Improved Ultrafast Digital Lock-In Amplifier for High Speed Atomic Force Microscopy

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Introduction

High Speed Atomic Force Microscopes (HS-AFMs) are new and exciting tools for watching biomolecules in action. The HS-AFM technique offers three orders of magnitude higher frame rate than the classical one while its resolution and capability to operate in liquid environment remains unchanged [1]. Such high frame rates were achieved as a result of exhaustive analysis of each component of the microscope and their optimization for higher imaging bandwidth [2].

For intermittent-contact mode, which is nearly exclusively used for biological AFM imaging, replacement of long classical cantilevers with short and thin cantilevers was one of the most important modifications. These new cantilevers have about 10-50 times higher resonance frequency. Consequently, these cantilevers are potentially 10-50 faster than the classical ones. To exploit this quick response time of these new cantilevers, it is necessary to determine their oscillation amplitude and phase from one cycle while keeping the signal to noise ratio as high as possible.

Last year, we introduced such an ultrafast lock-in amplifier, which fulfills these requirements. In this poster we demonstrate the device, and present the latest improvements on it. Due to the redesigned firmware of the device:

- Operation frequency range has been extended from 10 kHz up to 5 MHz
- Oversampling ratio is automatically adjusted to the operation frequency resulting in better signal to noise ratio and shorter delay

Theory of operation

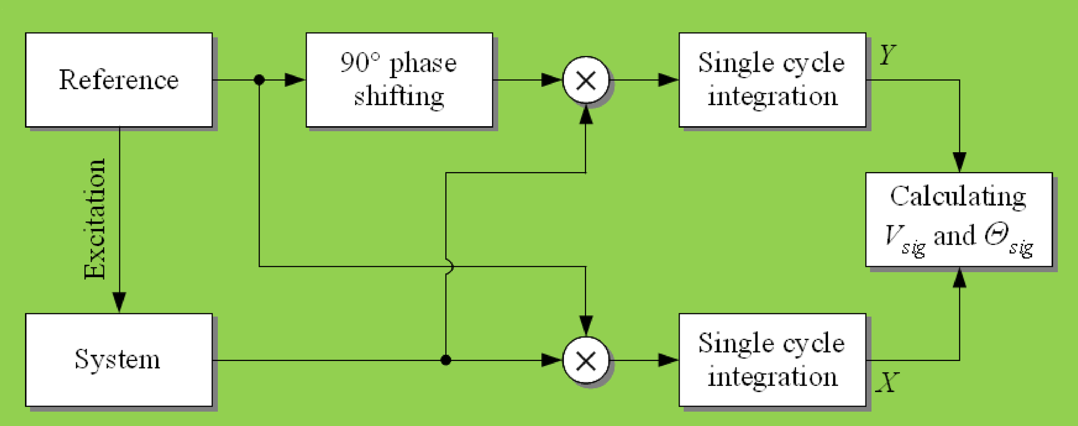
Lock-in amplifiers are used to detect weak signals at a given frequency, with a very narrow bandwidth. The reference signal – which is used to excite the system to be measured – is $V_{ref}\sin(\omega_{ref}t+\Theta_{ref})$, where V_{ref} is the excitation amplitude, ω_{ref} is the reference frequency, and Θ_{ref} is the phase. The system's response to this excitation can be written as $V_{sig}\sin(\omega_{sig}t+\Theta_{sig})$, where V_{sig}, ω_{sig}, and Θ_{sig} are the amplitude, frequency and phase of the signal, respectively. In a lock-in amplifier, these two signals are multiplied with each other, than the result is averaged. If we choose V_{ref} to unity and Θ_{ref} to zero than in case of $\omega_{ref}=\omega_{sig}=\omega$, the result of averaging is $X=V_{sig}\cos\Theta_{sig}$. In the other multiplier module, the signal is multiplied with the reference signal shifted by 90° resulting in $Y=V_{sig}\sin\Theta_{sig}$ after the averaging. Using X and Y, we can easily calculate the amplitude and phase of the response signal:

$$V_{sig}=\sqrt{X^2+Y^2} \qquad \theta_{sig}=\arctan\frac{Y}{X}$$

To calculate the amplitude and the phase in every single cycle of oscillation, we can use the Fourier method [3] :

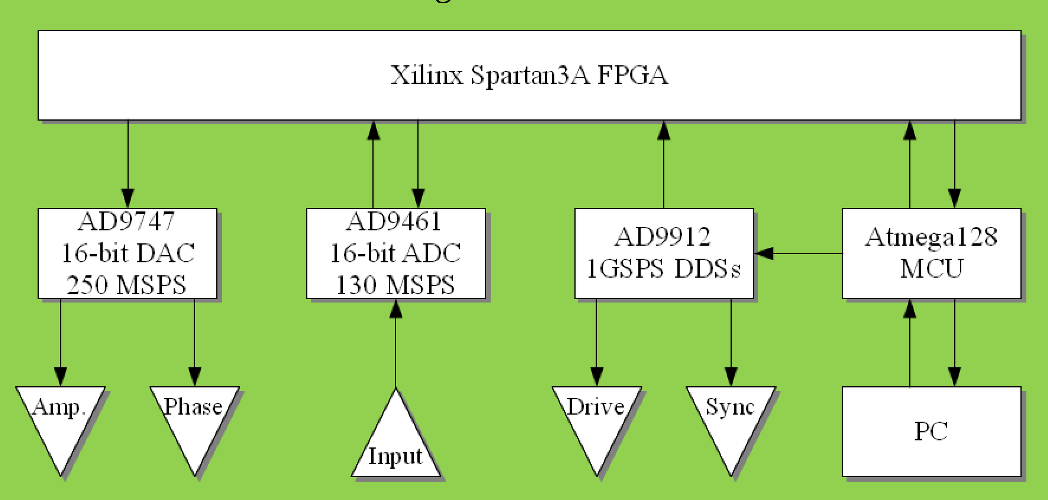
$$X=\int_0^{\frac{2\pi}{\omega}} V_{sig}\sin(\omega(t-\tau)+\theta_{sig})\sin(\omega(t-\tau))dt$$

$$Y=\int_0^{\frac{2\pi}{\omega}} V_{sig}\sin(\omega(t-\tau)+\theta_{sig})\cos(\omega(t-\tau))dt$$



The instrument

To meet the computing needs – about 2 Gb/s data flow, calculating square root and arcus tangent online –, we designed a digital FPGA system, which can operate at very high frequencies. To avoid window function problem at the Fourier method, we always use integer number of data points in each cycle, which is done by the use of two DDS chips. We use high speed 16-bit A/D and D/A converters to achieve high resolution. To automate the controlling of the device and to communicate with the PC, we use a 8-bit microcontroller with a USB controller. In order to improve signal to noise ratio, we remarkably oversample the cantilever signal using the A/D converter and the result is averaged.



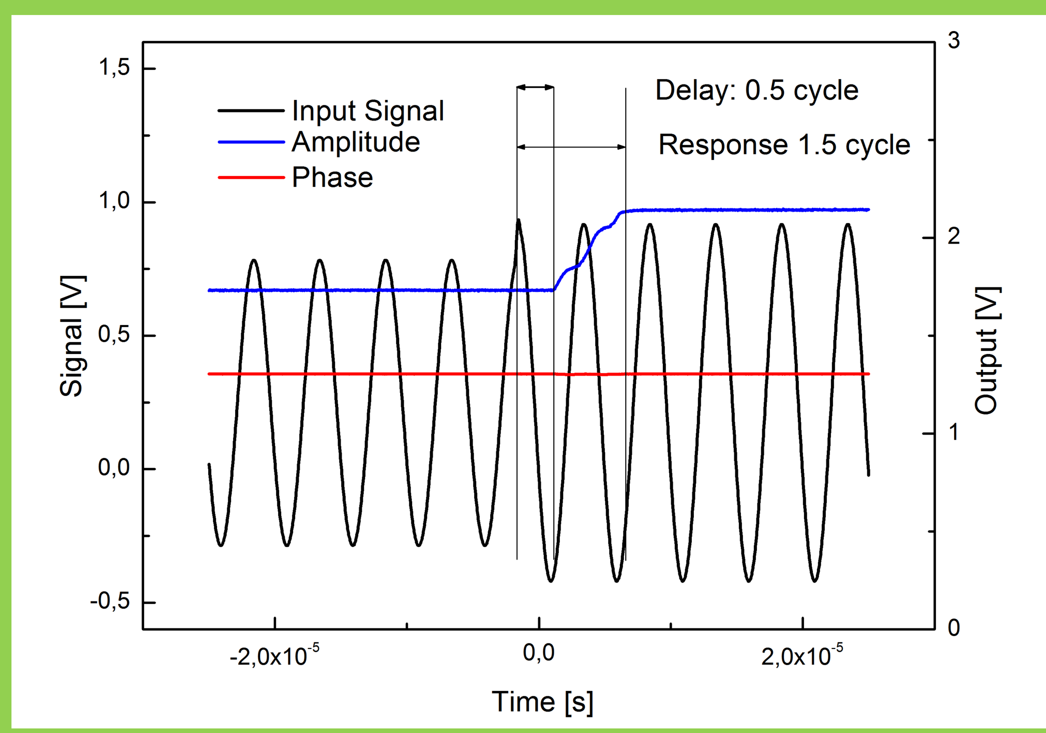
Our device can be adapted to every high speed or classical AFM and it offers flexible operation frequency range.

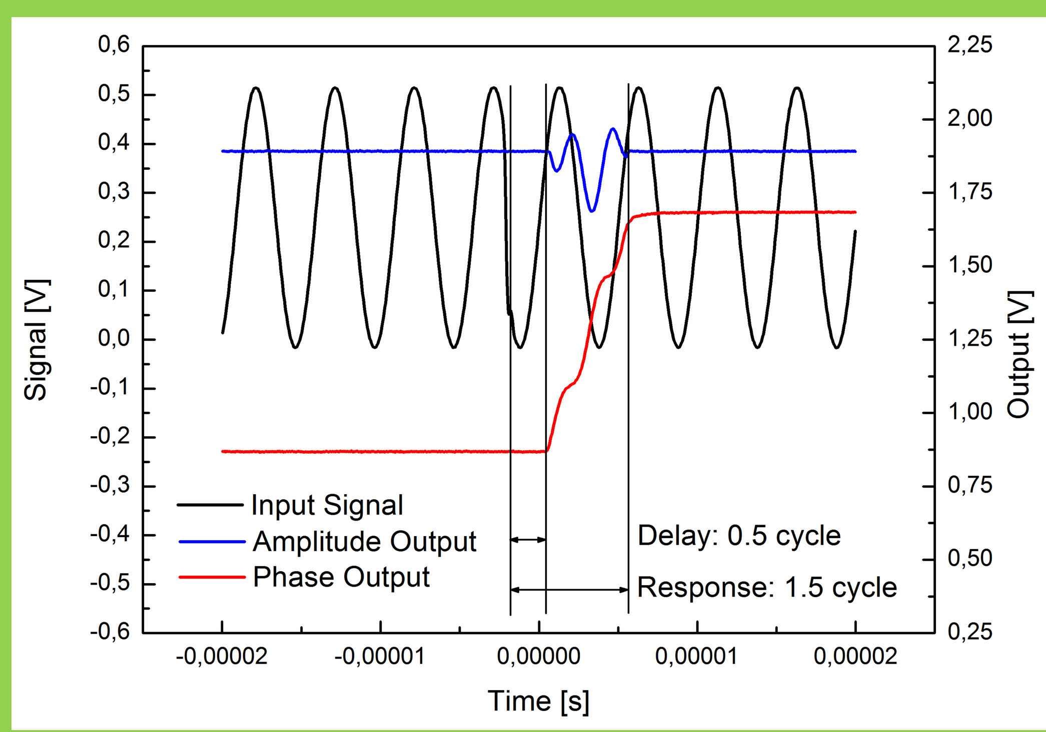
The communication interface of the instrument is a virtual serial port through a USB cable. The ASCII based command protocol makes the communication clear, and as a result, the device is controllable even with a simple serial port monitor program. Nevertheless, we have written a simple, easy to use Windows control software.

The features of the instrument are the following:

- Wide frequency range, from 10 kHz to 1MHz
- Drive amplitude between 0 and 4 V
- Automatic dynamic range setting
- Optional low-noise mode
- High signal to noise ratio, greater than 5000 at 1 MHz
- Fully controllable by a PC via USB cable
- Easy to use

The following graphs demonstrate the dynamic performance of the instrument:



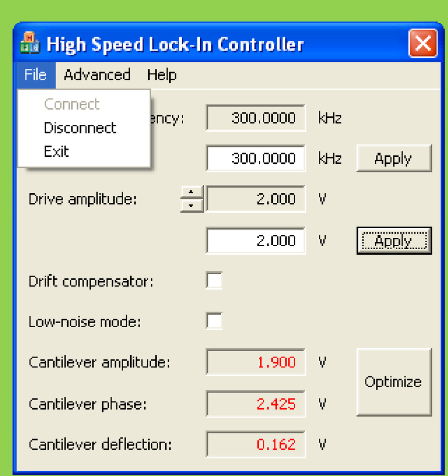


Improvements

Due to the unique feature of the digital system, we can apply further enhancements to our lock-in amplifier just by upgrading its firmware, leaving the hardware unchanged.

We have changed not only the FPGA firmware, but the MCU software as well. With these changes, we can present better performance:

- We have applied an updated oversampling method. Now the oversampling ratio is automatically adjusted to the operating frequency guaranteeing the best possible signal to noise ratio at every frequencies.
- FPGA firmware has been optimized, and this optimization further accelerated the device. As a result, not only the drive frequency range has been extended from 10 kHz up to 5 MHz, but also the delay was reduced.
- The instrument has an improved the communication protocol. Some instructions have been changed, and some new ones were introduced. The communication between the device and the PC is now faster, and the setting of the parameters can be more specific.
- Finally, we have upgraded the PC control software:
  - The communication algorithm was modified to adapt to the new protocol.
  - We have done some improvements on the user interface, in order to make it easier to use, and display the information more readable.



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