The clock laser system, including a TOPTICA TA pro, the DLC pro laser controller, frequency stabilization electronics and additional ADD-ONS modules, such as the fiber noise cancellation module

The power of ultra-stable lasers

With high coherence, low noise and sub-Hz linewidth, ultra-stable lasers enable quantum computing and next-generation optical clocks.

Steffen Schmidt-Eberle and Lukas Hartung

Quantum technologies like neutral atom and ion-based quantum computing rely on ultra-narrow clock transitions in elements such as ytterbium, strontium, and calcium$^+$. To address these transitions, sub-Hz linewidth lasers are essential, providing the stability needed for next-generation breakthroughs.

Innovation often relies on the commercialization of well-established components. While these components are fundamentally understood, they often lack critical attributes such as reproducibility, standardized specifications and interfaces, low maintenance requirements, and robustness against environmental variations. Ultra-stable lasers, for example, have been developed and used in research for decades. However, with the latest advancements in neutral atom and ion-based quantum computing as well as optical clocks, ultra-stable laser systems now represent a key enabling technology, requiring industrial-grade stability.

What these applications have in common is that they rely on ultra-narrow clock transitions in neutral atoms such as ytterbium and strontium as well as in ions such as calcium$^+$, ytterbium$^+$, strontium$^+$ and barium$^+$. To drive these transitions with the required precision, ultra-stable lasers with sub-Hz linewidths are indispensable. Additionally, each application imposes specific demands on laser performance that must be combined in industrial grade ultra-stable laser systems:

- **Optical clocks** are gaining attention for their superior precision compared to microwave-based atomic clocks. While microwave clocks rely on gigahertz transitions, optical clocks use ultra-narrow atomic transitions at hundreds of terahertz. To probe these transitions, an ultra-stable laser with exceptional coherence and a linewidth below 1 Hz is needed. Such a laser is stabilized to an atomic reference, allowing for corrections of its frequency drift on a slow timescale of seconds. Thus, achieving both short-term and long-term frequency stability

© 2025 Wiley-VCH GmbH

is crucial for clock accuracy. Additionally, these lasers must withstand environmental factors like temperature changes and vibrations to ensure reliable real-world use.

- **Quantum computing**, particularly ion-based and neutral atom computing, has attracted significant attention. Both approaches frequently utilize ultra-narrow clock transitions to implement optical qubits, primarily because these states exhibit lifetimes exceeding one second. The lifetime of these transitions sets a fundamental limit on the coherence time of the encoded qubit. Coherence time, in turn, is a critical factor that determines the achievable fidelity of quantum gates and, therefore, the overall performance of the quantum computer.

To drive these transitions, ultra-stable lasers with sub-Hz linewidths are essential to ensure that the coherence time of the laser does not limit the qubit coherence. Minimizing phase noise during gate operations (1 – 100 µs) is crucial, especially in the 10 kHz to 1 MHz range. In ion-based systems, phase noise beyond 1 MHz can disrupt qubit operations. As quantum computers move into less controlled environments, their laser systems must be resilient to environmental instabilities.

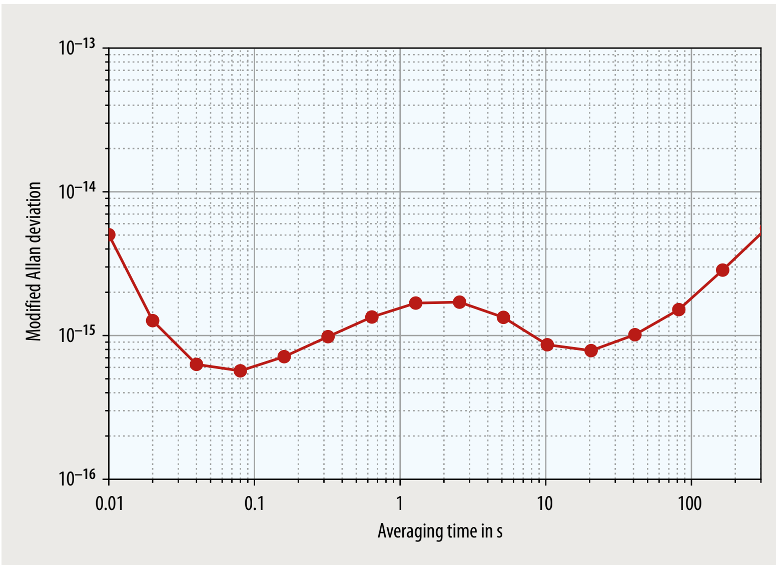
TOPTICA's ultra-stable clock laser systems (CLS) are designed to meet the demanding requirements of quantum computing and optical clock applications. These systems are based on external cavity diode lasers (ECDLs) that are frequency-stabilized to high-finesse ultra-low expansion (ULE) cavities. For wavelengths between 670 nm and 1762 nm, TOPTICA's DL pro or amplified TA pro lasers are directly locked to the ULE cavity. For wavelengths below 670 nm, the fundamental laser light is first stabilized to the ULE cavity and then frequency doubled via second harmonic generation (SHG). This approach enables the CLS to cover a broad wavelength range, making it suitable for driving a wide variety of clock transitions.

A key advantage of the ECDL architecture is its ability to support fast modulation via direct current tuning of the laser diode or, for even higher bandwidths, through an intracavity electro-optic modulator (EOM). This design allows for locking bandwidths exceeding 4 MHz, effectively shifting the servo bump beyond the most critical frequency range for quantum computing – typically between 10 kHz and 1 MHz. In addition to its precision performance, the CLS is designed to maintain exceptional frequency stability even in real-world, non-laboratory environments. Its robust design incorporates advanced passive shielding and active vibration compensation, ensuring resilience against external acoustic and seismic disturbances.

Additionally, a high-end temperature stabilization system guarantees minimal sensitivity to thermal fluctuations, further enhancing long-term stability. The system is offered in both tabletop and rack-integrated versions.

Authors

Steffen Schmidt-Eberle, Sales Manager Europe Quantum Technologies and **Lukas Hartung**, Product Manager Laser Phase & Frequency Stabilization, TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing, Tel.: +49 (0) 89 85837-0, info@toptica.com, www.toptica.com



The frequency stability of CLS in terms of the modified Allan deviation after removal of linear drift was determined by cross-correlation analysis of beat notes with two reference lasers.

© 2025 Wiley-VCH GmbH