Fabrication of Scale Gratings and Application to Surface Encoders

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論文内容要旨

This dissertation presents the fabrication of scale gratings and development of optical sensor heads for position and error motions measurement of precision stages. Inexpensive and compact 405 nm blu-ray laser diodes (LD) have been employed in a laser interference lithography (*LIL*) system for achievement of a cost-effective fabrication of one-axis sub-micron short pitched scale gratings. A three-beam Lloyd's mirror interferometer has been developed for production of two-axis gratings patterns with high pattern uniformity. A unique optical sensor head allowing a simultaneous measurement of six-DOF planar motions has been developed with using two-axis scale gratings. Both the basic performances and uncertainty of the surface encoder have been systematically investigated.

In Chapter 1, the background, motivations and tasks of this research are presented. Precision stages have been widely used in today's nanofabrication and nanometrology, such as precision machining, semiconductor manufacturing, scanning probe microscopy, and so forth. Two trends of the precision stages are ultra-precision linear stage and multi-degree-of-freedom (MDOF) planar stage. The ultra-precision linear stage is typically required to offer nanometric position accuracy to move a machining tool or a scanning probe for ultra-precision machining or metrology. The MDOF planar stage is typically required to have long motion strokes in the primary *XY* plane larger than 10 mm × 10 mm and a small amount of *Z*-directional motion in the order of 100 μm associated with sub-micron positioning resolutions. Position sensors are then indispensible for both the two types of precision stages to conduct a closed-loop control. In addition to measurement of the position, small amounts of translational and angular error motions are also required to be detected for position compensation or tracking. In contrast to conventional position and error motions measurement by using multiple sensor systems, the state-of-the-art two-axis linear encoder, three-axis planar surface encoder and three-axis autocollimator offer better solutions for these measurement requirements mentioned above. However, there are still some problems and challenges existing in the state-of-the-art sensors. The surface encoder developed for measurement of three-axis translational motions and the three-axis autocollimator for

measurement of three-axis angular error motions cannot measure the same point, resulting in Abbe error. Fabrication of the scale gratings, which are used as the measurement standard in the surface encoder, is challenged both by the cost and limitations of conventional fabrication system.

Thus, the motivation of this research is to solve the problems in these state-of-the-art position sensors for the precision stages. The motivation is specified to be three detailed tasks. Aiming for the requirement of nanometric positioning resolution, fabrication of one-axis sub-micron short pitch scale gratings for the newly developed two-axis linear encoder is set to be the first task. Cost-effectiveness of the fabrication is of the highest priority. Aiming for the simultaneous measurement of three-axis translational motions for the MDOF planar stage, fabrication of two-axis scale grating for the planar surface encoder is set to be the second task. High pattern uniformity in the two axes of the scale grating is of the first pursuit. Aiming for a six-DOF positions and error motions measurement with high accuracy and inexpensive instruments, development of a six-DOF surface encoder by combination of the three-axis planar surface encoder and the three-axis autocollimator to achieve a simultaneous six-DOF measurement with a single sensor head and a same measurement point is the third task. Efforts and achievements for these three tasks are discussed carefully in this dissertation as below.

In Chapter 2, a cost-effective and compact fabrication method has been proposed for fabrication of scale grating. A maskless lithography process called laser interference lithography (*LIL*) system is employed as the fabrication tool. In *LIL*, a collimated light source is divided by a Lloyd's mirror interferometer into two halves and recombined, forming a periodic intensity pattern that is then recorded by exposing a photosensitive substrate. The periodic interference pattern is finally transferred onto the substrate after developing the exposed substrate. The Lloyd's mirror interferometer is composed of a mirror and a substrate with photoresist coating. The mirror and the substrate mounted on a rotary stage are placed perpendicularly with each other and with their intersection line perpendicularly passing through the centre of the rotation stage. The centre of the rotary stage is aligned on the beam axis of the laser source. Thus, the periodicity of the interference intensity is only determined by the angle between the mirror and the beam axis that can be adjusted by rotating the rotary stage. The minimum value of the grating pitch in *LIL* could reach half of the wavelength, i.e. approximately 203 nm when a 405 nm blu-ray laser source was used, which allows a small signal periodicity that is desired in a measurement resolution of nanometre or sub-nanometre. Due to the wavefront-splitting configuration, the constructive and destructive interference pattern is rather stable, which allows a high-resolution grating structure. Both the fabrication cost and the system space of *LIL* technology have been greatly reduced by using inexpensive and compact 405 nm blu-ray laser diodes (LD). The fabrication system based on Lloyd's mirror interferometer with using blu-ray LDs has been constructed within a compact volume of 400 mm (L) × 300 mm (W) × 250 mm (H). A low-cost multimode LD used in blu-ray laser drive and a single-mode LD with an external mode selective cavity have been employed as the lasers sources one after another. The multimode LD with a temporal coherence length L_c of around 0.68 mm successfully fabricated a 570-nm pitched continuous grating pattern covering a width of 2 mm with a high pattern resolution. And the single-mode LD with an L_c of more than 1 m greatly expanded the width of continuous grating pattern that could be theoretically up to meter-order. Finally, a continuous one-axis grating pattern with high-resolution 570 nm pitch was successfully fabricated over an area of larger than 300 mm^2.

In Chapter 3, a new mechanism called three-beam Lloyd's mirror interferometer for fabrication of two-axis scale gratings by means of multiple-beam interference lithography has been proposed, constructed and evaluated. The interferometer is composed of a square grating substrate with photoresist coating and two rectangular mirrors. The substrate with normal in the *Z*-axis is placed edge to edge with the two mirrors with normals parallel to the *XZ*-plane (*X*-mirror) and the *YZ*-plane (*Y*-mirror), respectively. A linearly polarized incident laser light is divided into three sub-beams by the two-axis Lloyd's mirror, which are then projected onto the substrate and the two mirrors, respectively. The angle between the substrate and each mirror is set to be larger than 90 degrees so that the beams reflected by the mirrors can be superimposed with the direct beam at the substrate to produce two-axis grating structures in a single exposure. A polarization modulation technique with half-wavelength plates has been employed for removing the interference intensity term generated by the interference between the two sub-beams reflected by the two mirrors, which causes the generated grating structure to have an elliptical shape. Experiments have verified the capabilities and advantages of the proposed interferometer in fabrication of two-axis scale gratings. An experimental setup has been designed and constructed to fabricate two-axis hole grating structures over an area of 17 mm × 17 mm with a grating period of 570 nm in two orthogonal axes. Evaluation with an atomic force microscope (AFM) revealed that the average pitch and standard deviation were evaluated to be 567 nm and 2 nm, respectively. The average amplitude and standard deviation were evaluated to be were and 451 nm and 14 nm, respectively. The diffraction efficiency of the fabricated grating was evaluated by detecting the intensities of the transparent first-order diffraction beams. The average and standard deviation of the diffraction efficiency of the positive first-order diffraction beam were evaluated to be 13.6% and 2.2%, respectively. Those for the negative first-order diffraction beams were evaluated to be 13.2% and 2.5%, respectively. The results have indicated that the performance of the fabricated grating can meet the requirements of scale gratings for a planar encoder.

In Chapter 4, an optical sensor called surface encoder that allows a simultaneous measurement of six-degree-of-freedom (six-DOF) planar motions has been developed. The six-DOF surface encoder is composed of a scale grating and an optical sensor head, which would be mounted on the moving element and stage base of an *XY* surface motor stage, respectively. The six-DOF measurement has been realized by combining a three-axis displacement sensor and a three-axis autocollimator in a simple manner through sharing the same laser source. The three-axis displacement sensor is constructed in a Michelson interferometer configuration while the reference mirror and moving mirror are replaced by a two-axis reference grating and a two-axis scale grating, respectively. Thus, apart from the superimposition of the reflected beams, the first order diffraction beams from these two gratings also superimpose with each other and the other four pieces of interference signals are generated. Three-axis translational motions (Δx, Δy, Δz) of the scale grating can be simultaneously obtained from the four signals. The three-axis autocollimator is developed based on laser autocollimation. The scale grating here is used as the reflective target. The zero-th order diffraction beam is employed to measure the pitching and yawing by the same manner as that of conventional laser autocollimator, in which one of the four first order diffraction beam was innovatively employed for detection of the rolling of the scale grating.

Efforts have been made to design and construct the sensor head with a compact size of 95 mm (*X*) × 90 mm (*Y*) × 25 mm (*Z*) so that it can fit into an *XY* surface motor stage with two primary axes of motion (Δx, Δy) for precision positioning and four secondary axes of motion (Δz, θ_x, θ_y, θ_z) for compensation of error motions with sub-micrometer/sub-arcsecond resolutions. The grating period and grating area of the planar grating were designed and fabricated to be 0.57 μm and 60 mm (*X*) × 60 mm (*Y*), which dominate the resolution and measurement range in the *X*- and *Y*-directions, respectively. Experiments have been carried out to test the basic performances of the constructed six-DOF surface encoder. It has been verified that the surface encoder could distinguish 2 nm step motions in the Δx-, Δy- and Δz-directions, 0.1 arcsecond step motions in the θ_x- and θ_y-directions, 0.3 arcsecond step motion in the θ_z-direction. The peak-to-valley amplitudes of the interpolation errors were approximately ±6 nm, ±7 nm and ±6 nm in the *X*-, *Y*- and *Z*-directions, respectively. The nonlinear error components were approximately 2.2 arcseconds, 1.4 arcseconds and 2.5 arcseconds for θ_x, θ_y and θ_z, respectively. It should be noted that the error components can be reduced by a compensation process.

In Chapter 5, the measurement uncertainty of the surface encoder has been systematically investigated to confirm its feasibility for precision measurement of six-DOF planar motions as well as to reveal the largest uncertainty source for the surface encoder. Sources of uncertainties regarding the interpolation errors in position derivation, system stability in terms of environmentally thermal drift, misalignment factors among the scale grating, reading head and the stage and stability of the light source were considered. An uncertainty budget was summarized and a combined standard uncertainty of the developed six-DOF surface encoder was lastly calculated. Measurement results in testing of six-DOF translational motions and angular motions of the six-DOF surface encoder have been systematically evaluated in uncertainty. An expanded uncertainty of 124.4 nm has been calculated in the measurement results of testing three-axis translational motions over a travel range of 2.5 μm. An expanded uncertainty of 3.8 arcseconds has been evaluated in the measurement results of testing three-axis angular motions over a travel range of ±30 arcseconds. Periodic cross-talk error components have been observed in the angular outputs, which were caused by the polarization leakage in the optical paths of the diffraction beams. The cross-talk errors of the surface encoder outputs were identified to be the largest uncertainty source for the surface encoder. Optimization of the optical design of the surface encoder has then been proposed to eliminate the cross-talk errors.

In Chapter 6, conclusions and achievements of this dissertation are discussed.

論文審査結果の要旨

近年、半導体製造装置や超精密工作機械に用いられる位置決めステージシステムは、超精密位置決め技術のコアパーツとして用いられており、製品の加工精度に大きく影響する。ステージシステムの超精密位置決めに用いられる位置・姿勢検出センサは、クローズドループ制御による位置決め精度の限界を突破するのに必須な技術である。本論文は、ステージの多自由度位置・姿勢の超精密計測に用いるサーフェスエンコーダシステムと、その測定の基準として用いられる格子スケールの製作に関する研究をまとめたものであり、全編６章からなる。

第１章は緒論であり、本研究の背景、目的および構成を述べている。

第２章では、コンパクトで低コストな青色レーザーダイオードを用いた光干渉リソグラフィによる格子スケール作成手法の開発について述べている。回折格子のような周期構造の広範囲一括形成に有効である光干渉リソグラフィには、従来、可干渉長の長い大型ガスレーザーが用いられてきたが、レーザー装置のコスト及びサイズを考慮すると、その利用は容易ではなかった。本研究では、コンパクトかつ低コストな青色レーザーダイオードの大面積光干渉リソグラフィへの適用を試み、その実現可能性を検討した。ブラッググレーティングを用いた外部キャビティ形成による青色レーザー線幅の狭小化技術を活用することによって、面積３００mm^2以上の大面積一括パターン形成を実現した。これは光干渉リソグラフィによる大面積微細パターン形成技術にとって有益な成果である。

第３章では、ロイドミラー干渉計の原理をベースとした、２軸ロイドミラー干渉計による格子スケール作成手法の開発について述べている。従来では、対象面を９０°回転し、光干渉リソグラフィを２回実施することでしか２軸直交パターンを形成できなかった。本研究では、独創的な光学系構成を用いた１回露光による２軸直交パターン形成手法を提案し、コンピューターシミュレーションと実験によりその実現可能性を検討した。偏光制御を利用した干渉パターンのゆがみ除去手法も併せて提案し、ピッチ０．５７μm,面積３００mm^2以上の２軸直交パターンの一括形成に世界で初めて成功した。これは、理論的にも実用的にも価値の高い成果である。

第４章では、６自由度サーフェスエンコーダシステムの開発について述べている。サーフェスエンコーダシステムをサーフェスステージシステム内に搭載するため、エンコーダ光学ヘッドをコンパクトに設計する必要がある。本研究では、３軸変位センサユニットと３軸角度センサユニットの光学系を、同一のレーザービームおよびスケール格子をシェアするように設計することで、サーフェスステージシステム内の許容スペースに適用可能なサイズ９５mm×９０mm×２５mmに収めている。試作したサーフェスエンコーダシステムのプロトタイプを用いて実験的に検討を重ねた結果、１本の測定レーザー光による６自由度測定に成功するとともに、位置決めステージ用センサとして重要な評価要素であるＸＹＺ変位に対する測定分解能２nmおよび内挿誤差７nm、Ｘ、Ｚ軸まわり回転に対する測定分解能０．１角度秒、Ｙ軸まわり回転に対する測定分解能０．３角度秒および線形誤差 ２．５角度秒以内を実現している。これは、次世代超精密ステージシステムの多自由度位置・姿勢計測への対応を可能にした成果で、高く評価される。

第５章では、構築したサーフェスエンコーダシステムの測定不確かさに関する系統的分析について述べている。「計測における不確かさのガイド（GUM)」に準拠した形で拡張測定不確かさを算出し、ストローク２．５μmにおける３軸変位測定の不確かさは１２４．４nmで、±３０角度秒範囲における３軸回転測定の不確かさは３．８角度秒であることを明らかにした。更に、エンコーダ光学ヘッド内の光路における偏光状態に関する分析の結果より、３軸変位センサユニットと３軸角度センサユニットの配置を最適化し、各ユニット間のクロストークを１０％にまで低減した。これは開発した計測システムの精度と信頼性を高めた重要な成果である。

第６章は、結論である。

以上要するに、本論文は超精密位置決めステージの６自由度位置・姿勢を超精密に測定するための新しい計測手法及びそれに基づく計測システムを実現したものであり、ナノメカニクスおよび生産工学に寄与するところが少なくない。よって、本論文は博士(工学)の学位論文として合格と認める。