Sub-100 nm metrology using interferometrically produced fiducials

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Pattern-placement metrology plays a critical role in nanofabrication. Not far in the future, metrology standards approaching 0.2 nm in accuracy will be required to facilitate the production of 25 nm semiconductor devices. They will also be needed to support the manufacturing of high-density wavelength-division-multiplexed integrated optoelectronic devices. We are developing a new approach to metrology in the sub-100 nm domain that is based on using phase-coherent fiducial gratings and grids patterned by interference lithography. This approach is complementary to the traditional mark-detection, or ''market plot'' pattern-placement metrology. In this article we explore the limitations of laser-interferometer-based mark-detection metrology, and contrast this with ways that fiducial grids could be used to solve a variety of metrology problems. These include measuring process-induced distortions in substrates; measuring patterning distortions in pattern-mastering systems, such as laser and e-beam writers; and measuring field distortions and alignment errors in steppers and scanners. We describe a proposed standard for pattern-placement metrology, which includes both a fiducial grid and market-type marks. Finally, a number of methods through which phase-coherent periodic structures can be patterned are shown, including ''traditional'' interference lithography, achromatic interference lithography, near-field interference lithography, and scanning-beam interference lithography. © *1999 American Vacuum Society.* [S0734-211X(99)11806-7]

I. INTRODUCTION

Technology roadmaps are predicting minimum feature sizes in manufacturing approaching 25 nm within 15 years. Several lithographic pathways to an economic realization of such systems are under intensive development. In addition to the challenges of patterning and inspecting such small features there is the critical issue of pattern placement. Just as important as the control of pattern critical dimension (CD) is the ability to accurately register and overlay features from multiple mask layers. A successful lithography must control mask distortions, alignment, and other sources of overlay error to less than ~20% CD, or around 5 nm for 25 nm features. This implies that factory pattern-placement metrology tools must be able to measure such errors to ~1 nm precision, and that ''national'' metrology standards used to calibrate metrology tools need an accuracy of ~0.2 nm. Achieving such ''picoaccuracy'' will probably require the development of new metrologic paradigms.

Another area of advanced lithography where picoaccuracy is essential is in the patterning of grating filters for integrated optoelectronics.[1] For example, channel-dropping filters for $\lambda = 1.5$ μm wavelength-division-multiplexed communications, with 100 GHz channels, require that grating periods be controlled to ~50 pm.

Essentially all modern pattern-placement metrology tools depend on heterodyne laser interferometry for high-resolution *x-y* measurements. For example, coordinate measuring tools, such as the LMS 2020 manufactured by Leica[2] and the 6i manufactured by Nikon,[3] determine the dimensions and in-plane distortion of a workpiece by viewing cross-type alignment marks through a microscope while monitoring with a two-axis laser interferometer the *x-y* position of the table on which the sample is mounted. This results in a so-called ''market plot'' (see, e.g., Ref. 4).

Modern laser interferometers provide a position ''resolution'' or ''quantization'' of 0.3–0.15 nm. However, true accuracy is quite another matter. In addition to other sources of error the interferometer measures only the optical path length between a fixed reference and a movable mirror.[5] Metrology is limited by the flatness and orthogonality of the mirrors, and assumes that there is no shifting, drift, or misplacement of the workpiece and system elements relative to the mirrors, an assumption that is often invalid.[6,7] For example, laser interferometers, despite their extreme sensitivity, do not solve the problem of pattern-placement accuracy in electron-beam lithography.

Typical usage of market pattern-placement metrology falls into three categories: (1) *process distortion* (i.e., measuring process-induced distortion in substrates), (2) *mastering distortion* (i.e., measuring patterning distortion in general-purpose pattern-mastering systems, such as laser or e-beam writers), and (3) *replication distortion* (i.e., measuring field distortions and alignment errors in steppers, scanners, and other replication systems).

During measurement of process distortion, an array of marks is written or imaged onto a substrate, which is then scanned by the metrology tool. The substrate is then processed in some way (e.g., deposition, thermal cycling, clamping, etc.) and the sample is re-scanned by the metrology tool. The difference between the distortion maps is a direct measure of the distortion caused by the process.[8,9]

During measurement of mastering distortion, a typical

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market analysis proceeds by first writing a regularly spaced array of marks onto the substrate. The metrology tool then measures the coordinates of each mark and directly generates the distortion map of the patterning tool based on the deviations of the marks from their intended locations.[10,11]

During measurement of replication distortion an array of marks is written onto a reticle which is then scanned by the metrology tool. The metrology tool also scans other marks written on the reticle and substrate for the purpose of overlay alignment. The reticle is then aligned and imaged onto the substrate, which is then re-scanned by the metrology tool. The difference between the reticle and substrate distortion maps (after taking into account any reduction by the imaging optics) forms a measure of the distortion and alignment error of the imaging optics and alignment system.[4,10]

While market-plot analysis is a popular tool that is likely to improve and remain an important part of advanced lithography for quite some time,[4,8,9,12–14] it does suffer from a number of limitations and shortcomings. In addition to the issues of accuracy and precision, the point-by-point, sequential measurements made by coordinate-measuring tools are tedious, slow, and sample a limited area of the surface. The time that elapses between writing and measurement may amount to many hours or days, making it difficult to quantify rapidly changing sources of distortion such as charging, thermal drifts, substrate clamping, or subtle data rate and timing effects. In this article we report on progress in applying phase-coherent fiducial gratings and grids, produced by interference lithography, to overcome many of the limitations of traditional pattern-placement metrology.

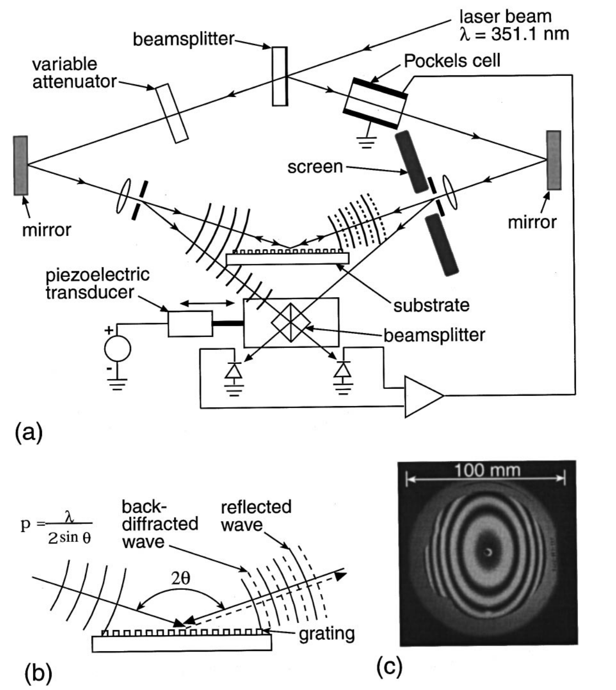

FIG. 1. (a) Schematic of the holographic phase-shifting interferometer. The system forms an interferogram on the fluorescent screen similar to a moiré pattern, which indicates the deviation between the grating on the substrate and the grating image formed by the interference of the interferometer arms. (b) Detail of the substrate showing reflected and backdiffracted beams. (c) Photograph of the interferogram on a screen in front of a spatial filter (in a deliberately misaligned interferometer) due to overlap of reflected and back-diffracted spherical waves. Fringes move in and out under control of the piezo attached to the beamsplitter cube, enabling a CCD to capture phase-shifted images, and a computer to calculate spatial-phase error (i.e., in-plane distortion).

II. USES OF PHASE-COHERENT FIDUCIALS IN METROLOGY

The availability of a technology for patterning phase-coherent fiducial gratings and grids on reticles and other substrates would enable a variety of powerful new pattern-placement metrology methods. By ''phase coherent'' we mean periodic patterns that have either a perfect linear phase (i.e., constant period), or a smoothly varying and well-characterized phase (e.g., hyperbolic phase[15]). Here in Sec. II we describe how phase-coherent fiducials can be used to solve a variety of metrology problems, either by direct viewing in beam systems or by a variety of holographic metrology techniques. In Sec. III we describe progress in developing a technology for patterning the required periodic structures using interference lithography (IL).

A. Process-induced distortion

Using a fiducial grid as a tool for measuring process-induced distortion requires that the substrate be patterned directly with the grid, and measured before and after a process step. For many processes this would be impractical due to the fact that product substrates are of interest, or that the process itself would obliterate the grid. However, there are a few applications where a shallow fiducial pattern on the substrate can be tolerated and/or the value of the information gathered is worth the limitations of using test substrates. One such example is the measurement of x-ray mask distortion.[16] Another is the study of wafer in-plane distortion caused by vacuum chucking.

We have developed a tool for measuring in-plane distortion called the *holographic phase-shifting interferometer* (HPSI),[15] depicted in Fig. 1(a) and described in more detail elsewhere in these proceedings.[16] A spherical wave backdiffracted from a shallow substrate grid and a second wave specularly reflected [see Fig. 1(b)], interfere on a fluorescent screen at the spatial filter. Interference fringes are illustrated in Fig. 1(c). By shifting the beamsplitter with a piezo, a computer can generate an *x-y* map of phase errors. Interference lithography is used to pattern the high-fidelity hyperbolic-phase gratings required by this method (see Sec. III A).

B. Mastering distortion

Most pattern-mastering lithography tools, such as e-beam lithography systems, have the ability to both read and write to the substrate. Any apparent distortion during reading a phase-coherent fiducial grid is a direct measure of system distortion.[17,18] Essentially, the fiducial grid serves as an absolute length-scale standard, by dint of having a perfect linear or otherwise smooth and well-characterized phase. Tran-

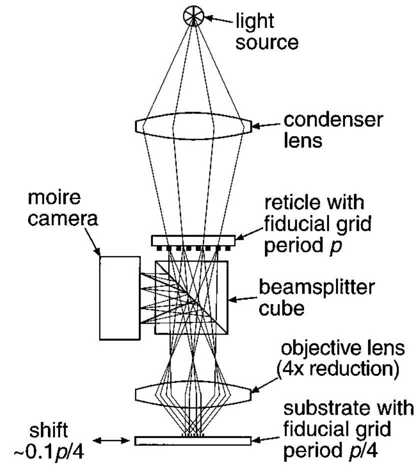

FIG. 2. Schematic of a stepper optical system (not to scale) that was modified to perform holographic metrology, which enables *in situ* measurement of objective-lens distortion and alignment error. Images of matched reticle and substrate fiducial grids are superimposed on a CCD, and form a moiré interferogram of objective-lens distortion. The moiré fringes are shifted by using the wafer stage to move the substrate fiducial grating.

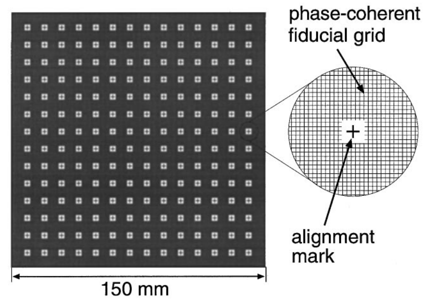

FIG. 3. Illustration of the proposed metrology absolute pattern placement standard. The background grid is produced by interference lithography, and the market-type alignment marks could be written by e-beam lithography and locked to the grid via spatial phase locking (Ref. 19).

sient pattern-placement errors, such as timing errors, vibration, charging, and substrate heating, are unavoidable and difficult-to-characterize features of e-beam systems.[11] Real-time *in situ* reading of the grid, especially while writing patterns, enables real-time measurement of transient pattern-placement errors. We are developing a new e-beam pattern-generating paradigm called *spatial phase-locked e-beam lithography* (SPLEBL), which utilizes a fiducial grid patterned directly on a substrate in an e-beam-transparent, scintillating polymer overlayer which is read in real time and used to correct pattern-placement errors on the fly.[19]

C. Replication distortion

A method is proposed for *in situ* holographic metrology of pattern-placement errors in replication tools such as steppers and scanners, illustrated in Fig. 2. The method uses the stepper optical system and a grating substrate to form another version of the HPSI described previously in Sec. II A. In this concept, a reticle patterned with a fiducial grid of period Rp is placed in the reticle stage of the stepper, and a matched substrate patterned with a fiducial grid of period p is placed on the substrate stage, where R is the reduction factor of the stepper (typically $R=4$) and p is the minimum printable period. In the wafer plane the substrate fiducial grid is overlayed with the reduced image of the reticle fiducial grid creating a moiré interference pattern which is a direct measure of system imaging distortion and alignment error. By utilizing a beamsplitter in the optical column, as shown in Fig. 2, the moiré pattern can be recorded with a charge coupled device (CCD) imager. The moiré image can be converted into a distortion map using the well-known method of phase measuring interferometery, as follows.[20] The wafer stage is used to move the substrate a small number of steps M of size p/M, where $M>4$. After each step the CCD camera captures the resulting moiré image that has slightly shifted fringes. The M images are analyzed yielding a phase-distortion map. The map is a direct measure of the stepper-field distortion. Slowly varying pattern-placement errors such as lens temperature effects or photon-induced refractive index shifts can be easily tracked with this method. More sophisticated methods can be used to measure rapidly varying contributions to overlay error such as step-and-settle vibration in steppers or reticle-substrate synchronization errors in scanners.

D. Metrology standards

In order to cross compare our grating-based metrology with industry standard coordinate measuring tools, we have proposed developing a metrology absolute pattern placement standard (MAPPS), illustrated in Fig. 3. The standard might consist of a quartz or Zerodur reticle that has been patterned with a well-characterized linear- or hyperbolic-phase grid by an interference lithography method. Superimposed on this pattern is an array of marks of the type suitable for metrology tools. The marks and grid could be referenced to each other using an e-beam inspection tool, or written by EBL and locked to the grid by SPLEBL.[19] Metrology standards of this type could also serve as the basis for high-accuracy stage motion encoders that could potentially eliminate the need to use laser interferometers in certain applications (with all their attendant shortcomings).

III. INTERFERENCE LITHOGRAPHY

Interference lithography is a means of exposing gratings or grids in resist by interfering mutually coherent light beams. If plane waves are interfered, linear-phase gratings result; if spherical waves are interfered hyperbolic-phase gratings result. IL has been developed at Massachusetts Institute of Technology (MIT) for over 25 years, and has been used effectively in a number of applications, including pattern-placement and CD metrology, quantum electronics, integrated optoelectronics,[1] high density magnetic data storage,[21,22] field-emitter-tip arrays for flat-panel displays,[23] and ultraviolet (UV), x-ray, and atom-beam filtering and diffraction.[24–26] Our laboratory has developed several specialized IL systems, including an IL facility designed for volume production. We recently completed a production run

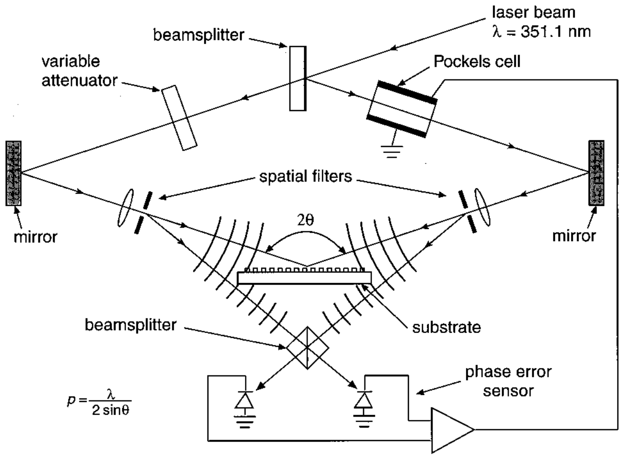

FIG. 4. Depiction of a ''traditional'' interference lithography system. Spherical waves emanating from spatial filters interfere at the substrate, creating a standing-wave grating with hyperbolic phase and center period given by $p = \lambda/2 \sin \theta$. The fringes are locked by a Pockels cell and feedback electronics.

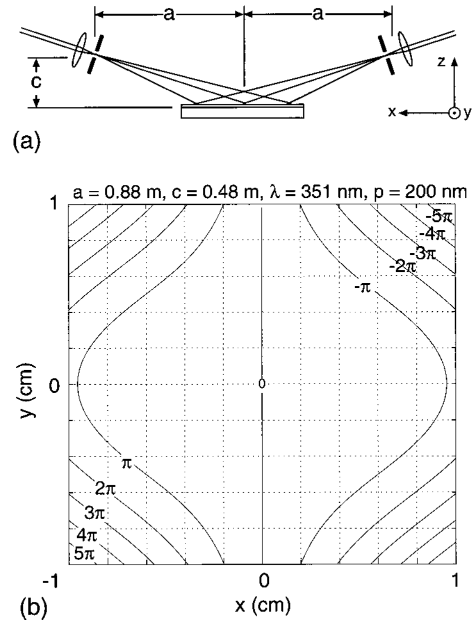

FIG. 5. (a) Simplified geometric parameters used in the MIT ''traditional'' IL system. (b) Plot of the phase difference between a hyperbolic-phase grating and a perfect linear-phase grating.

of over 1000 x-ray gratings with 200 and 400 nm periods for an x-ray spectrometer on the NASA *Chandra X-ray Observatory*.[26]

In Secs. III A–III D we describe advantages and limitations of four popular IL methods. We distinguish grating mastering tools, such as traditional IL (hyperbolic phase) and scanning-beam IL (linear phase) systems, with replication tools such as near-field IL and achromatic IL.

A. Traditional interference lithography

Figure 4 illustrates our ''traditional'' IL system that produces gratings and grids of hyperbolic phase. The system utilizes the $\lambda = 351.1$ nm argon-ion laser to pattern gratings with periods down to 200 nm. This system has evolved over the last 25 years into a sophisticated, high-yield production tool, that includes subsystems for active beam and fringe stabilization, real-time monitoring of beam profile and spectral purity, and imaging tools for monitoring power and contrast. A precision cube and an autocollimator enable us to fabricate grids with subarcsec orthogonality using a double-exposure technique.[16,18] Spherical waves emanating from spatial filters produce a standing-wave interference pattern with hyperbolic phase progression at the substrate location, about 1 m distant (see Fig. 5). A beamsplitter causes portions of the spherical waves to interfere on photodiodes. The difference signal is fed to a Pockels cell, which phase shifts one of the beams to stabilize the standing wave.[27] High quality gratings and grids are obtained over ~ 10 cm areas.

The use of spatially-filtered beams ensures that the resulting gratings are phase smooth over all spatial frequencies, unlike ruled e-beam or laser-patterned gratings, which generally have high-frequency phase jitter. For many applications, such as measuring process-induced distortion with the HPSI, the phase-smooth gratings are nearly ideal, and the hyperbolic phase is not a problem. For other applications, such as measuring distortion in pattern generating systems, linear-phase gratings are more generally useful, although hyperbolic-phase gratings can still be used if they are carefully characterized. Measurement of replication distortion is probably best achieved with gratings of linear phase, especially if reduction optics are used, because of the difficulties in matching reticle and substrate grating phase progression.

It is natural to ask why the interferometer in Fig. 4 cannot expose linear-phase gratings with the simple addition of collimating lenses after the spatial filters. While this may be feasible if large, high quality lenses are used, in general any figuring errors in the lenses, or scratches and dust on their surfaces, will translate directly into grating distortion. Instead, we are developing a new IL scheme that utilizes small diameter scanning beams. When completed, the system should be able to write ultralow-distortion linear gratings over large areas (see Sec. III D).

It is possible to use hyperbolic-phase gratings as absolute length-scale standards, but only if the parameters that define the geometric structure of the grating phase are carefully controlled and/or measured such that an accurate mathematical model can be built. This might be accomplished by using a high quality e-beam system and symmetry arguments to measure the eight degrees of freedom that define the hyperbolic nature of the phase (the phase calculation of Fig. 5 used a simplified geometry). Substrate flatness and systematic errors ultimately limit accuracy.

B. Achromatic interference lithography

Another form of IL developed at MIT, called *achromatic interference lithography* (AIL), is depicted in Fig. 6(a). The system utilizes the $\lambda = 193$ nm ArF excimer laser to expose 100 nm period gratings. It produces large-area, spatially coherent grids of the finest resolution achieved anywhere in the world, and they are shown in Fig. 6(b).[28] By using transmis-

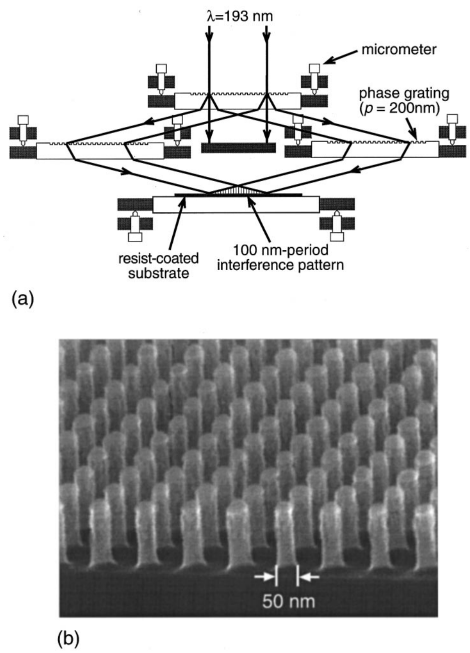

FIG. 6. (a) Schematic of an achromatic interference lithography system used to print 100 nm period patterns. The grating period and contrast are independent of the source bandwidth, which is desirable because phase errors due to spurious scattered beams can be avoided by using a short-coherence-length source. (b) Array of silicon posts patterned by AIL.

sion phase gratings for beamsplitting and recombining, and by blocking the zero order, an achromatic grating image with half the spatial period of the master is achieved, independent of the source bandwidth. A wide bandwidth (i.e., a short coherence length) is, in fact, desirable to eliminate phase errors due to spurious scattered and multibounce stray beams.

The extreme rigidity and simplicity of the AIL system makes it an attractive candidate for commercial volume production of fiducial periodic patterns. However, any distortions in the master grating will be faithfully replicated by this technique, as will additional phase errors due to thickness variations in the master plates. For this reason it is unclear if the AIL method can be used to pattern absolute length-scale grating standards unless these errors can be controlled and/or characterized.

C. Near-field interference lithography

Near-field interference lithography (NFIL), depicted in Fig. 7, utilizes a phase mask to interfere zero and first-order diffracted beams in the near field, effectively replicating the parent grating or grid. This method requires a well-collimated, monochromatic source and small, well-controlled gaps to succeed. Spatial-frequency doubling can be achieved by using a mask designed to suppress zero-order diffraction.[29,30] NFIL techniques are widely used to produce diffraction gratings for certain integrated-optical applications, and to expose gratings in optical fibers.[31] While the NFIL replication technique is attractive due to its extreme simplicity, it is unclear if it can be used directly to produce

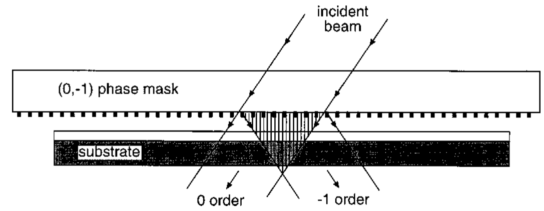

FIG. 7. Schematic of near-field interference lithography. Several variations are possible, including the zero/first-order interference shown, and plus/minus first-order interference, where zero order is suppressed, effectively spatial frequency doubling the mask.

fiducial grids in volume due to well-known concerns of working with small gaps, and the difficulty of controlling multibounce stray beams during the replication process which can cause high-frequency grating phase errors.

D. Scanning-beam interference lithography

Traditional methods of generating large-area, high-fidelity, linear-phase periodic patterns suffer from a number of well-known limitations. Methods such as mechanical ruling, e-beam or laser writing, are extremely slow and produce gratings with high-frequency phase jitter. The IL methods discussed in Sec. III A produce gratings with difficult-to-characterize hyperbolic-phase progression or, if collimating lenses are used, gratings limited by the size and figure quality of the lenses themselves. An IL system could, in principle, be designed to pattern fiducial grids with subnanometer fidelity over the several hundred millimeter areas of interest, but it would require a large and inflexible optical system with extremely expensive lenses.

We are developing a radially new approach called *scanning-beam interference lithography* (SBIL), illustrated in Fig. 8(a), which bypasses this set of problems by interfering two beams of small diameter, and scanning a stage to create gratings over a much larger substrate. The ultimate goal of this method is to produce periodic patterns over 300 mm diam areas with subnanometer phase error.

The basic idea behind the SBIL technique follows from the observation that while it is extremely expensive to fabricate collimating lenses with figures better than $\lambda/20$ (<30 nm) over the full optic, figure errors tend to be much smaller when measured over millimeter or smaller subapertures. SBIL utilizes a small ''traditional'' IL system (see Fig. 4) to overlap and interfere collimated millimeter-sized beams on a moving substrate, creating a small grating ''image'' with linear phase and very low distortion. The substrate is then scanned under the grating image in a serpentine manner, ''writing'' large-area gratings, as depicted in Fig. 8(b). Image scanning also helps to further reduce the effect of distortions.

The SBIL system can also perform diffractive metrology by scanning reference gratings using an optical configuration similar to that in the HPSI (see Sec. II A). The ability to ''read'' as well as write gratings enables measurements of grating distortions and detailed characterization of system phase stability, beam-phase linearity, and motion errors.

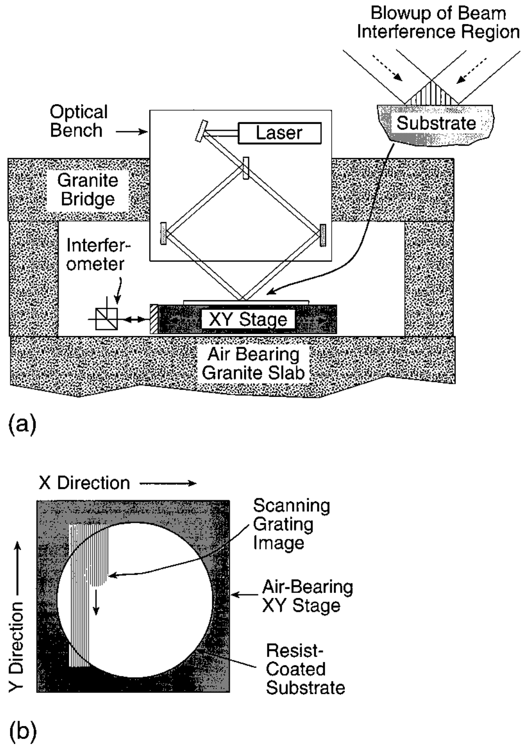

FIG. 8. (a) Schematic of the scanning-beam interference lithography system under development. The objective is to achieve linear-phase gratings over large areas for a variety of applications. (b) Depiction of the serpentine scanning method in SBIL. Phase locking the fringes to the moving substrate is a critical part of the design.

While simple in concept, the task of phase locking the grating image to a moving substrate requires a detailed understanding of system optomechanics, effective control of sources of phase disturbance, sophisticated environmental controls, and real-time digital signal processor (DSP)-based phase-locking opto-electronics. In many ways, the set of problems is similar to those faced by modern optical scanning lithography tools and coordinate measuring systems. As our system platform we have chosen a commercial high-speed, two-axis, linear-motor air-bearing stage, which is controlled by a DSP controller with positioning information supplied by a four-axis heterodyne laser interferometer. The system is capable of scanning at speeds up to several hundreds of mm/s over a 316×477 mm area, while maintaining subarcs pitch, yaw, and roll, and submicron travel straightness.

At this point the system is up and running in our laboratory and is writing gratings. For the initial set of tests we are running ''open loop,'' with no environmental controls or phase locking in place. Planned environmental controls include active vibration isolation and a <25 mK environmental enclosure which should considerably reduce the level of background disturbances. Turbulence-compensated interferometry will also be essential to achieve sub-30 nm phase control.[32,33] We are also in the process of upgrading the electronics to allow improved motor control algorithms and real-time measurement and control of the image phase.

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