Laser Interferometer Implementation

Laser interferometers represent the ultimate feedback device for high-precision motion control applications. The combination of high resolution and outstanding accuracy has made it the ideal transducer for wafer steppers, flat panel inspection, and high-accuracy laser micromachining.

A laser interferometer system employs a highly stabilized light source and precision optics to accurately measure distances. Interferometers are superior to glass encoders for several reasons. The most obvious advantage is that interferometers have greater inherent accuracy and better resolution. An additional advantage is that interferometers measure distances directly at the workpiece. Due to mounting considerations, linear encoders are often "buried" inside the positioning stage, some distance away from the work piece, introducing an additional source of error. A well-designed interferometer system is able to take measurements directly at wafer height, maximizing accuracy.

Theory of Operation

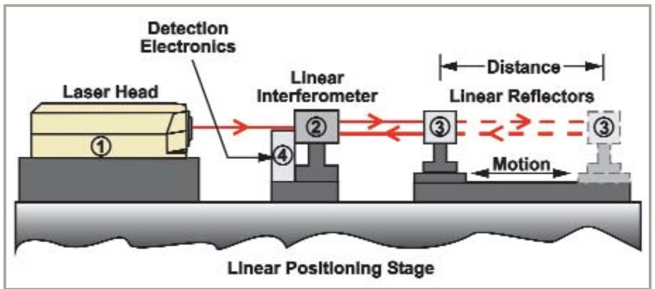

Figure 1: Basic elements of a single-axis laser interferometer system.

A typical laser interferometer system is based on the Michelson interferometer. It is composed of (refer to Figure 1): (1) a light source, in this case a frequency stabilized He-Ne laser tube; (2) a linear interferometer optic that is made by the combination of a polarizing beam-splitter and retroreflector; (3) a moving linear retroreflector; and (4) detection electronics. When the laser light reaches the interferometer optic, it is separated into two distinct beams (Figure 2). The first beam is reflected back to the detectors and is used as a reference beam. The second beam passes through the optic and is reflected off a moving retroreflector to provide the measurement beam. Due to the motion of the moving retroreflector, the second beam undergoes a shift caused by relative motion of the beam. When the reference beam and measurement beam recombine, they create an interference pattern.

The interference fringe appears as a dark and bright pattern (Figure 3). The intensity of this pattern is a sinusoidal

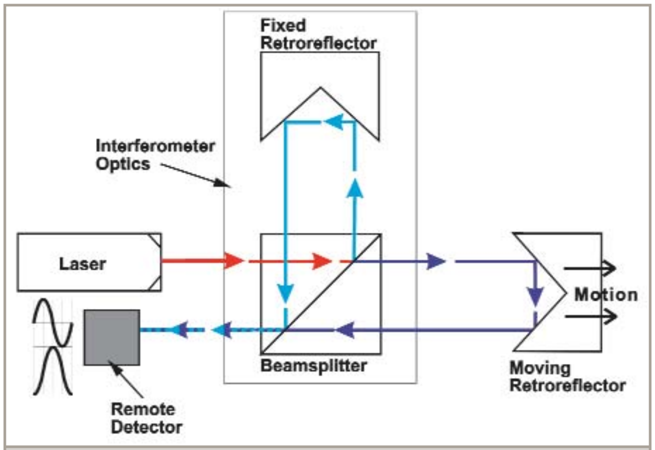

Figure 2: Optical beam paths for a simple interferometer-based position measurement system

signal that can be treated similar to a standard A-quad-B encoder signal. As an example, Aerotech's MXH-250 series high-resolution multiplier is capable of multiplication up to x1024 (Aerotech offers an MXH-500 with x2048). Since the fundamental wavelength (λ) of the laser light is 633 nm, and the signal output to the multiplier electronics is $\lambda/2$, the effective resolution of the system can be as low as 0.3 nm when utilizing a retroreflector-based system. Two-dimensional systems, which utilize plane mirror optics instead of retroreflectors, benefit by an optical doubling effect which improves the maximum resolution to 0.15 nm.

There are two basic approaches to the detector electronics. The simplest method is to incorporate the detector in the same housing as the laser. This provides a compact system and is best suited for single-axis applications. For multi-axis applications, use of a remote detector is highly recommended. Some remote detection systems embed the detection photodiodes in the same housing as the interferometer optics for optimal beam stability. When coupled with appropriate beam-splitting optics, this allows one laser head to be used as the source for multiple axes. This is useful for XY systems, or systems with active yaw control. Not only does purchasing a single laser source reduce the cost of the laser system, but valuable footprint space is saved, as well.

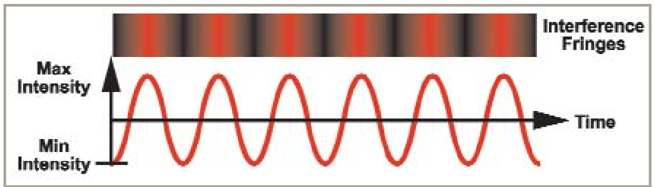

Figure 3: Interference fringe patterns created by combination of reference and measurement beam.

Laser Interferometer Implementation CONTINUED

Interferometer Implementation

A typical dual-axis implementation is illustrated in Figure 4. To ensure that a beam path is provided at all locations throughout stage travel, two-dimensional implementations require the use of plane mirror optics. The plane mirror implementation has the added benefit of optically doubling the laser signal, resulting in a fundamental resolution of $\lambda/4$. A single laser source is split to provide a signal to all axes of measurement, which in this example are the X and Y axes. These beams are steered to the interferometer optics and plane mirrors prior to their measurement at a remote detector. The detector electronics are located in the same housing as the interferometer optics, providing a compact solution. Some existing laser interferometer solutions require a signal processing board that interfaces directly to the motion controller. In many cases this is done so as to provide a parallel word directly to the motion controller, which allows for high data rates. While this may be required in high-speed, high-resolution applications, this solution has the distinct disadvantage of making the laser interferometer a proprietary, closed-architecture solution. Interfacing to both the interferometer board and motion controller requires an in-depth knowledge of both devices that is often impractical for most users.

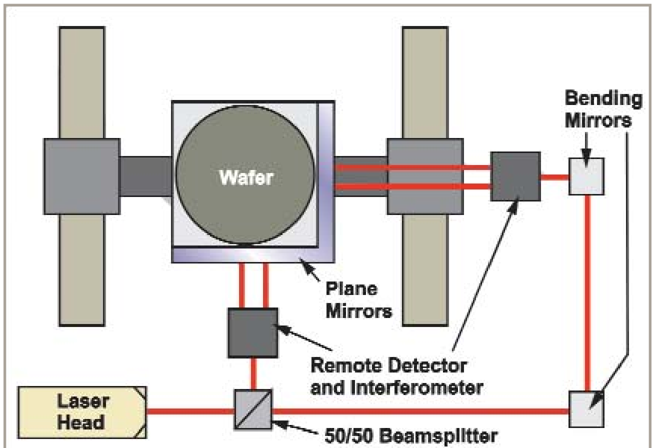

Figure 4: Dual-axis implementation using single laser source and remote detectors

Advances in motion controller technology have nearly made this approach obsolete. Interferometer output signals that are standard A-quad-B are electrically identical to the output of a traditional incremental encoder. To the motion controller, the interferometer appears to be a standard feedback device, simplifying system implementation. Aerotech's stand-alone and PC-bus-based controllers employ high-speed devices, resulting in serial data rates as high as 32 MHz. For a system with a resolution of 6 nm, that results in a speed of nearly 200 mm/s. While Aerotech also manufactures a laser interferometer signal processing board for high-speed applications, the need for this approach has been greatly minimized and often the much simpler serial approach proves to be the optimal solution.

While the position feedback may be straightforward to process, there are other important considerations that must be made when implementing a laser interferometer-based system. Issues such as home-marker implementation, losses of feedback signal, and error-source reduction require unique solutions in an interferometer-based system.

Since the interferometer is strictly an incremental device, there is no way to establish an accurate home reference. Traditional home devices such as LVDTs and optical proximity switches are only adequate in establishing an approximate home. For accurate wafer measurements, it is often necessary to acquire a fiducial directly from the wafer to establish a sufficiently accurate and repeatable home. Once the mark is acquired, the motion controller counters can be reset to zero (software homed) and the processing continues.

When implementing a laser interferometer as a feedback device it is absolutely necessary for the interferometer to provide a "beam blocked" signal. Unlike a linear encoder that places the read head in close proximity to the encoder glass, it is easy to block the feedback signal (in this case the laser beam) in an interferometer system. This condition requires the motion controller to immediately generate a fault condition and disable the axes.

Minimize Potential Error Sources

The same requirements that necessitate the use of a laser interferometer – high resolution and high accuracy – require that system-wide error sources be minimized. While it is inherently more accurate than alternate feedback schemes, without proper understanding of the error sources it will be no more effective than a low-cost linear encoder. Environmental conditions, mechanical design, and optical alignment must be considered in the design/implementation of any high-accuracy laser interferometer-based motion system.

Environmental Errors

The wavelength of light emitted by a He-Ne laser is by definition equal to 632.99072 nm in a vacuum. Interferometer accuracy in a vacuum is accurate to ±0.1 ppm. However, most applications require operation of the system in atmospheric conditions, so this accuracy degrades. The index of refraction of air effectively changes the frequency of the laser light which appears as a path length difference. Fortunately, the effects of temperature, pressure, and humidity as they affect the wavelength of light are well known and are related by Edlen's equation. As a result, some interferometer systems incorporate a "weather station" that samples the environmental conditions. These signals are digitized and processed to create a wavelength scale number that is used to generate a correction factor. An environmentally corrected system will have an accuracy of ±1.5 ppm or better. The final accuracy is largely a function of the stability of the environmental conditions.

Environmental Effects on Accuracy

Temperature:	1 ppm / 1°C
Pressure:	1 ppm / 2.5 mm Hg
Humidity:	1 ppm / 85% change

The most effective, and incidentally also the most expensive, means of compensating for changes in the refractive index of air is by utilization of a wavelength tracker. Also known as a refractometer, a wavelength tracker measures the relative change in the refractive index of air. Because it is a relative measure only, initial environmental conditions must be known and computed to establish an initial wavelength scale factor. The wavelength tracker is a purely optical device that is highly accurate, but is only used in very high-end applications due to its high cost.

Mechanical Vibration and Air Turbulence

Mechanical vibration or air turbulence can cause perturbations in the positioning feedback system that will limit overall system performance. Mechanical vibration errors can be minimized through proper design of the machine base vibration isolation system. Thermal gradients across the beam path are created due to turbulence in the air so careful design of the machine micro-environment is critical to subnanometer performance. A simple and effective means of minimizing these effects is to "shield" the beam by placing a tube around the system or simply by minimizing the flow of air.

Mechanical Errors

For truly cutting-edge performance, an XY system must utilize a high-performance positioning system made up of air-bearings mounted to a granite base. Air-bearing stages, with their superior geometric characteristics, are highly recommended for all laser interferometer-based systems, while the granite provides an extremely flat reference surface as well as good thermal stability. Without outstanding linear stages as the basis of operation, Abbe errors will drastically undermine the accuracy of the laser measurement system. Abbe errors are linear displacement errors that are caused by an angular deviation in the axis of motion. A properly designed system will place the center of the measurement mirror as close to the work piece as possible. By tracking the motion of the actual part under test, as opposed to the stage itself, the effect of any pitch/yaw deviations is vastly reduced. When combined with a linear stage system that is inherently geometrically accurate, Abbe errors are nearly eliminated.

Dead-Path Error

A less obvious source of error occurs as a result of both the environment and mechanical placement of the optics. This error is known as dead-path error and is caused by portions of the beam that are effectively uncompensated (Figure 5). While the moveable reflector translates throughout the measurement path, environmental compensation electronics compute and correct for the change in the index of refraction of air. The dead path is a distance that the laser beam travels where it undergoes no relative motion. Since the environmental compensation scheme only corrects for relative motion, this distance remains uncorrected. If uncorrected, the dead-path error effectively moves the zero point (X_0) of the system as the environmental conditions change. There are several means of addressing this, but the most straightforward ones are to compensate for the error or eliminate it. Software compensation for the dead path error requires an additional calculation to be performed that not only accounts for temperature, pressure and humidity, but for the dead-path distances as well. Mechanical compensation entails separating the interferometer's retroreflector from the beam-splitter by a distance equal to the dead-path error. As a result, both the measurement beam and reference beam have equal dead-paths that cancel each other out. This approach requires careful alignment of the optics and assumes that the environmental conditions are identical for both dead-paths.

Elimination of the dead-path requires that the linear interferometer optics be placed as close to the zero point of the moveable reflector as possible. As a rule of thumb, when the optics are placed within 50 mm of each other, the error due to dead-path is negligible.

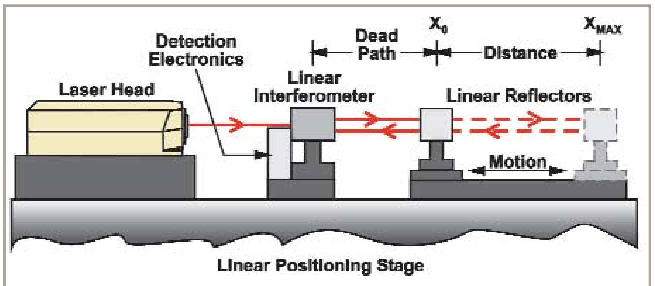

Figure 5: Illustration of dead-path in an interferometer system

Laser Interferometer Implementation

Alignment Errors

Assuming that the mechanical sub-system is sound, and environmental correction is properly implemented, the final pieces to the puzzle are the optics themselves and their alignment. All optics have inherent inaccuracies in the form of optical non-linearity. This error cannot be controlled by the user, and is a function of the quality of the optics. All interferometer optics will have some amount of nonlinearity, so this error cannot be completely eliminated but is minimized by the use of high quality optics.

An optical error that can be controlled by the user is a misalignment that is commonly known as cosine error. Cosine error occurs when the laser beam path and the axis of stage motion are not completely parallel. The relationship is best modeled as a triangle where the laser beam represents one leg of the triangle, and the actual motion is the hypotenuse (Figure 6). This error can be minimized through careful alignment of the optics to the stage.

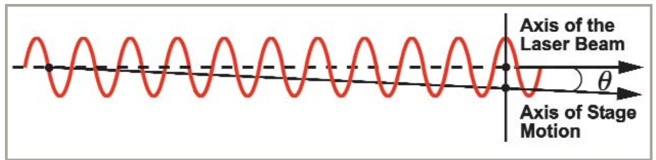

Figure 6: Illustration of cosine error