Monochromatic Collimated Light Source For An Indoor Lens Efficiency Tester

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Abstract. One promising way to convert solar energy into electrical energy is the use of point focusing Fresnel lenses in order to concentrate sun light on solar cells. The Fresnel lenses typically consist of a transparent polymer sometimes processed on a supporting substrate like glass. Regarding the system's performance the optical efficiency of the Fresnel lenses directly scales the electrical output. To verify computer predicted concentrator performance, to quantify production deviations from the desired lens design and for quality control we have built an appropriate measurement setup meanwhile in the 5th generation. This Lens Efficiency Tester (LET) evaluates the sample's concentrated light with the help of a scientific charge couple device (CCD). Therefore, the lens is exposed to a monochromatic, collimated, continuous light with sun-like divergence. This light source and some correctional steps are described in this contribution.

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INTRODUCTION

In order to characterize optical components of CPV applications, one consideration is to place the specimen in a reproducible, well defined environment concerning the illumination. This is of the highest importance as it is the inherent requirement of a CPV application. Furthermore, the more the artificial light shall resemble solar radiation, the more complex the setup might become. Three important characteristic aspects of the solar radiation on earth are the spectrum (≈300-2500 nm) [1], the irradiance (≈900 W/m^2) [1] and the angular divergence of ±4.65 mrad [2].

A look into literature reveals several approaches of the realization of light sources for measuring setups to characterize the optical stage of CPV systems. Researchers at University of Lleida, Spain and PROMES CNRS, France are directly using the sun light as a radiation source to characterize linear and point-focus Fresnel lenses [3]. Antón et al. [4] (UPM, Spain) use the sun as well to study a linear mirror. Other continuous polychromatic approaches are using Xenon lamps as shown in publications by Askins, Domínguez et al. (UPM, Spain) and Sansoni et al. (ARCETRI, Italy) in order to characterize Fresnel lenses [5-7] and in publications by Paretta et al. (University of Ferrara, Italy) to discuss CPC mirrors [8]. Three color LED powered measuring sites are published by Nitz et al. (Fraunhofer ISE, Germany) and Antón et al. (UCM, Spain), both working on Fresnel lenses [9, 10]. Schmid et al. (Fraunhofer ISE, Germany) are using a one color LED to characterize on-axis parabolic mirrors [11] and refractive secondary optical elements [12]. As monochromatic light source, Herrero et al. (UPM, Spain and NREL, USA) built up a scanning instrument with three lasers to characterize Fresnel lenses [13]. Parretta et al. (University of Ferrar, Italy) directs a He-Ne laser at the aperture of a reflective concentrator [8]. Diode Lasers were used in a scanning (Büyükcoşkun et al., Concentrator optics, Germany [14]) and a non-scanning device (Lawin et al., Orafol Fresnel Optics, Germany [15]). The latter publication discusses a very interesting approach of using a Shack-Hartmann wave front sensor. Rumyantsev et al. (Ioffe, Russia) is working on optics characterization as well [16], but the light source used was not mentioned in the publication.

In our case, a lens efficiency tester (LET) was designed to quantify the lens' efficiency as well as picturing an irradiance map behind the CPV optic in test. In previous work, we experienced that production deviations or thermo-mechanical deformations of Fresnel lens shapes and the corresponding optical properties are wavelength independent. This motivates to use a monochromatic light source to obtain high resolution results. These may be analyzed and verified by corresponding detailed thermo-mechanical simulations (using FEM) and ray tracing simulations [17]. The well-known chromatic influences (dispersion and absorption) and the verified thermo-mechanical behavior of the sample may then be used in further computer simulations to extrapolate the monochromatic findings to arbitrary environmental and spectral conditions [18].

MEASUREMENT SETUP

The measurement principle of our former measurement setup (see [9], Fig. 1) has been kept through all subsequent improvements and is revisited in Fig. 1. Fresnel lens arrays (or parabolic mirrors [11]) are exposed to monochromatic homogeneous irradiation, which is generated in a dust-proof enclosure above the Fresnel lens array. A motorized x-y stage enables an automatic positioning of the lens array in order to illuminate each individual lens sample. The concentrated light is recorded with high spatial resolution by a CCD at a distance to the Fresnel lens sample that usually is chosen to be close to the focal length of the specimen. The camera is mounted on a 3D stage to scan the relevant focal zone. All lenses of a lens array may be measured automatically without manual intervention. The maximum size of the Fresnel lens array is 1150x600 mm^2, with lenses of up to 156 mm in diameter. The CCD may be positioned at distances of 25 mm to 170 mm below the Fresnel lens sample which allows computer controlled scanning of the focal volume.

The lens efficiency tester contains a heating unit to adjust the temperature of the Fresnel lens sample to measure the temperature dependent behavior of the sample [17]. Lens temperatures up to 60°C are feasible during measurement.

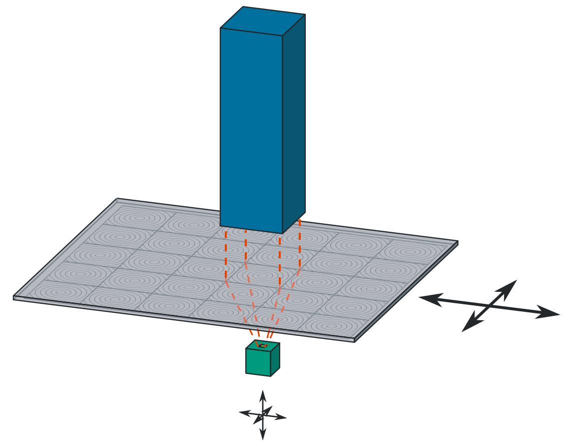

FIGURE 1. Schematic picture of the lens efficiency tester (LET) at Fraunhofer ISE. The light source (blue) is located above the concentrator optics (Frensel lens array, gray) in test. The concentrated light is recorded by the CCD sensor (green). Automated mechanical degrees of freedom are indicated by arrows.

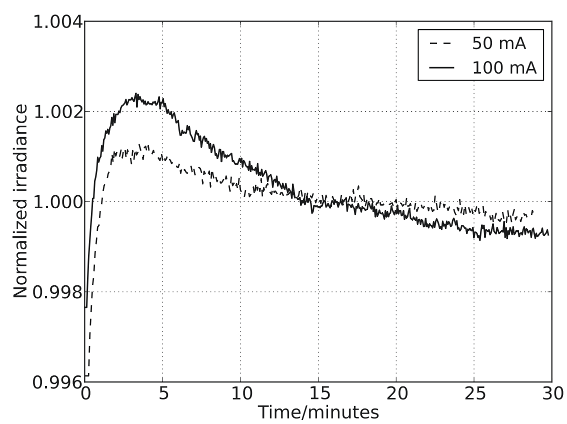

FIGURE 2. The light source intensity (irradiance at sample plane) shows short term and long term characteristic after turn-on procedure at LED current 50 mA and 100 mA respectively. The light source intensity is typically recorded during or a few seconds before each measurement sequence.

LED LIGHT SOURCE

Several high power LEDs of luminous efficacy of about 100 lm/W are combined as a monochromatic light source. Due to the temperature dependent wavelength and intensity of the emitted light [19] care should be taken to design a well dimensioned heat sink for proper cooling, both for the LEDs and the electrical power supply unit. In this context, the aforementioned CCD was used to quantify the long term intensity drift in diverse operating modes to approximately (0.011±0.002) %/min (e.g. after switch-on procedure at LED current 50 mA and 100 mA respectively, Fig. 2).

We determined the spectral peak at 622 nm (FWHM ≈ 14 nm) at room temperature with the help of a spectrometer. One has to keep in mind that every chromatic variant aspect (chromatic signature of sample, detector, collimator etc.) in the setup will be affected accordingly. As a consequence, due to the dispersion of all optical materials in the setup, a red LED is more suggested than a blue LED.

ARTIFICIAL SUN-SHAPE AND COLLIMATION OF LIGHT

One key aspect in imitating sun light is to provide a homogeneous direct radiation with a divergence angle of ±4.65 mrad [2]. If the luminosity is sufficient, an integrating sphere with a well-defined diameter of the exit aperture may be used to provide a corresponding result [5, 7]. In our setup we are using a diffusing screen in order to illuminate a well-defined circular aperture with diameter D with sufficient radiation.

A bi-convex aspheric lens with focal length $f \approx 1$ m collimates the light exiting from the circular aperture.

As claimed in [8], a $f\,/\,D \approx 100$ (more precise 107.5) ratio will lead to an appropriate divergence angle. As a consequence, the diameter of our circular aperture measures almost 1 cm because the focal length of the collimating lens is close to $f \approx 1$ m. Unfortunately, due to manufacturing tolerances the actual ratio $f\,/\,D$ = (109.18±0.68) is currently slightly greater than intended.

In our setup, the distance between circular aperture and collimator can be adjusted to ensure the correct collimation of light. To perform this adjustment fast and easily we developed a method which uses the CCD sensor to measure the irradiance distribution generated by the collimated light at two different distances to the collimator (see Fig. 3). The monochromatic CCD sensor gives two gray values (M_1 and M_2) at positions z_1 and z_2 respectively on the optical axis. The distance g between the circular aperture and the collimating lens may then be calculated by

$$g = \left(\frac{1}{f} - \frac{1}{z_2 - b'}\right)^{-1},\ b' = \frac{z_2 - z_1}{1 - \sqrt{M_2 / M_1}}. \quad (1)$$

This equation may be derived from conservation of energy, the geometry of the optical system and the imaging equation. The resulting value g allows to adjust the position of the circular aperture to the focal distance of the collimator lens ($g = f$). At that position the collimator lens correctly collimates the light from the pinhole and the grey values M_1 and M_2 measured at z_1 and z_2 respectively are equal.

The method's accuracy is increased with increasing distance $\Delta z = z_2 - z_1$ and is only valid if the CCD sensor area is small compared to the collimator lens aperture. The distances z must be smaller than a $100\,D_L$ with D_L denoting the collimator lens aperture diameter. One has to keep in mind that the described method is highly sensitive to stray light.

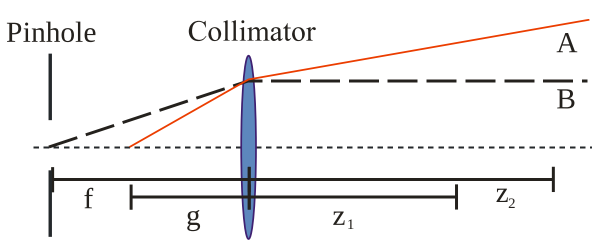

FIGURE 3. The optical paths of a collimated (B) and not collimated (A) light within the LET are shown schematically. If the pinhole's position g is not equal to the lens' focal length f, different light densities at camera positions z_1 and z_2 will result.

HOMOGENEITY OF ILLUMINATION

A second important aspect of the artificial light source is the homogeneity of illumination of the sample area. Fig. 4 shows a grayscale image of the full area illuminated by the light source. It was generated by scanning the whole area with the CCD sensor and has a full resolution of 126 Megapixels. The central part of the collimating lens shows the greatest deviation from the intended shape. This leads to a displeasing inhomogeneity by contrast to the very small variations in all other parts of the illuminated area. Fortunately, the central inhomogeneity only covers a small area of less than 314 mm² and the integrated radiant flux over this area is not affected. The average irradiation on concentric rings (Δr = 1/4 mm) with respect to the present rotational symmetry is changing within 2% peak to valley on the outer parts (10 mm < r < 78 mm, Fig. 5).

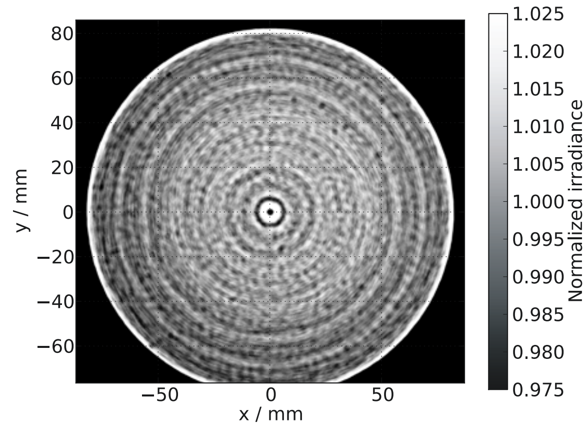

FIGURE 4. Irradiance map of the LET setup in the plane of the Fresnel lens sample holder is shown. This plane is orthogonal to the optical axis of the setup.

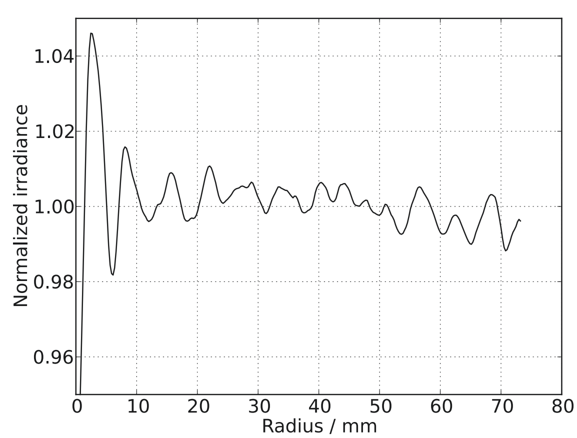

FIGURE 5. The radial irradiance profile calculated from Fig. 4. The values are changing within 2% peak to valley on the outer parts (10 mm < r < 78 mm).

CONCLUSION

We present a light source for the lens efficiency tester (LET) at Fraunhofer ISE. Within this setup non-coherent single color LEDs radiating at 622 nm provide light with long-term stable (less than 0.011 % intensity drift per minute) and reproducible intensity which is homogenized by a diffusing screen. A pinhole with diameter $D \approx 1$ cm and a correspondingly designed aspheric bi-convex lens are used to generate sun-like divergence and homogenous irradiation for a sample diameter up to 156 mm. Except for the central part of the illuminated area $r < 10$ mm the irradiation is highly homogenous with deviations of 2 % peak to valley. An in-situ procedure was developed to check the correct adjustment of the collimating elements.

Tab.1 summarizes the findings in this contribution. It also contains interesting mechanical aspects of the measurement site.

TABLE 1. Light source specifications of the LET setup.

Quality	Quantity
Wavelength	(622±7) nm
Sun-like divergence half angle	(4.58±0.03) mrad
Light intensity drift in %/minute	< 0.011±0.002
Homogeneity of irradiance (peak to valley) on averaged concentric rings with 10 mm < r < 78 mm	2 %
Maximum overall size of lens array	1150x600 mm^2
Maximum sample aperture diameter	156 mm
Sample focal length	25 mm to 170 mm
Maximum lens sample temperature	60°C

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