On the Development of a Low-Cost Photosynthetically Active Radiation (PAR) Sensor

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***Abstract*—This paper presents the design and development of a low-cost and low-profile sensor suitable for measuring Photosynthetic Active Radiation (PAR), which is defined as the photon flux density in 400 to 700 nm wavelength range. The sensor uses a silicon photodiode along with a bandpass optical filter and a diffuser housed inside a 3D-printed enclosure. A prototype of the sensor was built and tested with a halogen light source. Its performance was compared with research-grade commercially-available PAR sensors and with a spectroradiometer. It was found that the error of the sensor depends on light intensity being the most accurate when the light source was set to maximum intensity. The cost of the developed sensor is lower than commercial solutions, making it attractive for agricultural applications where cost is an important factor.**

I. Introduction

Photosynthetically active radiation (PAR) is defined as the portion of the electromagnetic spectrum that drives photosynthesis in plants [1]. The PAR incident on a plant determines the plant's growth rate, net carbon assimilation and the production rate of photosynthesis end products such as starch and other complex carbohydrates. Modelling and measurement of PAR are essential aspects in fields such as plant biology [2] and climate change [3], optimization of controlled environments such as greenhouses and urban agriculture [4], and energy generation from biomass [5].

It has been shown that only radiation within the 360 to 760 nm wavelength range has the potential to drive photosynthesis [6]. However, radiation of different wavelengths induces unequal amounts of photosynthesis [7]. For this reason, accurate measurements of PAR should follow the relative quantum efficiency curve of plants. This curve, which was developed by McCree [6], assigns different weights to different wavelengths in the 360 to 760 nm range. A sensor that measures PAR according to this curve, is said to measure the yield photon flux (YPF). A far more common approach for measuring PAR restricts the wavelengths of interest to the 400 and 700 nm range (to simplify calculations and measurements because contributions to photosynthesis outside this range are minimal) and assigns equal weight to each wavelength. The rationale for assigning equal weight to each wavelength comes from the Stark-Einstein law, which states that one absorbed photon excites one electron regardless of the photon's energy or wavelength [8]. PAR sensors that weight equally photons in the 400 to 700 nm range are said to measure the photosynthetic photon flux density (PPFD). Both YPF and PPFD sensors are called quantum sensors because they measure photon flux or the number of photons per unit time incident on a surface.

PAR quantum sensors are commercially available from different vendors. The most popular research-grade PPFD PAR sensors are made by LI-COR [9] and Apogee [10]. Although they are well calibrated and very precise, the cost of these sensors is in the \$300 to \$400 range (excluding the corresponding meter needed to display the sensor's output and/or a data logger). The relatively high cost of these sensors preclude their use in applications such as large-area light monitoring in forests or greenhouses, where a distributed network of PAR sensors is desirable. Low-cost PAR sensors would provide a suitable solution for these cases. Low-cost PAR sensors would also appeal to farmers in developing countries and to gardeners who want to make sure their plants are getting an appropriate amount of light. Another limiting factor of off-the-shelf research-grade PAR sensors lies in their size. At around 2.5 cm in diameter and 3.6 cm in height, it is difficult to integrate these sensors with low-profile sensor nodes.

Several efforts in developing custom and low-cost PPFD PAR quantum sensors have been reported in the literature [11]–[19]. Most of these sensors use silicon photodiodes as the photo-sensitive elements due to the good responsivity of silicon in the 400 to 700 nm wavelength range. The use of GaAsP photodiodes and selenium photocells in quantum PAR sensors has also been explored [15,17,19]. In either case, the photo-sensitive element is outfitted with an optical filter stack that blocks light outside the 400 to 700 nm range. An interesting approach reported in [14] uses blue and red light-emitting diodes (LEDs) operating in the photo-galvanic region as wavelength-selective photo-sensors. Although the spectral response of these LEDs does not exactly match the photosynthetic action spectrum of plants, their combined outputs exhibit a good degree of correlation with measurements from research-grade PAR sensors. In all these sensors, the current generated by the photo-sensitive element is converted to a voltage using a trans-impedance amplifier (TIA) built using an opamp and a feedback resistor. Although simple in

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concept, this type of TIA suffers from increased noise from the feedback resistor and limited dynamic range. To increase the dynamic range, a resistor bank or a potentiometer have been used to adjust the trans-impedance gain according to light intensity.

This work presents a low-cost and low-profile PPFD PAR sensor suitable for agricultural applications. The sensor uses a silicon photodiode and a band-pass optical filter with transmittance in the 400 to 700 nm range. The cost of the sensor is around \$110 making it suitable for agricultural applications where cost is an important factor.

The reminder of this paper is organized as follows: section II presents a brief overview of photosynthesis and provides a theoretical framework for quantum PAR sensors. Section III describes the main components of the proposed PAR sensor, section IV presents measurement results.

II. Background

A. Photosynthesis

Photosynthesis is a biochemical process, driven by radiant (light) energy, in which carbohydrates such as glucose are synthesized from carbon dioxide and water. Through the photosynthesis process, every year, plants and bacteria convert approximately 6×10^{10} tonnes of carbon into organic products, which these organisms use to sustain themselves as well as organisms that feed on them [20]. In plants, photosynthesis occurs primarily in leaves in organelles called chloroplasts. Chloroplasts contain light-absorbing pigments, such as chlorophyll, which transfer the energy from absorbed photons to a cascade of biochemical reactions that result in the formation of glucose and the release of oxygen (see Fig. 1). Glucose molecules are then combined with each other to form more complex carbohydrates such as starch and cellulose.

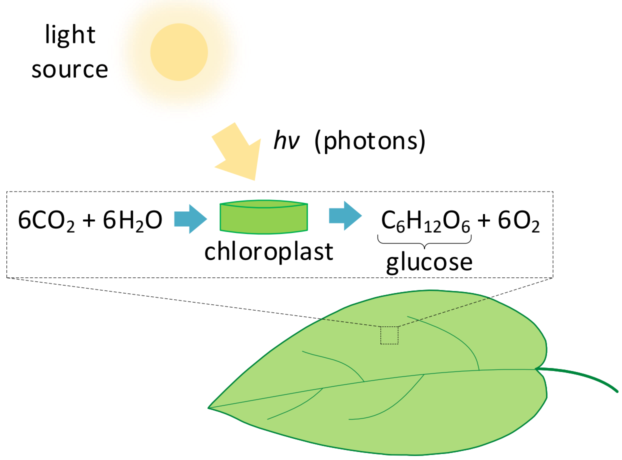

Fig. 1: Simplified diagram depicting the photosynthesis process in plants.

B. Measuring PAR

This work focuses on quantifying PPFD PAR. PPFD is defined as the photon flux density (ϕ) or the number of photons in the 400 to 700 nm wavelength range crossing an area per unit time divided by the area of incidence [21]. PPFD is measured in units of micro-moles of photons per square meter per second (μmol m^{-2} s^{-1}). One mole of photons is defined as $N_A = 6.022 \times 10^{23}$ (Avogadro's number) photons.

Plank's law states that the energy, E_{ph}, of a photon of wavelength λ is given by $E_{ph} = h\nu$ where, $\nu = c/\lambda$, h is Plank's constant and c is the speed of light. Let I_λ be the spectral irradiance defined as the radiant flux per unit wavelength and unit area and measured in units of W m^2 nm^{-1}. It follows that $I_\lambda \cdot d\lambda$ is the irradiance (or the radiation power per unit area) in an infinitesimally small $d\lambda$ wavelength range. Therefore, the photon flux density in the 400 to 700 nm range is:

$$\phi = \int_{400}^{700} \frac{I_\lambda(\lambda)\ d\lambda}{E_{ph}} \tag{1}$$

The PPDF can then be calculated as follows:

$$Q_{PAR} = \frac{\phi}{N_A} = \frac{1}{hcN_A} \int_{400}^{700} \lambda\ I_\lambda(\lambda)\ d\lambda \tag{2}$$

As shown in equation (2), the PPDF PAR can be directly calculated from measured spectral irradiance. Measuring the spectral irradiance, however, requires a calibrated spectroradiometer. Spectroradiometers are complex and costly optical instruments. Hence, their use in PAR measurement is restricted to high-end scientific applications. For most other applications, more practical and cost-effective (albeit less accurate) solutions are preferable. One such solution is to use a single broadband photodiode together with an optical filter with transmission in the 400 to 700 nm range. For mono-chromatic light, the photo-current, I_{ph}, of a photodiode is the product of its responsivity, R_λ, and the optical power incident on the photodiode. For broadband light (within the PAR wavelength range) the photo-current is given by:

$$I_{ph} = A_{pd} \int_{400}^{700} R_\lambda(\lambda) \cdot I_\lambda(\lambda)\ d\lambda \tag{3}$$

where, A_{pd} is the area of the photodiode.The external quantum efficiency, η, of a photodiode is related to its responsivity as follows:

$$R_\lambda = \eta\left(\frac{q\lambda}{hc}\right) \tag{4}$$

where q is the electron charge. Replacing (4) into (9) yields:

$$I_{ph} = \frac{qA_{pd}}{hc} \int_{400}^{700} \eta(\lambda) \cdot \lambda \cdot I_\lambda(\lambda)\ d\lambda \tag{5}$$

Assuming that $\eta(\lambda)$ remains fairly constant in the 400 to 700 nm wavelength range, equation (5) can be written as:

$$I_{ph} = \frac{qA_{pd}}{hc}\overline{\eta} \int_{400}^{700} \lambda \cdot I_\lambda(\lambda)\ d\lambda \tag{6}$$

where, $\overline{\eta}$ is the average of the external quantum efficiency in the 400 to 700 nm wavelength range.

Combining (6) and (2) yields the following expression for Q_{PAR}:

$$Q_{PAR} = \frac{I_{ph}}{qA_{pd}\overline{\eta}N_A} \tag{7}$$

Equation (7) shows how to calculate PPDF PAR from photodiode's current I_{ph}. Errors in PAR measurement with the approach outlined above arise from the approximation that the external quantum efficiency of the photodiode remains constant in 400 to 700 nm wavelength range.

III. PAR Sensor Design

A cross-section of the developed quantum PAR sensor is shown in Fig. 2. The main components of the sensor are a photodiode, a passband optical filter with transmission in the 400 to 700 nm, an optical diffuser and a current-to-voltage conversion circuit.

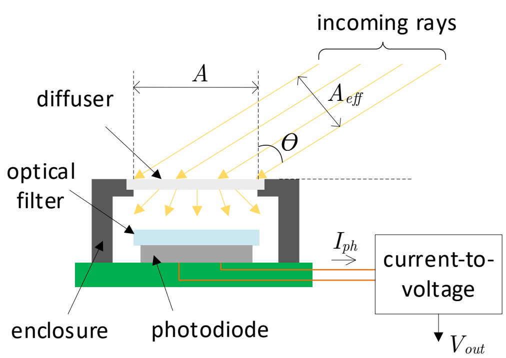

Fig. 2: Cross-section of PAR sensor.

The diffuser is made out of a translucent material of area A that disperses the incoming light rays before they reach the photodiode. When light rays arrive at an angle θ, the effective aperture area seen by the incoming rays is $A\cos(\theta)$, this results in the photon flux arriving at the photodiode to have an angle dependence. To correct for this dependence a cosine corrector (which weighs light from all angles correctly) is needed. A simple way to implement a cosine corrector is to use a light diffuser.

An schematic diagram of the electronic read-out circuit of the PAR sensor is shown in Fig. 3. It consists of a current integrator, a comparator, an analog-to-digital converter (ADC) and a field programmable array (FPGA). The current integrator is made out of an operation amplifier (A_1) and a feedback capacitor (C_F). Switch S_1 resets (discharges) C_F at the beginning of an integration cycle.

After an integration period of t seconds, the output of the integrator becomes:

$$V_{out} = V_{bias} + \frac{I_{ph} \cdot t}{C_F} \tag{8}$$

Hence, I_{ph} can be measured from V_{out} and from I_{ph}, the PPDF PAR can be estimated using equations (7) and (9). The integrator's capacitor C_F is reset when V_{out} crosses the voltage threshold V_{thr}. This action prevents saturation of the

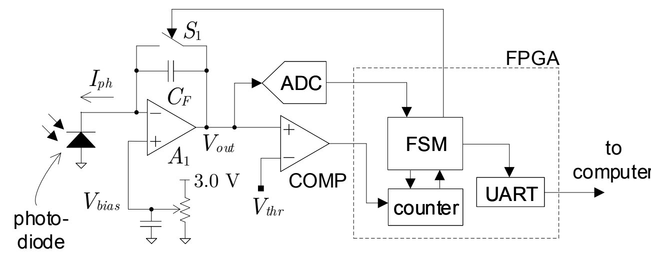

Fig. 3: Schematic diagram of the electronic read-out circuit for the developed quantum PAR sensor.

op-amp's output and allows to extend the dynamic range of the integrator beyond the power supply rail. Fig. 4 shows a time diagram of the integrator's output V_{out}.

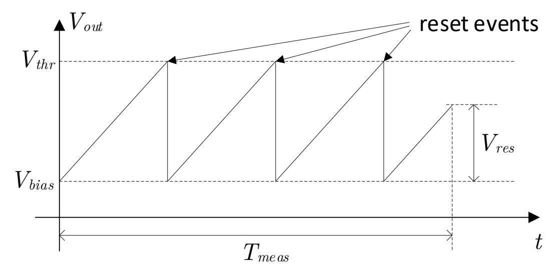

Fig. 4: Integrator's output waveform diagram. The integrator's capacitor is reset when V_{out} crosses the voltage threshold V_{thr}.

In the figure, T_{meas} is the PAR measurement time and V_{res} is the integrator's output voltage at the end of T_{meas}. From (8), I_{ph} can be solved resulting in:

$$I_{ph} = \frac{C_F}{T_{meas}}\Big(n(V_{thr} - V_{bias}) + V_{res}\Big) \tag{9}$$

where n is the number of reset events. V_{res} is measured with the ADC. The FPGA is used to implement a counter to count the reset events, a finite state machine (FSM) to control the sequence of events in one measurement and a universal asynchronous receiver transmitter (UART) to serially transmit the measurement results to a computer for display and conversion to PPDF PAR units.

IV. Results and Measurements

Fig. 5 shows the experimental setup employed to test the developed low-cost PAR sensor. A 150 W halogen illuminator (OSL2 from Thorlabs) provided a stable light source. A spectroradiometer (Black Comet from Stellar Net) was employed to measure the spectral irradiance of the light source. The test setup also includes a commercially-available PAR sensor (LI-190R from LI-COR) to provide reference PAR readings. The proposed PAR sensor uses the BPW34 silicon photodiode as the photo-detector and a UV-IR blocking optical filter (012315099 from Pixelteq) with transmittance greater than 90% in the 395 to 700 nm wavelength range. The photodiode and the optical filter are housed inside a 3D printed enclosure with a circular opening with diameter of 10.40 mm on the top side. This opening is covered with an optical diffuser with a diameter of 10 mm. The sensor's hardware includes a serial port to send the sensor's reading to a computer for display and analysis.

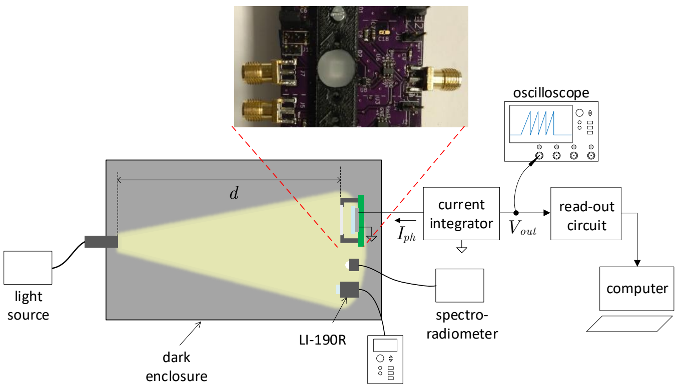

Fig. 5: Experimental setup employed to test the developed low-cost PAR sensor.

Fig. 6 shows the measured spectral irradiance of the light source. Using (2), the PPDF PAR of the light source was calculated to be 9.813 μmoles/m^2/s. The LI-190R sensor estimates the PAR of the light source as 9.81 μmoles/m^2/s.

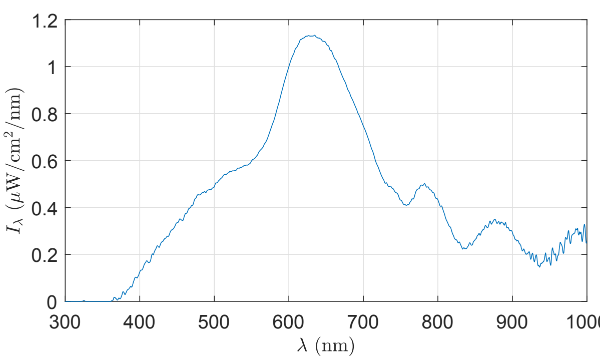

Fig. 6: Meaured spectral irradiance of the light source employed in the experiments.

Fig. 7 shows the measured output waveform of current integrator circuit. Using (9) and the output of the current integrator, I_{ph} is calculated to be 2.07 μA. Replacing this value of I_{ph} in (7) and using $\overline{\eta} = 0.47$ (average quantum efficiency of selected photodiode), yields a PPFD PAR of 9.749 μmoles/m^2/s.

Table I shows PPFD PAR values calculated from measured spectral irradiance using equation (2) along with the PAR readings from the LI-190R quantum sensor and the PAR values calculated from I_{ph} and using equation (7) as the power output of the light source is varied from 25% to 100%. The table also shows the error between the LI-190R and the developed sensor with respect to the PAR calculated from the spectral irradiance. The error of the developed PAR sensor is the lowest for the case of high light intensity. At low light intensities this

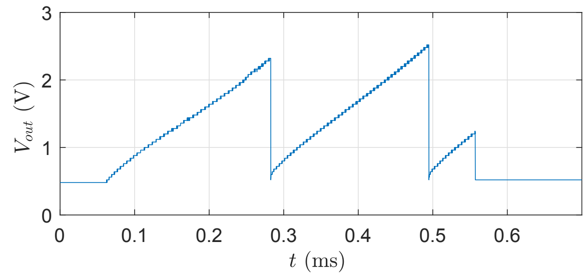

Fig. 7: Output waveform of current integrator as captured by an oscilloscope.

error increases considerably suggesting that this sensor is most suitable for environments with high irradiance.

TABLE I: Performance assessment of developed sensor. PAR measurements reported in units of μmole/m^2/s

light intensity	PAR from (2)	LI-190R		I_{ph}	developed sensor	
		PAR	error (%)	(μA)	PAR	error (%)
100%	9.813	9.81	0.00	2.07	9.749	-0.7
75%	9.307	9.24	-0.7	1.91	8.995	-3.4
50%	7.329	7.52	2.60	1.64	7.724	5.40
25%	1.701	2.17	27.6	0.65	3.061	80.0

Table II lists the cost of the different part of the developed PAR sensor. The total part cost is $111.83. This cost compares favourably with the cost of research-grade commercially-available PAR sensors such as the LI-190R, which costs around $360 (not including the meter needed to display the sensor's output which costs $695).

TABLE II: Cost of the developed PAR sensor

Items	Cost
photodiode	$1.01
optical filter	$61.74
3D-printed enclosure	$6.00
diffuser film	$6.49
electronic components	$26.48
printed circuit board	$10.11
Total cost	$111.83

V. Conclusion

This paper presented a low-cost sensor suitable for measuring the photosynthetic photon flux density (PPFD PAR). This type of sensor can be used in agricultural applications to monitor if plants are receiving enough light to drive photosynthesis. The sensor uses a silicon photodiode along with an optical filter and a diffuser housed inside a 3D-printed enclosure. The sensor was used to measure the PPFD PAR of a halogen light source. Its performance was compared with a commercially-available PAR sensor (LI-190R) and with a spectroradiometer. It was found that the error of the sensor depends on light intensity being the most accurate when the light source was set to maximum intensity.

Acknowledgment

The authors would like to thank Universidad Nacional de San Agustin, Peru for sponsoring this work.

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