

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 measurement is particularly important. For precision machine tools, nanoscale displacement measurement accuracy can significantly 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-nanometer 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 Manufacturing (ACSM), higher requirements are placed on measurement technology. Among many measurement techniques, heterodyne grating interferometry stands out because of its high precision, strong 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) expansion, current methods have difficulty achieving both high precision and miniaturization. Based on this, we designed an integrated six-DOF heterodyne grating interferometry system with close-to-atomic accuracy. Firstly, we utilized a dual-frequency light source to generate a beat frequency signal, achieving high-precision 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 from two two-dimensional gratings as the measurement signals. Three Quadrant Photodetectors (QPDs) and five Photodetectors (PDs) were used to achieve three degrees of freedom angular measurement and three degrees of freedom displacement measurement, respectively. This approach not only enabled high-precision six-DOF measurements but also facilitated a compact design, with the final prototype size being less than 15cm×15cm×5cm. Experimental results demonstrated that the resolution of the three-DOF displacement measurements is better than 0.3nm, approaching close-to-atomic levels. The resolution of the three-DOF angular measurements reached arcsecond levels. Additionally, the system exhibited excellent resistance to environmental interference. These experiments conclusively validate the superiority of our proposed method in high-precision six-DOF measurements.

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