High-resolution and wide range displacement measurement based on planar grating
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A B S T R A C T
High/ultra-precision motion measurements for precision translation stages are highly desired in modern manufacturing systems and instruments. In this work, we introduce a wide range three-axis grating encoder with nanometric resolution, which can measure the x-, y- and z-axial translational motions of a stage simultaneously. The grating encoder is composed of a reflective-type planar scale grating with a period of 8 μm and an optical reading head. A planar reference grating, which is the same as the planar scale grating except the length and width, is employed in the optical reading head. The x- and y-directional ±1st order diffractive beams of the planar scale grating interfere with the corresponding diffractive beams of the planar reference grating, forming the measurement signals. The x- and y-directional ±1st order diffractive beams of the two planar gratings propagate against their original incident path, working as the autocollimatic diffractive beams. Therefore, the z-axial measurement range of the proposed grating encoder is greatly enhanced. The x- and y-axial measurement ranges depend on the size of the planar scale grating. To make the grating encoder more compact, a double grating beam-splitting (DGBS) unit and two diffractive optical elements (DOEs) are introduced. The experimental results indicate that the z-axial displacement resolution is as high as 4 nm with an electronic data division card of 80 segments developed by our lab.

1. Introduction
In modern manufacturing systems and measuring instruments, precision translation stages always play important roles. For example, a dual stage immersion platform is used to precisely align wafers with the mask in a commercial optical lithography system [1]. Meanwhile, a precise translation stage is always a powerful tool for carrying specimens in a measuring instrument [2–4]. In these systems, the motion precision of the translation stages directly affects the manufacture and measurement. Therefore, high/ultra-precision motion measurements for precision translation stages are significant for manufacturing equipment and measuring instruments. The laser interferometry with nanometric resolution has been widely applied for high/ultra-precision displacement measurements. The measurement range of a laser interferometer is wide enough, and the resolution is as high as nanometric or sub-nanometric. However, a multiaxial displacement measurement system constructed by a laser interferometer is bulky and complex. Meanwhile, the sensitivity to environmental disturbances and the nonlinearity phenomena of a laser interferometer always introduce measurement errors [5]. Therefore, a laser interferometer is inconveniently applied in such fields. Grating displacement encoders are another kind of displacement measurement instruments. A grating encoder measures displacements in terms of the grating period, which can achieve nanometric or sub-nanometric resolution. When the scale grating is made of zero-expansion materials, the grating period is a constant even for the environmental temperature disturbances. Therefore, for grating encoders, the environmental temperature disturbances will not introduce measurement errors. Additionally, the structures of grating encoders are compact. Therefore, grating encoders have attracted the interest of many researchers [6–21].

Several three-axis grating encoders have been proposed [7,8,17]. The sub-nanometric surface encoder developed by Kimura et al. in 2012 could measure the three-axis displacements using a scale planar grating and an optical sensor head [8]. However, the z-axial measurement range of the encoder was about 4 mm, because the z-axial displacement would diminish the size of interference zones of the measurement signals. Hsieh et al. applied a heterodyne laser interferometer into a planar grating encoder to measure the displacement out of the grating plane in 2013 [7]. In this system, the z-axial measurement range was limited...
Fig. 1. Schematic of the three-axis grating encoder.

The authors proposed a grating encoder for wide range three-axis displacement measurement in 2015 [17]. The proposed grating encoder was composed of a scale planar grating and an optical reading system. The $z$-axial measurement range was greatly enhanced. To our best knowledge, it was the first grating encoder that the maximal measurable $z$-axial displacement could achieve 1263 mm theoretically. However, the grating encoder was constructed by discrete components, which was inconvenient and unstable for practical applications. In this work, we introduce a high-resolution and wide range three-axis grating encoder for the stage motion measurement. To make the grating encoder compact, a double grating beam-splitting (DGBS) unit is designed to divide the laser beam into four required parallel beams. Meanwhile, two diffractive optical elements (DOEs) are designed to simplify the encoder structure, which have 4-step relief structures and are fabricated by lithography and nanoimprint. The DOEs work as the optical deflection elements that are significant to enhance the $z$-axial measurement range.

2. Methods

The schematic of the proposed high-resolution and wide range three-axis grating encoder is shown in Fig. 1. The grating encoder is composed of a reflective-type planar scale grating and an optical reading head. A planar reference grating which is the same as the planar scale grating except the length and width, is employed in the optical reading head. The light beam from the laser is divided into four parallel beams by a DGBS unit. The configuration details of the DGBS unit are shown in Fig. 2. Two of the four parallel beams are in the $x$-$y$ plane and another two beams are in the $x$-$z$ plane. The four parallel beams are divided into two groups by a polarizing beam splitter (PBS). Each group is projected on a quarter wave plate (QWP) and a DOE. The DOEs work as the optical deflection elements. The beams passing through the two DOEs are deflected by a fixed angle of $\alpha$. The DOEs and the two planar gratings follow the autocollimatic configuration (the Littrow configuration) [17]. Therefore, the $x$- and $y$-directional $\pm 1$st order diffractive beams from the planar scale grating and the reference grating will return back against their each own original incident path. Consequently, the $z$-axial displacement of the planar scale grating would not diminish the size of interference zones of the measurement signals. The $z$-axial measurement range is greatly improved. As shown in Fig. 1, the detecting system includes a QWP, a non-polarizing beam splitter (BS), two PBSs and four detector units. One of the PBSs in the detecting system is rotated $45^\circ$ along the $x$-axis. The light beams diffracted by the two planar gratings are incident into the detecting system and interfere at the positions of each detector unit. Each detector unit is composed of four photodiodes.
and the interference signals are detected by the photodiodes. The optical axes of the three QWPs in the optical reading head are all aligned to 45°.

The interference signals formed by the \( X \)- and \( Y \)-directional \( \pm 1 \)st order diffractive beams from the two planar gratings are expressed as

\[
I_{X\pm 1} = |\tilde{U}_X(\pm 1) + \tilde{U}_Y|_d^2 \\
= 2U_0^2 \left\{ 1 + \cos \left[ 2\pi \left( \frac{\pm 1}{d} \Delta X + \left( \frac{2n_0}{\lambda \cos a} - \frac{\tan a}{d} \right) \Delta z \right) \right] \right\}
\]

\[
I_{Y\pm 1} = |\tilde{U}_Y(\pm 1) + \tilde{U}_Z|_d^2 \\
= 2U_0^2 \left\{ 1 + \cos \left[ 2\pi \left( \frac{\pm 1}{d} \Delta Y + \left( \frac{2n_0}{\lambda \cos a} - \frac{\tan a}{d} \right) \Delta z \right) \right] \right\}
\]

where \( \Delta X, \Delta Y \) and \( \Delta Z \) are the displacements of the planar scale grating along the \( X \)-, \( Y \)- and \( Z \)-axis with respect to the optical reading head, respectively. \( d \) is the period of the planar scale grating and the planar reference grating. \( n_0 \) is the refractive index of air. \( U_0 \) is the amplitude of the incident beam. \( \lambda \) is the wavelength of the laser. From Eqs. (1) and (2), we calculate the \( x \)-, \( y \)- and \( z \)-axial displacements of the planar scale grating can be calculated. To distinguish the directions of the displacements and provide multichannel signals needed by the electronic division system in a practical grating encoder, the instantaneous phase-shifting technology is adopted in the detecting system [11,22]. Therefore, the phase differences of \( I_x(90°) \), \( I_y(90°) \), \( I_x(180°) \), and \( I_y(270°) \) are 90°. The subscript \( i = X \pm 1, Y \pm 1 \), denoting the direction and order of the diffusive beam. \( I_x(\psi \, (\psi = 0°, 90°, 180° \text{ and } 270°)) \) are the phase-shifted interference signals detected by the four detector units. \( I_x(90°) \) can be directly calculated from Eqs. (1) and (2).

Consequently, the three-axis displacements \( \Delta X, \Delta Y \) and \( \Delta Z \) measured by the grating encoder can be expressed as

\[
\Delta X = \frac{1}{2\pi} \frac{d}{2\pi} \left[ \arctan(T_{X\pm 1}) - \arctan(T_{X\pm 1}) \right] = \Delta X
\]

\[
\Delta Y = \frac{1}{2\pi} \frac{d}{2\pi} \left[ \arctan(T_{Y\pm 1}) - \arctan(T_{Y\pm 1}) \right] = \Delta Y
\]

\[
\Delta Z = \frac{1}{2\pi} \frac{1}{2\pi} \left[ \frac{2n_0}{\lambda \cos a} - \frac{\tan a}{d} \right] \sum_{i = X \pm 1, \ Y \pm 1} \arctan(T_i) = \Delta Z
\]

From the expressions of \( \Delta X, \Delta Y \) and \( \Delta Z \), one can find that the grating encoder measures the \( x \)- and \( y \)-axial displacements in terms of the grating period \( d \). And the \( z \)-axial displacement is in terms of \( 1/|2n_0/(\lambda \cos a) - \tan a/d| \).

From previous description of the proposed grating encoder, it is clear that four parallel incident light beams are essential. Therefore, a beam-splitting unit is necessary to divide the laser light into four parallel beams. The beam-splitting unit is designed to be a DGBS unit as shown in Fig. 2. The DGBS unit is composed of a transmission-type planar grating and a binary optical element (BOE). The periodic structures of the transmission-type planar grating and the linear gratings on the BOE are both arranged along the \( y \)- axis and \( z \)-axis. The period \( d_i \) of the transmission-type planar grating and the period \( d_o \) of the linear gratings on the BOE are both 4.8 μm. The \( y \)- and \( z \)-directional \( \pm 1 \)st order diffractive beams from the transmission-type planar grating are employed. The four diffractive beams from the transmission-type planar grating are diffracted again after passing the BOE, and then become four parallel beams. In order to improve the energy utilization efficiency and signal noise ratio, both the \( y \)- and \( z \)-directional \( \pm 1 \)st order diffractive beams from the transmission-type planar grating and the \( \pm 1 \)st order diffractive beams from the BOE are designed to achieve the highest diffraction efficiencies. Applying the scalar diffraction theory, the maximal diffraction efficiencies of the \( y \)- and \( z \)-directional \( \pm 1 \)st order diffractive beams from the transmission-type planar grating are 13.6%. The corresponding structure parameters \( a_1 \) and \( h_1 \) are 3.1 μm and 0.615 μm. Similarly, the optimal structure parameters of the BOE are that \( a_2 \) is 2.4 μm and \( h_2 \) is 0.615 μm. The maximal diffraction efficiencies of the \( \pm 1 \)st order diffractive beams from the BOE are 40.5%. The transmission-type planar grating and the BOE are both fabricated by a kind of commercial glass with a refractive index of 1.5146. Meanwhile, the wavelength of the laser is 632.8 nm. The diffraction efficiency curves of the transmission-type planar grating and the BOE with the optimal structure parameters are shown in Fig. 3. Through changing the distance along the \( x \)-axis between the BOE and the transmission-type planar grating, the spacing distance between the four parallel beams from the DGBS unit can be adjusted.

The \( z \)-axial measurement range of the proposed grating encoder is greatly enhanced, because the optical deflection elements namely the DOEs, the planar scale grating and the planar reference grating follow the Littrow configuration. The optical deflection elements play the most important roles in the Littrow configuration. In Ref. [17], grating-based elements with 2-step relief structures were used as optical deflection elements. However, the grating-based elements will diffract an incident beam into two symmetrical autocollimatic incident beams. According to the principle of the grating encoder, only one of the two symmetrical autocollimatic incident beams is useful and the other beam is unwanted. The unwanted beams will cause energy loss and need to be obstructed by additional diaphragms. In order to solve this problem and obtain a compact grating encoder, two 4-step DOEs are designed to be the optical deflection elements as shown in Fig. 4. As shown in Fig. 4(a), the DOEs have 4-step relief structures located in four orthogonal rectangular
regions. The height and the width of every step are $h_3$ and $d_3$. To follow the Littrow configuration, $2d_3$ needs to be equal to the period of the planar scale grating. Therefore, the width $d_3$ of every step is 4 $\mu$m. Based on the scalar diffraction theory, the highest diffraction efficiency of the diffractive beams from the designed 4-step DOE is 81.1%. Moreover, only the 1st diffraction order occupies the highest diffraction efficiency as show in Fig. 4(b). It implies that the unwanted autocollimatic incident beams are eliminated. Therefore, the 4-step DOEs are better choice as optical deflection elements. The optimal $h_3$ of the DOE is 0.307 $\mu$m when the DOE is fabricated by the commercial glass with a refractive index of 1.5146. The intensities of other order diffractive beams can be neglected. Therefore, the measurement signals will not be disturbed by other order diffractive beams.

One of the two DOEs was firstly fabricated by the twice lithography technology. Firstly, 2-step relief structures were fabricated by lithography processing. Afterwards, by precisely aligning and second lithography processing, 4-step relief structures were fabricated. To keep the consistency of the two DOEs in the grating encoder, the second DOE was fabricated by the nanoimprint technology using the first DOE as the imprinting mold.

3. Results

The practical grating encoder is shown in Fig. 5. To simplify the process of assembling the grating encoder in our lab, optical elements with medium sizes were used. The edge-lengths of the PBSs and the BS are 20 mm. The geometric size of the optical reading head is 130 mm ($x$)×130 mm ($y$)×68 mm ($z$). For practical applications, a smaller optical reading head can be fabricated based on our proposed schematic. To satisfy such requirement, smaller optical elements can be used, such as PBSs with an edge-length of 5 mm or 10 mm. Meanwhile, the mechanical elements of the grating encoder can be optimized to be smaller.
An electronic data division card was developed to achieve 80 segments by our lab. With this data division card, the x- and y-axial displacement resolutions could reach $\frac{d}{20}$ (i.e., 100 nm). The z-axial displacement resolution could reach $\frac{1}{(80 \times \frac{\lambda}{\cos \alpha}) - \tan \alpha \frac{a}{d}}$ (i.e., 4 nm). The upper limit frequency of the signals that the data division card could process was 30 MHz. Therefore, the maximal measurement speed for the x- and y-axis could achieve 3 m/s, and it could achieve 120 mm/s for the z-axis. The z-axial displacement resolution was clarified experimentally. The planar scale grating was driven by a single-axis piezo-electric transducer (model P-753.1CD, PI) along the z-axis with a step of 4 nm, and every step persisted about 5 s. The z-axial displacement output of the practical grating encoder is shown in Fig. 6.

The result of the z-axial displacement resolution testing experiment demonstrates that the proposed grating encoder could distinguish 4 nm displacements along the z-axis with the 80 segment data division card. As shown in Fig. 6, nine steps were observable. It conformed with the step number that we applied to the piezo-electric transducer. The fluctuations of the z-axis displacement output at every step were caused by the vibrations of the platform where the grating encoder located. The x- and y-axial displacement resolutions can be further improved to the nanometric level, when a data division card with higher segments. For example, the Heidenhain IK220 data division card can achieve 120 mm/s for the z-axis. The z-axial displacement resolution could be fabricated more precisely through more advanced techniques, such as lithography and nanoimprint. The error of the planar grating period can be remarkably reduced. Moreover, two kinds of errors are nearly inevitable and will affect the measurement results. The first one is caused by the misalignment between the planar scale grating and the optical reading head. The second one is the periodical nonlinear errors mainly caused by the imperfections of the optical components in the detection system.

4. Discussions

Discussing the effects of the errors is meaningful for precise measurements. According to Eqs. (3) and (4), the measurement results in the grating plane are not affected by the wavelength and the air refractive index. However, the error of the planar grating period will directly affect three-axis measurement results. Fortunately, the planar gratings can be fabricated more precisely through more advanced techniques, such as lithography and nanoimprint. The error of the planar grating period can be remarkably reduced. Moreover, two kinds of errors are nearly inevitable and will affect the measurement results. The first one is caused by the misalignment between the planar scale grating and the optical reading head. The second one is the periodical nonlinear errors mainly caused by the imperfections of the optical components in the detection system.

4.1. Effects of the misalignment

The misalignment between the planar scale grating and the optical reading head is caused by the imperfect assembly and translational motions of the grating. The misalignment caused by the pitch ($\theta_x$), yaw ($\theta_y$), and roll ($\theta_z$) angles is shown in Fig. 8.

For the situation related to the yaw angle, the x-directional equivalent period of the planar scale grating is not changed. Therefore, the measuring basis of the x-axial displacement is unchanged. The plane composed of the x-directional ±1st order diffractive beams will rotate along the x-axis and deviation from the x-z plane with an angle of $2\theta_y$. The deviation will cause a change of the spacing between the interference fringes related to the x-directional ±1st order diffractive beams. However, as long as the interference fringes are wide enough for being detected, the x-directional measurement results will not be affected by the yaw angle. The y-directional equivalent period of the planar scale grating becomes $d \cos \theta_y$. Therefore, the y-directional measurement results will be influenced. Meanwhile, the yaw angle will affect the autocollimatic configuration of the y-directional ±1st order diffractive beams. Under the condition of the autocollimatic configuration, the deviations of the diffraction angles of the y-directional ±1st order diffractive beams are equal to the yaw angle $\theta_y$ [14]. Consequently, the yaw angle will also affect the z-directional measurement results.

For the situation related to the pitch angle, the analytic process is similar to the discussion about the yaw angle except the affected
4.2. Effects of the periodical nonlinear errors

Periodical nonlinearity in laser interferometers has been analyzed by some researchers [5,23,24]. The nonlinear errors are caused by 1) imperfections of the used optical elements such as the PBS, BS and wave plates and 2) misalignment of the optical axes of the optical elements with respect to that of the polarized beams. Therefore, the nonlinear errors are also existent in our grating encoder. Actually, although there are two kinds of error sources, the nonlinear errors are mainly from the imperfections of the optical components in the detecting system [24].

From the interference principle, the periodical nonlinearity for the phase \( \phi_i \) of the detected interference signals can be expressed as [24]

\[
NL_i = \arctan \frac{I_a(t)}{I_b(t)} - \arctan \frac{I_a(t_0)}{I_b(t_0)} = [\phi_i(t) - \phi_i(t_0)]
\]

where \( t \) and \( t_0 \) are the measuring and original moments respectively. \( I_a \) and \( I_b \) can be expressed as

\[
I_a = I_E(0^\circ) - 1E_0(180^\circ) = (S_{i,1}^2 - S_{i,2}^2) + (R_{i,1}^2 - R_{i,2}^2) + 2[S_{i,1}R_{i,2} \cos \phi_i + S_{i,2}R_{i,1} \cos(\phi_i + \delta_{a,b})]
\]

\[
I_b = I_E(90^\circ) - I_E(270^\circ) = (S_{i,2}^2 - S_{i,1}^2) + (R_{i,2}^2 - R_{i,1}^2) + 2[S_{i,2}R_{i,1} \sin \phi_i + S_{i,1}R_{i,2} \cos(\phi_i + \delta_{a,b})]
\]

where \( I_{E_i}(\cdot) \) is the actual detected intensity of the photodiode in the corresponding detector unit for the diffractive beam denoted by the subscript \( i \). \( S_{i,m} \) and \( R_{i,m} \) are the amplitudes of the measurement and reference beams, respectively. The subscript \( m \) goes from 1 to 4 corresponds to the beams reaching the four detector units, respectively. \( \delta_{a,b} \) are the phase delay errors of the two quadrature signals for the diffractive beam denoted by the subscript \( i \), respectively.

There are two kinds of imperfections of the optical components in the detecting system. The first kind is the imperfections of the transmittance and reflectance of the two PBSs and one BS. Obviously, \( S_{i,m} \) and \( R_{i,m} \) are only influenced by this kind of imperfections. Therefore, the direct-current part of the nonlinearity is only affected by this kind of imperfections, which are described by the first and second terms on the right side of Eqs. (9) and (10). The other kind of imperfections are the nonideal phase delay of the QWP and the additional phase caused by the PBSs and BS between their transmitted and reflected light. This kind of imperfections only affect \( \delta_{a,b} \). Therefore, the alternating-current components are influenced by the two kinds of imperfections. In order to reduce the nonlinear errors, some compensation methods and improved phase detecting technologies can be employed [24–26].

5. Conclusion

In this work, a high-resolution and wide range three-axis grating encoder was introduced and experimentally demonstrated. The grating encoder could measure the three-axis translational motions of a stage simultaneously. The practical grating encoder was integrated and compact. A DGBS unit and two DOEs were employed to simplify the grating encoder. In order to improve the energy utilization efficiency and signal noise ratio, the DGBS unit and the DOEs were optimized according to the scalar diffraction theory. Meanwhile, the 4-step DOEs eliminated the unwanted beams. With an 8 segmental data division card developed in our lab, the z-axial displacement resolution of the grating encoder achieved 4 \( \mu \)m and the grating encoder could measure the motion of a stage precisely. The size of the integrated grating encoder could be further miniﬁed with smaller optical and mechanical elements. The effects of the misalignment between the planar scale grating and the optical reading head as well as the periodical nonlinear errors were also discussed. We expect that the integrated encoder is feasible and convenient to measure the wide range three-axis motions of precision translation stages.

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References


