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► **To cite this version:**

Ahmad Sinno, Pascal Ruaux, Luc Chassagne, Suat Topçu, Yasser Alayli, et al.. Large area sample holder unit for enhanced near field microscopy applications. ISOT 2007 International Symposium on Optomechatronic Technologies, 2007, Lausanne, Switzerland. pp.67160E-67169E, 10.1117/12.754194 . hal-01212817

**HAL Id: hal-01212817**

**<https://hal.science/hal-01212817>**

Submitted on 7 Oct 2015

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# Large area sample holder unit for enhanced near field microscopy applications

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## ABSTRACT

Near-field microscopy applications sometimes require scanning the sample over the millimetre range. This paper describes a home-made displacement system that can replace the limited range XY scanner of a classical near-field microscope. The system lays on a coarse/fine displacements configuration to attain the millimetre. Nanometre scale repeatability and resolution are met thanks to a control loop based on phase shifting techniques. The system was tested under an Atomic Force Microscope. The setup of the experiments and the results obtained are herein presented.

**Keywords:** Dimensional nanometrology, long range of travel, laser interferometer, closed loop control, near-field microscopy sample-holder, high resolution displacement system.

## 1. INTRODUCTION

Mapping the properties of a macro system to the nanometre world is currently the area of study for a lot of industries. Nevertheless, many research institutes are seeking to push the limits of the nanometre to a larger scope [1]. Imaging small objects at a large scale is one of the obstacles nanometrology faces today. State of the art Scanning Probe Microscopes (SPMs) have an imaging area of about a hundred micrometres. This is mainly due to the limited range integrated scanner. Piezoelectric actuators, in addition to presenting nonlinearity defects, do not allow millimetre scans. Furthermore, commercial displacement systems that attain the millimetre do not achieve the desired nanometre repeatability and accuracy. Yet, many applications require scanning the sample over the millimetre range: Near field characterization of optical integrated structures, electronic lithography for designing highly resolved patterns, and microelectronics for example. Scanning optical integrated structures with a combined Atomic Force Microscope (AFM) and a Scanning Near Field Optical Microscope (SNOM) may reveal internal losses of the light that is propagating along the waveguides of the structure. Thus investigating a waveguide along its light propagation axis turns out to be necessary [2-3]. Such a waveguide sometimes spreads over a millimetre and even centimetre long. Electronic lithography using a Scanning Electron Microscope (SEM) often shows degraded resolutions due to the positioning system that does not manage to accurately stitch the sample [4]. This causes the operator to widen the pattern after the sample is moved. High resolution versus a reduced image size is what traditional Atomic Force Microscopes (AFMs) offer. The number of pixels or data points that can be acquired per a line of scan is usually limited to 1024 whatever the size of the image is [5]. If a full range image is needed, the operator will find the resolution reduced. For a 100  $\mu\text{m}$  square scan for example, the resolution is found to be around 100 nm square per pixel. An alternative solution that allows to overcome this limitation and even to cross the 100  $\mu\text{m}$  range barrier is stitching [3]. Stitching is a time consuming technique during which the surface of the sample is partitioned into small scan areas imaged each apart and then stitched together. These elementary scans called windows must overlap to allow accurately match the overlapping sections afterwards. Therefore, a sample surface that is not perfect is needed in order to facilitate the matching process by means of image recognition techniques. This makes the stitching technique not always applicable: firstly when the surface of the sample does not show distinguishable topography patterns, and secondly when the measurement parameters such as temperature are time dependent. Moreover, traceability in addition to accuracy is sometimes hard to ensure. Accreditation institutes are currently developing displacement and measurement systems. This is the case of Metrological Atomic Force Microscopes (MAFM) used as reference machines for characterizing and standardizing samples [6-12].

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These often suffer bad repeatability and accuracy due to the defects of their displacement system. Moreover, Coordinate Measuring Machines (CMM) are intended to make measurements over a large scale. However, the highest resolution ever reached for a 1 mm x 100  $\mu\text{m}$  scan is 100 nm [13].

We present a 2D displacement system with a 2-stage configuration to attain the millimetre range. The first stage performs coarse displacements while the second rectifies the defects of the first stage. The system is used as a sample holder as it was integrated into an Atomic Force Microscope to allow scans beyond the microscope's scanning area limit.

## 2. EXPERIMENTAL SETUP

### 2.1 Sketch of the system

The system developed is a Sample Holder Unit (SHU) that can be integrated to most of current commercial near-field microscopes. To achieve this, the SHU performs 2D lateral displacements relative to a fixed microscope's tip while carrying a sample (Fig. 1). Scans are carried out on a coarse and fine displacements basis. Two stages are used for each displacement axis. As a coarse stage, the SHU integrates two millimetre range motorized tables, Aerotech ANT50 [14], that allow a resolution of 10 nm and speeds up to 2 mm/s over 50 mm with a straightness of 1  $\mu\text{m}$ . The fine stage comprises a 2D piezoelectric actuator (PZT), PiezoSystem Jena, used for accurate positioning thanks to its sub-nanometric resolution and high bandwidth. Two laser interferometers, Zygo ZMI2001 [15], permit real time position sensing with a resolution of 0.31 nm. The laser source is a frequency stabilized HeNe laser [15] that ensures measurements traceable to the Metre. A Zerodur mirror cube acting as a moving mirror for the laser interferometers is placed on top of the displacement stages. This cube carries the sample to scan on its top face. A home made high frequency electronic board ensures the nanometre performances [16]. The board can in fact order PZT displacement steps resolved at 0.26 nm [17]. It also allows locking the system in its position thanks to a servo loop controller associated to a Phase Locked Loop (PLL) scheme. The electronic board uses phase shifting techniques which allow nanometric resolution and repeatability. The integrity of the system is controlled through a Labview interface.

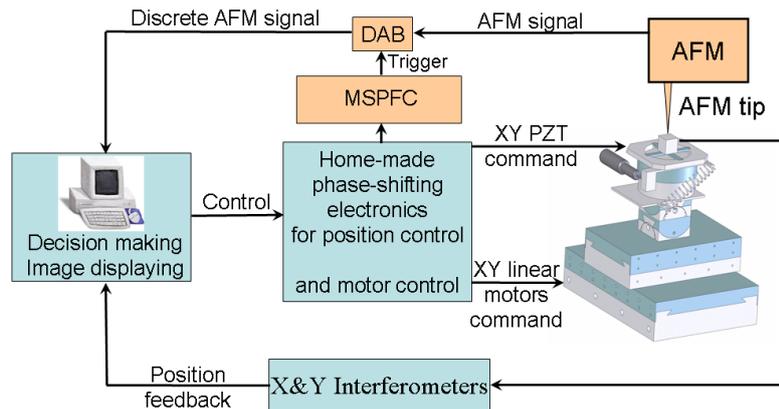


Fig. 1. Bloc diagram of the system. It shows the displacement system serving as a 2D scanner under an Atomic Force Microscope (AFM). The displacement system comprises 2 linear motors to execute coarse moves, and a 2D piezoelectric actuator for precise positioning. Two laser interferometers monitor the X and Y positions which are fed back to a computer for control. The computer processes the information and sends the necessary control commands to a homemade optoelectronic board able to accurately control the position of the XY PZT actuators, and to the controller of the linear motors for long range motion control. Simultaneously, a Motion Synchronized Pulse Firing Controller (MSPFC) senses the displacements. It allows acquiring the AFM signal (topography signal) synchronously with the lateral displacements using a Data Acquisition Board (DAB).

## 2.2 AFM integration

To allow topography imaging, the SHU was integrated to an Atomic Force Microscope (AFM). For this, an AFM (APHB-0100 Park Scientific Instruments) was placed above the SHU in such a way the tip of the microscope can sense the sample surface (Fig. 2). The XY PZT actuators of the microscope were inhibited. The SHU ensures the lateral displacements on a line per line basis. The SHU does not integrate z-axis control. It is the AFM that handles the force feedback loop for z-position sensing and imaging.

The microscope presents a major limitation: the number of data points acquired at each line of scan is limited to 1024. This yields to an image of 100  $\mu\text{m}$  square resolved at 100 nm per pixel. The SHU operates over a millimetre range. A resulting resolution of 1  $\mu\text{m}$  per pixel would then not be suitable. For this, we shunted the acquisition module of the AFM and a Labview Real Time based data acquisition board (NI PCI 6221) took hand over the acquisition. The aim is to have a resolution that is not correlated to the size of the image. The 16-bit registers of the acquisition board and its high sampling frequency (up to 100 KHz) agree with the desired resolution and ensure handling the high flow of data when the SHU runs at high speeds. The board acquires a signal that is proportional to the elongation of the Z piezoelectric actuator, that is, the topography signal.

The acquisition of the topography signal is synchronized with the displacements of the SHU. A Motion Synchronized Pulse Firing Controller (MSPFC) ensures this job. Each time the SHU steps, the MSPFC triggers an acquisition point. The MSPFC sampling signals are derived from signals of the optical encoders of the coarse stage and internal signals of the PLL control board.

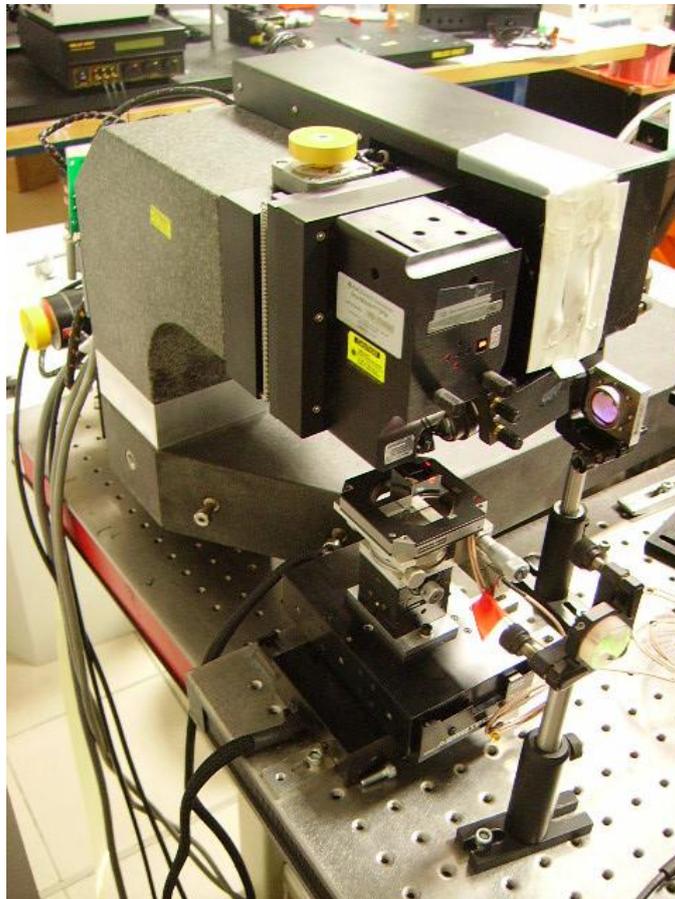


Fig 2. Top view photography showing the displacement and imaging systems: we can see the mirror cube which is positioned on top of the displacement system, the AFM with its head that was turned, and the X and Y reference mirrors. The sample to scan is placed on the top of the mirror cube allowing the tip of the microscope sense its surface. The whole is placed on an active anti-vibration table thus decoupling external noise.

### 2.3 Principle of the control loop

The displacements of the sample holder are based on double stage actuators: the linear motors and the piezoelectric actuators. These stages cooperate together to explore the surface of the sample. In fact, it is the PZT stage that rectifies the defects encountered by the motors along the path. The motors have mainly straightness defects. However, the PZT itself presents some limitations due to intrinsic defects such as hysteresis. For this, an upper control layer was introduced to help the PZT actuator track the desired path. The interferometers observe the position along both X and Y axes.

The control loop is based on a Phase Locked Loop (PLL) scheme. The interferometers deliver at their output a phase modulated position signal. We designed a high frequency optoelectronic board that controls the phase of the position signal with respect to a reference signal in order to control the position [17]. If the PZT actuators are to be moved, the position signal is phase-shifted with respect to the reference signal. If the PZT actuators are to be held at a specific position, the phase of the position signal is locked on that of the reference signal. This phase locking based principle ensures repeatable and highly resolved displacements. The optoelectronic board uses ultra-high stability and high frequency integrated circuits. The position resolution can be programmed down to 0.26 nm.

Contrarily to classical model-based control schemes [18], this PLL control loop tries to track the desired path by locking to a reference signal. No PZT model is needed. This has the advantage that the control loop bypasses any change that arises on the PZT behaviour. Consequently, the PZT actuator does not have to be calibrated previous to operation.

Another advantage is that the PLL is hardware implemented in the optoelectronic board. This may be advantageous when the SHU runs at a high speed; the bandwidth lays on the effectiveness of the servo loop controller that is implemented. A software control loop would require some processing time which could be limiting.

### 2.4 Mechanical adjustments

The SHU ensures long range displacements by stacking two stages: the coarse stage and the fine stage. Above these, the Zerodur mirror cube stands as a moving mirror for the laser interferometers. These three stages must have their axes aligned (Fig. 3); measurement errors might be encountered otherwise. These axes are the axes of the linear motors ( $X_m, Y_m$ ), the axes of the piezoelectric actuators ( $X_p, Y_p$ ) and the axes of the optical beams of the laser interferometers ( $X_o, Y_o$ ). For this to be achieved, three tilt adjustment elements are inserted (Fig. 4) in order to ensure three degrees of freedom (3-DOF) according to the yaw, pitch and roll angles.

Furthermore as a 2D system, the SHU requires its axes to be orthogonal [19]. For this, the axes of the motors were aligned with an uncertainty of 5 arcsec. The mirror cube has its faces orthogonal at 1 arcsec.

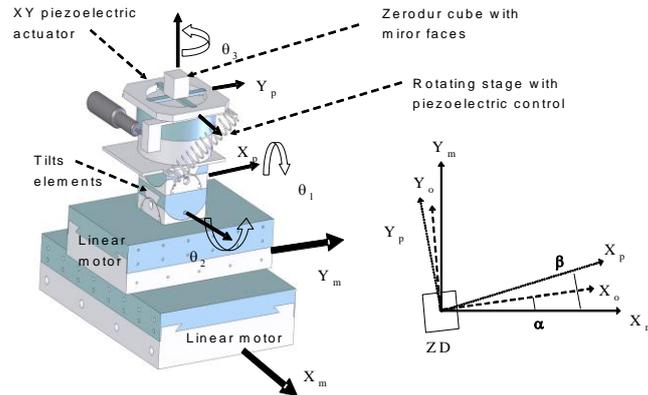


Fig. 3. (Left) this figure shows the Computer Aided Design of the SHU and highlights its degrees of freedom. The linear motors' axes ( $X_m, Y_m$ ), the 2D piezoelectric actuator's axes ( $X_p, Y_p$ ), and the optical axes ( $X_o, Y_o$ ) are to be aligned (forcing  $\alpha=\beta=0$ ). This can be achieved thanks to tilt and rotation adjustment elements. These allow adjusting the pitch, roll and yaw angles denoted  $\theta_1, \theta_2$  and  $\theta_3$ . (Right) ZD stands for the Zerodur mirror cube.

All these alignments are necessary before operating the SHU. The SHU is in fact operating over a range of one millimetre which magnifies any residual mechanical misalignment. Any remaining misalignment is processed online using the closed loop control as long as the misalignment remains below the range of the PZT actuator.

Another constraint to deal with is the parallelism between the upper surface of the sample and the displacement plane of the stages. Such a tilt misleads to an artefact on the resulting image giving the impression that the upper face of the sample is tilted with respect to its bottom face. Moreover, this tilt will make the Z-PZT actuator of the AFM contract/retract to track the surface of the sample. When scanning over a millimetre range, the Z actuator might not have enough range to recover the tilt, which might cause the AFM tip to unlock.

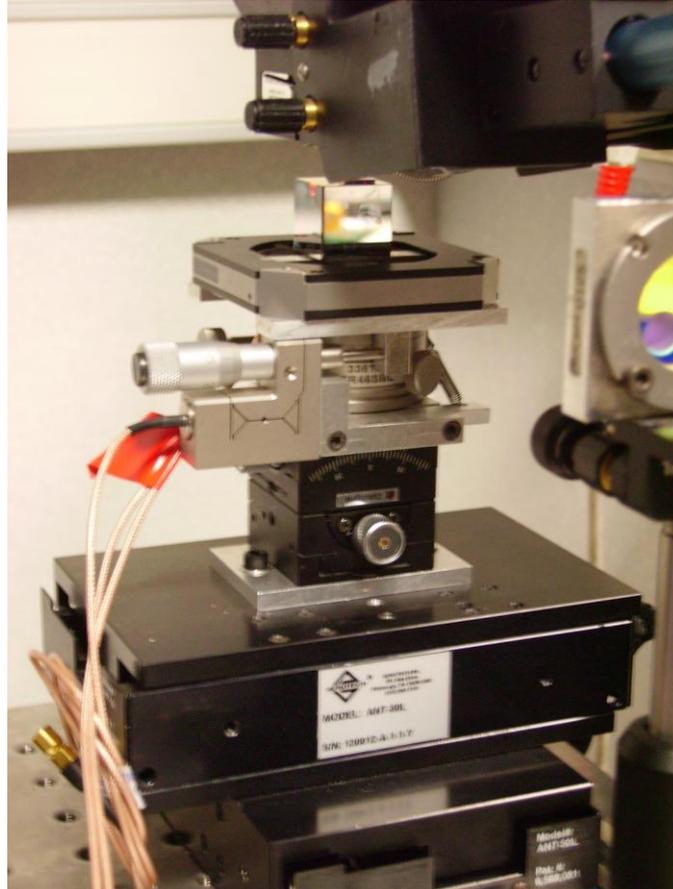


Fig. 4. Photography of the displacement system. It shows (bottom to up): the X and Y long range linear motors, the pitch and roll adjustment elements, the yaw adjustment element, the XY PZT actuator, and the mirror cube that moves with respect to the reference mirrors of the interferometers. Note also the head of the microscope that holds the tip and that is kept close to the top face of the mirror cube where the sample is placed.

## 2.5 Environment supervision

Besides mechanical adjustments that are critical in a multi-stage millimetre range scanner, care should be taken for the surrounding environment. Thermal drift will act to expand the metrological chain of the system. This chain includes the body of the microscope in addition to the multi-stacked elements of the SHU. A thermal expansion of any of the mechanical parts will be rectified by the servo control loops, leading to an artefact. For this, the mechanical parts of the system are made of low expansion coefficient materials. In addition to this, temperature of the room is controlled, and the system is turned on several hours previous to operation for heat up. Temperature control is also required to prevent any drift on the laser measurements [20].

Furthermore, the interferometers used feature immunity to refractive index gradients due to their Differential Plane Mirror Interferometer [21] configuration in which both arms of the interferometer are aligned. In addition to this, a small distance (1 cm) separates the optical beams of each of the interferometers. The reference mirrors and the moving mirror cube are kept close to each other to reduce any effect of the surrounding environment.

As for vibrations, the SHU and the microscope lay on an active anti-vibration table that attenuates external noise.

### **3. MEASUREMENTS AND DISCUSSIONS**

#### **3.1 Parameters of the experiment**

We chose to image a highly integrated silicon-on-insulator (SOI) substrate. The sample features waveguides on its surface. The waveguides are parallel but irregularly distanced. Their height is around 160 nm and their width 2.8  $\mu\text{m}$ . The sample was placed on the top face of the mirror cube, and then the tip of the AFM approached. The AFM was operating in tapping mode. A speed of scan of 40  $\mu\text{m}\cdot\text{s}^{-1}$  was chosen. The SHU allows higher speeds but the microscope's operation regulations prohibit excessive speeds. The temperature of the room was controlled to prevent the limited range Z scanner (around 7  $\mu\text{m}$ ) from saturating. These 7  $\mu\text{m}$  must be enough to handle thermal drifts over time, pitch and roll misalignments over the millimetre scanning range, in addition to abrupt tip overshoots in case the tip encounters high topography patterns. Instead of normal operation of the microscope where the Z actuator is centred, we chose to bias the actuator so it can operate over its full range (from -3.5 to +3.5  $\mu\text{m}$ ) rather half its range.

#### **3.2 Results for long topography imaging**

The image presented in Fig. 5 is 1 mm long and 725 nm wide. The long scan axis is labelled Y while X is used for the short scan axis. So the SHU was travelling perpendicularly to the waveguides along the Y axis, and then changing lines. The resolutions used are 20 nm along Y and 25 nm along X, so 29 lines were achieved. The number of data points acquired is then 29 times 50000. At a speed of 40  $\mu\text{m}\cdot\text{s}^{-1}$ , each line took 25 seconds to be scanned; the whole image took around 25 minutes due to the repositioning process when the SHU was changing lines.

Figure 5 is a raw image displayed using Matlab. It presents progressive shading off colours meaning that it is not perfectly horizontal. The image spreads from negative values of the topography signal (due to biasing the actuator) till positive values. The image is in fact tilted due to different probable factors. Firstly, although regulated, the temperature may have altered which may have caused a thermal drift on the resulting image due to the long measurement duration of 25 minutes. This tilt appears along the short scan axis X. Secondly, the pitch and roll angles were adjusted at best in order to prevent the Z scanner from saturating along a tilted surface. However, we had no means to measure the absolute tilt with respect to a zero reference. This tilt appears along the long scan axis Y. Thirdly, this tilt may also be due to the sample itself which may have been tilted during fabrication (sample's upper and lower faces not parallel).

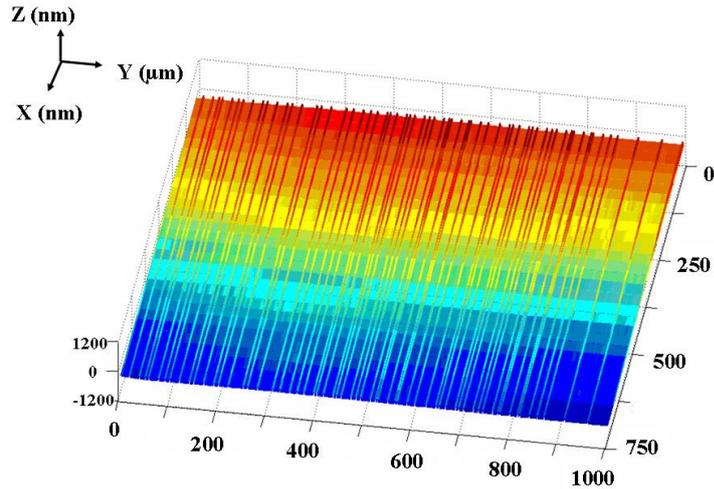


Fig. 5. 3D Atomic Force Microscope topography of a substrate comprising on its surface a set of parallel but unequally distanced waveguides. The waveguides spread along the X axis. The image is 1 mm long and 750 nm wide. Shading off colours reflect the fact that the image is tilted. This tilt is greater along X than it is along Y. This is because the SHU spent more time to travel along X than it did along Y (temperature effect).

For an in-depth view, a cross section is pointed out on Fig. 6. This figure shows a line travelled by the SHU along the long scan axis Y, that is, temperature had a minor effect on the tilt of this figure. It is the misalignment errors (pitch misalignment) that induced this tilt of around 1.5 μm.

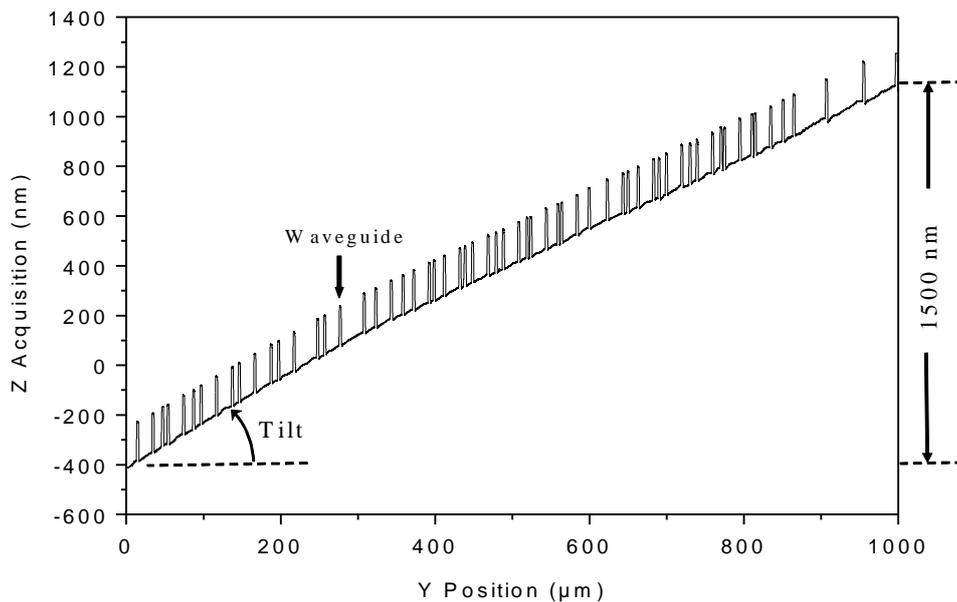


Fig. 6. Cross section of the previous image showing one of its lines along Y. A tilt appears meaning that the surface of the sample was not perfectly parallel to the plane of motion of the SHU. This made the piezoelectric actuator of the microscope contract of about 1500 nm when the SHU was moving forward (positive Y direction), and then retract of

the same amount during the backward motion. A larger tilt or a longer move along Y would cause the tip of the AFM to unlock if the tilt exceeds the range of the Z actuator.

Fig. 7 shows the rectified cross section. This figure reveals more information: it presents an un-straight profile which means that the surface of the sample is wavy. On the hand, some peaks appear on the lower right part of each waveguide. These are overshoots that may be due to abrupt tip-sample interactions which may themselves be due to scanning at a relatively high lateral speed of  $40 \mu\text{m}\cdot\text{s}^{-1}$ .

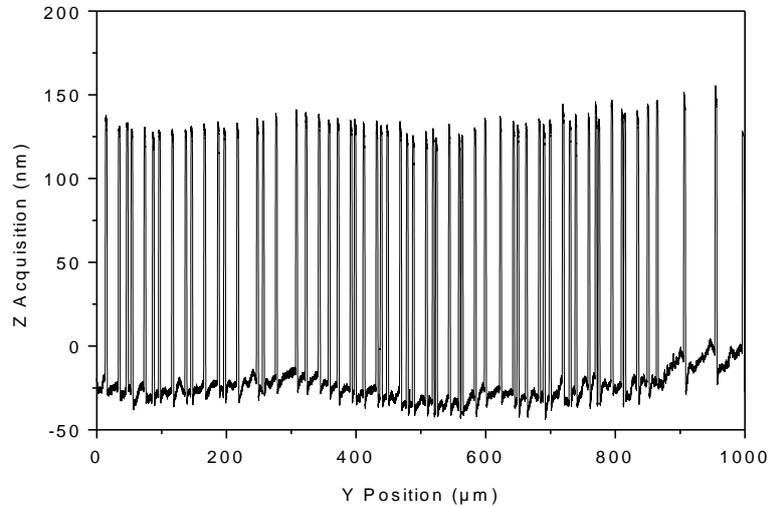


Fig. 7. Rectified cross section along the Y axis; the tilt was subtracted for better understanding the topography encountered by the SHU as it travelled along the long scan axis. Note the different scales used for the axes of this figure. This makes the waveguides seem distorted and appear that high. The figure reveals two properties: overshoots and waviness. Overshoots appear at the right bottom of each waveguide, and may be due to abrupt tip-sample interactions. On the other hand, the cross section has a non straight profile meaning that the surface of the sample is wavy.

Fig. 8 shows a zoom of a single waveguide around the Y position  $217 \mu\text{m}$ . The figure shows that the resolution is far higher from the dimensions of the waveguide. The dimensions of the waveguide can be measured on this cross section. The  $157 \text{ nm}$  height and  $2.85 \mu\text{m}$  width are compatible with those expected.

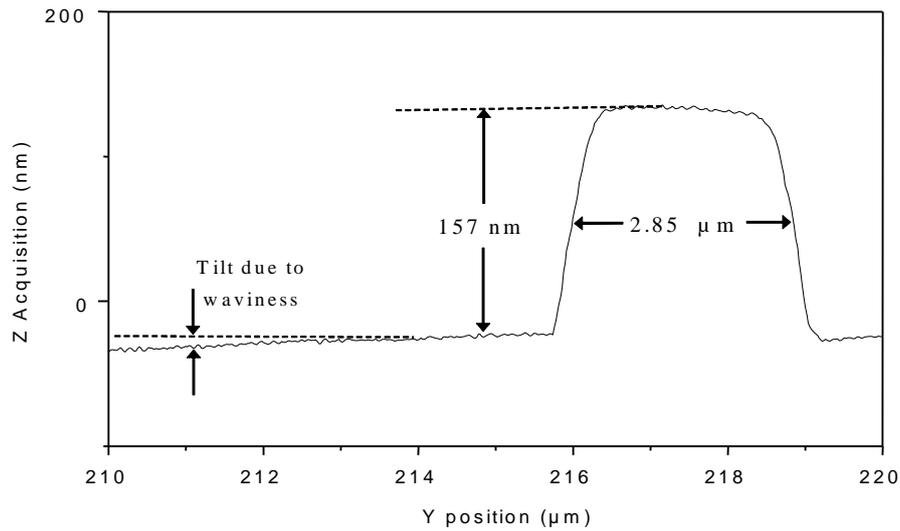


Fig. 8. Zoom of fig. 7. At this scale, the dimensions of a single waveguide were attained. The  $2.85 \mu\text{m}$  width and  $157 \text{ nm}$  height agree with those expected. This figure reveals the exact profile of a waveguide without having to scan once again as is the case with classical microscopes.

These consecutive zooms show one of the advantages of the SHU: no need to scan once again in order to zoom; the entire information can be retrieved from the original image. With a classical AFM, it would have been necessary to scan once again for a zoom. Moreover, the original image and its zooms have the same resolution because the resolution is dissociated from the size of the image. Large images can be achieved with resolutions not accessible with a classical microscope.

### 3.3 Discussions

We reported the results of a millimetre long scan achieved under an Atomic Force Microscope. The width of the image is  $725 \text{ nm}$ , limited by the range of the AFM actuator ( $Z$  axis actuator). In fact, the image presents a tilt that occupies the full range of the actuator. For wider scans, this tilt has to be better controlled. This can be done by better controlling the temperature in addition to finely aligning the surface of the sample with respect to the moving stages. Moreover, temperature control would offer more accurate measurements. Furthermore, the SHU does not integrate  $Z$  displacements. This causes the measurements to be limited by the range of the  $Z$  actuator of the AFM. A  $Z$  control shall help the SHU adapt to large altitude variations.

The SHU was integrated in this experimentation to an AFM but it may be integrated to other Scanning Probe Microscopes like the Scanning Near Field Optical Microscope (SNOM) for near field characterization of optical integrated structures.

## ACKNOWLEDGMENTS

The authors are grateful towards Mr. E. Oseret from the Laboratoire de Parallélisme, Réseaux, Systèmes, et Modélisation (PRiSM) for his useful discussions about handling high density images, and would like to thank Mr. P. Juncar from the LNME (Laboratoire National de métrologie et d'Essais) for his collaboration in dimensional metrology. This project is co-funded by the French Government (ACI Nanosciences) and by the Ile-de-France region.

## REFERENCES

1. St. Fahlbusch, S. Mazerolle, J-M. Breguet, A. Steinecker, J. Agnus, R. Pérez, J. Michler, "Nanomanipulation in a scanning electron microscope", *Journal of Materials Processing technology* 167, 371-382 (2005)
2. R. Bachelot, G. Lerondel, S. Blaize, S. Aubert, A. Bruyant, And P. Royer, "Probing Photonic and Optoelectronic Structures by Apertureless Scanning Near-Field Optical Microscopy", *Microscopy Research And Technique* 64, 441-452 (2004)
3. S. Blaize, S. Aubert, A. Bruyant, R. Bachelot, G. Lerondel, P. Royer, J.E. Broquin, V. Minier, "Apertureless scanning near-field optical microscopy for ion exchange channel waveguide characterization", *Journal of microscopy*, vol.209, n° 1-4, p. 588-593 (2003)
4. P. Rai-Choudhury, *SPIE Handbook of Microlithography, Micromachining and Microfabrication*, volume 1, 1997
5. Pacific Nanotechnology Inc., Nano-R atomic force microscope specifications, <http://www.pacificnanotech.com/nano-r-spm.html>
6. C-W Lee, S-W Kim, "An ultraprecision stage for alignment of wafers in advanced microlithography", *Precision Engineering* 21:113-122 (1997)
7. J. Schneir, T.H. McWaid, J. Alexander, and B.P. Wilfley, "Design of an atomic force microscope with interferometric position control", *J. Vac. Sci. Technol. B.* 12(6), 3561-3566 (1994)
8. M. Bienias, S.Gao, K. Hasche, R. Seemann, and K. Thiele, "A metrological scanning force microscope used for coating thickness and other topographical measurements", *Appl. Phys. A* 66, 837-842 (1998)
9. G.B. Picotto and M. Pisani, "A sample scanning system with nanometric accuracy for quantitative SPM measurements", *Ultramicroscopy* 86, 247-254 (2001)
10. S. Gonda, T. Doi, T. Kurosawa, Y. Tanimura, N. Hisata, T. Yamagishi, H. Fujimoto and H. Yukawa, "Real-time, interferometrically measuring atomic force microscope for direct calibration of standard", *Rev. Sci. Instrum.* 70 (8), 3362-3368 (1999)
11. J. Haycocks and K. Jackson, "A metrological atomic force microscope for calibration of transfer standards", in *Proc. Of the 2nd Euspen Conference*, Turin, Italy, May 27th-31st (2001) pp. 392-395
12. K. R. Koops, and K. Dirscherl, "Nanometrology standards in the Netherlands: the traceable scanning probe microscope", in *Proc. of 3rd Euspen Conference*, Eindhoven, the Netherlands (2002), pp. 525-528
13. G. Wilkening, L. Koenders, *Nanoscale Calibration Standards and Methods*, Ed. Wiley-vch, ISBN n°3-527-40505-X (2005)
14. Aerotech corporation, <http://www.aerotech.com>
15. Zygo corporation, <http://www.zygo.com>
16. S. Topçu, L. Chassagne, D. Haddad, Y. Alayli, P. Juncar, "Heterodyne interferometric technique for displacement control at sub-nanometric scale", *Rev. Sci. Instrum.*, Vol 74, n°11, pp4875-4880 (2003)
17. L. Chassagne, S. Topcu, Y. Alayli, P. Juncar, "Highly accurate positioning control method for piezoelectric actuators based on phase-shifting optoelectronics", *Meas. Sci. Technol.* 16 No 9, 1771-1777 (2005)
18. K. Dirscherl, "online correction of scanning probe microscopes", Ph.D. thesis, Technical University of Denmark, Lyngby, 2000
19. N. Bobroff, "Critical alignment in plane mirror interferometry", *Prec Eng.* 15(1), 33-38 (1993)
20. F.C. Demarest, "High resolution, high speed, low data age uncertainty, heterodyne displacement measuring interferometer electronics", *Meas. Sci. Technol.* 9, 1024-1030 (1998)
21. DPMI Accessory Operating Manual OMP-0223E, Zygo 2002