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High accurate positioning control method for piezoelectric actuators based on phase-shifting optoelectronics

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Abstract
We propose a sub-nanometric positioning control method for piezoelectric actuators based on a home-made high frequency phase shifting electronic circuit and a heterodyne interferometer. The method has been set up. Using a readily available piezoelectric actuator, we demonstrate that our method allows back and forth displacement without nonlinearities. Repeatability of 0.053 nm has been obtained over 1 μm displacement range. Displacement steps as low as 260 pm are presented. Such a method could be very useful for the nanotechnology and nanometrology communities for nano-scale manipulations or nano-assembly applications.

Keywords: heterodyne, laser interferometry, high frequency clocks, dimensional metro

1. Introduction

Demands for displacement transducers with nanometric level of accuracy have increased significantly in recent years. Such systems become an important issue in the field of semiconductor manufacturing equipment and applications are numerous: wafer inspection, nano-lithography, nano-scale manipulation and ultrahigh density data storage. Piezoelectric actuator (PZT) is a focus on the domain of high precision positioning technology. With the development of microelectronic technology, communication technology, nanotechnology and computer technology, the performance of high resolution positioning stepper PZT has been greatly improved. Compared to electromagnetic actuators, they have many advantages, such as simple configuration, small size, high resolution, good controllability. PZT can be operated in open or close modes. In the open mode, PZT exhibits hysteresis, creep behaviour and ageing process involving some problems of repeatability of the motion. Hysteresis is typically on the order of 10% to 15% of the displacement range. We propose a positioning control method for applications requiring high linearity, long-term position stability, repeatability and accuracy. The method is based on the use of piezoelectric actuators and a closed-loop composed with a heterodyne interferometer as a position measuring systems and a home-made phase-shifting electronic circuit. If the surrounding environment is controlled, the complete system provides nanometric accuracy and highly repeatable motions. A repeatability of 0.053 nm over 1 μm displacement range has been achieved. Moreover, steps of the piezoelectric actuator as low as 260 pm have been performed and reported in this paper.

2. Principle

In [1], we have proposed a method which allows us to perform position control of a translation stage with nanometric accuracy. In order to assess the improvement of the method presented in this paper, a brief description of the previous method is summarized hereunder.

Consider the sketch of figure 1. An electronic board put out two synchronized signals s_1 and s_2 at a same frequency of 20 MHz. It allows us to make phase-shift of quantified value on either signals. Signals s_1 and s_2 are respectively sent to a mixer and to a laser head which transpose the signal from ultrasonic range to optical frequency range thanks to a voltage controlled

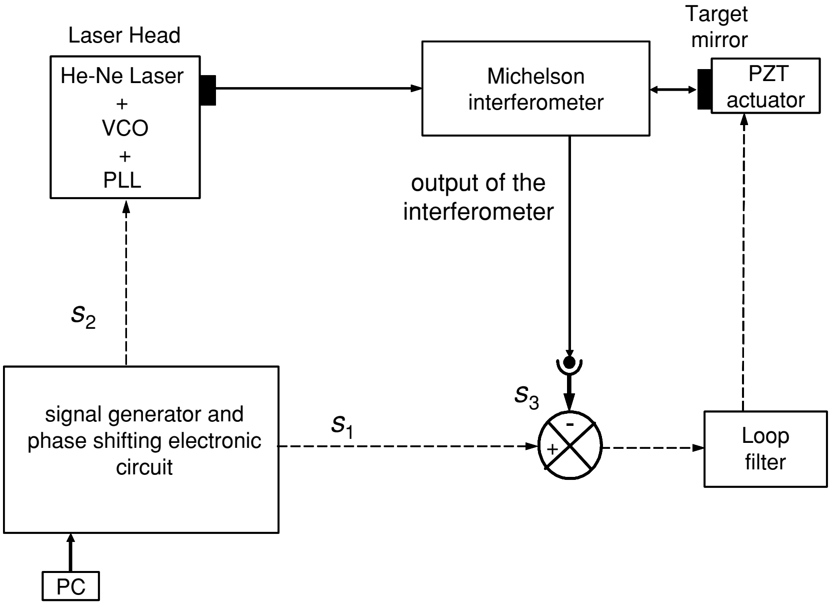

Figure 1. Principle of the position control method. A home-made electronic circuit puts out two synchronous signals both at a frequency of 20 MHz. A voltage controlled oscillator (VCO) in the laser head generates the heterodyne components of the laser source. This VCO is synchronized to the signal s_2 thanks to a PLL system. The other signal (s_1) is sent to a mixer to be phase compared with the signal s_3 coming from the output of the interferometer.

oscillator and a Bragg cell. This allows us to perform the two optical components of the heterodyne laser source. The optical beam passes through a double-pass Michelson interferometer. Neglecting refractive index of air fluctuations, a phase-shift of 2π between the reference beam and the measurement beam at the output of the interferometer corresponds to a displacement of a target mirror of $\lambda_0/4$ where λ_0 is the laser wavelength in vacuum. The two heterodyne components are recombined at the output of the interferometer, resulting in a signal s_3 at a same frequency that is of s_1 and s_2. Signal s_3 contains position information. Then the position of a target mirror is controlled with a phase locked loop system which compares phases of signals s_3 and s_1. If the phase-shifts are made onto s_1 or s_2 by an amount of $\Delta\phi$, the signal error becomes non-null. A servo-controller determines the voltage to send to the PZT, to move the target mirror and to compensate the phase-shift by Doppler-effect. The displacement value Δx in air of the mirror is directly related to the phase-shift by the equation

$$\Delta x = \frac{\lambda_0}{8\pi n}\Delta\phi \tag{1}$$

where n is the refractive index of air. If the phase-shift is quantified and equal to $\Delta\phi = 2\pi/N$ where N is an integer, it becomes possible to control the displacement of the translation stage with a known step given by $\Delta x = \lambda_0/4Nn$.

The Michelson interferometer we used has a beat frequency equal to 20 MHz (Zygo, ZMI2001) with a resolution of 0.31 nm [2]. To perform the signal generator and the phase-shifting electronic circuit, we used a programmable high frequency clock (HFC) operating at 640 MHz and frequency divisions made with logic flip-flop components. The principle for the generation of the phase-shifts is presented sketchily in figure 2. Consider a digital HFC, with a frequency equal to $2^p \times 20$ MHz where p is an integer. An inhibition of one pulse of this signal corresponds to a phase-shift of 2π. The frequency of this signal can be divided by 2^m with $0 \leqslant m \leqslant p$. Then a phase-shift of $2\pi/2^m$ occurs on the signal at a frequency $2^{p-m} \times 20$ MHz.

This method suffers from one drawback which is that the displacement is made step by step with a minimal value limited to about 5 nm ($N = 32$, $\lambda_0 = 632.991\,528$ nm). To reduce this minimal step value, one possibility consists in increasing the value of the HFC. Taking into account the state of the art of the high frequency digital electronic components, this solution hardly seems possible at the present time. Another possibility is to use a shorter wavelength laser source. But UV components are very expensive and only a factor 2 is achievable. In this paper we propose a low cost alternative method permitting to reduce this limit by a factor of 20.

This improved method is based on a differential phase-shifting electronic circuit. In the first version of the electronic board, the phase-shift can be performed either on s_1 or on s_2 but not simultaneously. If a phase-shift of $\Delta\phi$ occurs onto s_1, the mirror moves in one way. If the phase-shift is made onto s_2, then the mirror moves in the opposite way. The second version of the electronics board is able to perform the phase-shifts of $\Delta\phi_1 = 2\pi/p$ and $\Delta\phi_2 = 2\pi/q$ respectively, on s_1 and s_2 simultaneously. The resulting phase-shift is then given by

$$\Delta\phi = \Delta\phi_1 - \Delta\phi_2 = 2\pi\frac{q-p}{q \times p}. \tag{2}$$

Choosing judiciously the values of p and q, the resulting phase-shift can be very small. For example with $p = 36$ and $q = 34$, $\Delta\phi = 2\pi/612 = 10.3$ mrad resulting to a minimal step value equal to 0.258 nm giving hence the possibility for quasi-continuous displacements. It is important to remember that such a level of accuracy can be reached only if the surrounding environment is controlled, since temperature changes and vibrations will cause changes in position at the nanometer level.

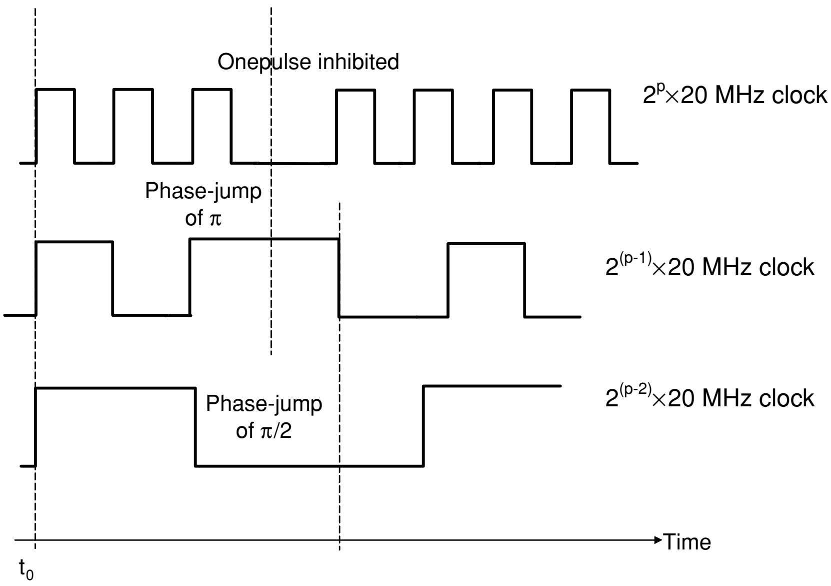

Figure 2. Principle for the generation of the phase-shifts. A high frequency clock generates a signal at a frequency of $2^p \times 20$ MHz. Others signals are generated from this signal with a frequency divided by 2^m with $0 \leqslant m \leqslant p$. An inhibition of one pulse of the primary clock corresponds to a phase-shift of $2\pi/2m$ of the signal at a frequency of $2^{p-m} \times 20$ MHz.

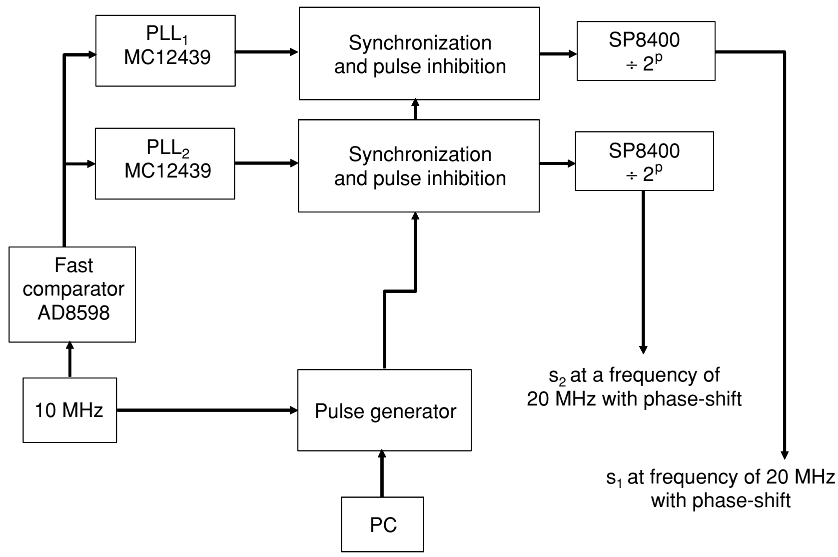

Figure 3. Sketch of the electronic board. Two synchronous high frequency clock, obtained from two phase locked loop MC12439, are synchronized to a 10 MHz reference quartz oscillator. Some positive emitter coupled logic components with working frequencies upper than 2 GHz and with very low phase noise characteristics are used to perform inhibitions and frequency divisions.

Unlike to [1], the new electronic board is designed with two synchronous HFC obtained with two phase locked loop MC12439. Their frequencies are programmable from 50 MHz to 800 MHz by steps of 1 MHz. Both HFC are synchronized to a 10 MHz reference clock, an ultrastable quartz oscillator ($\sigma_y < 10^{-9}$ per day). The frequency division ratios are obtained with logic divider Zarlink SP8400 components which are programmable from 16 to 8206 to obtain signals s_1 and s_2 both at a frequency of exactly 20 MHz. Some positive emitter coupled logic components with working frequencies upper than 2 GHz and with very low phase noise characteristics, are used to perform inhibitions and frequency divisions (figure 3). The inhibitions are done with a TTL command signal generated with a direct digital synthesis (DDS) (DS345 Stanford) synchronized to the 10 MHz reference and PC-controlled. The synchronism of the phase-shifts on s_1 and s_2 can be controlled independently with an accuracy below 1 ns.

3. Experimental setup and results

The experimental setup is depicted in figure 4. The laser beam at the output of the interferometer is divided by a neutral density beamsplitter. One part of the beam is sent to the Zygo data acquisition system to perform displacement measurements. The other part of the beam is sent to the mixer to be phase-compared with signal s_1 as seen previously. The piezoelectric actuator has a displacement range of 3 μm for an applied voltage of 30 V. All the systems are put

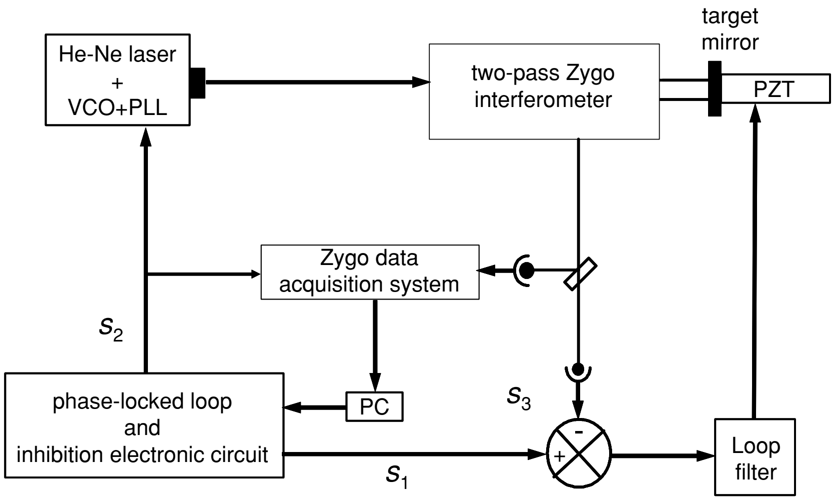

Figure 4. Experimental setup.

on an anti-vibration table to be less sensitive from mechanical disturbances. Simultaneously, a weather station measures the room temperature (PT100 thermistor—σ = 5 mK), the room pressure (Digiquartz—σ = 3 Pa), humidity content (MH4, General Eastern—σ = 1%) and CO_2 content (Paroscientifique—σ = 50 ppm). Using the Edlén equations [3], the refractive index of air is calculated with an uncertainty of 5×10^{-8}.

During the first step of the experiment, the phase of the signal s_3 at the output of the interferometer is locked on the phase of the reference signal s_1. The moving mirror of the interferometer is then in a fixed position. The output of the servo-loop control is sent to a fast Fourier transform apparatus (Stanford – SR785) and the noise of the voltage applied to the piezoelectric actuator is measured. A noise level of 1 mV rms integrated over a bandwidth of 750 Hz has been observed. This corresponds to a noise level on the position of the target mirror of less than 0.15 nm. The remaining noise is due to an insufficient acoustic insulation of external disturbances and a too low gain of the loop filter.

During the second step of the experiment, phase-shifts $\Delta\phi_1$ and $\Delta\phi_2$ are generated respectively onto s_1 and s_2. As the servo-loop is closed, the target mirror moves until the difference of the phase between s_1 and s_3 becomes null thanks to the Doppler shift as seen previously. The corresponding displacement of the mirror is calculated from equations (1) and (2)

$$\Delta x = \frac{\lambda_0}{4n} \frac{q - p}{q \times p}. \quad (3)$$

Several values for p and q have been tested. In each case, the phase-shifts are generated at a frequency of 2 Hz. In the first case, the phase-shifts are made only onto s_1 and $p = 32$ which leads to $\Delta\phi_1 = 2\pi/32$ and $\Delta\phi_2 = 0$. Taking $n = 1$, the corresponding theoretical step is equal to $\Delta x_1 = 4.945$ nm. In the second case, $p = 32$ and $q = 36$ which leads to $\Delta\phi = 2\pi/288$. The corresponding theoretical displacement of the target mirror is then equal to $\Delta x_2 = 0.549$ nm. In the last case, $p = 34$ and $q = 36$ leading to $\Delta\phi = 2\pi/612$ and $\Delta x_3 = 0.259$ nm. The experimental results are presented in figure 5. The parameters of the loop filter have been adjusted to minimize overshooting. The rise time is around 5 ms. It could be reduced to less than 1 ms by changing the parameters of the proportional integral derivative (PID) filter. The sampling frequency is equal to 10 kHz (limited by the data acquisition

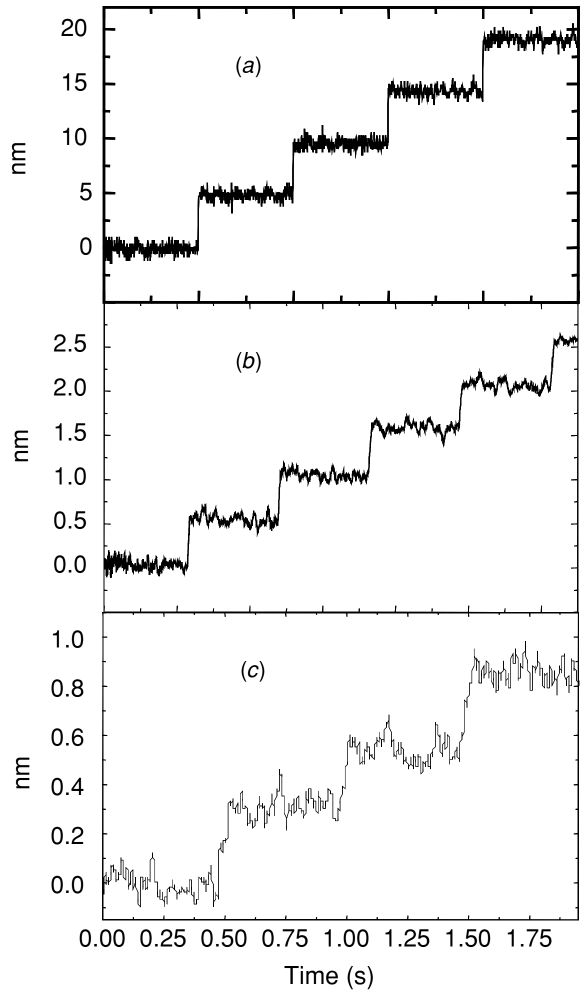

Figure 5. Experimental results. According to the values of p and q, different steps of the piezoelectric actuator are realized. (*a*) $p = 32$, $q = 0$, $\Delta x_1 = 4.945$ nm. (*b*) $p = 32$, $q = 36$, $\Delta x_2 = 0.549$ nm. (*c*) $p = 34$, $q = 36$, $\Delta x_3 = 0.259$ nm.

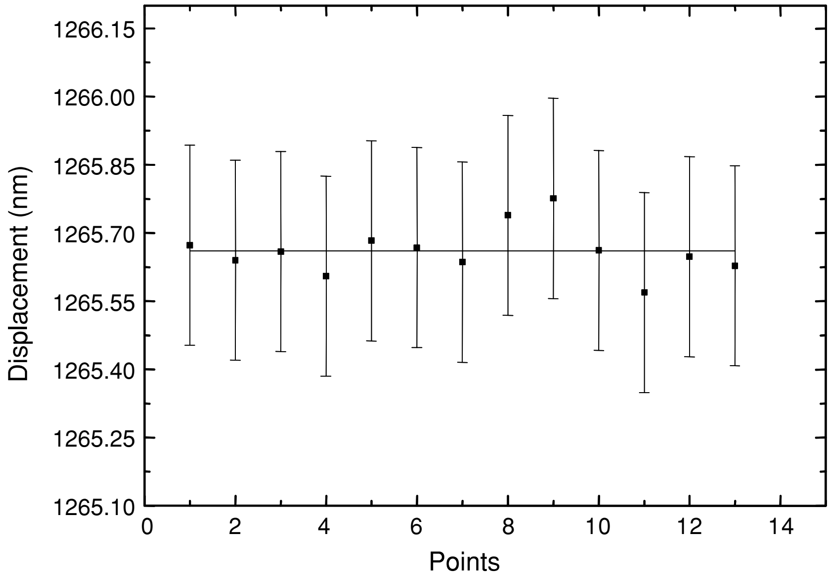

Figure 6. Repeatability of the method. K phase-shifts are programmed to generate a displacement of the target mirror from zero to x_B. The repeatability is given by the standard deviation of the set of the values of x_B. Straitght line represents the mean value.

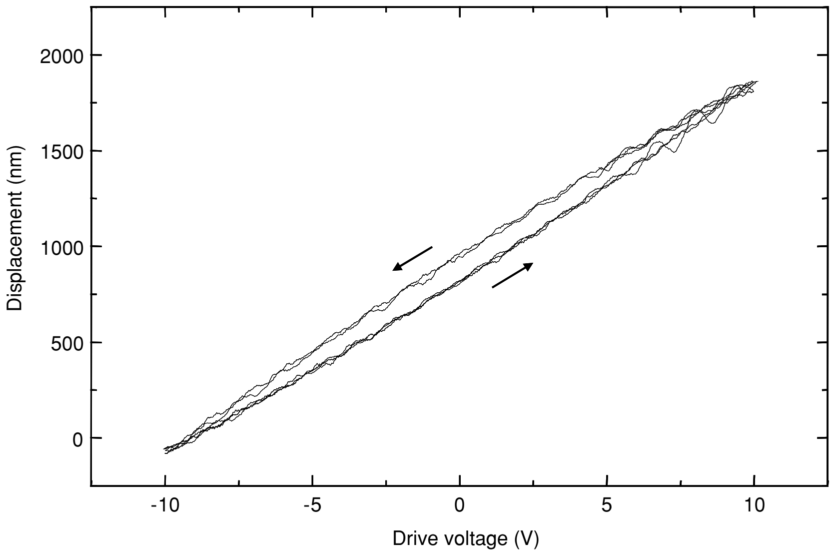

Figure 7. Hysteresis of the piezoelectric actuator used in our experiment in the open mode.

rate of the measurement software) and each point of the results depicted in figure 5 has been averaged over 1 ms. Furthermore, as the step levels Δx_2 and Δx_3 are near to the residual noise level of our system ($\sigma = 0.22$ nm), a first order Savitsky–Golay filter has been used to obtain figures 5 (b) and (c).

According to fruitful discussions with the nanotechnology community, it appears that in most applications (especially in near field microscopy characterization) the repeatability of the displacement is more important than the absolute value. To assess the repeatability of our method, the inhibition control is programmed to generate exactly K phase-shifts generating a displacement of the target mirror from zero to x_B. Then, the repeatability is given by the standard deviation of the set of the values of x_B.[3] The theoretical displacement is equal to $K \times \Delta x$. Figure 6 represents the results obtained with $p = 34, q = 36$ and $K = 4896$. The theoretical displacement in air is equal to 1265.666 nm (taking $n - 1 = 2.50 \times 10^{-4}$). We measure a mean value of 1265.660 nm over 13 measurements and a standard deviation of 0.053 nm. The theoretical and experimental mean values of the displacement are in good agreement. Hence, our method permits to achieve a repeatability at the sub-nanometric level over micrometric travel range.

Repeatability of the motions could be limited by the hysteresis of the actuator. We measure the hysteresis level of the piezoelectric actuator in the open mode (figure 7) and in the close mode (figure 8). In the open mode, the applied voltage is changed and the response of the actuator is measured by the Michelson interferometer. We can observe 8% of nonlinearity over a displacement of 2 μm. In the close mode, the displacement is controlled thanks to the electronic servo-loop ($p = 32, q = 0, f_c = 1800$ Hz) and back and forth displacements are imposed to the actuator. We can hence

[3] Guide to the expression of the uncertainty in measurements 1992 Iso/Tag/4/Wg:3.

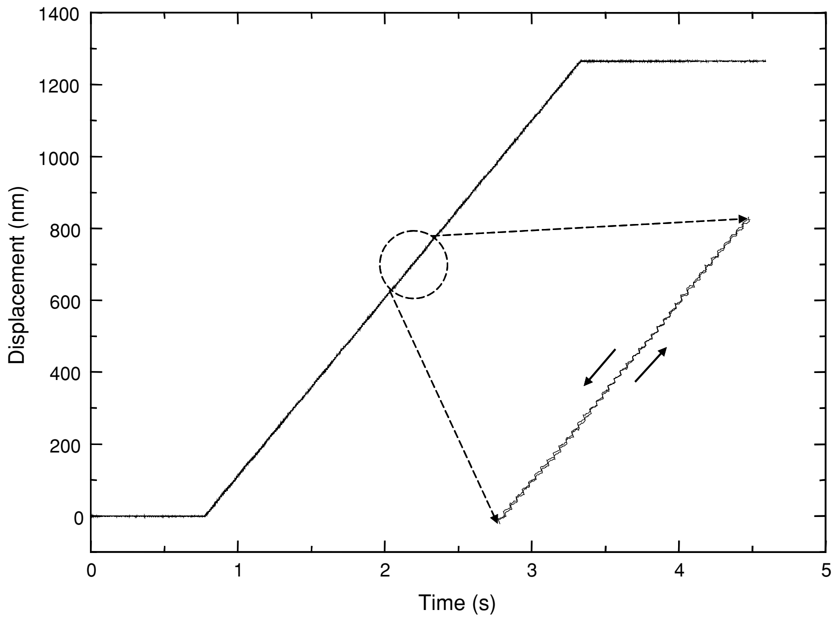

Figure 8. Hysteresis of the piezoelectric actuator used in the close mode. The centre of the curve has been zoomed over 200 nm.

verify that actually hysteresis becomes negligible in the closed mode.

4. Discussion

Authors want to highlight that all the results presented in this paper have been obtained only under a strict control of the surrounding environment (mechanical, environmental). Actually, as in most applications based on interferometry, variations of the refractive index of air and mechanical vibrations could distort the results. For this purpose, a complete weather station has been set up and the variations of the refractive index of air Δn have been measured thanks to the Edlèn equations with an accuracy of 5×10^{-8}. Furthermore, in order to minimize the optical path difference between both arms of the interferometer, we used a specific interferometer in which the reference arm and the measurement arm are lined up[4]. The distance between both mirrors are less than 5 mm. The corrective factor on the measured displacements due to the variations of the refractive index of air could hence be negligible ($\sigma < 10^{-12}$ m). Our method is also sensitive to the other classical errors [4] like the stability of the laser frequency, the cosine error in optical alignment, the nonlinearity of the laser source or thermal drifts of mechanical parts. The thermal drifts will change the optical path difference between both arms of the interferometer. Most parts of our optical components are made from Zerodur with a thermal expansion coefficient of 3×10^{-8} °C^{-1}. Furthermore, the mechanical platform supporting the piezoelectric actuator is made from aluminium with a high homogeneity and a thermal expansion coefficient of 23.7×10^{-6} °C^{-1}. During the measurements, we assumed that the room temperature fluctuations do not exceed 0.1 °C leading to a mechanical expansion below of 1 μm which is entirely compensated by the servo-loop control of the piezoelectric actuator. The length of the PZT actuator is 10 mm and its coefficient of thermal expansion is 1 ppm °C^{-1}. In the open-mode, the error induced by this factor is 1 nm. This is very small compared to the error due to the hysteresis (figure 7). In the closed-mode this error is not relevant. The laser frequency is stable enough to be considered as a negligible factor error ($\sigma_{\Delta\nu/\nu} \approx 10^{-9}$ per year leading to an error of 0.001 ppm). Laser nonlinearity and cosine error are repeatable errors. If one is interested only by highly repeatable displacements, these errors could be irrelevant. In other cases, there exist several methods for measuring and compensating laser nonlinearity to a sub-nanometric level. These include the use of a reference interferometer in combination with a mechanical magnification [5, 6], piezoelectric translators with integral capacitance measurement [7], measurement of the amplitude modulation of the heterodyne beat signal [8] and the technique of pressure scanning [9]. We use the classical method of autocollimation to minimize the cosine error. In our system, the reference and measurement beams are aligned within 2 arcmin. The maximum cosine error was therefore no greater than 0.17 ppm. A very efficiently autocollimation method based on scanning the retroreflection from the interferometer is described in [10].

We also estimate the long term drift of the optoelectronic circuit. The specific system which realizes the phase-shifts has been made with positive emitter coupled logic technology more suitable for our application because of their long term phase stability. Furthermore, the primary clock of 10 MHz used to generate all the useful signals is an ultra-stable quartz oscillator with a long term unstability lower than 10^{-9} in relative value for hours. All the systems have been tested for days and estimated with standard Allan variance [11] and we can assume that long term unstability of the optoelectronics is negligible ($\sigma_y < 10^{-9}$ for one day).

In some applications, it may be interesting to have high velocity displacements. The velocity of the target mirror is linked to the frequency of the phase-shifts f_c by $V = f_c \times \Delta x$. For a velocity higher than 1 mm s^{-1}, one needs inhibition rate up to tens of kilohertz. Metastability effects in flip-flop

[4] More details about ZMI2001 interferometers could be found in the website www.zygo.com.

could induce gap or double phase-shifts[5]. We verified that only one phase-shift occurs for each pulse of the command inhibition signal. For this purpose, a specific test bench has been developed. The phase-shifts are generated at a frequency f_c on the s_1 signal. This one is measured during few hours with a frequency counter (53132A, Helwett Packard). All the systems are synchronized using the ultrastable frequency quartz oscillator of the counter ($\sigma_y < 5 \times 10^{-10}$ for 1 s to 1000 s). The signal s_1 is phase-shifted with steps of $2\pi/32$ so its frequency is equal to $f_{S_1} = 20\,\text{MHz} - f_c/32$. For example, if $f_c = 32\,000$ Hz, the frequency of s_1 is equal exactly to 19.999 000 MHz. The frequency counter HP53132A can be configured with ten significant digits. We have verified for a large range of f_c (up to 10 MHz) that there is strictly no missing or additional phase-shift. The same verification has been done for the signal s_2. In a second time, the mixing signal s_m is tested. The beat frequency is measured and its stability expressed in terms of Allan standard deviation ($\sigma_y < 10^{-9}$ for hours).

5. Conclusion

We have developed a home-made electronic board associated with a heterodyne interferometer which allows us to control the displacement of a piezoelectric actuator at a sub-nanometric level. Some outstanding points of our method have to be noted. Firstly, it permits to achieve a high level of repeatability. It assures the traceability of the measurement as the nominal frequency laser is one of those recommended by the Comité International des Poids et Mesures to define the Mètre. Furthermore, the nonlinearity of the piezoelectric actuator and the mechanical defects of the holding sample are not relevant. This work is a part of an integrated project in Nanoscience field. The aim of this project is to control the displacement of the holding sample of the near field probe microscope over a millimeter course and with an uncertainty of 1 nm. For this purpose, we plan to use the method presented in this paper in a dual-level translation stage composed with an air-bearing long range translation stage and a piezoelectric actuator. This work is in closed collaboration with the University of Technology of Troyes (LNIO) and the CEA (LTM)[6].

Acknowledgments

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[6] LNIO : Laboratoire des Nanotechnologies et d'Instrumentation Optique, www-lnio.utt.fr - LTM: Laboratoire des Technologies de la Microélectronique.

Queries

(1) Author: Please provide page numbers in reference [11].