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Dedicated to Prof. Ioan-Iovitz Popescu's 75th Anniversary

To Sir, with love

NANOMETROLOGY OF MICROSYSTEMS: INTERFEROMETRY

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Abstract. The future of microelectronics and nanotechnology are intimately tied together. The smallest feature size (CD) is already below 50 nm. Many scientists in the field of nano- sciences are reporting < 1 nm accuracy in their experiments, which is suspiciously good. The reason is probably the general confusion between resolution and accuracy. No commercial instruments have yet nanometer accuracy but there are many having 0.1 nm resolution. The International Technology Roadmap for Semiconductors projects that in 15 years the smallest feature size will be < 10 nm, meaning we can measure it. This is the reason why we must pay a very special attention to the calibration process of the instruments we use. Accurate and traceable calibration of lateral and vertical standards (1D and 2D gratings) is a basic metrological task for nano-metrology. For this reason, the interferometric methods for artifact calibration are reviewed in this paper.

Key words: traceability, nanometrology, interferometry.

1. INTRODUCTION

Metrology is concerned with measurement at the highest level of accuracy. Advances in metrology depend on many factors: improvements in scientific and technical knowledge, instrumentation quality, and, since metrology makes a high impact on the overall quality of industrial products, they depend also on the level of demands from industry.

Is there meaning in talking about the *nanometrology* of *microsystems* today? We believe the answer is affirmative for the following reasons:

1. In order to measure microsystems dimensions with an accuracy better than 1 μm is needed;
2. Microsystems exists already in mass production and their widespread use demands imperatively interchangeability of the components;
3. Nano-sciences applications ranging from condensed matter physics to biology raise concerns regarding their ability to measure at the nano-scale;

4. Nanotechnologies are on the verge of a new industrial revolution spinning off many emergent sciences, technologies and industries;

5. The progress in miniaturization leads to increasing requirements for quality assurance;

The most commonly used microsystems are the MEMS, micro-electro-mechanical systems and MOEMS, micro-optical-electro-mechanical systems. Areas of metrology of particular interest for MEMS fabrication are about length: dimensions, roughness, step height measurement. The accepted tools in nano-science and nanotechnologies are scanning probe microscopes (SPM) [1, 2] [atomic force microscope (AFM) [3–5], white light interferometers (Linnik [6], Mirau [7, 8], Michelson [9, 10]), scanning electron microscope (SEM) [11], scanning near field optical microscope [12, 13]]. Optical profiling proved to be a versatile measurement technology for MEMS development and for control over novel silicon micromachining processes. Non-contact by nature and with scale capability ranging from nanometers to millimeters, optical profiling stands as a valuable measurement technique for MEMS characterization.

The instruments mentioned above are observing, not metrological devices. Their resolution, also known as sensitivity, the smallest change in a measured value that the instrument can detect, is very good, and they are usually nanometer sensitive. For an instrument to be metrological it must be traceable. More than that, the balance sheet of the inevitable strengths and weaknesses of each tool is favorable to optical instruments. Optical interferometers require skilled installation, calibration, and operation but they achieve accurate measurements in the nano-meter domain. Contact profile-meters lack sensitivity at the nanometer scale, while AFMs suffer stability issues with their piezoelectric probes. Profile-meters and AFM transducers with good stability do not have the sensitivity to observe a nanometer, and transducers with good sensitivity are not stable enough for reliable and usable measurements[14, 15]. Overall the optical instruments are preferable for calibration and characterization purposes.

2. LENGTH-MEASURING LASER INTERFEROMETRY

Traceability [16, 17] refers to the completeness of the information about every step in a process chain. The term traceability is used in metrology to refer to an unbroken chain of measurements relating an instrument’s measurements to a known standard. Traceability can be used to certify an instrument’s accuracy relative to a known standard. In nanometrology the main quantity is the length and the corresponding standard is the **meter**.

The definition of the **meter**, according to BIPM, in the International System of Units (SI), since 1983, is the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second [18]. The definition sets the speed of light at c_0 = 299,792,458 m/s. The definition connects the meter to the second. For a practical definition of the unit of length any of the three following approaches may be used:

1: the length L of the path traveled by light in a measured time t is given by $L = c_0 t$;

2: the wavelength of light of measured frequency f in vacuum is given by $\lambda = c_0/f$;

3: the vacuum wavelengths of a number of standard reference radiations have internationally accepted values, determined from frequency measurements (see Table 1) [19].

Table 1

High precision value of standardized wavelengths

Spectral domain	green	red	infrared
Wavelength [nm]	543.515077	633.96139822	780.24629163

Optical interferometry has been a classical method in metrology, commonly used for measuring and testing with micrometer accuracy. An interferometer system measures the change in distance by counting the number of wavelengths of light seen by detection optics. As the wavelength is known with great accuracy, then the overall distance can be calculated with great accuracy too.

Table 2

Interferometers used in nanometrology

Interferometer type	**Measurand**
Michelson, Mirau, Linnik	micro-profile, roughness
Fizeau	flatness
Smart	front shape, aberrations
shear speckle pattern interferometer	stress gradients
Moiré interferometry	shape
phase-shift interferometry	shape
white light interferometry	roughness, micro-geometry, shape
Twyman-Green	length
Murty (lateral shear interferometry)	stress gradients
holographic interferometer	shape, mechanical constants (Poisson, Young modulus), vibration amplitude and mode pattern.
speckle pattern interferometer	vibration measurements and testing
absolute length-measuring interferometer	length
multiple-wavelength interferometry	length, expansion coefficient

In nanometrology too optical interferometry is a main tool for measurement and testing, but in order to increase the sensitivity and accuracy, one uses phase-shift interferometry or multiple wavelength interferometry and, of course, advanced digital means for detection and information processing. In any case the accuracy of length or wavelength measurement depends on how accurate one can determine the fringe structure and position [20–24]. The laser interferometer is the *de facto* length scale.

A two-beam interferometer works by dividing a coherent light beam into two beams of equal intensity, directing one beam onto the reference mirror and the other onto the specimen, and measuring the optical path difference (the difference in optical distances) between the resulting two reflected light waves. In order to implement this method, various instrument types have been devised, employing several devices to split the light wave and to ensure the appropriate optical paths, many of them being listed in Table 2.

3. CALIBRATION

The *measurement* process consists in associating a number to a quantity by comparing it to the standard for the quantity. *Accuracy* is the degree to which the values given by an instrument match the true values. In the case of length measurement the standard is the ***meter***. Oftentimes in practice one uses a substitute for the standard in the measurement process. Measurement accuracy is critical at the microscopic scale. Traceable / metrological instruments for nanometrology are very expensive and generally they cannot be found on the market. As dimensional tolerances for such applications as semiconductors and optical discs get tighter, the need for precision length standards at the nanometer length scales becomes more important. They require periodic calibration to produce accurate results. *Calibration* is the process of checking and correcting the performance of a measuring instrument or a specimen against the accepted standard. An instrument or specimen of unknown accuracy is compared to an instrument or artifact of known accuracy, corrections are applied and the instrument becomes metrological and the specimen becomes artifact. *Calibration specimens or artifacts* with feature sizes or positions directly traceable to international length standards are key tools for obtaining accurate and reliable results.

Finally we must admit that measuring a nanometer is quite a task and to realize such a measurement is a demanding activity even with a very good instrument. On the other side, good instruments may be misused or underused.

The sophisticated tools used to measure these features, tools such as AFMs, WLIs, SNOMs, SPMs, require periodic calibration to produce accurate results. Metrologic tools, such as optical interferometers, constitute an essential element needed by these applications, and they become critically important as the miniaturization process reaches the atomic scale.

4. VERTICAL CALIBRATION / HEIGHT MEASUREMENT

4.1. THE MIRAU INTERFEROMETER

Vertical standards, such as step height or depth setting standards, are utilized to calibrate the *z*-axis of SPM. However, prior to use, these standards have to be calibrated traceably by metrological instruments. Vertical scanning interferometer is a digital interferometer that vertically scans through focus. The fringe modulation corresponding to each plane of focus is recorded by the detector and transferred to the system's computer. Computerized calculations demodulate the peak. Interference signals determine the Optical Path Difference (OPD), and subsequently, the surface heights (see Fig. 1).

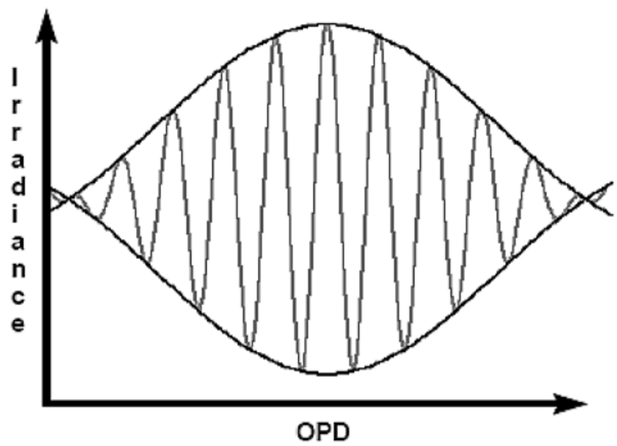


Fig. 1 – Irradiance at a single sample point as the sample is translated through focus.

In Fig. 2 is shown a simplified schematic of a coherence peak sensing interference microscope. The configuration shown in Fig. 1 utilizes a two-beam Mirau interferometer at the microscope objective. Typically the Mirau interferometer is

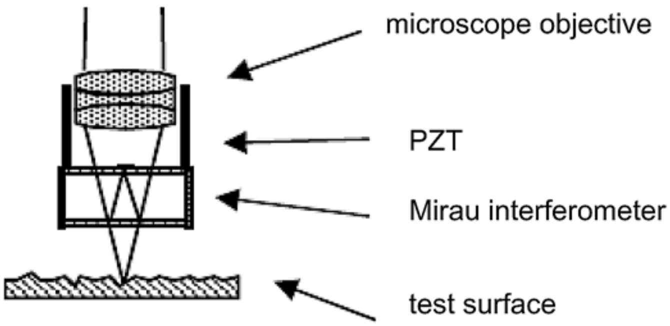


Fig. 2 – Schematic of a coherence peak sensing interference microscope.

used for magnifications between 10X and 50X, a Michelson interferometer is used for low magnifications, and the Linnik interferometer is used for high magnifications. A separate magnification selector is placed between the microscope objective and the CCD camera to provide additional image magnifications. A tungsten halogen lamp is used as the light source. Light reflected from the test surface interferes with light reflected from the reference. The resulting interference pattern is imaged in the plane of the CCD array. Also, the digital output of the CCD array is fed to the computer. The Mirau interferometer is mounted on either a piezoelectric transducer (PZT) or a motorized stage for controlled axial translation. During the translation the distance from the lens to the reference surface remains constant. Thus, a phase shift is introduced in one arm of the interferometer. By introducing a phase shift in only one arm while recording the interference pattern that is produced, one can perform either phase-shifting interferometry or vertical scanning coherence peak sensing interferometry.

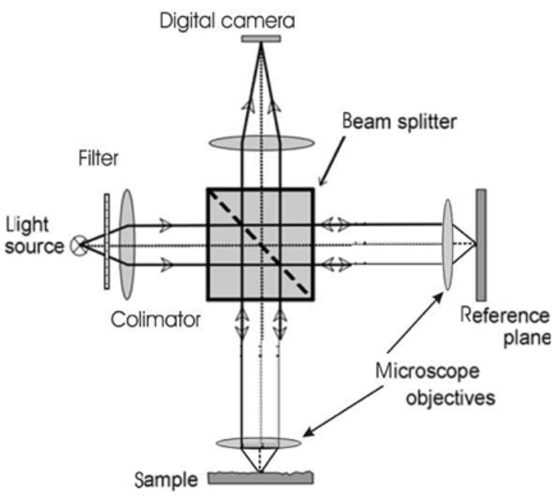
The Mirau interference objective is an interference objective of comparatively high magnification (10X, 20X or 40X) used in instruments produced by the Nikon Corporation. The principle of the device, as illustrated in Fig. 2, relies on placing a reflection reference mirror in the center of the objective lens, and interposing a half mirror between the objective lens and the specimen. These components are so arranged that an interference pattern will appear if the system is focused upon the specimen. The fringe modulation corresponding to each plane of focus is recorded by the detector and transferred to the system's computer. Computerized calculations demodulate the peak Interference signals to determine the optical path difference (OPD), and subsequently, the surface heights.

Optical coherence tomography – topography (OCT) is a measurement method based on the interference of low-coherence light waves. Within the past several years OCT has been developed into a powerful diagnostic tool, providing a spatial resolution as fine as a few micrometers, especially in the fields of biology and medicine and in particular in ophthalmology. Possible configurations include Linnik, Fizeau and Mirau interferometers. The conventional Mirau interferometer has the disadvantage of reduced working distance, which is due to the insertion of a beam splitter between the sample and the microscope objective. The Mirau interferometer has an advantage, however, in that it requires a small number of components and is highly insensitive to vibration. In a conventional Mirau interferometer the objective lens must have a long working distance to make room for the beam splitter. Measurement principle of an interferometer with a source of short coherence is used. Demodulation of the fringe signal leads to the coherence function. The peak of the function gives the measure of the surface height.

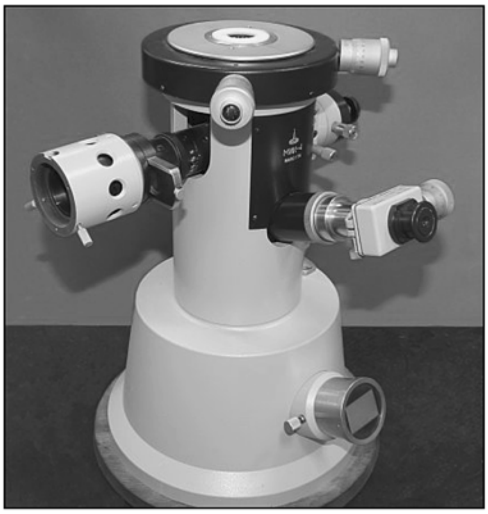
The advantage of white-light interferometry is that its broadband source removes the phase ambiguity problem experienced with laser interferometers.

4.2. THE LINNIK INTERFEROMETER

The Linnik interferometer we used had a high magnification (490) objective lens so that we could observe minute details. The experimental principle is that of the Michelson interferometer. Fig. 3 presents the basic arrangement, comprising a light source, a collimator, a beam-splitting prism, an eyepiece or CCD camera, uniform objective lenses with completely identical optical distances, a specimen surface which generates an image when illuminated, and a reference mirror which reflects the incident plane wave. Because identical, interchangeable objective lenses are difficult to manufacture, only a small number of such instruments have been marketed. Interference fringes are observed in the object plane following the geometry of the sample.



a)



b)

Fig. 3 – The Linnik interferometer: a) principle schematics; b) picture of an actual interferometer.

The height is measured in λ/2 units. White light fringes give the height's integer number of λ/2 units, while the monochromatic light fringes provide the fractional part. This measurement principle is illustrated in Fig. 4. Using white light we cannot assure the traceability of the measurement. The monochromaticity of the light is ensured by the use of 2 filters – red and green – of only 10 nm spectral widths.

White Light Interferometry (WLI) is a powerful technique for non-contact measurement of surface topography at high vertical and moderate lateral resolution. Almost any surface can be measured, even quite dark ones. A measurement is made in a few seconds.

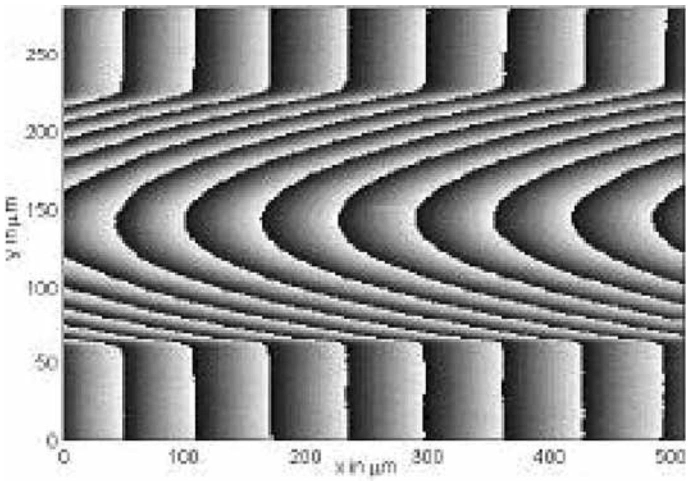


Fig. 5 – Another example of height measurement (step height measurement).

4.3. THE MICHELSON INTERFEROMETER

In this section we describe the peak fringe scanning microscopy principle. It measures, without contact and with high accuracy, the micro-relief of a surface and quantifies its roughness-undulation by means of a statistical analysis. The vertical nanometric displacement is controlled by computer and the interferometric data is automatically computed to render 3D imaging of the topography. With this technique a complete 3×2.5 mm can be taken in less than 30 seconds with very high resolution. The instrument can also be used to measure the thickness of translucent layers or films.

The detailed principle of operation is illustrated in Fig. 6. A beam splitter splits the beam emitted by the source (So) into two "half-beams". One half-beam is reflected on the reference mirror (M), the other on the sample (P). The beam splitter (Sp) transmits both reflected beams to the CCD camera (C) through the lens (L). The intensity $I(d)$ measured at the camera varies as a function of the path difference (d) between the beams 1 and 2. The $I(d)$ signal (fringes pattern (F)) is maximum for $d = 0$.

The method could be summarized by considering that the system generates a horizontal plane light-wave (P) that can be used as a probe. A vertical displacement in the z direction of the measured surface relief makes the latter cross up the probe plane. The successive intersections between the probe plane and the sample are the relief level curves (isophots). The acquisition system keeps the coordinates (x, y, z) of all the points belonging to every isophot and interpolates from one level curve.

The displacement of the measured surface along (Z) is servo-controlled by capacitive sensors. The principle of the capacitance-based technology, well known for its high accuracies, is the following: the measured capacity is conversely proportional to the desired distance. The positioning is better than 1 nm.

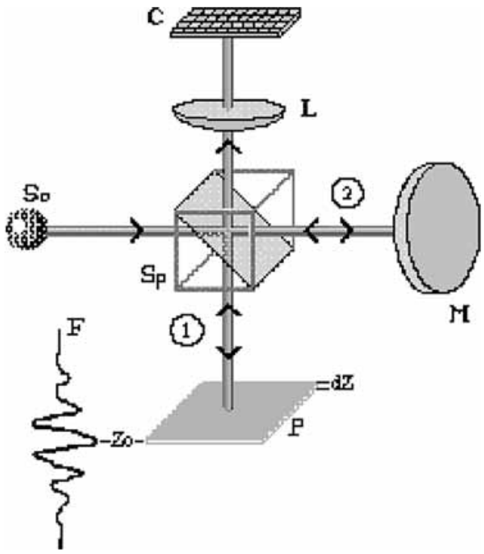


Fig. 6 – The working principle of a Michelson interferometer.

The CCD target (782×582 pixels) carries out simultaneously the measurement of all the points on the measured surface. There is no need to mechanical scanning along the *x* and *y* axes. This allows for small areas to be scanned with very high resolutions very quickly.

4.4. TOTAL INTERFERENCE CONTRAST MICROSCOPY

TIC, the abbreviation for Total Interference Contrast, denotes the new polarization/optical shearing micro-interferometer from Carl Zeiss (Fig. 7). Contrary to traditional polarization interferometers, work is carried out in circular polarized light and not in linear polarized light. This enables rotation of the TIC prism without alteration of the contrast of the interference pattern. There is no longer any need for stage rotation, which was necessary in conventional techniques, and specimen cohesion remains. This is of particular advantage for the imaging and measurement of specimen structures found in various directions. The differences in height in the specimen structures being analyzed are then determined directly from the optical path difference Δ or the displacement of the observed interference fringes in relation to the immediate environment, and can be calculated in accordance with Fig. 5 with the help of a simple formula:

$$d = \Delta/2n_u . \quad (1)$$

In general the layers are embedded in air (refractive index of the embedding medium $n_u = 1.0$), which means that Δ is exactly twice the layer thickness or the layer thickness d is equal to half the path difference.

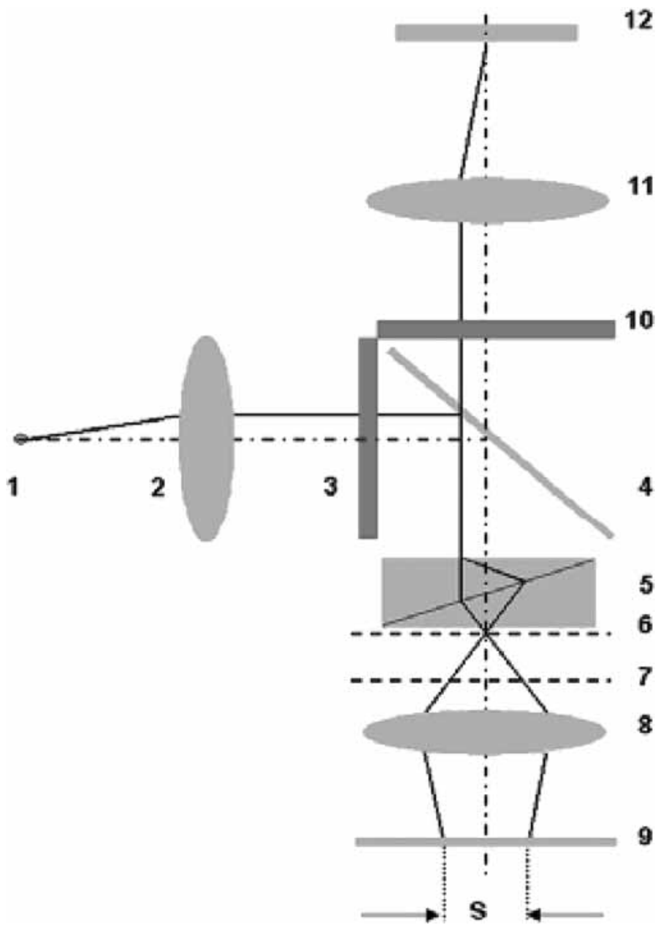


Fig. 7 – Schematic structure of the TIC shearing micro-interferometer.

In Fig. 7 the principle of the Carl Zeiss microscope TIC shearing micro-interferometer is illustrated. The light emitted from the light source 1 passes the collector 2 and is circularly polarized by the circular polarizer 3. The plane glass reflector 4 reflects the circular polarized light partly toward prism 5. This results in a shear s in the object plane 9, which is far greater than the resolution limit (because of the creation of a dual image split). The TIC prism 5 is dimensioned and arranged in such a way that the interference plane 6 does not coincide with the specimen exit pupil 7. This creates a dual pupil image and results in an interference fringe pattern in the field.

After reflection on the object, the two images, polarized at 90° with respect to each other, pass the lens 8 again, are reunited by the prism 5 and pass the circular analyzer 10. The resulting visible interference pattern is imaged through the tube lens 11 into the detector plane 12.

5. LATERAL CALIBRATION / 1D GRATING MEASUREMENT

Lateral standards such as 1D and 2D gratings are used as transfer standards for scanning probe microscopes to calibrate the magnification and to characterize the image distortions of the *xy*-plane of all kinds of microscopes. Vertical standards, such as step height or depth setting standards, are utilized to calibrate the *z*-axis of scanning probe microscopes (SPMs) and stylus profilometers. However, these standards have to be calibrated traceably and precisely by metrological instruments prior to usage.

There are a number of different *calibration standards* for SPM available on the market. Among the most widely used is the diffraction grating with a submicron pitch. A large number of periods have to be measured to get reasonable accuracy, which complicates the calibration procedure (see Fig. 8).

For grating pitch measurement we used the SIOS Interferometer shown in Fig. 9. SIOS is a precision laser interferometric length measurement instrument, equipped with triple-faceted retro-reflectors. The miniaturized sensor head and triple-faceted retro-reflector allow for an easy use and implementation of the

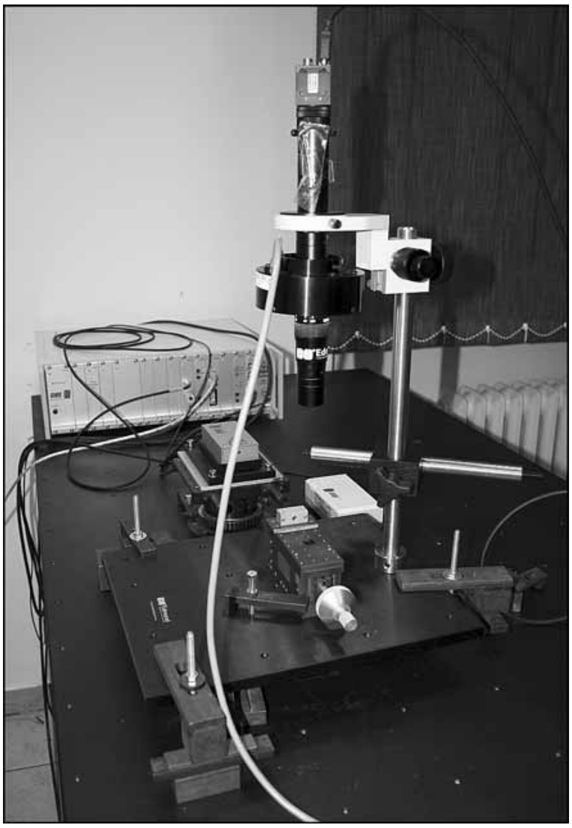


Fig. 9 – A SIOS interferometer comprising the mobile tri-faceted reflector, the power supply and processing units and the observation microscope.

interferometric metrological system. The miniature interferometer converts motions of the triple-faceted retro reflector into optical interference signals that are transmitted to the optoelectronic signal processing unit (Fig. 9) for conversion into lengths. A He-Ne laser serves as the light source for the miniature interferometer, and the fact that is frequency stabilized allows for a large dynamic range. Compensation of environmental influences form the basis for high metric precisions and are achieved through the correction of laser wavelengths.

Lateral calibration is achieved by measuring pitch of the grating. Many grating lines are included in a measuring range so the pitch value is a medium size. The gratings are visualized by an optical microscope while the grating is moved by a mechanical table from Luminous Instruments Ltd. with the retro-reflector on the table. The experimental results obtained using the SIOS interferometer are displayed as a statistical distribution in Fig. 10.

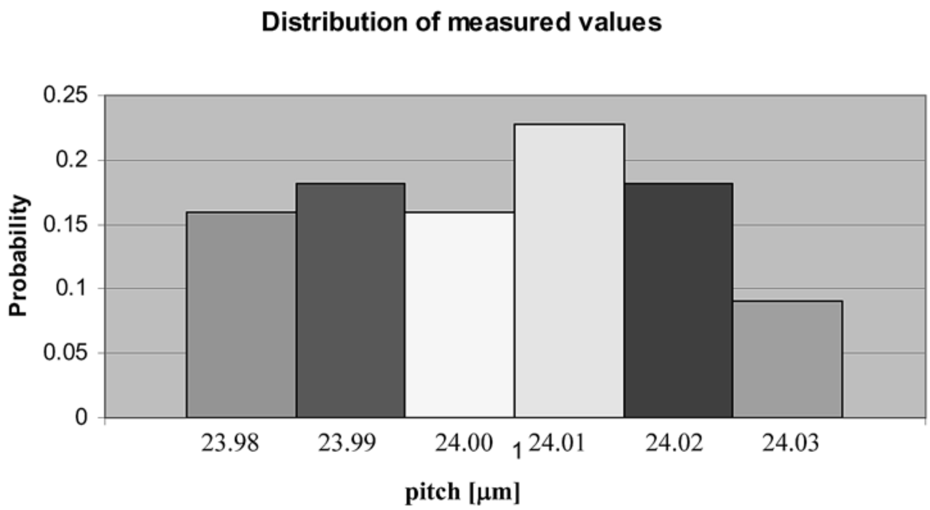


Fig. 10 – Distribution of measured pitch values obtained using the SIOS interferometer.

6. CONCLUSION

There are multiple measurement techniques for measuring length at the nanoscale. However, only the interferometric techniques are readily traceable and metrological. They can be used for the calibration of other measurement techniques, either for vertical or lateral calibration. The traceability of the interferometric length measurement techniques is due to the definition of the meter standard, connected to the frequency stabilized lasers. This occurrence makes the interferometric measurement techniques naturally traceable and metrological.

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