Coherent Imaging Algorithm of Super-Resolution Optical Inspection with Structured Light Shift

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Abstract:
Microfabricated structures continuing to shrink with development of nano-technology, an inspection technology which can be applied to sub-micrometer features is getting important. A super-resolution inspection method beyond the diffraction limit using the structured light shifts is one of the potential inspection techniques. In this article, in order to expand the application of this optical super-resolution inspection method to coherent imaging condition, a novel coherent imaging algorithm based on the special three-light-flux standing wave structured light was proposed. Numerical simulation analyses confirm that proposed method can be applied to coherent imaging condition such as general microstructured surface.

Keywords: Super-resolution, Coherent Imaging, Structured Light Illumination, Defect Inspection, Image Reconstruction

1. Introduction
With development of nano-technology, the sizes of microfabricated structures (such as semiconductors, MEMS, etc.) keep shrinking. The sizes of killer defects diminish inevitably. Therefore, the demand of defect inspection technology for the fine defects such as 100 nm scale is increasing [1]. The inspection technology with high speed, non-destructive, and high resolution characteristics is needed. Optical methods and electron beam methods have been mainly used for detecting the critical defects on the microfabricated structures, but the resolving power of the optical methods is generally low for defects at sub-wavelength geometries, while the scanning electron microscope needs vacuum and induces contamination in measurement. In order to find a solution to these problems, we propose an application of optical super-resolution technique using structured light [2] to optical inspection for the critical defects [3-5].

Figure 1 shows a basic principle of super-resolution optical inspection with structured light illumination shifts [5]. Instead of an illumination having almost uniform distribution such as conventional optical microscopy, a structured illumination having sinusoidal distribution is employed. Since optical responses of scattering objects on a surface directly depend on illumination distribution, microscopic scattered light distribution obtained with imaging optics is modulated under the structured light illumination. Indeed each modulated image is still degraded by diffraction limit but post-processing using multiple modulated images, which can be detected with structured light illumination shifts, can reconstruct scattered light distribution on the surface beyond the diffraction limit because the high frequency information of the structured light distribution with nano meter scale shifts can reflect the improvement of spatial resolution of optical system.

Figure 2 shows a typical example of basic flow of super-resolution optical inspection with structured illumination shifts. This example indicates the case for distinguishing two discrete dots on a flat surface such as particulate contaminations on a semiconductor surface, which is useful for evaluating its resolving power quantitatively. As shown in upper right figure, a normal

![Figure 1: Principle of super-resolution optical inspection with structured light illumination shifts](image-url)
observed image obtained under uniform illumination means that these two discrete dots cannot be resolved. Applying the standing wave structured light illumination to these two discrete dots (fig. 2(a)), modulated scattered light images can be observed depending on the lateral positions of the standing wave structured light (fig. 2(b)). From these multiple modulated scattered light images, we can numerically solve scattered distribution beyond the diffraction limit, based on mathematical process such as a successive method [3] (fig. 2(c)) dealing with the optical imaging formula.

This super-resolution process is one of the powerful optical inspection methods but it is restricted to application to only incoherent imaging such as sample emitting fluorescent light [4] or limited-conditioned coherent imaging [6] and it is difficult to apply as a general scattering sample inspection method, which needs coherent imaging algorithm. In this paper, we aimed to develop a novel super-resolution method with structured light shift based on three-light flux interference, which allows an application to coherent imaging as well as incoherent imaging. The resolving power of the proposed method is examined by numerical simulation. It is confirmed that 40 nm scale structure can be resolved by proposed method.

2. Problem point of application to coherent imaging with conventional super-resolution based on standing wave structured light shifts

Figure 3 shows an example of conventional super-resolution result in coherent imaging using standing wave structured light. This example indicates the case for distinguishing two discrete dots having a gap of 200 nm (fig. 3(a)). If we observed this sample through an optical system with optical conditions that wavelength and numerical aperture of imaging lens are 488 nm and 0.95, respectively, we can get normal image (fig. 3(b)) under uniform illumination. Since the Rayleigh diffraction limit can be calculated as 313 nm, the discrete dots having 200 nm gap cannot be resolved. And figure 3(c) indicates a super-resolution result by the conventional super-resolution process using standing wave structured light. From this result, it can be seen that two discrete dots cannot be resolved.
Figure 4 shows difference of mechanism of image formation between coherent and incoherent imaging using standing wave structured light. As shown in this figure, it is true that sinusoidal intensity distribution can be generated with conventional standing wave by interference effect of two counter propagating beams, but, there is phase difference in next peak to each other from the viewpoint of amplitude. Therefore, in the case of coherent imaging, imaging is formed not only by just addition of scattered amplitude but also by destructive superposition of scattered amplitude depending on the location of scattering objects, while incoherent imaging is formed by just addition of scattered intensity. On the other hand, we cannot detect amplitude and phase information but detect intensity information. Those facts mean that reconstruction from multiple detected images is mathematically impossible due to lack of phase information in the case of coherence imaging which includes destructive superposition process depending on phase information.

3. Proposed standing wave illumination enabling coherent imaging algorithm

In order to overcome abovementioned problem in the case of coherent imaging, we propose novel standing wave illumination enabling coherent imaging algorithm. Figure 5 shows conceptual diagram of the proposed standing wave (fig. 5(b)) compared with conventional standing wave (fig. 5(a)). This proposed standing wave is generated by not only conventional two counter propagating beams.
but also the third beam perpendicularly incident on a surface. This third beam has the same frequency as other counter propagating two beams and has a function of adding bias amplitude to the superposition of the conventional two beams. Under this three-light-flux condition, by adjusting the initial phase of three beams properly, we can get special standing wave condition where no phase difference in the sinusoidal amplitude distribution as shown in figure 5(b).

The above is described using math expression. Let the horizontal direction of Fig. 5 be x axis, and let a vertical direction be y axis. Let a direction perpendicular to both of xy axes be z axis. 3-light-flux has an electric field ingredient only in the z axis. The incidence angle of counter propagating two beams is set to \( \theta \). Since only a sample surface is considered, it is referred to as \( y = 0 \).

The electric field ingredient of counter propagating two beams is set to \( E_1 \) and \( E_2 \), respectively. Let the initial phase of three beams as \( \delta_1 \) and \( \delta_2 \). The conventionally standing wave is expressed as expression (3).

\[
E_i + E_2 = 2a \cdot \sin(\omega \cdot t + \delta_1 + \delta_2) \cos(k \cdot \sin \theta \cdot x - \frac{\delta_1 - \delta_2}{2})
\]

(3)

The expression (4) is electric field ingredient of perpendicularly incident third beam.

\[
E_3(t) = b \cdot \sin(\omega \cdot t + \delta_3)
\]

(4)

If amplitude conditions are arranged (expression (5)) and the initial phase of three beams are adjusted (expression (6)), the proposed standing wave is expressed as expression (7).

\[
2a = b
\]

(5)

\[
\delta_1 = \delta_2 = \delta_3 = 0
\]

(6)

\[
E_i + E_2 + E_3 = 2a(\cos(k \cdot \sin \theta \cdot x + 1) \sin(\omega \cdot t))
\]

(7)

4. **Fundamental verification of coherent imaging algorithm using the proposed standing wave**

Firstly, we numerically analyzed a dynamic behavior of the proposed standing wave amplitude distribution under initial phase matching condition (Figure 6). It can be seen that amplitude of superposition of three beams at all positions does not have any phase difference at every moment of its oscillation. Under this illumination, image formation is not performed by destructive superposition of amplitude but just by addition of amplitude. This fact means the super-resolution processing can be applied even to the coherence condition like incoherent condition. In order to verify the feasibility of this special standing wave, numerical simulations were carried out. Table 2 shows the simulation condition, where employed optics and samples are as same as figure 3. Figure 7 shows the result. This result suggests that super-resolution using standing wave structured light illumination can be performed even under the coherent imaging condition with our proposed algorithm based on the special three-light-flux standing wave.

The resolving power of the proposed method is examined. It succeeded in resolving with a two-point interval of 40 nm under the condition of iteration times 10,000,000 (Figure 8). Resolving of the structure below 30 nm was not realized on this condition. It is confirmed that the resolution of 40 nm is expectable with the proposed method.

<table>
<thead>
<tr>
<th>Wavelength ( \lambda )</th>
<th>488 nm</th>
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<tbody>
<tr>
<td>Standing wave pitch</td>
<td>254 nm</td>
</tr>
<tr>
<td>2 beam interference: ( T )</td>
<td>508 nm</td>
</tr>
<tr>
<td>3 beam interference: ( 2T )</td>
<td></td>
</tr>
<tr>
<td>Objective lens: NA</td>
<td>0.95</td>
</tr>
<tr>
<td>Standing wave shift times: ( t_{shift} )</td>
<td>10</td>
</tr>
<tr>
<td>Standing wave shift step size: ( S_{shift} )</td>
<td>( T/(t_{shift}+1) )</td>
</tr>
<tr>
<td>Iteration times</td>
<td>100,000</td>
</tr>
<tr>
<td>1 pixel cover area</td>
<td>5 nm</td>
</tr>
</tbody>
</table>

**Figure 6: Analysis of dynamic behavior of three-light-flux standing wave structured light**

**Figure 7: Super-resolution result of 200 nm structure in coherent imaging based on novel coherent imaging algorithm using the proposed three-light-flux standing wave structured light**
5. Conclusion
We developed a coherent imaging algorithm for super-resolution inspection by focusing on phase difference and verified that the proposed method can apply not only to incoherent imaging such as fluorescent sample but also to coherent imaging such as general scattering sample. That means that the proposed method can be applied as super-resolution optical inspection for microstructured surface.

Using numerical simulation, the possibility of resolving 40 nm structure with the proposed method is confirmed.

As the future work, experimental verification of proposed method will be performed.

Acknowledgement
This work has been partially supported by JSPS under the Grant-in-Aid for Scientific Research (A) and for Challenging Exploratory Research.

References