NEEDS AND ADVANCES IN METROLOGY FOR PRECISION MOTION CONTROL IN MECHATRONICS

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Abstract: Precision mechatronics are essential for the future manufacturing of nano devices and systems. Without accurate means to pattern, assemble, image and measure nano structures, we will be unable to meet the challenges of the next decade. In this paper we discuss the current state-of-the-art in metrology used for motion control systems and make suggestions regarding possible future technologies that might improve the situation. What is required is a method to reduce the errors in stage position measurement which is currently interferometric on most production machines. The limitations of this technology are discussed as well as an alternative of using nano gratings to replace the interferometry.

Keywords: heterodyne, interferometry, lithography, nano grids, nanotechnology

1. INTRODUCTION

Due, in a large part, to the National Nanotechnology Initiative in the U.S., there are a number of new and interesting results in nano scale science and engineering. We should note, however, that the government's primary interest in nanotechnology is the creation of jobs and other economic benefits, not new scientific results. It is our opinion that many of these results are unlikely to reach the factory floor unless there are advances in metrology and instrumentation for nanomanufacturing. One of us (Hocken) recently co-chaired a study effort that has led to a major publication on the needs and requirements for metrology and instrumentation in nanotechnology [1].

Of course, the nanotechnology era is really already upon us. Biological systems, catalysts, carbon nano tubes, etc., have been in the nanometer domain for decades. What has actually changed is our ability to engineer, image, and manipulate systems on the nano scale. There are really two approaches that are rapidly converging. The convergence is coming from the top and from the bottom simultaneously. As we learn to manipulate these atomic structures the semiconductor and optoelectronic and information technology-related industries are relentlessly shrinking devices. It is expected that this push will terminate near the 10 nm level in several decades. At the other end of the scale our ability to image, manipulate, and assemble individual atoms, molecules, and nano particles is moving from the old scales of organic and inorganic chemistry to scales in the 10- to 100-nm regime.

There is really a large number of new initiatives in industry, government, and academia around the world, and researchers are reporting many potentially useful devices and systems. For example, see Likharev [2]. Those of us who have been involved in manufacturing recognize that in order to successfully move these discoveries to the factory, manufacturing and metrological infrastructure needs to be developed.

We argue that a metrology infrastructure underpins all industrial revolutions and that nanotechnology is no exception [3]. For example, the industrial revolution, which began in the 19^{th} century and led to our modern mechanized society, required an easy to use system of accurate, interchangeable dimensional measurements. This primarily was provided by the gage block coupled with the micrometer and the vernier caliper [4].

Similarly, microelectronics, which began in the 1950s and is based around precision lithography, would not have been possible without a much more accurate length scale. This new length scale was based on a polarization-encoded, heterodyne laser interferometer system that allowed the transfer accuracy from masks to substrates to approach today's limits [5].

In several papers it has been pointed out that nanotechnology will require us to go well beyond the limits of current optical metrology. One of the earliest ones was by Teague [6] who pointed out the dimensional metrology in the picometer range would be essential for nanotechnology. This was also pointed out by Hocken [7]. Further, as will be discussed more later, in a paper entitled, "State-of-the-art and Ultimate Physical Limitations of Dimensional Metrology," Kunzmann [8] addressed the issues of dimensional metrology as they apply to manufacturing.

2. CURRENT METROLOGY LIMITATIONS

Modern ultra-precision manufacturing machines, such as lithography and metrology equipment, scanning electron microscopes, atomic force microscopes, nano imprint machines, CMMs, etc., depend on laser interferometers for measuring and controlling the relative motion of the stage supporting the sample or workpiece with respect to the probe or the image (see Fig. 1). For nanotechnology to succeed, these mechatronics tools will need significantly increased accuracy.

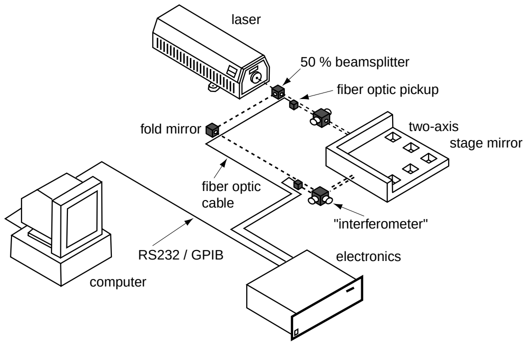


Figure 1. Typical substrate stage controlled by a laser interferometer. The biggest source of error in these systems is the atmosphere and the environment. Also, the heavy reference mirrors on the stage degrade its dynamic performance.

The best documented case is in the semiconductor manufacturing industry. Their transistor gate structures are well under 50 nm today and are predicted to shrink to 7 nm by 2018 [9]. Also, many other types of nano devices, such as quantum dots, etc., have even more stringent tolerance than the CMOS devices of the semiconductor industry. What is shown in Fig. 1 is an idealization of a two-axis, interferometrically-controlled positioning stage. Several current measuring machines also have three-axis stages of a similar design [10,11]. In most cases the interferometers themselves are operating in air and are of the type mentioned earlier, that is, polarization-encoded heterodyne systems. For these types of interferometers, the largest source of error is the atmosphere. Turbulence and fluctuations in the air temperature, pressure, and humidity cause errors. Even when the environment is well controlled, the absolute uncertainty of these measurements is approximately 5 parts in 10^8, as was pointed out in the 1980s [12]. The situation has not improved since then. If, however, measurements are made in a vacuum, considerably higher accuracies have been claimed [13]; however, intercomparisons at this level have never, to our knowledge, been performed.

In addition, commercial interferometers suffer from position-dependent geometric errors and a variety of optical and electronic non-linearities. The most common of these is called, "beam mixing." What this means is that some of the reference beam of the interferometer traverses the measurement path and some of the measurement beam traverses the measurement path. This leads to errors at the laser wavelength and sub-multiples thereof. A good example is given in the literature of an eight-pass heterodyne interferometer system used on the Sub-Atomic Measuring Machine [14]. This interferometer is shown in Fig. 2. When run at constant velocity the Fourier transform of the measurement signal, which should only have a single peak at the fringe-passing frequency, shows multiple error terms [15]. This spectrum is shown in Fig. 3. Note that the peaks representing the higher-order errors yield position dependent errors of approximately 1 nm. This fact, of course, has been noted by the manufacturers of these interferometers and methods for correcting them are being developed [16,17]. It is unlikely that such efforts will lead to picometer accuracy. Of course it is possible to build a heterodyne system without beam mixing. This is a peculiar property of the polarization-encoded systems which have dominated the commercial market. One of us (Hocken) built such a system in the early 1970s as part of his Ph.D. thesis. In such systems the frequency-shifted beams are often separated in space rather than by polarization. A new design was recently demonstrated at NIST where they developed a quadruple heterodyne Michelson interferometer [18]. This is not a commercial instrument and works in vacuum.

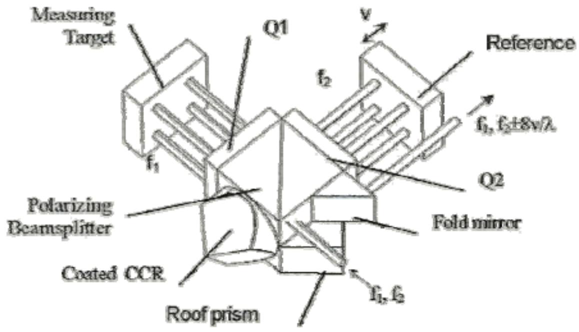


Figure 2. The Eight-pass interferometer which demonstrates the beam mixing shown in Fig. 3.

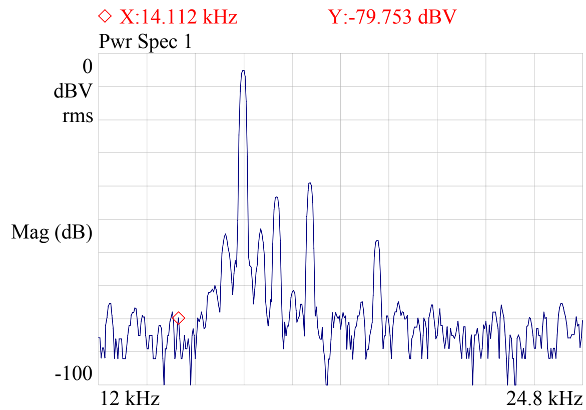


Figure 3. The Fourier transform of the interferometer signals running at constant velocity.
Without beam mixing there should be a single peak.

Perhaps more fundamentally the problem of using HeNe lasers for length standards is related to the size of the periodicity which can be used for counting purposes, namely, the wavelength of visible red light which is around 633 nm. For realizing the high accuracy that will be required for the devices of the future, that is, say 0.1 nm or smaller, this involves, in conventional interferometric configurations, splitting a fringe into many thousand parts. Such interpolation is error prone and often requires averaging, taking considerable time. What is really desired for the new length scales is some well-defined scale whose basic periodicity is many times smaller than that of visible light. Teague mentions two alternatives (see Ref. [6]), both of which have been explored for some years. The first is the x-ray interferometer (or diffractometer) originally proposed and demonstrated by Bonse and Hart [19]. Such instruments use the silicon lattice to provide a grating spacing and have periodicities near 0.2 nm. They have been used successfully in many experiments to determine crystal lattice spacings in terms of the optical wavelength and also to put the x-ray wavelength scale on the optical scale [20,21]. X-ray interferometers, however, are still very short range, though they have been used successfully to provide the length scale for scanning tunneling microscopes [22,23]. The second alternative suggested by Teague was a frequency-tracking Fabry-Pérot. Such instruments have been used for years for measuring the stability of materials (for example, see Patterson [24]). In recent years advances have been made at NIST in Fabry-Pérot interferometry. There a Fabry-Pérot interferometer for displacements up to 50 mm was developed [25]. In this instrument two adjacent modes of a Fabry-Pérot are used. The absolute optical frequencies of these modes and their difference are used to determine displacements as the cavity length is changed. This instrument, however, is also far from being commercialized and works in a vacuum. This may not be a problem for lithography in the extreme ultraviolet, where the working components of the lithography machine are in vacuum. Such a machine has been built by ASML and was described at a recent meeting of euspen [26]. It is difficult, however, for the authors to envision large numbers of machines working in vacuum because of the many problems such construction engenders.

3. GRATING DIMENSIONAL METROLOGY

Gratings of various sorts have long been rivals of laser interferometers for measurements of displacement on many types of precision inspection and manufacturing instruments. Although various manufacturers' scales work on slightly different physical principles, they have some features in common. Most grating-based measurement systems, also called optical encoders, consist of three parts: one, a fine-pitched grating or grid; two, a read-out sensor; and three, electronics. Such a system is schematicized in Fig. 4. The resolution of an encoder is dependent on the pitch of the grating and the interpolation provided by the sensor and electronics. While read-out electronics can easily achieve sub-nanometer resolution, accuracy is naturally quite different. High-frequency jitter and line position, noisy electronics, and just grating inaccuracy and distortion can degrade accuracy.

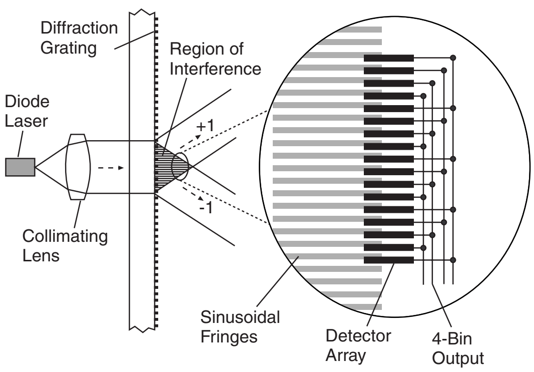
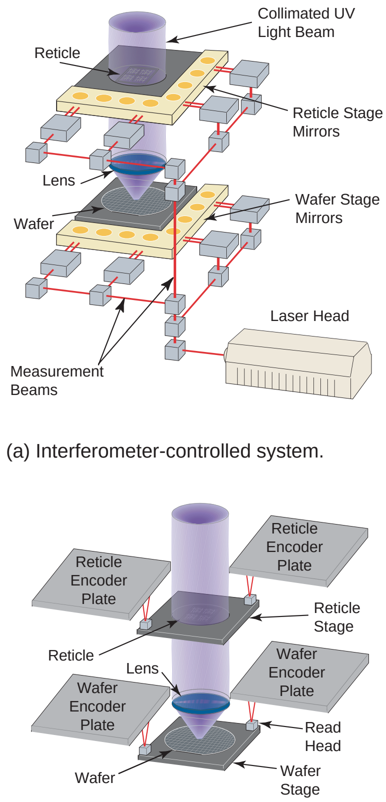


Figure 4. Principle of an optical encoder. Relative motion of the sensor with respect to the encoder plate is sensed by counting fringes. (Many other readout schemes are possible.) Because the air paths are short and balanced, encoders can be much more accurate than laser interferometers (Courtesy of Micro-E Corp.).

The main benefit of using gratings over lasers is that these systems can eliminate the effects of the atmosphere and other errors due to diffraction and optical non-linearity. Imagine, if you will, that gratings could be used on a modern lithography scanner, scanners that typically have between six and 12 interferometers to provide metrology. Converting such a tool to a grating-based encoder could eliminate the errors due to the atmosphere and laser frequency stability. It would also have the additional benefit of allowing the removal of the heavy stage mirrors. The encoder gratings would be stationary and attach to the "metrology frame" [27]. Such a concept design is shown in Fig. 5.



(a) Interferometer-controlled system.

(a) Encoder-controlled system.

Figure 5. (a) Lithography scanner with interferometer-controlled stages. (b) Same system but with stages controlled by stationary grating encoder plates, resulting in faster and more accurate stage position. Encoder plates with crossed gratings (i.e., grids) enable sensing all six degrees of freedom.

We, at Charlotte, are currently working with MIT to improve the accuracy of such gratings and to compare them to laser interferometry. A key instrument in this research is an MIT-built tool, called the Nanoruler. It uses the principle of scanning beam interference lithography to pattern large gratings. A precision below 3 nm, 3 σ has been demonstrated. The Nanoruler won a 2004 R&D 100 Award and is, arguably, the most precise grating patterning tool in the world. Efforts to improve its accuracy a factor of 10 to 100 are ongoing. Figure 6 shows a photograph of a 300-mm diameter silicon wafer pattern using the MIT Nanoruler.

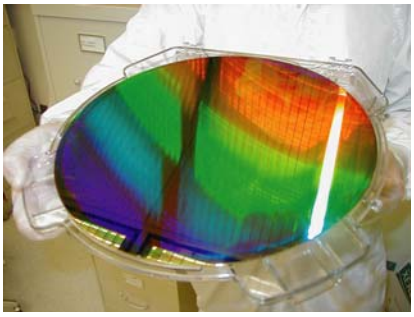


Figure 6. Photograph of a 300-mm-diameter silicon wafer patterned with a 400-nm-period grating using the MIT Nanoruler. Diffraction of overhead fluorescent lighting from the grating is visible. The Nanoruler writes and reads gratings with a typical phase error of 2.1 nm, 3 σ.

The Nanoruler is based on the principle of scanning-beam interference lithography (SBIL) which is essentially a hybrid of the ruling engine and interference lithography concepts. This technique avoids distortions typical of lithography by interfering millimeter diameter beams on the substrate. This results in a small, but low distortion grating image. By scanning the substrate with an interferometric-controlled stage and repeating this by overlapping, large area low-distortion gratings are produced. This system is shown schematically in Fig. 7.

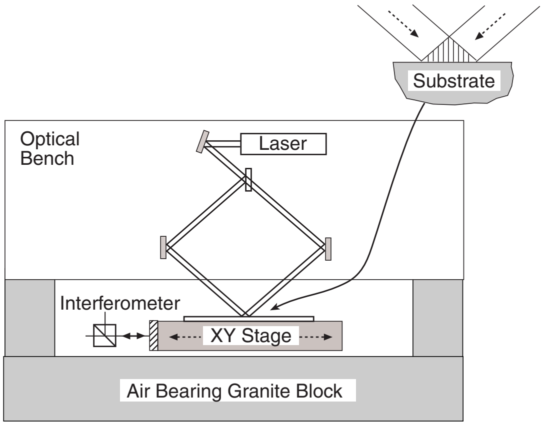
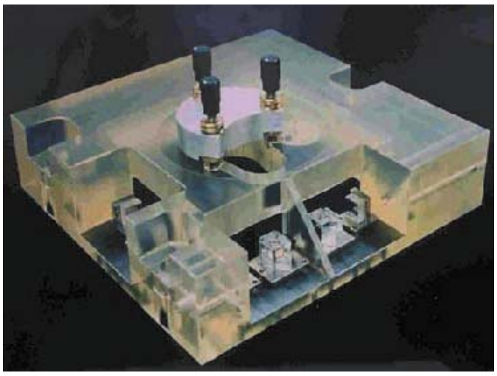


Figure 7. Schematic of a scanning-beam interference lithography system as used on the Nanoruler.

Gratings made on the Nanoruler will be measured at UNC Charlotte on the jointly-built Sub-Atomic Measuring Machine (SAMM). The SAMM is a unique ultra-precision system developed with NSF funding. It has eight-pass laser interferometer systems, Zerodur sample chamber and metrology frame, and operates not in vacuum but in helium. Modifications to this machine are being made so that it can run in vacuum. A photograph of the metrology frame for SAMM and a graph showing the machine's response to a 1-nm step are shown in Fig. 8.



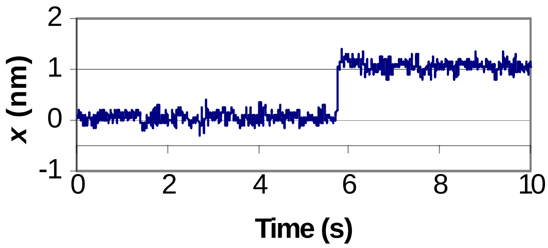


Figure 8. Photograph of the metrology frame for the Sub-Atomic Measuring Machine and the results of a 1-nm step. The RMS stage positioning noise is approximately 0.4 nm, 3 σ.

4. CONCLUSIONS

Taking nanotechnology to the factory floor will require that we advance the displacement measuring capability of mechatronic systems considerably over what is currently commercially available. Major efforts are being made to improve interferometry and, at the same time, other researchers are attempting to improve measurements based upon grating scales. Considering the breadth of the nanotechnology advances, we expect that applications will be found for systems where both types will be used either concurrently or separately. In any event, the research in these areas is definitely advancing the state-of-the-art in modern dimensional metrology.

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