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3-D Surface Profile Measurement Using An Acousto-optic Tunable Filter Based Spectral Phase Shifting Technique

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An acousto-optic tunable filter based 3-D micro surface profile measurement using an equally spaced 5 spectral phase shifting is described. The 5-bucket spectral phase shifting method is compared with a Fourier-transform method in the spectral domain. It can provide a fast measurement capability while maintaining high accuracy since it needs only 5 pieces of spectrally phase shifted imaging data and a simple calculation in comparison with the Fourier transform method that requires full wavelength scanning data and relatively complicated computation. The 3-D profile data of micro objects can be obtained in a few seconds with an accuracy of ˜ 10 nm. The 3-D profile method also has an inherent benefit in terms of being speckle-free in measuring diffuse micro objects by employing an incoherent light source. Those simplicity and practical applicability is expected to have diverse applications in 3-D micro profilometry such as semiconductors and micro-biology.

Keywords : Interferometry, Profilometry, Spectral phase shifting, White light, Tunable filter

OCIS codes : (120.3180) Interferometry; (120.5050) Phase measurement; (120.3930) Metrological instrumentation; (120.6200) Spectrometers and spectroscopic instrumentation; (120.6650) Surface measurements

I. INTRODUCTION

There have been great interest and advances in interferometry for the last several decades.[1-21] The phase shifting method using either a monochromatic light or a white light source has been a powerful and promising tool which is widely used for various applications such as 3-D micro profilometry, digital holography and ellipsometry.[1-5] The application of common phase computation algorithms in Phase Shifting Interferometry (PSI) provides subnanometer resolution and a high degree of accuracy.[1-2] White-light Scanning Interferometry (WSI) can solve the inherent 2π ambiguity problem of PSI.[6] As an alternative approach to PZT based phase shifting, the spectral phase shifting approach was performed in heterodyne interferometry by tuning the wavelength of laser diode.[7] Likewise as in PZT based phase shifting in the z-scan domain, the spectral phase shifting approach also suffers from an inherent 2π ambiguity problem. There have been various studies on solving the 2π ambiguity problem of the phase shifting method by use of multi-wavelength schemes.[8-11] Although multi-wavelength approaches can provide a feasible solution to some degree, a promising resolution to the ambiguity problem is possible by using wavelength scanning interferometric profilometry.12-16 The 3-D profile data can be obtained without the 2π ambiguity problem by using a Fourier transform method in wavenumber k-domain.[12-16] Also, there was an attempt to maximize the measurement range by positioning a reference mirror in the halfway between the top and the bottom of the total step height.16 Those sequential phase measurement methods described above are summarized in Table 1. In this scheme, the data set is captured sequentially in

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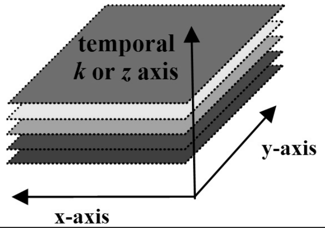
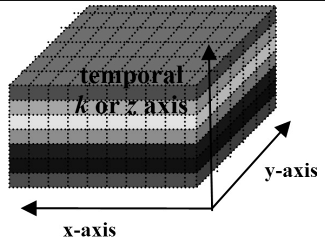
TABLE 1. *Classification* of *sequential* phase measurement methods

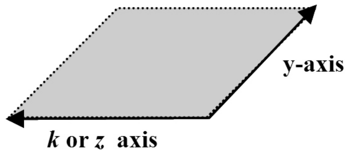
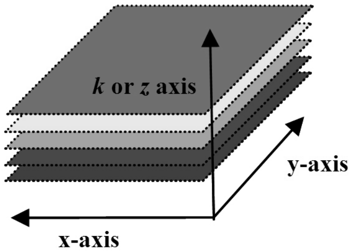
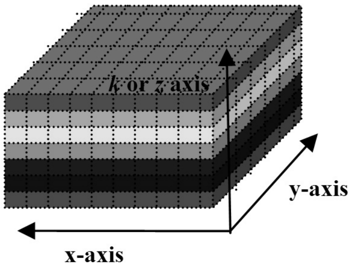
Method	*k-domain*	*z-domain*	*Data set structure*
Phase shifting	*Tunable coherent source* laser diode (LD) [7]	*Monochromatic coherent source* PZT [1-2]	
	Incoherent source Tunable filter (AOTF)		
Full range scanning	*Tunable coherent source* LD [12] or dye laser [13] *Incoherent source* Tunable filter [14-16]	*Incoherent source* PZT [6]	

the temporal domain.

Although those sequential phase measurement methods can provide high accuracy, they have a limitation due to its temporal property for measuring a time-evolving surface. A summary on instantaneous parallel phase measurement approaches is given in Table 2. The parallel phase measurement methods provide high measurement speed and system robustness to external noise. Thus, they are considered to be appropriate for dynamic event and time evolving surfaces, especially in the presence of vibrations. The instantaneous phase measurement for 2-D profilometry can be accomplished by using the carrier frequency concept both in k and z scan domain. The carrier frequency can be produced either by tilting the reference mirror in the spatial domain[17] or by positioning the reference mirror away from a measured object to generate large path difference between the two interferometric arms for the analysis in the spectral domain. Such instantaneous 2-D profile measurement has been achieved by employing a grating as the dispersive device through spectral domain approach.[18] In this approach, only 2-D section surface profile can be obtained since one lateral axis of the 2-D image sensor is used either as a chromatic measurement axis or a high frequency spatial axis. In order to obtain 3-D profile data by means of a parallel scheme, multi-CCD was used to capture multiple phase shifted images simultaneously.[19] The possibility of implementing a real time 3-D profilometry by combining multi-CCD and wavelength selectable interference filters would be straightforward by using the spectral phase shifting concept as classified in Table 2. However, the multi-CCD approach has a practical shortcoming in terms of requiring additional calibration procedures and high quality imaging optics. The 3-dimensional data set structure should be captured simultaneously for implementing an ideal one-shot 3-D profiling as seen in Table 2. The concept of Punctuated Quadrature PSI (PQ-PSI) which uses averaged results of two PSI channels operating in phase quadrature and a CCD with an interline-transfer architecture, and 'smart sensor' with simultaneous parallel measurement capability of the spectral data set was studied.[20-21] Nevertheless, the practical instantaneous 3-D profile measurement system has not been developed yet and remains as a technical challenge.

The two tables classify interferometry by categorizing the distinct ways of obtaining the 3-dimensional data set structure. This paper emphasizes the potential of the spectral domain approach as a promising alternative tool to conventional z-scan domain methods. In this paper, we propose an acousto-optic tunable filter based 3-D micro surface profile measurement method using an equally spaced 5-bucket spectral phase shifting. The proposed approach can be categorized as shown with bold characters in Table 1. The novelty of this paper is in applying the conventional wavelength scanning interferometric profilometer employing an incoherent light source and an AOTF for spectral phase shifting interferometry by using spectral 5-bucket method. The reason of employing 5-bucket phase shifting method is based on the fact that phase shifting approach in the spectral domain inevitably causes non-linear phase shifter error. It is proven to be the least sensitive to the phase shifter non-linearity in the z-scan approach.[1-2] One advantage of the proposed method is that the same equally spaced 5 phase shifting method is employed for the spectral phase shifting approach. The system configuration provides a benefit of being speckle-free for measuring diffuse micro objects compared with heterodyne interferometry employing a coherent tunable laser diode, since it is employing an incoherent light source and an AOTF as the phase shifter. Although the spectral phase shifting method has an ambiguity problem, it can provide a fast 3-D micro surface profile measurement capability

TABLE 2. Classification of *parallel* simultaneous phase measurement methods

Method		*One shot*		*Data set structure*
2-D	Carrier frequency	*Incoherent source* A grating & a CCD [18]	*Monochromatic coherent source* single CCD [17]	
3-D	Multi Channel	*Incoherent source* Multiple CCD and interference filters	*Monochromatic coherent source* Multiple CCD [19]	
	Ideal concept	Smart sensor [21]	Punctuated quadrature PSI [20]	

while maintaining high accuracy in comparison with a Fourier transform method that requires full wavelength scanning data and relatively complicated computation.

II. 5-BUCKET SPECTRAL PHASE SHIFTING METHOD

The 3-D surface profile data of micro objects can be obtained by use of a 5-bucket spectral phase shifting method. It can provide an alternative capability of 3-D surface shape measurement to conventional PZT based phase shifting interferometry. Fig. 1 shows the schematic diagram of the proposed 3-D micro profilometry. It consists of an AOTF for accurate equally spaced 5 spectral phase shifting with spectral scanning ranging from 400 nm to 650 nm, inversely corresponding to RF signal from 180 MHz to 120 MHz, a 2-D CCD sensor, and a Michelson interferometer with an objective lens that has a numerical aperture of 0.13 at x5 magnification. Here, the AOTF is used for generating accurate equally spaced 5 spectral phase shifting and it has a band pass of 1~5 nm dependent on diffracted wavelengths and a tuning speed of 20 μs. The 3-D surface profile that is a function of spatial measurement coordinates x and y, will hereafter be labeled as $h(x,y)$. It indicates the distance between an imaginary reference plane and the object surface as shown in Fig. 1. The output intensity of a two beam interferometer illuminated under monochromatic light with wavenumber of $k=2\pi/\lambda$ is given as follows.

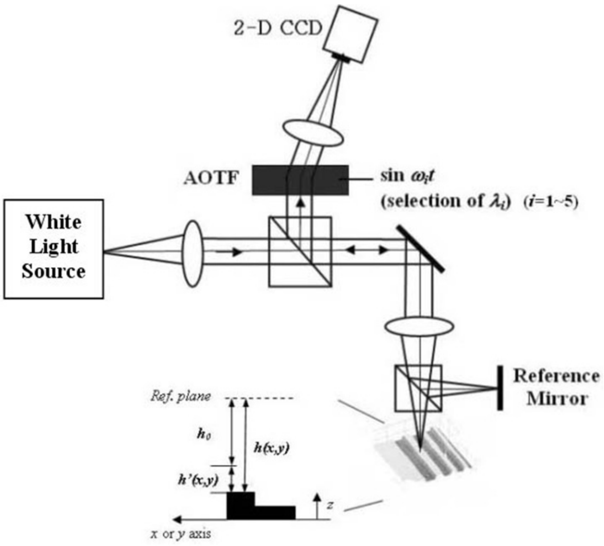


FIG. 1. Schematic diagram of the proposed AOTF based spectral phase shifting micro- profilometry.

$$\begin{aligned} I(x,y,k,h) &= \left|E_r(x,y,k) + E_t(x,y,k,h)\right|^2 \\ &= i_0(x,y,k)\{1+\gamma(x,y,k)\cos[\phi(x,y,z,k,h)]\} \\ &= i_0(x,y,k)\{1+\gamma(x,y,k)\cos[2k(h(x,y)-z)]\}. \end{aligned} \tag{1}$$

Here, E_r and E_t represent the reflected wave functions from the reference mirror and the object sample, respectively, and I is the interference intensity. Also, i_0 and γ are the dc term of the interference signal and visibility function, respectively. The phase shifting method is based on the introduction of phase shifts in the phase term $\phi(x,y)$ in Eq.(1). Note that both factors k and z can play the same role for phase shifting. The phase shifting can be performed through wavelength variation. However, in spectral phase shifting, special care should be taken into account since the wavenumber k and surface profile data $h(x,y)$ are coupled with each other as shown in Eq.(1). It can not be as easily interpreted as in the z-scan domain. In this spectral scanning approach, z can be set to zero since no moving part is required. If the monochromatic wavenumber k is changed form k_1 to k_2, the phase shift difference introduced is given by $2(k_2-k_1)h(x,y)$. The combination of an AOTF and a CCD provide 2-D spectral phase shifting capability.

With the condition that the profile variation range of the object is much less than the spectral carrier frequency h_0, and h_0 is less than half of the equally spaced spectral sampling frequency Δk, an exactly alternative equally spaced 5 phase shifting method in the spectral domain can be performed by using the conventional 5 bucket algorithm.[1] Let us redefine the surface profile $h(x,y)$ as $h'(x,y)+h_0$ as shown in Fig. 1 and the selected wavenumber $k=k_c+\delta k$. As mentioned above, in case that h_0 $i_0h'(x,y)$, Eq.(1) can be approximated as follows:

$$\begin{aligned} I(x,y,k,h) &= i_0(x,y,k)\{1+\gamma(x,y,k)\cos[2(k_c+\delta k)(h'(x,y)+h_0)] \\ &\approx i_0(x,y,k)\{1+\gamma(x,y,k)\cos(2k_c h(x,y)+2h_0\delta k)\}. \end{aligned} \tag{2}$$

Here, k_c and δk is the central wavenumber and scanned wavenumber deviation, respectively. k_c and h_0 are set as arbitrary known values. The term of $\delta kh'(x,y)$ is omitted for the approximation and it corresponds to the non-linear shifter error term in the spectral phase shifting approach. Note that equally spaced 5 spectral phase shifting algorithm is employed to minimize the sensitivity to this non-linear phase shift error problem. If an appropriate spectral carrier frequency h0 is applied, $i_0(x,y,k)$ and $\gamma(x,y,k)$ can be treated as slowly varying functions, which means that they can be thought of as constants regardless of variation of wavenumber k. This assumption is based on a proper initial setting of the object position, which makes it possible to employ the same 5 bucket algorithms used in spatial interferogram analysis for spectral domain analysis with high accuracy.1 In order to obtain the phase value $\phi(x,y)$ for each coordinate (x,y) at the central wavenumber k_c, five intensity values corresponding to each five wavenumbers are required as follows:

$$\begin{aligned} I_1(x,y) &= i_0(x,y)\{1+\gamma(x,y)\cos[2k_c h(x,y)-2h_0(2\Delta k)]\} \\ I_2(x,y) &= i_0(x,y)\{1+\gamma(x,y)\cos[2k_c h(x,y)-2h_0\Delta k]\} \\ I_3(x,y) &= i_0(x,y)\{1+\gamma(x,y)\cos[2k_c h(x,y)]\} \\ I_4(x,y) &= i_0(x,y)\{1+\gamma(x,y)\cos[2k_c h(x,y)+2h_0\Delta k]\} \\ I_5(x,y) &= i_0(x,y)\{1+\gamma(x,y)\cos[2k_c h(x,y)+2h_0(2\Delta k)]\} \end{aligned} \tag{3}$$

Here, Δk means the wavenumber increment which can be selected arbitrarily but appropriately. With these five intensity values, the 3-D surface profile data $h(x,y)$ can be calculated as follows.[16]

$$h(x,y) = \frac{1}{2k_c}\tan^{-1}\left[\frac{1-\cos(4\Delta k h_0)}{\sin(2\Delta k h_0)}\left(\frac{I_2-I_4}{2I_3-I_5-I_1}\right)\right]. \tag{4}$$

III. FOURIER TRANSFORM METHOD

As an alternative approach for the same target, we can use the Fourier transform method. Detailed theoretical explanation of the Fourier transform method is described in this section. This is not only for representing how the Fourier transform method is applied for wavelength scanning interferometric profilometry in the spectral domain, but also for comparing with the proposed 5-bucket spectral phase shifting method. As mentioned, the Fourier transform method requires full wavelength scanning data $I(k)$ to produce the total phase function $\phi(k)$, which contains the 3-D surface profile data $h(x,y)$, without ambiguity through FFT- inverse FFT procedures. This also can be conducted with the condition that the greatest gradient of phase $\phi(k)$ is less than the spectral carrier frequency h_0 and h_0 is less than half of the spectral sampling frequency Δk.[12-16] Simple conversion of the amplitude terms $i_0(k)$ and $\gamma(k)$ in Equation (1) to $a(k)$ and $b(k)$, respectively, and induction of an additional spectral carrier frequency h_0 to the slowly varying function $\phi(k)$ gives the following.[15-16]

$$\begin{aligned} I(k) &= a(k)+b(k)\cos[\phi(k)+2kh_0] \\ &= a(k)+c(k)\exp(2kh_0 j)+c^*(k)\exp(-2kh_0 j) \end{aligned} \tag{5}$$

Here,

$$c(k) = \frac{1}{2}b(k)\exp[(\phi(k)j] \tag{6}$$

Likewise, the spectral carrier frequency h_0 can be induced by positioning the reference mirror away from the sample to generate a high frequency intensity distribution as shown in Fig. 2(a). First, the intensity function

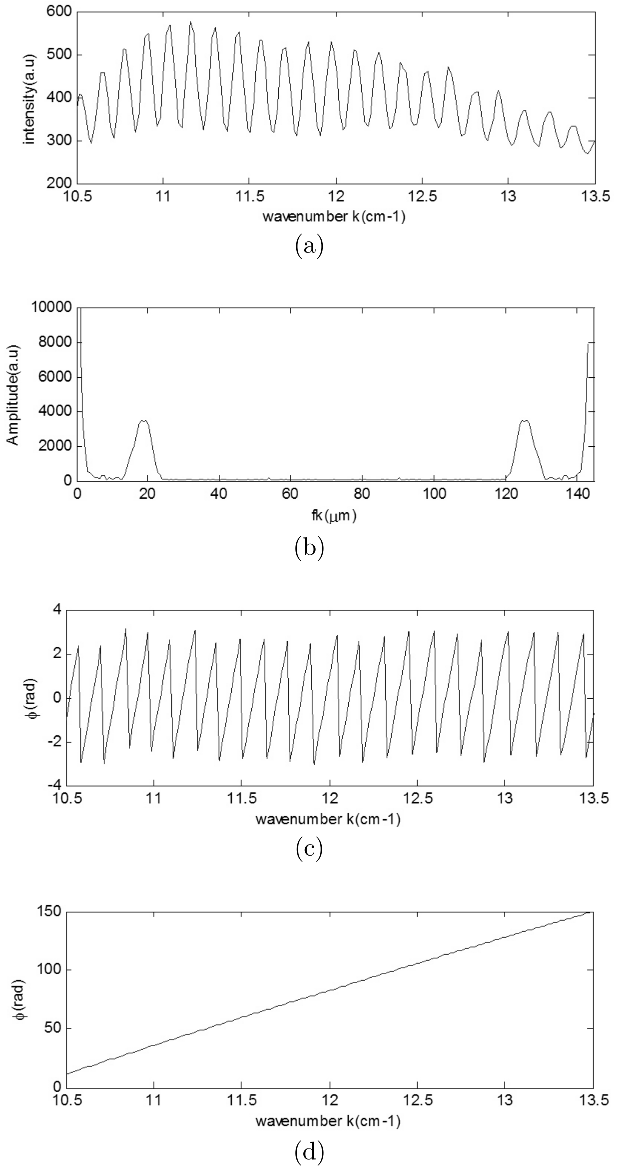


FIG. 2. FFT- inverse FFT method: (a) spectral carrier frequency induced wavelength scanning intensity distribution $I(k)$ versus wavenumber k, (b) amplitude part resulted from the FFT of $I(k)$, (c) total phase function $\phi(k)$ after inverse FFT of filtered $C(f_k\text{-}h_0)$ and (d) phase unwrapped result.

is transformed by Fast Fourier Transform (FFT), which leads to the following.

$$I(f_k) = A(f_k) + C(f_k - h_0) + C^*(f_k + h_0) \qquad (7)$$

Here, $A(f_k)$ and f_k indicate the dc term and spectral frequency, respectively, and $C(f_k)$ is the Fourier transformed function of $c(k)$. The spectral carrier frequency h_0 is induced so that $C(f_k - h_0)$ is entirely separated from $A(f_k)$.

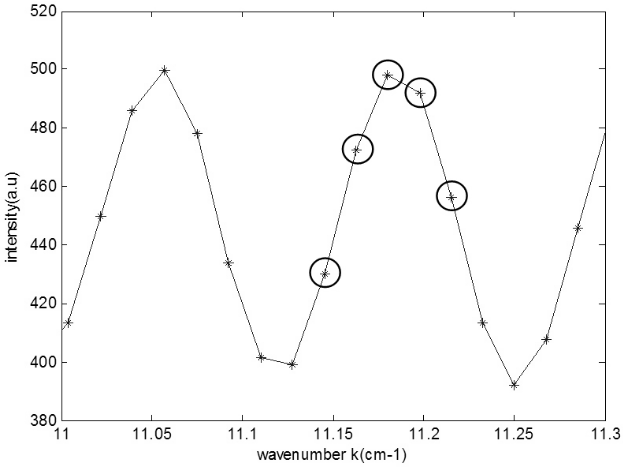


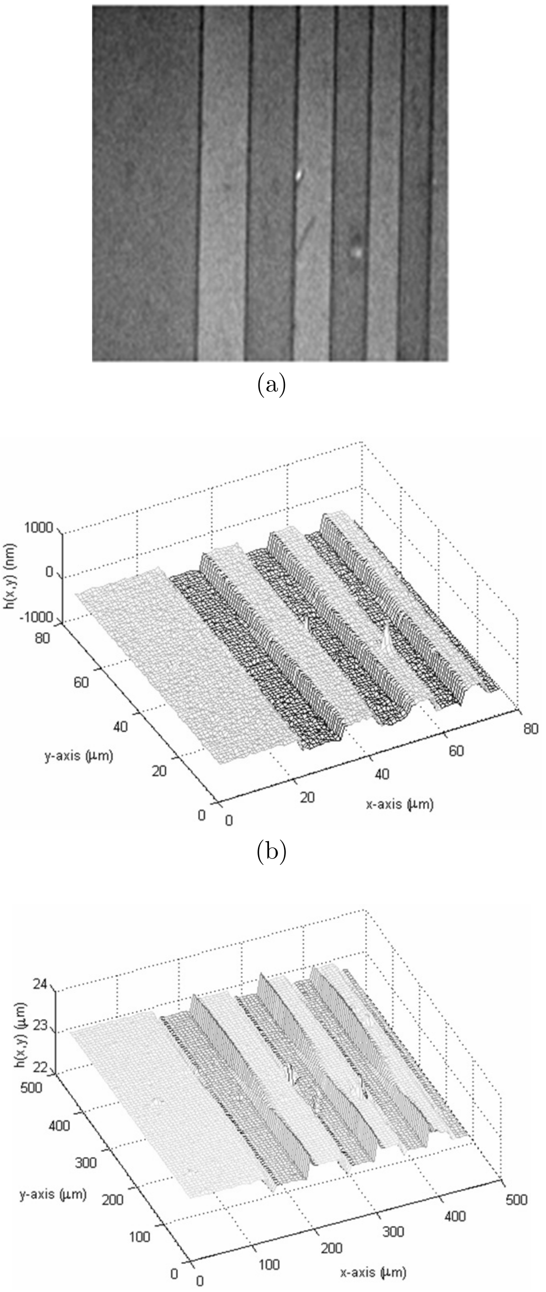
FIG. 3. 5-bucket spectral phase shifting method: a set of marked 5 intensity data $I(k_i)$ (i=1~5) used for the calculation of the spectral phase value $\phi(k_c)$ at a specific point (x,y).

Fig. 2(b) represents the amplitude term of $I(f_k)$. In order to obtain the phase function $\phi(k)$, $C(f_k - h_0)$ needs to be filtered with a rectangular function. After the filtering procedure, $C(f_k\text{-}h_0)$ is inversely Fourier transformed to obtain $c(k)=1/2b(k)\exp[\phi(k)+2kh_0+\mathit{offset}]$. Fig. 2(c) describes the phase term of $c(k)$. Finally, the phase term of $c(k)$ needs to be unwrapped to obtain a continuous phase function $\phi(k)=2k(h+h_0)+\mathit{offset}$. Although the generation of an uncertain h_0 is inevitable, h_0 does not affect the calculation of $h(x,y)$ since it is a constant for all coordinates (x,y). The above FFT - inverse FFT signal processing procedure inherently induces the offset term in the spectral phase. However, the offset term is eliminated through the derivative procedure. Once the total phase function $\phi(k)$ is obtained, the profile information h can be found using Eq.(8). The slope of the total phase function $\phi(k)$ indicates the surface profile data $h(x,y)$.

$$h(x,y) = \frac{1}{2}\frac{\partial\phi(x,y)}{\partial k} - h_0 \qquad (8)$$

IV. EXPERIMENTS AND DISCUSSION

An experiment using a binary patterned diffractive optical element as shown in Fig. 4(a) was carried out. This binary pattern sample is made to have the height difference corresponding to π/2 phase difference at 632.8 nm. Spectral imaging must be conducted with consideration for the AOTF characteristic of image shift depending on diffracted wavelength. In order to apply the spectral carrier frequency h_0, the measured sample surface is positioned such that the distance between the two arms was around 30 μm. With this initial setup of measured target, five spectral phase shifting with the



(a)

(b)

(c)

FIG. 4. (a) Photograph of the measured diffractive optical element, and 3-D micro surface profile measurement results obtained by (b) 5-bucket spectral phase shifting method and (c) FFT- inverse FFT method.

wavenumber increment Δk of 0.017 cm^{-1} at k_c of 11.175 cm^{-1} has been carried out in order to obtain the five spectral intensities $I(k)$s as marked in Fig. 3.

Fig. 4(b) illustrates the 3-D surface shape obtained by using the spectral 5 bucket algorithm. In order to compare the result with the FFT- inverse FFT method based on the analysis in k-domain, entire spectral scanning has been performed by use of the AOTF in the same experimental setup. The 3-D measurement result of Fourier transform method is shown in Fig. 4(c).

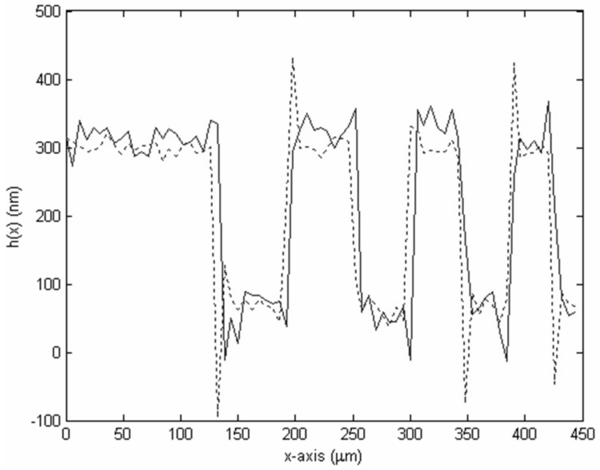


FIG. 5. .2-D sectional profile data comparison between 5-bucket spectral phase shifting method (solid line) and FFT- inverse FFT method (dotted line).

More detailed comparison using a line surface profile is illustrated in Fig. 5. It shows that the 3-D surface profile data $h(x,y)$ can be acquired very accurately by the proposed equally spaced 5-bucket spectral phase shifting method. The average step height difference shows that it can provide an accuracy of ~10nm even though the exact comparison is difficult to do due to the poor surface state of the measured sample. This technique is faster than Fourier transform method in the k-domain since it requires only 5 pieces of scanning data and simple calculation. Using a PC, the total measurement time including calculation of the FFT- inverse FFT method was about a few minutes for getting the final 3-D reconstruction result. In contrast, that of the proposed method required only a few seconds. Thus, the proposed spectral 5 bucket phase shifting approach has the advantage of high measurement speed while maintaining high accuracy. White noise, mainly caused by the inherent dark signal of the CCD and light source may be reduced by signal processing. A possible major systematic error source is the AOTF image shift calibration due to discrete CCD pixels which can be calibrated.

V. CONCLUSION

An acousto-optic tunable filter based 3-D micro surface profile measurement using an equally spaced 5 spectral phase shifting method is described. This is accomplished by applying a 5-bucket spectral phase shifting scheme to conventional wavelength scanning profilometry employing a white light and an AOTF. The 5 phase shifting method which is the least sensitive to the phase shifter non-linearity has been used. This approach also has an inherent benefit of being speckle-free in measuring diffuse micro objects by employing an incoherent source. The 3-D volumetric profile data is obtained and compared with the result obtained by Fourier-transform method in the *k*-domain. It can provide a fast measurement capability while maintaining high accuracy since it needs only 5 spectrally phase shifted imaging data and a simple calculation to obtain phase data containing 3-D profile information in comparison with Fourier transform method that requires full wavelength scanning and relatively complicated computation. Those simplicity and practical applicability is expected to have diverse applications in 3-D micro profilometry such as semiconductor and micro biology fields. The 3-D profile data of micro objects can be obtained in a few seconds with an accuracy of around 10nm.

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