FRESNEL LENS CHARACTERIZATION – CALIBRATION AND AUTOMATION

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

ABSTRACT

Fresnel Lens Characterization – Calibration and Automation

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Lens-based solar concentrators have been widely used to reduce the photovoltaic(PV) receiver area and increase the solar irradiance on the PV receiver. In our previous work an indoor Lens Characterization Unit (LCU) was developed to measure the focal length and irradiance patterns resulting from refracted lasers at the focal plane of large scale Fresnel lenses with unknown optical qualities. A new feature of a wirelessly controlled laser position x-y-scanner has been added to the system to improve the system automation. Spot size and the M^2 factor of the power tunable laser source have been analyzed using Gaussian beam characterization for calibration of irradiance profile on the diffuser. An outdoor lens characterization solution based on the use of a photodiode based pyranometer and a two-axis focal area scanner has been developed to measure the normalized solar irradiance distribution of the focal area. Measurements performed on large scale Fresnel lenses in outdoor conditions demonstrated advantages in feasibility and accuracy comparing with the indoor solution.

CHAPTER I

INTRODUCTION

Due to the inexpensive and lightweight nature of Fresnel lenses, they are key components in many solar energy concentration systems [5]. The motivation for this paper is to develop an inexpensive and fast methodology with high accuracy for characterizing any size or type of lenses. Our recent paper [3] showed an indoor method of measuring the focal length and intensity patterns resulting from refracted lasers at the focal plane of large scale Fresnel lenses with unknown optical qualities. The principle concept behind this indoor method is to direct a collimated laser beam orthogonal to the lens and then capture the resulting intensity pattern falling on the diffuser with a CCD camera. Here, this paper describes two major improvements on this indoor method. The first one is that a new feature of a wirelessly controlled laser position x-y-scanner has been added to the system. The second one is that the fixed power laser was replaced with a power tunable laser source. Spot size and the M^2 factor of this laser source have been analyzed using Gaussian beam characterization method.

The optical performance of a photovoltaic concentrator is dependent on the efficiency of its transmittance [4] and the normalized irradiance spatial distribution of the focal area. The efficiency of transmittance is defined as the ratio of the power collected out of the concentrator, $P_{out}(W)$, to the power arriving at the aperture of the concentrator, $P_{in}(W)$ [4]. Input power $P_{in}(W)$ can be controlled by the power tunable laser source in indoor conditions. And the efficiency of a targeted area of the focal area, η_{target}, which is defined as the ratio of the targeted area irradiance to the focal area total irradiance can be calculated from the normalized irradiance spatial distribution. An outdoor lens characterization system dedicated to the normalized irradiance spatial distribution characterization of Fresnel lenses has been developed.

CHAPTER II

METHODOLOGY

Outdoor lens characterization based on the use of a photodiode based pyranometer

Our new design of an outdoor lens characterization system shown in figure II.2 has 4 major components: a photodiode based pyranometer, a Fresnel lens, a solar tracking system and a two-axis focal area scanner. The schematic of the photodiode based pyranometer is shown in figure II.1 which is mounted on the two-axis scanner. This system is capable of scanning a area of 30 by 17 cm on the focal plane and measuring the irradiance at a matrix of positions. The position matrix has 300 rows and 170 columns. The distance between adjacent points in the same row or column is 1mm. The photodiode used in the circuit is SFH206K [6] which has spectral range of sensitivity

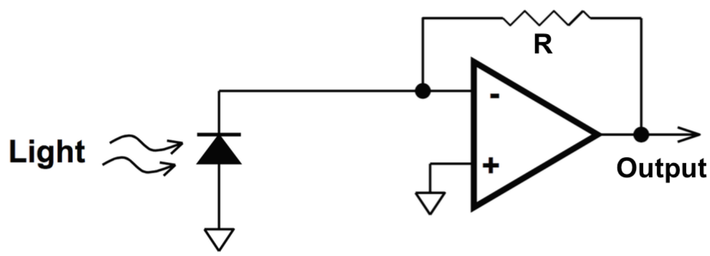

Fig. II.1.: Photodiode based pyranometer

from 400 nm to 1100 nm and half angle of $\pm 60^\circ$. The details of this photodiode specifications are shown in figure II.3. The plot of relative spectral sensitivity is shown in figure II.4.

Geometrical characterization and irradiance distribution of the focal area is of major interest for optical concentrators used in CPV systems since an inhomogeneous illumination of the cell may drastically decrease its conversion efficiency [1]. In able to calculate the percentage of intensity falling within a targeted area, a method which sums the intensities of all points at the focal area, the intensities of points at the targeted area, and then divides the targeted area intensity by the total intensity has been developed. The equation is shown in II.1 where η_{target} is defined as the intensity ratio of the targeted area, and I_{ij} is the intensity at point (i, j). The intensity ratio can

Fig. II.2.: Outdoor lens characterization system

be simply obtained by applying the output voltage as intensity at each point, since the intensity is proportional to the output voltage.

$$\eta_{laser} = \frac{\sum_{Point\ (i,j)}^{Points\ at\ Target\ Area} I_{ij}}{\sum_{Point\ (i,j)}^{Points\ Focal\ Area} I_{ij}} \tag{II.1}$$

Gaussian shaped beam characterization of power tunable laser source

In our previous design, the indoor lens characterization system [3] used a fixed power laser source. Here the laser has been replaced with a power tunable laser of which the output intensity can be

Parameter Bezeichnung	Symbol Symbol	Values Werte	Unit Einheit
Spectral sensitivity Fotoempfindlichkeit (V_R = 5 V, standard light A, T = 2856 K)	S	80 (≥ 50)	nA/lx
Wavelength of max. sensitivity Wellenlänge der max. Fotoempfindlichkeit	$\lambda_{S\,max}$	850	nm
Spectral range of sensitivity Spektraler Bereich der Fotoempfindlichkeit	$\lambda_{10\%}$	400 ... 1100	nm
Radiant sensitive area Bestrahlungsempfindliche Fläche	A	7.02	mm^2
Dimensions of radiant sensitive area Abmessung der bestrahlungsempfindlichen Fläche	L x W	2.65 x 2.65	mm x mm
Half angle Halbwinkel	φ	± 60	°
Dark current Dunkelstrom (V_R = 10 V)	I_R	2 (≤ 30)	nA
Spectral sensitivity of the chip Spektrale Fotoempfindlichkeit des Chips (λ = 850 nm)	$S_{\lambda\,typ}$	0.62	A / W
Quantum yield of the chip Quantenausbeute des Chips (λ = 850 nm)	η	0.90	Electrons /Photon

Fig. II.3.: Photodiode specifications [6]

controlled by an input Pulse Width Modulation (PWM) signal. This laser source is mounted on an aluminum frame with a threaded rod through its center connected to a second smaller vertical aluminum frame with its own threaded rod through a small aluminum plate. Two small stepper motors are used to move the laser along both the x and y axes. Stepper motors are controlled using an Arduino Uno microcontroller, and two motor control drivers. The laser optical path is on the z-axis which is orthogonal to the XY plane.

A solar power meter SM206 was used to measure the intensity of a laser at a fixed distance. In able to verify the correlation between the input PWM signal and the laser intensity, we varied the duty cycle of the given PWM signal from 0 percent to 100 percent using an Arduino Uno

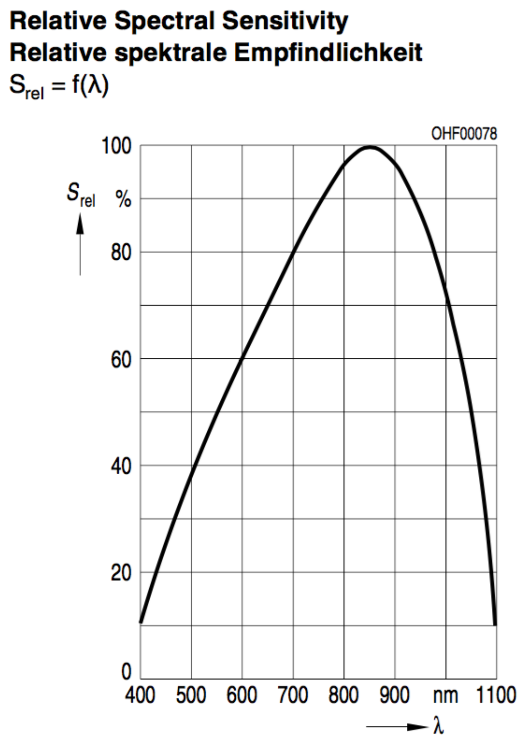

Fig. II.4.: Photodiode relative spectral sensitivity [6]

microcontroller, and we read the intensity on the solar meter in W/m^2. The setup diagram is shown in figure II.5.

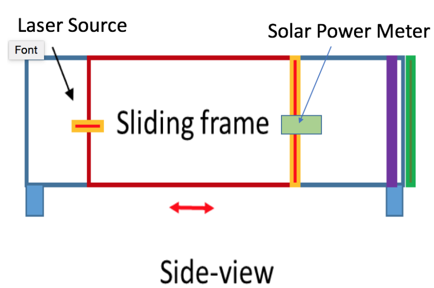

Fig. II.5.: Laser intensity measurement

Of the various laser beam mode types, a fundamental Gaussian mode is mostly used because of its superiority in power, directionality, and coherence [8]. When a laser beam is used as the optical source, it is important to know the spot size of the beam as a fundamental parameter. A beam profiler THORLABS BP209 Dual Scanning Slit Beam Profiler is used here to accurately measure the spot size and the Rayleigh range of the Gaussian beam. The experiment setup is shown in figure II.6.

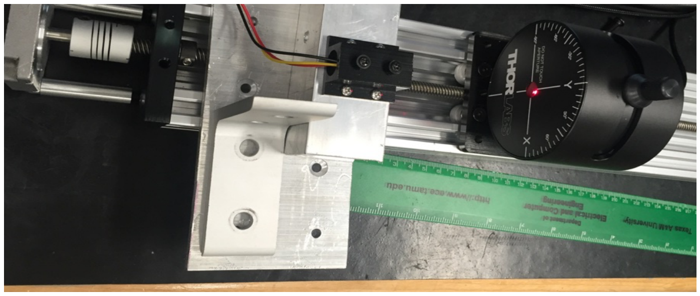

Fig. II.6.: Gaussian beam characterization

Another fundamental parameter that measures the quality of the laser beam is the M^2 factor which is the deviation of its profile from the Gaussian form. It is defined as the ratio of the waist-diameter-divergence product [7], where waist diameter is $2W_m$, and angular divergence is $2\theta_m$.

$$M^2 = (\frac{2W_m \cdot 2\theta_m}{4\lambda/\pi}) \tag{II.2}$$

The M^2 factor is determined by making use of the beam profiler to measure the beam spot size at various locations along the axis of the beam [7]. First, the beam center is located by finding the plane using the beam profiler at which the spot size is minimized. The waist radius is then measured. The axial distance from the beam center to the plane at which the beam diameter increases by a factor of $\sqrt{2}$ provides the Raleigh range z_0 [7]. The angular divergence $2\theta_m$ calculated by equation II.3, and the M^2 factor is computed by means of II.2.

$$\theta_m = \sqrt{\lambda/\pi z_m} \tag{II.3}$$

Remote laser scanner control

Remote controlling laser scanner is a very useful feature that helps the indoor lens characterization system to decrease the calibration and testing time. The system for controlling motors remotely via WiFi consists of an Arduino Uno with 2 DRV8824 Stepper Motor Drivers and a Raspberry Pi 1 Model B+ with a WiFi adapter. The Arduino Uno is connected and communicated with the

Raspberry Pi via a USB cable. The Raspberry Pi creates a DHCP enabled Ad-hoc network, so the user can run programs on it via SSH.

There are three steps to create an Ad-hoc network. The first step is to install and configure DHCP server on Raspberry Pi. The second step is to change the wlan0 mode to ad-hoc. The last step is to setup IP address, SSID, network key and netmask [2]. After creating an Ad-hoc network, an isc-dhcp-server needs to be installed on the Linux system. Thus, users will see the Ad-hoc SSID in their WiFi list. The program running on Raspberry Pi sends commands of direction and distance via a serial port to Arduino Uno which controls the laser x-y-scanner.

CHAPTER III

RESULTS

Normalized irradiance distribution of the focal area

The methodology of normalized irradiance distribution measurement of the focal area was applied to characterize a 30 by 50 inches Fresnel lens with the focal length of 32 inches in outdoor conditions. The lens was facing directly to the Sun. The photodiode based pyranometer scanned a area of 30 by 17 cm on the focal plane and measured irradiance at 300 by 170 points. Figure III.1 shows the normalized irradiance spatial distribution in the focal area. The irradiance shown in the Z direction of the plot has been normalized to the range between 0 and 1. The area where the normalized irradiance is greater than 0.4 is considered as the focal area of the Fresnel lens. The focal area here is 127 cm^2. It can be seen that the light intensity in the focal area has a Gaussian-like distribution.

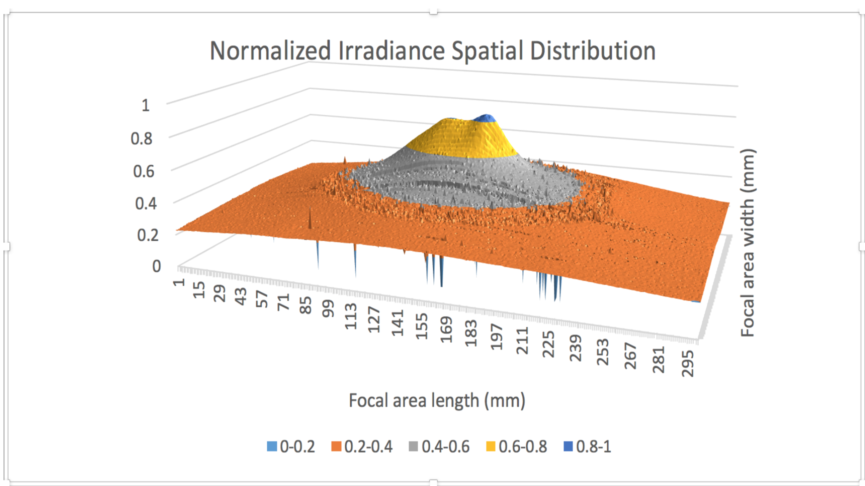

Fig. III.1.: Normalized irradiance spatial distribution of the focal area

The center of intensity is calculated by applying the method of calculating the center of mass in physics. Equation III.1 shows the row and column number of the center of intensity. Square target area centered at the center of intensity is applied to calculate the targeted area efficiency using equation II.1. Table III.1 shows the efficiency of 5 different size of targeted area. In able to receive 50% of the total power in the focal area, a square target area of 57.76 cm^2 is required.

$$X_{center} = 148, \; Y_{center} = 89 \tag{III.1}$$

Table III.1: Targeted area efficiency

Target area width (cm)	7.6	6	4	3	2
Target area efficiency	50.23%	34.01%	16.44%	9.58%	4.37%

Gaussian shaped beam characterization of power tunable laser source

Profile X

The waist diameter $2W_{mx}$ measured by the Dual Scanning Slit Beam Profiler is 192.69 μm. The axial distance from the beam center to the plane at which the beam diameter increases by a factor of $\sqrt{2}$ provides the Raleigh range z_{0x} of 2.5400cm. An estimate of angular divergence $2\theta_{mx}$ is calculated by equation III.2.The M_x^2 factor is computed by equation III.3, which falls into the range of collimated TEM_{00} diode-laser beams 1.1 to 1.7 [7].

$$\theta_{mx} = \sqrt{\lambda/\pi z_{mx}} = 2.8209 \times 10^{-3} rad \tag{III.2}$$

$$M_x^2 = (\frac{2W_{mx} \cdot 2\theta_{mx}}{4\lambda/\pi}) = 1.3446 \tag{III.3}$$

Profile Y

The waist diameter $2W_{my}$ is 224.86 μm, and the Raleigh range z_{0y} is 3.8100cm.

$$\theta_{my} = \sqrt{\lambda/\pi z_{my}} = 2.3033 \times 10^{-3} rad \tag{III.4}$$

$$M_y^2 = (\frac{2W_{my} \cdot 2\theta_{my}}{4\lambda/\pi}) = 1.2812 \tag{III.5}$$

Verification

As a verification of the characterization, the percentage error of waist radius at $z_x = 10.478cm, z_y = 11.5725cm$ is computed using estimated parameters of the laser beam. The waist radius is calculated by the equation III.6. For profile X, the estimated waist diameter is $817.87\mu m$, and the measured diameter is $808.25\mu m$. The percentage error is 1.175%. For profile Y, the estimated waist diameter is $719.05\mu m$, and the measured diameter is $659.81\mu m$. The percentage error is 8.239%.

$$W(z) = W_0\sqrt{1+(z/z_0)^2} \tag{III.6}$$

In able to determine the correlation between the duty cycle of the PWM signal and the laser intensity, we measured the intensity of the laser source at the distance of 6.875 inches with duty cycles from 0 percent to 100 percent. The result is shown in figure III.2.

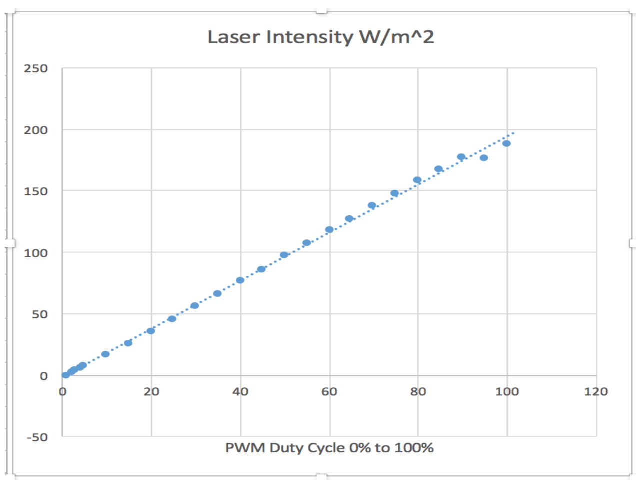

Fig. III.2.: Correlation between the duty cycle and the laser intensity

As is evident from figure III.2, there is a linear correlation between the duty cycle and the laser intensity.

Indoor lens characterization system noise filter calibration

The high pass noise filter threshold for calculating normalized laser intensity on the diffuser using indoor lens characterization system is an important parameter that needs to be calibrated. The first step of calibration consists of measuring the total intensity of images captured under given laser output power conditions, which is controlled by changing laser duty cycle value. The second step is comparing the ratio of total intensity and the ratio of laser duty cycle. It is important to check whether CCD camera pixels are saturated. FigureIII.3 shows that there was no saturation happened in all three color channels during the measurement. The maximum pixel value of 100% duty cycle was 251 out of 255. FigureIII.4 shows total intensity ratios at different threshold conditions. The expected intensity ratio of 50% to 100% laser duty cycle is 0.5. The threshold value is chosen when the intensity ratio reaches the laser duty cycle ratio.

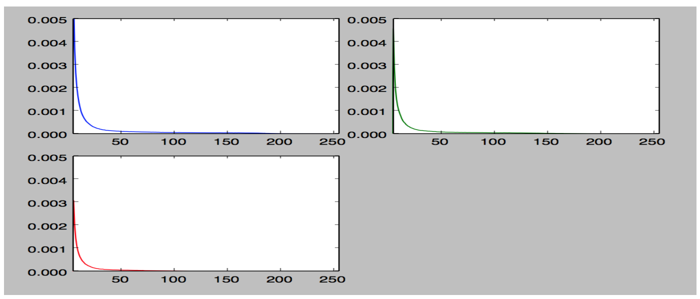

Fig. III.3.: Histograms of pixel value frequency in RGB channels

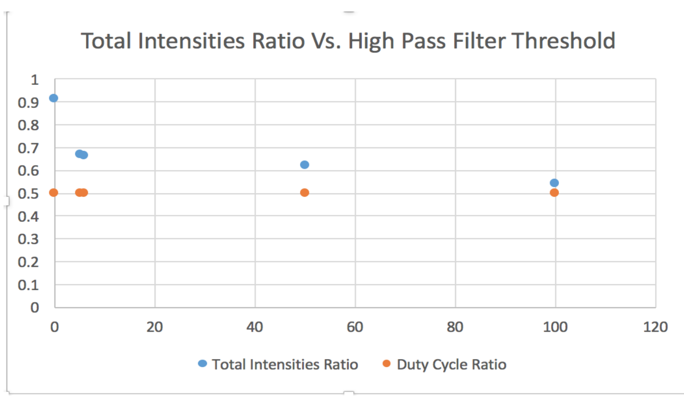

Fig. III.4.: Total Intensities Ratio Vs. High Pass Filter Threshold.

CHAPTER IV

CONCLUSION

As illustrated by the results obtained in this work, the outdoor lens characterization method is considered to be a better choice comparing to the indoor method which requires additional processes of input laser characterization, camera calibration, noise filter calibration and image processing. A major advantage of the outdoor lens characterization method is that it can be applied to various types and sizes of optical concentrators without recalibrating optical source and detector parameters and it provides a fast and accurate way to measure normalized irradiance spatial distribution of the focal area. By knowing characteristics of the optical concentrators, we can design more efficient solar cells. In the future, we plan to test small Fresnel lens arrays and measure absolute power distribution of the focal area.

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