Application Note

Interferometer Stabilization with Linear Phase Control Made Easy

Zurich Instruments

Applications: Photonics, Metrology, Imaging
Products: MFLI, UHFLI

Release date: August 2018

Abstract

This application note explains how to use the Zurich Instruments MFLI, a 500 kHz/5MHz Lock-in Amplifier, to measure, stabilize and control the relative distance of two interferometer paths to sub-wavelength precision over multiple wavelengths. By introducing a phase modulation on one of the interferometer arms, a signal is generated to display the relative displacement linearly and continuously. This signal is then processed by an internal PID controller to stabilize the relative path length to an adjustable setpoint.

Motivation

Optical interferometers measure precisely the relative phase difference between two paths of light propagation. One application is the detection and control of relative optical path length changes of two interferometer arms to a fraction of the light wavelength as used for instance in quantitative phase imaging [1]. Figure 1 shows the Michelson-Morley scheme of interferometry but other configurations like Mach-Zehnder are also common. Tiny relative changes of refractive index in the two pathways, which can be caused by changes in air temperature or pressure, will lead to a large measurable signal. One downside of this high sensitivity is that small fluctuations introduced, for instance by mechanical noise or varying temperature gradients, can cause tiny mirror displacements and thus induce systematic measurement errors. Continuous measurement and active stabilization of the relative interferometer phase angle can help to suppress such error sources. However, using the relative phase angle directly as an input for a feedback system limits the control range to less than $\pi/2$ or a quarter of wavelength, along with other drawbacks.

Here we present an elegant technique introduced in [2] based on the work presented in [3] offering the following advantages:

- working at arbitrary relative phase angles
- covering an arbitrary large displacement range
- easy to set up and monitor
- manual and computer controlled operation

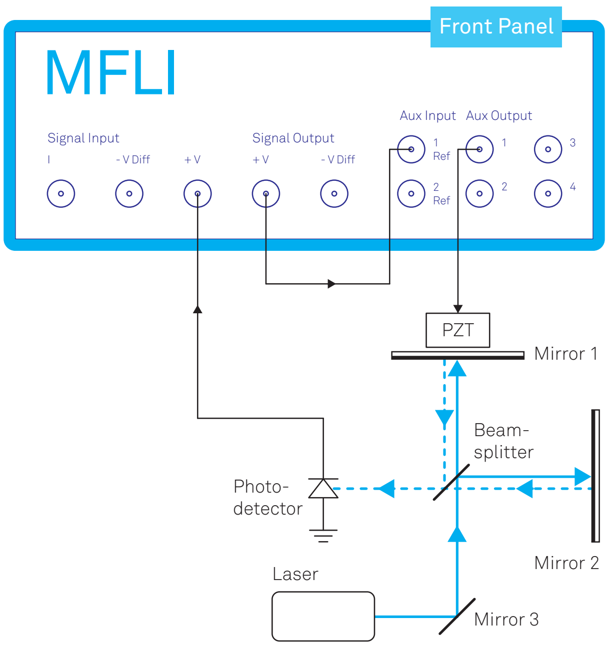

Figure 1. Michelson-Morley interferometer actively stabilized by a closed-loop system using the Zurich Instruments MFLI Lock-in Amplifier. The Auxiliary Output provides both a modulating signal and a controlling offset for the piezo electric transducer (PZT). The external loop-back from the Signal Output to the Auxiliary Input is required to generate the linearized and continuous error signal for PID control (see text).

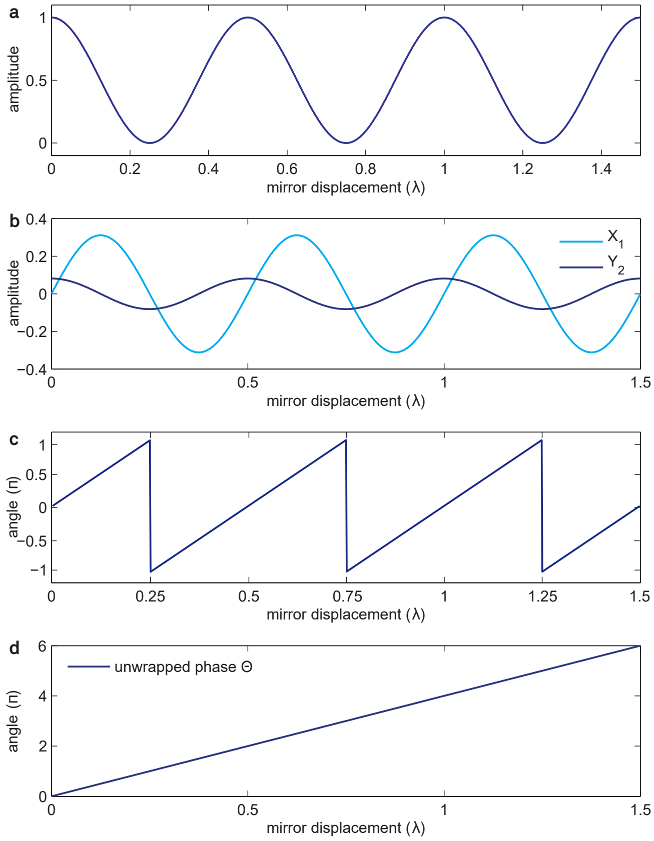

Figure 2. (a) shows the sinusoidal signal detected by the photodetector over the relative displacement between mirrors 1 and 2. (b) shows the signals X_1 and Y_2 demodulated at Ω and $2\,\Omega$. (c) shows the phase angle between the normalized X_1 and Y_2 components given in Equation 5. (d) shows the unwrapped version of the same phase in (c) used by the PID controller to drive the PZT.

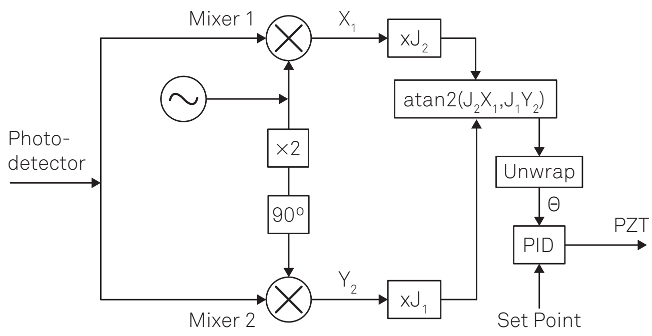

Figure 3. Linear phase control for interferometer stabilization requires the following steps: (1) Provide a reference signal at Ω to apply a phase modulation. (2) Apply lock-in detection to the photodetector signal to obtain the demodulation signals X_1 and Y_2 at the modulation frequency Ω and its 2nd harmonic. (3) Apply correction factors J_1 and J_2. (4) Determine the phase θ by atan2(J_2X_1, J_1Y_2) (5) Unwrap the phase θ. (6) Apply PID controller to provide feedback.

Description

In the example given in Figure 1, the light intensity I detected by the photodetector satisfies the following expression

$$\frac{I}{I_0} = \frac{1+\cos\phi}{2}, \tag{1}$$

where I_0 is the intensity of the laser light at wavelength λ, and ϕ is the the phase difference between the two arms of the interferometer.

Figure 2 (a) depicts the photodetector signal described in Equation 1. It shows two challenges detecting the mirror displacement via the phase ϕ with the photodetector signal. One is the difference in sensitivity of the points of maximum slope and the extrema of the curve. The other challenge is to get rid of the ambiguity imposed by the photodetector signal I as a non-monotone function of ϕ. By reading the photodetector voltage at the extrema points, one cannot see whether the displacement is continuing in the same direction, or it is going through a turning point. Both issues can be solved by introducing a phase modulation to one of the beam paths, for instance by applying a sinusoidal voltage of frequency Ω to the piezoelectric transducer, which controls the relative path difference. This phase modulation can be described as

$$\phi = \theta + \psi\sin(\Omega\,t), \tag{2}$$

where ψ is the modulation depth and $\theta = 4\pi\frac{\Delta L}{\lambda}$ is the initial phase offset due to the length difference ΔL between the interferometer arms. Substituting Equation 2 for ϕ in Equation 1 results in a phase-modulated signal consisting of higher harmonics of Ω. Using the Jacobi-Anger expansion, the first and the second harmonics, I_1 and I_2, are expressed in terms of Bessel functions J_1 and J_2 at the modulation depth ψ as follows.

$$I_1 = -I_0 J_1(\psi)\sin(\theta)\sin(\Omega\,t), \tag{3a}$$
$$I_2 = I_0 J_2(\psi)\cos(\theta)\cos(2\,\Omega\,t), \tag{3b}$$

where the components

$$X_1 = J_1(\psi)\sin(\theta), \tag{4a}$$
$$Y_2 = J_2(\psi)\cos(\theta), \tag{4b}$$

resemble the form of the first and the second derivatives of the original fringe pattern. Figure 3 shows how the slowly-varying signal components X_1 and Y_2, depicted in Figure 2 (b), are extracted from the original photodetector signal by demodulation at the frequencies Ω and $2\,\Omega$. To linearize the response signal, it is important that both components X_1 and Y_2 contribute with exactly the same strength. This is achieved by either adjusting the modulation depth to ψ = 2.63 rad where $J_1(\psi)$ and $J_2(\psi)$ are equal, or by introducing the correction factors J_1 and J_2, as indicated in Figure 3. In both cases, the resulting parametric plot of these two signals should describe a circle instead of an ellipse. This way, the phase offset θ is obtained by the following expression

$$\theta = \text{atan2}(J_2(\psi)X_1, J_1(\psi)Y_2). \tag{5}$$

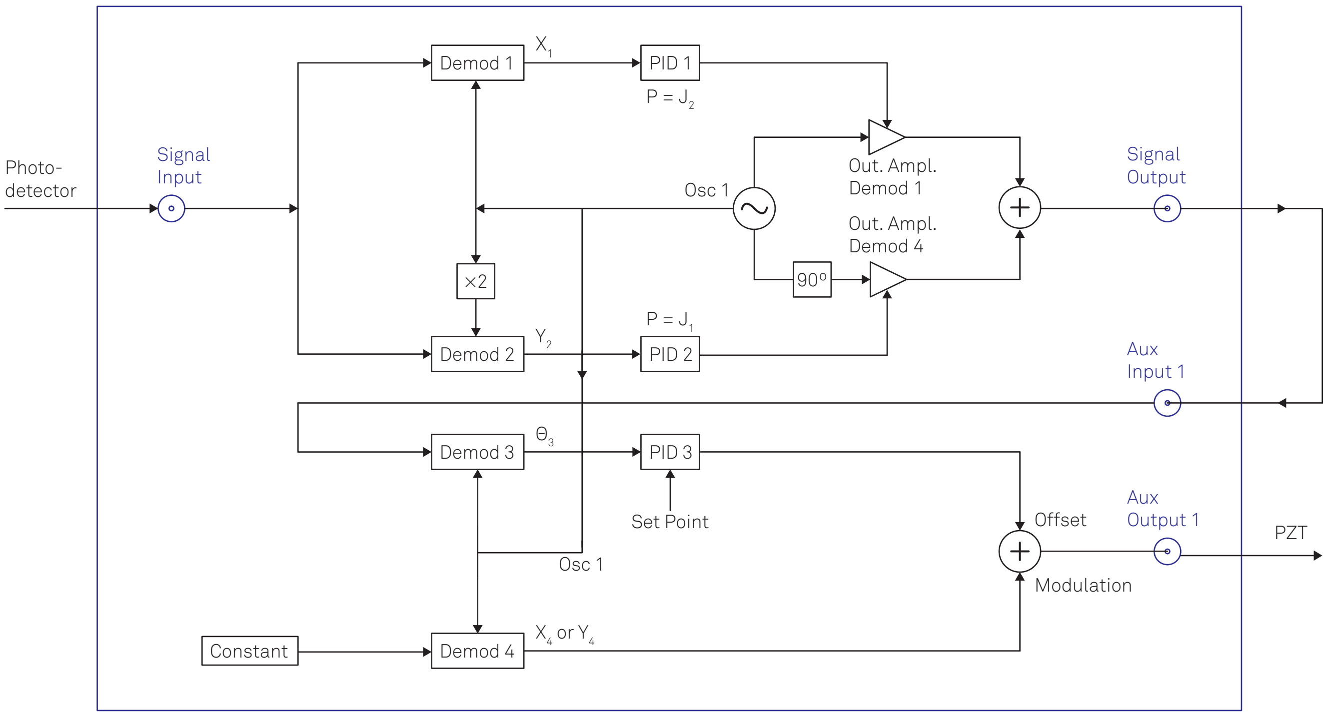

Figure 4. Detailed description of the instrument configuration to be implemented using the LabOne user interface. In total, 4 demodulators (Demods) of the instruments are required. Two PID controllers are used as proportionate functions to apply the Bessel coefficients. The third PID controller is used to drive the offset signal controlling the mirror displacement.

It should be noted that the function 'atan2' is used to determine unambiguously the phase within a range $-\pi < \theta \leq \pi$ from the two arguments. The result compared to the original photodetector signal is shown in Figure 2 (c).

As a final step to obtain a monotonic function of displacement between the arms, a phase unwrap is performed to extend the available phase range from the 'atan2' operation to an infinite scale. The resulting unwrapped phase signal versus the relative displacement in units of wavelengths is shown in Figure 2 (d). This signal can now be used by a PID controller to provide feedback to the PZT in the form of an offset voltage to control the relative path lengths of the interferometer and keep the phase exactly at the defined setpoint of the PID controller. The remaining error signal of the closed-loop controller now delivers a direct measure of the intended and unintended disturbances of the setup.

An essential part of this scheme is the modulation in one of the interferometer arms. This clearly poses the limitation that the stabilization is not absolute but only on average. However, for pulsed laser experiments where the stabilization is done with a CW laser, a proper synchronization with the repetition rate of the pulsed laser will remove this problem.

Implementation

In practice, the mechanical resonance frequency of the piezo-mirror assembly in Figure 1, is a few ten kHz at most, which poses an upper limit on the modulation speed and also the loop filter bandwidth. The MFLI can handle modulation bandwidth of up to 200 kHz, limited by the Auxiliary Output bandwidth, while the photodetector bandwidth can be as high as 5 MHz. The maximum loop filter bandwidth depends on the setup properties, and can be as high as 50 kHz. To implement the scheme detailed in Figure 3, the MFLI needs to be equipped with the MF-MD Multi-demodulation and the MF-PID Quad PID/PLL Controller options. In order to apply the correction coefficients $J_1(\psi)$ and $J_2(\psi)$ and to determine the phase between the output of two independent demodulators, we apply an interesting technique detailed in Figure 4.

The reference signal at frequency Ω is generated in the path of demodulator (Demod) 4 and sent out through the Auxiliary Output to drive the PZT. The photodetector signal, which includes several harmonics of Ω due to the phase modulation, is received at the Signal Input and demodulated at Ω by Demod 1 to obtain X_1 and $2\,\Omega$ by Demod 2 to get Y_2, as shown in Figure 4. The correction factors $J_1(\psi)$ and $J_2(\psi)$ are applied to the demodulated signals X_1 and Y_2 using the PID controllers 1 and 2 in their proportionate mode, i.e. I and D parts are set to zero. The PID outputs then alter the amplitude of a sine and a cosine wave at Ω through the path of Demod 1 and Demod 4; the resulting signal available at the Signal Output is expressed as

$$\begin{aligned} s(t) &= J_2 X_1 \cos(\Omega t) + J_1 Y_2 \sin(\Omega t) \\ &= J_2 J_1 \sin(\theta) \cos(\Omega t) + J_1 J_2 \cos(\theta) \sin(\Omega t) \\ &= J_1 J_2 \sin(\Omega t + \theta). \end{aligned} \quad (6)$$

According to Equation 6, the phase difference θ due to the length difference between the two arms of the interferometer can now be extracted by demodulating $s(t)$ at frequency Ω. This is done by looping back the Signal Output to the Auxiliary Input and demodulating the signal using Demod 3 as shown in Figure 4. The phase extracted by Demod 3 is described by Equation 5 and depicted in Figure 2 (c). The phase signal is then used as an input for PID 3, which unwraps the phase before comparing the signal to the setpoint. After passing through the PID controller the signal is added to the reference signal in the Auxiliary Output connected to the PZT to close the loop.
In order to set this up conveniently, LabOne®, Zurich Instruments' control software, provides a web-based user interface with many powerful tools for further analysis. As a first step, one could for instance characterize the transfer function of the PZT-mirror assembly by recording a Bode plot with the Parametric Sweeper tool. The frequency where the phase gets close to ±90° is a rough indication of the maximum loop filter bandwidth. In a second step, one could display the signals X_1 and Y_2 in the integrated FFT Spectrum Analyzer to confirm the signal dynamics. Once a proper estimate for the required loop filter bandwidth is obtained, the gain parameters for PID 3 can be easily derived from the PID Adviser and then iteratively refined. This entire procedure can also be automated by using any of the LabOne APIs, available for MATLAB®, LabVIEW®, Python, .NET and C, to integrate it in an existing control environment.

Fast Modulation

Setups requiring high-speed modulators, such as acousto-optical modulators (AOM) or electro-optical modulators (EOM), can operate at modulation frequencies of several hundred MHz. This allows for higher loop-filter bandwidths to cancel out noise components at higher frequencies. For these cases, we recommend the use of the Zurich Instruments UHFLI, a 600 MHz Lock-in Amplifier, which can also be equipped with 4 PID controllers to implement the above scheme. The main implementation difference with the UHFLI is its ability to generate the reference signal at a Signal Output instead of an Auxiliary Output. It eliminates the limitation of the modulation frequency to the Auxiliary Output bandwidth, so that the reference signal can cover the whole frequency range of the instrument, in this case up to 600 MHz.

The other Signal Output is used for the signal $s(t)$ containing the phase information, which is again looped back to one of the Signal Inputs to extract its phase. The other Signal Input receives the photodetector signal to demodulate it at the first and second harmonics. The UHF-MF Multi-frequency option is required to freely select several demodulators and assign them to appropriate signals and adjust their frequency and phase. Three of the four PID controllers provided by the UHF-PID Quad PID/PLL Controller option are also required to apply the correction factors and to generate the control signal for mirror displacement.

Conclusion

With the MFLI and UHFLI, Zurich Instruments provides single-instrument solutions for interferometer stabilization and control up to modulation frequencies of 600 MHz. The scheme presented here can be quickly and easily implemented with the LabOne user interface which has various built-in tools to characterize and monitor the experimental setup. Full computer control is also available using LabOne APIs.
Please contact us directly on info@zhinst.com or +41 44 515 04 10 for further information. We are curious to discuss your specific experimental requirements.

References

[1] H. Iwai, C. Fang-Yen, G. Popescu, A. Wax, K. Badizadegan, R. R. Dasari, and M. S. Feld. Quantitative phase imaging using actively stabilized phase-shifting low-coherence interferometry. Opt. Lett., 29(20):2399–2401, 2004.

[2] A. A. Freschi and J. Frejlich. Adjustable phase control in stabilized interferometry. Opt. Lett., 20(6):635–637, 1995.

[3] U. Minoni, E. Sardini, E. Gelmini, F. Docchio, and D. Marioli. Adjustable phase control in stabilized interferometry. Rev. Sci. Instrum., 62:2579, 1991.

Zurich Instruments
Technoparkstrasse 1
CH-8005 Zurich
Switzerland
www.zhinst.com
info@zhinst.com
+41 44 515 04 10