Direct spectral phase function calculation for dispersive interferometric thickness profilometry

Daesuk Kim and Soohyun Kim

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology
373-1, Kusong-dong, Yusong-gu, Daejon, 305-701, Republic of Korea
daesukkim@kaist.ac.kr

Abstract: A direct spectral phase function calculation method based on spectral phase shifting is described. We show experimentally that the direct phase function calculation method can provide a simple and fast solution in calculating the spectral phase function, while maintaining the same level of accurate measurement capability as that based on the Fourier transform approach.

©2004 Optical Society of America

OCIS codes: (120.4290) Nondestructive testing; (120.5050) Phase measurement; (120.3180) Interferometry; (120.6200) Spectrometers and spectroscopic instrumentation.

References and links

14. The Levenberg-Marquardt algorithm is available as lsqnonlin function by a commercial S/W MATLAB.

1. Introduction

With rapid progress in the optoelectronics industry, demands on fast, non-destructive 3-D micro profilometry have greatly been increased. In most cases, multiple transparent thin-film layers are deposited upon patterned structures and each of the multiple thin films forms a new 3-D profile. In order to measure such complex multiple 3-D surface profile data, however,
we commonly use destructive methods, such as the scanning electron microscope (SEM), since it can provide high accurate multiple 3-D surface profile section information.

For accurate surface profile measurements, phase shifting interferometry (PSI) and heterodyne interferometry have been widely used although they have an inherent $2\pi$ phase ambiguity problem [1-3]. White-light scanning interferometry (WSI) and spectral scanning profilometry have been regarded as a more generalized profiling tool because they can provide a relatively broad measurement range [4-10]. However, for patterned opaque structures upon which transparent thin films are deposited, a multi-reflection phenomenon occurs due to those thin film layers and it makes it difficult to obtain the accurate 3-D surface profile data. Recently, some attempts were made to measure the 3-D volumetric thickness profile data of a patterned structure upon which a single thin film was deposited [9-10].

Since the Fourier-transform method was proposed by M. Takeda [11], it has been one of the most useful techniques for calculating phase functions from interferogram data in the spatial, the temporal and the spectral domain [5-13]. In particular, in the spectral domain, three-dimensional surface profile data can be obtained by measuring the slope of the spectral phase function, which can be calculated by use of the Fourier transform method. For spectral scanning, various devices such as a diffraction grating [5], a liquid-crystal tunable filter (LCTF) [6], an acousto-optic tunable filter (AOTF) [8-9] and a tunable laser [7] have been employed. Likewise, for measuring 3-D volumetric thickness profile data, the spectral phase function containing the 3-D thickness profile information must be calculated. So far, the Fourier-transform method was the only approach for calculating the spectral phase function for the spectral domain analysis [9]. The Fourier transform approach has a benefit in terms of its flexible signal processing capability. However, it has some disadvantages in terms of long computation time and complexity of use compared with the proposed direct spectral phase calculation method.

In this paper, we describe a novel direct spectral phase function calculation method based on a spectral phase shifting technique. We show experimentally that the direct phase function calculation method can provide a simple and fast solution for obtaining the spectral phase function while maintaining the same level of high accurate thickness profile measurement capability as that obtainable by use of the Fourier transform method.

2. Theory

Figure 1 represents the schematic of the spectral scanning interferometric thickness profilometer for measuring 3-D thickness profile data of a patterned structure upon which multiple thin films are deposited. The system consists of a broadband light source such as white light, a spectral scanning device such as an AOTF, a 2-D CCD array sensor and an interferometer. The intensity $I$ captured by the CCD array sensor can be represented as follows:

\[ I(x, y, k) = i_0(x, y, k)[1 + \gamma(x, y, k)\cos[\phi(x, y, k)]] \quad (1) \]

Here, $i_0$ is the DC term of the interference signal and $\gamma$ is the visibility function. $k$ is the wavenumber defined as $k=2\pi / \lambda$. The phase function $\phi(k)$ at a specific coordinate $(x, y)$ contains all meaningful 3-D object information $p_i(x, y)$ ($i=1, 2, ..., n$) and indices of refraction $n_i(x, y)$ ($i=1, 2, ..., n$) for generalized cases. Here, $i$ indicates the index of different mediums. For simplifying the generalized theory on 3-D thickness profilometry, let us consider the case where only two thin-film layers are deposited upon a pattern structure as depicted in Fig. 1. For this simplified model, the spectral phase function $\phi(x, y, k)$ can be represented in the form of $2kp_1(x, y) + \psi(k, x, y, p_2, p_3, n_1, n_2, n_3)$. Here, $\psi$ represents the non-linear phase term that can be modeled by the multi-reflection theory of thin films [9]. $p_1$ represents the distance from the reference plane to the upper surface of the thin film as shown in Fig. 1. Medium 1 corresponds to the air. On the other hand, $p_2$ and $p_3$ represent the thicknesses of the two thin films.
Assuming that we know refractive indices of all the mediums, we can construct a 3-D thickness profile map by measuring those three unknowns.

First, \(I(k, x, y)\) must be measured throughout the entire wavenumber range with the scan sampling size of \(N\). Assume that the dimension of the 2-D CCD array is \(L \times M\). Then, the total data set can be represented by a 3-D cubic data of \(L \times M \times N\). For each coordinate \((x, y)\), we need to extract the spectral phase function \(\phi(k)\) from \(I(k)\). For this, the Fourier transform method can be used. In this paper, however, we propose a direct phase function calculation method based on the spectral phase shifting technique. The direct calculation approach can provide a simple and fast alternative solution for calculating the spectral phase function. However, in order to apply the phase shifting technique for the spectral domain analysis, we must realize that the wavenumber \(k\) and the top surface profile data \(p_1(x, y)\) are coupled with each other. At this stage, we redefine the surface profile as \(p_1(x, y) = s_0 + p_1'(x, y)\) and the wavenumber \(k = k_c + \delta k\). Here, \(k_c\) represents the central wavenumber for spectral phase shifting and \(\delta k\) is the amount the wavenumber is shifted. Then, for each coordinate \((x, y)\), Eq. (1) can be re-written as follows:

\[
I(k, p_1, p_2, p_3, n_1, n_2, n_3) = I_0(k)[1 + \gamma(k) \cos(2kp_1 + \phi(k, p_2, p_3, n_1, n_2, n_3))]
\]

\[
= I_0(k)[1 + \gamma(k) \cos(2k, p_1 + \phi(x, y, k, p_2, p_3, n_1, n_2, n_3) + 2s_0 \delta k + 2p_1' \delta k)]
\]

(2)

With the condition that \(s_0 \gg p_1'(x, y)\) and \(2p_1' \delta k\) is much smaller than \((\phi / \delta k) \delta k\), the last term \(2p_1' \delta k\) can be omitted. Also, \(\delta k\) is redefined as \((3-m)\delta k\). Here, \(\Delta k\) indicates the minimum wavenumber variation induced by the spectral scanning device. The intensity \(I\) can be re-written with the subscript of \(m\) as follows.

\[
I_m(k, p_1, p_2, p_3, n_1, n_2, n_3) = I_0(k)[1 + \gamma(k) \cos(2k, p_1 + \phi(x, y, k, p_2, p_3, n_1, n_2, n_3) + 2s_0 (m-3)\Delta k)]
\]

(3)
Here, \( m \) is an integer number varying from 1 to 5 which represents consecutively measured five interference data according to each spectral phase shifting. When the appropriate spectral carrier frequency \( s_0 \) is applied, \( i_d(k) \) and \( \gamma(k) \) can be treated as slowly varying functions, which means that they can be considered to be constants regardless of the variation of wavenumber \( k \).

In order to obtain the phase value \( \phi(k_c) \) at the central wavenumber \( k_c \), five intensity values \( I_1 \sim I_5 \) are used as follows:

\[
\phi(k_c) = 2k_c p_1 + \psi(k_c, p_2, p_3, n_1, n_2, n_3) = \tan^{-1} \left( \frac{1 - \cos(4\Delta k s_0)}{2\sin(2\Delta k s_0)} \left( \frac{I_5 - I_4}{I_4 - I_3} \right) \right)
\]

The above equation explains how to get a phase value at the specific wavenumber \( k_c \). By sweeping the central wavenumber \( k_c \) throughout the entire wavenumber scanning range, we can obtain the spectral phase function \( \phi(k) \). The proposed spectral phase calculation method ensures a fast solution for obtaining the spectral phase function since the computation time is shorter than that of the Fourier transform approach.

Once the spectral phase function \( \phi(k) \) is obtained for all coordinates \((x, y)\), we can use it for measuring 3-D thickness profile data of a patterned structure upon which multiple thin films are deposited. For the simplest case, when considering only a patterned structure with no thin films, \( \phi(k) \) becomes \( 2k p_1 \) which is a linear function of the variation of wavenumber \( k \). Therefore, we can obtain the 3-D surface profile data without the \( 2\pi \) phase ambiguity problem simply by calculating the averaged slope of the spectral phase function \( \phi(k) \) for each coordinate \((x, y)\):

\[
p_i(x, y) = \frac{\delta \phi(x, y, k)}{2\delta k}
\]

For measuring thickness profile data of the patterned structure upon which thin films are deposited, the spectral phase function \( \phi(k) \) has to be analyzed by employing other techniques such as least square fitting [14]. Assuming that all refractive indices of thin films are known, we use a phase model \( \phi_{\text{model}}(k, p_1, p_2, p_3) = 2k p_1 + \psi(k, p_2, p_3) \) for the following error function. The 3-D thickness profile data can be obtained by finding out \( p_1, p_2 \) and \( p_3 \) which minimize the following error function.

\[
\eta(p_1, p_2, p_3) = \sum_{i=1}^{N} \left[ \phi_{\text{model}}(k_i, p_1, p_2, p_3) - \phi_{\text{measured}}(k_i) \right]^2
\]

3. Experimental results

Experiments were carried out to show that the proposed direct phase function calculation method based on the spectral phase shifting can provide a faster way of obtaining the spectral phase function \( \phi(k) \) than the Fourier transform method, while maintaining the benefit of the high accurate thickness profile measurement capability of the Fourier transform approach. We conducted the experiments with two different patterned objects as shown in Fig. 2. The first object is a Fresnel zone plate (FZP) with no thin-film layer on it. The second one is a rectangular patterned silicone wafer upon which a SiO\(_2\) thin-film layer is deposited and then planarized by a chemical mechanical planarization process. For each patterned object, we acquire 3-D cubic data with the size of \( L \times M \times N \) by performing spectral scanning of the 2-D spectral image as stated in Section 2. For this, we employed an AOTF as the spectral scanning device with the tunable range from 400 nm to 650 nm. Throughout the entire experiment process, we used 2-D spectral images with the size of \( 75 \times 75 \) and the spectral scanning data with the data size of 220. Thus, the 3-D cubic data set for each case is \( 75 \times 75 \times 220 \). For the interferometric setup, we employed a Michelson interferometer with an objective lens of x5 magnification. As the next step, we need to extract the spectral phase function \( \phi(k) \) from the measured intensity function \( I(k) \). We can obtain the phase data \( \phi(k_c) \) for the wavenumber \( k_c \) by
use of the spectral phase shifting technique described in Eq. (4). By performing the same procedure throughout the entire wavenumber scanning range, we can obtain the spectral phase $\phi(k)$ as a function of $k$. As stated, the spectral phase function $\phi(k)$ can also be obtained by use of the FFT- inverse FFT method [9]. The main subject of this paper is to compare these two methods in terms of the calculation speed and the measurement accuracy.

Fig. 2. Measured samples: (a) Fresnel Zone Plate (FZP) with no thin films and (b) rectangular patterned Si wafer upon which a SiO$_2$ thin film is deposited and planarized by a chemical mechanical planarization process.

For comparing the calculation time between the two methods, we performed an experiment to show how fast the direct method is compared with the Fourier transform method according to the variation of the number of data used for each single calculation process. Figure 3(a) represents the computation time required to obtain the phase value of a specific point $(x,y)$. Figure 3(b) shows how fast the direct method can calculate the spectral phase function $\phi(k)$ compared with the Fourier transform method. The result shows that the direct method is at least around four times faster than the Fourier transform approach. For measuring the 3-D information of those two samples in Fig. 2, we employed $N=220$, which allows us to obtain the spectral phase function five times faster.
Figure 4(a) and (b) show the calculated spectral phase functions at a specific coordinate \((x, y)\) of the two different patterned samples in Fig. 2, respectively. The continuous solid line in each spectral phase function \(\phi(k)\) is obtained by using the Fourier transform method while discrete star markings represent the spectral phase function obtained by use of the proposed direct calculation method. Figure 4(c) and (d) represent the phase differences between the two approaches. For the first object, we obtained the phase differences of less than \(\pm 0.05\) rad between the two methods, while for the second one, relatively bigger phase differences of around \(\pm 0.2\) rad exist for the entire scanning range. The degradation of the obtained spectral phase function for the second object could be due to the phase term \(\psi(k)\) represented by the multiple reflection theory of thin films. For this second thin film deposited sample, you can see that the phase differences between the two methods, to some extent, depend on the non-linear behaviors caused by thin-film layers as shown in Fig. 4(b) and (d). These results show that the proposed direct phase function calculation can provide an alternative approach to the Fourier transform method.

In order to estimate the performance of the spectral scanning interferometric thickness profilometry based on the direct spectral phase function calculation method in comparison with that based on Fourier transform method, we conducted measurements of the 3-D shape information for the two objects. Figure 5(a) and (b) show 3-D measurement results obtained by use of the direct spectral phase function calculation method for the two patterned objects in Fig. 2. Figure 6(a) and (b) represent 2-D section profiles of the two objects for comparison.
with those obtained by use of Fourier transform approach. These compared data, in terms of thickness profile measurement capability, show that the proposed direct spectral phase calculation method can provide the same level of accuracy as can be obtained by use of conventional Fourier transform method in measuring 3-D thickness profile data while having some benefits in terms of its simple and fast computation capability.

Fig. 5. Three-dimensional thickness profile measurement results by use of the proposed direct spectral phase calculation method (a) for the object in Fig. 2(a) and (b) for the object in Fig. 2(b).
4. Conclusions

A novel direct spectral phase function calculation method based on 5-bucket spectral phase shifting is described. We can measure thickness profile data of a patterned structure upon which thin films are deposited by analyzing the phase function \( \phi(k) \) since it contains 3-D object information. The direct spectral phase function calculation method can be used for an alternative approach to the Fourier transform method in spectral scanning interferometric thickness profilometry. We showed experimentally that the direct phase function calculation based on spectral phase shifting can provide a simple and fast solution of obtaining the spectral phase function while maintaining the same level of accurate measurement capability as that based on Fourier transform method.