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DOI
10.1117/12.2295688

Publication date
2017

Document Version
Final published version

Published in
Proceedings of SPIE- International Society for Optical Engineering

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Hai Gong, Oleg Soloviev, Michel Verhaegen, Gleb Vdovin, "Shack-Hartmann reflective micro profilometer," Proc. SPIE 10616, 2017 International Conference on Optical Instruments and Technology: Optical Systems and Modern Optoelectronic Instruments, 106160M (10 January 2018); doi: 10.1117/12.2295688

Event: International Conference on Optical Instruments and Technology 2017, 2017, Beijing, China

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ABSTRACT

We present a quantitative phase imaging microscope based on a Shack-Hartmann sensor, that directly reconstructs the optical path difference (OPD) in reflective mode. Comparing with the holographic or interferometric methods, the SH technique needs no reference beam in the setup, which simplifies the system. With a pre-registered reference, the OPD image can be reconstructed from a single shot. Also, the method has a rather relaxed requirement on the illumination coherence, thus a cheap light source such as a LED is feasible in the setup. In our previous research, we have successfully verified that a conventional transmissive microscope can be transformed into an optical path difference microscope by using a Shack-Hartmann wavefront sensor under incoherent illumination. The key condition is that the numerical aperture of illumination should be smaller than the numerical aperture of imaging lens. This approach is also applicable to characterization of reflective and slightly scattering surfaces.

Keywords: microscope, wavefront sensing, optical profilometer, phase imaging

1. INTRODUCTION

Characterization of the profile of a surface is required in various applications in both industrial and biomedical fields, including MEMS characterization, precision micro-optics, living cell monitoring.[1–3] The existing profiling methods can be put into two categories: contact and non-contact.

Generally, the contact methods use a stylus to scan the surface to achieve resolution in nanometer or sub-nanometer scale. The mechanical system is bulky and the scanning process is relatively slow, especially for a 2D areas. Because of the invasive tip, certain materials, such as biological samples, are difficult to measure.

Therefore, the non-contact optical methods are gaining popularity in profilometry. Currently, the interferometric methods, such as the scanning interferometry and digital holography, are dominant. In general, they exploit the interference between the reference and samle beams. The phase difference between the two beams is extracted from the recorded interferogram or hologram. These methods can measure the surface topography with lateral resolution down to the diffraction limit. The axial resolution can achieve a sub-nanometer range. However, aberrations are difficult to avoid through all the optical components in the setup. Building a high sensitive interferometric system needs a very good alignment which takes a lot of efforts to achieve in practice. Most interferometric methods rely on highly coherent light source, which will suffer the speckle noises from not only the measured sample but also the scattering of optical components.[4,5] Both the requirements on system alignment and light source add the cost to a commercial instrument.

Applying the wavefront sensing technique to the profilometry is also a trend. Methods like the partitioned aperture wavefront sensing,[6] and the quadriwave lateral shearing interferometry[7] obtain good results. Also in our previous work, an optical path difference microscopy based on high resolution Shack-Hartmann wavefront sensing technique in transmission configuration has been developed.[8,9]

In this work, we investigate further the reflective profilometry with the Shack-Hartmann wavefront sensor. We consider the requirements to illumination coherence and image sampling. Then the Fourier demodulation wavefront reconstruction technique is described. An experimental setup has been built to validate the feasibility of the method. A hexagonal microlens array mold is chartacterized using the method. The experimental results indicate that it is promising to instrumentalize this technique with its simple and robust feature.

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2017 International Conference on Optical Instruments and Technology: Optical Systems and Modern Optoelectronic Instruments, edited by Y. T. Wang, B. H. Jia, K. Tatsuno, Proc. of SPIE Vol. 10616, 106160M
 · doi: 10.1117/12.2295688

2. SYSTEM OPERATION

2.1 Shack-Hartmann wavefront sensor

The Shack-Hartmann wavefront sensor (SHWFS) is widely used in the field of adaptive optics and optical testing. It originates from the work of Roland Shack in the beginning of the 20th century, and Ben Platt in 1971.[10] Modified from the Hartmann testing screen by adding lenslets, the SHWFS is more photon efficient which makes it more suitable for low-light applications. Although, in the early stage, this wavefront sensor suffered from the limited lenslet numbers, the resolution increases significantly with the development of microlens array fabrication technology.

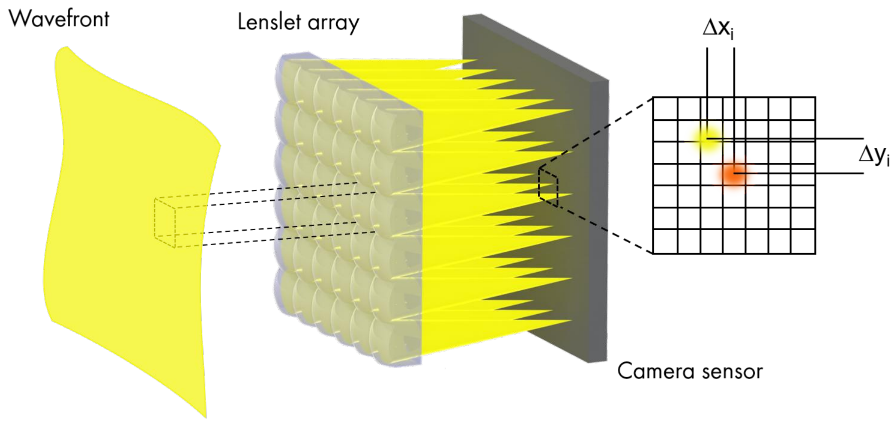

Figure 1. Schematic of a general Shack-Hartmann wavefront sensor.

As shown in Figure 1, a SHWFS is basically composed of a lenslet array and a camera sensor at the focal plane. With an incident plane wave, the light within the aperture of a lenslet is focused in the center of the sub-region (as the red spot shown in the figure). Then a spots-pattern (SH pattern) will be recorded by the camera. When the wavefront of incident light is distorted, these focal spots will be shifted from their centers. The local gradients can be estimated from the deviations of the focal spots in two dimensions as:

$$\frac{\partial W_i}{\partial x} = \frac{\Delta x_i}{F}, \ \frac{\partial W_i}{\partial x} = \frac{\Delta x_i}{F}, \tag{1}$$

where F is the focal length of lenslets. The wavefront is then reconstructed by combining all the local slope measurements of the sub-apertures. When compared with a reference wavefront, the optical path difference (OPD) between them can be obtained, which gives us the topography of the surface.

2.2 Illumination condition

In the framework of geometrical optics, the measurement result in the SH sensor is independent on the wavelength. This relaxes the requirement of the temporal coherence: the method can work with various light sources, including lamp or LED illumination.

If the sample image is obtained on the surface of the microlens array, the spot size in the subaperture of a SH sensor is defined by the spatial coherence of the illumination beam and the scattering in the sample.The spot should fit into the field of view, also have some freedom to move, to facilitate precise measurements of local tilts. This is possible, if the condition is satisfied:[8]

$$\frac{\lambda}{C} + S + 2T \ll A, \tag{2}$$

where C is the characteristic size of the spatial coherence of illumination in the plane of the sample, S is the scattering angle on the sample, T is the maximum expected tip/tilt of the sample surface, and A is the numerical aperture of the imaging lens. Condition (2) allows for engineering compromise between the spatial coherence C of the illumination, sample scattering S, and the measurement range T, especially if A is not large enough.

2.3 OPD reconstruction from the Shack Hartmann pattern

Generally, the gradients are extracted from Shack-Hartmann pattern by using centroid method.[11] When the number of lenslets is small, direct calculation of the centroids within each sub-aperture is efficient enough. However, in the high resolution case, this process is cumbersome. Since the SH pattern is periodic, we can retrieve the spot shifts by Fourier processing which is more efficient. This method is introduced and extensively studied by E.N. Ribak.[12,13]

Figure 2 offers a brief sketch of the Fourier demodulation process from SH pattern and the OPD reconstruction:

1. Fourier transform of the SH pattern.

2. The OPD gradient information is encoded in the components near the first side lobes (the dotted line boxes in the Fourier domain).

3. By translating the side lobes to the center and adding a low frequency filter, the carrier frequency is removed and only gradient components are left.

4. Argument of the inverse Fourier transform provides gradients in x or y dimension.

5. Phase unwrap the retrieved gradients.

6. OPD map is reconstructed by the integration of two dimensional gradients.

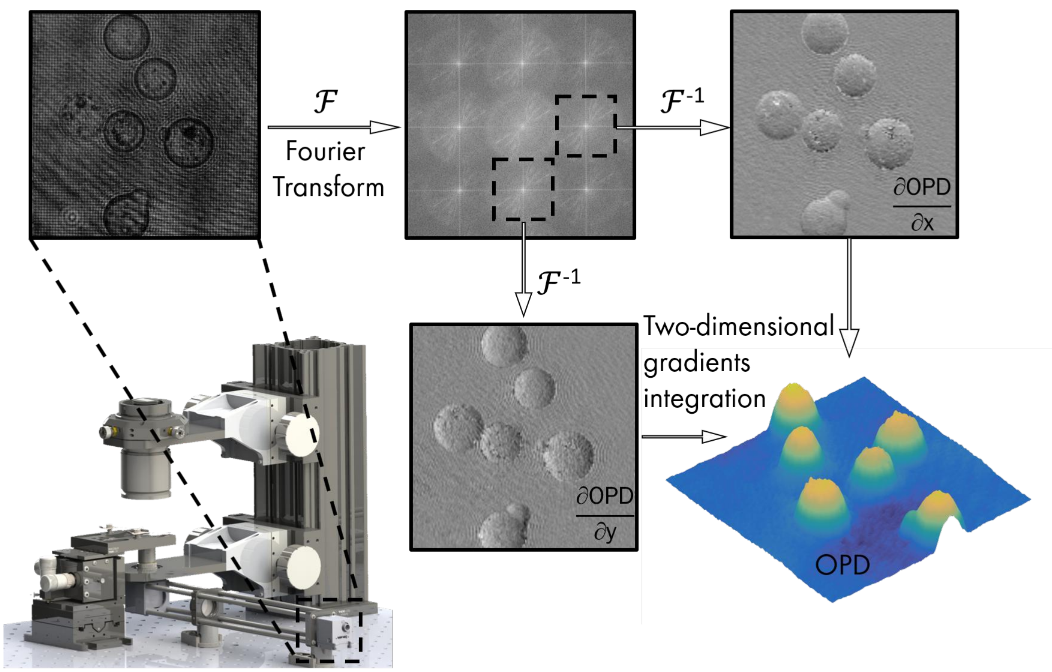

Figure 2. Fourier demodulation processing of SH pattern illustrated in a transmissive configuration for measuring micro beads. The gradients of OPD are extracted from the camera recordings. Then the OPD is reconstructed by the integration of gradients.

Actually, by filtering the SH pattern, the intensity information can also be restored which allows the system still to work as a normal microscope without additional cameras. The intensity information is also helpful in determining whether the measured surface is in focus.

2.4 Reflective profilometer based on SH wavefront imaging

Figure 3 depicts an implementation of the SHWFS based microscope in a reflection configuration which is suitable for micro surface profiling. This implementation can be easily modified from a standard reflective microscope. A converging lens is used before the objective lens to collimate the light incident on the sample. The SHWFS locates at the imaging plane after the tube lens which is conjugated with the focal plane of objective lens with a system magnification. All the objective lens, tube lens and the types of SHWFS can be tuned to satisfy the illumination condition in Section 2.2 with respect to the applications.

The difference from the transmission configuration is that the retrieved gradients in Section 2.3, Step 4 are twice the OPD gradients. It is because of the reflected angle is doubled the local tilt with respect to the normal of surface. This factor should be eliminated before the OPD reconstruction.

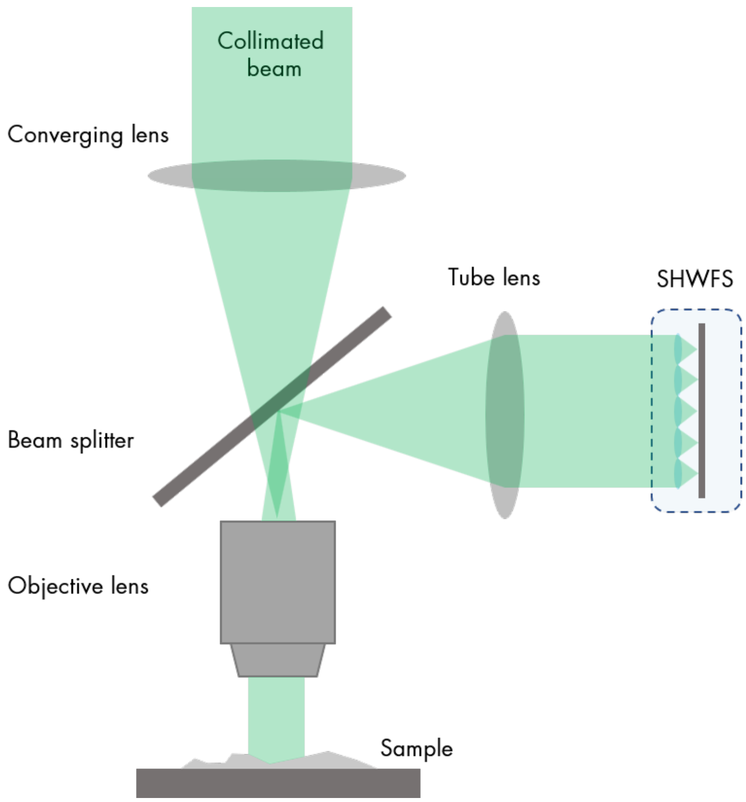

Figure 3. Setup of a SHWFS based reflective micro-profilometer.

3. EXPERIMENTS

An off-spec silicon mold, provided by Flexible Optical BV, see Figure 4, is characterized to verify the feasibility of the approach. The mold has been fabricated by anisotropic etching of silicon.[14,15] This hexagonal array has 127 micro-mirrors with a pitch of $p = 300\ \mu m$, radius of curvature $r \approx 9.52\ mm$ and sag $s \approx 1.18\ \mu m$.

The schematic of our experiment is shown in Figure 3. A collimated green LED (central wavelength 530nm, M530L3, Thorlabs) is used as the light source. A positive lens with focal length of 200 mm, in combination with a 10$\times$ objective (NA = 0.25) is used to form collimated sample illumination. The imaging/sensing arm is formed by the objective and a $f = 400\ mm$ tube lens, providing total magnification of 25$\times$). The mold images are projected onto the microlens array of the SH sensor, to form a sharp image. The SHWFS (FS3370-O-P63-F2, Flexible Optical BV) has 140×140 lenslets in orthogonal arrangement. The pitch of the lenslet array is 63 μm. The focal length of each lenslet is about 2 mm. The sampling interval in the measurement plane is equal to $63/25 \approx 2.5\mu$m.

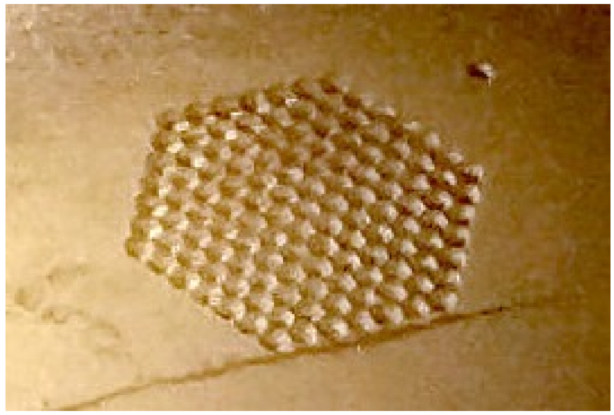

Figure 4. Silicon mold of a hexagonal microlens array, with pitch of $300\mu m$.

A reference is obtained with a flat mirror in the sample plane. This calibration step only has to be carried out just once. Then, the mold was put at the focal plane with a SH pattern being recorded. The reconstructed OPD is shown in Figure 5 (a). We can clearly identify the hexagon structure and the surface shape from the reconstruction. A profile of the center is shown in Figure 5 (b) after a tilt correction. We flip this measurement upside down to compare with the ideal surfaces of the expected microlens in Figure 5 (c). The mirror figure defect, due to non-uniform etching rate, is clearly visible in the measurement result.

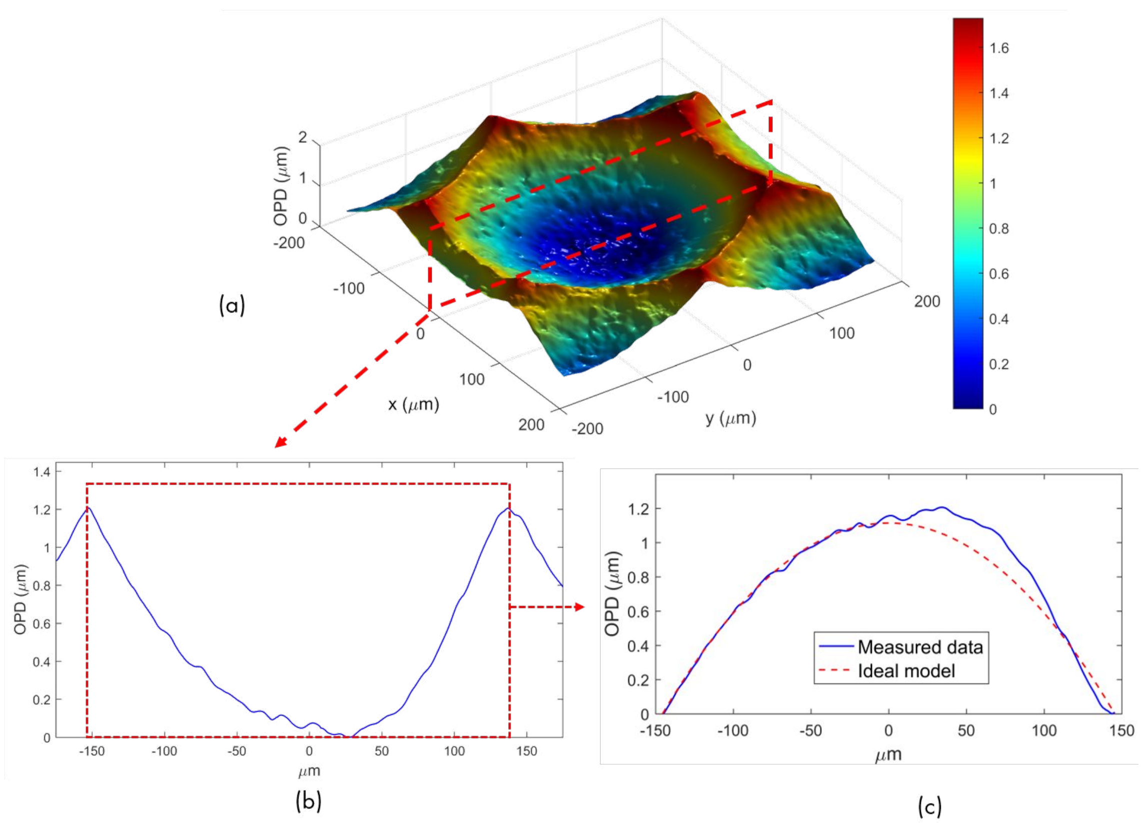

Figure 5. Reconstruction of the profile of a single 300 μm micro-mirror: the reconstructed OPD map (a), the cross-section profile of the micro-mirror (b), and the comparison between the measured and prescription profile data (c).

4. DISCUSSION

We have experimentally shown that the SH sensor can be used for micro-profilometry in a very simple setup, with relaxed requirements to the coherence of illumination and the sample scattering. The throughout investigation of the accuracy, range, and the sensitivity of the method, will be carried out in the future. In this particular experiment, we used this micro-profilometer to characterize the quality of a microfabricated silicon mold and have demonstrated a quite promising performance.

Moreover, there are some considerations of applying this approach as a micro-profilometer:

- The system can tolerate a certain amount of scattering on the sample, however significant roughness and scattering of the surface make essential contribution to the left part of condition (2), resulting in bad signal to noise performance and failing measurements.
- Instead of measuring the height directly, it is the OPD gradients being measured. The optical system works as a low pass filter for the gradients, so any reflected ray at an angle which is larger than the system NA (*i.e.* the high frequency components in angular spectrum) will be ignored, causing black spot in the image. Steep surfaces are difficult to detect with this method. A high numerical aperture system or multiple angle detection is needed to improve the performance.
- For samples with non-uniform reflection/absorption the high dynamic range (HDR) technique can be considered to extend the intensity dynamic range. Beside that, the non-uniform intensity also affects the wavefront reconstruction[16] and needs to be investigated further.

5. CONCLUSION

We have successfully demonstrated a miro profilometer based on reflective Shack-Hartmann wavefront sensing technique. The technique can be implemented by simply modifying a standard reflection microscope. It can work with a low cost light source under relaxed requirements to the spatial and temporal coherence, making it an inexpensive alternative to the existing techniques.

ACKNOWLEDGMENTS

The work is supported by the China Scholarship Council (CSC) (201406280043), the European Research Council, ERC 339681, under the European Unions Seventh Framework Programme, and the Ministry of Education and Science of the Russian Federation.

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