Spatial-Phase-Shift Imaging Interferometry Using Spectrally Modulated White Light Source

Shlomi Epshtein,[1] Alon Harris,[2] Igor Yaacobovitz,[1] Garrett Locketz,[3] Yitzhak Yitzhaky,[4] Yoel Arieli,[5*]

1AdOM Technologies, Hamlacha 1, Lod 7152001, Israel

2Glick eye center Indiana university medical center, Indianapolis, Indiana 46202

3Sackler School of Medicine, Tel Aviv University, Tel Aviv 6997801, Israel

4Ben-Gurion university of the Negev, Beer Sheva 8410501, Israel

5Jerusalem College of Technology, Havaad Haleumi 21, Jerusalem 9372115, Israel

**Corresponding author: arieli.yoel@gmail.com*

An extension of the White Light Spatial-Phase-Shift (WLSPS) for object surface measurements is described. Using WLSPS, surface measurements can be obtained from any real object image without the need of a reference beam, thus achieving inherent vibration cancelation. The surface topography is obtained by acquiring multiple images of an object illuminated by a spectrally modulated white light source and using an appropriate algorithm. The modulation of the light source obviates the need for the continuous phase delay to obtain the interferograms.

OCIS codes: (170.0110) Imaging systems; (170.3010) Image reconstruction techniques;

The need for high-accuracy wavefront analysis for surface measurement applications has necessitated the invention of many surface measurements methods [1–5]. Recently [1], we have introduced the WLSPS method; a novel, vibration-insensitive imaging interferometry technique for surface measurements and wavefront analysis, wherein white light fringes are obtained by dividing the wavefront reflected from an object into two parts and introducing a continuous phase delay to one part of the wavefront relative to the other. Due to the imaging implementation of the method, the WLSPS method can be used to analyze an imaged wavefront, thus enabling it to be added as a measurement sensor to any optical system that images unaberrated wavefronts.

In this paper, we extend the WLSPS by using it in conjunction with a spectrally modulated white light source. In this approach, instead of introducing a continuous phase delay to one part of the wavefront relative to the other, multiple images of the object are acquired while illuminating it by a spectrally modulated white light source and using appropriate algorithm. The modulation of the light source obviates the need for the continuous phase delay to obtain the interferograms.

The basic optical system for measuring an object's surface using the White Light Spatial-Phase-Shift (WLSPS) method is a 4F optical system. The object to be measured is placed in the front focal plane of the objective lens and is illuminated normally by a collimated broadband light beam.

For each wavelength, the complex amplitude of the wavefront reflected from the object is:

$$o(x,y,\lambda) = A(x,y,\lambda)\exp\left[i\varphi(x,y,\lambda)\right] \quad (1)$$

where A and φ are respectively the amplitude and the phase functions of each wavefront.

The phase map $\varphi(x,y,\lambda)$ of each wavefront is given by:

$$\varphi(x,y,\lambda) = -4\pi\frac{h(x,y)}{\lambda} \bmod 2\pi \quad (2)$$

where $h(x,y)$ is the height map of the object and "mod 2π" is the phase modulo 2π.

In the back focal plane of the objective lens, the complex amplitudes of each wavelength are proportional to the Fourier transform of the reflected wavefronts $o(x,y,\lambda)$. At the Fourier plane, all wavefronts are divided into two complementary spatial parts that are characterized by the two spatial functions $G(u,v)$ and $1-G(u,v)$, and a phase shift θ is introduced between the two parts[1]. The imaging lens images the modified wavefronts on the image plane where a CCD camera is located. It can be shown [1] that the complex amplitudes of all wavefronts at the image plane are proportional to:

$$o'(x,y,\lambda) = C(\lambda)\left\{o(x,y,\lambda) + S(x,y,\lambda)\left[\exp(i\theta) - 1\right]\right\} \quad (3)$$

where C is a wavelength-dependent constant for a given optical system, and $S(x,y,\lambda) = o(x,y,\lambda) * \Im\left[G(u,v)\right]$.

The sign * denotes a convolution and $\Im$ denotes the wavelength scaled Fourier transform operation.

The signal at each camera's detector is:

$$I(x,y) = \int R(\lambda)\left|C(\lambda)\left\{o(x,y,\lambda) + S(x,y,\lambda)\left[\exp(i\theta) - 1\right]\right\}\right|^2 d\lambda \quad (4)$$

where $R(\lambda)$ is the spectral responsivity of the detector.

This equation is quite similar to the equation obtained at the standard White Light Interferometry (WLI)[5], where the function $S(x,y,\lambda)$ plays a similar role to the reference beam.

The main difference between the WLSPS and the standard WLI is that while the standard WLI reference beam is uniform in its spectrum and phase all over the image plane, the WLSPS complex function $S(x,y,/)$, which serves as the reference beam, is wavelength-dependent and its spectrum and phase may vary over the image plane. In this point of view, the function $S(x,y,/)$ attains a "virtual reference position" and its virtual location in space depends on the phase shift θ.

The interferograms obtained in WLI for each object's point while introducing a continuous phase delay between the reference and object's beams are actually the auto-correlation of the light amplitude reflected from that point. According to **Wiener-Khintchine theorem**[6], there is a **Fourier** transform relation between the auto-correlation and the spectral power density. Thus the auto-correlations can also be calculated by splitting the illumination into two beams and measuring the spectrum of the interference of the beam of light that is reflected from the object and the beam of light that is reflected from a fixed reference mirror. When using Fourier Transform Spectroscopy (FTS) to measure the spectrum of light, the auto-correlation of the reflected light amplitude is measured directly by using an interferometer, and there is no need for the Fourier transform. Since the interferometer in the FTS is actually a variable cosine spectral filter, it follows that by modulating the spectrum of the light source with a variable cosine function, the auto-correlation of the light amplitude of the interference of the light reflected from the object and the reference mirror is obtained directly. This approach can also be applied for a white light common path interferometry, such as the WLSPS, when multiple images of an object are acquired while illuminating it with a variable spectrally modulated light. In the WLSPS, the interference is created between the two complementary spatial parts $G(u,v)$ and $1-G(u,v)$ of the wavefronts in Fourier plane of the objective lens, where a fixed phase shift is introduced between both parts.

The optical system for the WLSPS using spectrally modulated light source is shown in Fig.1. The setup includes two parts; the illumination and the imaging apparatuses.

The illumination apparatus includes a Philips halogen reflector bulb, an EKE 150W light source and a pinhole. The pinhole (PH) is located close to the focal plane of the reflector. The pinhole plane is imaged to infinity and the collimated beam propagates through a Michelson interferometer. By moving one of the interferometer's mirrors continuously, a continuous spectrally modulated illumination light is obtained. In the effective focal plane of the combined lenses L_1 and L_2, a slit (S_1) is placed. The light that passes through the slit illuminates the object by a collimated beam. The imaging apparatus consists of two groups of lenses, an objective lens close to the object and an imaging lens close to the detector's plane where a CCD camera is located. The objective lens consists of the two lenses L_2 and L_3, each has a focal length of 100 mm. The imaging lens consists of four lenses, each has a focal length of 1000 mm. The light reflected from the object passes through a Diffractive Optical Element (DOE) that splits the wavefronts to two complementary spatial parts $G(u,v)$ and $1-G(u,v)$, and introduces a fixed phase shift between both parts. The DOE consists of a long rectangle groove on a 3 mm thick glass plate. The width of the groove is 10 microns and its depth is 180 nm. The DOE is placed in the Fourier plane of the objective lens which is also the image plane of the slit. After the phase shifting by the DOE, the object was imaged on the CCD plane by the imaging lens, with X5 magnification.

A circular steps object was measured using the spectrally modulated light source and the WLSPS setup described above. The object includes three aluminum circular foils coated with thin gold coating. Each foil thickness is 50µm. The foils are put between a silicon wafer and a visible AR coated window. The circular steps object is shown in Fig. 2.

Multiple images of the circular steps object were taken while constantly modulating the spectrum of the light source by moving one of the interferometer's mirrors. As the spectrum of the light varied continuously, an interferogram was created for each point on the image. Assuming that the maximum contrast of the interferogram was obtained at a corresponding OPD between the two interferometer's mirrors and the OPD between a point on the object's surface and the "virtual reference position" attained by the function $S(x,y,\lambda)$, the three dimensional object was reconstructed. A cross-section of the reconstructed circular steps object is shown in Fig. 3. As can be seen in this figure, the WLSPS method yielded a highly accurate reconstruction of the object.

An extension of the White light Spatial Phase Shift method by using it in conjunction with a spectrally modulated white light source is introduced. In this approach, white light interference was obtained by using a spectrally-modulated light source and introducing a fixed phase shift between two parts of the wavefronts in a common path interferometer. A three dimensional circular steps object was measured using the setup and by calculating the OPDs where the maximums contrasts had obtained at each point, the three dimensional object was reconstructed with a high degree of accuracy.

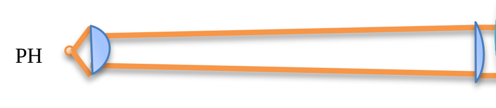

Figure 1. The optical system for the WLSPS includes two parts, the illumination and the imaging apparatuses.

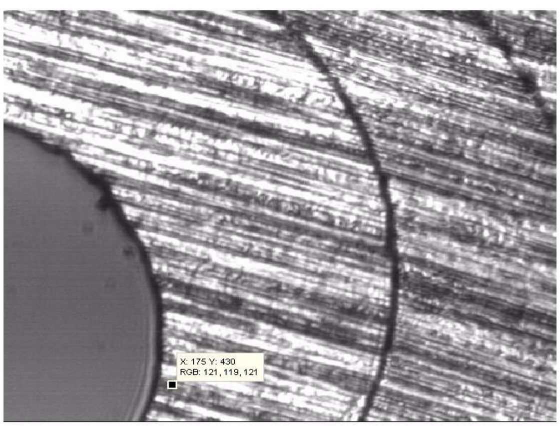

Figure 2. The measured steps object

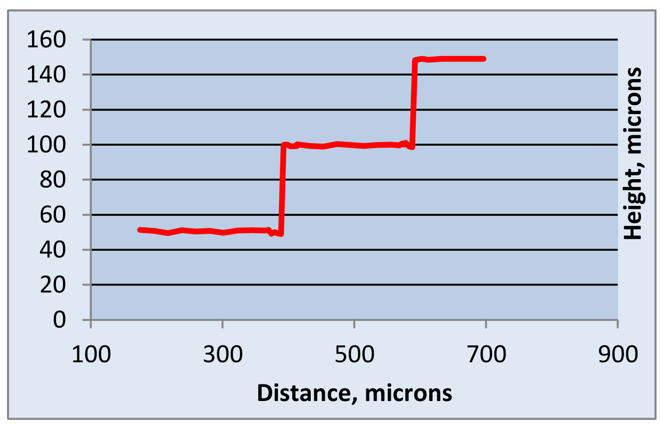

Figure 3. A cross-section of the reconstructed circular steps object.

References

1. Y. Arieli, S. Epshtein, I. Yaacobovitz, Y. Weitzman, G. Locketz, A. Harris. Optics Express Vol. 22, 13, pp. 15632–15638, (2014).
2. O. Soloviev and G. Vdovin. Opt. Exp. 13, 3743–3753 (2005).
3. S. Cain. Opt. Eng. 43, 1670–1681 (2004).
4. A. Shevchenko, S. C. Buchter, N. V. Tabiryan, and M. Kaivola. Opt. Commun. 232, 439–442 (2004).
5. J. C. Wyant. Proceedings of SPIE Vol. 4737, pp. 98-107 (2002).
6. N. Wiener. M.I.T. Press, Cambridge, Massachusetts. p. 42 (1964).

References

7. Y. Arieli, S. Epshtein, I. Yaacobovitz, Y. Weitzman, G. Locketz, A. Harris, "Surface Measurements by White Light Spatial-Phase-Shift Imaging Interferometry", Optics Express Vol. 22, 13, pp. 15632–15638, (2014).
8. O. Soloviev and G. Vdovin, “Phase extraction from three and more interferograms registered with different unknown wavefront tilts,” Opt. Exp. 13, 3743–3753 (2005).
9. S. Cain, “Design of an image projection correlating wavefront sensor for adaptive optics,” Opt. Eng. 43, 1670–1681 (2004).
10. A. Shevchenko, S. C. Buchter, N. V. Tabiryan, and M. Kaivola, “Self-focusing in a nematic liquid crystal for measurements of wavefront distortions,” Opt. Commun. 232, 439–442 (2004).
11. J. C. Wyant, "White Light Interferometry", Proceedings of SPIE Vol. 4737, pp. 98-107 (2002).
12. N. Wiener, "Time Series", M.I.T. Press, Cambridge, Massachusetts. p. 42 (1964).