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Series connected photovoltaic array performance under non-uniform illumination

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ABSTRACT

The performance of a series connected photovoltaic array is limited by the photocell that is illuminated the least. This paper quantifies the effects of single-mode and multi-mode illumination and discusses the design parameters.

Keywords: Photovoltaic array, optical power transfer, fiber illumination

1. INTRODUCTION

The use of optics to replace electrical function in critical systems is growing rapidly. This is due primarily to the fact that optics offers immunity from Electromagnetic Interference (EMI). A significant part of this technology is the optical transfer of power from a primary source into a critical region.

Powering of electrical circuitry, sensors and actuators over optical fiber offers immunity from RF, EMI, voltage breakdown, lightning and high voltage hazards. Optical power transfer is being employed in military systems and in industrial applications such as electric power, communications, remote sensing, and aerospace. Important advances are being made in high voltage generation using Series Connected Photovoltaic Arrays (SCPA) [1]-[2]. Optical power transfer systems developing 1.7 kV have been demonstrated using SCPA as little as 2.5 mm in diameter [3]. SCPA's also offer the advantage of producing high voltages in a volume that is much smaller than what would be required for electronic generation of the same voltage. The reduction in the volume required to generate high voltage results from eliminating the need for a DC-DC converter that consists of several components including a bulky transformer. In addition to energetics applications (initiation of explosives), optically generated high voltages can have applications in areas such as controlling light with light through the electro-optic (Pockel's) effect, micro-displacement using the piezoelectric (or capacitive) effect, and optical and radiation detectors.

The performance of an SCPA is dominated by the least illuminated photocell making the illumination profile a critical parameter. This paper quantifies the effects of single-mode (Gaussian) and multi-mode step-index optical fiber illumination and discusses the design parameters. In a system where a single-mode source is used to illuminate an SCPA consisting of rectangular photocells arranged in a circular fashion the illumination efficiency is a function of the ratio of the Gaussian beam radius ($1/e^2$) and the radius of the SCPA. The optimum beam-to-SCPA radius is $\sqrt{2}$ and at this condition the illumination efficiency is only 36.8%. Multi-mode optical fiber illumination has a speckled intensity pattern and the illumination efficiency is a function of the ratio of the area of the individual photocells within the array and the speckle correlation area. The speckle correlation area is directly related to both the wavelength and propagation distance and inversely related to the fiber core diameter. Also, for a given illumination source there is a limit to the open-circuit voltage that an SCPA can generate at a particular efficiency. Making the SPCA larger or smaller will not increase or decrease the efficiency, respectively.

Single-mode illumination is discussed first and covers the loss mechanisms, system design parameters, and maximum efficiency associated with this type of illumination. Most of what is covered in this section is a review of a previously published paper [4] with the addition of using a single-mode beam to illuminate an SCPA with wedge shaped photocells. Multi-mode optical fiber illumination is covered next where the loss mechanisms, system design parameters, experimental results, and a general equation that approximates the maximum SCPA voltage in terms of the fiber parameters, illumination wavelength, illumination efficiency, and volts per photocell is given.

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2. SINGLE-MODE ILLUMINATION

In this section the illumination of an SCPA with a single-mode source is discussed. There are two loss factors associated with single mode illumination and there is an optimum beam diameter with which to illuminate an SCPA consisting of rectangular photocells arranged in a circular fashion. At the optimum radius the illumination efficiency is at a maximum and a beam radius other than the optimum will result in reduced illumination efficiency. Taking into account the current limiting effect and calculating an effective power the responsivity of the SCPA can be determined also be determined. Under ideal conditions, illuminating an SCPA consisting of wedge shaped photocells will perform as if they were uniformly illuminated. Note that losses due to the illumination efficiency are in addition to the conversion efficiency of the photocells.

2.1 Illumination Efficiency

There are two loss mechanisms to consider when illuminating an SCPA with a single-mode source. The intensity along the circumference of the SCPA determines theshort-circuit current and a beam radius smaller than the SCPA will result in an under filled condition where the photocells along that circumference will be weakly illuminated. If the beam radius is larger than the SCPA the illumination profile is more uniform but now there is a significant amount of light that is incident outside of the SCPA. Figure 1 depicts an overlay of a Gaussian beam profile upon an SCPA consisting of rectangular photocells arranged in a circular fashion.

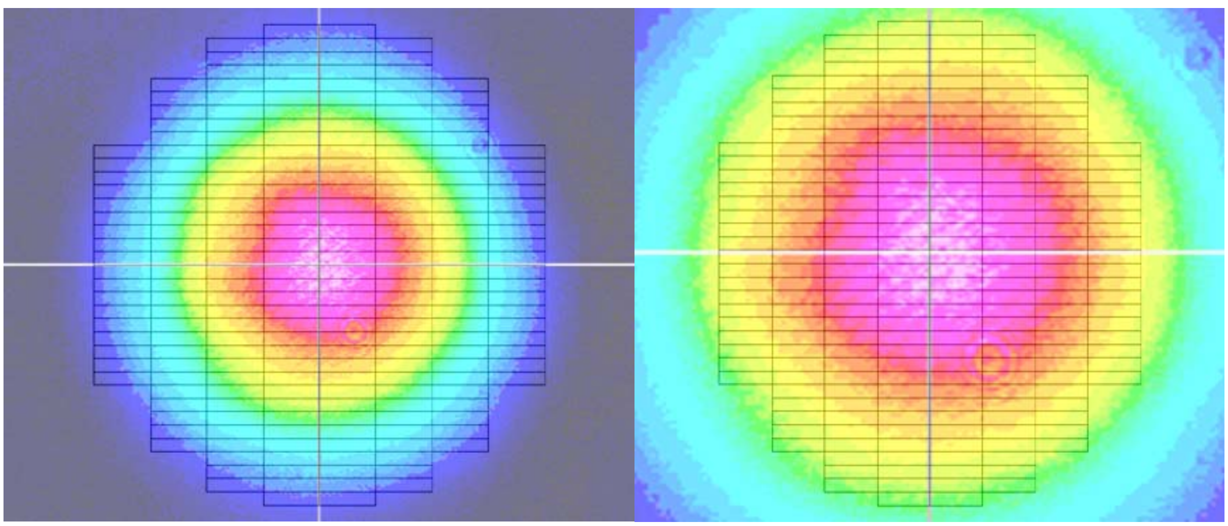


Fig. 1. The image on the left shows an under filled condition where the beam radius is smaller than that of the SCPA. In this condition the photocells along the circumference of the array are weakly illuminated thereby limiting the current. The image on the right shows the over filled condition where the beam radius is larger than that of the SCPA. In this condition the SCPA is more evenly illuminated than in the under filled condition. The primary loss mechanism in this case is due to light being incident outside of the SCPA.

The condition for which the illumination efficiency is at a maximum is given by

$$w_{opt} = \sqrt{2}r \, , \tag{1}$$

where w_{opt} is the $1/e^2$ radius of the beam and r is the radius of the SCPA. Given that intensities above what is incident along the circumference does not contribute to the generation of current the effective optical power is defined as

$$P_{effective} = AI_p(r) = r^2 \frac{2P_{total}}{w^2} e^{-\frac{2r^2}{w^2}} \, , \tag{2}$$

where A is the area of the SCPA, $I_p(r)$ is the intensity at the circumference, and P_{total} is the total beam power. The illumination efficiency is the ratio of the effective power and the total power

$$\eta_I = \frac{P_{effective}}{P_{total}} = r^2 \frac{2}{w^2} e^{-\frac{2r^2}{w^2}} \tag{3}$$

and is at a maximum for the condition $w = w_{opt}$ which gives an illumination efficiency of 36.8%. The results of Eq. (2) can be used in conjunction with measuring the SCPA short-circuit current (I_{SC}) to calculate the responsivity for the array,

$$\mathscr{R}_{array} = \frac{I_{SC}}{P_{effective}} . \tag{4}$$

2.2 Illumination Efficiency for an SCPA with Wedge Shaped Photocells

Illumination efficiency in addition to being dependent on the illumination profile is also dependent on the geometry of the SCPA and the individual photocells within the array. If the SCPA is circular and the photocells are wedge shaped in geometry the illumination efficiency in the case of single-mode illumination is the same as if the illumination profile were uniform (Fig. 2). The reason for this is that the photocells extend radially across the SCPA and therefore the radial variations in the Gaussian intensity profile are averaged through integration,

$$P_{cell} = \int_0^{\frac{2\pi}{N}} \int_0^r \frac{2P_{total}}{\pi w^2} e^{\frac{-2r^2}{w^2}} r dr d\theta = \frac{1}{N} P_{total} \left(1 - e^{\frac{-2r^2}{w^2}} \right). \tag{5}$$

This, of course, assumes that the beam has a perfect Gaussian intensity profile, there are no misalignments between the beam and the SCPA, and all of the light is incident upon the SCPA.

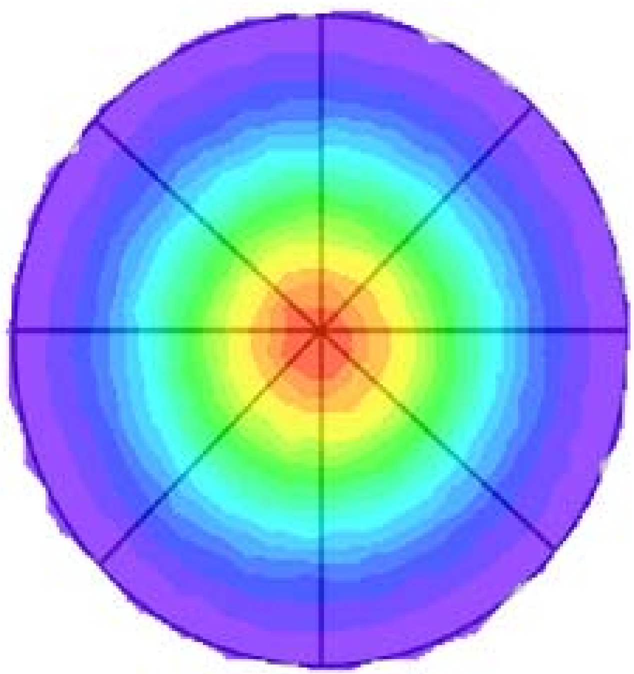


Fig. 2. This image shows a Gaussian profile overlaid upon an SCPA with wedge shaped photocells. Ideally, the illumination efficiency for this configuration would be the same as if the illumination profile were uniform. This again is for an ideal case. A non-ideal beam profile, misalignments, and light being incident outside the array will reduce the efficiency.

3. STEP-INDEX MULTI-MODE OPTICAL FIBER ILLUMINATION

Illuminating an SCPA using a step-index multi-mode optical fiber is discussed in the section. The illumination profile produced under such illumination contains speckle. Speckles are random regions of fluctuation in the intensity profile. If the speckle is large enough it can create a situation where photocells within an SCPA are weakly illuminated and thereby limiting the current (Fig. 3). The illumination efficiency is a function of the ratio of the individual photocell area and the speckle correlation area and rapidly decreases for a ratio of less than 5 and at a ratio of 100 the illumination efficiency is ~92%.

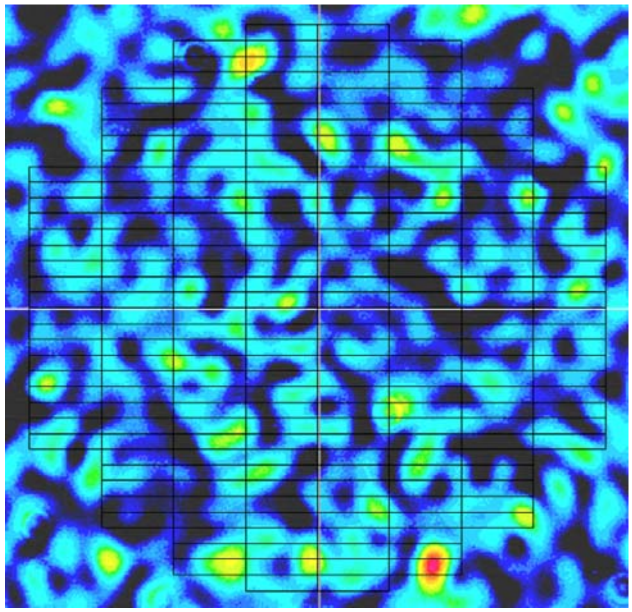


Fig. 3. The illumination profile from a step-index multi-mode fiber is speckled. This image depicts a speckled intensity pattern overlaid upon an SCPA. In this image there are several photocells that are weakly illuminated which would result in current limiting.

3.1 Mean Speckle Correlation Area

The mean speckle correlation area is calculated by evaluating the normalized mutual intensity of the speckled intensity pattern incident upon the array [5]-[7]. The mean speckle correlation area of an intensity pattern propagating from a step-index multi-mode optical fiber is given by

$$A_c = \frac{\lambda^2 z^2}{\pi a^2} \tag{6}$$

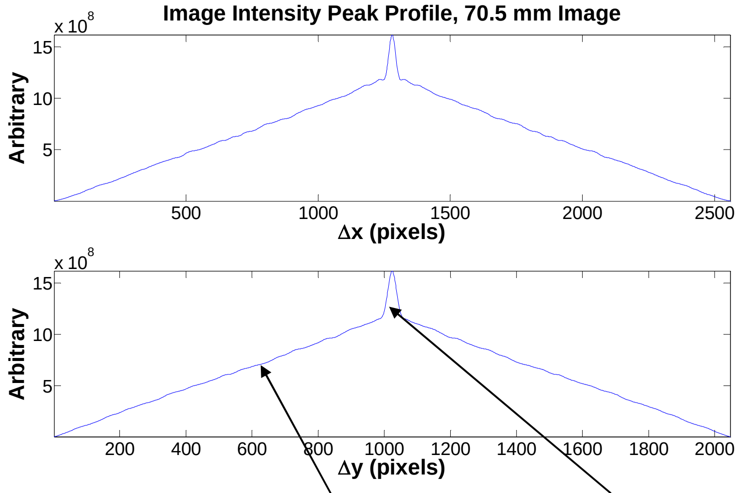
where λ is the wavelength, z is the propagation distance from the fiber, and a is the core diameter of the fiber. Keeping the wavelength and propagation distance to a minimum while maximizing the fiber diameter are critical in reducing the size of the speckle and therefore increasing the illumination efficiency.

Mean speckle correlation area is measured by taking the autocorrelation of the speckled image intensity [5]-[7]. The result of the autocorrelation contains two terms,

$$R_I\left(x_1, y_1; x_2, y_2\right) = \left\langle I\left(x_1, y_1\right)\right\rangle \left\langle I\left(x_2, y_2\right)\right\rangle + \left|J\left(x_1, y_1; x_2, y_2\right)\right|^2, \tag{7}$$

where the first term is the intensity envelope (triangular base) and the second term, J, is the mutual intensity which appears as a “spike” (Fig. 4). The base width of the spike, S_0, is related to the mean speckle correlation area by

$$A_C = \frac{\pi}{3.83^2} S_0^{\ 2} = 0.214 S_0^{\ 2}\,. \tag{8}$$



$$R_I\left(x_1,y_1;x_2,y_2\right)=\left\langle I\left(x_1,y_1\right)\right\rangle\left\langle I\left(x_2,y_2\right)\right\rangle+\left|J\left(x_1,y_1;x_2,y_2\right)\right|^2$$

Figure 4. This figure shows the results from taking the autocorrelation of a speckled intensity pattern using a beam profiling camera. The triangular base represents the intensity envelope and the spike represents the mutual intensity.

3.2 Integrated Speckle

Since a photocell integrates the incident intensity, integrated speckle statistics must be considered before an equation for the illumination efficiency is defined. A quantity that will prove to be of great importance in calculating the illumination efficiency is the contrast of the integrated speckle pattern,

$$C=\frac{\sigma_W}{\overline{W}}, \tag{9}$$

where $\overline{W}$ and σ_W are the mean and the standard deviation of the integrated speckle pattern intensity, respectively. Next, it will be shown that the illumination efficiency is determined by the ratio of the mean speckle correlation area and the photocell area. For this purpose it is convenient to define the parameter M [5]-[7],

$$M=\left[\frac{1}{A_D{}^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}K_D(\Delta x,\Delta y)\left|\mu_A\left(\Delta x,\Delta y\right)\right|^2 d\Delta x d\Delta y\right]^{-1}, \tag{10}$$

where A_D is the photocell area, K_D is the autocorrelation of the photocell aperture, and μ_A is the normalized mutual intensity also known as the complex coherence factor. This parameter can be thought of as the average number of speckles incident upon a photocell. For the case of a non-polarized speckle pattern [Goodman],

$$C=\frac{1}{\sqrt{2M}}. \tag{11}$$

3.3 Illumination Efficiency

The illumination efficiency is determined by the photocell that is illuminated the least,

$$\eta_I=\frac{W_{\min}}{\overline{W}}, \tag{12}$$

and the least illuminated photocell defined as being illuminated at a level one standard deviation below the mean,

$$W_{\min}=\overline{W}-\sigma_W, \tag{13}$$

results in

$$\eta_I = \frac{\overline{W} - \sigma_W}{\overline{W}} = 1 - \frac{\sigma_W}{\overline{W}}. \tag{14}$$

Inserting Eq. (9) into Eq. (14) gives

$$\eta_I = 1 - C = 1 - \frac{1}{\sqrt{2M}}. \tag{15}$$

3.4 Experiment

To verify the theory an experiment was performed where SCPAs that have a radius of 2.2 mm were illuminated with 100 µm and 400 µm core diameter step-index multi-mode optical fibers. Two different types of SCPAs were used. One type consists of 920 cells and the other type has 230 cells. These four different configurations were used to achieve a wider ratio of the photocell area to the mean speckle correlation area. The speckle correlation area is increased by increasing the distance between the fiber and the SCPA. The decreased illumination intensity at greater the distances was compensated for in the experimental calculations. Figure 5 shows the experimental results with the illumination efficiency plotted as a function of the ratio of the photocell area and the speckle correlation area, N_E.

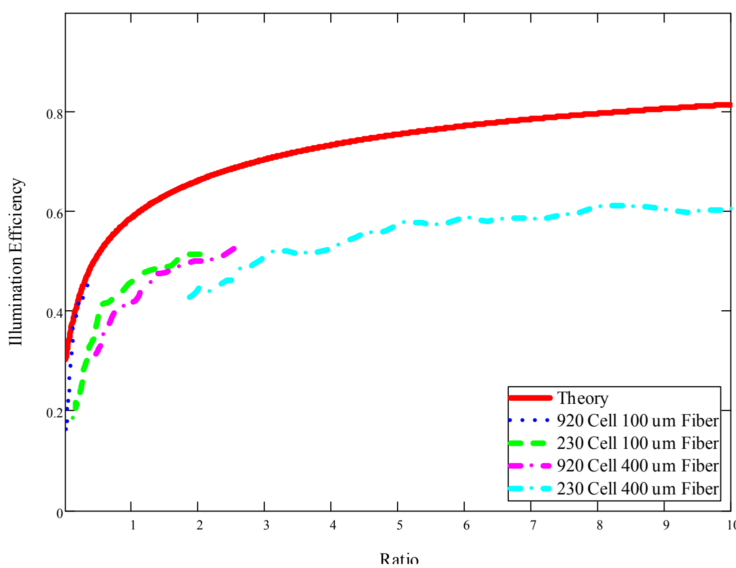


Figure 5. This figure is a plot of the illumination efficiency as a function of the ratio of the photocell area and the mean speckle correlation area.

The trend in the data follows the theory quite well but the measured efficiencies in three of the four configurations are lower than predicted. This occurred in the configurations where the 230 cell SCPA was illuminated with both fiber types and where the 920 cell SCPA was illuminated with the 400 µm core diameter fiber. This can be explained by the way that the illumination efficiency is defined. Recall that in Eqs. (12) and (13) the illumination efficiency is defined as the minimally illuminated photocell in the array being illuminated at a level that is a standard deviation below the mean. Probabilities exist that the minimally illuminated photocell will be illuminated at a level lower than a standard deviation below the mean therefore resulting in lower illumination efficiencies.

The configuration where the 920 cell SCPA is illuminated with a 100 µm core fiber does not follow the trend of the other three configurations. It is believed that reverse bias breakdown of the weakly illuminated photocell(s) is occurring. For this particular configuration we have the smallest ratio of photocell to speckle areas and it is likely that one or more of the photocells area relatively unilluminated. Such a condition would prevent or severely limit current flow through the SCPA and as such that photocell would become reverse biased at amplitude equal to the open-circuit voltage of the

SCPA. The open-circuit voltage for the 920 photocell SCPA is approximately 600 V. It is shown in Fig. 6 that only ~8 V is necessary to reverse bias one of the photocells within the array.

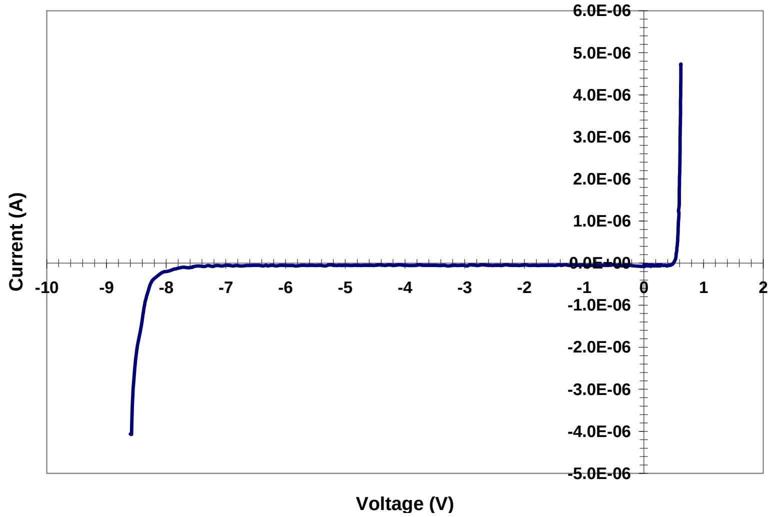


Figure 6. The reverse bias breakdown voltage for a single photocell within the 920 photocell SCPA is ~8 V.

3.5 General SCPA Equation

A general equation that approximates the maximum SCPA voltage can be given in terms of the fiber parameters, illumination wavelength, illumination efficiency, and the volts per photocell (V_{cell}),

$$V_{OC} \approx \frac{V_{cell} A_B}{N_E A_C}, \tag{16}$$

where A_B is the beam area required to fully illuminate the SCPA,

$$A_B = \pi {r_{beam}}^2 \approx \pi z^2 \tan^2\left(\theta_{\max}\right), \tag{17}$$

and θ_{max} is the maximum acceptance angle for the core of the fiber optic. The approximate maximum SCPA voltage for a given illumination efficiency is reduced to

$$V_{OC} \approx \frac{V_{cell}}{N_E} \frac{\pi z^2 \tan^2\left(\theta_{\max}\right)}{\frac{\lambda^2 z^2}{\pi a^2}} \approx \frac{V_{cell}}{N_E} \frac{\pi^2 a^2 \tan^2\left(\theta_{\max}\right)}{\lambda^2}. \tag{18}$$

This generalized equation can also be used to calculate the approximate illumination efficiency for a given SCPA open-circuit voltage

$$N_E \approx \frac{A_D}{A_C} \approx \frac{V_{cell}}{V_{OC}} \frac{\pi^2 a^2 \tan^2\left(\theta_{\max}\right)}{\lambda^2}. \tag{19}$$

The illumination efficiency is found by referring to the illumination efficiency curve at the point N_E. There is no z dependence in Eqs. (18) and (19) which means that making the SCPA area smaller or larger has no effect on the performance. For example, if the area of the SCPA is increased (and therefore the individual photocell areas) the distance from the fiber must also be increased to allow the beam to expand enough to fully illuminate the device. As a result of the increased propagation distance the speckle correlation area has now increased and negated the benefit of increasing the SCPA area. The SCPA voltage and illumination efficiency is only dependent on the source parameters and the volts per photocell.

4. SUMMARY

In summary the criteria for illuminating an SCPA using single-mode and multi-mode step-index optical fiber illumination were given. The loss factors in single-mode illumination are current limiting caused by the weakly illuminated photocells along the circumference of the SCPA and light that is incident outside of the SCPA. For single-mode illumination the illumination efficiency a circular SCPA with rectangular photocells is a function of the beam radius and the radius of the SCPA. The optimum ratio is $\sqrt{2}$ and at this ratio the illumination efficiency is 36.8 %. If an SCPA with wedge shaped photocells is illuminated with a single-mode beam it will, under ideal conditions, it will perform as if it were uniformly illuminated.

Step-index multi-mode optical fiber illumination produces a speckled intensity pattern. If the speckle is large enough a photocell(s) will be weakly illuminated which is the primary loss factor. The illumination efficiency is determined by the ratio of the photocell area and the speckle correlation area. The speckle correlation area is determined by the source properties and the propagation distance. When designing an optical power transfer using an SCPA and step-index multi-mode optical fiber illumination one must keep in mind that there is a fundamental limit to the maximum open-circuit voltage that can be achieved for a given illumination efficiency. The maximum open-circuit voltage (or illumination efficiency) is determined the source and fiber parameters as well as the volts per photocell and is independent of the size of the SCPA.

We would like to mention that there are ways in which to improve the illumination efficiency, beyond what is mentioned here, by incorporating beam shaping methods to more uniformly illuminate the SCPA [8]-[13]

5. AKNOWLEDGEMENTS

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