Revelations in the Art of Fringe Counting: The State of the Art in Distance Measuring Interferometry

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1 Fringes for Distance Measurement

The ancestral roots of the Fringe conference are in the automatic processing of fringe patterns. When we think of *patterns*, an image comes to mind of flowing lines beautifully wrapped around surface contours. But automatic processing of fringes is not limited to this kind of pattern: The fringes may be laid out along a line of sight as the time history of an object displacement, captured by a detector and processed to tell us something about how the object has moved, or more generally, where the object is with respect to a reference point in space.

This paper is about distance measurement interferometry, summarizing the current state of the art in this century-old technique. High-performance distance measurement today is highly refined; encompassing gravitational wave detectors to commercial systems that measure to better than a nanometer while the object is rapidly changing orientation and position [1]. This short overview will concentrate on applications relevant to the photolithography industry—one of the most important consumers of high-performance metrology systems today. In this context, we shall have a look at modern stage position monitoring as well as multi-point fiber sensors for high-precision absolute position.

2 Stage Position Monitoring

In its most elemental form, *displacement* measuring interferometry or DMI for stage positioning measures the *change* in position of an object by observing the passage of fringes. Modern systems achieve a relative resolution better than 1 part in 10^9 at data rates of several MHz along multiple measurement axes. DMI is used extensively for calibration and servo control of mechanical stage motions in precision machining, microlithography, e-beam mask writing, and scanning electron microscopy.

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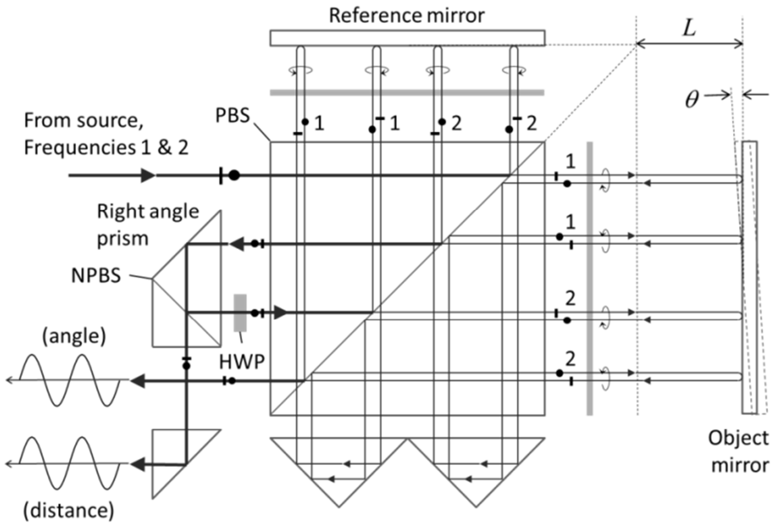

Fig. 1 Modern high-stability dual-axis (distance and angle) interferometer for stage motion [2]

Fig. 1 shows a DMI system for monitoring the linear displacement of a stage. Although some instruments employ homodyne detection, most state-of-the-art high-precision, multi-axis interferometer systems are heterodyne. The modulated laser head provides two collinear collimated beams of orthogonal polarizations and slightly different frequencies so as to generate a heterodyne beat signal when combined [3, 4]. The interferometer optics separate the polarizations and direct them to the object and reference mirrors in a double-pass configuration such that the beams recombine at the detector without tilt fringes, independent of small-angle variations in the stage mirror orientation. The interferometer in Fig. 1 monitors both displacement and one angle [5]. Monolithic interferometers compare the relative two-angle orientation, straightness of motion and position of stage components with respect to subsystems or a fixed metrology frame [6]. Specialized interferometers monitor changes in the environment [7] as well as the overall stability of the structure that carries the stage and photolithography projection optics.

High-speed electronics interpret the heterodyne beat-signal phase and report stage position. Phase detection involves sliding-window Fourier methods with embedded data age and cyclic error correction [8-11]. Typical performance characteristics include sub-nm uncertainty for stage metrology at velocities of up to 2 m/s. The stage motion is fast enough that the electronics must take into account the amount of time that it takes for the interference information traveling at the speed of light to reach the data processing unit. Detailed uncertainty analyses are mandatory when controlling for photolithography overlay budgets and other demanding applications [12, 13]. Stage metrology solutions measure dozens of orientation and position parameters in production photolithography systems, as shown in Fig. 2.

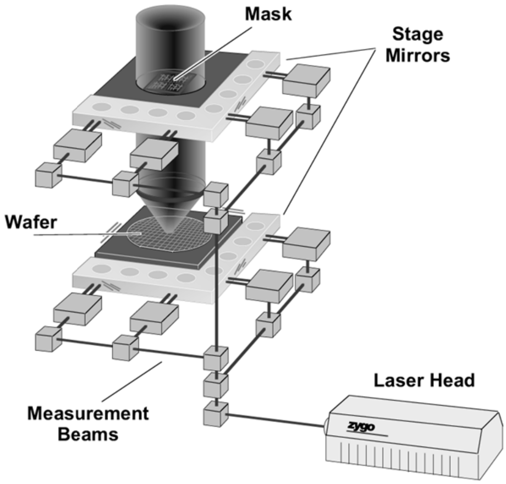

Fig. 2 Photolithography stage measured by heterodyne interferometry. Modern systems have multiple measurement axes and include optical encoders such as the subsystem shown in Fig. 3.

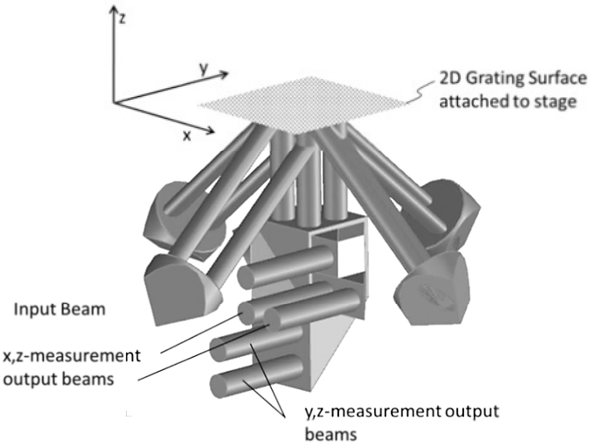

Fig. 3 Optical heterodyne encoder based on DMI components and a for monitoring the in-plane and out-of-plane motion of a 2D diffraction grating [14]

Metrology systems are becoming more complex with the continuing reduction in feature size of semiconductor electronics, but continue to be based on the basic principles of highly-refined fringe counting. Most recently, photolithography systems have moved towards optical encoders as a means of overcoming the problem of air turbulence [14-18]. Here the "fringes" are physically imprinted on 2D grid and monitored by new optical configurations such as the three axis heterodyne encoder illustrated in Fig. 3.

3 Fiber Sensor for Ultra-precision Positioning

High-accuracy, interferometric fiber-based distance sensors represent a new generation of devices that combine compact size with installation flexibility. Interferometric sensors eliminate the range-resolution trade off characteristic of capacitance and intensity based fiber sensors. The new sensors enable high-resolution (pm) measurements over macroscopic ranges (mm). This class of sensors addresses metrology applications for the measurement of both *displacement* and *absolute distance* without phase ambiguity over short ranges, providing the ability to establish an absolute home position in a manner similar to capacitance gages.

Numerous requirements drive the design of such systems for position monitoring in advanced photolithography systems including sub-nm drift over extended periods (hours), zero heat dissipation in the sensing elements, extremely high reliability (many years with negligible chance of failure) to prevent system down time, flexibility in the location of sensors, compact sensor size, a clearly defined (and accessible) measurement datum and insensitivity to electromagnetic interference (EMI).

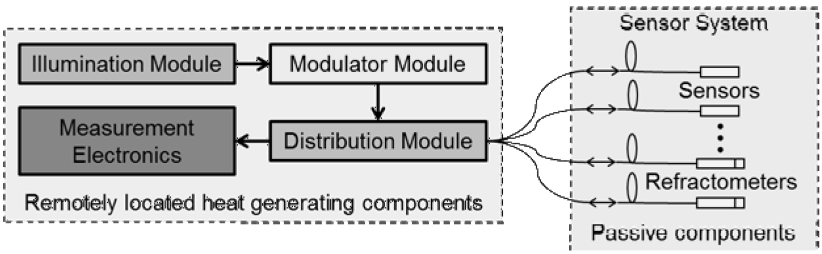

Fig. 4 Fiber interferometer system architecture

Fig. 4 depicts the modular architecture of the system which segregates the portions that may require maintenance/replacement from the passive high-reliability sensors that are embedded within restricted access areas [19, 20]. This architecture confines the heat generating components to locations outside the thermally controlled envelope. A spectrally broad light source whose mean wavelength can be set at three discrete values provides illumination. While only one wavelength is required for displacement measurement, the multiple wavelengths and the method of exact fractions enable the establishment of the absolute position of the target relative to the measurement datum [21]. The modulator module imparts a phase modulation to the incoming illumination to enable the recovery of phase information in the measurement electronics. The optical distribution module that follows directs the modulated illumination to a multiplicity of sensors in the sensor subsystem. It also recovers the reflected light from the reference surfaces of the sensors and targets and directs it to the measurement electronics. Sensors can be configured to sense position or refractive index of the medium of operation. The measurement electronics convert the optical signals into electrical signals and ultimately produce a position or index readout.

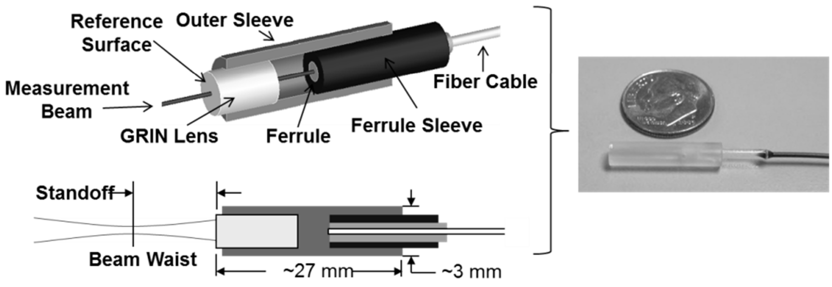

Fig. 5 Details of position sensor construction

The entirely passive position sensor element depicted in Fig. 5 leverages the reliability of telecommunication components and construction techniques. The exposed surface of the GRIN (gradient index) lens forms one side of the interferometer cavity and serves as the datum for the measurement. The system is designed for high bandwidth, high resolution measurements for over 60 measurement channels. Table 1 summarizes the performance characteristics of the system. Particularly remarkable are the exceptionally low noise of 0.014 nm-Hz$^{-1/2}$ and the drift specification of 1 nm/day.

Table 1 Performance characteristics of the fiber interferometer

Parameter	Value	Parameter	Value
Number of channels	64	Bandwidth	100 kHz
Measurement range	1.2 mm	Noise (3σ)	0.014 nm-Hz$^{-1/2}$
Standoff	3.5 mm	Drift	1 nm/day
Repeatability (1 kHz)	0.5 nm	Linearity	2 nm

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