Using Semiconductor Photodiodes as Detector Element for Solar Radiation Measurements

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ABSTRACT:

An innovative pyrheliometer configuration utilizing optical fiber for solar radiation capture requires a detector element for the optical power measurements. In this sense, three distinct photodiodes—two silicon-based and one indium gallium arsenide (InGaAs)— are evaluated. Specifications of each photodetector are analyzed, including their spectral response, response time, and thermal characteristics, as well as the desired specifications for the application, also compared with a thermopile. The characteristics of semiconductor photodiodes are shown to be more appropriate for the application compared to thermopiles, which are conventionally utilized in radiometric instrumentation. Experimental results compare the three photodiodes against a commercial pyrheliometer, demonstrating that the system's behavior changes substantially depending on the type of photodetector employed. Among the three photodiodes investigated, one of the silicon-made devices exhibits performance most closely aligned with the commercial pyrheliometer, suggesting its potential as an optimal detection element in this novel proposal for radiometric measurements.

Key words: Photodetector, thermopile, photodiode, pyrheliometer, radiometer, solar irradiance, optical fiber, spectral response.

1.- Introduction

The intensity of solar radiation across Earth's surface is subject to several factors, including geographic location, time of day, and weather conditions. Measuring solar irradiance is critical for many applications, particularly in photovoltaic (PV) and concentrating solar power (CSP) plants, as it helps to optimize the efficiency of electricity generation. Solar irradiance can be categorized into three: Direct Normal Irradiance (DNI), originating from a small solid angle centered on the solar disk; Direct Horizontal Irradiance (DHI), corresponding to the scattered beams due to meteorological phenomena; and Global Horizontal Irradiance (GHI), which adds up both [1].

As defined by the International Organization for Standardization (ISO), the pyrheliometer is the most common instrument for the measurement of the DNI, while pyranometers are, in general, used for the measurement of DHI and GHI, although they can also act as a device for measurements of direct irradiance [2]. In both cases, the solar radiation captured needs to be converted into an electrical signal to be processed digitally, allowing to analyze and determine the value of the incident solar radiation. Generally, two options are available for this process: a thermopile in conjunction with a surface that absorbs light and converts it into heat, or a semiconductor photodiode, which transforms incident light into electric current [3].

In this work, four different photodetectors are discussed as detecting elements for solar radiation, presenting results from the use of three photodiodes. In section two, the experimental assembly is showcased. In section three, the application requirements and photodetectors compared are introduced. In section four the results are shared; and in section five the conclusions and future work are presented.

2.- System Description

The proposed optical fiber-based pyrheliometer has been already presented by the authors in [4,5], describing all the details on the configuration and the choice of the optical fibers used for the DNI measurements. Regarding the calibration algorithm, which is also introduced in literature, the aforementioned articles only consider one silicon-based photodiode for the measurements, while in this case 3 photodetectors are compared (two Si-based photodiode and one InGaAs-based photodiode); which means different data used as input for the algorithm (corresponding to each response spectrum of the different photodiodes) and resulting in different values of the correction factor, which will be mentioned later in this article. The photodetectors analyzed in this work are all commercialized by THORLABS. Specifically, these include silicon photodiodes S140C and S150C, representing volumetric and compact types, respectively, and the volumetric InGaAs photodiode is model S144C.

Table 1: Summary of technical specifications considered for the current application for 4 THORLABS photodetectors.

Device	***Sensitivity***	***Response time***
Silicon S140C	*1nW*	*<1*µs
Silicon S150C	*10pW*	*<1*µs
InGaAs S144C	*1nW*	*<1*µs
Thermopile S401C	*1µW*	*1.1s*

(a)

(b)

Figure 1. (a) Mounting of the fibers onto the solar tracker and placed next to a commercial pyrheliometer and (b) photodiodes THORLABS S140C and S144C, optical power monitor THORLABS PM320E and power tracing software.

For the evaluation of the photodetectors, two optical fibers have been mounted next to a commercial KIPP & ZONEN CHP1 pyrheliometer (to validate the DNI measurements). The optical fibers were mounted on the KIPP & ZONEN SOLYS Gear Drive solar tracker to ensure consistent tracking of the sun throughout the day; while the other tips were taken to an indoor laboratory, to prevent the effects of temperature in the measurement, and connected to the different photodetectors, which were linked to the optical power monitor (OPM) THORLABS PM320E. The measured optical power, after processing through the calibration algorithm, provides accurate DNI measurements, aligning closely to conventional pyrheliometer results, allowing to compare the behavior of the different photodetector devices. Fig. 1a displays the fibers and commercial pyrheliometer mounted onto the solar tracker, while Fig. 1b showcases two of the photodiodes along with OPM and computer software.

3.- Application Requirements and Specifications

The photodetector represents a critical component in the proposed optical fiber-based pyrheliometer design, being responsible for transforming captured radiation into electrical energy to generate an optical power measurement. While any photodetector could theoretically fulfil this function, certain desirable parameters in the device specifications are essential to ensure fast, accurate and precise solar radiation measurement.

Sensitivity and response time are critical parameters in performance. Optimal sensitivity, characterized by low power, enhances the detection of minor irradiance variations, while a fast response time is essential for real-time detection. Semiconductor photodiodes outperform thermopiles in both aspects, enabling faster response and higher sensitivity across specific electromagnetic spectrum ranges. In contrast, thermopiles rely on slower heat transfer processes and are characterized by longer response times and diminished sensitivity at certain wavelengths. The third fundamental parameter to consider is the spectral response or responsivity of the photodetector, which determines the device's response across different wavelengths of the electromagnetic spectrum. In our application, it is desirable for this response to cover most of the solar spectrum, ranging from 300 nm to 4000 nm [1], and to remain as flat as possible. In this regard, thermopiles exhibit superior performance. As previously mentioned, thermopiles operate based on heat transfer processes, resulting in a flat response curve. Initial analysis suggests that thermopiles should theoretically be the optimal devices for this application, given their implementation in traditional pyrheliometers. However, constraints imposed by the requirements of the current application preclude this conclusion. Given the technical specifications on the thermopile, and taking into account its low value of sensitivity, the thermopile is discarded as an option to act as photodetector in the proposed radiometer configuration, as it needs to be able to detect small variations in solar radiation captured by small-sized optical fibers. In this sense, the optical power value captured by the 105µm core diameter fiber when measuring 900W/m^2 is around 6µW. Considering that sensitivity in thermopile is 1µW, small changes and low irradiance values will never be tracked by this type of photodetector. The necessity of semiconductor photodiodes for the purpose of this application therefore imposes the implementation of a calibration algorithm to compensate the effects of the limited and irregular photodiode sensitivity, as documented in [4,5].

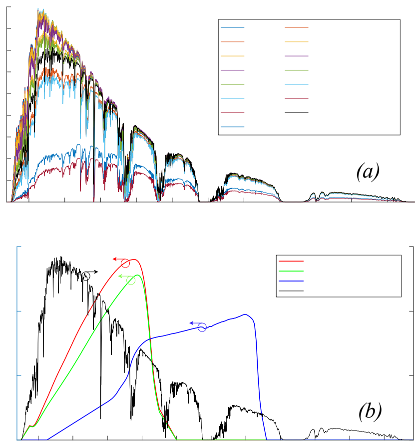


Figure 2. (a) Spectral irradiance evolution measured in Seville, Spain over 28th June 2019, compared against ASTM 1.5 G173-03 Reference Spectra. (b) Spectral response of the semiconductor photodiodes [8] analyzed against the reference solar spectrum [7]. The spectral response of photodiode S150C has been scaled for the purpose of the illustration.

An important consideration is that the solar spectrum is neither constant throughout the day nor across different locations. The angle of solar light incidence on the surface, and the atmospheric path length, which depends on the season, fundamentally alter the solar light spectrum received at sea level. The most substantial spectral modifications occur predominantly during dawn and dusk. Additionally, meteorological phenomena contribute to further spectral variations [6,7]. Fig. 2a illustrates the previously mentioned phenomenon, depicting the evolution of the solar spectrum received in Seville, Spain, over 28th June 2019, compared with the ASTM 1.5 G173-03 Reference Spectra [8]. It is crucial to consider this aspect, as in the case of semiconductor photodiodes, the current generation at the output is intrinsically linked to the device's characteristic spectrum, with varying sensitivity across different wavelengths. These wavelength sensitivities can be predominant depending on the time of day or season.

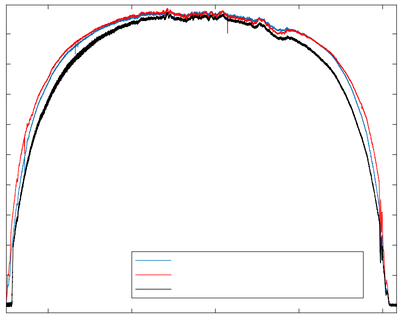
As was mentioned earlier, the main advantages of the semiconductor photodiodes are the extremely low values of the response time, which is lower than 1µs for all of them, and the sensitivity, which is 10pW for the silicon S150C photodiode and 1nW for both volumetric devices. In Table 1, a summary of these parameters is displayed, as well as the specifications of thermopile S401C, where it is clear the great difference between both types of photodetectors when considering these parameters.

In contrast, photodiodes have their main weakness in the spectral irradiance specification, which is limited and changes throughout the entire range, as shown in Fig. 2b. This characteristic complicates irradiance value calculations, introducing the necessity of the calibration algorithm. In the mentioned figure, it can be seen how the InGaAs photodiode exhibits sensitivity in a higher spectral region, resulting in elevated power measurements when wavelength ranges starting from 1100 nm dominate the received power—a condition predominantly occurring during dawn and dusk. Due to the nature of the optical power meter, working with this type of photodiodes requires selecting a calibration wavelength within the detector's operating range. Consequently, the calibration factor used is not unique for each photodiode but varies depending on the selected wavelength. In this case, the chosen calibration wavelengths were 635 nm for the S140C, 1050 nm for the S144C, and 950 nm for the S150C, resulting in calibration factors of 1.3, 2.98, and 2.34, respectively.

4.- Results for DNI measurements

The first results for DNI measurements, presented in Fig. 3a are for measurements during the same day with two different photodiodes (silicon S140C and InGaAs S144C) using fiber FG105LVA, compared against a commercial pyrheliometer, it is clear that the behavior of both photodiodes is similar during the central hours of the day, where the irradiance values after being processed are similar to those from the commercial device, proving great sensitivity and similar response times to the pyrheliometer, keeping relative errors below 5% from 10:30h to 19:00h. This error is due to the tolerance in core diameter manufacturing tolerance, which is around 3%; as well as influenced by the use a model and not real spectral irradiance, and both could be enhanced by a refinement in the calibration.

(a)



(b)

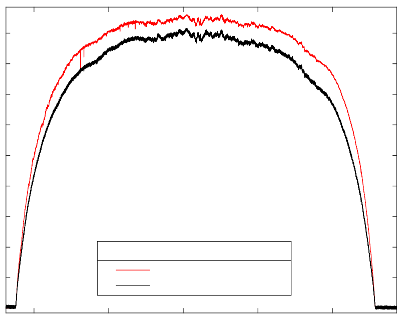


Figure 3. DNI measurement using as optical collector an optical fiber with 105µm core-diameter and: (a) silicon S140C and InGaAs S144C photodiodes and (b) silicon S150C photodiode, in all cases compared against a commercial pyrheliometer.

If the analysis is focused on the greatest divergencies seen on the comparison, they happen mainly at dawn and dusk, where the spectral irradiance suffers most variations against the model used in the calibration algorithm. If examined with further detail, the values from the InGaAs photodiode are higher than the silicon photodiode also at these times, while this did not happen at central hours of day. As shown in Fig. 2b, the responsivity of the InGaAs photodetector covers higher wavelengths in the spectrum, having more influence of these components at sunrise and sunset.

Lastly, Fig. 3b demonstrates that the performance of the S150C photodiode is analogous to previously discussed photodiodes. However, the divergence between the curve generated by this device and the commercial pyrheliometer is more pronounced, although the relative error consistently remains below 10%, which could be due to fiber misalignment, manufacturing tolerance or a divergence between theoretical and real photodiode response curves. This phenomenon is consistently observed across all measurements conducted with this fiber and detector, so it could potentially be mitigated by refining the calibration algorithm. This could be done in several ways, but current work focuses on changing the spectra used as a reference for the calibration factor computing depending on different conditions, such as time of day and season of the year; given its variability depending on those factors, as shown in Fig 2a. Besides, the use of a photodiode that is less sensitive to changes in spectrum could be beneficial, reducing the influence of these changes. In this sense, the InGaAs photodiode S144C has a flatter response, and covers a side of the spectrum with less changes along the day, potentially being the best option.

5.- Conclusions

In this work, various photodetectors were analyzed as solar radiation detectors in a new optical fiber-based pyrheliometer configuration. The study encompassed two stages: an initial phase examining the specifications of different employed devices and assessing their suitability for the intended application, followed by a second phase where the photodetectors were tested in a novel radiometer setup previously demonstrated. Among the options considered, semiconductor photodiodes exhibited superior performance leveraging their sensitivity and response time capabilities while overcoming spectral response curve limitations through the calibration algorithm employed; compared to the thermopile, which was considered an invalid option for this application due to its low sensitivity and response time. Among the evaluated photodiodes, the two volumetric models demonstrated the most promising performance, generating results comparable to those of a conventional pyrheliometer. Although both behave similarly, the silicon photodiode gave more accurate results, whereas the InGaAs photodiode behaved worse at the start and end of the day.

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