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# Optical inspection of solar cells using phase-sensitive optical coherence tomography

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ABSTRACT

The inspection and measurement of solar cells has become an important technique in evaluating the efficiency and quality of solar cell devices. Currently, surface defect detection of solar cells can be achieved by several approaches such as machine vision, photoluminescence, and electroluminescence imaging techniques. Nevertheless, it is still difficult to inspect the inner structures of solar cells. In response to this need, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) have become common techniques for investigating the nanostructures of solar cells. However, both carry the disadvantages of destructive imaging, high cost, and a small inspection area. Moreover, it is difficult to simultaneously estimate multiple optical properties with the aforementioned techniques.

In this study, we propose the use of phase-sensitive optical coherence tomography (PS-OCT) for the inspection of solar cells. We develop a two-reference-arm configuration to reduce the phase noise that intrinsically accompanies the OCT system. Based on the proposed approach to extract the amplitude and phase terms from OCT interference signals, the 3D microstructure of solar cells can be obtained while simultaneously probing the nanostructures on arbitrary planes of the solar cell. The OCT microstructural results show that the structures of different layers can be nondestructively visualized and quantitatively evaluated. From the phase signal, the inverted pyramid structure, which is commonly used for the reduction of interface reflection, can be visualized. Moreover, based on the two-reference-arm configuration, the optical reflection coefficient (ORC) can be estimated in order to evaluate the interface reflection from the surface of solar cell. Results show that PS-OCT can be a valuable tool for providing nondestructive inspection of the micro/nanostructures of solar cells.



## 1. Introduction

Solar power has become an attractive source of electrical energy. A solar cell can directly convert sunlight or artificial light into electricity, producing both a current and a voltage to turn out electrical power [1,2]. To effectively convert the photon energy into electrical power, the material from which the solar cell is constructed is a key issue. Although a variety of materials can induce photovoltaic energy conversion, semiconductor materials that implement p–n junctions have become a common solution. In addition to the material used for solar cells, the structure of solar cells also plays an important role in increasing the efficiency of energy conversion. For example, to increase light-trapping efficiency, the inverted-nanopyramid, thin-crystalline, silicon membrane was fabricated on the top surface of a solar cell [3].

Post-fabrication inspection is also a crucial factor in securing high-efficiency solar cells. In order to nondestructively inspect the defects on solar cells, machine vision techniques have been widely used [4]. For example, a 2D superficial image of a sample can be obtained by using a 1D/2D charge-coupled device (CCD) with a stepping motor to provide a lateral scanning. Combined with software algorithms, this allows for defects on solar cells to be automatically recognized. However, the results yielded by this technique are limited by an optical lens used for imaging, and therefore machine vision only can provide a micrometer-scale resolution, which restricts our ability to inspect the nanostructures present in a solar cell. Moreover, only a superficial image of sample can be obtained from the machine vision method and no

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depth-resolved information of the sample can be acquired. Additional information, such as the reflection coefficient and the thickness of the sample, fails to be provided by the machine vision method.

As alternative techniques for inspecting solar cells, photoluminescence (PL) and electroluminescence (EL) imaging have attracted recent attention [5–8]. By utilizing an excitation laser and a CCD camera in the near-infrared range (NIR), defects on the solar cells can be detected due to the weaker PL emission. Additionally, EL imaging, which is achieved by applying a voltage, is similar to the machine vision technique in that no depth-resolved information can be acquired, and the imaging resolution is limited.

Lastly, scanning electron microscopy (SEM) [9,10] and transmission electron microscopy (TEM) [11,12] can be implemented for the measurement of nanostructures. These microscopy techniques yield an ultrahigh resolution. However, the disadvantages of destructive inspection, high cost, and a small inspection area limit the practical implementation of SEM and TEM in production line applications.

To overcome the limitations of the aforementioned techniques, optical coherence tomography (OCT) is proposed in this study for the inspection and measurement of solar cells. OCT, which is based on an interferometer configuration by receiving the backscattered signal from the sample, can reconstruct the depth-resolved microstructures of a sample in a depth range of 3 mm [13,14]. In the last decade, the development of Fourier-domain OCT techniques, including spectral-domain OCT (SD-OCT) [15,16] and swept-source OCT (SS-OCT) [17,18], greatly improved the system sensitivity and the imaging speed. Currently, either SD-OCT or SS-OCT can easily achieve an imaging frame rate of more than 100 frames/s, enabling real-time imaging capabilities for industrial or biomedical applications. In addition to the advantages of depth-resolved and high-speed imaging, micrometer-scale resolutions in the axial and transverse directions easily lend themselves to impressive optical measurement capabilities in the inspection of industrial devices [19,20].

The axial resolution of the OCT system is determined by the center wavelength and the full-width at half-maximum (FWHM) spectrum of the light source. By way of contrast, the transverse resolution is dependent on the objective lens used for sample scanning. Typically, the resolutions in both directions can reach 1–10 μm. However, despite the success of these imaging techniques in certain aspects, the limitation in the OCT resolutions results again in a severe limitation on the inspection of nanostructures.

In order to obtain the nanostructural information of samples, previous studies reported that the surface displacement in the nanometer scale can be detected with OCT by extracting the phase term of the interference signal, a process called phase-sensitive OCT (PS-OCT) [21–26]. From these reports, it has been demonstrated that PS-OCT can provide a subnanometer sensitivity. However, most of the previous studies on PS-OCT were based on the SD-OCT mechanism, due to the high phase stability. Compared with SD-OCT, SS-OCT shows an inferior phase stability as a result of the time jitter of the swept source, in addition to the asynchronization between the laser trigger and the OCT interference signal.

Although phase stability is important when using OCT for the measurement of nanostructures, penetration depth (or imaging depth) is also a key issue to the OCT system, especially for imaging industrial products with a certain amount of opacity. Currently, SD-OCT can achieve superior phase stability and can provide a high displacement sensitivity of 25 pm, which is based on a common-path configuration [23]. However, such an SD-OCT configuration yields a shallower imaging depth, thereby limiting its practical applicability. Furthermore, by extracting the phase term from the interference signal to measure nanostructures, the phase of the OCT signal oscillates $2\pi$ rad at every shift of half a wavelength of optical path difference. This renders measurements of the displacement of sample to be limited to less than half a wavelength [26].

In this study, we propose to use a phase-sensitive SS-OCT system, based on a two-reference-arm configuration, for the optical measurement and inspection of solar cells. To acquire a deeper imaging depth than the SD-OCT provides, a swept source with a center wavelength of 1.3 μm is utilized. To reduce the phase noise in the SS-OCT system, the two-reference-arm configuration is developed by using one of the reference arms as the reference of the phase noise level. Aside from the reduction in phase noise based on this configuration, a parameter to evaluate the surface reflection of the solar sell can also be estimated, which can be used for the measurement of surface reflection and defect inspection.

## 2. System setup and method

### 2.1. System setup

To reduce the phase noise of the SS-OCT system, a two-reference-arm configuration was proposed, as shown in Fig. 1. A Microelectromechanical System (MEMs)-based swept source (HSL-20, Santec Corporation, Japan) with a center wavelength of 1310 nm and a scanning spectrum of 110 nm was implemented in our OCT system. The scan rate of the swept source can achieve a frequency of 100 kHz. The output end of the light source was connected to a Mach–Zehnder interferometer, and the light was split into the reference and sample arms. The light backscattered from the sample and the reference arms was simultaneously detected by a balanced detector. At this point, the detected light signal from the balanced detector was digitized by a high-speed digitizer (ATX-9350, AlazarTech, Canada). To reduce the time-dependent phase noise induced by the jitter of the wavelength sweeping (and also from the asynchronization between the laser and the digitizer), reference arm II was used to be the phase reference, and the path difference in free space between the two-reference arms was fixed to be 3 mm. Since the light source can provide a long coherence length of 18 mm, the two-reference arms were still able to separately interfere with the sample arm. Moreover, since the path difference between reference arms I and II was invariable, the intensity and phase noise levels of the interference signal induced by the two-reference arms were almost constant. This crucial fact can be exploited

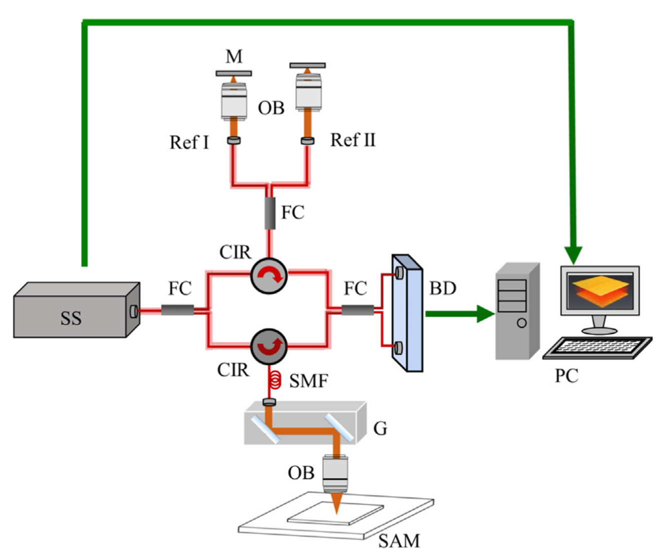


**Fig. 1.** Schematic diagram of a two-reference-arm, phase-sensitive optical coherence tomography (PS-OCT) setup. The path difference in free space between the two-reference arms (I and II) was set to be 3 mm in our experiment. SS: swept-source, FC: fiber coupler, CIR: circulator, Ref I/II: reference arm I/II, SMF: single-mode fiber, M: mirror, OB: objective lens, BD: balanced detector, PC: personal computer.