Structural Analysis of a Micro Hexagonal Mesh Using a Three-way Grating by Hexagonal Digital Moiré Method

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Abstract
The hexagonal digital moiré method for analyzing the planar structural information of hexagonally assembled micro/nano structures is presented in detail. The structure of a micro hexagonal mesh fabricated by ultraviolet nanoimprint lithography is characterized. A three-way grating is constructed as a reference grating, whose pitches in three directions are close to those of the 1D arrays of the micro hexagonal mesh. The pitches and the orientations of the three 1D arrays in three directions are simultaneously measured. This method is effective in evaluating the fabrication quality of a hexagonally assembled structure in a large view field.

Key words
Hexagonal Digital Moiré Method, Three-way Grating, Micro/nano Structure, Hexagonal Mesh, Nanoimprint

1. Introduction
Due to excellent performances, micro/nano structures are getting more potential applications [1, 2] in diverse fields of electronics, optics, biology, medicine, etc. For the sake of stability, most micro/nano structures are assembled in a hexagonal pattern [3], such as graphenes, carbon nanotubes, nanoparticles, nanoholes, nanodots and nanopillars etc. There are also numerous hexagonally assembled micro/nano structures in the nature world, such as pillar-like projections on a cicada wing [4], particle-like ommatidia of an insect eye, etc. Among the many kinds of hexagonally assembled structures, micro/nano hexagonal meshes such as honeycomb widely exist in industries and the nature world. Structural analysis plays an increasingly significant role in the synthesis and characterization of a micro/nano hexagonal mesh.

Observation using high power microscopes including an atomic force microscope, a scanning electron microscope, a scanning laser confocal microscope and a transmission electron microscope, is a most common way to characterize a micro/nano structure. However, the view field is extremely small and it is difficult to obtain the structure information in a large view field by this point-by-point observation way. Although powder X-ray diffraction and atomic moiré interferometry [5] can allow us to know the average structural information, the structural differences in different regions are neglected. The fast Fourier transform (FFT) technique provides another way to analyze the periodic structures. Nevertheless, the pixel numbers of the analyzed image should be an integer power of 2.

The moiré pattern resulting from a mismatch of two gratings or periodic grids is a useful tool for understanding structural properties. The electron moiré method [6, 7] shows its superiority in characterizing hexagonally assembled micro/nano structures in a large region. Yamauchi et al [8] used electron moiré fringes to explore the domain sizes and the nanopore arrangements of nanoporous anodic alumina (PAA) films and the replicated Ni cone arrays. However, their analysis was based on the assumption that the three adjacent nanopores could form an equilateral triangle. It is difficult to perform their method on common micro/nano structures due to more or less deflections in the structure arrangements. Kishimoto et al [9] investigated the domain sizes and the orientation directions in ordered assembled nanoparticles utilizing two groups of electron moiré fringes. In spite of simple analysis, the experiment operation will be troublesome, because two groups of parallel moiré patterns captured at two times are necessary in the same region.

To simultaneously acquire the pitches and the orientations of the three 1D arrays of a hexagonally assembled micro/nano structure in three directions in a large view filed without restriction to the image size, the authors proposed the hexagonal digital moiré method [10] based on traditional moiré methods [11]. In this paper, we will introduce the measuring principle and the measuring accuracy of this method. Finally, a hexagonal mesh at the micro scale fabricated by ultraviolet nanoimprint lithography will be characterized.

2. Hexagonal Digital Moiré Method

2.1 Hexagonal moiré fringes formation
A three-way grating including three one-way gratings (r₁, r₂ and r₃) illustrated in Fig.1 is constructed as a reference grating. The included angles between each two one-way gratings are 60°. The three one-way gratings have equal pitches (a) which are close to the pitches of the 1D arrays of a hexagonally assembled structure. Small hexagons in the intersection area of the three one-way gratings labeled in a dashed circle in Fig.1 are the basic components to generate hexagonal moiré fringes with a structure. Because the three-way grating is produced by a computer, the measurement method using the generated hexagonal moiré fringes is called as the hexagonal digital moiré method [10].

When the three-way grating is superimposed on a hexagonally assembled micro/nano structure with misalignment, hexagonal moiré fringes will appear, as seen in Fig.2. If the micro/nano structure can be derived from an uniform expansion and a rotation of the three-way grating,
the generated hexagonal moiré fringes will be regular (Fig.2a), while in other situations the formed moiré fringes are not regular, called as general hexagonal moiré fringes (Fig.2b). In most cases, the emerged moiré fringes are general hexagonal moiré fringes.

2.2 Measuring principle

The three groups of parallel moiré fringes in Fig.3a are formed by the superimposition between the three one-way gratings (r1, r2 and r3) and the three 1D arrays (s1, s2 and s3) of a analyzed structure. The formation principle of the parallel moiré patterns is the same as in traditional moiré methods. If we can obtain the moiré spacings and the orientations of the parallel moiré patterns from the hexagonal moiré fringes, it will be easy to calculate the pitches and the orientations of the micro/nano structure using the moiré inversion method [12, 13].

Fig.3b shows the enlarged view of the hexagonal moiré fringe labeled in Fig.3a, revealing the relationship between the sizes of the labeled hexagonal moiré fringe and the pitches of the parallel moiré patterns. The symbols $d_1$, $d_2$ and $d_3$ denote the spacings of the three groups of parallel moiré patterns (m1, m2 and m3) corresponding to the three one-way gratings, respectively. $D_1$, $D_2$ and $D_3$ are the distances between the opposite sides of the labeled hexagonal moiré fringe along the directions of m1, m2 and m3, respectively. The symbols $a_1$, $a_2$ and $a_3$ express the included angles between m2 and m3, m3 and m1, m1 and m2, respectively.

According to the geometric relationship in Fig.3b, the spacings of the three groups of parallel moiré patterns can be expressed by

$$d_i = D_i \sin a_i$$

From the midpoints of the six sides of the labeled hexagonal moiré fringe, we can determine the directions of the parallel moiré patterns, because the lines between the midpoints of the opposite sides of the hexagonal moiré fringe are parallel to m1, m2 and m3. The lines between the centers of the adjacent hexagons are also parallel to m1, m2 and m3. As a consequence, the angles $a_1$, $a_2$, $a_3$ and the distances $D_1$, $D_2$, $D_3$ can be measured directly with the hexagonal moiré image in Fig.3a. The spacings of the parallel moiré patterns can then be calculated using Eq. (1). Because a hexagonally assembled structure can be uniquely determined when the pitches and the orientations of only two arrays are measured, we can use only two of the three expressions in Eq. (1). To reduce the
measurement errors of $D_1$, $D_2$, $D_3$, $a_1$, $a_2$, $a_3$, the relationship between the sides and the angles $D_1/\sin a_1=D_2/\sin a_2=D_3/\sin a_3$ can be used to verify.

![Diagram](image)

Fig.3 Measuring principle of the hexagonal digital moiré method. (a) Relationship between the hexagonal moiré fringes and the three groups of parallel moiré patterns (m1, m2 and m3), where r1, r2 and r3 stand for three one-way gratings. (b) Relationship between the sizes ($D_1$, $D_2$ and $D_3$) of the labeled hexagonal moiré fringe and the pitches ($d_1$, $d_2$, $d_3$) of the parallel moiré patterns, where $a_1$, $a_2$ and $a_3$ express the included angles between m2 and m3, m3 and m1, m1 and m2, respectively.

Define $\varphi_1$, $\varphi_2$ and $\varphi_3$ as the angles between the three one-way gratings (r1, r2 and r3) and the corresponding parallel moiré patterns (m1, m2 and m3), which can also be measured with the hexagonal moiré image. The values of $\varphi_1$, $\varphi_2$ and $\varphi_3$ range from 0° to 180°, depending on the anticlockwise rotation angles from r1, r2 and r3 to m1, m2 and m3. The pitches ($a_1'$, $a_2'$ and $a_3'$) of the micro/nano structure can then be calculated from

$$d_i' = \frac{d \cos \varphi_i}{\sqrt{d_i^2 + a_i'^2 - 2d_ia_i' \cos \varphi_i}} \quad (i = 1, 2, 3)$$  \hspace{1cm} (2)

where $a$ is the pitch of the three-way grating, and $d_1$, $d_2$ and $d_3$ represent the spacings of the parallel moiré patterns. It should be noted that, Eq. (2) is suitable for the case of $a>a_1'$, $\varphi<90°$, or $a<a_1'$, $90°<\varphi<180°$. If $a=a_1'$, $\varphi<90°$, or $a=a_1'$, $90°<\varphi<180°$, the negative sign in Eq. (2) should be replaced by a positive sign.

We can obtain the angles ($\theta_1$, $\theta_2$ and $\theta_3$) between the three 1D arrays (r1, s2 and s3) of the micro/nano structure and the three one-way gratings (r1, r2 and r3) by

$$\theta_i = \arctan \left( \frac{-\sin \varphi_i}{d_i/a} \right) - \cos \varphi_i \quad (i = 1, 2, 3)$$  \hspace{1cm} (3)

The applicable condition of Eq. (3) is the same with that of Eq. (2). The two negative signs in Eq. (3) should be substituted by two positive signs when $a>a_1'$, $\varphi<90°$, or $a<a_1'$, $90°<\varphi<180°$. The values of $\theta_1$, $\theta_2$, and $\theta_3$ are within $-90°$ and $90°$, in which a positive value means anticlockwise rotation from a one-way grating to the corresponding 1D array of the micro/nano structure.

After the pitches ($a_1'$, $a_2'$ and $a_3'$) and the orientations ($\theta_1$, $\theta_2$ and $\theta_3$) of the three 1D arrays of the micro/nano structure are calculated, the planar micro/nano structural feature will be determined uniquely.

2.3 Measuring accuracy

In the hexagonal digital moiré method, the pitch of the three-way grating ($a$) is always chosen to be close to the pitches ($a_1'$) of the three 1D arrays of the micro/nano structure, and usually $4/5 ≤ a/a_1' ≤ 5/4$ ($i = 1, 2, 3$). Therefore, the absolute value of the strain of a 1D array of the micro/nano structure relative to the corresponding one-way grating of the three-way grating satisfies $|\varepsilon| = |a'/a| ≤ 1/4$. Because the strain of a specimen can be calculated from $|\varepsilon| = a'/d$ in traditional moiré methods, we can get $d/a ≥ 4$, and usually $4 ≤ d/a ≤ 100$. Suppose the measurement errors of the moiré spacing $d$, and the angle $\varphi$, are $\varepsilon_d$ and $\varepsilon_\varphi$, respectively. Commonly, $|\varepsilon_d| ≤ 0.03$ and $|\varepsilon_\varphi| ≤ 0.03$.

Based on Eq. (2) and Eq. (3), the errors of the pitches ($\varepsilon_a'$) and the errors of the orientation angles ($\varepsilon_\varphi$) of the three 1D arrays of the micro/nano structure can be obtained, adopting $4 ≤ d/a ≤ 100$, $|\varepsilon_d| ≤ 0.03$ and $|\varepsilon_\varphi| ≤ 0.03$. From the calculation results in the two cases of adopting negative signs and adopting positive signs in Eq. (2) and Eq. (3), we find that the ranges of $\varepsilon_a'$ and $\varepsilon_\varphi$ are $|\varepsilon_a'| ≤ 0.01$ and $|\varepsilon_\varphi| ≤ 0.05$. That is to say, the measurement errors of the pitches of the three 1D arrays of the micro/nano structure are less than 0.01, and the measurement errors of the direction angles between the three 1D arrays of the structure and the corresponding one-way gratings are less than 0.05 in the hexagonal digital moiré method.

3. Application in Characterizing Micro Hexagonal Mesh

3.1 Micro hexagonal mesh fabrication

The micro hexagonal mesh is fabricated using the ultraviolet nanoimprint lithography technique. The used ultraviolet
curable resin is PAK01. After the resin is coated on a glass slide by a spin coater with the speed of 2000 rpm, a quartz mold with a hexagonal mesh pattern is pressed into the resin. A light-emitting diode (LED) is then used to provide ultraviolet rays to harden the resin. The irradiation time of the ultraviolet rays is set to be 30s. After demolding, the hexagonal mesh pattern will be duplicated on the surface of the glass slide. The length and the width of one side of a small hexagon in the hexagonal mesh are 1.13 μm and 200 nm, respectively. The micro hexagonal mesh image is recorded by a scanning laser confocal microscope (Lasertec, 1LM15).

3.2 Structural characterization

The hexagonal digital moiré method is used to inspect the uniformity of the fabricated hexagonal mesh in a large view field, and simultaneously obtain the pitches and the orientations of the 1D arrays of the micro hexagonal mesh. The first step is to construct a three-way grating. Because the approximate pitches of the three 1D arrays of the micro hexagonal mesh are larger than 1.7 μm, we set the pitch of the three-way grating to be \( a' = 1.62 \) μm (\( a'' = 1.71 \) μm). When the three-way grating is superimposed on the micro hexagonal mesh image, distinct hexagonal moiré fringes (Fig.4a) will appear after the three-way grating is rotated to an appropriate position. The uniformity of the formed hexagonal moiré fringes suggests the good quality of the fabricated hexagonal mesh by the ultraviolet nanoimprint lithography technique.

Next we will measure the pitches and the orientations of the three 1D arrays of the micro hexagonal mesh. A hexagonal moiré fringe is taken as an example. From the centers of the adjacent hexagons, the directions of the three groups of parallel moiré patterns (m1, m2 and m3) can be determined. The distances \( D_1, D_2 \) and \( D_3 \) between the opposite sides of the analyzed hexagon along the directions of m1, m2 and m3 are labeled in Fig.4a. Because only two determined arrays can decide a hexagonally assembled structure, we only use the first two expressions in Eq. (1).

\[
D_1 \text{ and } D_3 \text{ are measured to be } D_2 = 15.7 \text{ μm and } D_1 = 22.2 \text{ μm, respectively. According to the directions of the three one-way gratings (r1, r2 and r3) and the parallel moiré patterns (m1, m2 and m3), we can acquire the angles between the three one-way gratings and the corresponding parallel moiré patterns: } \phi_1 = 36^\circ, \phi_2 = 42^\circ, \phi_3 = 57^\circ \text{ (Fig. 4b). The above values of } D_1, D_2, D_3, \phi_1, \phi_2, \phi_3 \text{ are measured by the software MB-Ruler. Therefore, the included angles between m2 and m3, m1 and m2 can be obtained: } \alpha_1 = 75^\circ, \alpha_2 = 66^\circ. \text{ Using the first two expressions in Eq. (1), the spacings of two parallel moiré patterns m1 and m2 are calculated to be } d_1 = 14.3 \text{ μm and } d_2 = 21.4 \text{ μm.}
\]

As a result of \( a > a'' \) and \( \phi > 90^\circ \) (\( i=1,2 \)), we can directly use Eq. (2) and Eq. (3) without replacing negative signs by positive signs. Substituting the values of \( a, d_1, d_2, \phi_1, \phi_2 \) into Eq. (2) and Eq. (3), we can obtain the pitches of two 1D arrays of the micro hexagonal mesh: \( a_1' = 1.77 \) μm, \( a_2' = 1.71 \) μm, as well as the angles between s1 and r1, s2 and r2: \( \theta_1 = -4^\circ, \theta_2 = -3^\circ \). The negative values of \( \theta_1 \) and \( \theta_2 \) mean that it needs clockwise rotations from the one-way gratings r1 and r2 to the 1D arrays s1 and s2.

On the basis of the geometric relationship among the three 1D arrays of the hexagonal mesh, the pitch of the third 1D array is calculated to be \( a_3' = 1.71 \) μm. The calculated results are displayed in Fig.4b. The included angles between the three 1D arrays of the micro hexagonal mesh are 57°, 62° and 61°, respectively. The unequal angles come from the fabrication process of the micro hexagonal mesh.

![Fig.4](image)

Fig.4 Structural analysis of a micro hexagonal mesh fabricated by the ultraviolet nanoimprint lithography technique. (a) Hexagonal moiré fringes formed by the mismatch between a three-way grating and the hexagonal mesh. (b) The pitches (\( a_1', a_2', a_3' \)) and the orientations (\( \theta_1, \theta_2, \theta_3 \)) of the three 1D arrays of the hexagonal mesh obtained by the hexagonal digital moiré method. The symbols m, r, s express a group of parallel moiré pattern, a one-way grating, a 1D array of the hexagonal mesh, respectively. \( \theta_i \) represents the angle between a one-way gratings (r) and the corresponding parallel moiré pattern (m). \( \alpha_i \) and \( \alpha_i' \) are the included angles between m2 and m3, m1 and m2, respectively. \( i=1,2,3 \).

To reduce the measurement errors and verify the calculation results, we can also measure the value of \( D_1 \) to calculate \( d_1 \) using the third expression in Eq. (1). The spacing of the third moiré pattern is calculated to be \( d_3 = 14.8 \) μm using the measured values \( D_3 = 22.2 \) μm and
α₂=39°. The pitch (α1') of the third 1D array can then be obtained using Eq. (2). The calculated result is α1'=1.71 μm, equal to the result obtained from the geometric relationship with α1' and α2'. This demonstrates the validity of the hexagonal digital moiré method.

4. Conclusion
In summary, the hexagonal digital moiré method is introduced to explore the pitches and the orientations of hexagonally assembled structures at the micro- and nanoscales. Hexagonal moiré fringes are generated by a mismatch between a three-way grating and a hexagonally assembled structure. The measuring principle from general hexagonal moiré fringes and the measuring accuracy are presented. The pitches and the orientations of the three 1D arrays of a micro hexagonal mesh fabricated by the ultraviolet nanoimprint lithography technique are measured. The uniformity of the formed hexagonal moiré fringes suggests the good quality of the fabricated hexagonal mesh. The hexagonal digital moiré method can also identify the structural differences in different regions from the shape variation of the hexagonal moiré fringes. As a consequence of the flexibility of the three-way grating produced by a computer, this method is effective in characterizing structures from nano- to meter-scale.

Nomenclature

\( a \)  pitch of a three-way grating [m]
\( a_1' \)  pitch of a 1D array of a hexagonally assembled structure [m]
\( d_i \)  spacing of a group of parallel moiré pattern [m]
\( D_i \)  distance between the opposite sides of a hexagonal moiré fringe along the directions of \( m_i \) [m]
\( i \)  serial number (i=1,2,3)
\( m_i \)  a group of parallel moiré pattern
\( ti \)  a one-way grating of a three-way grating
\( si \)  a 1D array of a hexagonally assembled structure
\( α_i \)  included angle between m(i+1) and m(i-1) [°]
\( Δα_i \)  measurement error of \( α_i \)
\( Δd_i \)  measurement error of \( d_i \)
\( Δθ_i \)  measurement error of \( θ_i \)
\( θ_i \)  angle between a one-way grating (\( t_i \)) and a 1D array (\( s_i \)) of a hexagonally assembled structure [°]
\( φ_i \)  angle between a one-way gratings (\( t_i \)) and the corresponding parallel moiré pattern (\( m_i \)) [°]

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References


