Progress towards a general grating patterning technology using phase-locked scanning beams.

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ABSTRACT

The fabrication of large high-quality diffraction gratings remains one of the most challenging tasks in optical fabrication. Traditional direct-write methods, such as diamond ruling or electron-beam lithography, can be extremely slow and result in gratings with undesired phase errors. Holographic methods, while generally resulting in gratings with smoother phase, frequently require large aspheres and lengthy optical setup in order to achieve desired period chirps. In this paper we describe a novel interference lithography method called scanning-beam interference lithography (SBIL) that utilizes small phase-locked scanning beams to write general periodic patterns onto large substrates. Small mutually coherent beams are phase controlled by high-bandwidth electro-optic components and caused to overlap and interfere, generating a small grating image. The image is raster-scanned over the substrate by use of a high-precision interferometer-controlled air bearing stage, resulting in large grating patterns. We will describe a prototype system in our laboratory designed to write gratings with extremely low phase distortion. The system is being generalized to pattern gratings with arbitrary period progressions (chirps). This technology, with extensions, will allow the rapid, low cost patterning of high-fidelity periodic patterns of arbitrary geometry on large substrates that could be of great interest to astronomers.

Keywords: diffraction gratings, periodic patterns, holographic lithography, interference lithography

1. INTRODUCTION

Traditional methods of manufacturing large diffraction gratings are generally slow and expensive, and the resulting grating quality is not high when compared to state-of-the-art refractive and reflective optics. A grating is typically judged to be of good quality if it produces diffracted wave fronts deviating by less than $\lambda/10$ from the desired shape. However, for many applications, such as metrology gratings, diffracted wave front fidelity exceeding $\lambda/1000$ is desired (i.e., < 1 nanometer of wave front distortion). A wide range of applications for periodic patterns could benefit from improved grating patterning technology.

The three most popular methods for patterning submicron-period gratings are diamond ruling, holographic imaging, and electron or laser beam lithography. Diamond ruling is certainly the oldest method, having been in use now for well over one hundred years. It involves dragging a specially shaped diamond over a substrate coated with soft metal, forming regular grooves. The primary problem with diamond ruling is its extremely slow speed. For example, it would take several years to rule a 200 nm-period grating on a 300x400 mm substrate. Grating phase fidelity is also low and pattering curved lines is difficult.

While holographic patterning is significantly faster, a special optical setup is required for every change of period. Gratings with variable periods require expensive collimating optics specially designed for the desired period chirp, which can take weeks to manufacture. The resulting grating also has no better phase quality than that of the collimating optics.

Electron beam lithography is also very slow and expensive, and the resulting patterns suffer from high-spatial-frequency phase jitter. For example, the Leica ZBA 350, a high-performance commercial e-beam lithography tool, would take well over 100 hours to write a 200 nm period-grating on a 300x400 mm substrate, and the resulting grating would suffer from ~15 nm of high-frequency phase errors. Laser beam lithography typically has even worse performance.

We are developing a novel scanning beam interference lithography system for writing arbitrary periodic patterns that we believe will revolutionize grating and diffractive optic manufacturing. The goal of the current phase of the work is to pattern constant-period gratings on 300x400 mm substrates for nanometrology applications. These gratings need to have less than 0.5 nanometers of distortion. A new research effort, reported here, seeks to generalize this concept for patterning continuously varying periods. Such a system would enable the rapid and low-cost fabrication of a variety of high-quality periodic patterns for large diffractive optics such as spectroscopy gratings, zone plate lenses, and null correctors. Also of interest is the patterning of Bragg waveguides for integrated optoelectronic applications.

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2. INTERFERENCE LITHOGRAPHY TECHNOLOGIES

2.1 "Traditional" interference lithography

Figure 1 depicts a "traditional" interference lithography (IL) method, also called holographic lithography. A beam of UV light from a coherent source of radiation, such as a laser, is split, spatially filtered and expanded, and then recombined, resulting in a standing wave grating of period $p=\lambda/(2\sin\theta)$, where λ is the wavelength and θ is the half-angle between the beams. The pattern exposes a UV-sensitive resist coating on the substrate. Stable, high-contrast fringes are essential for good results. Unfortunately, environmental disturbances such as air turbulence and vibration cause the fringes to constantly shift. We utilize a pickoff beamsplitter near the substrate, as shown in Fig. 1, to measure the phase difference between the arms and use this signal to drive a phase shifter in one arm, thus locking the fringes in place during the exposure.[1] The use of spatial filters ensures smooth wavefronts, but at the expense of hyperbolic phase curvature in the resulting grating which is undesirable for many applications.[2]

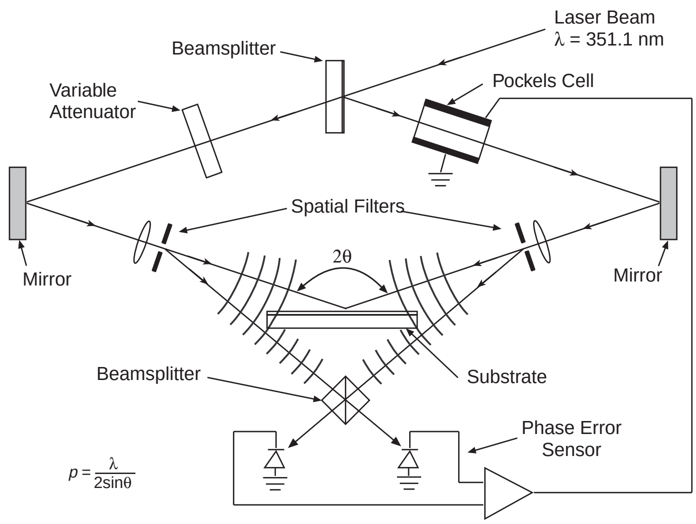

Figure 1. Depiction of "traditional" interference lithography (IL), also called holographic lithography, as practiced in our laboratory. Beams from an argon-ion laser (λ=351.1 nm) are split, expanded, and recombined to generate a large standing wave grating pattern. The pickoff beamsplitter allows measurement of the phase difference between the arms, which is used to drive a phase shifter in one arm (Pockels cell), thus locking the pattern phase and eliminating environmental disturbances.

To eliminate the hyperbolic phase distortion, an alternative IL method utilizes collimating optics after the spatial filters. While this results in gratings with much higher phase fidelity at low spatial frequencies, defects or manufacturing errors in the optics are directly written into the phase of gratings, resulting in undesired errors especially at mid-range spatial frequencies.

2.2 Scanning beam interference lithography

We are developing a novel grating patterning technology in our laboratory, called *scanning beam interference lithography* (SBIL), depicted in Fig. 2.[3] This system uses small Gaussian beams (~1 mm diameter) to form fringes in a small grating image. The image is much smaller than the substrate and has very high phase fidelity due to the beams sampling only a small area of the collimating lenses.[4] The substrate is smoothly scanned under the image using a high performance stage, thus "writing" a much larger grating. A uniform exposure dose is achieved by tightly overlapping subsequent scans, as depicted in Fig. 3. For example, a step size of 0.9 times the Gaussian beam $1/e^2$ radius produces a dose uniformity of better than 1%.

In general, substrate scanning may be described as a combination of two basic types: parallel scanning and Doppler scanning. During parallel scanning the substrate moves essentially parallel to the fringes in the image (Fig. 4a). In this scheme, the frequency and phase differences between the interfering beams are essentially identical. To avoid fringe smearing, the direction angle of stage motion must be parallel to the fringes to a small fraction of the period divided by the spot size. During Doppler scanning the substrate moves essentially perpendicular to the image fringes (Fig. 4b). In this scheme, the frequency difference between the interfering beams must be equal to the stage velocity divided by the fringe period. To avoid fringe smearing in all cases, the image fringes must be stationary to a small fraction of a period in the reference frame of the moving substrate.

Unfortunately, even the most advanced interferometrically-controlled air-bearing stage is incapable of meeting these tight control requirements, and a high-bandwidth electro-optic system driven by a high-speed controller and digital signal processor (DSP) is required to overcome this limitation. Fig. 5 depicts the main components of the system under development. A brief system overview follows including an explanation of the nature of the disturbances and the means to control them. Details can be found elsewhere.[5, 6]

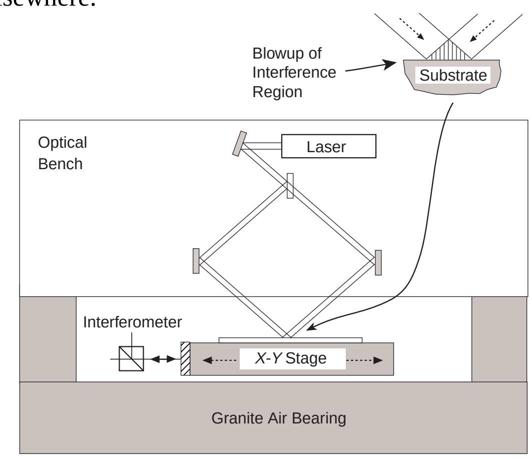

Figure 2. Depiction of SBIL concept. A small laser beam is split and recombined on the substrate, creating a small grating image. A high-performance air-bearing stage is scanned under the image, “writing” a much larger grating.

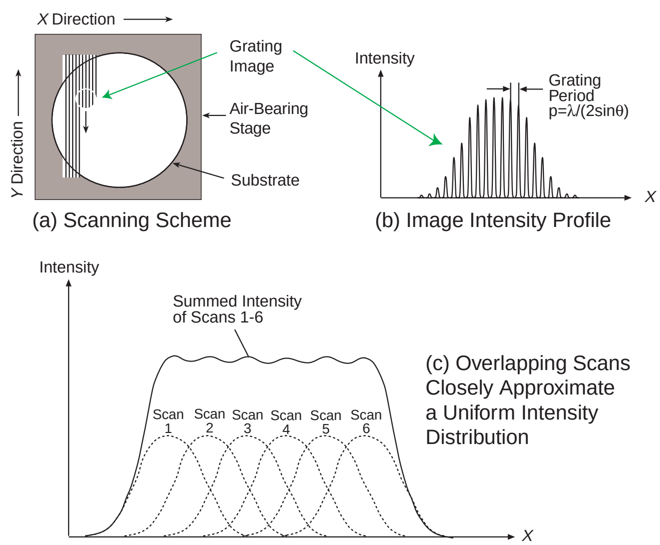

Figure 3. Depiction of SBIL writing scheme. (a) A small grating image is raster-scanned over the substrate. (b) Intensity profile of the image. (b) Summed intensity of six tightly overlapped scans.

In the SBIL system we speak of two interferometers: the *stage interferometer* utilizes HeNe laser beams (λ=632.8 nm) in a heterodyne measurement scheme to determine the stage position and control the DC motors that drive the ~100 kg air bearing stage, while the *writing interferometer* utilizes an argon-ion laser (λ=351.1 nm) to form the grating image on the substrate. It is critical that image fringes be tightly controlled in period, phase, and rotation. Unfortunately, environmental disturbances, such as thermal expansion, vibration and air turbulence, cause them to constantly shift. These disturbances also compromise the accuracy of the stage interferometer. The first line of defense is to utilize the most sophisticated environmental controls available to reduce these disturbances to the lowest practical level. The remaining disturbances then are measured and corrected using high-speed electro-optic controls. The system design includes a cleanroom environmental enclosure that controls the temperature to ± 5 mK and the humidity to ± 0.8% RH. Compensation for pressure variation is provided by a high-accuracy refractometer. The enclosure also provides excellent acoustic isolation. Vibration is controlled by passive and active vibration isolators utilizing digital controls with stage position and acceleration feedforward.

Image fringe period and rotation drift, and beam overlap errors, are caused by variations in the angle and lateral position of the incoming argon-ion laser beam with respect to the writing interferometer. These disturbances are controlled by a pair of high-speed two-axis tip-tilt mirrors, driven by a digital signal processor that reads beam angle/position sensors.[7]

High-bandwidth knowledge and control of the image fringe position in the laboratory reference frame is critical. This is equivalent to controlling the phase difference between the arms in the writing interferometer. For this reason the writing interferometer utilizes an interferometer subsystem called the *phase reference interferometer* (PRI). Like the stage interferometer, the PRI also utilizes a heterodyne fringe measurement scheme. Environmental disturbances that compromise fringe measurement accuracy have their greatest power in the DC to few-hundred Hertz band. By shifting the measurement frequency into the MHz band, high accuracy, high-bandwidth knowledge of fringe position can be obtained. Low data age, data age uncertainty, and actuator latency are also essential to achieve tight fringe control.

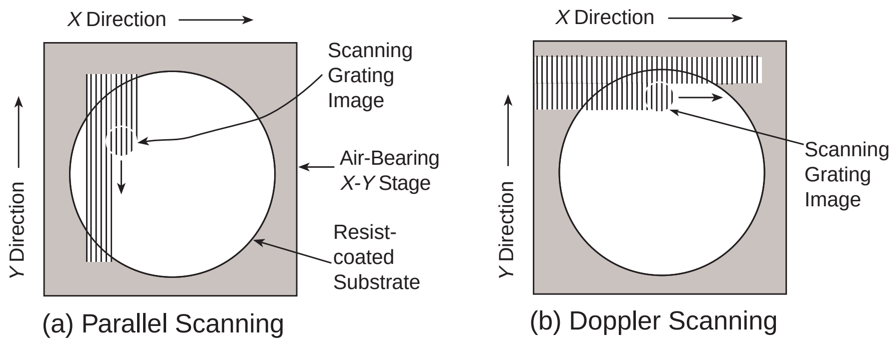

Figure 4. Depiction of two primary SBIL writing schemes. (a) During parallel scanning the stage moves parallel to the fringes. (b) During Doppler scanning the stage moves perpendicular to the fringes, requiring a frequency shift between the interferometer arms.

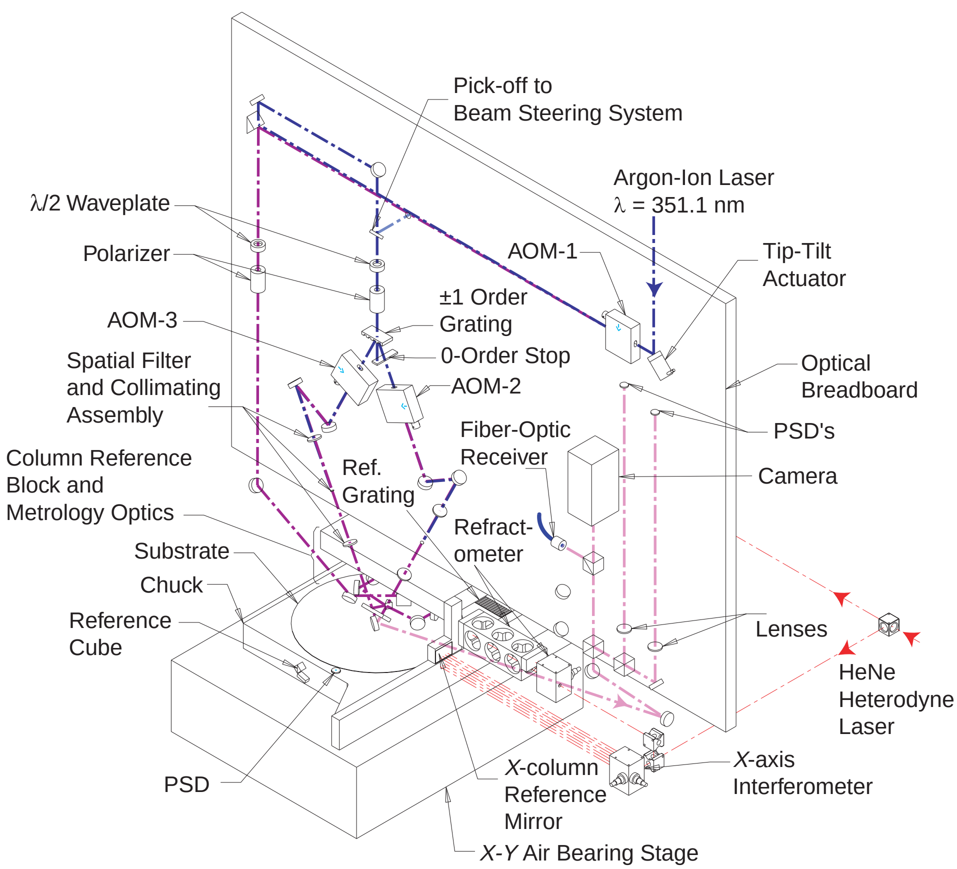

Figure 5. Engineering drawing of the SBIL tool showing major system components.

Details of the PRI are depicted in Fig. 6a. A high-performance digital frequency synthesizer drives an acousto-optic modulator (AOM1) to split a weak reference beam of frequency $f_H \sim f_0$+20 MHz from the main beam of frequency f_0. An additional pair of modulators (AOM2 and AOM3) controls the frequency and phase of the left arm (f_L) and the right arm (f_R), respectively. The reference beam f_H, after being delivered to the PRI by fiber optic or free-space transmission, is split and mixed with a weak split beam from the left arm, generating signal f_L-f_H detected by phase meter PM1, and from the right arm, generating signal f_R-f_H detected by phase meter PM2. The digital output of these phase meters is compared by a high-speed digital signal processor (DSP), and the resulting phase error signal $\Delta f = (f_L-f_H)-(f_R-f_H) = f_L-f_R$, which is directly proportional to the image fringe position, is used to control the frequency synthesizer which in turn drives AOM2 and AOM3, thus controlling frequency difference Δf. Frequency f is related to phase ϕ through $f = d\phi/dt/(2\pi)$.

High-bandwidth control of the image fringes is also important to eliminate stage follower error. The digital controller drives the DC stage motors to power the ~100 kg air-bearing stage to follow a raster scan path, the controller constantly attempting to drive the path error to zero, as determined by the stage interferometer. Due to environmental disturbances and the finite loop gain of the controller, however, this process is never perfect, leading to so-called *stage follower error*. This error is always known to high accuracy by the stage interferometer, so can be used as additional input to the digital controller driving the frequency synthesizer. This technique, in effect, ensures that the fringes are locked *in the reference frame of the moving substrate*. Several other sources of error, including relativistic effects,[8] must also be taken into account by the controller if sub-nanometer accuracy is desired.

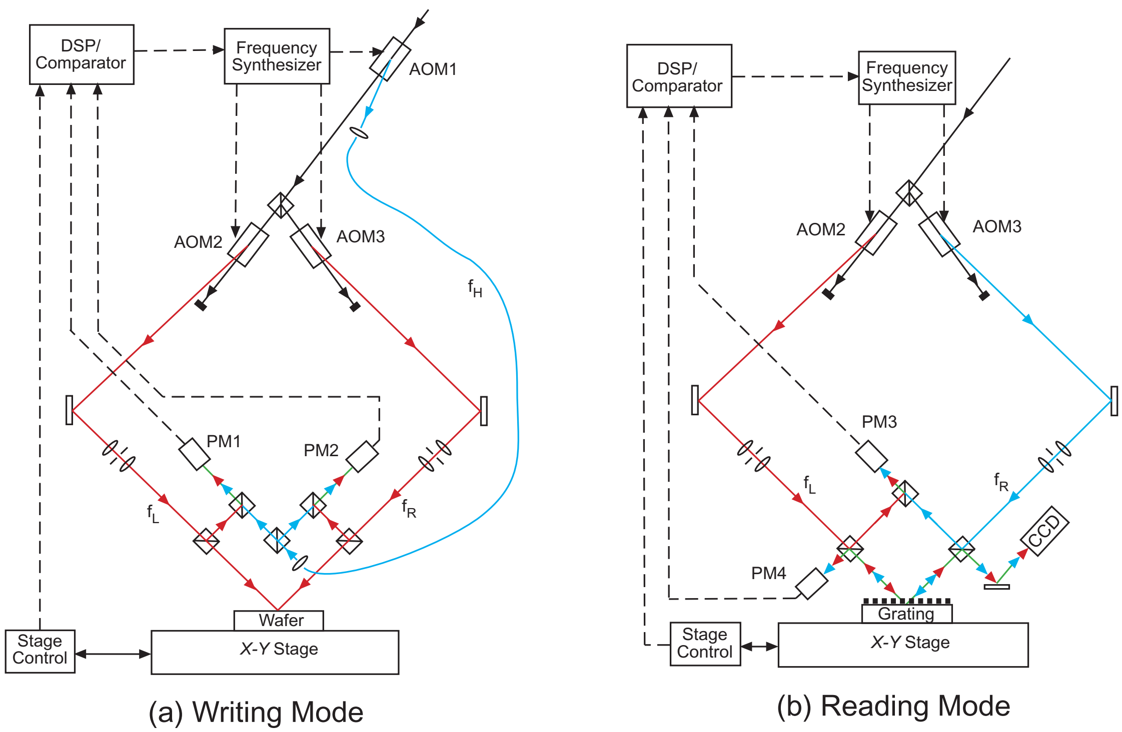

Figure 6. Details of SBIL writing interferometer and phase reference interferometer optics. The system is depicted twice, where components unused in a particular mode have been suppressed. (a) Writing mode. (b) Reading mode.

An important feature of the SBIL system is the dual capability of the writing interferometer to function either in reading or writing mode. Writing mode, as depicted in Fig. 6a, has already been discussed. Fig. 6b depicts the writing interferometer configured in reading mode. In both parts of Fig. 6, optical components unused in the particular mode are suppressed for clarity. Rapid switching between the modes is performed electronically.

Reading mode allows the SBIL system to read and map the phase of previously patterned gratings with high accuracy. This capability enables the use of symmetry transformations (e.g., substrate translation and rotation) to map the internal distortions of the stage interferometer reference frame. This map can be used as a lookup table during writing to eliminate stage-induced errors. Reading mode is also an important internal check on stage drift due to thermal and pressure variations. The SBIL system can also be used to provide an important metrology service by reading and mapping the errors of externally provided gratings.

Referring to Fig. 6b, during reading mode a previously patterned grating is placed on the substrate stage. The left and right arm modulators AOM2 and AOM3, respectively, are configured to create a large frequency difference between the arms, such that f_L-f_R ~ 20 MHz. Weak split beams from the left arm (f_L) and right arm (f_R) are mixed forming signal $\Delta f = f_L - f_R$ that is detected by phase meter PM3. Meanwhile, the right beam as reflected off of the substrate, of frequency f_R, is mixed with the left beam back-diffracted from the substrate, of frequency $f_L - u_S/p$, forming signal $f_S = u_S/p - \Delta f$ that is detected by phase meter PM4, where $u_S = dx_S/dt$ is the stage velocity, x_S is the stage x-position, and p is the grating period. Since u_S is known to with high accuracy in real time by the stage interferometer, we can solve for $p(x_S,y_S) = u_S/(f_S+\Delta f)$. This enables the system to make high-accuracy maps of grating phase $\phi_p(x_S,y_S)$ using the relationship $2\pi/p = d\phi_p/dx_S + d\phi_p/dy_S$.

2.3 Variable-period scanning beam interference lithography

While the SBIL system remains under intensive development, our initial success has compelled us to visualize an improved system that allows general and continuous control of image fringe period and rotation in order to write arbitrarily complex pre-determined periodic patterns. The concept involves continuously varying the image phase, period and rotation while the substrate is moving. In order to avoid fringe smearing, the maximum period variation Δp over the image diameter d must satisfy the relationship $\Delta p/p \ll (p/d)^2$. Thus, rapidly varying grating periods require a small spot. A spot diameter in the range of 10-100 microns is optimal.

After studying a number of alternatives, we settled on the interferometer design depicted in Fig. 7 for development. A simplified system description follows. An argon-ion laser beam (λ=351.1 nm) is split into two beams, each of which is diffracted by an acousto-optic modulator (not shown) for phase/frequency control, and then reflected from a two-axis galvanically-actuated gimbal mirror mount. The gimbal mirrors provide high-speed two-axis beam rotation without translation. The two beams are then recombined by a 50/50 beamsplitter plate or cube and directed to an objective lens that causes the beams to overlap and interfere on the substrate, creating a grating image.

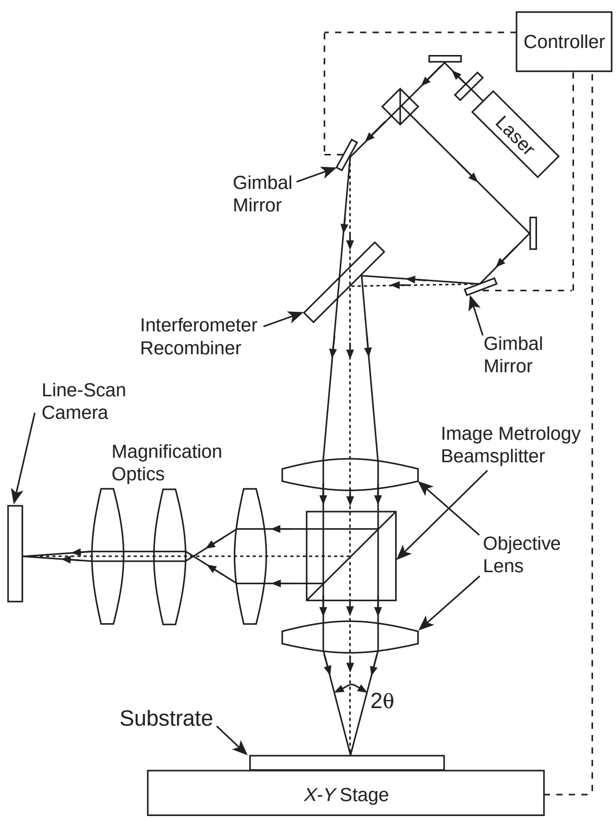

Figure 7. Depiction of variable period SBIL concept. Symmetric gimbal mirrors deflect the beams to create an image with arbitrary fringe period and rotation. A magnified version of the image is projected onto line-scan cameras that collect fringe metrology information for the controller as feed back for the beam phase and angle actuators. The dashed line indicates beams travelling close to the optical axis, producing low-density fringes. The solid lines indicate beams travelling close the NA limit of the lens, producing high-density fringes.

The gimbal mirrors are symmetrically controlled such that the resulting beams are always mirrored across the optic axis. Each gimbal mirror controls an arm of the writing interferometer such that at one extreme of the gimbal's rotation the beams travel very close to the optical axis of the system (dashed lines), creating an image with an arbitrarily small fraction of a fringe, while at the other extreme of rotation the beams travel near the NA limit of the lens (solid lines), creating an image with the highest attainable fringe density. Rotating the beams in the plane of the figure controls the period of the image fringes, while rotating out of the plane controls the rotation angle of the image fringes. In this manner, complete control of the image fringes is obtained.

Real-time knowledge of image phase, period, and angle are essential in order to close the digital control loops that drive the AOM phase shifters and gimbal mirror motors. The required image metrology can be performed by placing a sampling beamsplitter in the interior of the objective lens, as shown in Fig. 7, and then projecting a magnified image onto a set of orthogonal line-scan cameras. Our high-speed DSP can perform real time 1D-FFTs on the line-scan images to obtain continuously updated fringe period, phase and rotation. This information is used to continuously drive the beam actuators while the substrate moves.

As described, this concept utilizes a homodyne fringe detection scheme that is susceptible to low-frequency phase noise. We have also designed a more sophisticated method utilizing a heterodyne fringe detection scheme that should enable high-speed fringe control in the few-nanometer range.

3. SUMMARY AND FUTURE PLANS

We have described a family of scanning-beam interference lithographies that we believe will revolutionize the writing of periodic patterns. Further extensions of this method should allow the patterning of gratings with arbitrary blazes on non-flat substrates that are common in spectroscopic applications.

ACKNOWLEDGEMENTS

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