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ENHANCED 3D SURFACE PROFILOMETRY OF CHROMATIC CONFOCAL MICROSCOPY WITH SPATIALLY VARYING RICHARDSON-LUCY DECONVOLUTION

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Abstract: This study introduces a novel optical design in line-scan chromatic confocal microscopy to reduce crosstalk, using a Galvano mirror and an innovative Spatial Light Modulator (SLM) with Liquid Crystal On Silicon (LCoS) to replace the detector slit. This allows direct PSF measurement using Fourier optics and convolution theory. The system employs Richardson-Lucy deconvolution for image restoration, successfully refining micrometer-level features in micron-scale concentric circular gratings and bumps, confirmed by white light interference comparisons. Our measurement results, indicate that the approach significantly minimizes morphological errors, with line bias and depth deviation improved to under 1 micron and 0.2 microns, respectively, enhancing feature resolution in both lateral and axial dimensions to sub-micrometer accuracy.

Key words: Chromatic confocal microscopy, Optical measurement, Automated optical inspection (AOI).

1. INTRODUCTION

Surface profilometry plays a crucial role in various fields such as semiconductor manufacturing, biomedical imaging, and precision engineering, facilitating precise measurements of surface topography at the micrometer or even nanometer scales. However, traditional methods often face challenges such as limited resolution, slow acquisition speeds, and susceptibility to noise and artifacts. In recent years, advancements in optical microscopy techniques have led to the development of novel approaches aiming to overcome these limitations and enhance the accuracy and efficiency of surface profilometry.

Chromatic confocal microscopy (CCM) [1-3] has emerged as a powerful tool for high-resolution surface profiling. Its optical design offers several advantages, including high-speed scanning due to the elimination of axial scanning and non-contact measurement capabilities. However, the CCM setups typically suffer from crosstalk in adjacent axial signals and lateral signals as well, limiting their

performance, especially in scenarios requiring precise feature resolution.

To improve CCM capabilities and achieve enhanced surface profilometry, this research focuses on advancing the capabilities of line-scan chromatic confocal microscopy (LSCCM) through the integration of spatially varying Richardson-Lucy (RL) deconvolution [4]. This approach is complemented by a novel optical design incorporating a single-axis Galvano mirror to help us do the full-field scanning and a spatial light modulator (SLM) with Liquid Crystal On Silicon (LCoS) [5,6] to improve axial resolution and reduce crosstalk, thereby enabling more accurate and reliable surface profiling.

This paper introduces our LSCCM system and a novel algorithm framework that integrates Fourier optics and convolution theory. This framework enables direct point spread function (PSF) measurement and subsequent image restoration using deconvolution to reduce crosstalk. Experimental validation demonstrates its ability to refine micrometer-level features in concentric circular gratings and bumps with sub-micrometer accuracy. We validate our

approach using experimental testing on these objects, comparing the results against white light interferometry measurements.

2. METHODOLOGY

2.1. Spatially variant PSF modeling

A complete imaging system generally consists of an object plane, an image plane, and an ideal lens. The light field $U_i(u, v)$ at the image plane can be represented by the integral product of the system's response function $h(u, v; \xi, \eta)$ and the light field $U_o(\xi, \eta)$ at the object plane[[8]],

$$U_i(u, v) = \iint_{-\infty}^{\infty} h(u, v; \xi, \eta) U_o(\xi, \eta) d\xi d\eta \quad (1)$$

where (ξ, η) is the coordinate of the source plane, and (u, v) is the absolute position in the observation plane. Equation (1) shows that PSF varies with the coordinates of the planes. From incoherent imaging theory in Fourier optics, if PSF only depends on the relative coordinates of the two points, the light field on the image plane $U_i(u, v)$ can be represented by two-dimensional convolution of the PSF $h(u, v)$ and the light field on the object plane $U_o(\xi, \eta)$ [[8]]:

$$U_i(u, v) = h(u, v) \otimes U_o(u, v) \quad (2)$$

where $\otimes$ denotes the two-dimensional convolution operator.

2.2. Richardson-lucy with total variation regularization

In the fields of astronomy and biomedical imaging, the applications of deconvolution algorithms have been employed to enhance image quality [9-11]. This method is also suitable for LSCCM, as it helps reduce lateral crosstalk and further improves the resolution. The two most prominent non-blind deconvolution methods have distinct core principles: Wiener deconvolution, which operates in the frequency domain, and RL deconvolution, which functions in the spatial

domain [[12]]. Equation (3) is the basis form of RL deconvolution.

$$o_{r+1}(x, y) = o_r(x, y) \left[\frac{i(x, y)}{o_r(x, y) \otimes h(x, y)} \otimes h(-x, -y) \right] \quad (3)$$

For imaging systems with unknown noise models, despite its slower computational speed, RL is more flexible than Wiener deconvolution and exhibits a higher acceptance of non-Gaussian noise [[12]]. However, for images with high-frequency noise, RL deconvolution can excessively amplify high-frequency components, leading to oscillations in the edge known as ringing artifacts. To address this issue, it has been proposed to incorporate a total variation regularization term[[12]] to suppress this side effect, thus smoothing the image while preserving edge sharpness. This approach is known as RL deconvolution with total variation algorithm (RL-TV), which can be written as :

$$o_{r+1}(x, y) = \frac{o_r(x, y)}{1 - \lambda_{TV} \text{div} \left(\frac{\nabla o_r(x, y)}{|\nabla o_r(x, y)|} \right)} \times \left[\frac{i(x, y)}{o_r(x, y) \otimes h(x, y)} \otimes h(-x, -y) \right] \quad (4)$$

where $\text{div}(\cdot)$ represents the divergence operator, ∇ denotes the gradient operator, and λ_{TV} stands for the total variation regularization constant. The divergence of the gradient is also equivalent to the Laplace operator, used to quantify the rate of change of the gradient. A significant gradient suggests potential high-frequency noise that requires suppression. Therefore, using a larger λ_{TV} leads to smoother restoration, while a smaller λ_{TV} preserves more details.

2.3. Spatial varying deconvolution

The non-blind deconvolution algorithms introduced in the previous sections all assume that the PSF exhibits spatial invariance, a property consistent with the derivation results under the paraxial approximation assumption of imaging theory. However, in general, whether in aberration theory or real-world scenarios, the

PSF varies spatially. Using incorrect convolution kernels can lead to biased or erroneous deconvolution outcomes. Additionally, it may result in inaccurate peak detection results and reconstructed surfaces. Therefore, we introduce the concept of Principal Component Analysis (PCA), implemented through Singular Value Decomposition (SVD) to describe the spatial variation of the point spread function.

PCA efficiently describes multidimensional data by identifying the most representative coordinate axes, known as data dimensionality reduction. The goal is to preserve the original data's variability by selecting the most essential and representative features while reducing its dimensionality.

Based on incoherent imaging, the system response $h(u, v; x, y)$ can be decomposed into a linear combination of a series of orthogonal basis functions[10]:

$$h(u, v; \xi, \eta) = \sum_k a_k(u, v) p_k(\xi - u, \eta - v) \quad (4)$$

where a_k is the set of bases termed coefficient distribution, and p_k is so-called the set of eigen PSF. This decomposition decouples the absolute coordinates of the object and the relative coordinates of the PSF. The eigen PSFs are sorted in order of importance, with smaller k indicating more significant importance.

By combining the generated coefficient distribution set a_k the eigen PSF set p_k with the RL deconvolution, it is possible to derive and apply a full-field spatially varying RL deconvolution, which allows for a comprehensive analysis of spatial variations across the entire field of view:

$$o_{r+1}(x, y) = \frac{o_r(x, y)}{1 - \lambda_{TV} \text{div} \left(\frac{\nabla o_r(x, y)}{|\nabla o_r(x, y)|} \right)} \left[\sum_{l=1}^M p_l(-x, -y) \frac{i(x, y) a_l(x, y)}{\sum_{k=1}^M p_k(x, y) \otimes a_k(x, y) o_r(x, y)} \right] \quad (5)$$

where r denotes the current iteration number, M represents the modulus or number of eigen PSFs used for deconvolution, $i(x, y)$ refers to the original image, while $o_r(x, y)$ denotes the

restored image; $p_k(x, y)$ is the k^{th} eigen point spread function and $a_k(x, y)$ is the corresponding coefficient array. $\nabla o_r(x, y)$ represents the gradient of $o_r(x, y)$. The term $\nabla o_r(x, y) / |\nabla o_r(x, y)|$ normalizes the gradient to a unit vector with a length of 1.

3. EXPERIMENTS AND RESULT ANALYSES

3.1. Overall system setup

Fig. 1 illustrates the optical configuration of the developed system. The chromatic confocal microscopy setup adopts a coaxial architecture, enabling high-speed measurements without axial scanning while preserving sample integrity and achieving sub-micrometer resolution. The illumination module consists of a xenon lamp, two positive lenses, and a cylindrical lens that shapes the beam into a line profile. A single-axis galvanometer performs lateral scanning, while a telecentric scan lens maintains consistent optical mapping across the field.

The reflected light from the sample is directed back into the spectrometer, passing through a polarizer and a liquid crystal on silicon (LCoS) device before being recorded by a camera. The system integrates a programmable LCoS within the line-scan chromatic confocal microscope (LSCCM), enabling flexible and precise modulation. By replacing the conventional detector slit in the spectrometer with a reconfigurable LCoS-based aperture, point spread functions (PSFs) at multiple spatial positions are acquired on the sensor, facilitating resolution enhancement via a full-field deconvolution framework.

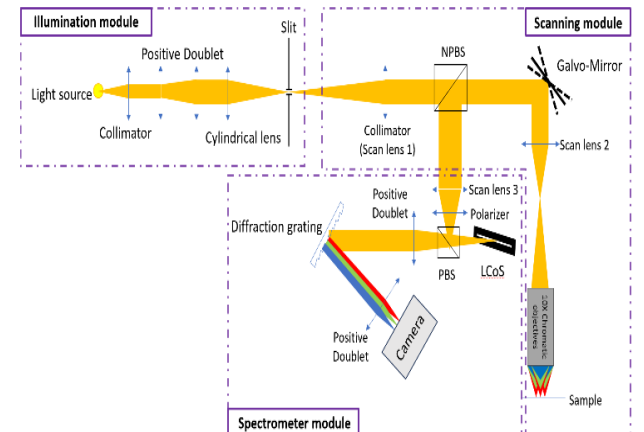


Fig. 1. System configuration of the Galvano-based LSCCM system with LCoS-modulated detection

3.2. Reconstruction of the circular grating and Result Analyses

To validate the system's feasibility, measurements will be conducted using a circular grating as the test object. The grating is prepared on a wafer surface with a depth-to-width ratio of less than 1, making it geometrically and reflectively well-suited for the task. Additionally, the concentric circular form of the micrometer-scale structure allows for the direct capture of a cross-section through the center. This enables the direct acquisition of critical dimensions such as width (W), spacing (S), and depth, facilitating comparisons with verification-grade measurement techniques like white light interferometry. In this experiment, a W10S10 concentric circular grating, featuring a nominal width and spacing of 10 μm each, is being measured.

The measurement results of the W10S10 grating are displayed in Fig. 1, comprising the raw measurement data, results after deconvolution, and a comparison of the two data with the measurement results obtained from white light interferometry. Since the reconstructed grating surface exhibits fluctuations, it is necessary to define a method for measuring and calculating critical dimensions.

Table 1 compares the critical dimensions of the concentric circular grating W10S10 obtained from deconvolution and white light interferometry (WLI). Labels A–E denote the original measurement, deconvolved result, WLI reference, original bias, and deconvolution bias, respectively.

Table 1. Comparing the critical dimensions of concentric circular grating W10S10 using deconvolution and white light interferometry results, where A,B,C,D,E represent the original result, the deconvolution result, the WLI result, the original bias, and the deconvolution bias respectively.

	A (μm)	B (μm)	C (μm)	D (μm)	E (μm)
Width	6.85	9.59	6.9	-0.05	2.69
Period	19.865	20.580	20.201	-0.715	0.379
Depth	2.43	3.157	3.350	-0.920	-0.193

The comparison highlights the effectiveness of system reconstruction: the deconvolution process produces steeper sidewalls and smoother grating bottoms, closely matching the WLI measurements. Both period and depth deviations are within 1 μm . While the overall depth accuracy shows clear improvement, the linewidth remains largely unchanged, likely due to suboptimal parameter selection, as confirmed by experimental observations.

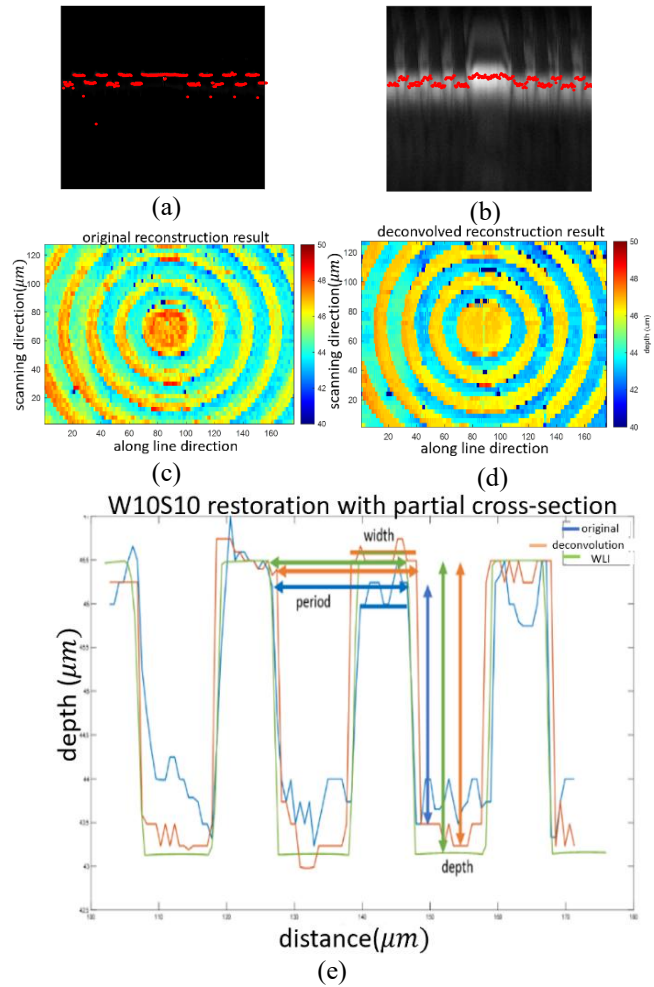


Fig. 1. (a) W10S10 Deconvolved spectral image and peak detection of W10S10 (b) W10S10 spectral image and peak detection (c) W10S10 original reconstructed overhead view of the concentric circular grating (d) W10S10 algorithmically reconstructed overhead view of the concentric circular grating (e) W10S10 cross-sectional view, taken from the red dashed line in (c) and (d), through the center of the concentric circular grating showing the system's reconstructed results and the results from white light interferometry (WLI).

3.3. Reconstruction of micro bumps array and result analyses

Another sample we measured is an array of micro bumps, arranged in a matrix form of

numerous dome-like structures. We selected one microsphere for comparison of the deconvolution effects in Fig 2. By examining the data before and after the application of the global RL deconvolution algorithm, the most notable improvement is the elimination of the ringing effect. The difference between the regions and cross-sectional views with and without full-field deconvolution is substantial, aiding in the accurate measurement of actual critical dimensions. The sharp features at the edges of the deconvolved cross-section are more pronounced, and the connection between the microsphere and the base is closer to a sharp angle rather than a smooth one, aligning with the expected morphology.

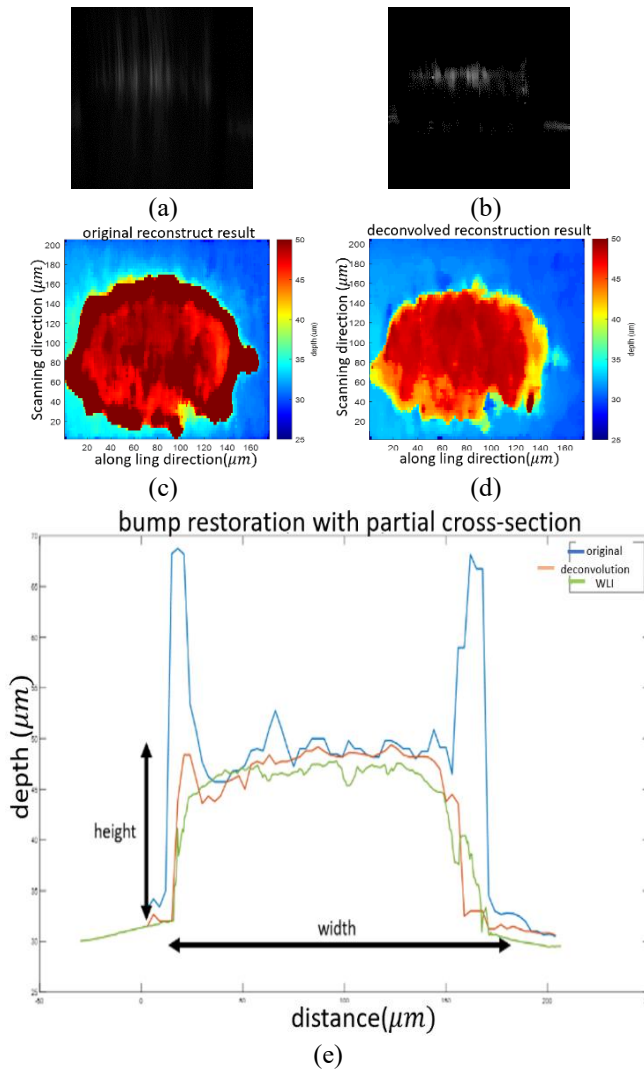


Fig 2 (a) Original spectral image of the bump (b) Spatially varying deconvolved spectral image of the bump (c) Overhead view of the target bump's reconstructed results (d) Overhead view of the target bump's deconvolved reconstructed results (e) Cross-section of the micro bump, including the overlaid reconstruction results from the

original (blue line), deconvolved (red line), and white light interferometry (yellow line) techniques. Verification data for the micro bump using a Mitutoyo Hyper QV WLI 404 white light interferometer.

From Fig 2, it is apparent that before and after algorithm integration, the most notable enhancement attained through full-field RL deconvolution is the reduction of the ringing effect, facilitating the measurement of critical dimensions. Table 2 also presents the results of the lateral dimensions and heights of microbumps, which closely match those obtained from white light interferometry (WLI).

Table 1 Microbumps using deconvolution and WLI results

	Deconvolution Result	WLI result
Lateral dimensions	150.0 μm	156.7 μm
Height	17.1 μm	17.3 μm

In this section, the comparison of critical dimension measurements for different samples demonstrates the effectiveness of our algorithm in enhancing both the lateral and axial resolution of the linear chromatic confocal system.

4. CONCLUSIONS

This study focuses on the development of a Galvano-mirror-based LSCCM and the deconvolution algorithm for surface profile enhancement. In terms of hardware, an innovative optical design was achieved by incorporating a spatial light modulator (LCoS) into the system's spectrometer to replace the detection slit found in traditional confocal systems. This enables the system not only to measure spatially varying PSFs but also to perform morphology measurements, achieving automated optical inspection. In software development, efforts are made to enhance lateral resolution by introducing the full-field spatially varying deconvolution algorithm. This algorithm improves iterative efficiency and introduces a total variation regularization term to avoid ringing artifacts.

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Profilometrie 3d îmbunătățită a suprafeței prin microscopie confocală cromatică cu deconvoluție richardson-lucy variabilă spațial

Rezumat: Acest studiu introduce un nou design optic în microscopia confocală cromatică cu scanare liniară pentru reducerea diafoniei (crosstalk), utilizând o oglindă Galvano și un modulator spațial de lumină (SLM) inovator, bazat pe tehnologia Liquid Crystal On Silicon (LCoS), pentru a înlocui fanta detectorului. Această abordare permite măsurarea directă a funcției de dispersie a punctului (PSF) utilizând optica Fourier și teoria convoluției. Sistemul utilizează deconvoluția Richardson-Lucy pentru restaurarea imaginilor, reușind să rafineze caracteristici de ordin micrometric în rețele circulare concentrice și proeminente la scară micronica, fapt confirmat prin comparații cu interferometria în lumină albă. Rezultatele măsurătorilor indică faptul că această metodă reduce semnificativ erorile morfologice, îmbunătățind deviația liniară și abaterea de adâncime la valori sub 1 micron, respectiv 0,2 microni, sporind astfel rezoluția caracteristicilor atât în direcția laterală, cât și axială, până la o precizie submicrometrică.

First author's Name Surname, Title, Position, Institution, Name of Department, E-mail, Office Phone, Home Address., Home Phone. The same for all authors.