MenloSystems

White Paper

Menlo Systems‘ ORS Ultrastable Laser System: A portable solution for state-of-the-art performance in high-precision measurements

This White Paper describes the operating principle, technical details, and performance of the Menlo Systems ORS Ultrastable Laser System. It gives a general overview of applications for ultrastable lasers, with specific use cases of Menlo Systems’ ORS systems. A more detailed presentation of an application using a novel approach for clock comparisons [1] demonstrates the capabilities of a commercial ultrastable laser system to perform state-of-the-art measurements, and the potential for future field applications.

Introduction

The precise measurement of time intervals relies on a stable high-frequency oscillator, the performance of which is typically rated in terms of the fractional frequency uncertainty, $\Delta\nu/\nu$. Cesium clocks oscillating close to 10^{10} Hz reach uncertainties approaching 10^{-16} and have formed the basis of the reference for Universal Coordinated Time (UTC) since 1967 [2]. Optical clocks represent the next level in timing accuracy. Such clocks involve the resonant interaction between atoms or ions and a cavity-referenced laser source that drives narrow linewidth transitions. These clocks can achieve relative fractional frequency instabilities on the order of 10^{-19} [3, 4, 5] using laboratory-based cryogenic-cavity-stabilized lasers with linewidths on the order of a few mHz [6].

Historically, these systems were developed on standard optical tables and were operated under controlled laboratory conditions. As high-precision spectroscopy has proceeded to form the base of real-world and commercial applications, the apparatus must be increasingly portable and user friendly. State-of-the-art commercial ultrastable laser systems with an elaborate system design push the performance to the limit, at the same time supporting a fully portable package.

In this White Paper we present Menlo Systems’ ORS Ultrastable Laser solutions. We demonstrate their value for next-generation high-precision and quantum applications, and in particular, their capability to perform tasks, which compete with highest achievements of laboratory systems.

Menlo Systems’ cavity-stabilized optical reference systems

Menlo Systems’ Optical Reference System (ORS) is an ultrastable laser, consisting of a single mode laser source, an optical reference cavity, and the associated optics and electronics for the implementation of feedback control. Moreover, the portable platform includes the vacuum system, thermal, acoustic, and vibration isolation, and the system electronics.

Figure 1: 5 cm cubic Fabry-Pérot cavity (left) and 12.1 cm cylindrical cavity (right), each comprising an ultra-low expansion (ULE) glass spacer with optically contacted highly reflective mirrors (external faces anti-reflection coated).

A high-finesse Fabry-Pérot cavity serves as the optical reference and represents the central part of the system. It comprises two mirrors, equipped with high reflectivity coatings and optically contacted onto a spacer. The spacer and the mirror substrates are manufactured from ultra-low expansion (ULE$^{®†}$) glass. ULE glass boasts the property of vanishing thermal expansion around the so-called “zero-crossing temperature,” which prevents changes of the cavity length due to external temperature drifts when the zero-crossing temperature is chosen as the working point. The specific case of the zero crossing at room temperature minimizes the effort of thermal stabilization, since complex thermal management is unnecessary. For an even lower residual thermal noise floor, fused silica (FS) mirror substrates can be chosen and combined with ULE compensation rings, ensuring the zero crossing remains at room temperature.

The cavity spacer is available in two different geometries. In the case of the rigidly-mounted 5 cm long cubic spacer (Fig. 1, left), licensed from the National Physical Laboratory, the resonator is optimized for high mechanical stability. The 12.1 cm long cylindrical spacer (Fig. 1, right), designed by the Physikalisch Technische Bundesanstalt, is horizontally mounted on four support points. The portability of the cylindrical design is ensured by a mechanical locking mechanism which protects the laser coupling into the cavity against loss of adjustment during transportation.

One of the key parameters for the overall performance of a high-finesse Fabry-Pérot cavity is the linewidth of its resonant transmission frequencies, which is given by the ratio of its free-spectral range and the finesse, $\Delta\nu_{FWHM} = FSR/F$. A longer cavity length L reduces the free-spectral range $FSR = c/2L$ of the resonator, where c is the vacuum speed of light, and thus also the cavity linewidth. The finesse is directly related to the reflectivity R of the cavity end mirrors through $F = (\pi\sqrt{R})/(1-R) \sim \pi/(1-R)$. Higher reflectivity of the mirror coatings leads to higher Finesse, and hence to lower cavity linewidth.

The mirror coatings are made of dielectric (ion beam sputtered, IBS) or crystalline (XTAL™) materials. XTAL coatings are available in combination with FS mirror substrates for reduced thermal noise and highest stability. The high reflectivity coatings are available over a broad wavelength range, and also as multiple wavelength coatings. A typical coating reflectivity on the order of 99.999% yields a finesse value of >300,000.

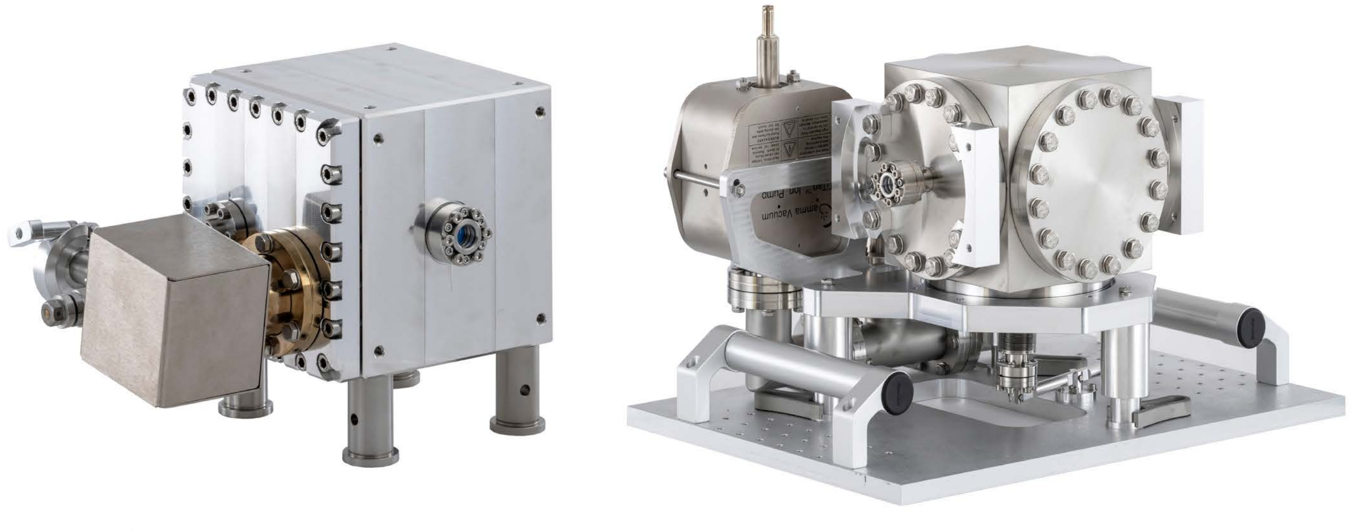


Figure 2: ORC-Cubic (left) and ORC-Cylindric (right) Optical Reference Cavity systems enclosed in a vacuum housing, including the ion getter pump.

The reference cavity system is secured in a sealed vacuum housing, with an ion getter pump maintaining ultrahigh vacuum in the cavity. The subsystem containing the cavity, vacuum housing, pump, and active thermal shielding is available as a self-contained, highly customizable “ORC” Optical Reference Cavity product series, with the ORC-Cubic based on the cubic cavity spacer and the ORC-Cylindric based on the cylindrical cavity spacer (Fig. 2) [7]. The XM-ORC [8] is a co-branded solution by Menlo Systems and Thorlabs, including “XTAL” crystalline mirror coatings on fused silica substrates for highest frequency stability performance. When integrated into the complete ORS, the vacuum system is mounted on an active vibration isolation platform and shielded from thermal and acoustic perturbations.

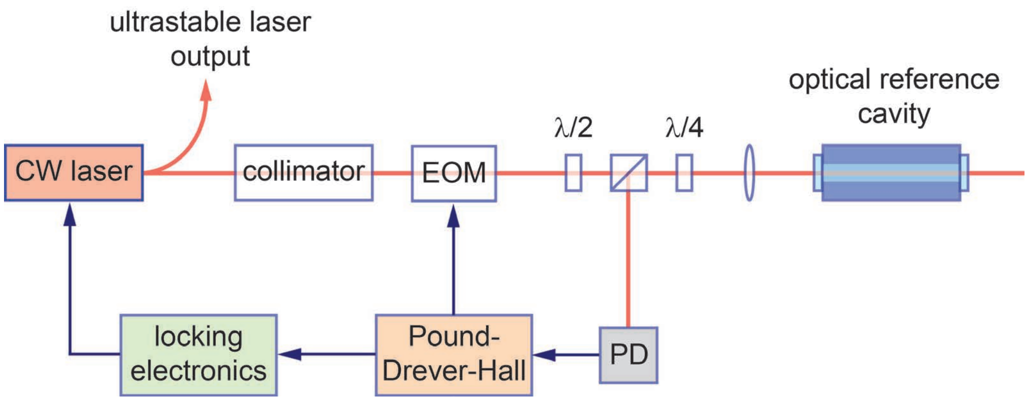
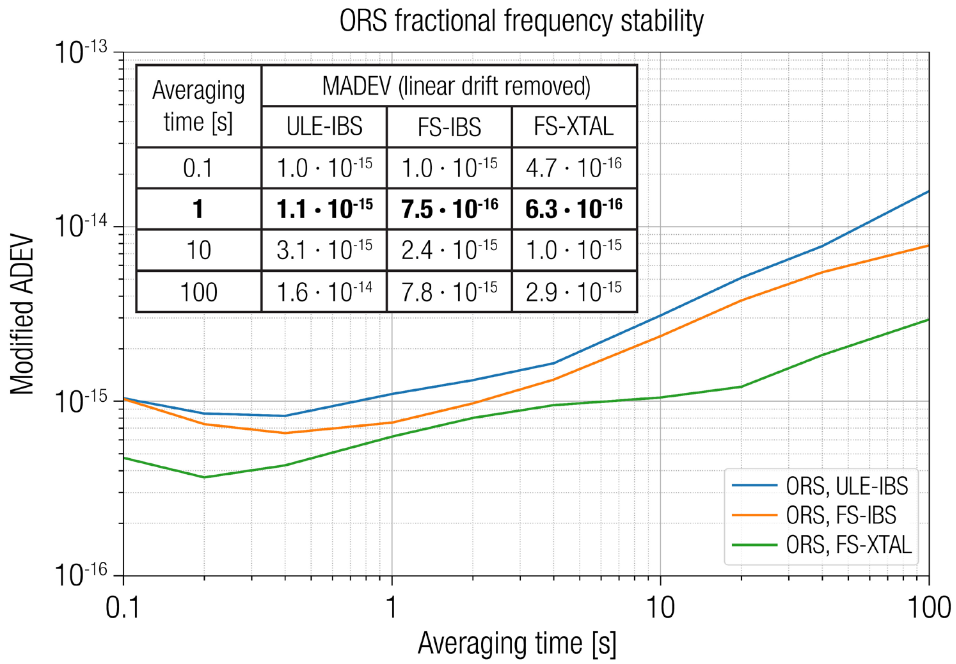


Figure 3: Principle of operation of an ultrastable laser system. A small fraction of the single mode laser light is directed into the reference cavity. The reflection off the cavity mirror is measured by a photodiode (PD) and the resultant electrical signal is converted to an error signal by the Pound-Drever-Hall method for feedback to the single mode laser.

The light source of the ultrastable laser system is a single-mode continuous-wave (CW) laser, which is actively stabilized to a transmission mode of the reference cavity using a Pound-Drever-Hall (PDH) stabilization technique. Figure 3 depicts the principle of the PDH feedback loop. An electro-optic modulator (EOM) modulates the phase of the laser light, adding sidebands in the frequency domain. A photodiode (PD) detects the fraction of light returned from the cavity. Subsequent down-mixing with the modulation frequency generates an error signal, which contains the information of how far the carrier is off the cavity resonance. This error signal can be used for active stabilization of the laser to the cavity resonance using a PID loop filter.

Figure 4: From left to right: ORS, ORS-Compact, and ORS-Mini complete ultrastable laser systems

Menlo Systems' ORS product line of complete ultrastable laser systems comprises different models (Fig. 4). The careful choice and compact design of all system components results in a transportable 19" rack-mounted device delivering state-of-the-art laser linewidth and stability. The configuration of each system with respect to laser wavelength and stability is customizable. The "ORS" Ultrastable Laser [9] is the top-of-the-line system designed for ultimate phase noise and frequency stability performance. Utilizing the cylindrical reference cavity, the system's fractional frequency stability reaches less than 7 x 10^{-16} at one second sampling time (MADEV) (Fig. 5, green line). The "ORS-Compact" [10] utilizes the cubic reference cavity and is a high-performance system, with excellent phase noise and a frequency stability better than 1.5 x 10^{-15} (MADEV, at 1 s sampling time), in a more compact format. The "ORS-Mini" [11] is the most compact and robust ultrastable laser solution, with best-in-class performance, suitable for field applications and OEM integration. The frequency stability is better than 5 x 10^{-15} (MADEV, at 1 s sampling time).



Averaging time [s]	MADEV (linear drift removed)		
	ULE-IBS	FS-IBS	FS-XTAL
0.1	$1.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-15}$	$4.7 \cdot 10^{-16}$
1	**$1.1 \cdot 10^{-15}$**	**$7.5 \cdot 10^{-16}$**	**$6.3 \cdot 10^{-16}$**
10	$3.1 \cdot 10^{-15}$	$2.4 \cdot 10^{-15}$	$1.0 \cdot 10^{-15}$
100	$1.6 \cdot 10^{-14}$	$7.8 \cdot 10^{-15}$	$2.9 \cdot 10^{-15}$

Figure 5: Comparison of the ORS fractional frequency stability using different substrates and coatings of the cavity end mirrors.

Figure 5 compares the fractional frequency stability of the ORS using the different substrates and coatings of the cavity end mirrors available. Highest performance is achieved with the combination of XTAL coatings and FS substrates (green line).

Ultrastable lasers enabling quantum applications

With their ability to reduce the noise of a measurement to a realm where quantum effects become tangible, ultrastable lasers play a key role in quantum technologies. When combined with an optical frequency comb, the high stability and spectral purity of the ultrastable laser is transferred without added phase noise to other spectral regions (Fig. 6) [12, 13]. The availability of such commercial quantum instrumentation acts as a driving force, with new opportunities arising, from communication and navigation, to medical care and fundamental research.

Quantum metrology and sensing, for instance, help to unravel the mysteries of the universe by detecting gravitational waves, searching for dark matter, or testing the principles of quantum mechanics. MAGIS-100, a next generation quantum sensing project at Fermilab, USA, is a 100-meter vertically-arranged atom interferometer. It uses Menlo Systems' complete quantum laser system comprising an ultrastable laser and an optical frequency comb as reference and laser sources for the strontium atom optical clock, and for the manipulation and detection of the atomic states [14].

Other experiments in fundamental research and astronomy involve synchronization of remote frequency references and thus require interconnection by stable optical fiber links. The cross-border fiber link between Brno (CZ) and Vienna (AT) [15] uses Menlo Systems' optical frequency combs and ultrastable lasers for the frequency transfer. Similar to optical fiber links, ultrastable lasers are also crucial for new-generation global satellite navigation systems (GNSS) and satellite geodesy, where they serve as a reference for free space optical communication links between satellites and ground-based apparatus such as telescopes or laser ranging systems [16].

Quantum computing promises new groundbreaking solutions to applications such as climate modelling or drug discovery. The first quantum computers have entered the market with companies such as Atom Computing, Inc. [17], who use Menlo Systems' ORS to perform quantum computational tasks in spin qubits of individual strontium atoms trapped in arrays of optical tweezers. Scalability and practicability of quantum computers have also become a focus of global funding agencies. BMBF-funded research projects MUNIQC-Atoms [18] and Rymax [19] use Menlo Systems' ultrastable laser systems to demonstrate scalable quantum computers, addressing Rydberg states in strontium and ytterbium atoms, respectively.

Quantum computers based on atomic qubits rely on the ability to precisely control their quantum state. Technical noise of the driving laser source due to spontaneous emission limits the fidelity of the qubit control. The ORS serves in the study of such laser-qubit interactions [20], which introduces a metric that helps assessing whether the noise of a stabilized laser is optimized for quantum control of the cubits.

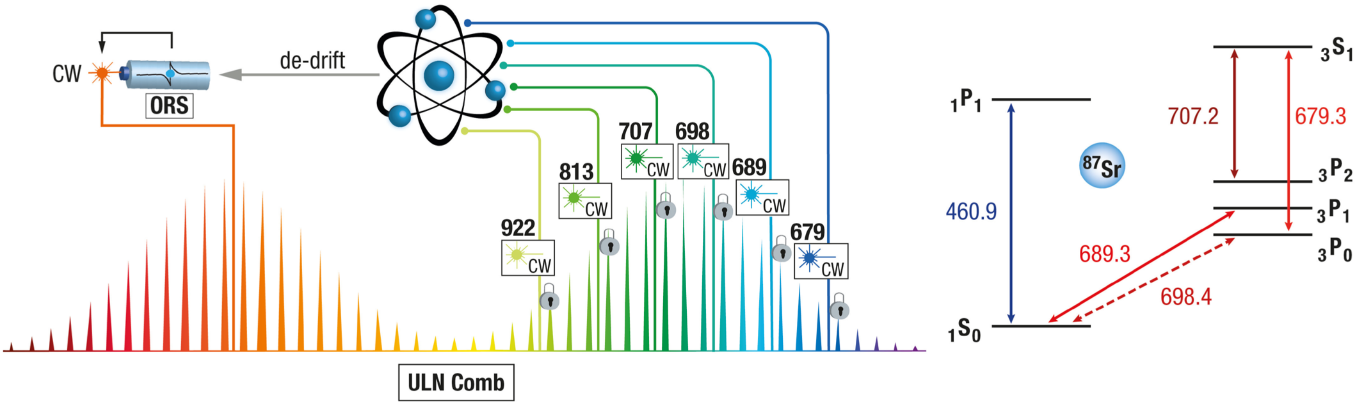


Figure 6: The spectral purity of a CW laser stabilized to a reference cavity is transferred via an ultralow noise (ULN) optical frequency comb to all CW lasers of the optical clock application (left). Scheme of the hyperfine transitions in strontium (Sr) atoms with the ultranarrow clock transition at 698.4 nm (right).

Field-deployable optical clock technology

Optical atomic clocks (Fig. 6) aim to revolutionize how we measure time, and all applications that require precision timing and measurements. Novel approaches have the potential to simplify or even replace existing methods. In most cases, it is a prerequisite to be able to compare remote quantum oscillators without impairing the time measurement by instabilities of the apparatus. Many such applications involve field deployment - a requirement which cannot be fulfilled by immobile laboratory-based laser setups. Latest developments in transportable, rack-mounted ultrastable laser systems have been shown to enable state-of-the-art performance [21].

Recently, one of the most accurate clock comparisons ever measured was undertaken with the use of Menlo Systems' ultrastable laser with <1 Hz linewidth by the research team of Associate-Prof. Shimon Kolkowitz at The University of Wisconsin-Madison [1]. The experimental scheme is referred to as a "spatially multiplexed optical lattice clock" within a vertically aligned one-dimensional optical lattice. The vertical orientation of the setup uses the effects of gravity to lift the degeneracy between lattice sites, thereby suppressing redistribution of the atoms due to quantum tunnelling effects. The authors loaded two ensembles of strontium atoms into different sites of the lattice, with the lattice sites displaced from each other by a distance of about 1 cm. Each atom ensemble contained in the lattice represented a single clock. This is possible since sources of noise common to all ensembles confined within the same optical lattice are eliminated. Critically, the high stability of the optical reference ensures there is no contribution of noise from the interrogating clock laser, with only intrinsic noise from atomic motion within the lattice remaining. A comparison between the two atomic ensembles yielded a coherence time of 26 s and a relative instability of 8.9 x 10^{-20}, which is among the lowest instabilities ever reported. Such a small instability is the equivalent of the two clocks being out of synchronization by just 1 s in 300 billion years.

It is particularly noteworthy that this groundbreaking performance has been achieved with the use of a commercially available laser system, the importance of which cannot be underestimated. This proves that ultra-sensitive measurements can be performed outside a closed laboratory environment, in field measurements, and could even enable space-borne measurements in the future.

The backbone of ultrahigh precision measurement applications

Commercial ultrastable laser systems have become true partners in the race to develop new optical clock applications, and for the dawning quantum age in which global efforts are pushing to bring turnkey quantum computers to market. The expertise honed in the development of portable ultrastable laser systems is key to the advancement of quantum technologies, which the European Quantum Technology Flagship structures by the four pillars of communication, computation, simulation, and sensing & metrology. By offering state-of-the-art performance in a compact, truly portable, and user-friendly package, Menlo Systems' ORS and ORC product series represent the backbone of some of the most challenging high-precision applications in science and technology. By alleviating the burden of developing such a system in the laboratory, it diverts the focus of the work onto the effectiveness of the application itself. System customization and a high level of integration ensure a tailored fulfilment of the individual requirements in the different application scenarios.

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†ULE is a registered trademark of Corning, Inc.

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About Menlo Systems

Precision in Photonics. Together we shape light.

Menlo Systems GmbH is a leading developer and global supplier of instrumentation for high-precision metrology. The company with headquarters in the west of Munich is known for its Nobel Prize winning optical frequency comb technology. With subsidiaries in the US, Japan, and China, and a global distributor network, Menlo Systems is closely connected to its customers from science and industry. The main product lines are optical frequency combs, time and frequency distribution, terahertz systems, ultrafast and ultra-stable lasers, and complete systems for quantum technology applications. Besides standard products, Menlo Systems develops and manufactures tailored solutions for laser-based precision measurements.

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