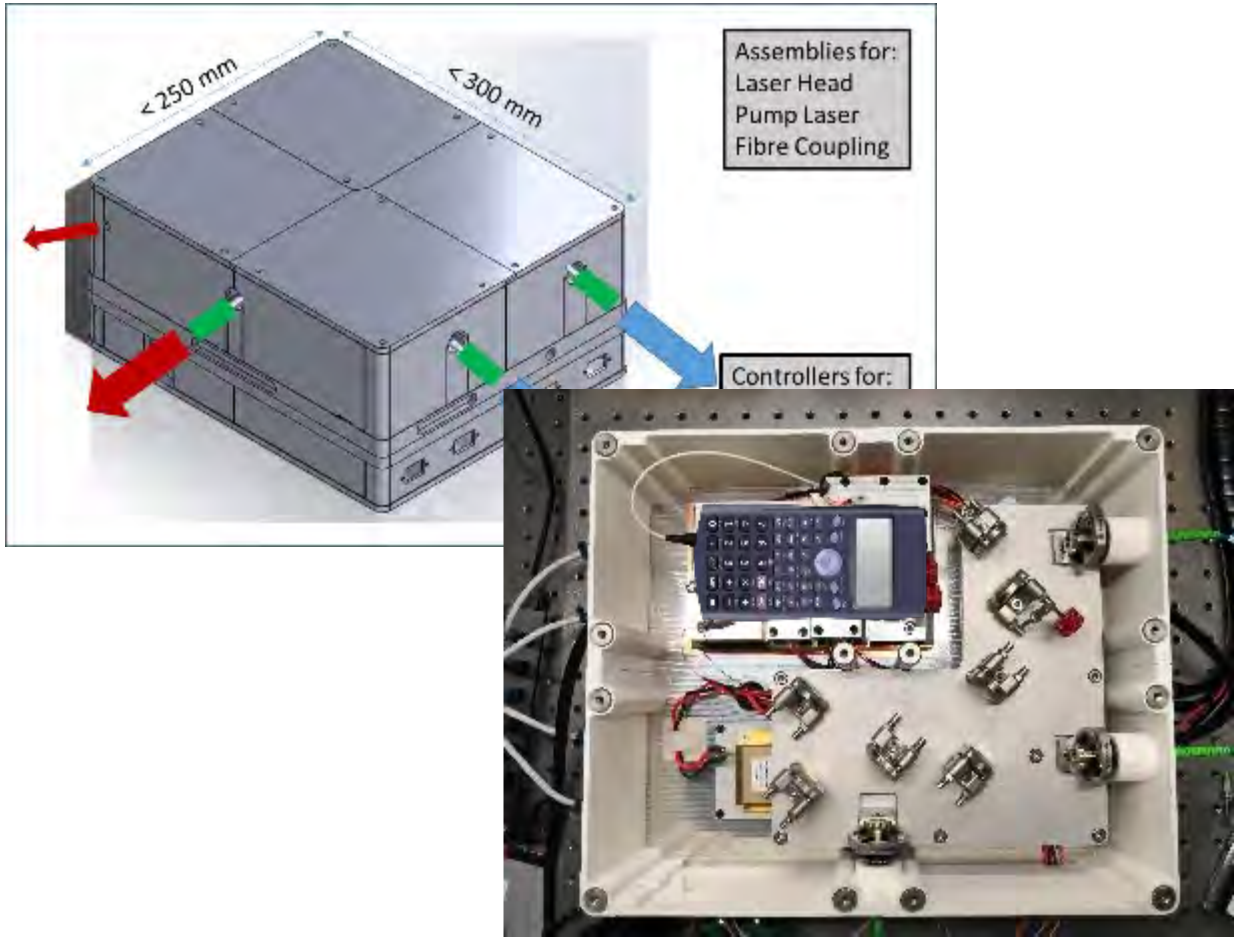


Selected System Target Parameters

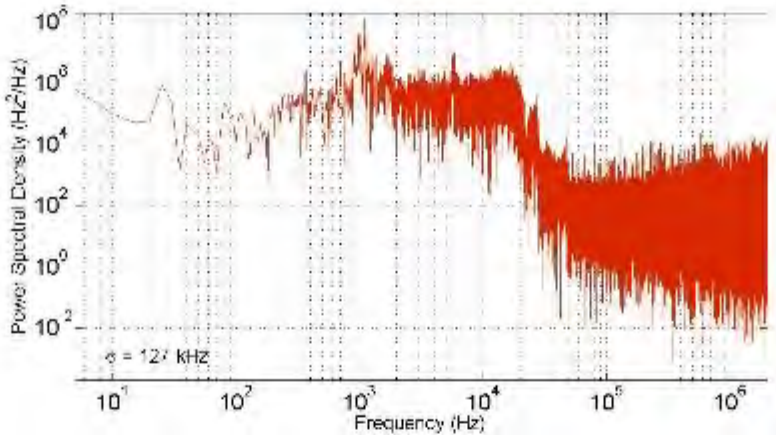
	Sr first stage cooling
Wavelength	461 nm ~ 650.5036 THz
Atomic transition	^{87}Sr; $^1S_0 \rightarrow ^1P_1$
Power	>150 mW
Linewidth	<1 MHz
Frequency deviation	<1 MHz in 24 h
Frequency tuning	>400 MHz in 10 s
Laser output I/Fs	Max 4 fibre coupling units, 2 delivering > 50 mW each; FC/APC connectors
Mass (guideline)	13 kg
Volume (guideline)	11 l
Lifetime (guideline)	> 3 years

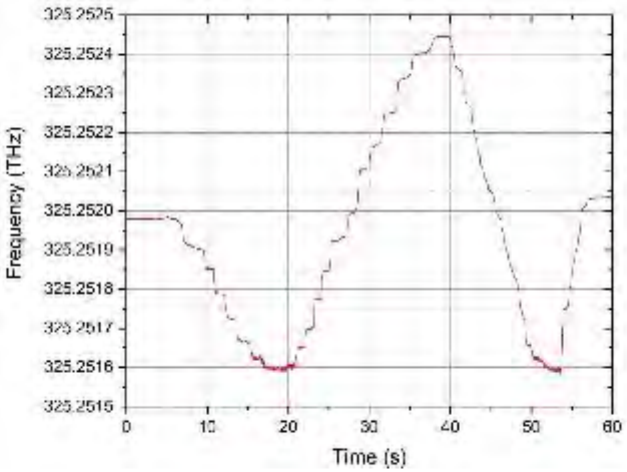
SDL system

- Dimensions:
  - H = 145 mm, W = 250 mm, L = 300 mm
  - V < 11 l
- Weight:
  - 13 kg (4 kg laser head)
  - Including controllers (temp and LD)
- Fundamental IR outputs x2
  - for locking and monitoring
- Frequency doubled blue outputs x2
  - Fibre coupled

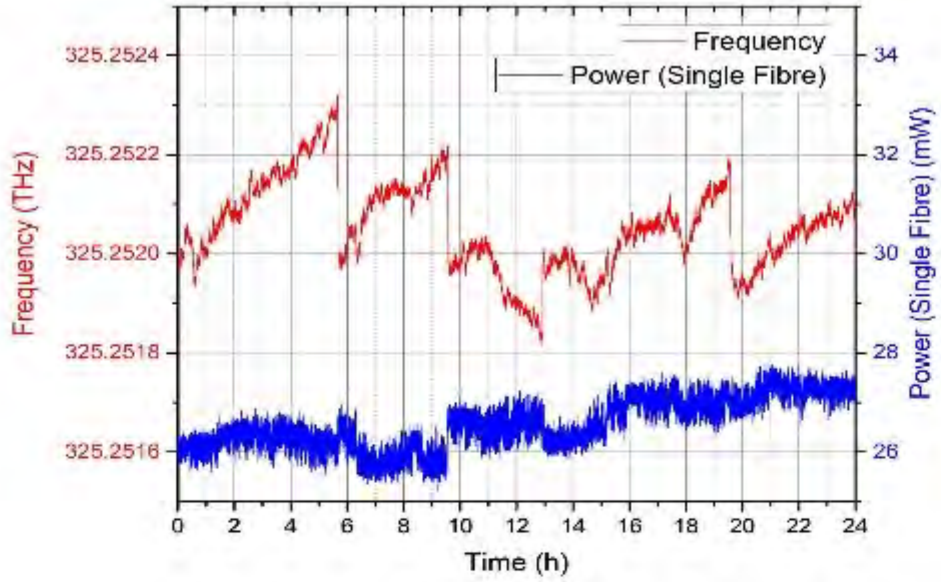


SDL performance





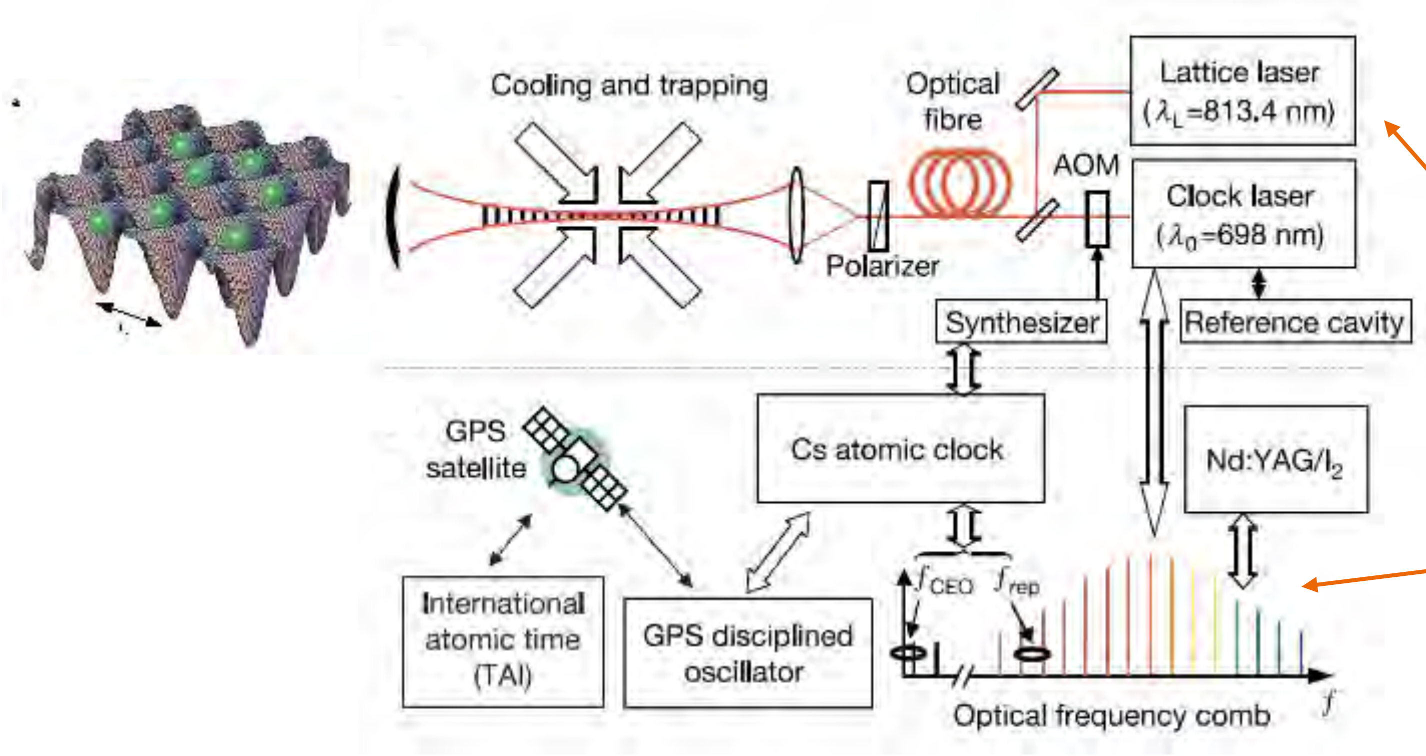
- Single frequency operation:
  - Side-of-fringe, power spectral density linewidth < 500kHz
- Target Frequency
  - 325.2520 THz using Wavelength meter (HighFinesse)
  - Free running stable emission over hours
- Locked to Fabry-Perot Interferometer (FPI100)
  - Manual fine-tuning range ~ 1 MHz
    - Within < 10 s
  - > 24 hour mode-hop free locking
  - Readjustment of FPI100 to compensate for drift
- Total blue power P_{461nm} > 60 mW



European Space Agency

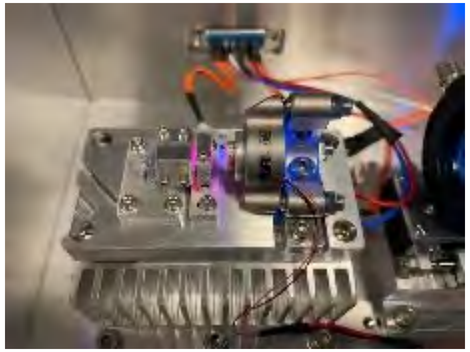
Fraunhofer UK

Advanced solid-state laser technology for Neutral Strontium Optical Clock Standards in Space



M. Takamoto, et al. "An optical lattice clock," Nature **435**, 321 (2005)

- *Microchip-type single-frequency Ti:sapphire laser*



Diode-pumped Ti:sapphire laser technology

- *Compact Ti:sapphire laser based frequency comb*

High Power and High Spectral Purity Lattice Laser at 813 nm: key technical features

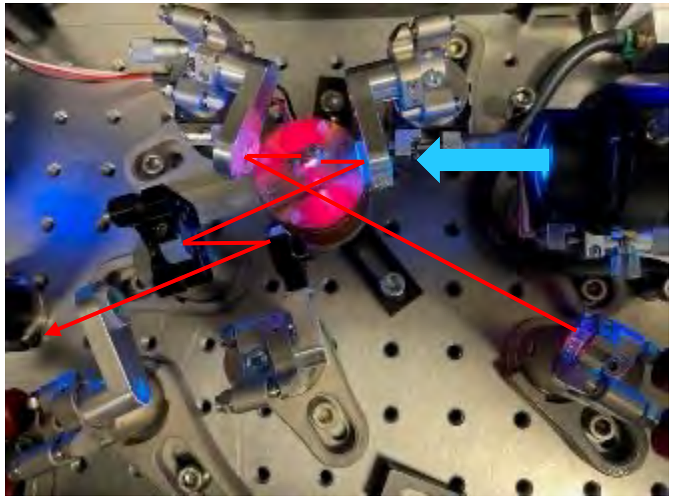
- mm-size laser cavity architecture with unique combination of features
- Single-longitudinal-mode operation is supported by an ultra-narrow volume Bragg grating
- > 0.7 W output power sufficient for trapping and cooling of neutral strontium atoms
- 170 kHz linewidth when locked to an external reference cavity
- Fully tested with laboratory strontium clock system
- The system shows a significant reduction in size weight and power over alternative approaches, being suitable for further deployment in space.

For more information please see

Opt. Lett. ***47****, 2995 (2022)*

Ultra-compact femtosecond Ti:sapphire laser based frequency comb source

~ 10 cm

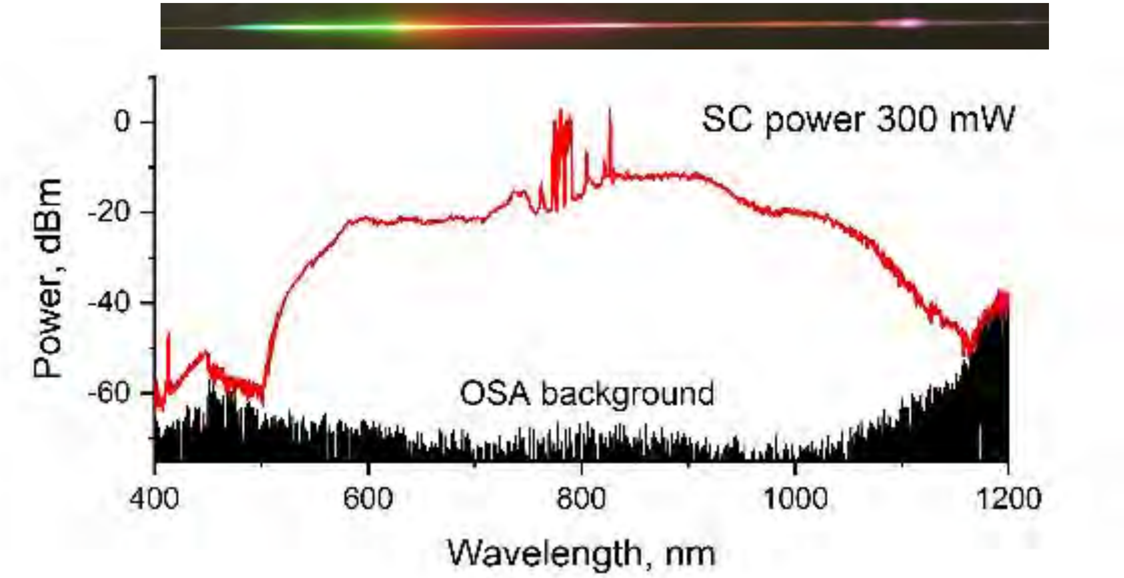


~ 6 cm

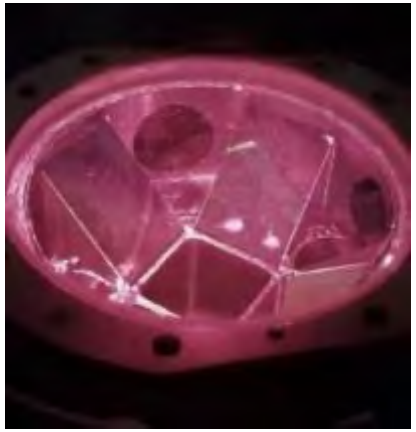
- Diode-pumped ultrafast Ti:sapphire
- 37-fs pulses, 0.6 GHz repetition rate
- 0.8 W average power

Photonic Crystal Fiber

- *Octave-spanning supercontinuum*

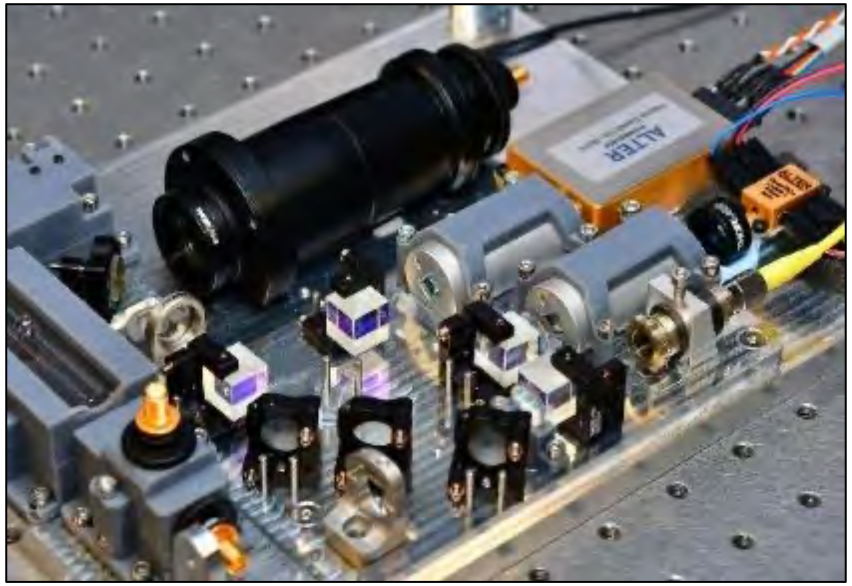


Optical systems for atom sensor systems



- Novel source and light delivery approaches
- Working with collaborators to develop prototype atom sensor systems
- Projects on many topics including
  - Gravity gradient
  - Inertial sensing
  - Cold-atom clocks
  - Magnetometers

Tunafish: Fibre-coupled rubidium- and offset-locked laser system.



Quantico: 852 nm, 1470 nm and 843 nm stabilised laser system for THz detection.

Pioneer Gravity: interferometry laser trapping 3.4 E8 atoms

ALTER TECHNOLOGY

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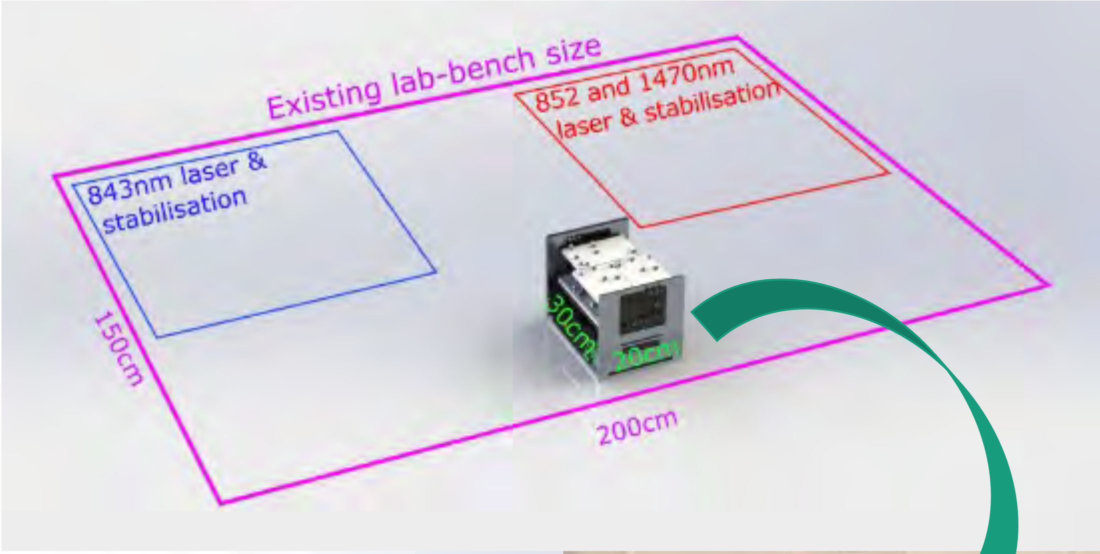
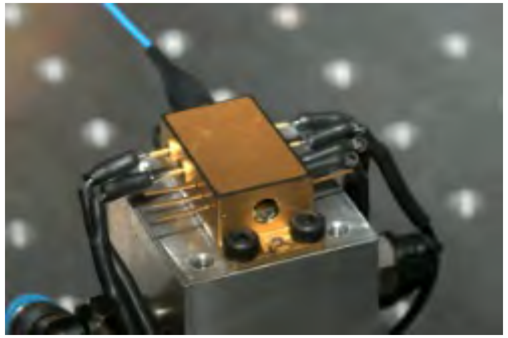
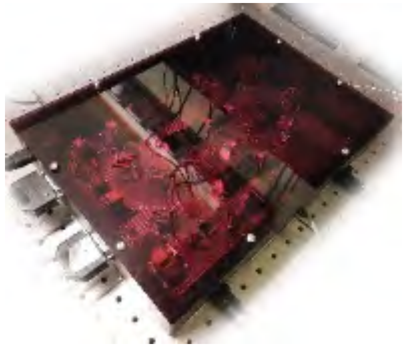
Optical systems for atom sensor systems

- We help develop and use high TRL subsystems and components to shrink large systems
- Laser systems engineered for portability (SWaP) and robustness – some systems qualified for flight, most are operated outside the lab
- Complex, comprehensive 19” rack mountable laser systems for atom interferometry and BEC sensors
  - ~10 switchable outputs, >60 dB extinction
  - 10 – 350 mW stabilised output power per channel
  - <100 kHz linewidth (where needed)
  - Agile frequencies – tunability
  - Operation in real-world environments







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