FC1500-Quantum

MenloSystems

Complete CW Laser System with Optically Referenced Frequency Comb

Menlo Systems' FC1500-Quantum is the all-in-one solution for your Quantum 2.0 application. Whether your intent is to build a quantum optical clock, an atom interfer-ometry experiment, or a quantum computer based on ions or neutral atoms, Menlo Systems will tailor a system according to your requirements and deliver an engine for operating your physics package. This rack-mounted system consists of Menlo's ORS Ultrastable Laser with a sub-Hz linewidth, an FC1500-250-ULN Ultra Low Noise Opti-cal Frequency Comb with light in the visible and infrared spectral range, and several customizable CW lasers. The ULN comb transfers the narrow linewidth and stability of the ultrastable laser throughout the entire comb spectrum, and via high-fidelity phase-lock loops stabilizes the CW lasers required to drive atomic transitions of the application. Optical lattice clocks and quantum computers based on ions or neutral at-oms require up to eight lasers operating at specific frequencies. The FC1500-Quantum includes them all in three 19" racks, providing sub-Hz linewidth and accurately tuned CW lasers in optical fibers ready to be sent to your physics package. For instance: For the critical clock transition at 698 nm in neutral strontium, a spectral purity transfer down to the 10-18 level at 1 second is achieved. Among CW laser manufacturers, we integrate lasers from MOGLabs, AOSense, Toptica Extended Cavity Diode Lasers, NKT Photonics fiber lasers, and M-Squared Ti:Sapphire lasers.

FEATURES & BENEFITS

- rack-mounted ultra-low-noise optical frequency comb
- rack-mounted cavity-stabilized laser with sub-Hz linewidth
- rack-mounted spectral broadening units, cw lasers, wavemeter, and locking electronics
- centralized and automated control of all sub-systems
- multiple CW lasers, referenced to the frequency comb, ready for your application
- integrated MOGLabs cateye ECDLs; M Squared Ti:Sapphire lasers and others on request

APPLICATION IN STRONTIUM LATTICE CLOCKS

- Strontium lattice clock system consists of all lasers for the clock transition, the lattice laser, cooling, and repumping: 461 nm, 679 nm, 2 x 689 nm, 698 nm, 707 nm, 813 nm
- spectral purity transfer from 1542 nm to the clock transition at 698 nm on the 10^{-18} stability level in one second.
- cw laser output power from mW level up to Watt level (e.g. for the lattice laser at 813 nm)
- optical reference system stability down to $<7 \times 10^{-16}$ in one second with optional crystalline mirror coatings (fused silica mirrors with ULE compensation rings, or regular ULE mirrors on request)
- includes de-drifting of cavity against customer's atom interrogation or radio frequency reference

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Complete solutions for quantum applications

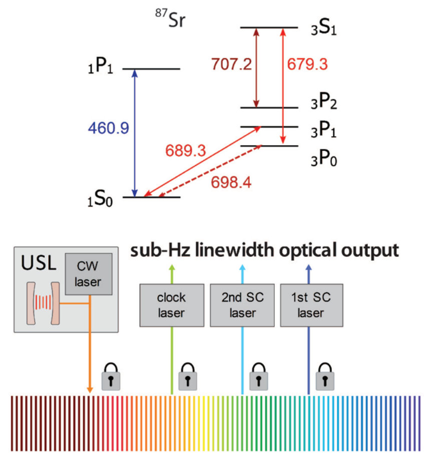
Menlo Systems' optical frequency combs and ultra-stable lasers enable the second quantum revolution

Quantum technology lets us exploit the laws of quantum mechanics for tasks like communication, computation, simulation, or sensing and metrology. As the second quantum revolution is ongoing, we expect to see the first novel quantum devices replace classical devices due to their superior performance.

There is a strong impetus to transform quantum technologies from fundamental research into a broadly accessible standard. Quantum communication promises a future with absolute security through quantum key distribution; quantum simulators and computers can perform calculations in seconds where the world's most powerful supercomputers would require decades; quantum technologies enable advanced medical imaging techniques. Further applications will likely arise that we cannot anticipate yet. The global market has realized the huge potential of quantum technologies. Menlo Systems, a pioneer in the field, provides commercial solutions for these novel challenges.

The link between photonics and quantum physics is obvious. Quantum simulation and computation use cold atoms and ions as qubits, labs worldwide use optical frequency combs and ultra-stable lasers in these types of experiments. Quantum communication often relies on single photons, which are generated with precisely synchronized femtosecond laser pulses in the near-infrared spectral range. Quantum sensing and metrology require the highest stability and accuracy in frequency comb and laser technology. And - an application worth highlighting - optical atomic clocks are under way to replace the current definition of the second in the International System of Units (SI).

The transition frequency in optical clocks is on the order of hundreds of terahertz, corresponding to the visible or the ultraviolet region of the electromagnetic spectrum. Counting these optical frequencies is only possible using a frequency comb [1], a mode-locked laser with evenly spaced frequency modes within its optical spectrum. When referenced to a CW laser which is stabilized to a high-finesse optical cavity, the bandwidth of the comb lines narrows down to below 1 Hertz [2], corresponding to a stability of 10^{-15} or better. The newest generation of optical atomic clocks enabled by this technology reach an accuracy of 10^{-18} [3], two orders of magnitude higher than the best cesium atomic clock.



*The hyperfine transitions in strontium (Sr) atoms with the ultra-narrow clock transition at 698.4 nm (upper part). A commercial **FC1500-Quantum** system for optical clock applications contains an ultra-stable laser transferring its spectral purity onto an optical frequency comb and all other lasers which are also locked to the comb (lower part).*

Menlo Systems' FC1500-Quantum is a complete CW laser system with an ultrastable frequency comb. It provides several CW lasers for atom cooling, repumping, and addressing the sub-Hertz linewidth clock transition in atoms or ions used in optical clocks (see figure). The low phase noise obtained on the comb-disciplined CW lasers is essential for coherent gate manipulation in many atom optical quantum computing schemes and for fast and high-fidelity gate operations. The laser light is delivered via optical fiber to the "physics package" consisting of vacuum chamber with all the necessary optics and electronics components and the atoms. Labs no longer need to undergo the time consuming process of designing and building their own ultra-stable lasers. Eventually, the comb itself has two purposes: It acts as reference for all the lasers to maintain their narrow linewidth, and it is the clockwork that transfers the optical frequency's spectral purity to the microwave region, or to a different optical frequency [4].

References:

[1] J. Reichert et al.: *Opt. Commun.* **172** (1 - 6), pp. 59 – 68 (1999)
[2] R. W. P. Drever et al.: *Appl. Phys. B.* **31**, pp. 97 – 105 (1983)
[3] E. Oelker et al.: *Nat. Photonics* **13**, pp. 714 – 719 (2019)
[4] M. Giunta et. Al.: *Nat. Photonics* **14**, pp. 44–49 (2020)

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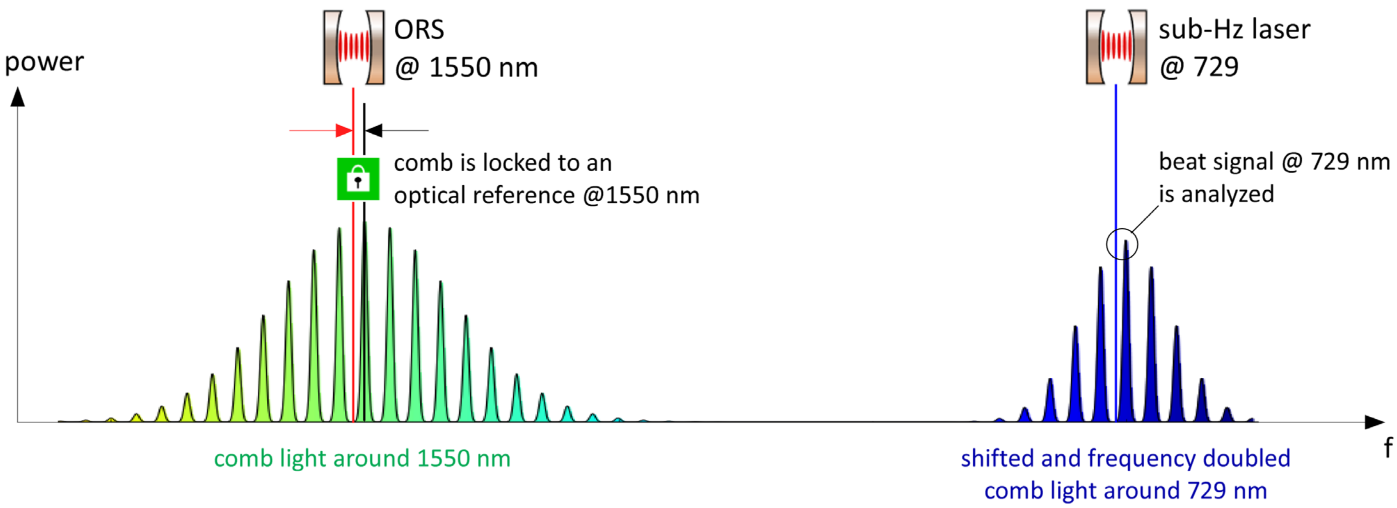
Menlo Systems Frequency Comb Technology

Menlo Systems optical frequency combs are the only combs on the market with the patented ultra-low-noise (ULN) figure9® oscillator design (US9705279B2, EP3041093B1). This special design enables our combs to perform "spectral purity transfer":
The superior spectral purity of Menlo Systems' optical reference systems is copied to every comb line.

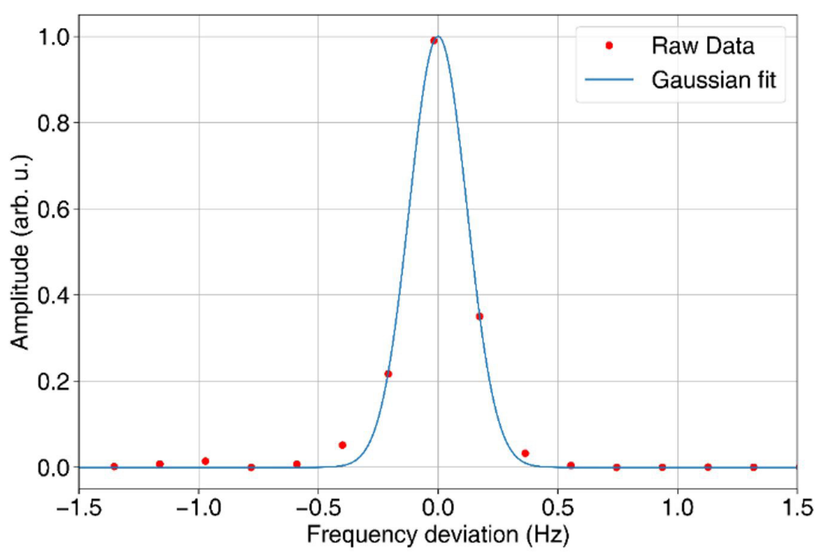
This includes all frequency extensions, reaching from 500-2000 nm and even Mid-IR comb light at 3.1 µm.

1. Setup for measuring sub-Hz linewidth transfer



A Menlo Systems ultra-low-noise frequency comb is stabilized to an optical reference system (ORS) operating at 1550 nm. The light of a second sub-Hz linewidth laser is superimposed with comb light at 729 nm, producing a beatsignal with a **linewidth of 0.3 Hz.**
This measurement proves sub-Hz linewidth transfer from 1550 nm to 729 nm which corresponds to a frequency distance of 210 THz.

If you are thinking about purchasing a frequency comb: Ask for phase noise data at your specific target wavelength(s)!



Phase noise is the most meaningful measure for most comb applications. The phase noise of any proper frequency comb is low close to the optical reference which is used to stabilize the comb. But only Menlo Systems' ultra-low-noise figure 9® oscillators are capable of transferring the spectral purity of the optical reference to **all comb lines**!

Menlo Systems Frequency Comb Technology

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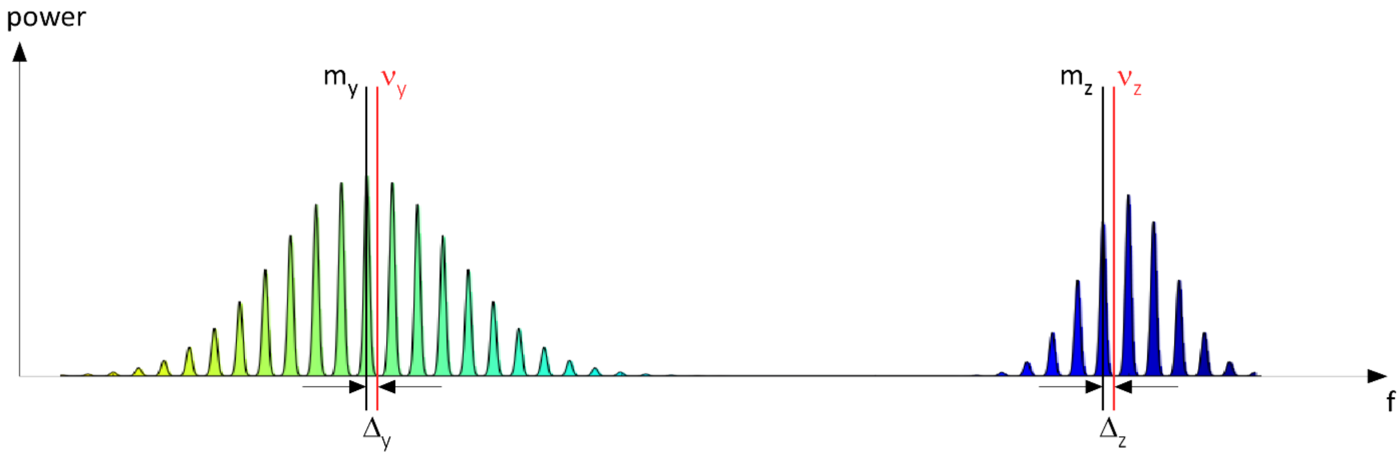
2. Why transfer oscillator schemes are not suitable to qualify frequency combs

A frequency comb can be used as a so called **transfer oscillator**. This technique links different optical frequencies using a frequency comb as a transfer oscillator and specialized high-end electronics (see [1] for a more detailed description). This application can be used for example in comparing optical clocks that have vastly different wavelengths.

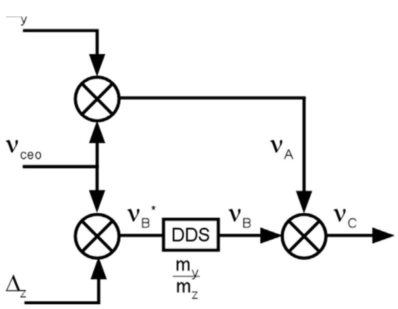
Let us call the optical frequencies of interest ν_y and ν_z. The corresponding comb mode numbers and resulting beat signal frequencies are called m_y, m_z and Δ_y, Δ_z.



In terms of the combs repetition rate (ν_{rep}) and carrier envelope offset frequency (ν_{ceo}), the optical frequencies of interest are given by:

$$\nu_y = m_y \cdot \nu_{rep} + \nu_{ceo} + \Delta_y$$
$$\nu_z = m_z \cdot \nu_{rep} + \nu_{ceo} + \Delta_z$$

The frequency difference is expressed as: $\nu_y - \nu_z = (m_y - m_z)\, \nu_{rep} + (\Delta_y - \Delta_z)$ and will include comb induced noise via ν_{rep} and the noise of the beat signals Δ_y, Δ_z.



The transfer oscillator scheme is designed to reject frequency comb induced noise. This is done by mixing both beat signals with ν_{ceo} and multiplying one of the resulting signals with the exact ratio of the comb mode numbers (m_y / m_z). A third mixer is used to generate the "projected beat signal" ν_C which is given by:

$$\nu_C = \nu_A - \nu_B = \nu_y - (m_y / m_z)\nu_z$$

This rf signal is independent of the frequency comb's repetition rate and ceo-frequency (up to a certain bandwidth, see [1] for further details). Obviously, a scheme which rejects frequency comb induced noise, is not suitable for comb noise analysis or comb-comb comparisons.

Benkler et.al. [2,3] demonstrated frequency transfer at the 10^{-21} stability level. To measure such stabilities, Benkler et. al. used two different frequency combs in the transfer oscillator scheme and compared the projected beat signals. The reference comb was a Menlo Systems FC1500-ULN. The impressive result of a relative frequency stability on the 10^{-21} level proves that frequency combs, used as transfer oscillators, are excellent tools to compare two different optical frequencies. But since the projected beat signals do not include comb induced noise, a measurement in the transfer oscillator scheme cannot provide any information about the stability or phase noise of the frequency comb itself.

References:

[1] H. R. Telle et al.: *Applied Physics B* **74**, pp. 1 - 6 (2002)

[2] E. Benkler et al.: *Optics Express* **27**, pp. 36886-36902 (2019)

[3] E. Benkler et al.: *Optics Express* **28**, pp.15023-15024 (2020)