Resolution Improvement of Optical Imaging by Spatial Control of Light and Multi-Image Reconstruction

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Abstract – According to the industrial requirement for optical imaging, particularly in microscopic imaging, resolution improvement is one of the most important issues. In digital microscopic imaging, resolution of an optical system is limited by both optical parameters such as light wavelength and the objective lens numerical aperture and by spatial sampling such as pixel size of charge-coupled device camera. Focused on exceeding these limits and improving the resolution of optical imaging, spatial control of light is useful. In this study, spatial control of illumination with sub-wavelength accuracy improves resolution in diffraction limited imaging; besides spatial control of imaging path with sub-pixel accuracy improves resolution determined by the spatial sampling. High-resolution image can be reconstructed by using multiple images acquired with spatial control of light. This paper includes theoretical discussions, numerical simulations, and experimental verifications of some techniques proposed in our related works.

Key Words: Microscopic imaging, Resolution improvement, Spatial control of light, Multi-image reconstruction

1. Introduction

Numerous industries now require high resolution optical imaging techniques, e.g., in inspecting patterned semiconductor wafers, printed circuit boards, and micron-scale industrial components. The inspection must measure components nondestructively at high resolution without compromising inspection speed. This is especially important since defect detection is becoming an increasingly challenging task with the shrinking size of components. Such inspection is conventionally performed by microscopic imaging using either an optical method or an electron beam method. However, the inability of the optical method to handle the continuous miniaturization of components has become a major issue, because the resolution of the method is limited to the scale of wavelengths which diffraction occurs. The electron beam method does possess nano scale resolution, but it is a destructive method, and it is not useful for wide-area inspection because of its low throughput. In this study, we focused on the optical method because it ensures nondestructive and high throughput and can potentially provide a higher resolution on the subwavelength scale.

Generally in microscopic imaging, the lateral resolution of an optical system is limited by the diffraction limit determined by light wavelength and the objective lens numerical aperture. This indicates that the resolution of an optical system improves with an increase in the numerical aperture and decreases with increasing wavelength. In the practical use of microscope, however, it is difficult to decrease the wavelength to ultraviolet region. Moreover, the upper limit value of numerical aperture in dry condition is 1.0. Therefore, in order to overcome the diffraction limit, we have proposed an optical measurement technique that has higher resolution than conventional methods. The proposed method combines structured illumination microscopy [1] with the spatial control of illumination and multi-image reconstruction to deliver optimal sensitivity and a higher signal-to-noise ratio for critical defect detection at the subwavelength scale. This method enables the resolution of patterns that cannot be resolved by conventional methods. From the perspective of defect detection, the nanoscale spatial shift of the structured illumination is a primary requirement for improving the resolution and providing higher sensitivity as is the acquisition of multiple images with respect to each spatial position of the structured illumination. The optical measurement system used in this study is characterized by specific properties such as non-destructiveness, high-resolution, and high-throughput. Theoretical and experimental verifications reveal that the use of structured light illumination together with successive approximation (which provides the extrapolation effect) causes the resolution of the proposed method to exceed the optical diffraction limit [2].

However, the resolution of the optical imaging system is limited not only by the diffraction limit but also by the spatial sampling, which in turn is determined by the optical magnification and the pixel size of the area sensor such as charge-coupled device (CCD) camera. The maximum spatial frequency passed by the CCD is one half of the sampling frequency. Any frequency higher than this frequency will be aliased at lower frequencies. To acquire maximum resolution of the microscopic imaging, the imaging system should be limited by optics, and the CCD should provide sampling that reaches the diffraction limit mentioned above. In practical use, this means that at least two pixels of the CCD should be equivalent to a distance of resolution. This problem is related to the measurement throughput. A smaller sampling interval leads to slower optical measurements, because the visual field of the imaging optics is determined by the size and number of CCD pixels. In order to overcome this problem, we proposed subpixel sampling technique using spatial control of imaging path [3]. This technique is based on active subpixel shifting of the optical axis and multi-image reconstruction. In conventional multi-image super resolution, pixel displacement between images is passive, so it requires long calculation time and expensive calculation for spatial pixel-displacement estimation. By using the proposed technique, high-resolution images are expected to be acquired rapidly without spatial pixel displacement estimation and with higher noise tolerance. Furthermore, sub-pixel image processing can improve the resolution without narrowing the visual field of the microscopic imaging, so this technique can be applied for high-resolution, non-destructive, and high-speed inspection.
without necessitating the mechanical movement of the components of the imaging optics such as the CCD camera, the specimen stage, or the objective lens.

2. Resolution improvement in diffraction limited imaging

2.1 Basic principle of resolution improvement in microscopic imaging using spatial control of illumination

An optical imaging system is generally shift-invariant, so an image can be represented by the convolution of a scattered light signal and a point spread function. The scattered light image \( r(x) \) is determined from the specimen distribution \( a(x) \) and the illumination intensity distribution \( i(x) \) by the following equation.

\[
   r(x) = PSF(x) \otimes (a(x) \cdot i(x)).
\]

In this equation, \( PSF(x) \) is the point-spread function of the imaging optics, which represents the airy disk image formed by diffraction, and \( \otimes \) is a convolution operator. The scattered light image \( r(x) \) is modulated by shifting the structured illumination intensity \( i(x) \) to different positions.

The structured illumination shift method is illustrated in Fig. 1, one of the factors influencing the improvement in resolution is the extension in the spectrum of the observed optical system by the spatial distribution of the structured illumination, which is periodic and harmonic. Therefore, \( r(x) \) can be expressed as

\[
   i(x) = \frac{1 + \cos(2\pi f_s x + \phi)}{2},
\]

where \( f_s \) and \( \phi \) are the spatial frequency and the phase of the structured illumination, respectively. From equations (1) and (2), we obtain

\[
   R(f) = \frac{1}{2} OTF(f) A(f) + \frac{1}{4} e^{i\phi} OTF(f) A(f - f_s) \quad \text{(3)}
\]

where \( R(f) \) and \( A(f) \) are the Fourier transforms of the image with the structured illumination \( r(x) \) and of the specimen distribution, respectively, while \( OTF \) is the optical transfer function. The first term of equation (3) implies that, as in the case of a conventional image with uniform illumination, the spatial frequency of \( r(x) \) is restricted by the cutoff frequency \( f_s \), which depends on the \( OTF \). The second and third terms imply that the spatial frequency of \( r(x) \) is expanded to that of the structured illumination \( f_s \). Then, we obtain the resolution with the structured illumination. On the basis of the Rayleigh criterion, the improvement in the resolution brought about by the effectiveness of the high-frequency components of the structured illumination can be expressed as follows.

\[
   \text{Resolution with Structured Illumination} = \frac{1.22}{f_c + f_s}
\]

where \( f_c \) is the cutoff frequency of the imaging system.

This implies that the resolution depends on the spatial distribution of the structured illumination as well as on the imaging optics. Furthermore, we found that the proposed method can possibly provide an even higher resolution if we use successive approximation as the extrapolation effect, as explained in the next section.

2.2 Multi-image reconstruction for spatial control of structured illumination

In order to use the spatial information of the structured illumination in our calculations, we constructed a multi-image reconstruction algorithm that includes iterative operations. Equation (1) is discretely described as

\[
   r_i = \sum_{j=1}^{N} psf f_m i_j \quad (1 \leq i \leq N),
\]

where \( r_i \), \( psf \), \( f_m \), and \( i_j \) are the image distribution, \( PSF \), illumination intensity distribution, and specimen distribution, respectively. Suffix \( i \) represents a discrete position in the image plane; suffix \( j \) that in the object plane. Equation (5) can be simply described by using a coefficient matrix as

\[
   R = KA_i
\]

where \( A \) is the specimen distribution matrix; \( R \), the image matrix; and \( K \), the imaging coefficient matrix determined by the \( PSF \) and the illumination intensity. \( A \) is converted into \( R \) with the help of \( K \); thus, the imaging process is represented by a linear simultaneous equation.

The improvement in resolving power is realized by solving equation (6) for \( A \), but the mathematical constraints involved make this computation highly complex. In particular, under actual conditions such as those with high levels of noise, it is difficult to achieve convergence in the resolving calculation.

In order to solve this equation, we constructed an iterative image reconstruction algorithm in which one of the multiple images is used in the reconstruction and an assumed solution is then reconstructed. The block diagram of this algorithm is shown in Fig. 2 and the steps of the procedure are as follows.

Step 1: The specimen is assumed to be a scattering factor distribution. The assumed specimen has a constant initial value \( A_0 \). Then, the assumed specimen is illuminated with the structured illumination, which is computationally calculated. The initially calculated multiple images \( R_{m} \) are given, where \( m \) is the iteration number.

Step 2: An actual image of the specimen with the structured illumination is experimentally acquired. The observed multiple images \( R_{obs} \) are acquired by diffraction-limited imaging optics.

Step 3: The differences between the calculated and observed images are given as an error ratio with respect to each element of the image matrix. The error ratio \( E_{m} \) is expressed as

\[
   E_{m}(i) = \frac{R_{m}(i) - R_{obs}(i)}{R_{obs}(i)},
\]

where \( i \) represents an element of the matrix (row number \( i \)).

Step 4: The error ratio \( E_{m} \) is again input to the assumed specimen. The
Calculated images grating structures with pitches of <0.25 \mu m were acquired using the diffraction-limited imaging optics, so the longitudinal and transverse directions are shown in Fig.4. These images acquired by the spatial shift of the structured illumination along conditions was 0.36 \mu m. Examples of multiple modulated images beyond the diffraction limit imposed by the Rayleigh criterion for the simulation were not resolved in all the observations.

Step 5: The assumed specimen \( A_0 \) (initially \( A_3 \)) is replaced by the reconstructed specimen \( A_{n+1} \). The reconstructions are applied to the other shifted position of the standing wave illumination.

Step 6: Steps 1 - 5 are iteratively applied to decrease the error ratio and converge the solution.

By using the reconstruction method described above, the assumed specimen approaches the object distribution of the actual specimen, thereby leading to improvement in the resolving power.

2.3 Numerical simulations

To verify the multi-image reconstruction algorithm described above, numerical simulations based on Fourier optics were carried out. First, we attempted to improve the resolving power for a specimen comprising longitudinal and transverse grating structures including discrete defect-like objects. The specimen used in the numerical simulations and the diffraction-limited image of the specimen with uniform illumination are shown in Fig.3. The specimen has grating structures with pitches of 1 \mu m, 0.5 \mu m, 0.25 \mu m, and 0.125 \mu m. The conditions of optical imaging used in the simulations are listed in Table 1.

Table 1 Conditions of optical imaging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength of illumination light</td>
<td>0.532 \mu m</td>
</tr>
<tr>
<td>Numerical aperture of objective lens</td>
<td>0.9</td>
</tr>
<tr>
<td>Diffraction limit imposed by Rayleigh criterion</td>
<td>0.36 \mu m</td>
</tr>
<tr>
<td>Number of pixels in the image</td>
<td>800 x 800</td>
</tr>
</tbody>
</table>

The smaller figures located above the images show the corresponding directions and phases of the structured illumination. Table 2 lists the conditions used for the structured illumination and multi-image detection. In the proposed method, the spatial pitch of the structured illumination plays an important role in improving the optical resolving power. Furthermore, the structured illumination with a spatial pitch of 0.5 \mu m can be generated in the form of standing wave illumination by interference between two beams. The structured illumination thus generated is spatially shifted by a piezoelectric transducer (PZT) phase shifter with a size of 0.05 \mu m; for this reason, 10 images were used in the reconstruction to reflect the spatial information of the structured illumination in the final reconstruction.

The reconstructed images acquired using the multiple images mentioned in the preceding subsection are shown in Fig.5. In the reconstructions, the number of iterations was 10 and 50, so that the evaluation function values converged to <0.1% and <0.01% of the initial values, respectively. In Fig.5(a), the reconstructed image approximately corresponded to the specimen; the 0.25-\mu m structure that could not be resolved by uniform illumination was resolved beyond the diffraction limit. In addition, discrete defect-like objects in the specimen were observed in this figure. Several research groups that are focused on improving the resolving power using structured illumination have achieved improvements in the resolving power by a factor of approximately two. However, further improvement in the resolving power can be achieved by using digital image processing; the iterative reconstruction algorithm proposed above can be used for this purpose. In fact, further improvement in the resolving power was obtained by performing 50 iterations, as shown in Fig.5(b). This improvement can probably be attributed to the out-of-band extrapolation effect. Out-of-band extrapolation is based on maximum likelihood estimation and it takes into the constraint posed by the non-negative brightness of images, a constraint of zero-value outside the domain of objects, and so on [4]. Numerical simulations that were performed for verifying the improvement in resolving power using the proposed method reveal that the resolving power is improved by a factor of more than three.
where $\theta$ is refracting angle and $l$ is thickness of the glass plate. $S$ represents the subpixel displacement of observed images.

The 3 mm thick glass plate in experiments has a refractive index of 1.52 for the visual light wavelength, and the CCD pixel size is 6.45 $\mu$m. From Eq.(9), the glass plate orientation giving the one-tenth pixel size for the optical axis shift is 628 $\mu$rad. The galvano scanner realizes the orientation and subpixel shift highly accurately at the rotation stage at repeatability for rotations of 5 $\mu$rad. Other approaches for generating subpixel image displacement actively include displacing the CCD camera or observation object directly, but increase inertia moment and displacement error, making rapid high-resolution (HR) imaging difficult.

### Table 2 Conditions of simulation

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial pitch of the structured illumination</td>
<td>0.5 $\mu$m</td>
</tr>
<tr>
<td>Size of spatial shift of the structured illumination</td>
<td>0.05 $\mu$m</td>
</tr>
<tr>
<td>Number of images used in the reconstruction</td>
<td>10</td>
</tr>
</tbody>
</table>

### 3.2 Experimental verification

In the experimental apparatus based on the optics in Fig.6 and shown in Fig.8, two glass-plate-parallel substrates assembled in Galvano scanners for active optical axis shifting were inserted between the imaging lens and CCD camera in light microscopy. Experimental conditions are shown in Table 3 and the test target in Fig.9. To determine pixel resolution using our proposal, we varied optical magnification from 0.13 to 1.0 and determined spatial sampling by CCD pixel size and optical magnification. The resolution limit of the spatial sampling interval is bigger than the diffraction limit, so this evaluated only pixel resolution.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical magnification</td>
<td>0.13 – 1.0</td>
</tr>
<tr>
<td>Pixel size of CCD camera (μm)</td>
<td>6.45</td>
</tr>
<tr>
<td>Thickness of glass plate (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Repeatability of galvano scanner (μrad)</td>
<td>5</td>
</tr>
<tr>
<td>Numerical aperture of objective</td>
<td>0.055</td>
</tr>
<tr>
<td>Resolution limit by spatial sampling interval (μm)</td>
<td>12.9</td>
</tr>
</tbody>
</table>

An observed test target LR image from the apparatus we developed and the resulting experimentally reconstructed HR image are shown in Fig.10 -- (a) observed LR image with 76 × 76 pixels, 0.5 optical magnification corresponding to a pixel size of 12.9 μm; (b) reconstructed HR image with 304 × 304 pixels from 4 × 4 = 16 images in (a) using our proposal; (c) observed LR image with 38 × 38 pixels and 0.25 optical magnification corresponding to a pixel size of 25.8 μm; (d) reconstructed HR image of 304 × 304 pixels from 8 × 8 = 64 images in (c). Fig.10(b) shows a resolved 16 μm structure to group 6 line 1 in Fig.9, close to the spatial sampling interval resolution limit in the original HR image. Fig.10(d) shows greater pixel-resolution improvement than the LR image in Fig.10(c). Calculation time for multi-image reconstruction including image acquisition was 0.03 s with a 2.53 GHz CPU and 2 GB RAM, which was better than conventional, which is 0.2 s, including subpixel displacement time estimation. Rapid HR imaging is thus possible even under practical experimental conditions and the spatial test target frequency is well restored using our proposal.

4. Summary

Spatial control of illumination and multi-image reconstruction allow the resolution in diffraction limited imaging to be improved by a factor of more than three. Besides, spatial control of imaging path provides us pixel resolution improvement in digital microscopic imaging. These techniques can be incorporated into existing imaging system directly and easily, therefore they have great potential for practical applications to rapid high-resolution image inspections.

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References


Fig. 9: Test target in experiments.
(a) Test target patterns. (b) Number of line-pairs/mm.

Fig. 10 Observed LR and HR images reconstructed experimentally

Fig.11 Comparison of MTF intensity of reconstructed HR images