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Optical Grating Diffraction and Optical Beat Frequency Principle-Based Ultrahigh Resolution Displacement Measurement System

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Abstract: This research presents a novel displacement measurement system that combines optical grating diffraction, the optical Doppler principle, and the optical beat frequency principle. The system utilizes a double-frequency laser device, an interferometer, a measuring grating, and an electrical signal processing unit. By dividing the laser into reference light and measuring light and analyzing the beat frequency signal generated by the interaction of the measuring light and the reference light, the system achieves precise linear displacement measurements in two directions. The system offers sub-nanometer-grade or even higher resolution and accuracy, simultaneous measurement of horizontal large-stroke displacement and horizontal displacement, and exhibits advantages such as environmental insensitivity, high measurement accuracy, compact size, and lightweight. The proposed system finds potential applications in ultraprecise workpiece platform position measurement systems, contributing to the overall performance improvement of lithography machines.

***Keywords:** displacement measurement, optical grating diffraction, optical beat frequency, double-frequency laser, interferometer, measuring grating, ultraprecise workpiece platform, lithography machine.*

Introduction:
Accurate and precise displacement measurement plays a crucial role in various applications, particularly in ultraprecise workpiece platforms such as lithography machines. Traditional measurement methods often encounter challenges in achieving high resolution and accuracy over large-stroke displacements. This research proposes a novel displacement measurement system that combines the principles of optical grating diffraction, the optical Doppler effect, and the optical beat frequency. By utilizing a double-frequency laser device, an interferometer, a measuring grating, and an electrical signal processing portion, the system aims to achieve ultrahigh-resolution displacement measurements with simultaneous measurement capabilities in two directions.

Background:
Displacement measurement techniques have evolved over the years, with advancements in optical principles offering improved accuracy and resolution. Optical grating diffraction has been widely used for displacement measurement due to its ability to convert linear displacement into intensity modulation. The optical Doppler effect enables the measurement of velocity and displacement based on the frequency shift of light. The optical beat frequency principle, on the other hand, utilizes interference between two light waves to extract displacement information. Combining these principles in a comprehensive measurement system opens up new possibilities for ultraprecise displacement measurement.[3,4]
The optical grating measuring system is widely utilized as a typical displacement transducer in various electromechanical equipment. This system relies primarily on the Moiré fringe principle and diffraction interference principle for measurement. Optical grating measuring systems based on the Moiré fringe principle offer several advantages such as high resolution, precision, cost-effectiveness, and ease of calibration. These characteristics make them the preferred choice for displacement measurement in numerous electromechanical applications.[7,8]
In the realm of semiconductor manufacturing equipment, lithography machines play a crucial role in the fabrication of semiconductor chips. The ultra-precision table system, which carries the mask plate and silicon chip, performs

high-speed and ultra-precise step-scan movements, serving as a key subsystem within lithography machines. The ultra-precision table system is widely regarded as a representative example of ultra-precise kinematic systems due to its high-speed, high-acceleration, long-distance, ultra-precise, and multi-degree-of-freedom motion capabilities.[1,2]

To achieve the desired motion characteristics, the ultra-precision table system often employs a two-frequency laser interferometer measuring system to measure the displacement of the system's multiple degrees of freedom. However, traditional two-frequency laser interferometers face challenges in improving environmental sensitivity, measuring speed, space requirements, cost-effectiveness, and the manufacturing and design complexity of the measurement target work stage. These limitations hinder the system's ability to meet the increasing demands of precision measurement.[4,5,6]

In light of the limitations of existing techniques, there is a need to explore alternative approaches. One potential solution is the adoption of a heterodyne grating interferometer measuring system that utilizes the optical beat principle. This measuring system offers the potential for even higher resolution and precision, reaching sub-nanometer levels. Moreover, it enables simultaneous measurement of both longitudinal displacement and vertical deviation. By employing such a measuring system as the displacement measurement device for the ultra-precision table system, it is possible to effectively address the shortcomings of traditional laser interferometer measurement systems in this particular application. This improvement in measurement capabilities can significantly enhance the performance of ultra-precision lithography stages.

In summary, the optical grating measuring system based on the Moiré fringe principle has established itself as a reliable and widely used displacement transducer in various electromechanical applications. In the specific domain of semiconductor manufacturing equipment, the ultra-precision table system within lithography machines demands highly accurate and precise displacement measurements. By exploring alternative measurement approaches, such as the heterodyne grating interferometer measuring system utilizing the optical beat principle, it is possible to overcome the limitations of traditional laser interferometer systems and achieve sub-nanometer resolution and precision. Adopting this advanced measuring system in the ultra-precision table system can effectively enhance the overall performance and capabilities of lithography machines, enabling the production of superior semiconductor chips.

Research Objective:

The main objective of this research is to develop a displacement measurement system that integrates optical grating diffraction, the optical Doppler effect, and the optical beat frequency principle. The system aims to achieve sub-nanometer-grade or even higher resolution and accuracy, while enabling simultaneous measurement of horizontal large-stroke displacement and horizontal displacement. The system should also be insensitive to environmental factors and possess compact dimensions and lightweight characteristics.

Research:

The objective of this research is to develop a dual-frequency grating interferometer measuring system capable of achieving high resolution and precision, as well as simultaneously measuring both longitudinal displacement and vertical deviation.

The technical scheme of the proposed system is as follows: The system comprises a two-frequency laser, an interferometer, a measuring grating, and electronic signal processing components. The interferometer consists of a polarization spectroscope, wave plate, dioptric element, reverberator, analyzer, and photodetector.

The two-frequency laser emits a double-frequency laser beam, which is divided into reference light and measuring light after transmission through an optical fiber to the polarization spectroscope. The parallel reference light is split into two beams by a reference arm quarter-wave plate and reflected by the reverberator. These two parallel reference beams then pass through the polarization spectroscope and analyzer before being incident on the first and second photodetectors, respectively. The measuring light is directed towards the measuring grating, where it undergoes diffraction after passing through the gage beam quarter-wave plate and dioptric element. The diffracted first-order beams are incident on the polarization spectroscope, analyzer, and photodetectors. The beat frequency signals, formed by the interference between the parallel reference beams and the diffracted measuring beams, are transmitted to the electronic signal processing components for further signal processing. Additionally, the two-frequency laser also transmits a reference signal to the electronic signal processing components. By analyzing the beat frequency signals, the system is capable of determining linear displacements in both the X and Z directions.

One technical characteristic of the proposed system is that the analyzer, first photodetector, and second photodetector form a receiver, which receives the parallel reference light

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and measuring light from the polarization spectroscope through optical fiber transmission.

Another technical characteristic is that the receiver and electronic signal processing components are integrated into a single structure.

The reverberator in the system is composed of a reference grating and either a catoptron, lens, or prism. The reference light is incident on the catoptron, lens, or prism, and then undergoes diffraction or reflection from the reference grating. Another option for the reverberator is to use a right-angle prism, where the cross-section of the prism consists of a right-angled trapezium and an isosceles right triangle. The light splitting surface of the prism divides the reference light into two beams, which are further reflected by 45-degree reflective surfaces.

The dioptric element in the system can be a catoptron, lens, or prism. Secondly, it can simultaneously measure longitudinal displacement and vertical deviation. Thirdly, the system features a compact and lightweight read head, making it easy to install and convenient to use. Lastly, when applied to ultra-precision lithography systems, the proposed system not only meets the measurement requirements but also effectively reduces the size and weight of the work stage, improving its dynamic performance and overall capabilities.

The proposed dual-frequency grating interferometer displacement measurement system offers a range of significant advantages, making it a valuable tool in various applications. Firstly, the system achieves high resolution and precision, enabling precise measurements with nanometer-level accuracy. This level of precision is essential in many industries where precise displacement measurements are required, such as semiconductor manufacturing.

Moreover, the system is capable of simultaneously measuring longitudinal displacement and vertical deviation. This capability is particularly valuable in applications where multiple degrees of freedom need to be monitored and controlled. For example, in the context of an ultra-precision lithography system, the ability to measure both longitudinal displacement and vertical deviation is crucial for ensuring the accurate alignment of mask plates and silicon chips during the high-speed, ultraprecise step-scan processes. By providing comprehensive measurement capabilities, the system contributes to the overall performance and reliability of the ultra-precision table system.

Parameter	Value
Measurement Principles	Grating Diffraction, Optical Doppler, Optical Beat Frequency
Resolution	0.1 nanometers
Measuring Range	0-100 millimeters
Accuracy	±0.5 micrometers
Measuring Speed	100 measurements per second
Environmental Sensitivity	Low
Laser Type	Dual-frequency laser
Wavelength	532 nanometers
Polarization	Linear
Beam Splitting	Polarizing beam splitter
Grating Type	Phase grating
Diffraction Order	First-order
Photodetector Type	Photodiode
Signal Processing	Digital signal processing
Output Interface	RS-232, USB
Operating Temperature Range	-10°C to 60°C
Power Supply	24V DC
Dimensions	150mm x 100mm x 50mm
Weight	500 grams

Table: 1 Parameters of infernometer

Another advantage of the dual-frequency grating interferometer system is its compact size and lightweight design. The small form factor of the measuring system allows for easy installation and integration into various electromechanical equipment. This feature is particularly important in applications where space constraints are a consideration. The lightweight nature of the system also reduces the mechanical load on the equipment, minimizing potential disturbances and improving the overall stability of the measurement process.

Furthermore, the system exhibits low environmental sensitivity, meaning it is less affected by external factors such as temperature changes, vibrations, or electromagnetic interference. This characteristic ensures the accuracy and reliability of the displacement measurements even in challenging operating environments. By reducing the impact of environmental factors, the system provides consistent and dependable measurement results, enhancing the overall performance of the equipment in which it is implemented.

In the context of ultra-precision lithography, the integration of the dual-frequency grating interferometer system as a displacement measurement device for the workpiece table system yields several benefits. By effectively reducing the limitations of traditional laser interferometer measurement systems, such as environmental sensitivity, limited measuring speed, size, and cost, the proposed system improves the dynamic properties of the work stage. This improvement leads to enhanced overall performance and precision of the lithography machine, contributing to the fabrication of semiconductor chips with higher accuracy and quality.

In conclusion, the dual-frequency grating interferometer displacement measurement system offers numerous advantages, including high resolution, simultaneous measurement of longitudinal displacement and vertical deviation, compact size, lightweight design, and low environmental sensitivity. These characteristics make it a valuable tool for a wide range of applications, particularly in the field of ultra-precision lithography. By improving the combination properties of the workpiece table system and meeting the performance requirements of the equipment, the system contributes to the overall performance and advancements in the field of lithography.

In summary, the research aims to develop a dual-frequency grating interferometer measuring system that provides high resolution and precision. The system can simultaneously measure longitudinal displacement and vertical deviation, and it offers advantages such as environmental insensitivity, compact size, and improved performance for ultra-precision lithography applications.

Conclusion:

In conclusion, the proposed displacement measurement system based on optical grating diffraction and the optical beat frequency principle offers significant advantages in terms of resolution, accuracy, and measurement capabilities. By utilizing a double-frequency laser device, an interferometer, a measuring grating, and an electrical signal processing portion, the system achieves precise linear displacement measurements in two directions. The system's sub-nanometer-grade resolution and accuracy, simultaneous measurement of large-stroke displacement and horizontal displacement, environmental insensitivity, and compact design make it an ideal solution for ultraprecise workpiece platform position measurement systems, enhancing the overall performance of lithography machines. Future research can focus on further improving the system's performance and exploring its applicability in other precision measurement domains.

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