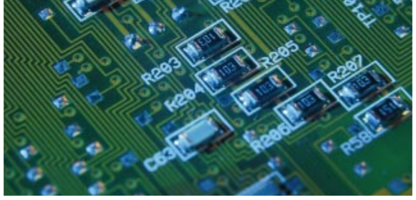

SEMICONDUCTOR MANUFACTURING

Simpler feedback for precise positioning

Advances in technology have made it easier to use laser interferometers in precision motion control.

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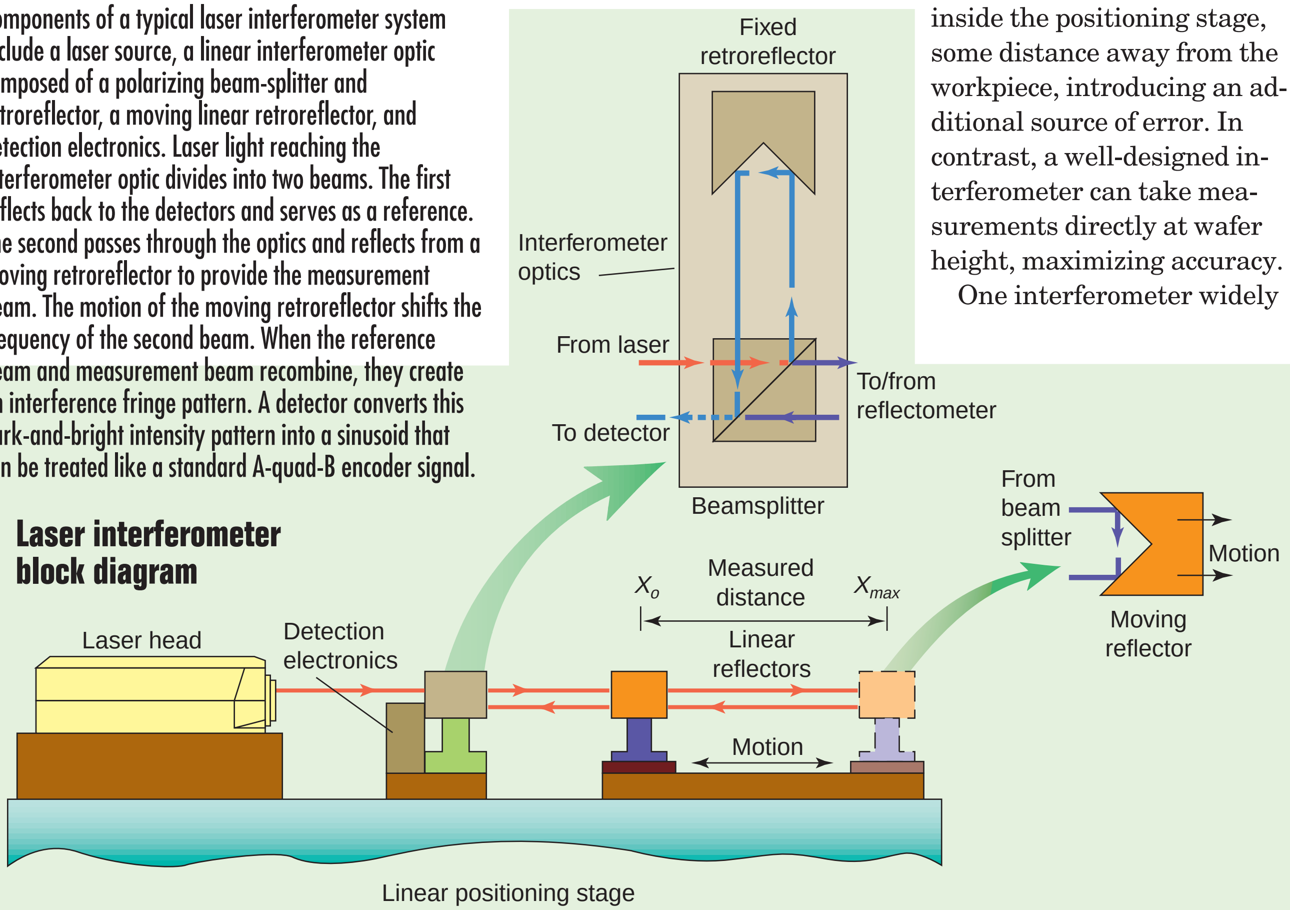
Laser interferometers represent the ultimate feedback device for high-precision semiconductor processing and inspection. As feature sizes shrink, the accuracy of motion systems has had to increase. Just as linear motor-driven air bearings have supplanted ball-screw-driven mechanical bearing stages, linear interferometers are becoming the feedback device of choice in semiconductor inspection. Now integral elements of wafer steppers, laser interferometers are showing up in an increasing number of wafer-inspection applications.

A laser interferometer 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. Mounting considerations often force linear encoders to be "buried" inside the positioning stage, some distance away from the workpiece, introducing an additional source of error. In contrast, a well-designed interferometer can take measurements directly at wafer height, maximizing accuracy.

One interferometer widely

Components of a typical laser interferometer system include a laser source, a linear interferometer optic composed of a polarizing beam-splitter and retroreflector, a moving linear retroreflector, and detection electronics. Laser light reaching the interferometer optic divides into two beams. The first reflects back to the detectors and serves as a reference. The second passes through the optics and reflects from a moving retroreflector to provide the measurement beam. The motion of the moving retroreflector shifts the frequency of the second beam. When the reference beam and measurement beam recombine, they create an interference fringe pattern. A detector converts this dark-and-bright intensity pattern into a sinusoid that can be treated like a standard A-quad-B encoder signal.



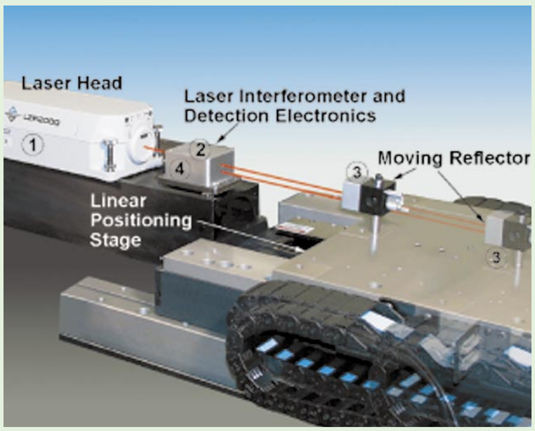
Laser interferometer block diagram

applied in semiconductor processing comes from Aerotech Inc. This device is based on the Michelson Interferometer. It includes a light source, in this case a frequency stabilized He-Ne laser tube; a linear interferometer optic composed of a polarizing beamsplitter and retroreflector; a moving linear retroreflector; and detection electronics. When the laser light reaches the interferometer optic, it divides into two distinct beams. The first reflects back to the detectors and serves as a reference beam. The second passes through the optic and reflects from a moving retroreflector to provide the measurement beam. The motion of the moving retroreflector shifts the frequency of the second beam. When the reference beam and measurement beam recombine, they create an interference pattern.

The interference fringe appears as a dark and bright pattern. The intensity of this pattern is a sinusoid that can be treated like a standard A-quad-B encoder signal. The Aerotech MXH-Series high-resolution multiplier can multiply such signals by factors of up to 1,024. Because the fundamental wavelength of the laser is 633 nm, and the signal output to the multiplier electronics is half that value (half wavelength), the effective resolution can be as low as 0.3 nm (from 633 nm/2/1,024) using a retroreflector-based system. Two-dimensional systems, which use plane mirror optics instead of retroreflectors, benefit by an optical doubling effect that improves the maximum resolution to 0.15 nm.

There are two basic approaches to detector electronics. The simplest combines the detector and laser source in the same housing. This makes the system compact and works best for single-axis applications. For multiaxis applications, a remote detector is preferred. The Aerotech LZR-Series remote-detection systems, for example, embed the detection photodiodes in the same housing as the interferometer optics for optimal beam stability.

When coupled with appropriate beam-splitting optics, this lets one laser head serve as the source for multiple axes. Such a configuration is useful for *XY* systems, or even for *XY* systems with active yaw control. Purchasing a single laser source not only cuts costs, but also saves valuable footprint space.

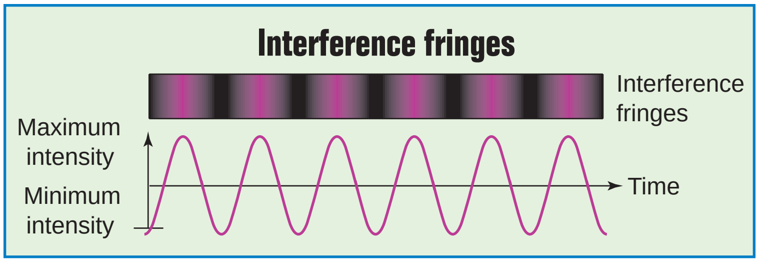


MAKING MEASUREMENTS

Two-dimensional implementations must ensure that there is a beam path at all locations throughout the stage travel. This requires the use of plane-mirror optics.

The plane mirror implementation has the added benefit of optically doubling the laser signal, providing a fundamental resolution of a quarter wavelength. A beam-splitting optic splits the single laser source to produce a signal for all axes of measurement which, for 2D instruments, are commonly the *X* and *Y* axes. These beams are steered to the interferometer optics and plane mirrors before they're measured at a remote detector. The detector electronics sit in the same housing as the interferometer optics, for compactness.

Some existing laser interferometers require a signal processing board that interfaces directly to the motion controller. In many cases designers take this approach to provide a parallel word directly to the motion controller, thus allowing high data rates. However, the disadvantage of this scheme is that the resulting laser interferometer has a proprietary, closed architec-



Interference fringe patterns are created by a combination of reference and measurement beams. They create a sinusoidal intensity pattern that detector electronics convert into A-quad-B signals analogous to those of ordinary incremental encoders.

ture. It takes an in-depth knowledge of both the interferometer board and motion controller to do the required interfacing, making the task impractical for most users.

Advances in motion controller technology have nearly made this approach obsolete, at least for applications that don't demand super high speeds. Modern designs make the interferometer appear as a standard feedback device. For example, output signals from the Aerotech LZR-Series laser interferometer are standard A-quad-B, electrically identical to the output of a traditional incremental encoder. Today's motion controllers increasingly employ high-speed electronics that permit serial data rates as high as 32 MHz. For a system with a resolution of 6 nm, the resulting speeds can be nearly 200 mm/sec. All in all, interferometer signal-processing boards still have a high-speed niche, but the much simpler serial approach often proves to be optimal.

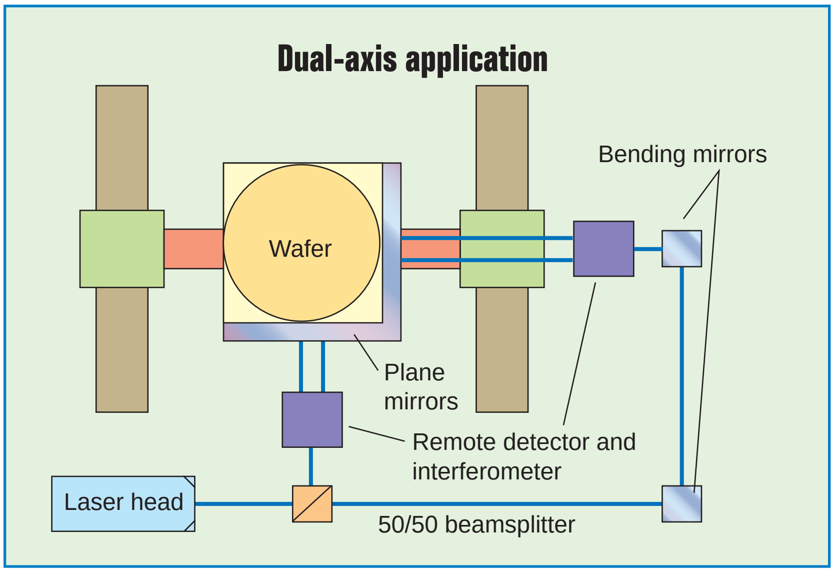
ERROR PROOFING

Several considerations enter into the design of a system that uses laser interferometer feedback. Some of the most important issues include home marker implementation, handling loss of feedback, and reducing the effects of error sources.

Because the interferometer is strictly an incremental device, there is no way it alone can establish an accurate home reference. Traditional home devices such as LVDTs and optical or proximity switches are adequate to establish an approximate home only. The high precision involved in wafer measurements necessitates a highly accurate and repeatable home. In many applications a registration mark is acquired directly from the wafer itself. Once the motion controller acquires the mark, its counters reset to zero (software homed) and processing continues.

It is absolutely necessary that the interferometer provide a "beam blocked" signal and that the motion controller has proper fault logic to process it. Unlike a linear encoder, where the read head is in close proximity to the encoder glass, it is easy to block laser-feedback signals. This condition requires the motion controller to immediately generate a fault condition and disable the axes. Loss of feedback in a servosystem can lead to a runaway condition and potential damage.

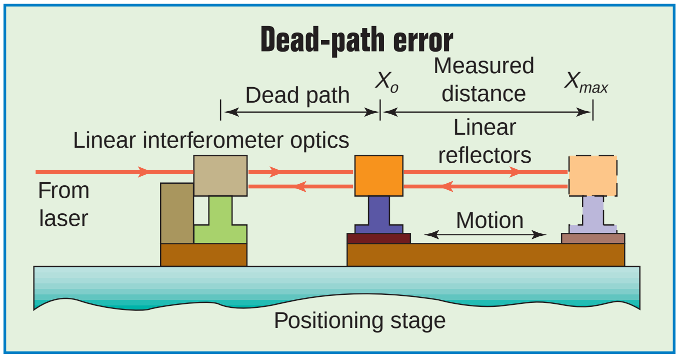
The same factors that necessitate use of a laser interferometer — high resolution and accuracy — require a system-wide minimization of error sources. Without proper regard for error sources, laser interferometers will perform no more effectively than a low-cost linear encoder. Environmental conditions, mechanical design, and optical alignment all enter



A typical dual-axis implementation of a laser interferometer employs a single laser source and two remote detector/interferometer optics stations, one for each axis. With accuracies of ±1.5 ppm and resolution in the subnanometer range, laser interferometers not only have resolution and accuracy better than glass-scale encoders, but also have the advantage of measuring motion directly at the wafer under test.

into the design.

The wavelength of light emitted by a He-Ne laser is by definition 632.99072 nm in a vacuum. Interferometers in a vacuum are accurate to ±0.1 ppm. But most applications operate in atmospheric conditions, so this accuracy degrades. Air's index of refraction effectively changes the frequency of laser light, which appears as a path length difference.



Dead-path error arises from the distance over which the laser beam travels where it undergoes no relative motion. Dead-path error effectively moves the zero point (X_0) of the system as environmental conditions change. Software compensation for the dead-path error requires an accounting for temperature, pressure, humidity, and for dead-path distances. 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.

Fortunately, the effects of temperature (1 ppm/°C), pressure (1 ppm/2.5-mm Hg), and humidity (1 ppm/85% change) on the wavelength of light are well known. As a result, all high-accuracy interferometers incorporate a "weather station" that samples the environment. These signals are digitized and processed to create a wavelength scale number that is used as a correction factor. Environmentally corrected systems will have accuracies of ±1.5 ppm or better. The final accuracy is largely a function of the stability of environmental conditions.

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

TURBULENCE

Mechanical vibration or air turbulence can cause perturbations in the positioning feedback system and limit its performance. A well-designed machine base and isolation system will limit vibration effects. Air turbulence is an often overlooked factor that must also be considered. Thermal gradients across the path are created by this turbulence, so the machine microenvironment is critical to subnanometer performance.

A simple and effective means of mini-

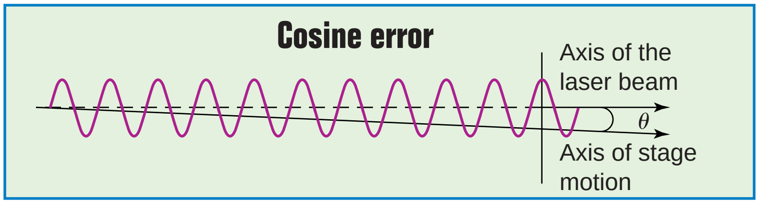
Laser feedback key to next-generation wafer stage

Not only must next-generation wafer-processing systems outperform their predecessors, they must also work seamlessly with older equipment. Backward compatibility is a must because most wafer-inspection machines have several man-years of software and hardware development.

Such was the challenge when a major wafer-inspection company needed to upgrade its *XY* stage platform. The new machine was to be a high-performance *XY* air-bearing system with 2.4-nm resolution. The feedback scheme, besides providing higher resolution and speed, had to work with an existing real-time data-acquisition system designed around the linear encoders used in the previous generation machine.

High resolution and repeatability made a laser interferometer the obvious choice . But a parallel interface board, which had enough bandwidth to handle the speed and data rate, was not an option because it would have required making big hardware and software changes in the inspection machine. Development speed was an issue and there was no time to redevelop analysis routines-

The solution involved mating the laser interferometer output to a high-speed MXH-Series resolution multiplier box and then to a Unidex 500 PCI-bus-based motion controller, both from Aerotech Inc. With a system data rate of 32 MHz, the final speed was nearly 80 mm/sec. The output from the multiplier box was standard A-quad-B, minimizing the hardware integration effort.



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, and the actual motion is the hypotenuse. Careful alignment of the optics to the stage can minimize this effect.

mizing such effects is either to "shield" the beam with a tube or to simply minimize airflow. But there is a trade-off because systems often need "downdraft" airflow to maintain wafer cleanliness.

For truly cutting-edge performance, an *XY* positioning system must use air bearings mounted to a granite base. Air-bearing stages have superior geometrical qualities, while granite provides an extremely flat reference surface as well as good thermal stability. In the absence of outstanding linear stages, Abbe effects will drastically undermine the accuracy of the laser system. Abbe errors are linear displacement errors caused by an angular deviation in the axis of motion.

A properly designed system will place the center of the measurement mirror in the same plane and same axial orientation as the wafer under test. The effect of any pitch/yaw deviations drops drastically by tracking the motion of the actual part under test, as opposed to the stage itself. This practice combined with a linear stage system that is inherently geometrically accurate nearly eliminates Abbe errors.

A less obvious source of error arises from the environment and mechanical placement of the optics. Known as dead-path error, it is caused by portions of the beam that are effectively uncompensated.

The moveable reflector translates throughout the measurement path, and environmental compensation electronics correct for the change in the index of refraction of air. But the environmental compensation scheme only corrects for relative motion. The distance over which the laser beam travels where it undergoes no relative motion remains uncorrected. Absent of any further correction, the dead-path error effectively moves the zero point (X_0) of the system as environmental conditions change.

There are several means of addressing dead-path error, but the most straightforward ones are to compensate for the error or eliminate it. Software compensation for the dead-path error requires performing an additional calculation that not only accounts for temperature, pressure, and humidity, but also for dead-path distances. 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 both dead-paths have identical environmental conditions.

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

Assuming the mechanical subsystem is sound, and environmental correction is properly implemented, the final pieces of the puzzle consist of the optics themselves and their alignment. All optics have inherent inaccuracies in the form of optical nonlinearity. The user can't control this error as it is a function of the optical quality. Because all interferometer optics will have some nonlinearity, this error cannot be completely eliminated. But high-quality optics can minimize it.

Cosine error is an optical misalignment error that the user can control. 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, and the actual motion is the hypotenuse. Careful alignment of the optics to the stage can minimize this effect. ■