The sharpest laser in the world: Physicists develop a laser with a linewidth of only 10 mHz

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One of the two silicon resonators. Credit: PTB

No one had ever come so close to the ideal laser before: theoretically, laser light has only one single color (also frequency or wavelength). In reality, however, there is always a certain linewidth. With a linewidth of only 10 mHz, the laser that the researchers from the Physikalisch-Technische Bundesanstalt (PTB) have now developed together with US researchers from JILA, has established a new world record. This precision is useful for various applications such as optical atomic clocks, precision spectroscopy, radioastronomy and for testing the theory of relativity. The results have been published in the current issue of *Physical Review Letters*.

Lasers were once deemed a solution without problems - but that is now history. More than 50 years have passed since the first technical realization of the laser, and we cannot imagine how we could live without them today. Laser light is used in numerous applications in industry, medicine and information technologies. Lasers have brought about a real revolution in many fields of research and in metrology - or have even made some new fields possible in the first place.

One of a laser's outstanding properties is the excellent coherence of the emitted light. For researchers, this is a measure for the light wave's regular frequency and linewidth. Ideally, laser light has only one fixed wavelength (or frequency). In practice, the spectrum of most types of lasers can, however, reach from a few kHz to a few MHz in width, which is not good enough for numerous experiments requiring high precision.

Research has therefore focused on developing ever better lasers with greater frequency stability and a narrower linewidth. Within the scope of a nearly 10-year-long joint project with the US colleagues from JILA in Boulder, Colorado, a laser has now been developed at PTB whose linewidth is only 10 mHz (0.01 Hz), hereby establishing a new world record. "The smaller the linewidth of the laser, the more accurate the measurement of the atom's frequency in an optical clock. This new laser will enable us to decisively improve the quality of our clocks", PTB physicist Thomas Legero explains.

In addition to the new laser's extremely small linewidth, Legero and his colleagues found out by means of measurements that the emitted laser light's frequency was more precise than what had ever been achieved before. Although the light wave oscillates approx. 200 trillion times per second, it only gets out of sync after 11 seconds. By then, the perfect wave train emitted has already attained a length of approx. 3.3 million kilometers. This length corresponds to nearly ten times the distance between the Earth and the moon.

Since there was no other comparably precise laser in the world, the scientists working on this collaboration had to set up two such laser systems straight off. Only by comparing these two lasers was it possible to prove the outstanding properties of the emitted light.

The core piece of each of the lasers is a 21-cm long Fabry-Pérot silicon resonator. The resonator consists of two highly reflecting mirrors which are located opposite each other and are kept at a fixed distance by means of a double cone. Similar to an organ pipe, the resonator length determines the frequency of the wave which begins to oscillate, i.e., the light wave inside the resonator. Special stabilization electronics ensure that the light frequency of the laser constantly follows the natural frequency of the resonator. The laser's frequency stability - and thus its linewidth - then depends only on the length stability of the Fabry-Pérot resonator.

The scientists at PTB had to isolate the resonator nearly perfectly from all environmental influences which might change its length. Among these influences are temperature and pressure variations, but also external mechanical perturbations due to seismic waves or sound. They have attained such perfection in doing so that the only influence left was the thermal motion of the atoms in the resonator. This "thermal noise" corresponds to the Brownian motion in all materials at a finite temperature, and it represents a fundamental limit to the length stability of a solid. Its extent depends on the materials used to build the resonator as well as on the resonator's temperature.

For this reason, the scientists of this collaboration manufactured the resonator from single-crystal silicon which was cooled down to a temperature of -150 °C. The thermal noise of the silicon body is so low that the length fluctuations observed only originate from the thermal noise of the dielectric SiO2/Ta2O5 mirror layers. Although the mirror layers are only a few micrometers thick, they dominate the resonator's length stability. In total, the resonator length, however, only fluctuates in the range of 10 attometers. This length corresponds to no more than a ten-millionth of the diameter of a hydrogen atom. The resulting frequency variations of the laser therefore amount to less than 4 × 10-17 of the laser frequency.

The new lasers are now being used both at PTB and at JILA in Boulder to further improve the quality of optical atomic clocks and to carry out new precision measurements on ultracold atoms. At PTB, the ultrastable light from these lasers is already being distributed via optical waveguides and is then used by the optical clocks in Braunschweig.

"In the future, it is planned to disseminate this light also within a European network. This plan would allow even more precise comparisons between the optical clocks in Braunschweig and the clocks of our European colleagues in Paris and London", Legero says. In

Boulder, a similar plan is in place to distribute the laser across a fiber network that connects between JILA and various NIST labs.

The scientists from this collaboration see further optimization possibilities. With novel crystalline mirror layers and lower temperatures, the disturbing thermal noise can be further reduced. The linewidth could then even become smaller than 1 mHz.

More information: D. G. Matei et al. 1.5 µm Lasers with Sub-10 mHz Linewidth, *Physical Review Letters* (2017). DOI: 10.1103/PhysRevLett.118.263202

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