Ultrafast amplitude detector for use in high-speed atomic force microscopy

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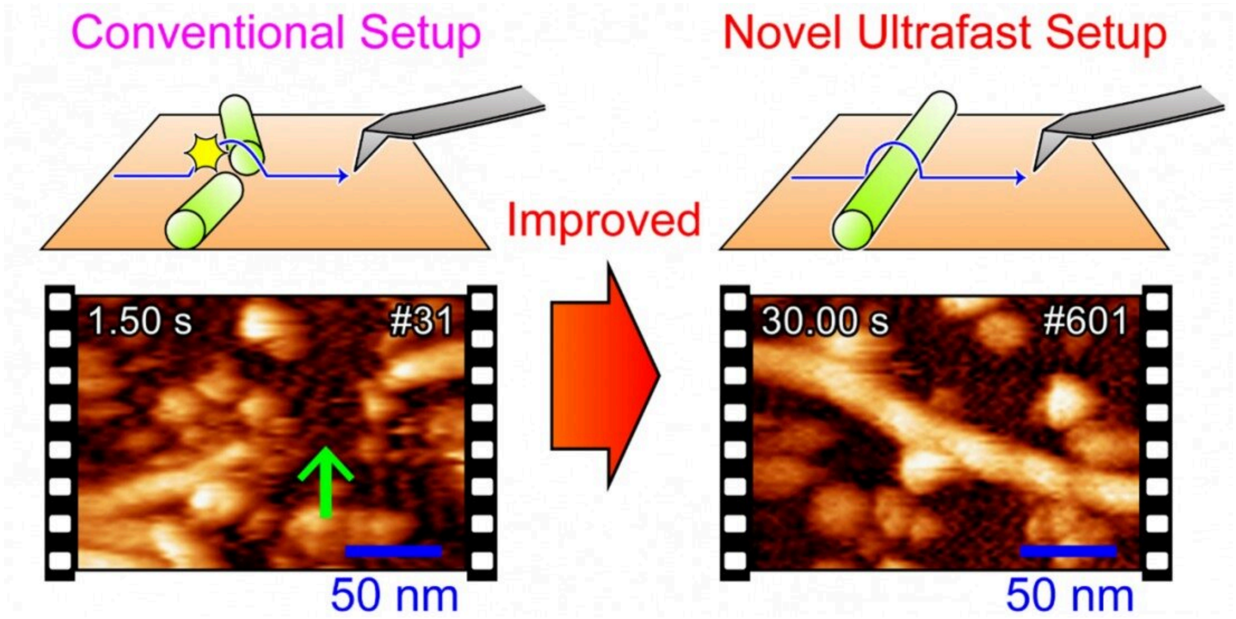

Comparison of AFM images taken by conventional and ultrafast amplitude detector.A novel ultrafast amplitude detector developed in the present study allows us to perform low-invasive high-speed AFM imaging for biological samples. Now, actin filaments, one of the cytoskeletal protein filaments in eukaryotic cells, can be successfully imaged at video rate without breaking them. Credit: Kanazawa University

To improve our understanding of biomolecular processes happening within cells, techniques for visualizing and recording them are of key importance. High-speed atomic-force microscopy (HS-AFM) has become an important technique for the real-time observation of biological processes on the sub-molecular spatial scale and with sub-second time resolution. Still, a higher video frame rate is required for recording many important processes, such as ion transport motion or signaling mechanisms within membranes. Now, Kenichi Umeda, Toshio Ando and Noriyuki Kodera from Kanazawa University and colleagues have designed an amplitude detector with ultrafast operation, the use of which in HS-AFM leads to a significantly improved temporal resolution.

The basic idea of AFM is to make a very small tip scan the surface of a sample. During this horizontal ('xy') scan, the tip, which is attached to a small cantilever, follows the sample's vertical ('z') profile, inducing a force on the cantilever that can be measured. The magnitude of the force at the 'xy' position can be related to the 'z' value; the 'xyz' data generated during a scan then result in a height map providing structural information about the investigated sample. In HS-AFM, the working principle is slightly more involved: the cantilever is made to oscillate near its resonance frequency. When the tip is moved around a surface, the variations in the amplitude of the cantilever's oscillation—resulting from the tip's interaction with the sample's surface—are recorded, as these provide a measure for the local 'z' value. Amplitude variation detectors have an intrinsic slowness, called latency, as a finite time interval is normally required to detect a change in amplitude. Amplitude detector latency is one of the main bottlenecks towards improving the speed of HS-AFM.

Umeda and colleagues invented a cleverly designed amplitude detector that has zero intrinsic latency. The detector is based on the trigonometric calculation, in which the calculation of $A^2 = A^2(\sin^2\omega_c t + \cos^2\omega_c t) = (A\sin\omega_c t)^2 + (A\cos\omega_c t)^2$ is performed using an incoming sin wave $A \sin\omega_c t$. The key step for the fast detection was to obtain the cosine wave $A\cos\omega_c t$ by the differential operation. Hence, the electronic circuit invented here was named DB (differential based) amplitude detector.

The scientists built a test circuit with this architecture, and evaluated its speed performance in the range of 300–1500 kHz carrier frequency. The DB amplitude detector resulted in about 10 times faster characteristics than the schemes typically used until now.

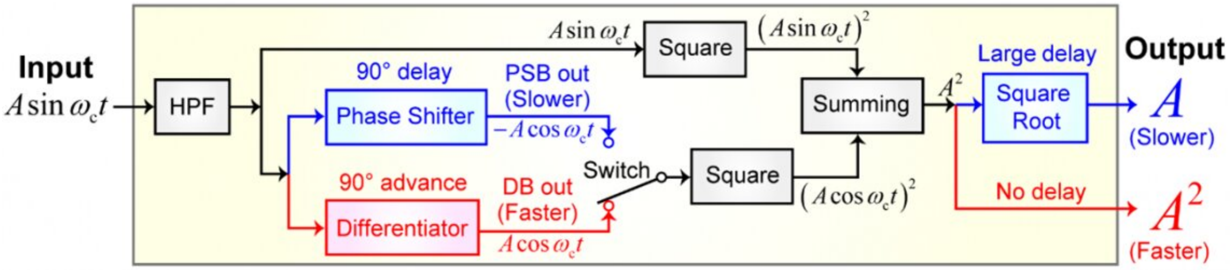

Diagram of amplitude detection based on the trigonometric calculation. To obtain amplitude A from an incoming sin wave Asinωct, after the calculation of A2 = A2(sin2ωct + cos2ωct) = (Asinωct)2 + (Acosωct)2 is performed, the square root operation is subsequently performed. So far, a phase-shift-based (PSB) operation that has finite intrinsic latency has been used to calculate Acosωct (blue box shown in the center). Here, the scientists use a differential-based (DB) operation that has zero intrinsic latency to calculate Acosωct (red box shown in the bottom center). Furthermore, it was found that a faster amplitude detection and less invasive imaging were achieved by skipping the square root operation. Credit: Kanazawa University

The researchers also tested the DB amplitude detector in a real HS-AFM experiment. They successfully recorded actin filaments, one of the cytoskeletal filaments found in eukaryotic cells, with a scanning velocity of 800 micrometers per second, which is four times faster than with a typical setup. The higher recording speeds not only results in a higher video frame rate (50 milliseconds per frame) but it also has the advantage of being less invasive—in the standard setup, the filament collapsed after 1 second, whereas with the new detector, the biomolecule was stably observed for 30 seconds.

The detector promises better performance in terms of imaging speed and less-invasiveness compared to conventional detectors. According to the scientists, "by overcoming the obstacle of the amplitude detector bandwidth, we have opened the road to increasing the temporal resolution of HS-AFM."

More information: Kenichi Umeda et al, Architecture of zero-latency ultrafast amplitude detector for high-speed atomic force microscopy, *Applied Physics Letters* (2021). DOI: 10.1063/5.0067224

Provided by Kanazawa University

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