ULTRASTABLE LASERS FOR OPTICAL CLOCKS

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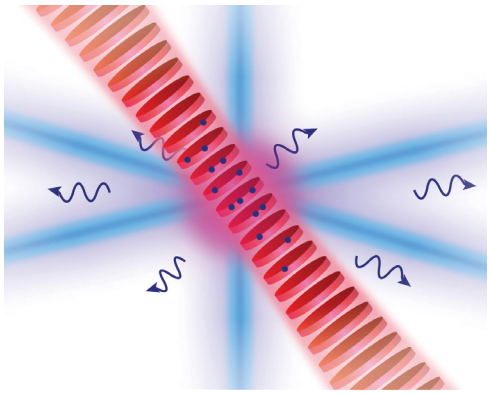

In quantum science and technology applications such as optical clocks, ultrastable laser sources can address extremely narrow atomic transitions without introducing noise to the system. The required level of stability and precision has historically only been achieved under controlled laboratory conditions. Novel commercial solutions combined with new approaches are now meeting the high demands for field applications of emergent quantum technologies.

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Since its first experimental demonstration in 1960, the laser has evolved from being "a solution in search of a problem," to a ubiquitous tool in our everyday lives. Spectroscopy is one such "problem" that lasers have revolutionized, bringing high-precision spectroscopy to prominence in real-world commercial applications. The ability to address ultra-narrow linewidth transitions in matter has led to an explosion of research in the fields of optical clocks, metrology, and generally in quantum science and technology [1,2].

Precise measurement of time intervals relies on a stable, high-frequency oscillator, whose performance is rated in terms of the fractional frequency stability. Cesium atomic clocks, based on the transition between hyperfine states of cesium-133, oscillate in the microwave region at 9 192 631 770 Hz and can reach accuracies of around 10^{-16}. They have formed the basis of Universal Coordinated Time since 1967 [3], but to reach the next level of timing accuracy, a higher frequency oscillator is required. Moving from microwave to optical frequencies, realizing an optical atomic clock, results in several orders of magnitude increased oscillations and can offer better performance, but such frequencies are harder to measure.

An optical clock involves the spectroscopy of atoms or ions using laser light for higher-energy transitions on the order of hundreds of THz, as opposed to 9 GHz atomic transitions in Cs. These so-called clock transitions typically have narrow linewidths, requiring an ultrastable laser with linewidths of less than 1 Hz, and can result in an optical clock with an accuracy of 10^{-18}. But historically, the laser sources required for this were large, complex systems requiring optical tables and controlled laboratory environments. Here we discuss compact technological solutions that can enable the newest generation of optical atomic clocks.

ULTRASTABLE LASERS

The typical linewidth of a stable free-running laser is on the order of a few hundred kilohertz, so to reach the criteria for the high-precision spectroscopy in an optical clock, some kind of method of frequency stabilization is required.

One method of achieving this involves the comparison of the laser output frequency with an ultrastable reference, and then converting the resulting offset between the two into an electrical signal. This electric signal can then be fed back to the laser control parameters to realize active frequency stabilization. The frequency comparison can be performed between the laser output frequency and a chosen resonance frequency of an ultrastable reference cavity. Modulation of the laser frequency across the resonance results in peaks (dips) in the transmission (reflection) signal on a photodiode. The resulting error signal slope, with zero crossing at the resonance frequency, serves as the locking point for the laser control parameters. This approach is known as the Pound-Drever-Hall (PDH) technique [4].

Put simply, a cavity-based ultrastable reference laser system typically comprises a single-mode laser source, an optical reference cavity, as well as the necessary optics and electronics for feedback control. A Fabry-Pérot cavity can be used as the optical reference, and is the heart of the entire system. It is formed of two mirrors with highly-reflective coatings, optically-contacted to a spacer that defines the cavity length. The challenge is keeping the distance of the mirrors stable at the 10^{-16} level on the timescale of a second, despite the impact of environmental perturbations. Ultralow expansion (ULE®) glass can be used for the spacer and the mirror substrates, to minimize thermal effects on the cavity length. ULE glass boasts the property of vanishing thermal expansion at the so-called "zero-crossing temperature." In the specific case where the zero-crossing temperature is room temperature, the need for bulky and complex thermal management is reduced. ULE compensation rings enable the use of alternative substrate materials for the mirrors, for example fused silica, to achieve a lower thermal noise floor.

Figure 1 shows examples of resonator cavities with two different spacer geometries; a 5 cm cubic cavity and a 12.1 cm cylindrical cavity. The shape can help optimize the mechanical stability and decoupling from environmental perturbations like vibrations, but one of the critical parameters determining the overall performance of a high-finesse Fabry-Pérot cavity is the linewidth of its resonant transmission frequencies. This is given by the ratio of its free-spectral range (*FSR*, the frequency spacing of the resonator modes) and the finesse (*F*, a measure of how sharp the resonances are):

$$\Delta\nu_{FWHM} = \frac{FSR}{F}$$

A longer cavity length, *L*, reduces the FSR of the cavity and thus also the cavity linewidth (*c* is the vacuum speed of light):

$$FSR = \frac{c}{2L}$$

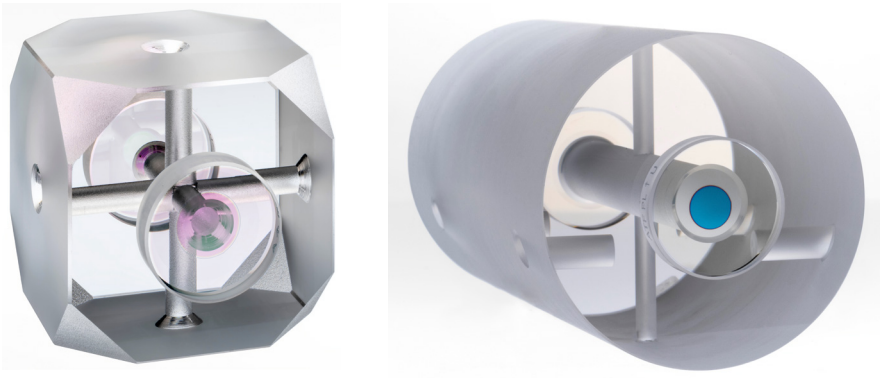
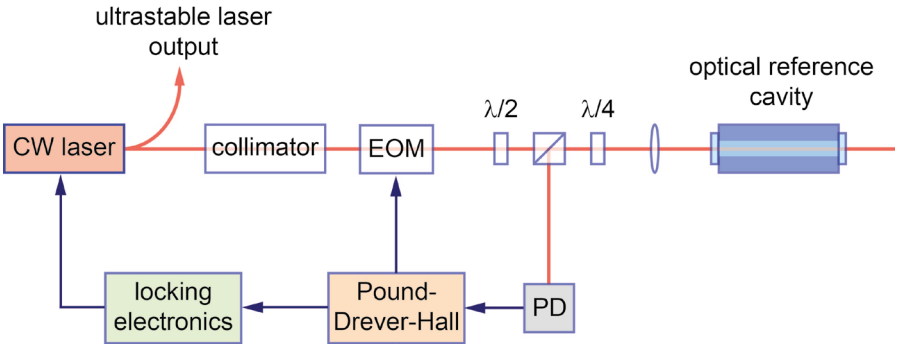


Figure 1: A 5 cm cubic Fabry-Pérot cavity developed by the National Physical Laboratory (left), and a 12.1 cm cylindrical cavity designed by the Physikalisch-Technische Bundesanstalt (right), each comprising an ultra-low expansion (ULE) glass spacer with optically contacted highly reflective mirrors (external faces anti-reflection coated).



The finesse related to the reflectivity, R, of the cavity end mirrors via:

$$F = \frac{\pi\sqrt{R}}{1-R}$$

The higher the reflectivity of the cavity mirror coatings, the higher the finesse, and the lower the cavity linewidth. A typical reflectivity on the order of 99.999% yields a finesse value of >300,000.

The PDH technique is a powerful scheme used for the active stabilization of a laser frequency to an ultrastable optical reference. Figure 2 depicts the principle of PDH stabilization of a continuous-wave (CW) laser. An electro-optic modulator (EOM) adds sidebands to the laser light in the frequency domain to modulate the phase of the laser light. A photodetector (PD) detects the fraction of light reflected from the cavity, delivering a signal that is dependent on the EOM modulation frequency. Subsequent down-mixing with the modulation frequency results in an error signal, which contains information on how far off the carrier is from the cavity resonance. This error signal can thus be used for the active stabilization of the laser to the cavity resonance by serving as a feedback mechanism to the laser controls.

Figure 2: Principle of the Pound-Drever-Hall locking scheme: A small fraction of the single mode laser light is inserted into the reference cavity after frequency modulation. The reflection off the cavity end mirror is measured by a photodiode (PD) providing an electrical signal, which is converted into an error signal serving as laser feedback.

Fluctuations of the cavity length can impact the performance of the cavity-locked laser. It is thus important to ensure the cavity is isolated from ambient conditions like temperature, pressure, acoustic noise, and mechanical vibrations. This can be achieved via operation of the cavity in a vacuum, active temperature stabilization, acoustic shielding, and vibration isolation. Examples of commercial, 19-inch rack-mounted ultrastable reference systems, complete with CW laser, ultrastable reference cavity, PDH locking electronics, vacuum system, and environmental shielding, are shown in Figure 3. The system on the left-hand side includes a vibration isolation

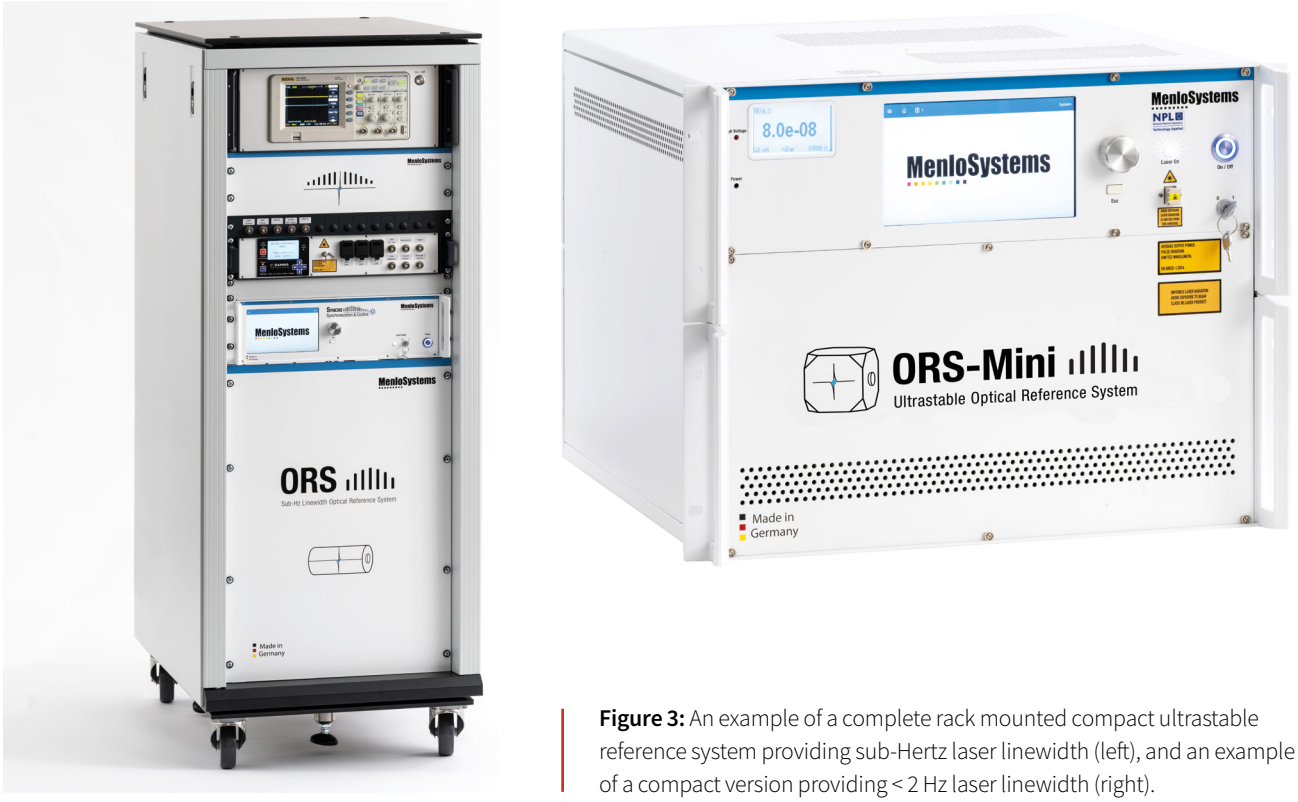
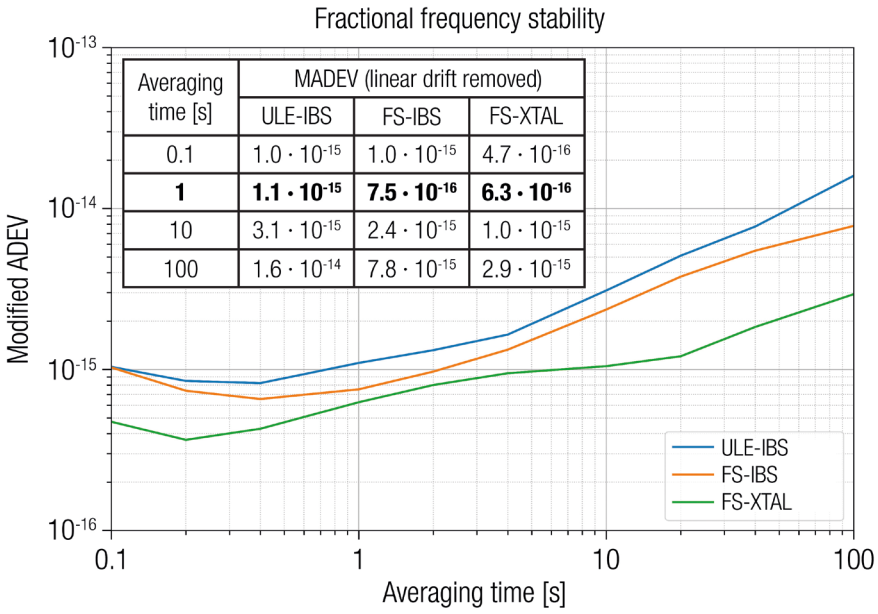


Figure 3: An example of a complete rack mounted compact ultrastable reference system providing sub-Hertz laser linewidth (left), and an example of a compact version providing < 2 Hz laser linewidth (right).



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	$\mathbf{1.1 \cdot 10^{-15}}$	$\mathbf{7.5 \cdot 10^{-16}}$	$\mathbf{6.3 \cdot 10^{-16}}$
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 4: Comparison of the fractional frequency stability of a commercial ultrastable laser using different substrates and coatings of the cavity end mirrors.

platform and is 1.6 m tall. The system on the right-hand side does not include the vibration isolation platform, but is only 8 height units. This shows substantial development from the historical systems that occupied large areas in research laboratories, to a rack-mounted system that can be turnkey operated.

The performance of an ultrastable reference is given by the fractional frequency stability. For the system shown in Figure 3 on the left-hand side, the fractional frequency stability, measured by the modified Allan deviation (modified ADEV), is shown in Figure 4, where comparisons of performance using different cavity mirror substrates and coating technologies are presented: ULE-IBS (ultralow expansion glass-ion beam sputtering), FS-IBS (fused silica-ion beam sputtering), and FS-XTAL (fused silica-crystalline coatings). A slow linear frequency drift, arising due to continuous length shrinking of the ULE substrates due to aging, has been removed by data post processing. Such an ultrastable reference can provide CW laser light with < 1 Hz linewidth measured over several seconds, and fractional frequency stability better than 7×10^{-16} at 1 s sampling time. This level of stability is comparable to many complex setups from research laboratories, albeit in a smaller footprint, and can enable some of the most demanding applications where high precision is required. By way of comparison, the system on the right-hand side of Figure 3 can demonstrate sub-2-Hertz linewidth and fractional frequency stability of $< 5 \times 10^{-15}$.

OPTICAL ATOMIC CLOCK

One such demanding application is for optical atomic clocks. Optical clocks have the potential to dramatically improve the accuracy of precision timing ● ● ●

Optical clocks have the potential to dramatically improve the accuracy of precision timing and measurements, but their operation and the ability to measure their frequencies is challenging.

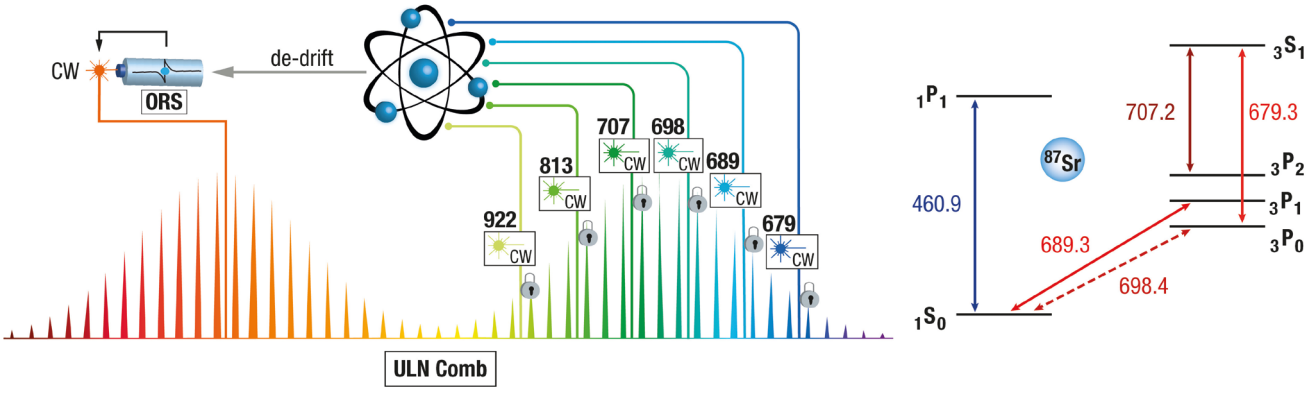


Figure 5: Schematic of a strontium-87 optical lattice clock (left), starting with an ultrastable reference (ORS), which is used to stabilize an ultralow noise frequency comb (ULN Comb), which is then frequency shifted to reach all wavelengths required to realize the clock. Simplified energy level transitions in strontium-87 atoms (right).

and measurements, but their operation and the ability to measure their frequencies is challenging. Optical clocks make use of ultranarrow transitions in the visible part of the spectrum to exploit long coherence times for high-precision measurements. In order to access this high precision, we rely on lasers tuned precisely to the transition frequency. Not only this, but optical clocks require some way of counting the oscillations of the transition – some kind of optical clockwork that "converts" the optical oscillations into oscillations of a lower frequency that can be measured by standard electronics [5]. This can be achieved by combining an ultrastable reference laser with an optical frequency comb.

Figure 5 shows the principle of doing exactly this to realize a type of optical clock known as an optical lattice clock [1], using strontium-87 atoms. In an optical lattice clock, the atoms are confined within an interference pattern of several laser beams to minimize the effect of atomic motion on clock performance. Each atomic species has a so-called "magic" wavelength, where the trapping light does not perturb the resonant frequency of the clock transition. For strontium-87, the magic wavelength is 813 nm. The clock transition in strontium-87 is around 429 THz with sub-Hertz linewidth, so a sub-Hertz ultrastable laser is required at 698 nm for a strontium optical clock. In addition to these two wavelengths, laser light is required to trap and cool the strontium atoms; these wavelengths are 461 nm, 689 nm, 679 nm, and 707 nm.

To realize the strontium-87 optical lattice clock, the scheme in Figure 5 starts with an ultrastable reference laser around 1542 nm. This is then used to stabilize all comb lines of an optical frequency comb, the output of which is then shifted to reach the wavelengths needed for the clock. This process transfers the frequency stability of the ultrastable reference to all wavelengths. The stabilized comb light is then sent to the strontium physics package to result in an optical lattice clock. Finally, to measure the optical clock frequencies the frequency comb is used to convert the optical oscillations into microwave oscillations, which can be counted by electronics. This can be achieved by measuring either the carrier-envelope-offset frequency or the pulse repetition rate of the frequency comb. When these parameters are known, all frequencies of the comb can be determined.

Commercial ultrastable laser systems have become partners in the race to develop the most accurate optical clocks, and are paving the way to portable systems that can be used in the field. By alleviating the need to build such systems in the lab, more resources can be focused on the application itself and outcomes can be accelerated. This is the case not only for optical atomic clocks, but for the burgeoning quantum technology market as a whole, where a high-level of integration ensures turn-key operation for some of the world's most challenging applications.

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