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ABSTRACT
Moiré fringes are created by superimposing two periodic or quasi-periodic networks of lines. This established technique is an important metrological tool for methods such as super-resolution microscopy. Biogenic guanine crystals show light and dark striped patterns on the broadest surface of their crystal plates when optical interference occurs because of the flatness and transparency of the crystal. In this work, using the optical interference pattern of a goldfish guanine crystal plate, we successfully observe the appearance of moiré fringes on a guanine crystal plate floating in water above herringbone patterns with micron and sub-micron periods. It is demonstrated experimentally that a variety of moiré fringes can be obtained by varying the long-axis direction of the guanine crystal plate using an in-plane magnetic field, which corresponds to a change in the direction of the structured illumination, because of the diamagnetic anisotropy of the crystal. The results of observation of the moiré fringes formed when the tilt angle of the guanine crystal’s (102) plane relative to the substrate is varied using a vertical magnetic field are also presented.

I. INTRODUCTION
Many promising ideas based on optical interference effects have emerged for use in measurement methods, sensors and other applications. It is well known that moiré fringes are created by superimposing two periodic or quasi-periodic networks of lines. This technique has become established as an important metrological tool for applications including displacement and alignment sensors and strain measurement. In super-resolution microscopy using a structured illumination method, displaced super-resolution information is extracted from moiré fringe information. To reproduce fine structures, multiple moiré fringe images obtained by varying the phase and direction of the structured illumination are required. Biogenic guanine crystals derived from fish skin and scales can act as micro mirrors because they offer high reflectivity from the broadest surface of the crystal plate. The orientations of guanine crystal plates in water suspensions can be controlled magnetically using magnetic fields of hundreds of millitesla because of their diamagnetic anisotropy, which enables variation of the light scattering using magnetic fields. Additionally, periodically aligned guanine crystals show a structural color caused by the light interference effect between them due to the optical transparency of the crystals.

It was previously reported that two cross-stacked guanine crystal plates derived from goldfish showed a light-and-dark striped pattern, i.e., light interference fringes, on the area where the broadest surfaces of the crystal plates overlapped, and dynamic color change was also observed there. Our previous work showed that this light interference pattern can also be observed on the broadest surface of...
a single guanine crystal plate when combined with a mirror surface substrate. Using this phenomenon, optical detection and estimation of minute curvatures and thin steps that cannot be measured directly using an optical microscope were demonstrated.  

In this study, we observe a guanine crystal plate taken from goldfish floating in water above herringbone patterns using an optical microscope and show that moiré fringes appear on the guanine crystal surface because of its optical interference stripe pattern. This measurement technique offers the advantage of being magnetically controllable, as demonstrated experimentally, because the guanine crystal plates are magnetically oriented as a result of their diamagnetic anisotropy.

II. EXPERIMENT

We fabricated two types of herringbone patterns using microfabrication techniques. Type A is an etched Si pattern and type B is a multilayer film pattern that include a Cr layer on a glass substrate. An electron beam resist was spin-coated on the Si substrate for type A and on a CrO (8 nm)/Cr (62 nm)/CrO (30 nm) multilayer film deposited on soda-lime glass, i.e., a hard mask photolithographic blank, for type B. Exposure was performed using an electron beam writing system with an acceleration voltage of 50 kV. A schematic of the exposed herringbone pattern is shown in Fig. 1 and the design dimensions for 1/1 \( \mu \text{m} \) line-and-space (L/S) and 0.5/0.5 \( \mu \text{m} \) L/S patterns are summarized in Table I. After the resist was developed, grooved herringbone patterns with a depth of approximately 1 \( \mu \text{m} \) were fabricated in type A by dry etching using a Bosch process. In type B, the CrO/Cr/CrO multilayer film was patterned by wet etching. Finally, the electron beam resists were removed by \( \text{O}_2 \) plasma ashing. Figure 2 shows fabricated samples with the 1/1 \( \mu \text{m} \) L/S herringbone patterns of (a) type A and (b) type B. The line-and-space widths are almost identical in both cases.

The guanine crystal plates were obtained from goldfish scales. Each crystal has an elongated hexagonal thin plate shape with typical dimensions of 20 \( \mu \text{m} \times 5 \mu \text{m} \times 100 \text{ nm} \) (thickness). The broadest smooth surface of the guanine crystal plate corresponds to the crystal’s (102) plane. A 9\( \times \)9 \( \text{mm}^2 \) frame seal with a 25 \( \mu \text{l} \) capacity (Bio-Rad SLF0201) was set on both samples. Water containing the guanine crystal plates was dropped into the frame seal chamber and the chamber was then sealed using a cover glass. Observations were performed using an optical microscope under blue light-emitting diode (LED) illumination at a peak wavelength of 460 nm.

III. RESULTS AND DISCUSSION

Figure 3(a) and 3(b) show optical microscope images of guanine crystal plates in water above the 1/1 \( \mu \text{m} \) L/S herringbone patterns of (a) type A and (b) type B, respectively. The 1/1 \( \mu \text{m} \) L/S herringbone patterns under water can still be observed directly in both samples. The reflected light intensities from the light and dark portions of the herringbone pattern were estimated from microscope images captured using a complementary metal-oxide-semiconductor (CMOS) camera. The light portion/dark portion intensity ratios for type A (ratio=1.24) and type B (ratio=1.27) were almost equal. As clearly shown in both images, moiré fringes appear on each guanine crystal (102) plane surface. When the crystal plate is tilted slightly with respect to the substrate surface, light and dark stripes occur on the broadest surface of the crystal plate because of the light interference effect, which acts as structured illumination. As a result, moiré fringes are successfully obtained using the interference pattern of the guanine crystal plate.

![FIG. 1. Schematic of exposed herringbone pattern.](image1)

![FIG. 2. Optical microscope images of fabricated herringbone patterns of (a) type A and (b) type B.](image2)

![FIG. 3. Optical microscope images of guanine crystal plates in water above 1/1 \( \mu \text{m} \) L/S herringbone patterns of (a) type A and (b) type B. (c) Schematic view of overlapping herringbone pattern and interference strips.](image3)

TABLE I. Design values for herringbone pattern.

| L/S       | 1/1   | 0.5/0.5 [\( \mu \text{m} \)] |
|-----------|-------|-----------------------------|
| A         | 9.40  | 9.98                        |
| B         | 3.85  | 3.43                        |
| L         | 1     | 0.5                         |
| S         | 1     | 0.5                         |

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fringes are due to the different relative angles between the herringbone pattern and the crystal plate’s interference stripes. Figure 3(c) shows a schematic view of the overlapping herringbone and interference stripe patterns. The moiré fringes shown in Fig. 3(a) and 3(b) are both reproduced.

As mentioned earlier, the goldfish guanine crystal plate has an elongated hexagonal shape and the first easy axis for the magnetic field is in the crystal plate’s long-axis direction. When an in-plane magnetic field, i.e., oriented parallel to the water’s surface, of more than 100 mT is applied, the long axis of the guanine crystal’s (102) plane is aligned in parallel with the magnetic field direction. Therefore, by changing the direction of the in-plane magnetic field, the relative angle between the herringbone and the guanine crystal interference patterns can be changed. Two neodymium magnets (each magnet dimensions: 20×20×4 mm³) are used to apply the magnetic field here. These magnets are combined horizontally so that their surface poles oppose each other, as drawn schematically in Fig. 4(a). The distance between the sample and the magnet’s surface is approximately 3 mm. An in-plane magnetic field of 300 mT is generated at the center position of the combined magnets. The in-plane rotation field can then be applied by rotating the combined magnets within the plane. Experimental results for the guanine crystal plate’s in-plane rotation above the type B 1/1 μm L/S herringbone pattern are shown in Fig. 4(b). The moiré fringes, which depend on the relative angle between the herringbone and the guanine crystal’s interference patterns, are obtained continuously. These results indicate that various moiré fringes can be obtained via magnetic rotation of the guanine crystal plate, which corresponds to the directional change in the structured illumination required in the super-resolution microscopy to acquire the necessary information to reproduce fine structures. However, the guanine crystal plate’s optical interference pattern varies with its Brownian motion. To obtain an appropriate optical interference pattern for the crystal plate stably, it is necessary to establish a more stable magnetic control method for the guanine crystal plate direction, e.g., using magnetic beads.

The magnification of the image observed as moiré fringes is dependent on the stripe pattern period of the structured illumination. When the light and dark stripe patterns of the illumination and the observed specimen overlap each other in parallel, the moiré fringe magnification increases because the illumination pattern period is closer to that of the specimen. The interference pattern period of the guanine crystal plate depends on the tilt angle between the substrate plane and the guanine crystal’s broadest surface ((102) plane). As shown in Fig. 3(a)–3(c), when a magnetic field of more than 100 mT is applied perpendicular to the (102) plane, the guanine crystal plate rotates around the (102) plane’s long axis and the (102) plane becomes parallel to the magnetic field (Fig. 5(c)) to reduce the diamagnetic energy. A moiré fringe observation experiment with guanine crystal out-of-plane rotation caused by a vertical magnetic field, i.e., a magnetic field perpendicular to the water’s surface, has been conducted. First, the guanine crystal plate was set in the appropriate direction using the in-plane magnetic field generated at the combined position of the magnets. The combined magnets were then moved sideways so that the guanine crystal plate was at the center of one magnet to apply the vertical magnetic field. The continuous change in the moiré fringes with the out-of-plane guanine crystal rotation was captured using the CMOS camera. Figure 5(d) shows the moiré fringes for various guanine crystal plate tilt angles relative to the substrate in the type B 1/1 μm L/S herringbone pattern case. The tilt angle in each figure is estimated using the guanine crystal interference pattern period. As the tilt angle increases and the optical interference pattern period shortens, clear moiré fringes are observed at tilt angles of 2.3°, 2.5° and 3.3°, and the magnification of the moiré fringes at 3.3° is greater than that at 2.3°. These

FIG. 4. (a) Schematic view of experimental setup. (b) Optical microscope images of guanine crystal plate in water above type B 1/1 μm L/S herringbone pattern with in-plane rotation field.

FIG. 5. Optical microscope images of guanine crystal plate (a) without and (b), (c) with applied vertical magnetic field. When the vertical field is applied, the guanine crystal plate rotates around its long axis as shown in (c) via (b). (d) Optical microscope images of continuous change in moiré fringes with out-of-plane guanine crystal plate rotation above type B 1/1 μm L/S herringbone pattern.
results indicate the possibility of obtaining moiré fringes with suitable pattern periods, i.e., the magnification required for specimen microstructure observation, by using the magnetic field. Additionally, the guanine crystal plate stands such that the (102) plane lies parallel to the vertical magnetic field. Because the guanine crystal is quite a thin plate (Fig. 5(c)), it allows the specimen image to be observed directly, which is helpful during reference signal acquisition.

Figure 6 shows optical microscope images of the guanine crystal plates above the 0.5/0.5 μm L/S herringbone patterns of (a) type A and (b) type B, respectively. In Fig. 6(a), while the herringbone pattern around the guanine crystal plate is invisible, the moiré fringes are observed on the guanine crystal plate. In these experiments, moiré fringes could not be obtained in the type B sample. However, as Fig. 6(b) shows, the herringbone pattern can only be seen below the guanine crystal plate, because the reflected light intensity increases greatly under the plate. These points indicate that the guanine crystal plate is expected to improve the image resolution of minute regions during e.g., living cell observation.

IV. CONCLUSIONS

Using the optical interference patterns of goldfish guanine crystal plates, we have successfully observed moiré fringes on crystal plates floating in water above 1/1 μm and 0.5/0.5 μm L/S herringbone grooves fabricated by Si etching. It has been demonstrated that various moiré fringes, which depend on the relative angles between the herringbone grooves and the guanine crystal interference patterns, can be obtained continuously via magnetic orientation of the crystal plate using the in-plane rotation field. The possibility of changing the magnification of the moiré fringes, which is related to the guanine crystal's interference pattern period, using the guanine crystal's magnetic orientation property also proposed.

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