Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optics Communications 260 (2006) 117–126
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

A new method of three-dimensional measurement by differential interference contrast microscope

Hiroshi Ishiwata [a,*], Masahide Itoh [b], Toyohiko Yatagai [b]

[a] *Olympus Corporation, Corporate R&D Center, 2951 Ishikawa-cho, Hachioji-shi, 192-8507 Tokyo, Japan*
[b] *Institute of Applied Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan*

Received 6 April 2005; received in revised form 7 October 2005; accepted 13 October 2005

Abstract

Based on weak phase approximation and the partial coherence theory, we analyze the image characteristics of a phase object using a microscope. We show that the image of the phase object is formed by the interplay between the phase distribution and the defocus.

Using this theory, we also show the image characteristics of a differential interference contrast (DIC) microscope.

We develop a method for extracting the phase component from the DIC image using two images with different retardation to reconstruct the phase distribution of the object. We call our new microscope a "retardation-modulated DIC (RM-DIC) microscope". We describe the RM-DIC microscope and confirm our method using grating samples with depths of 20 and 50 nm.

To measure the three-dimensional (3D) figures of the microstructures on the object using a DIC microscope we need to extract the phase component from the DIC image and to deconvolute the phase component by means of the modulation transfer function (MTF) of the DIC microscope.

We conclude that our RM-DIC microscope can take quantitative measurements of the phase distribution, making it a very useful tool for 3D measurement of an object's microstructures.

Keywords: DIC microscope; 3D measurement; MTF; Microstructure; Phase object; Deconvolution

1. Introduction

Differential interference contrast (DIC) microscopes [1,2] are commonly used for observing objects' phase distribution. The DIC microscope is a very powerful means of revealing detailed structures in living cells and small steps on the surfaces of semiconductor wafers. Current DIC microscopes have high sensitivity and high resolution. However, DIC microscopes have a drawback in that, they are unable to make quantitative measurements of the phase distribution of the phase object.

Previous researchers have tried to measure surface profiles and have discovered a method of surface slope measurement with a DIC microscope [3,6–8,11]. These methods were very useful for surface slope measurements but could not be extended to the reconstruction of the microstructures of an object because they used only the reflected light component to analyze the phase object. If the object has microstructures, the light used to illuminate it is diffracted at the edges of these surface structures, and the diffracted and the reflected lights interfere with each other and form interference patterns. Under these conditions, the phase information on edges, a DIC microscope is able to acquire from interference patterns, is limited to the average slope of the surface.

To overcome this disadvantage, it is necessary to analyze the images formed by diffracted light. Using the partial coherence theory, we analyzed the image characteristics of a phase object using a DIC microscope.

In this paper, we describe a new method of quantitative measurement using a DIC microscope and show the experimental results of applying this new method to a DIC microscope.

* Corresponding author. Tel.: +81 426 2254; fax: +81 426 9114.
E-mail address: h_ishiwata@ot.olympus.co.jp (H. Ishiwata).

0030-4018/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2005.10.079

First, we analyze the image characteristics of a phase object under a microscope and theoretically show that the image of the phase object is formed by the interplay between the phase distribution and the defocus. Second, we discuss the image characteristics of the DIC microscope. We explain that the DIC image has four components and each component is analyzed corresponding to the property of the object. Using a blazed grating approximation, we show that light reflected from a gentle slope is replaced with diffracted light from a blazed grating.

Third, we describe the principle and experimental setup of our retardation-modulated DIC (RM-DIC) microscope. Finally, we present the experimental results of three-dimensional (3D) measurements made with the RM-DIC microscope.

2. Image characteristics of a DIC microscope

2.1. Image characteristics of a phase object

To begin with, we discuss an image of a phase object viewed with a microscope to represent the image characteristics of a DIC microscope.

According to the partial coherence theory, the image intensity distribution of a microscope is given by [4,5,10]

$$I(x,y) = \iiiint_{-\infty}^{\infty} R(f_x,f_y,f'_x,f'_y)\mathrm{O}(f_x,f_y)\mathrm{O}^*(f'_x,f'_y) \times \exp[-2\pi\mathrm{i}\{(f_x-f'_x)x+(f_y-f'_y)y\}]\,\mathrm{d}f_x\,\mathrm{d}f_y\,\mathrm{d}f'_x\,\mathrm{d}f'_y, \tag{1}$$

where $R(f_x,f_y,f'_x,f'_y)$ means the transmission cross-coefficient (TCC) and is expressed as

$$R(f_x,f_y,f'_x,f'_y) = \iint_{-\infty}^{\infty} Q(\xi,\varsigma)p(\xi+f_x,\varsigma+f_y) \times p^*(\xi+f'_x,\varsigma+f'_y)\,\mathrm{d}\xi\,\mathrm{d}\varsigma. \tag{2}$$

In Eqs. (1) and (2), $\mathrm{O}(f_x,f_y)$ is the Fourier transform of an object $o(x,y)$, $p(\xi,\varsigma)$ is the pupil function of an imaging system and $Q(\xi,\varsigma)$ is the intensity distribution at the pupil of the illuminating optical system.

To make the description easier, we use a simple model that has a one-dimensional phase distribution along the x-axis and which is constant along the y-axis. We discuss the intensity distribution of a microscope image in the case of a pure phase object. We make the phase distribution of the object a function $\phi(x)$ with uniform absorption C. According to the weak phase approximation, $o(x,y)$ and $\mathrm{O}(f_x,f_y)$ are expressed as

$$o(x) = C\exp\{\mathrm{i}\phi(x)\} = C\{1+\mathrm{i}\phi(x)-\tfrac{1}{2}\phi(x)^2\} \tag{3}$$

and

$$O(f_x) = C\{\delta(f_x)+\mathrm{i}\Phi(f_x)-\tfrac{1}{2}\Phi(f_x)\otimes\Phi^*(f_x)\}, \tag{4}$$

respectively, where $\Phi(f_x)$ is the Fourier transform of the phase distribution of $\phi(x)$. The mark $\otimes$ is the convolution operator.

By substituting Eq. (4) to Eq. (1), we can obtain the approximate image intensity distribution of the phase object as

$$\begin{aligned}I(x) = C\Bigg[&\bigg[R(0,0,0,0)-\frac{1}{2}\int_{-\infty}^{\infty}\{R(f_x,0,0,0)+R(0,0,-f_x,0)\}\\ &\times\Phi(f_x)\otimes\Phi^*(f_x)\exp(-2\pi\mathrm{i}f_xx)\,\mathrm{d}f_x\bigg]\\ &+\bigg[\mathrm{i}\int_{-\infty}^{\infty}\{R(f_x,0,0,0)-R(0,0,-f_x,0)\}\Phi(f_x)\\ &\times\exp(-2\pi\mathrm{i}f_x)\,\mathrm{d}f_x\bigg]\\ &+\bigg[\frac{1}{2}\int_{-\infty}^{\infty}R(f_x,0,f_x,0)\Phi(f_x)\Phi^*(f_x)\,\mathrm{d}f_x\bigg]\\ &+\bigg[\frac{1}{2}\int_{-\infty}^{\infty}R(f_x,0,-f_x,0)\Phi(f_x)\Phi^*(-f_x)\exp(-4\pi\mathrm{i}f_xx)\,\mathrm{d}f_x\bigg]\Bigg].\end{aligned} \tag{5}$$

Eq. (5) shows that, in this approximation, the image of a phase object consists of four image components. The first term of Eq. (5), which includes a constant term and the first integral, is the image component of the transmitted or reflected light. The second term corresponds to the linear image component of the phase distribution. The third term describes the image component of the reflected or deflected light. The fourth term is a nonlinear image component that is proportional to the square of the phase distribution.

When the object does not have a gentle slope, the $\Phi(f_x)\Phi^*(f_x)$ in the third term is zero and the light is not refracted or reflected.

Let us assume that the microscope is ideal and focused on the sample. $\{R(f_x,0,0,0)-R(0,0,-f_x,0)\}$ in the second term is zero, so the intensity image, which is proportional to the phase distribution, does not appear.

When a phase object is observed with a microscope at the focus point, we can usually observe a traditional intensity distribution, formed by transmitted or reflected light and the square of the phase distribution.

However, even when a microscope shows aberrations such as defocus, the term of $\{R(f_x,0,0,0)-R(0,0,-f_x,0)\}$ remains, allowing an intensity image to be observed.

2.2. Image characteristics of a DIC microscope

In the previous section, we described the image characteristics of a phase object with a microscope and showed that an intensity image can be derived at an out of focus point.

Using the partial coherence theory we now describe the image characteristics of a DIC microscope in the previous section.

Since a DIC microscope is based on a polarization interference microscope, we should note that it is necessary to consider the polarization components.

Fig. 1 shows a block diagram of a DIC microscope used for observing a transmitted sample. Since we define the