

μQOC: Microcombs for Quantum Optical Clocks

Applications of miniature optical atomic clocks

- Optical atomic clocks are our most accurate clocks that use optical transitions of atoms to keep time to uncertainties as low as 10^{-18}
- This allows geopotential measurement with 1 cm height resolution
- They will be the basis for the forthcoming redefinition of the SI second
- Portable optical clocks are beginning to be commercialised, that although are less accurate than their lab-based counterparts, still outperform microwave atomic clocks of comparable SWaP
- Current commercial offerings are ~3U 19in rack size but increasingly small and even chip-scale versions are being developed
- Miniature optical clocks will require chip-scale frequency combs



- Applications include geodesy, astronomy, phased radar, GNSS-resilient and GNSS-free timing and navigation, ultrahigh-throughput telecoms and quantum computing and networking

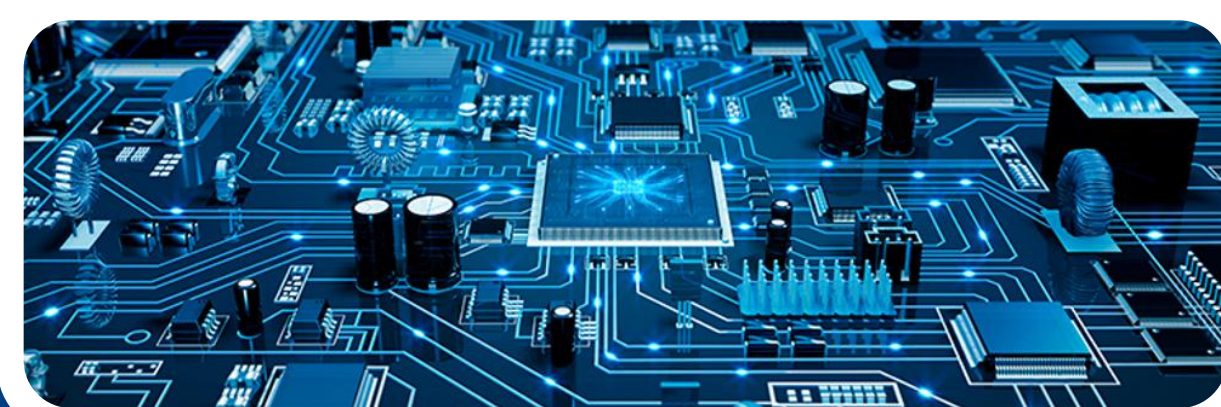
Optical atomic clock architecture

Physics package

Vapour cell clock e.g. Rb 2-photon	Optical lattice clock e.g. Sr, Yb	Trapped ion clock e.g. Sr ⁺ , Yb ⁺ , Ca ⁺
- Magnetic shielding - Magnetic field coils		
Atomic vapour cell	- Vacuum chamber - Atomic beam oven - Cooling, readout and repump lasers	- RF Paul trap and drive - Ionisation laser

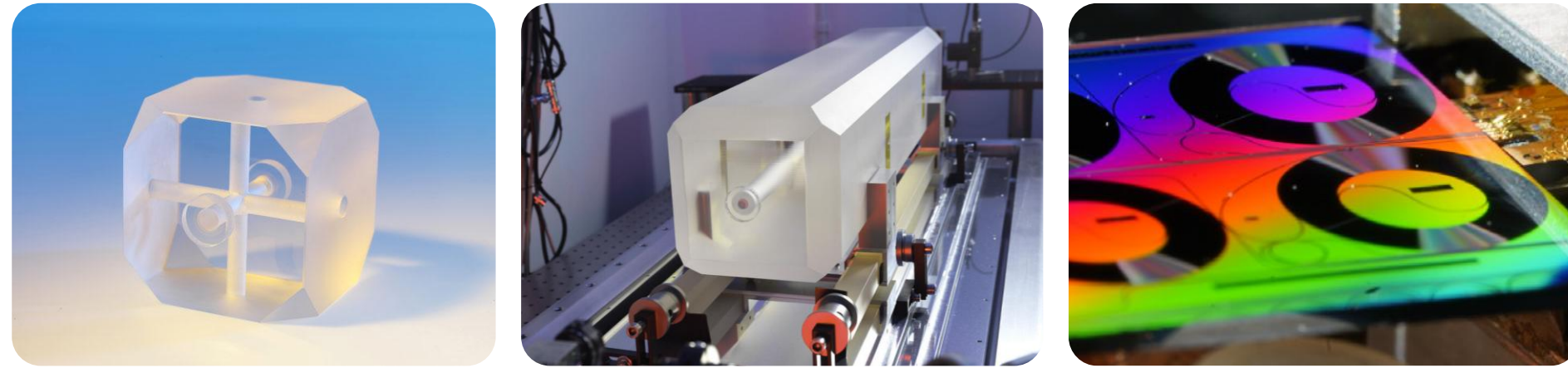
Control electronics

- Drives lasers, magnetic field coils, heaters, TECs, photodetectors
- Fast feedback for laser locking
- Slow feedback for other parameters including clock laser frequency
- Start-up and laser relocking
- Microwave signal processing



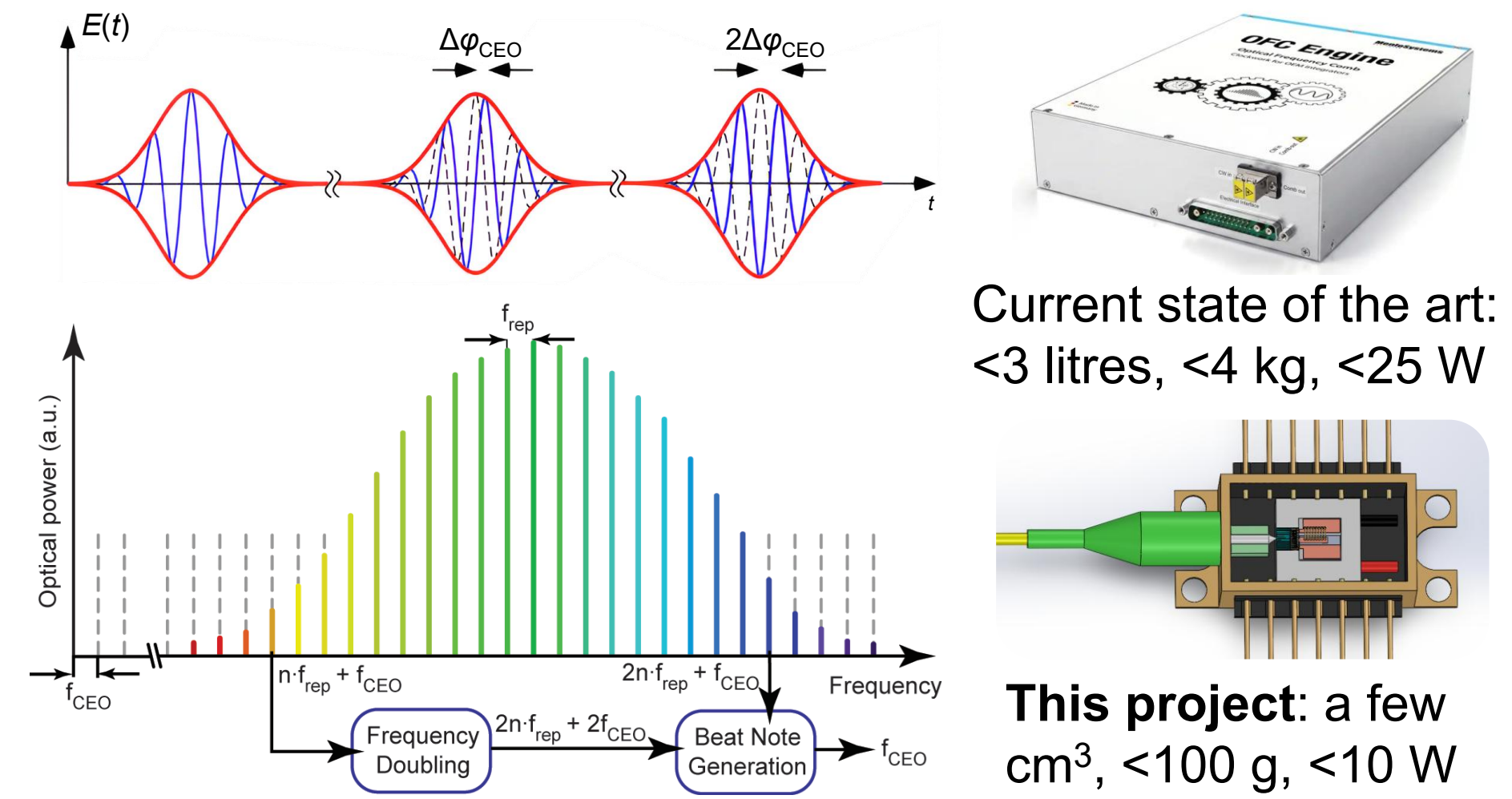
Clock laser

- Interrogates clock transition
- Narrower than clock spectroscopic feature
- Good short-term stability extracts best clock performance
- Pre-stabilised to cavity or different atomic spectroscopy signal
- Steered to centre of clock spectroscopic feature

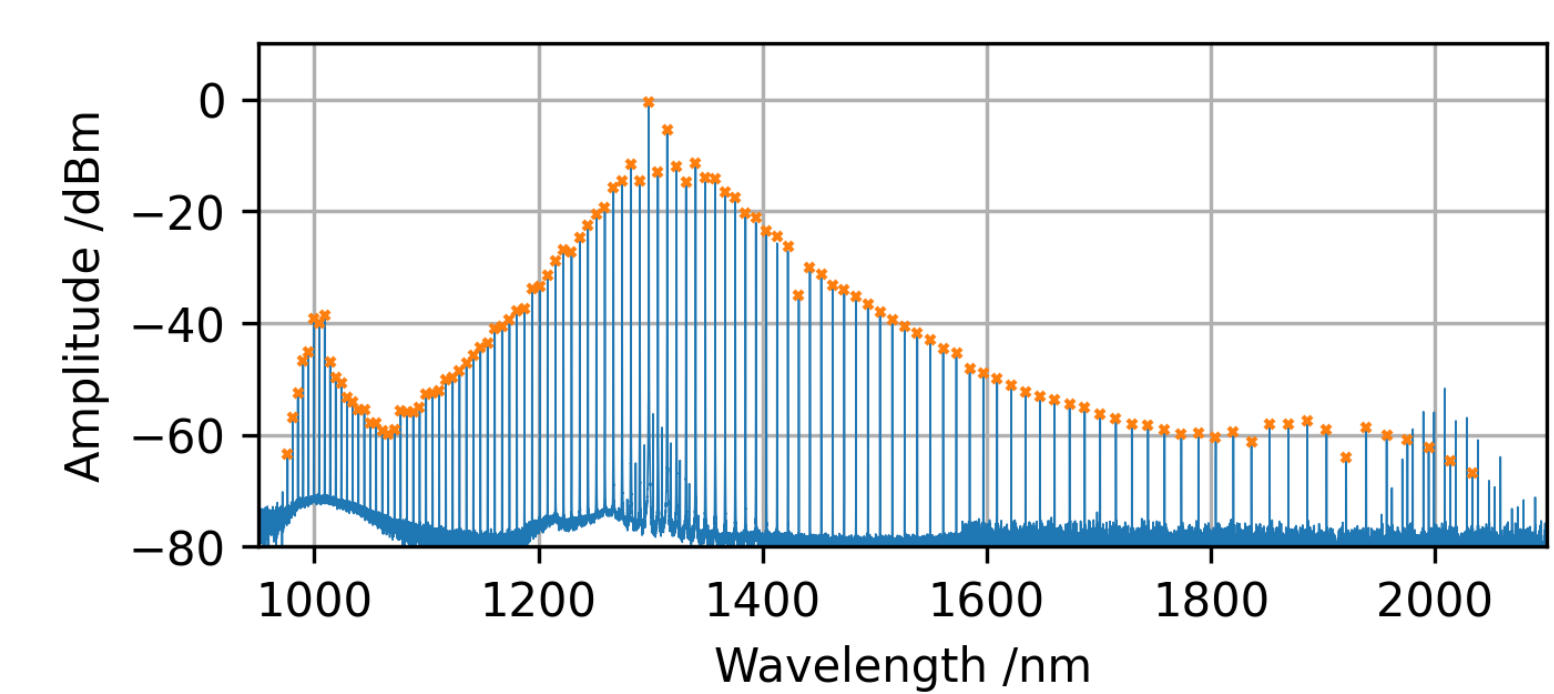


Frequency comb

- Allows clock laser to be phase-coherently divided down to a microwave frequency that can be used or counted
- Optical-to-microwave down-conversion has uses besides clocks, including ultrastable microwave generation for radar
- Allows coherent conversion of clock laser to other wavelengths for optical clock comparisons with different atomic species or over telecom fibre links
- Comb must be self-referenced to measure the carrier-envelope offset frequency f_{CEO} . The simplest way to achieve this is via f - $2f$ interferometry which requires an octave-spanning comb.

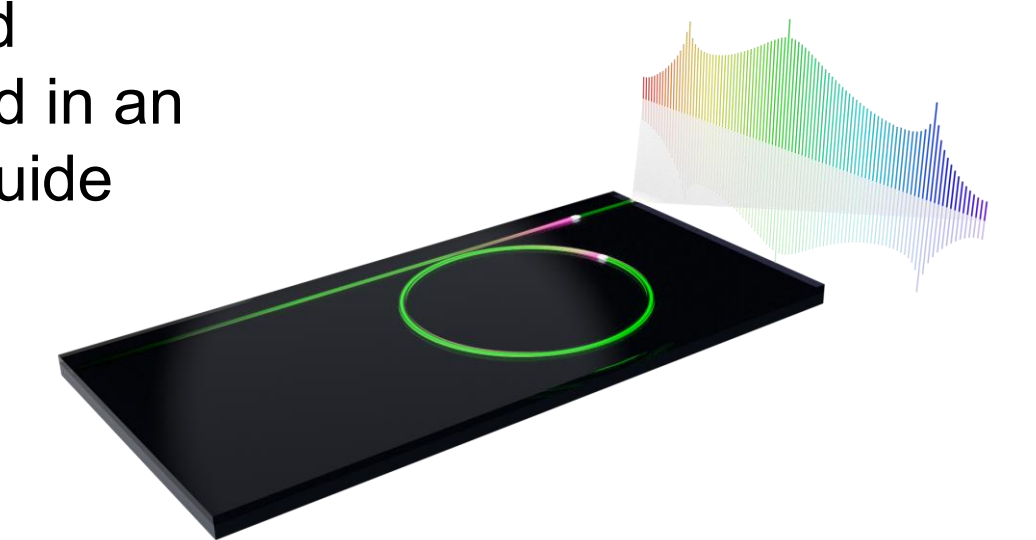
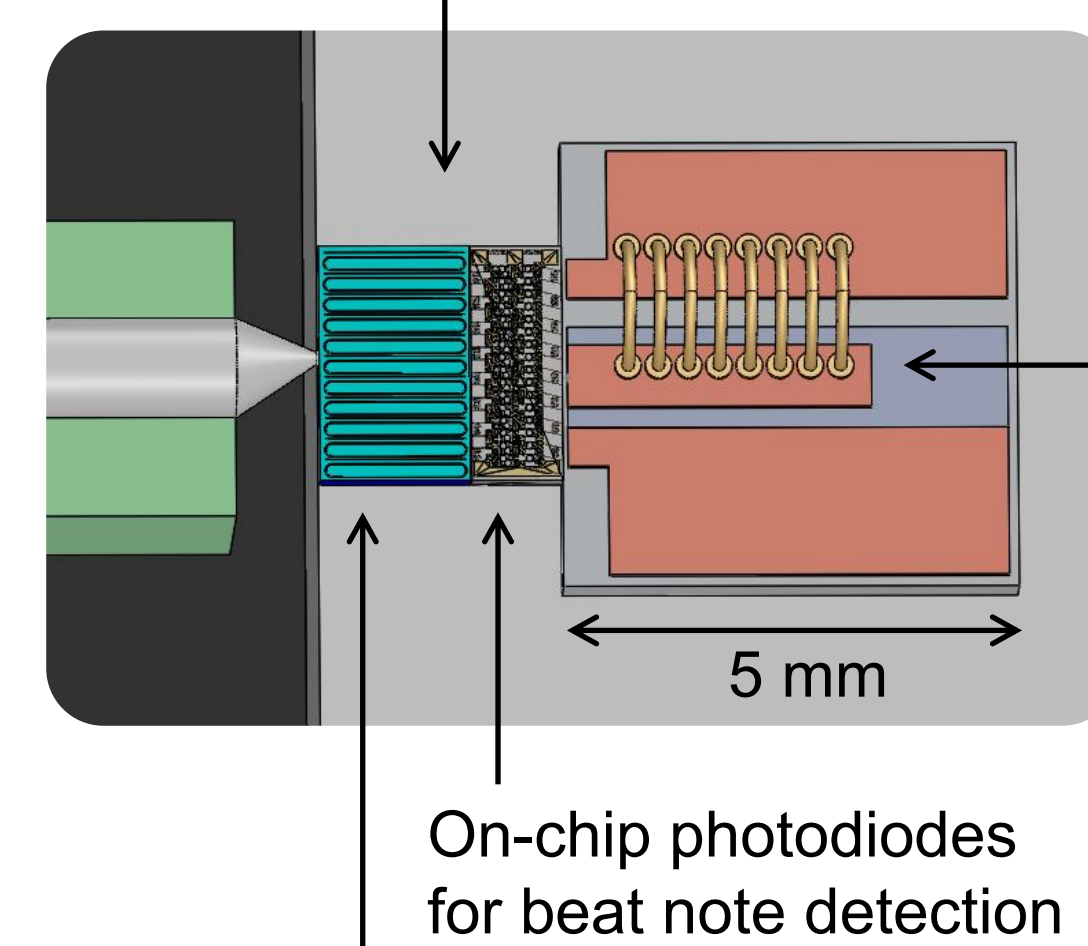


Self-referenced microcomb



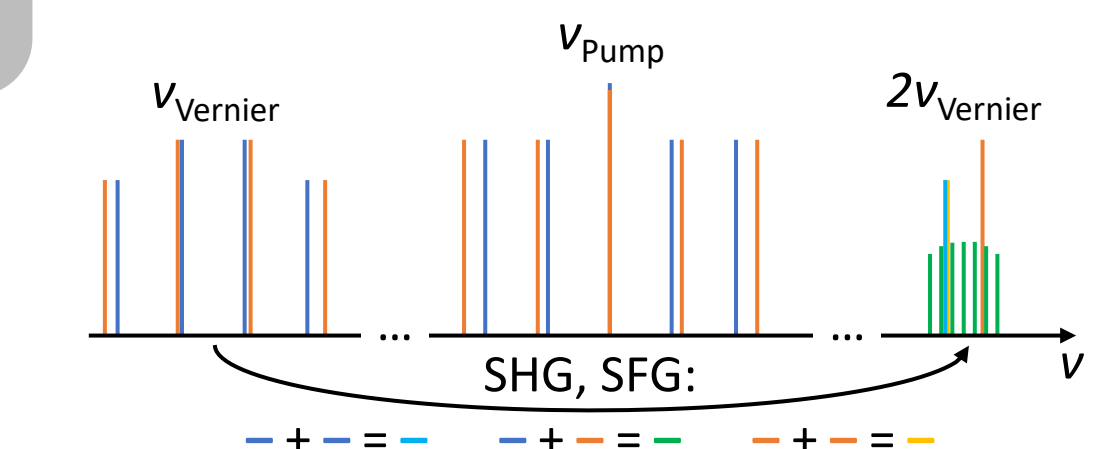
Single-soliton frequency comb generated in the microresonator via the Kerr, or $\chi^{(3)}$, optical nonlinearity starting from a single pump wavelength

Octave-spanning microresonator-based frequency comb (microcomb) generated in an ultrahigh-Q ($\sim 10^7$) silicon nitride waveguide ring resonator with diameter $< 100 \mu\text{m}$



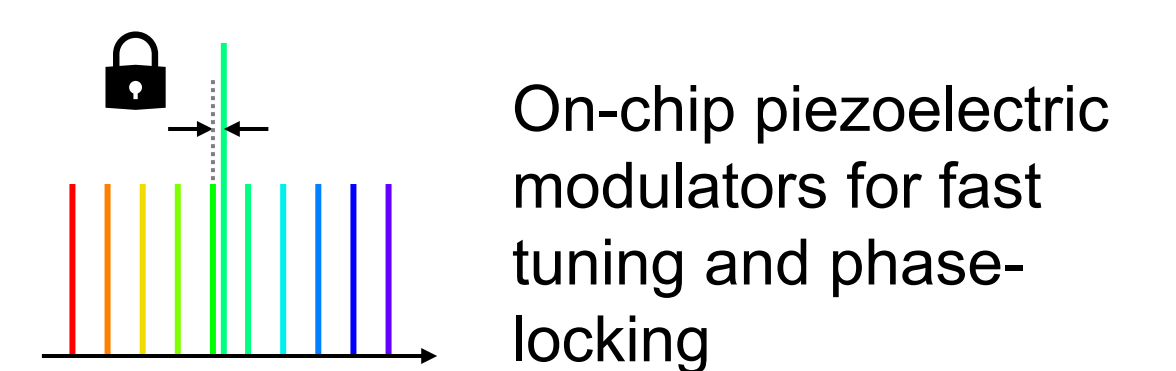
Pumped with a butt-coupled reflective semiconductor optical amplifier (RSCA) self-injection-locked to the microresonator

Ultra-efficient on-chip second-harmonic generation in thin-film lithium niobate or via electrically induced $\chi^{(2)}$ nonlinearity in silicon nitride for self-referencing and generating a clock wavelength from its subharmonic



Vernier technique for measuring $\sim 1 \text{ THz}$ repetition rate (f_{rep}) and carrier-envelope offset frequency (f_{CEO}). SHG/SFG: second-harmonic/sum frequency generation

Comb phase noise originating from thermorefractive noise can be reduced by injection-locking two comb lines to external lasers



Project consortium

NPL
National Physical Laboratory

Jonathan Silver
Ulaş Gökyay

- Silicon nitride photonic integrated circuit (PIC) design and simulation
- PIC and device characterisation

Fraunhofer
IZM

Wojciech Lewoczko-Adamczyk
Gunnar Böttger

- PIC co-integration and packaging
- Development of novel glass microbenches for PIC mounting
- Thermal modelling

Fraunhofer
ISIT

Shanshan Gu-Stoppel
Lena Wysocki
Elkin Santos

- Silicon nitride PIC fabrication
- On-chip piezoelectric modulators

UNIVERSITY OF BATH

Dmitry Skryabin
Francesco Talenti

- Thin-film lithium niobate (TFLN) PIC design and simulation
- Periodic poling of TFLN ring resonators

EPFL

Ileana-Cristina Benea-Chelmus

- TFLN PIC fabrication
- > 1 million intrinsic Q factor
- Electrode deposition for poling

MenloSystems

Daniel Fersch
Ronald Holzwarth

- End-user testing
- Market studies
- Commercialisation