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A novel optical super-resolution microscopy for coherent imaging system for micro-structured surface inspection

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Abstract
Although optical measurement would be useful for micro-structured surface inspection, the resolution is limited by diffraction. Structured Illumination Microscopy (SIM) is a super-resolution technique, which has been developed for fluorescent observation. This technique, however, premises incoherent imaging systems and application to coherent systems including semiconductor defect inspection has not been realized. We propose a coherent super-resolution method based on SIM. To obtain relative phases of field on images which are indispensable for coherent systems, we exploit a characteristic of standing wave illumination. Simulation results show the theoretical validity of the proposed method.

Keywords: In-process measurement, Microscope, Microstructure, Visual inspection

1. Introduction

In micro-structured surface inspection, optical measurement has some advantages including dispensability of vacuum conditions and being non-destructive over other techniques such as SEM or AFM. The resolution, meanwhile, is limited by diffraction. To surpass the limit, super-resolution techniques [1][2] have been developed especially in fields of biology. Structured Illumination Microscopy (SIM)[3] is one of the super-resolution techniques with advantages such as large field of view and less dependency on fluorescence characteristics. In SIM, spatial high frequency component contained in patterned light illumination is utilized to expand the passband of the system. However, SIM premises incoherent imaging systems where emission light does not interfere, which is not the case in coherent imaging conditions required in micro-structured surface inspection such as semiconductor inspection. Due to destructive interference among scattered lights from a sample, imaging equations cannot be expressed as *intensity*-based formula but as *field*-based formula. Therefore, it is necessary to obtain field distribution with phase information rather than just intensity distribution. Although in general, it is possible to obtain relative phases by using reference light projected on the image plane, it requires multiple phase shifts of the reference light with precise phase control, which results in impracticability. Consequently, SIM has been applied only to fluorescence observation. In this paper, we propose a field estimation method by utilizing one-time reference light shift without precise phase control nor explicit knowledge of the shift and hence a super-resolution method for coherent systems. Simulation experiments indicate the theoretical validity.

2. Super-resolution SIM for coherent imaging system

2.1. Formulation in coherent imaging system

The formulation here is based on field distribution, which is obtained in the manner described in Sec. 2.2. For the simplicity, we explain one-dimensional formulation. In coherent imaging systems, due to coherence of scattered light, a sample distribution needs to be expressed as coefficient of electric field of illumination which can be negative values. Here, we assume that phases of scattered lights from the sample solely depend on that of illumination, thereby expressing the sample distribution (scattering efficiency) as non-negative values. We define $\mathrm{S}(x)$ as the latent sample distribution, $\mathrm{I}(x)$ as electric field distribution of a standing wave formed by two-beam interference, and $\mathrm{H}(x)$ as the point spread function of the optical system. The field distribution $\mathrm{D}(x)$ formed by scattered light from the sample is;

$$\begin{aligned}\mathrm{D}(x) &= \{\mathrm{I}(x)\cdot\mathrm{S}(x)\}\otimes\mathrm{H}(x)\\ &= \{I_0\cos(2\pi px+\phi_0)\cdot\mathrm{S}(x)\}\otimes\mathrm{H}(x)\end{aligned} \quad \text{Eq. 1}$$

where $I_0, p, x, \phi_0, \otimes$ denote amplitude of electric field, spatial frequency of structured illumination, position, initial phase, and convolution integral, respectively. Note that we omit a time-related factor and employ a static expression which is sufficient to express that relative phase of field varies along x-axis every other node of the standing wave, with the phase difference being always π. The Fourier transform of Eq.1 is given as;

$$\widetilde{D}(k) = \frac{I_0}{2}[\tilde{S}(k+p)e^{-i\phi_0} + \tilde{S}(k-p)e^{i\phi_0}]\cdot\widetilde{H}(k) \quad \text{Eq. 2}$$

where $\tilde{X}$ denotes a Fourier transform of X, and k frequency. It should be noted that $\widetilde{H}(k)$ functions as a band-pass filter with cut-off frequency of NA/λ (numerical aperture divided by the wavelength). In order to solve Eq. 2 about the unknown variables $\tilde{S}(k+p)$ and $\tilde{S}(k-p)$, we form a set of simultaneous equations with another field distribution with a different phase ϕ_1 obtained after shifting the structured illumination. To cover the lack of low frequency component, $\tilde{S}(k)$ is derived from Fourier transform of square root of an image under spatially uniform intensity illumination. Subsequently, high frequency components of the sample $\tilde{S}(k+p)$ and $\tilde{S}(k-p)$, and the low frequency component $\tilde{S}(k)$ are combined in Fourier domain, and thus an image with a resolution enhanced by p is obtained by inverse Fourier transforming. Theoretically, under ideal conditions including NA=1 and a standing wave formed by antiparallel beams, the resolution at the best should be the half of wavelength of the light source, which is a twofold resolution enhancement compared to the conventional microscopy with uniform intensity illumination.

2.2. Electric field estimation with reference light

Prior to forming the equation described in Sec.2.1, it is necessary to obtain field distribution $\mathrm{D}(x)$ which includes phase information. We exploit a characteristic of a standing wave; the number of possible relative phase values of fields in a standing wave and thus those of its scattered lights are only two with a difference of π. Note that only relative phases make sense in this static model of standing wave field, thus the phase definition is arbitrary. To obtain relative phases on the entire image, we utilize interference on the image plane between the scattered light and an on-axis reference light with the same wavelength. First, an image intensity distribution resulting from the interference between the scattered light and the reference light is captured. The phase of the reference light is afterwards shifted arbitrarily (without need for explicit knowledge of the quantity of the shift) and the resultant image is captured. This second interference has either increased or decreased the intensity at each position on the image plane depending on the relative phase of the field which would be formed without a reference light. Because the number of possible phases is only two with a difference of π, phases at positions where light intensity has increased are different from those where light intensity has decreased, and the former can be defined as phase 0 and the latter π. Note that this arbitrariness of phase definition does not apply to the image under uniform intensity illumination for $\tilde{S}(k)$ in Sec.2.1; its phase is uniquely determined considering consistency of arguments of frequency components which overlap those from $\tilde{S}(k+p)$ and $\tilde{S}(k-p)$. Consequently, the electric field distribution including the phase on the image is obtained, which enables the formulation described in Sec.2.1 and thus coherent super-resolution.

3. Super-resolution simulation experiments

To verify the theoretical validity of the proposed method, we conducted simulation experiments based on Fourier optics. The sample is shown in Fig. 1(a). This sample has multiple peak lines which has a sinusoidal distribution, and the distance between adjacent lines varies from 100 nm on the left to 1000 nm on the right with an increment of 50 nm. Although the sample is arranged in a two-dimensional plane, it has a one-dimensional pattern, and thus resolution would be enhanced only in this direction. The main known parameters are λ (the wavelength of the light source), NA (numerical aperture), θ (the incident angle of the oblique beams which form a standing wave), and φ (the quantity of the standing wave shift), which are 488 nm, 0.5, 70 degrees, and $\pi/2$, respectively. Under the condition, the diffraction-limited resolution is 976 nm. An image under uniform intensity illumination is shown in Fig. 1(b). Only the largest distance 1000 nm is resolved correctly. Fig. 1(c) shows the intensity profiles of images formed by the interference between scattered light (before shifting the standing wave illumination) and the reference light with two different phases. There are positions where its intensity increased after the second interference and those where its intensity decreased. This difference enables estimation of the relative phase of the original electric field on the image plane. The resolution-enhanced image by the proposed method is shown in Fig. 1(d). The adjacent lines whose distances are from 1000 nm to 350 nm are resolved, which accords with the theoretically achievable resolution of 338 nm.

We also conducted simulations with simpler samples. In semiconductor inspection, scattering efficiency on a sample surface is expected to vary discretely, for light is not scattered on flat areas and is scattered only at sharp processed structures. Taking this into account, the sample distributions are given discretely. The main parameters λ, NA, θ are 405 nm, 0.67, and 80 degrees. Under the condition, the diffraction-limited resolution is 604 nm, and the resolution of 244 nm is expected to be achieved at the best by the proposed method. The result of 250 nm distance case is shown in Fig. 2 as an example. Although some artifacts appear, the two peaks are recognizable; the reconstructed value of the valley is 17 % of that of the reconstructed peaks, which is sufficient to distinguish the two peaks. These results indicate a potential of the proposed method for application to micro-structured surface inspection with resolution beyond the diffraction limit under coherent conditions.

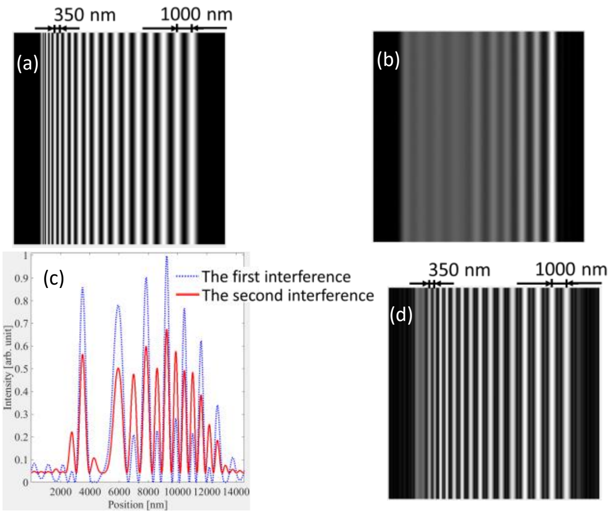

Fig. 1 (a) Sample with multiple lines. (b) An image by the conventional system with uniform intensity illumination. (c) Intensity profiles when the first and second interference between scattered light under a structured illumination and the reference light. (d) Resolution-enhanced image by the proposed method.

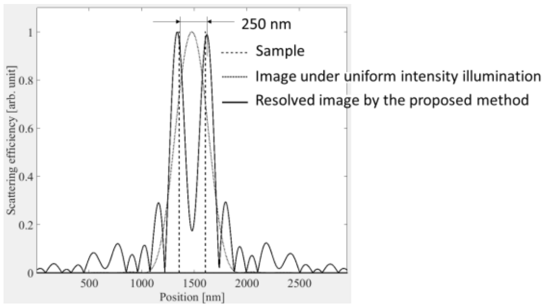

Fig. 2 Simulation result of 250 nm distance two-point sample.

4. Conclusions

We proposed a super-resolution method for coherent systems with a field estimation method by using one-time reference light shift. We also conducted simulation experiments and the basic theoretical validity was demonstrated.

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