Optical frequency comb integration transforms absolute distance measurement precision

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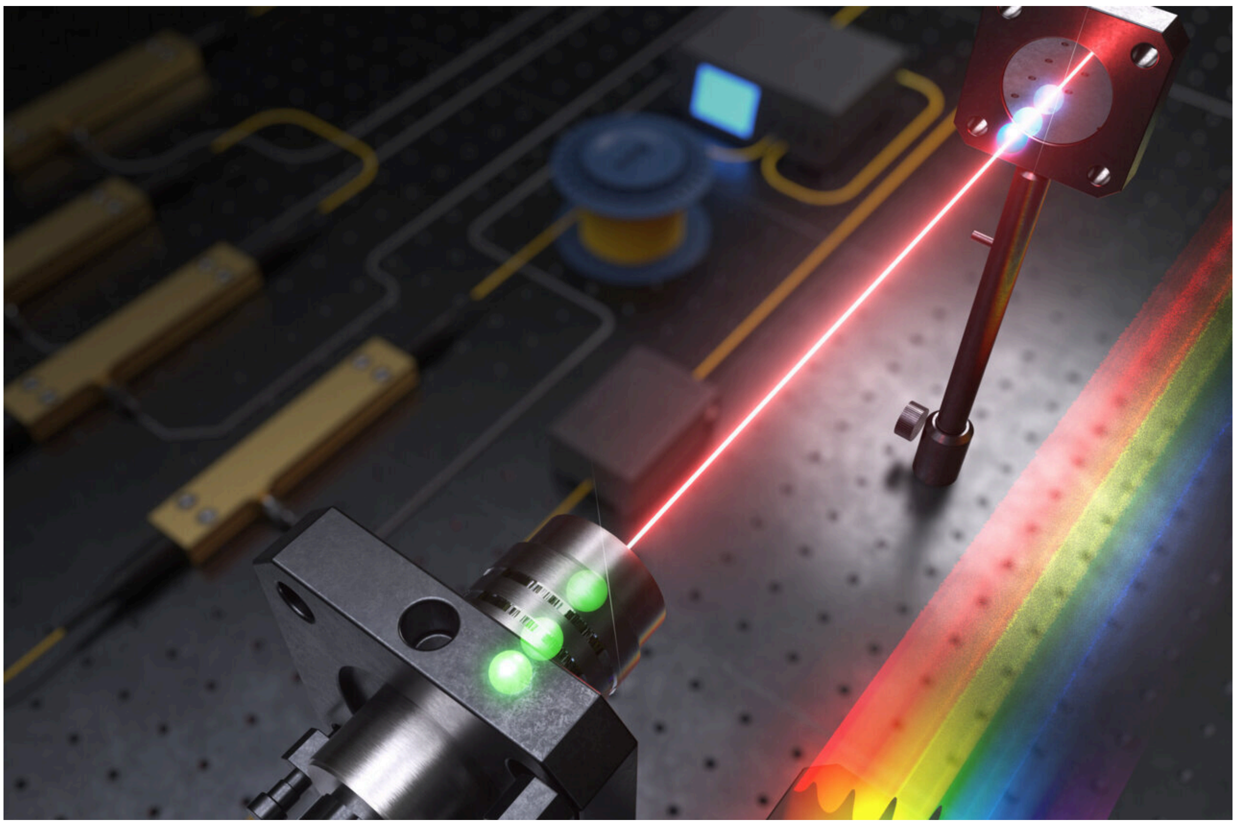


Schematic of the absolute distance measurement system based on the optical frequency comb interferometry developed by KRISS. Credit: Korea Research Institute of Standards and Science (KRISS)

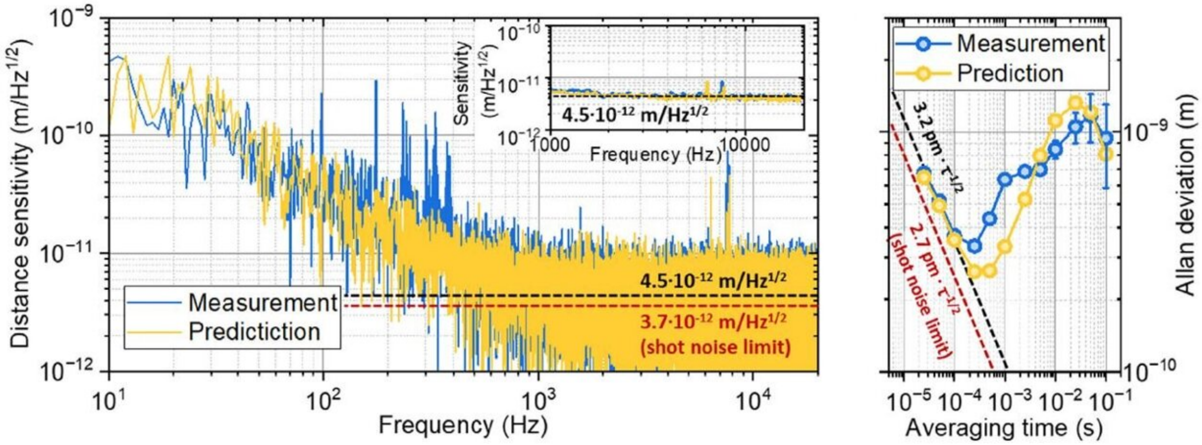
The Korea Research Institute of Standards and Science has successfully developed a length measurement system that achieves a level of precision approaching the theoretical limit allowed by quantum physics.

The system boasts world-leading measurement accuracy while maintaining a compact and robust design suitable for field deployment, making it a strong candidate to serve as the new benchmark for next-generation length metrology. The work is published in the journal *Laser & Photonics Reviews*.

Currently, the most precise instruments for measuring length are national length measurement standards, which define the unit of one meter. These instruments, operated by leading national metrology institutes including KRISS, utilize interferometers based on single-wavelength lasers to perform ultra-precise length measurements.

Single-wavelength lasers are characterized by extremely uniform wave distributions—like the evenly spaced markings on a ruler—allowing for measurement precision at the nanometer scale (1–10 nm, or one-billionth of a meter).

However, the length measurement standards are limited in the range of distances they can measure at once, because single-wavelength lasers have a very narrow spectral bandwidth. In other words, while their ruler markings are very fine, the ruler itself is short.



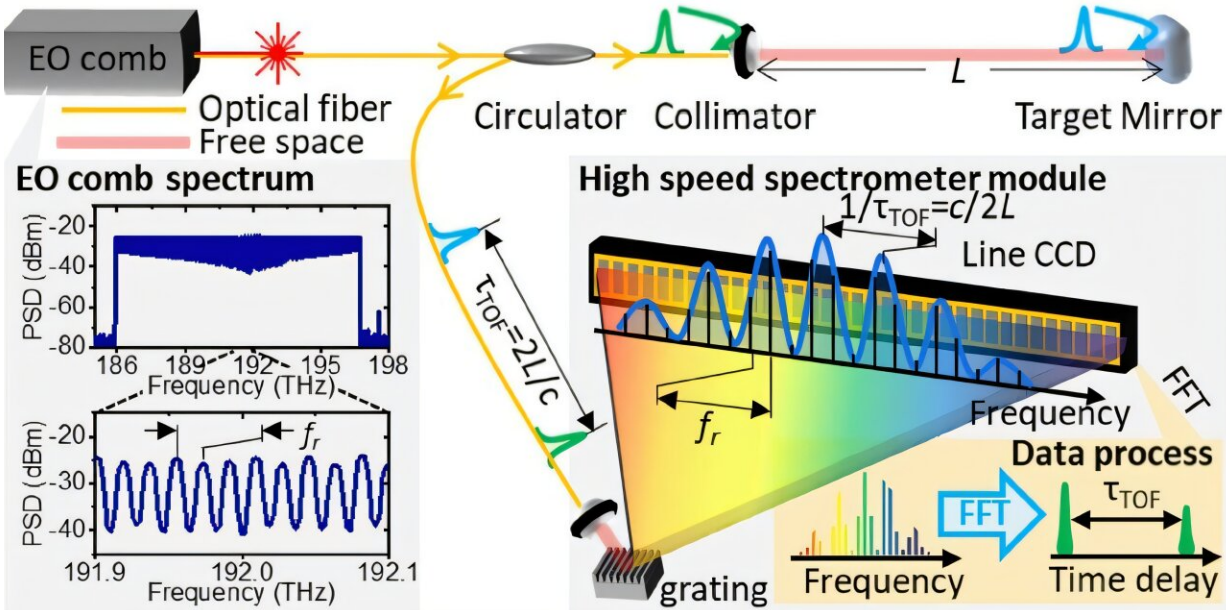
(2-2) Measurement results from the optical frequency comb-based absolute distance measurement system developed by KRISS. Credit: Korea Research Institute of Standards and Science (KRISS)

To measure distances beyond the laser's wavelength range, multiple repeated measurements must be stitched together, significantly increasing the total measurement time. This process also requires precise mechanical systems to move the interferometer stably, resulting in considerable time and spatial constraints.

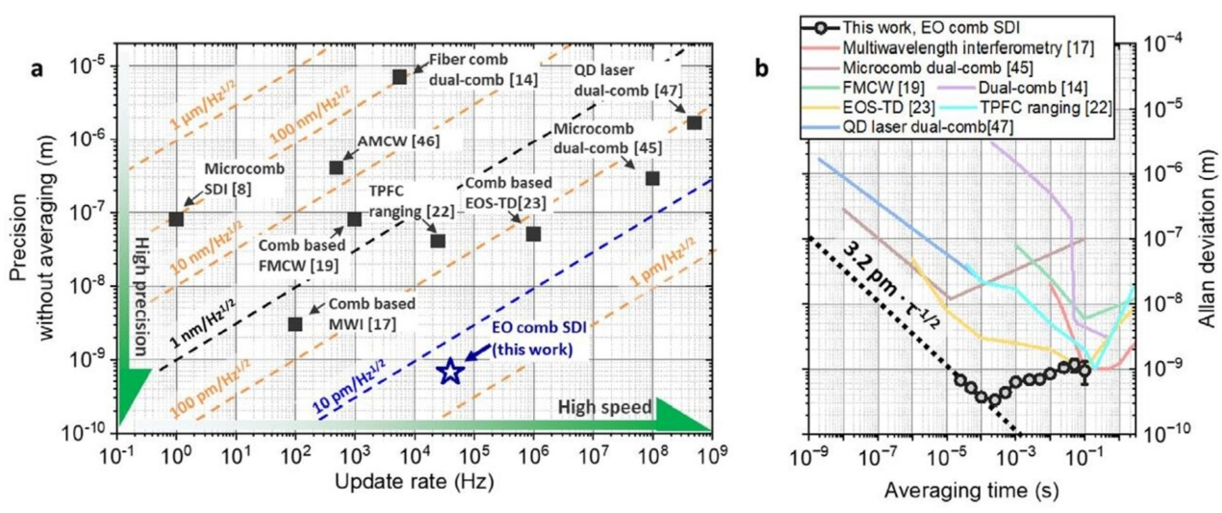
In contrast, absolute distance measurement systems are designed to measure long distances in a single operation, though with lower precision. These systems typically calculate the distance by emitting a light pulse from a reference point to a target and measuring the time it takes to return.

Thanks to this relatively simple method, the systems can be miniaturized and are capable of fast, long-range measurements, making them widely used in industrial settings. However, conventional absolute distance measurement systems are limited to a precision of only a few micrometers (μm), since measuring the time of flight (ToF) of light with ultra-fine resolution remains extremely challenging using current technologies.

(3-1) KRISS researchers inspecting the electro-optic modulated optical frequency comb laser (Left: Dr. Jang Yoon-Soo / Right: Dr. Kim Dae Hee). Credit: Korea Research Institute of Standards and Science (KRISS)



(2-1) Measurement principle of the optical frequency comb-based absolute distance measurement system developed by KRISS. Credit: Korea Research Institute of Standards and Science (KRISS)



(2-3) Comparison of measurement results with other national absolute distance measurement systems. Credit: Korea Research Institute of Standards and Science

(KRISS)

The Length and Dimensional Metrology Group at KRISS has successfully enhanced the precision of absolute distance measurement systems to the level of national length standards by employing an interferometer based on an optical frequency comb (OFC).

The research team devised a method to integrate an OFC into a spectra interferometry based absolute distance measurement setup. An optical frequency comb is a spectrum composed of thousands of discrete, evenly spaced frequency lines—similar to the keys of a piano. Unlike conventional interferometric light sources, optical frequency combs feature both a broad spectral bandwidth and precisely spaced wavelengths, enabling simultaneous high-precision measurement over long distances.

The absolute distance measurement system based on optical frequency comb spectral interferometry, developed by the KRISS research team, combines the precision of national length standards with the convenience of absolute measurement systems. The system achieves a precision of 0.34 nanometers, representing one of the highest levels of accuracy among existing technologies, and approaching the quantum-limited precision defined by the laws of quantum physics.

With a measurement speed of 25 microseconds (μs), it operates rapidly and reliably enough for field deployment, offering significant potential to enhance precision metrology in high-tech industries.

The research team plans to continue developing the system by evaluating its measurement uncertainty and refining its performance, with the goal of establishing it as a next-generation national length standard.

Dr. Jang Yoon-Soo, senior researcher at the Length and Dimensional Metrology Group at KRISS, emphasized, "The competitiveness of future industries such as AI semiconductors and quantum technologies hinges on the ability to accurately measure and control distances at the nanometer scale. This achievement marks a significant step for Korea toward becoming a leading country in establishing next-generation length standards."

More information: Yoon-Soo Jang et al, Approaching the Quantum-Limited Precision in Frequency-Comb-Based Spectral Interferometric Ranging, *Laser & Photonics Reviews* (2025). DOI: 10.1002/lpor.202401995

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