Six Degrees of Freedom Heterodyne Grating Interferometry with Close-to-Atomic Accuracy

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In the manufacture of precision machine tools and integrated circuits, the significance of ultra-precision measurem ent is particularly important. For precision machine tools, nanoscale displacement measurement accuracy can signi ficantly improve machining accuracy and product quality, reduce error accumulation, and thus improve production efficiency and product performance. In integrated circuit manufacturing, measurement accuracy at the sub-nanomete r level is critical to the photolithography, alignment and assembly process, which directly affects the function and reliability of the chip. As manufacturing technology enters the third stage: Atomic and Close-to-Atomic Scale Man ufacturing (ACSM), higher requirements are placed on measurement technology.

Among many measurement techniques, heterodyne grating interferometry stands out because of its high precision, s trong anti-interference ability and easy expansion of multiple degrees of freedom. However, existing methods have some problems, there are two main reasons: 1. Polarization/frequency confusion and optical dead zone effects lead to measurement errors, and poor resistance to environmental interference. 2. In six-degree-of-freedom (DOF) expan sion, current methods have difficulty achieving both high precision and miniaturization.

Based on this, we designed a integrated six DOF heterodyne grating interferometry system with close-to-atomic ac curacy. Firstly, we utilized a dual-frequency light source to generate a beat frequency signal, achieving high-precis ion and high-speed measurement at the same time. Subsequently, we adopted a quasi-common optical path design to eliminate frequency/polarization mixing and optical path dead zone effects, significantly enhancing measurement accuracy and system robustness. In the extension to six DOF measurement, we employed five diffracted beams fro m two two-dimensional gratings as the measurement signals. Three Quadrant Photodetectors (QPDs) and five Phot odetectors (PDs) were used to achieve three degrees of freedom angular measurement and three degrees of freedo m displacement measurement, respectively. This approach not only enabled high-precision 6-DOF measurements but also facilitated a compact design, with the final prototype size being less than 15cm×15cm×5cm. Experimental re sults demonstrated that the resolution of the three degrees of freedom displacement measurements is better than 0. 3nm, approaching close-atomic levels. The resolution of the three degrees of freedom angular measurements reache d arcsecond levels. Additionally, the system exhibited excellent resistance to environmental interference. These expe riments conclusively validate the superiority of our proposed method in high-precision 6-DOF measurements.

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