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Heterodyne encoders for high-precision displacement measurement

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Abstract
We describe a heterodyne encoder system for demanding photolithography applications, comprised of thermally-stable, multi-axis heads for full 3D displacement measurement. A remote, frequency stabilized 20 mW HeNe laser with custom acousto-optic modulators (AOMs) and intra-cavity etalons powers the encoders. The heterodyne principle allows for simultaneous operation of multiple multi-axis heads from this single light source to a noise level of less than 0.15 nm RMS, in spite of the inherently low optical efficiencies of the 2D gratings that serve as targets. A novel double-pass encoder geometry enables out-of-plane displacements as large as 1 mm. Angled beams suppress polarization mixing, and real-time Fourier processing reduces residual periodic (cyclic) errors to less than 0.05 nm RMS. Careful selection of materials, bonding methods and constraints ensure low thermal sensitivity and long-term stability.

Heterodyne, interferometer, encoder, displacement, metrology, periodic error, cyclic error, Abbe offset, Abbe error, air turbulence

1. Introduction

Demands for displacement metrology in lithographic applications are driven by the ever-shrinking feature size or critical dimensions (CD) on integrated circuits. The current CD is 16 nm and headed towards 10 nm [1]. The lithography process allocates ~3% of the CD for stage displacement metrology, i.e., a stage metrology budget of 0.3 nm for a CD=10 nm [2]. This precision is maintained at stage speeds of > 1 m/s to achieve the throughput required (20 s/wafer) to make lithography economically viable [3]. As the requirements have tightened, air turbulence has become the limiting factor in the achievable precision, accounting for 80% of the total error. While there have been serious attempts at compensation via dispersion interferometry [4], these efforts have been overtaken by ever-tightening requirements. The winning practical solution has been the adoption of optical encoders with drastically shorter air-paths relative to conventional interferometry [5-9].

This paper describes a new generation of multi-DOF (degree of freedom) heterodyne encoder systems, starting with the basic operating principle and concluding with practical systems that meet requirements for resolution, immunity to stage tip/tilt, speed, and allowance for large (~ 1 mm) stage motions in a direction perpendicular to the grating.

2. Principle of operation of new designs

FIGURE 1 illustrates an encoder concept based on a double-pass linear interferometers using retro-reflectors [4], where the measurement beam is directed onto an encoder grating twice with a retro-reflection in between. This geometry renders the encoder system insensitive to tip/tilt of the encoder grating. Both in-plane x and out-of-plane motions z of the encoder grating contribute to the measured phase in the configuration shown in FIGURE 1 [11]. This basic geometry is the building block for monitoring multiple degrees of freedom in complex, high-speed stage motions.

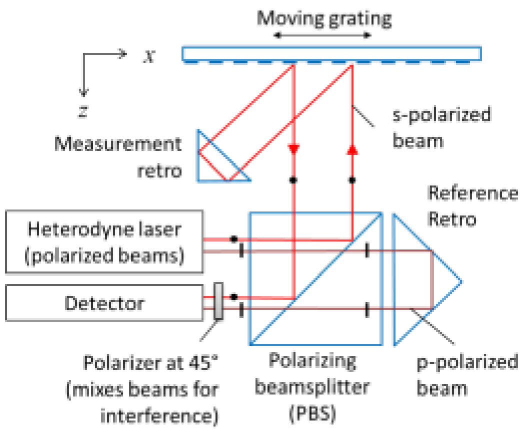

Figure 1. Basic optical geometry of a heterodyne encoder

The motions in the two directions x and z may be discriminated by exploiting the other diffraction orders in a compact geometry similar to that shown in FIGURE 2. A change of the sum of two measured phases $(\phi^+ + \phi^-)$ corresponds to the out-of-plane z motion of the encoder grating, whereas $(\phi^+ - \phi^-)$ is a measure of in-plane x motion. Two such appropriately-oriented two-channel encoders combine for a full x, y, z displacement measurement of a 2D grating. Additional encoder heads enable simultaneous measurement of pitch and yaw, allowing for correction of Abbe errors.

While the measurement range in the plane of the grating is limited by the size of the encoder grating, out-of-plane motions are limited by the loss of signal due to the dynamic beam shear of the measurement beam relative to the reference beam. FIGURE 3 shows a recirculating optical geometry [12] that compensates for beam shear due to changes in distance to the grating. After a first diffraction at the grating, the beam is reflected at a roof prism after passage through a refractive compensation element. A second cycle of diffractions in conjunction with the compensation element provide compensation for both tip/tilt as well as the beam shear due to changes in z.

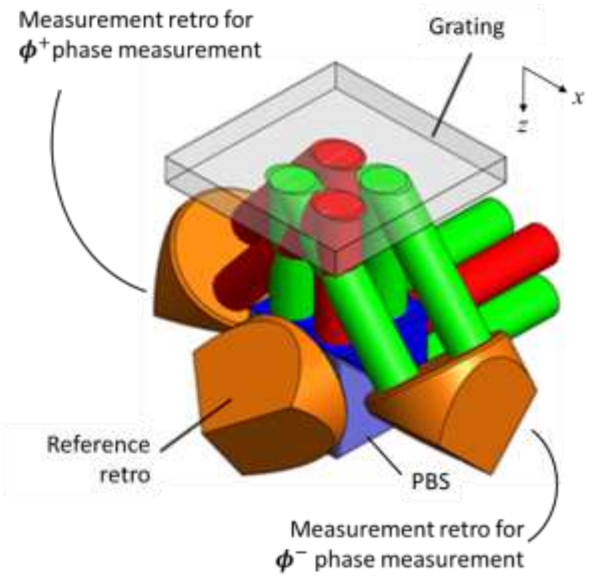

Figure 2. A two-axes encoder based on the concept shown in FIGURE 1.

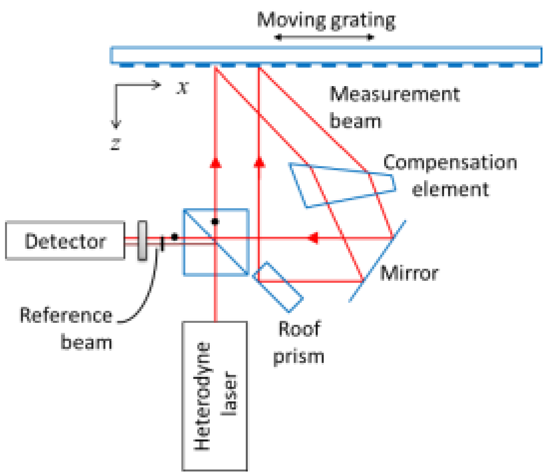

Figure 3. Conceptual drawing of a double-pass heterodyne encoder compensated for beam shear over large z-axis motions.

These new encoder designs are fed by specially designed 20mW, single-mode, frequency-stabilized HeNe laser [13] that provides adequate signal to compensate for the inherently low efficiency of the grating targets.

3. Performance

A critical measure of the performance of an encoder system in lithographic systems is its repeatability. This implies minimization of non-repeatable error components such as noise, periodic (cyclic) error and drift.

Polarization mixing, uncontrolled reflections, etc., cause cyclic errors that can easily surpass several nm [14]. To suppress these errors, the two orthogonally polarized beams are deliberately angled, greatly reducing the cyclic errors [15]. This, combined with advanced firmware for the suppression of residual errors [16], reduces residual cyclic errors to <0.05nm RMS for encoder heads in production. This has been evaluated on over a 100 production heads using Fourier techniques. Noise performance of these devices is less than 0.1 nm 3σ at a 20kHz bandwidth.

Sub-nm stability of these heads is ensured by careful location of the thermal centers by the design and location of constraints in conjunction with material selection, bonding, mounting and assembly techniques [17].

4. Conclusion

Optical encoders have displaced traditional interferometers for monitoring the critical stage motions in photolithographic semiconductor manufacturing. While the inherently shorter air paths in an encoder nearly eliminate the effects of air turbulence, their unprecedented levels of performance rely on careful optical designs, advanced mechanical and thermal design practices, and a range of signal processing and calibration techniques. Here we have reviewed basic concepts and geometries underlying the current state of the art for optical encoders for production lithographic tools.

References

[1] Yoda Y, Hayakawa A, Ishiyama S, Ohmura Y, Fujimoto I, Hirayama T, Shiba Y, Masaki K, and Shibazaki Y 2016 Next-generation immersion scanner optimizing on-product performance for 7nm node in Optical Microlithography XXIX, *Proc. SPIE.* **9780** 978012-978012-10

[2] Schmidt, R-H M 2012 Ultra-precision engineering in lithographic exposure equipment for the semiconductor industry. *Phil. Trans. of the Royal Soc. of London A: Mathematical, Physical and Engineering Sciences* **370** 3950-3972

[3] Butler H 2011 Position Control in Lithographic Equipment [Applications of Control] *IEEE Control Systems* **31** 28-47.

[4] Badami V and de Groot P 2013 Displacement Measuring Interferometry in *Handbook of Optical Dimensional Metrology*, ed K Harding (Taylor & Francis, Boca Raton) Chapter 4

[5] Hercher M and Wijntjes G J 1991 Interferometric measurement of in-plane motion, *Proc. SPIE* **1332** 602-612

[6] Kimura A, Gao W, Arai Y and Lijiang Z 2010 Design and construction of a two-degree-of-freedom linear encoder for nanometric measurement of stage position and straightness *Prec. Eng.* **34** 145-155

[7] Wang J L, Zhang M, Zhu Y, Wu Y F, Hu C X, and Liu Z 2014 A novel heterodyne grating interferometer system for in-plane and out-of-plane displacement measurement with nanometer resolution *Proc. 29th Annual Meeting of the ASPE* **59** 173-177

[8] Trutna WR Jr, Owen G, Ray A B, Prince J, Johnstone E S, Zhu M and Cutler L S 2008 Littrow interferometer. US Patent 7,440,113

[9] Slocum A H 1992 Optical Encoders. *Precision Machine Design*, Chap.4.3. Prentice Hall, Englewood Cliffs

[11] Deck L L, de Groot P J and Schroeder M 2012 Interferometric encoder systems. US Patent 8,300,233

[12] de Groot P, and Liesener J 2015 Double pass interferometric encoder system. US patent number 9,025,161

[13] Holmes M L, Shull W A and Barkman, M L 2015 High-powered, stabilized heterodyne laser source for state-of-the-art multi-axis photolithography stage control *Proc. 15th International Conference of euspen* 135-136

[14] de Groot P 1999 Jones matrix analysis of high-precision displacement measuring interferometers in Topical Meeting on Optoelectronic Distance Measurement and Applications, *Proc. ODIMAP IEEE LEOS*. **II** 9-14

[15] de Groot P and Schroeder M 2014 Interferometric heterodyne optical encoder system. US Patent 8,885,172

[16] Demarest F C 2014 Cyclic error compensation in interferometric encoder systems. US Patent 8,913,226

[17] Badami V G 2015 Thermally stable optical sensor mount. US Patent 9,200,892