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# Measuring range extension of spectrally-resolved interferometry by using a polarization pixelated CMOS camera

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## Abstract

In this investigation, we propose a polarizing spectrally-resolved interferometer to extend the measuring range limited by the Fourier method, which has the dead zone caused by the minimum measurable range. Adopting a polarization pixelated CMOS camera which can obtain the spatially phase-shifted four spectral interferograms, the spectral phases can be extracted with a single operation, and the proposed interferometer provides a fixed distances corresponding to the line of a specimen at once. By the nature of phase shifting technique, moreover, the directions of measured distances are identified, and the measuring range is extended twice longer than that of the spectrally-resolved interferometer based on the Fourier method. In the experimental results, the measuring range was 104 µm, and the capability to obtain a line profile of a specimen with a single operation was confirmed.

Spectrally-resolved interferometer, polarization pixelated camera, spatial phase shifting, minimum measurable range, dead zone

## 1. Introduction

Spectrally-resolved interferometry (SRI) can measure a fixed distance with an acquisition of spectral phase without any mechanical or electrical moving mechanisms [1]. By using a dispersive elements such as a diffraction grating or a prism, an interference signal is spectrally resolved, and each spectral density of the interference signal can be detected corresponding to its wavelength. Typically, this spectral interference signals are analyzed by the Fourier method, and the distance can be determined from the relation between the spectral phase and optical frequencies [2] . However, SRI has the limitation of measuring range caused by a minimum measurable range ($L_{\min}$). $L_{\min}$ is originated by the characteristics of the Fourier method, which cannot distinguish the signal peak purely in case that it is overlapped with a DC peak in the Fourier domain. Moreover, SRI does not have directionality of the signal, which means it always take the positive value of the distances [3,4]. Because of $L_{\min}$ and the direction ambiguity caused by the Fourier method, subsequently, the measuring range of SRI is significantly reduced [3,4] and it becomes only half the whole measuring range.

Meanwhile, a phase shifting SRI (PS-SRI) [5] can remove the measuring range limitation caused by $L_{\min}$ because the spectral phases are obtained by the phase shifting technique. As long as the phase shifting technique is applied to SRI, the spectral phase can be obtained at any circumstances, even the spectral interferogram is null. Furthermore, the directions of the measured distances are also determined by the direction of the phase increases in the phase shifting technique. However, PS-SRI needs a phase shifting mechanism such as a mechanical or an electrical moving part, which needs additional measurement time. It malinly lowers the advantage of SRI. Besides, PS-SRI should compensate the phase shifting errors corresponding to all wavelengths [6].

In this investigation, we propose a polarizing spectrally-resolved interferometer to extend the measuring range, which are limited by the Fourier method, which has the dead zone caused by the minimum measurable range. Adopting a polarization pixelated CMOS camera which can obtain the four spatially phase-shifted spectral interferograms, the spectral phases can be extracted with a single operation, and the proposed interferometer provides a fixed distances corresponding to the line of a specimen at once. By the nature of phase shifting technique, moreover, the directions of measured distances are identified, and the measuring range is extended twice than that of the spectrally-resolved interferometer based on the Fourier method.

## 2. Principle

Figure 1 shows the optical configuration of the modified SRI in this investigation. As a light source, a broadband light is used and split into a reference and a measurement beams by a polarizing beam splitter (PBS) after passing through a 45° rotated linear polarizer ($P_{45°}$).

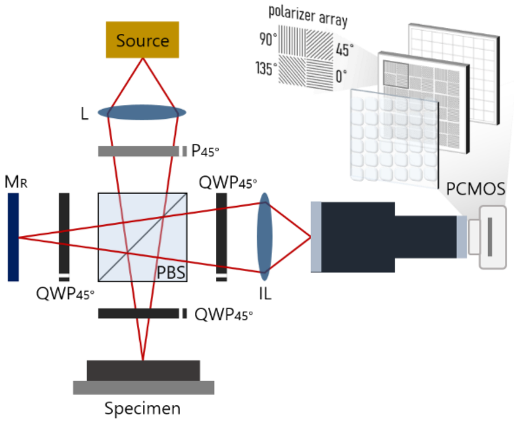


**Figure 1.** Optical configuration of modified SRI; L, lens; $P_{45°}$, 45° rotated polarizer; PBS, polarizing beam splitter; $QWP_{45°}$, 45° rotated quarter waveplate; $M_R$, reference mirror; IL, imaging lens; IS, imaging spectrometer; PCMOS, polarization pixelated CMOS camera.

The reference beam is reflected off by a reference mirror ($M_R$) while the measurement beam is reflected off by a specimen. Each beam goes through a 45° rotated quarter waveplate twice ($QWP_{45°}$) and is incident to an imaging spectrometer (IS). In front of IS, another QWP$_{45^\circ}$ acts as a role of converting linearly orthogonal polarization states of two beams into circularly orthogonal polarization states. Then, four phase-shifted spectral interferograms can be obtained in a polarization pixelated CMOS camera (PCMOS), which has a 0°, 45°, 90° and 135° rotated polarizer array [7]. The spectral interferograms of the system can be mathematically described as

$$\begin{aligned} I_0 &= s(v)[1+sin\varphi(v)], \\ I_{45} &= s(v)[1+cos\varphi(v)], \\ I_{90} &= s(v)[1-sin\varphi(v)], \\ I_{135} &= s(v)[1-cos\varphi(v)] \end{aligned} \tag{1}$$

where $I_0$, $I_{45}$, $I_{90}$ and $I_{135}$ are the interferograms detected by 4 different pixel sets of PCMOS, respectively. As known from Eq. (1), four interferograms are consecutively π/2 phase-shifted, and $\varphi(v)$ can be extracted simply by four-step phase shifting algorithm [7] as

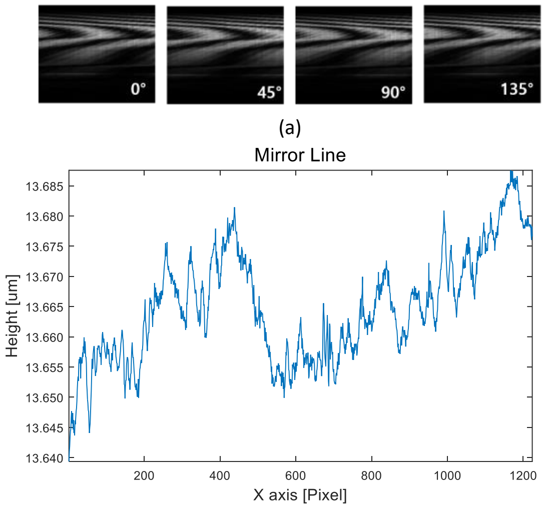
$$\varphi(v) = tan^{-1}\left(\frac{I_0-I_{90}}{I_{45}-I_{135}}\right) \tag{2}$$

Four PCMOS pixels are a single set to provide $\varphi(v)$ at a specific $v$ of a single point. Along the vertical axis (spectral axis) of the obtained image of PCMOS as shown in Fig. 2(a), $\varphi(v)$ is calculated by Eq. (2), and the optical path difference (OPD) between the refrence and the measurement paths, the distance is calculated as a linear slope of $\varphi(v)$. Then, the same analysis is repeated along the horizontal axis (spatial axis) to obtain the heights corresponding to the line of the specimen. Based on spatial phase shifting technique, the proposed SRI does not have the measuring range limitation because $L_{\min}$ does not exist, and the direction can be definitely determined. Therefore, the measuring range of the porposed SRI becomes longer than twice of the measurable range of typical SRI.

## 3. Experimental result

To confirm the extended measuring range of the proposed SRI, a plane mirror was used as a target and moved by a motorized stage with 1 μm step size. As a light source, a laser driven plasma light was used, and a 1x telecentric imaging lens was used to image the measurement line. The available spectral range was from 550 nm to 700 nm, and a commercial imaging spectrometer with 2.8 nm spectral resolution was used to obtain the two-dimensional spectral-spatial interferogram. A commercial PCMOS was used to obtain four phase-shifted spectral interferograms. Figure 2(a) shows an example of four phase shifted spectral interferograms near the OPD is around 13 μm and Fig. 2(b) presents the calculated heights of the measured line. Figure 3 shows the distance measurement results of the proposed SRI according to the stage movements. At each stage position, the line profile was calculated, and their mean value was used as a representative position value of the stage. For the comparison, the measurement results by Fourier method in typical SRI were also presented. As shown in Fig. 3, the measurement results by Fourier method has dead zone of approximately 4 μm, and the direction was not distinguished. Opposed to the typical SRI, the measurement results of the proposed SRI clearly shows the linear relationship with the position of the moving stage, and there is no dead zone. As the result, the proposed SRI can measure the distance in the range of 104 μm compared to the measuring range of 50 μm in the typical SRI based on Fourier method.

One of the benefits of the proposed SRI is to measure a line profile of the specimen at once without any mechanical or electrical moving parts although a lateral scanning stage is necessary to obtain the 3D surface profile of a specimen. However, the spatial phase shifting by the PCMOS should be rigorously calibrated to ensure the accurate phase calculation by Eq. (2). In this investigation, it was confirmed that each polarization axis of the polarizer array in the PCMOS was calibrated with the extreal polarization reference.



(a)

(b)

**Figure 2.** (a) Four phase shifted images and (b) the calculated line profile of a plane mirror.

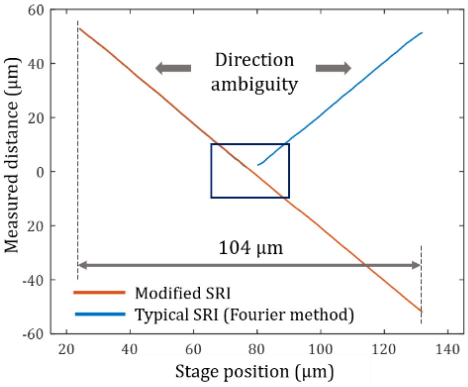


**Figure 3.** Measurement result of measurable range extension.

## 4. Conclusion

We proposed and experimentally verified a modified spectrally-resolved interferometer (SRPI) to use a polarization pixelated CMOS camera to extend the measuring range of the typical SRI based on Fourier methods. A line profile of a specimen can be obtained with a single operation without any mechanical or electric moving parts, and there is no dead zone caused by the minimum measurable range. In the experimental result, the measuring range was longer than twice that of the typical SRI, and direction ambiguity was avoidable.

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