euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

High-powered, stabilized heterodyne laser source for state-of-the-art multi-axis photolithography stage control

Michael L. Holmes, William A. Shull, and Michael L. Barkman

Zygo Corporation, an AMETEK Inc. Company, Middlefield, Connecticut 06457 USA

mike.holmes@ametek.com

Abstract
A new HeNe laser based system provides an unprecedented power output for interferometric stage control in photolithography systems. The high power level enables advanced position control strategies that include optical heterodyne encoders for high precision without sensitivity to air turbulence. This system is comprised of ten HeNe laser tubes each with a nominal 20 mW capability of single-mode wavelength-stabilized light. The 20 mW HeNe tubes require a laser cavity that is substantially longer than typical HeNe lasers. In our tubes, a narrow-passband intra-cavity etalon selects the longitudinal mode. Advanced digital control technology maintains the passband of the etalon at the center of the HeNe gain curve while simultaneously driving the optical resonance of the laser tube.
Combined with state-of-the-art Acousto-Optic Modulator (AOM) technology, this light source represents a significant advancement in heterodyne interferometry light sources providing for many axes of stage control in photolithography systems with < 4ppb (3-σ) wavelength stability. Our AOMs make use of anisotropic Bragg diffraction to achieve diffraction efficiencies in excess of 95%. The AOMs provide optical feedback isolation for the laser tubes while also generating the second beam for heterodyne interferometry. This technology provides excellent beam-purity with > 50 dB of isolation between output beam components with a tuneable heterodyne frequency set to 20 MHz. This relatively high frequency allows for stage velocities up to 8 meters-per-second all while maintaining 7-picometer stage-displacement measurement resolution.

Keywords: Stage control, laser, heterodyne, interferometer, encoder

1. Introduction

Displacement measuring interferometry (DMI) is the primary position measurement technology used in photolithographic stage metrology [1]. Advances in photolithography primarily focus on decreasing the minimum printed feature size. Decreasing the minimum feature size requires a more accurate knowledge of stage position thereby decreasing the allowable DMI measurement uncertainty. As the demands of DMI have become more rigorous, various sources of DMI measurement error have been mitigated in order to meet the arduous measurement uncertainty requirements. In recent history air-turbulence effects have been the single most significant contributor to DMI measurement uncertainty. Most recently, photolithography system makers have turned to optical heterodyne encoders to reduce the effects of air turbulence for critical stage motions [2]. These encoders require significantly more light than their free-space plane-mirror interferometer counterparts. Existing DMI light sources have insufficient power to source a system of heterodyne encoders of a necessary size and for this reason we have developed this new high-power stabilized heterodyne laser source. In section 2 of this paper we present the performance goals and summarize the methods used to meet these goals. In section 3 we present the optomechanical design. In section 4 we summarize the control strategies and present some performance data. In section 5 we make some closing comments and plans for future work.

2. Performance goal driven design methods

In order to meet the displacement measurement signal-to-noise requirements, we estimated that we would need a raw single-frequency 633 nm output power near 200 mW. As there are no currently viable solid-state laser sources that meet the beam quality requirements (i.e., narrow line-width, wavelength-stabilized, Gaussian beam profile, etc.), we opted to develop a HeNe based solution. To avoid environmental contamination of the laser intra-cavity optics, an internal mirror tube design was chosen allowing all optics to be within the vacuum envelope. We use ten of these lasers (as shown in figure 1) with sufficient tube length for a nominal 20 mW output each housed in a Laser Module, which are, in turn, housed in a Laser Base Module along with the Control Module.

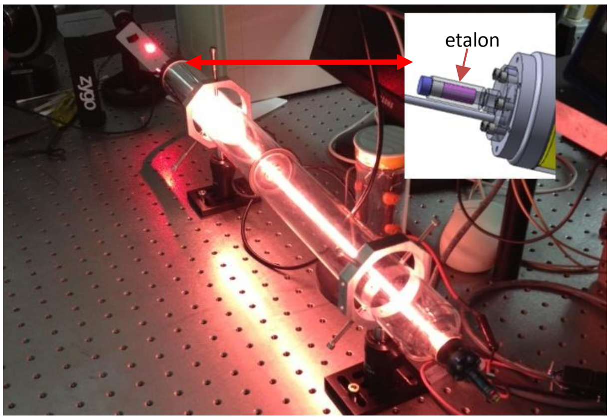

Figure 1. Zygo intra-cavity etalon 20 mW HeNe laser tube

The Free Spectral Range (FSR) of this laser is such that multiple longitudinal modes run simultaneously beneath the HeNe gain curve hence the need for the intra-cavity etalon. The position of the etalon's narrow passband beneath the HeNe gain curve is actively controlled as is the optical resonance of the laser tube. The primary goals of the control efforts are to 1) establish/maintain adequate output power, 2) find/maintain single-mode operation, and 3) stabilize the output wavelength. There is a power monitor and spectrum analyser built into each laser module that allows monitoring of the laser tube output power and spectrum, respectively. We developed high-efficiency AOM technology that provides optical feedback isolation for the laser tube as well as generates the two beams with a 20 MHz frequency split to source the optical heterodyne encoders [3][4].

3. Optomechanical design summary

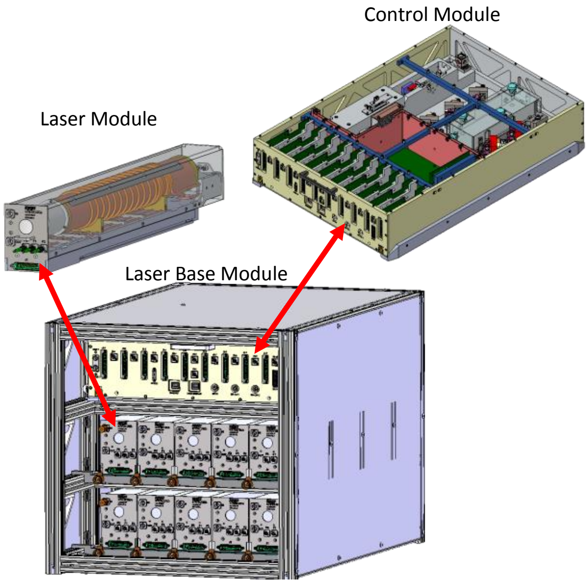

Figure 2. High-power Laser System

The solid models for the laser, control, and laser base modules are shown in figure 2. This system dissipates about 580 W all but about 200 mW in the form of heat. We use active cooling (circulating liquid coolant) to remove the significant portion of this heat in a controlled manner. Single-mode fibers (not shown) direct the light to the optical heterodyne encoders (also not shown) and to the control module as required in support of the control efforts. The control module contains ten laser driver cards each containing one control-effort-dedicated Field Programmable Gate Array (FPGA). Also contained in the control module is a wavelength-stabilized reference laser to which each of the ten lasers is actively locked. The reference laser beam is mixed with a raw sample from each of the ten laser tube outputs via a heterodyne module also contained in the control module. The ten mixed optical signals are directed to corresponding laser driver cards via multi-mode fibers. Each laser driver card contains a transimpedance amplifier to convert the optical signal into an electrical signal, which is then used as the feedback signal to the wavelength stabilization controller. The ten laser driver cards reside in a bus contained on the “motherboard”. This motherboard contains a microprocessor and a FPGA for system-level functions (i.e., clock generation, program interface to FPGAs, system initialization and control, etc.). The motherboard also contains the wavelength stabilization controller for the reference laser and is affixed to the bottom of the control module.

4. Control

The control of the etalon passband beneath the HeNe gain curve is actively controlled. A thermistor mounted on top of the etalon heater provides the temperature feedback signal. The etalon passband is positioned to maximize the output power from the tube. We simultaneously measure the tube’s output power via a slow detector mounted near the anode-end (rear) of the laser. Similarly, the optical resonance of the laser tube is controlled via the laser tube’s temperature. The two thermal systems have been designed to sufficiently decouple their responses thereby allowing individual controllers working independently of one another. The laser module control effort begins with a three-stage initialization followed by a hand-off to the wavelength stabilization controller. The first stage of initialization establishes an etalon and laser tube temperature bias. The second centers the etalon passband beneath the HeNe gain curve. The third centers one of the laser’s longitudinal modes within the etalon passband. Figure 3 contains wavelength stability data in the top graph, output power data in the middle graph, and etalon temperature data in the bottom graph. The etalon is responding to 2°C ambient temperature excursions. Note the strong correlation between etalon temperature and output power and the lack of similar structure in the wavelength stability data, on scales of interest.

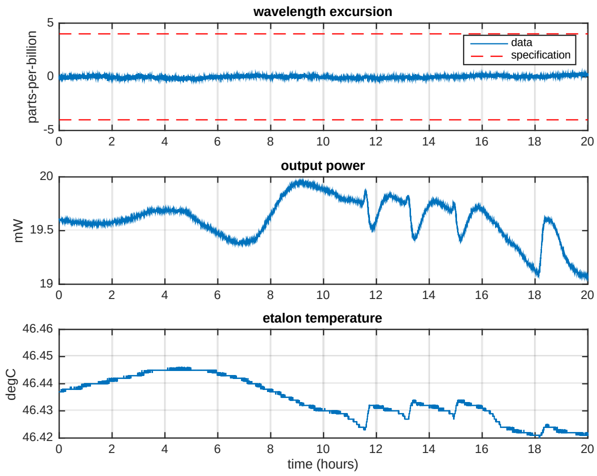

Figure 3. Performance data

5. Summary and future work

The new high-power stabilized heterodyne laser source enables state-of-the-art multi-axis photolithography stage control based on heterodyne optical encoders. We have shown internal mirror HeNe laser tubes to be a viable solution for power demanding applications. Future work will be focused on a solid-state solution, which offers the promise of less expensive light.

References

[1] Badami, V. and de Groot, P., "Displacement Measuring Interferometry," in Handbook of Optical Dimensional Metrology, chapter 4, pp. 157-238 (Taylor & Francis, Boca Raton, 2013)

[2] de Groot, P. and Liesener, J. "Double pass interferometric encoder system," US Patent Application 20130114061, 2013.

[3] Sommargren, G. E. "Apparatus to transform a single frequency, linearly polarized laser beam into a beam with two, orthogonally polarized frequencies," US Patent 4,684,828 (1987).

[4] Hill, H. A. "Apparatus for generating linearly-orthogonally polarized light beams," US Patent 6,157,660 (2000).