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OPTICAL PHASE CONTROL FOR INTERFEROMETRIC NEAR-FIELD OPTICS APPLICATIONS

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Optical phase control for interferometric Near-Field optics applications

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Abstract.

The interest for studying metallic nanostructures is increasingly attracting to the scientific community. Integrating a near-field microscopy in an heterodyne interferometer, the dynamic properties of light propagation in such structures can be visualize. This project aims to redesign the position control of the mirror used for the delay line in an heterodyne interferometer. We explain the strategy used to built-up the delay-line. We present the results of simulation of the dynamical response and the real implementation.

Keywords. Near-field optics, heterodyne interferometer, photon scanning tunneling microscope, nano-scale positioning

1. Introduction and Heterodyne Optical Near Field Microscopy

Optical studies of metal nanostructures which have intriguing properties due their nanoscale engineering want to be done. Scanning Near-Field Microscopy is a powerful tool to study such structures [1]. It consists of a nanometric optical probe scanning slowly the surface of the sample of study [2]. If the probe is only few nanometers far for the sample, the signal detected is mainly due to evanescent waves allowing sub-wavelength spatial resolution [3]. Although diffraction limit is overcome, this method of optical investigation suffers from it slowness (to build a complete picture, the probe has to scan pixel by pixel the surface of the sample) and makes almost impossible dynamical studies.

Nevertheless, when the scanning near field microscope is integrated into a Mach-Zender interferometer, interesting dynamical response of the propagation of light at the surface of these structures can be measured [4]. At ICFO, a photon scanning tunneling microscope (PSTM) combine with an heterodyne interferometer has been built-up. This set up enables measuring the local near-field optical amplitude and phase allowing a full characterization of the optical field, light propagation and interactions [5].

Figure 1 shows the basic scheme of this microscope. Light coming from a laser source system is split by a beam splitter in two branches. The first branch, which is

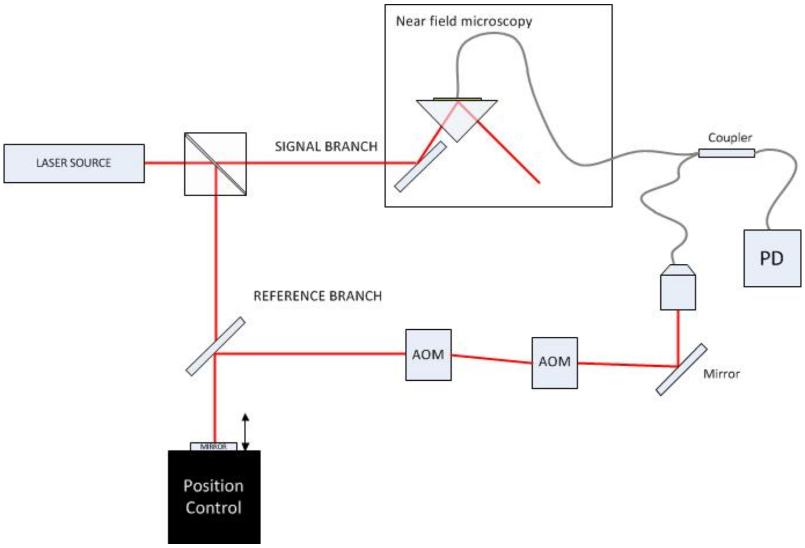


Figure 1. Experimental set-up of a heterodyne interferometer with a PSTM

called the signal branch, contains the Near-Field Microscope with the sample placed. Under special conditions, evanescent fields of the structure of interest are generated. This field is picked up by an optical probe which is usually an optical fiber tapered at one of its end in a sharp tip (50 nm). The reference branch is compound by two acousto-optic modulators and an optical delay line based on a mirror controlled in position. The two acousto-optic modulators shift slightly the frequency of the optical signal (40 kHz) for the heterodyne detection.

The delay line allows a fine tuning of the difference optical path between the two branches. The two signals (signal branch and reference branch) area recombined through an optical fiber coupler and optical intensity is directly measured with a photodetector and demodulated using a Lock-In amplifier performing the heterodyne detection. Local phase and amplitude of the optical signal picked by the optical probe are then retrieved.

To study the temporal optical response of nanostructures, femtoseconds lasers are used to measure phenomenon of picosecond or subpicosecond time scales [6]. The configuration of heterodyne photon tunneling microscope is well adapted to retrieve optical response at this speed. By changing gradually the optical path in the reference branch, we shift in the time domain the arrival time of the pulses coming from the reference branch and the signal branch. For example a change of 300nm in the reference branch length, makes a time shift of 1 femtosecond $(\frac{300nm}{3*10^{18}})$. As a result, the measurement of intercorrelation of the local response of the nanostructure with the incident pulse and the reference pulse at the femto-second scale is possible [7]. This demands a precise and an absolute control of the position of the mirror used for the delay line.

My work at ICFO had as main objective to redesign the electronic part of the mirror control. The existing electronics was implemented with technology of the 90s and needed to be renewed with a modern programmable controller system. After explaining the strategy used to built the delay-line, I will present results of simulations of the dynamical response of the complete feedback loop including all physical elements taking place in the mirror positioning control . I will then present the real implementation using a real time control and data acquisition system called ADwin. I will finally show the performances of the new implementation.

2. Strategy

Due to the necessity of using femtoseconds pulses a nanometric control of the mirror in the delay line is needed. We would need to control this positioning over large distances (few milimeters) in order to:

- find precisely where the optical path between the two branches are equal by scanning the mirror position over few centimeters,
- be able to study time response at the picosecond time scale
- measure the propagation of light on structures of few milimeters length.

Figure 2 shows the mechanical elements of the delay line.

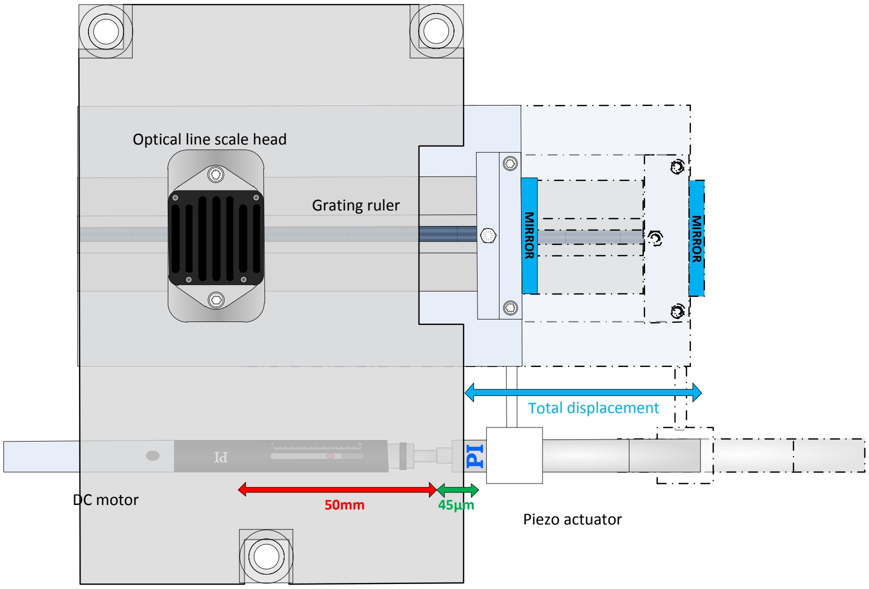


Figure 2. Mechanical elements of the delay line

The mirror is mounted on a movable grating rule. The motion is achieved through a M-227.50 DC-Mike High-Resolution Linear Actuator with a large range up to 50mm and a resolution of 100nm which will roughly set the position. To reach the nanometric resolution, we stack on the motor a piezoelectric stage from Physical Instruments with subnanometer resolution for positioning compensation.

The feedback position is read thanks to a Heidenhain LIP 372 Exposed Linear Encoder.

When moving, the mirror carries with him the scale rule with a periodic structure. An optical scale head fixed and placed over the scale rule measures steps of 0.001 m (1 nm). We obtain the total displacement by counting the individual increments read by the optical line scale head.

3. Simulation of the complete feedback loop

The figure 3 show the simulation of the complete set up for controlling the position of the mirror.

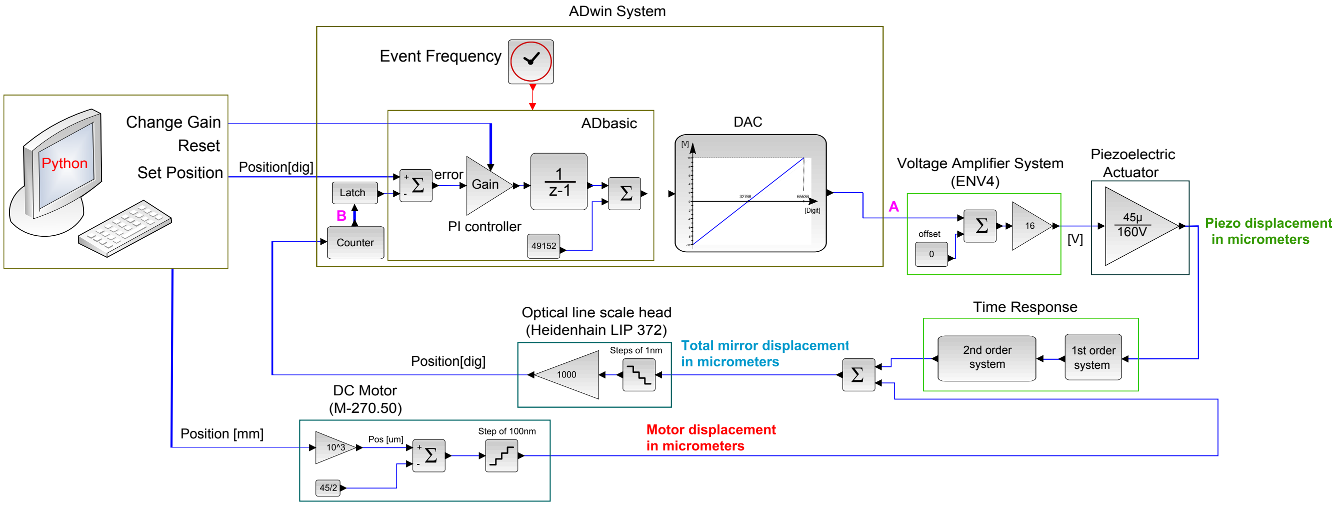


Figure 3. Simulation of the control of the mirror

This scheme shows the basic elements blocks involved on the mirror positioning:

- The first block is a computer, from where we set the mirror position and an additional parameters using two functions (change gain and reset).
- Next block is the core of the positioning control of the mirror. It is a digital PI controller. It purpose is to process the error signal providing a fast response for driving the piezoelectric actuator to the desired position (a 0 steady-state error). It has been implemented using the ADwin System. The ADwin System is a real time control and data acquisition system which has a dedicated processor, local memory and is equipped with analog and digital inputs and outputs. The ADwin system communicates with the computer via a Python interface. Having its own processor and memory it is able to work independently to the computer. If the computer crashes, the ADwin system will continue running, maintaining the control and collecting data.

The dedicated processor runs programs written with a language with a similar syntax to the Basic called ADbasic. For the control of the mirror position we wrote a program in ADbasic which calculates from the error signal the voltage to be applied to the piezoelctric actuator. This procces is refresh at a frequency called Event Frequency.

- The following block is a high voltage amplifier. In the experimental setup it has been used the Voltage Amplifier System ENV40 which amplifies low voltages from 0 to 10 to high voltages up to 160V.
- This high voltage drives the piezoelectric actuator used for the positioning control of the mirror. The piezoelectric actuator is from Physical Instruments and is controlled by voltages up to 160V providing a motion up to 45μm.
- The part of the scheme between A and B represent the displacement of the mirror in terms of counts measured by the head scale line when we applied a signal before the high voltage amplifier. It represent the cumulate time response of the high voltage amplifier, the piezoelectric actuator, the movable mechanical part where the mirror is fixed (see figure 2) and the line scale head.

  The frequency response between A and B was experimentally measured and is presented at figure 4 in dashed red trace. It represents the Bode diagram up to 500Hz with a resonance at 150Hz probably due to mechanical effects.

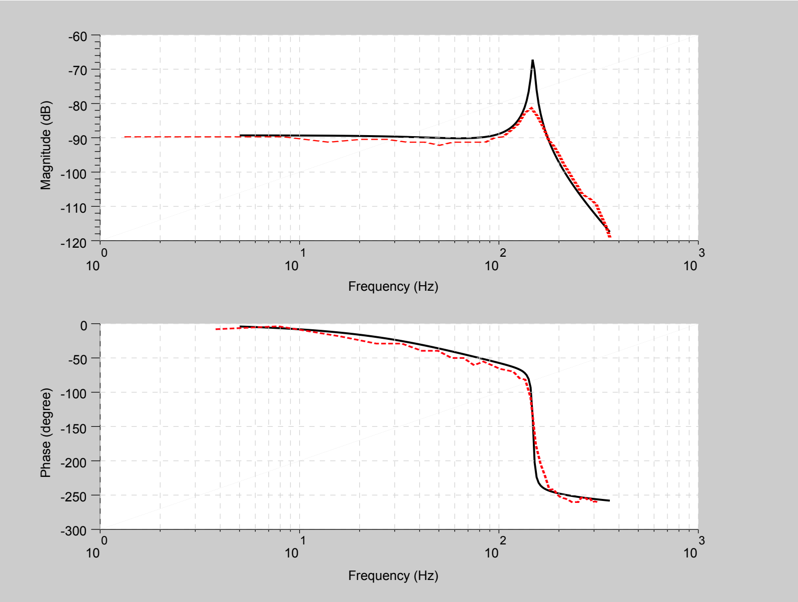


Figure 4. Bode plot of the open loop

Note that, if it exists a frequency in which there is a phase change of 180^o and a gain equal or bigger than unity, the close loop system can be unstable (Nyquist criteria). For example, an input sine wave, passing through the whole loop phaseout 180^o will be continuously amplified until saturation of the system. In fact, it is not necessary to deliberately introduce a sine wave for this to happen just internal noise is enough to obtain self oscillations.

In our case, a phase change of -180^o coincide with the mechanical resonance frequency making the close loop system critical at this frequency.

To model this behavior in our simulation, we add a new block called 'Time response' in the diagram, at figure 3. Accordingly to the previous experimental result we deduce the following transfer function:

$$T(s) = \frac{2\xi w_2}{(1+T_1 s)*(s^2+2\xi w_2 s+w_2^2)} \tag{1}$$

where the damping ratio $\xi = 0.016$, $T_1 = 1/w_1$, being $w_1 = 2\pi f_1$ with $f_1 = 70Hz$ and $w_2 = 2\pi f_2$ with $f_2 = 148Hz$. It is a 1^{st} order followed by a 2^{nd} order system and it is draw at figure 4 in a continuous black trace. We observe a good agreement between the experimental bode diagram and the one of the proposed transfer function.

- The next block is the mirror positioning detector.

  We have used the Heidenhain LIP 372 Exposed Linear Encoder, previously described in figure 2, which is an incremental linear encoder with very high accuracy. An optical scale head mounted over a fixed scale rule measures steps of $0.001\mu m$. The optical head read the individual increments obtaining the absolute position of the mirror.

  The optical head delivers 2 TTL squared-wave pulse trains phase-shifted by 90^o being the distance between two successive edges one measuring step.
- Finally, the last block is the large range actuator, up to 50mm. It has been implemented with the DC Mike M270.50 motor which have a 100nm resolution. The position of the mirror is the sum of the piezo length and the motor position.

Before starting with the physical implementation, it was necessary to simulate the behavior of the close loop to avoid any damage of the equipment of the setup. According to the scheme on figure 3 the two parameters we can change are the gain and frequency event.

We start with a low gain (0.01) and increase it step by step to avoid any self oscillations of the system. To prevent aliasing problems, analog filters are commonly used to filter the high frequencies before being sampled. In our case, the output signal is hold between two sampling times, making a natural low pass filter for the rest of the system. The event frequency should be below the frequency which has a phase change of 180^o to avoid any instability. The figure 4 shows that this frequency is around 150Hz.

At figure 5, we represent the error signal of the process at two different frequencies events and the same gain (0.4). In part (a) the frequency event is 50Hz, smaller than 150Hz so that the system is stable, by contrast, in part (b), the frequency event is 500Hz, the system let the high frequencies through and shows instabilities in the error signal. This shows that sampling at high frequencies is not always the best choice.

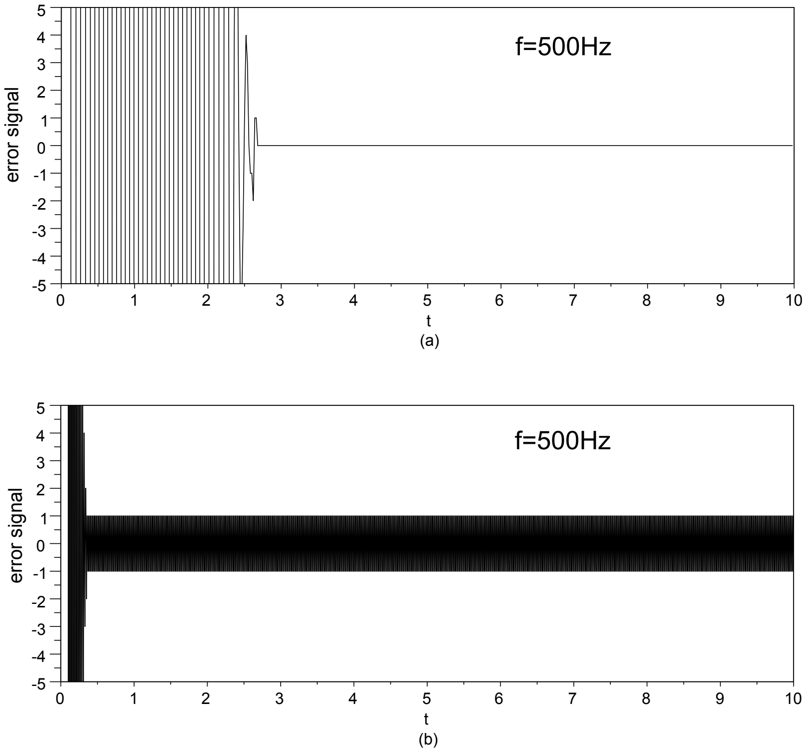


Figure 5. Simulation of the error signal with (a) frequency event 50Hz and (b) frequency event 500Hz

4. Implementation of the complete feedback loop

The program runs by the processor of the ADwin System is writen in ADbasic. The program I did to control the mirror is separated in 3 main sections:

- Configuration of the counter for counting the steps detected by the line scale head. The counter of the ADwin has been configured in Four Edge Evaluation mode, which determines the clock and direction of the 2 TTL signals incoming from the scanning head. The counter incorporates a latch for reading the actual value without perturbing the counts of the counter. Reading the counter the real position of the mirror can be obtained with high precision in a 32-bit value.
- The PI controller.
  Once we have both, the real position measured by the optical head line scale and the set position define by the computer, we subtract them to obtain the error value. A PI controller is a proportional gain in parallel with an integrator. In our case, we multiply the error value by a gain and replace the integrator with a simple discrete sum in order to emulate a analog PI controller.
- User Interface functions.
  To be able to change easily parameters of the controller an user interface with three different function has been built:
  Set Position - For setting the desired position of the mirror.

Table 1. Response of the system for a $Gain = -0.2$

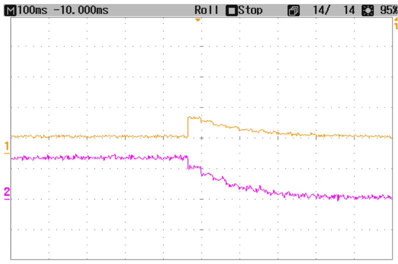
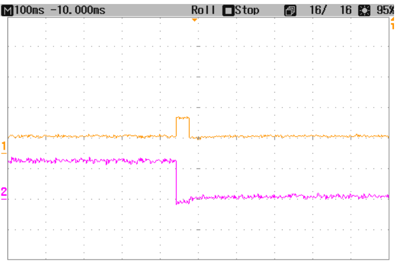
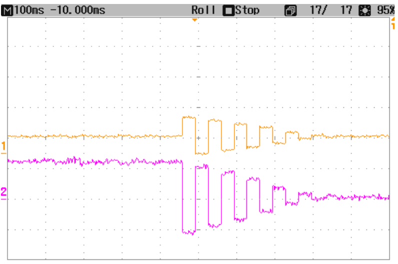
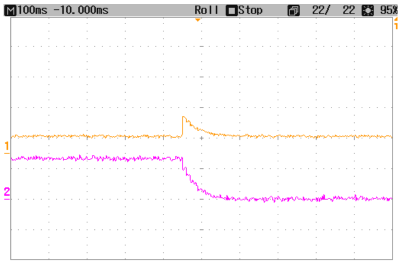
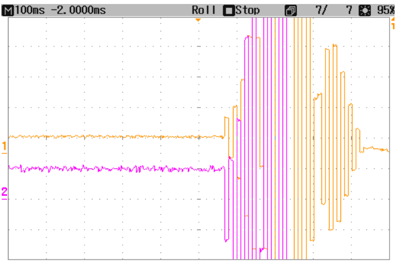
$f_1 = 30Hz$	$f_2 = 70Hz$	$f_3 = 100Hz$
		
$\tau < 250ms$	$\tau < 60ms$	$\tau < 400ms$

Table 2. Response of the system for a $Gain = -1.5$

$f_1 = 30Hz$	$f_2 = 70Hz$	$f_3 = 100Hz$
		
$\tau < 80ms$	$\tau < 40ms$	Instable

Change Gain - Which change the gain of the PI controller.
Reset - For Reseting the counter and send the mirror to 0 position.

As it has been mentioned before important parameters to take into account are the frequency event and the gain. The choice of the frequency event set the cut-off frequency of a low pass filter acting as anti-aliasing.The choice of the gain is a compromise between a fast response and high stability.

In order to see how the system response several test against change of gain and frequency event have been performed. To carry out the experiment at first the piezo is set at his middle position and at a given time we send a signal with the Python interface to move it by 100nm. The tables 1 and 2 show the time evolution of the error signal (orange trace) and output voltage applied to the piezoelectric actuator before amplification (pink trace). We reproduce the same experiment for three different frequency event (30, 70 and 100Hz) and two different gain (0.2 and 1.5). We estimate the rising time τ for each realization of the experiment.

The results present our expectations, the rising time decreases while increasing the gain and the system becomes instable when the event frequency became closer to 150Hz (the frequency which has a phase change of 180^o in open loop, see figure 4).

We observe a rising time of less than 50ms and the fluctuations on the pink trace represent less than 10nm of the mirror position In For our applications in Near-Field optics at ICFO those values are small enough.

5. Conclusion

The heterodyne interferometer used in this thesis allow phase sensitive and time-resolved near field measurements. We have show the implementation of the control position at nanometric scale of a mirror. This control is able to response to an order for changing the position is less than 50ms. We also achieved fluctuations smaller than 10nm.

The used of a anti aliasing filter will allow the system been faster. In this setup this idea was not implemented owing to the fact that the event frequency acts as the cut-off frequency of an anti aliasing filter.

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