Energy Collection Efficiency of Low Concentration Holographic Planar Concentrators

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Abstract
In this presentation we evaluate the energy collection efficiency and energy yield of different holographic planar concentrator designs. The holographic planar concentrator replaces expensive photovoltaic cell material with holographic collectors that cost approximately 1% of the photovoltaic material. An analysis is performed using a combination of raytracing and coupled wave theory. Other loss factors such as Fresnel reflection and polarization are also incorporated. The performance of single gratings is optimized to maximize the spectral and angular bandwidth that matches the spectral responsivity of different photovoltaic devices. Multiple grating collectors are also modeled to maximize energy collection over the course of a year accommodating the movement of the sun. The results show that approximately half of the light illuminating the hologram can directly be collected by diffraction and directed to the photovoltaic cell. A test system is evaluated and the experimental results compare well with the analysis.

1. Introduction

Although solar energy is abundant and capable of satisfying the energy needs of the planet it is not cost competitive with fossil fuels. Therefore without major subsidies or a carbon tax on fossil fuels solar energy will not become a major energy source. The current cost of photovoltaic modules is ~\$3.50/W_p however the estimated cost for competition with existing energy sources is ~\$1/W_p [1]. Therefore a factor of 3-4× is required to make photovoltaic systems cost effective. Three major approaches are being pursued to reduce the cost of photovoltaic systems [2]. The first is incremental improvement to existing flat panel modules with crystalline and multi-crystalline silicon cells. The cost of such modules have decreased significantly however without major changes in material or manufacturing methods it will take 30-40 years before this approach will reach the \$1/W_p level. The second path to lower cost is the development of thin film PV cells that are formed using low cost deposition techniques with minimal use of expensive semiconductor materials. Several companies have made significant strides in reducing cost however the low conversion efficiencies, larger land areas required, and conventional module packaging methods raise questions about the impact that this approach will have on solving the world's energy needs. A third approach to reducing the cost of PV is to use large optical concentrators in conjunction with high efficiency multi-junction solar cells. This technique can potentially produce more energy/m^2 than less efficient modules and thin film materials. However these systems require complex optics, tracking, and mounting hardware. In addition it is not clear how the complex multi-junction cells used in these systems will hold up to continuous, very high solar irradiation levels.

Another potential cost reduction method is to combine low concentration optical systems that have 2-5× concentration ratios with moderate efficiency PV cells [3]. Assuming that the majority of the cost of a PV module is due to the PV material it may be possible to significantly reduce the overall system cost and reduce the time it takes for PV modules to reach the \$1.00/W_p performance level. This can be achieved provided the concentrator system adds less cost to the overall PV system. In the work presented in this paper we investigate the use of holographic optical elements as low concentration ratio optical concentrators.

2. Holographic Optical Elements

Holographic optical elements have a variety of attributes that are useful for optical concentrators. They can be fabricated into large areas with low cost mass production methods into high efficiency lightweight films that can be laminated into conventional PV module packages. However their angular and wavelength bandwidth properties must be properly incorporated into the design to be effective solar concentrators.

A hologram is formed by interfering two coherent beams and exposing a photosensitive material. Holograms can be formed to function as transmission as well as reflection components as shown in Figure 1. The power in the diffracted

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beam can be made to approach 100% by forcing the reconstruction beam to interact many times with the modulated medium as it propagates through the hologram Figure 1 [4].

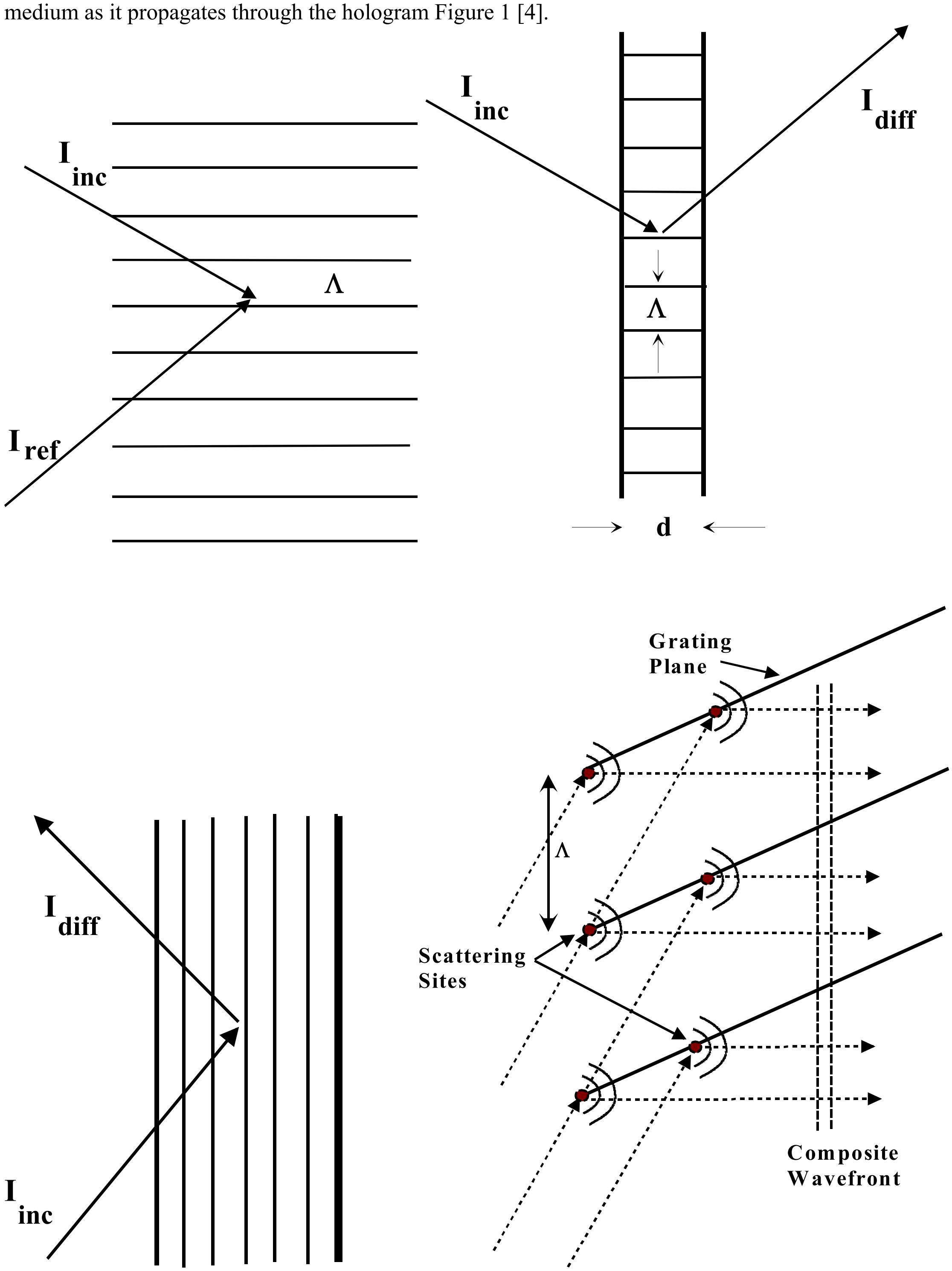

Figure 1: Hologram construction and reconstruction (top figures) for a transmission hologram. A reflection hologram (lower left) and a volume hologram (lower right).

A holographic collector or concentrator must be capable diffracting light with high diffraction efficiency over a broad range of angles and wavelengths. This can be achieved in a phase hologram formed in a relatively thin layer (4-5 μm) with a large refractive index modulation. Holograms can be formed in a variety of materials however dichromated gelatin (DCG) provides the necessary refractive index modulation and thickness to realize angular and wavelength bandwidth for solar collectors [5]. Figure 2 shows the experimental diffraction efficiency as a function of zenith and azimuth angle changes relative to the normal of DCG hologram that is 4 μm thick. As indicated high diffraction efficiency can be realized over a large range of incident angles.

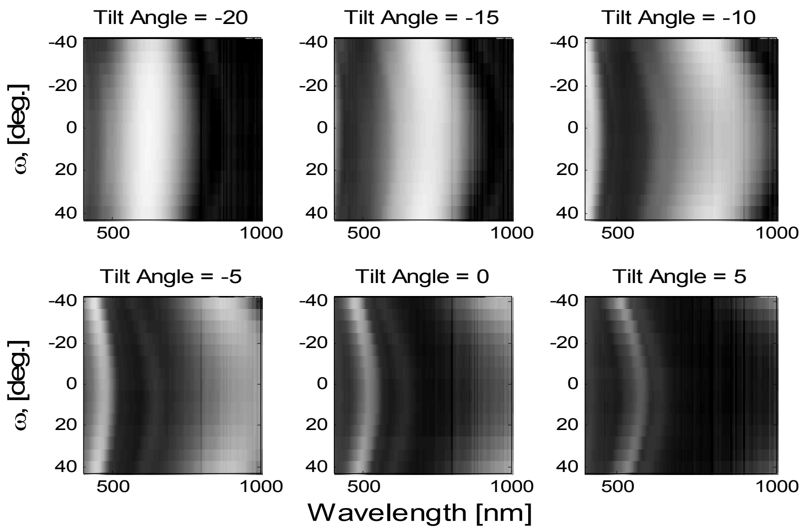

Figure 2: Measured diffraction efficiency as a function of reconstruction and tilt angles with different reconstruction wavelengths.

3. Holographic Planar Concentrator

The basic configuration for a holographic planar concentrator is shown in Figure 3. The holographic planar concentrator is similar to a compound parabolic concentrator with the hologram replacing the parabolic reflectors. Light that directly illuminates the PV cell surface is augmented by light illuminating the holographic apertures. If the concentration ratio is relatively small (i.e. 2-3×) the acceptance angle of the system can potentially be made large enough to provide effective energy collection without the need for tracking.

The range in collection angle that can be achieved without tracking can be estimated with the following relation for a 2D concentrator:

$$C_{2D} = \frac{D_{in}}{D_{pvc}} = \frac{n}{\sin\theta_{in}}$$

Therefore with a concentration ratio of 2 and a substrate index of 1.5 the half width of the acceptance angle is 48.6^{o}. This range in acceptance angle can provide significant energy collection efficiency without the need for tracking.

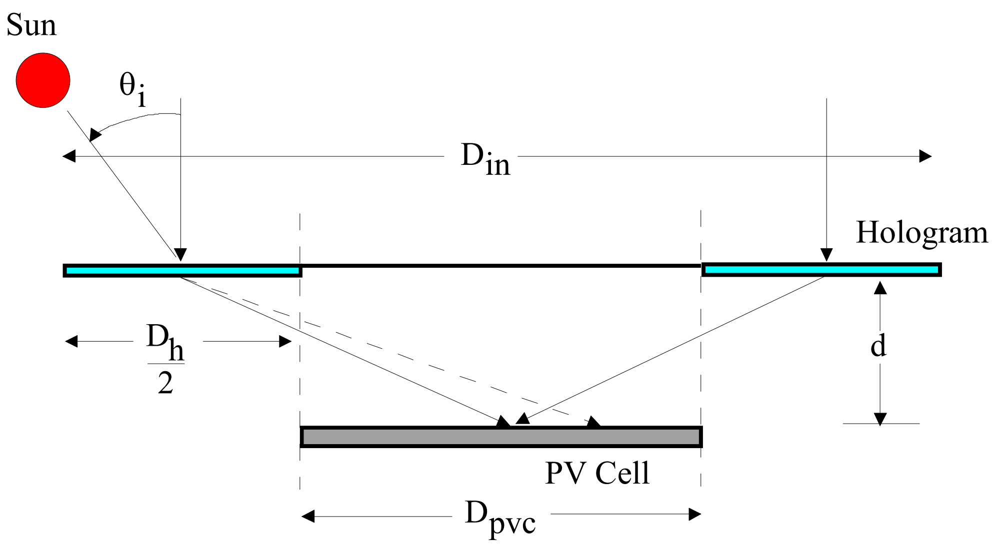

Figure 3: Schematic diagram for a holographic planar concentrator with the hologram area (D_h) split on each side of the PV cell area (D_{pvc})

4. HPC Energy Collection Efficiency

The energy collection efficiency provides an important performance measure of the holographic collector. The energy collection efficiency of the holographic collector is defined as:

$$ECE(d) = 100 \frac{\int [P_{PV}(t,d) + P_H(t,d)]dt}{C_{2D-\max} \int P_{PV}(t,d)dt} \%$$

where $P_{PV}(t,d)$ and $P_H(t,d)$ are respectively the electrical power produced by light illuminating the PV cell and hologram surface on a particular day (*d*), and $C_{2D-\max} = (2D_H + D_{PV}) / D_{PV}$.

In order to compute this parameter the model must include the spectral content of solar illumination at different times of the day over the course of a year, the PV cell spectral response, the geometry of the system, and the change in angle of incidence. In addition losses due to reflection at the interface between different materials and polarization sensitivity of holographic elements must also be considered.

As an example of the energy collection efficiency of a specific system the basic system shown in Figure 4 is evaluated. Both the zenith (θ) and azimuth (ψ) angles are allowed to change to simulate daily and seasonal variations in the sun's position relative to the hologram. In addition the hologram can be tilted by different amounts (β) to optimize average energy collection. An AM 1.5 spectrum for solar illumination is used and is modified for different sun angle positions using SMARTS2. The useful spectrum diffracted by the hologram is further modified by the spectral response of the PV cell. The combined power spectrum for a silicon PV cell at a specific position of the sun is illustrated in Figure 5.

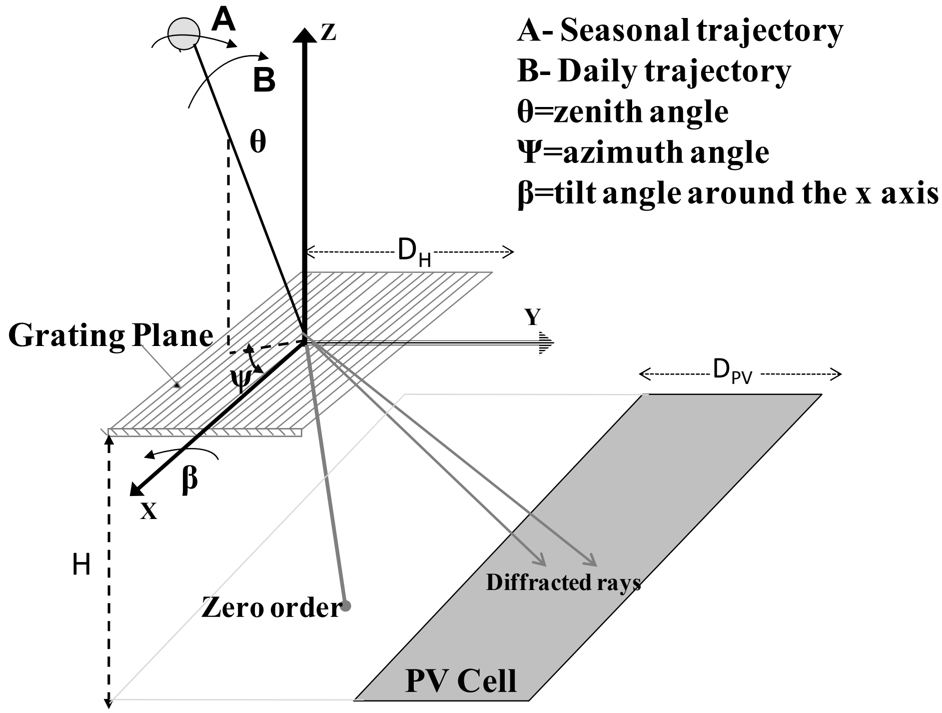

Figure 4: Geometry used for the holographic planar concentrator.

To obtain the largest annual energy yield it is necessary to maximize the ECE for the greatest number of days during the year. An HPC with a single hologram optimized for declination angles corresponding to days 61 and 286 of the year (61,286) are shown in Figure 6. The ECE peaks but then rapidly decreases therefore the annual energy yield is not optimal. In order to increase the energy yield the design of the HPC is modified so that the hologram is divided equally on either side of the PV cell surface and a second hologram is cascaded with the first. The cascaded holograms on the left side of the PV cell are optimized for days (61, 281) and (161,181) while those on the right for days (101,241) and (1,365). The results from this system are shown in Figure 7 and shows that the ECE can be maintained near a value of 150% for the entire year. This indicates that half of the available power hitting the hologram area is converted into useful energy by the PV cell.

5. Conclusions:

The holographic planar concentrator is method of reducing the cost of photovoltaic energy systems by using a low cost holographic element in conjunction with a single junction photovoltaic cell. The hologram acts as a low concentration ratio concentrator that has a significant acceptance angle without the need for tracking the sun. The calculated energy collection efficiency (ECE) obtained with an optimized system is approximately 150% over the course of a year.

6. Acknowledgements:

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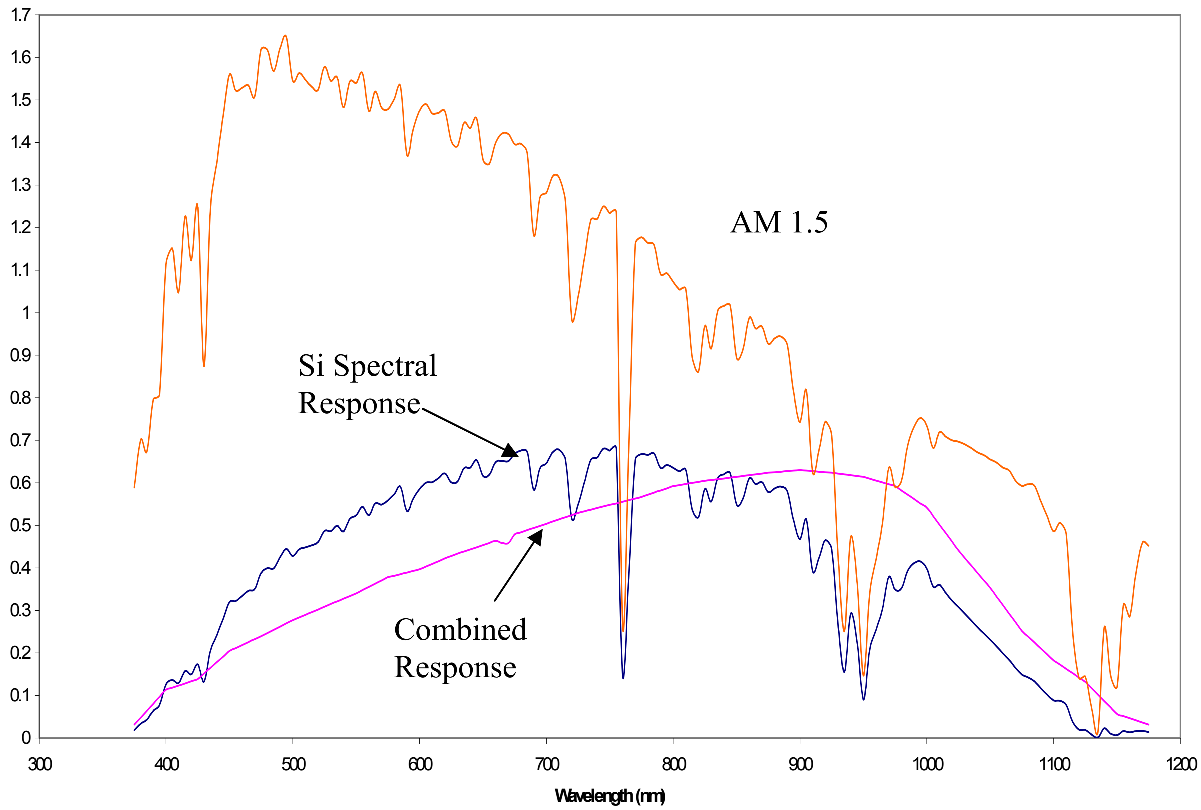

Figure 5: Spectral irradiance corresponding to solar illumination with and air mass of 1.5, the spectral responsivity of a silicon PV cell, and a combined spectral response.

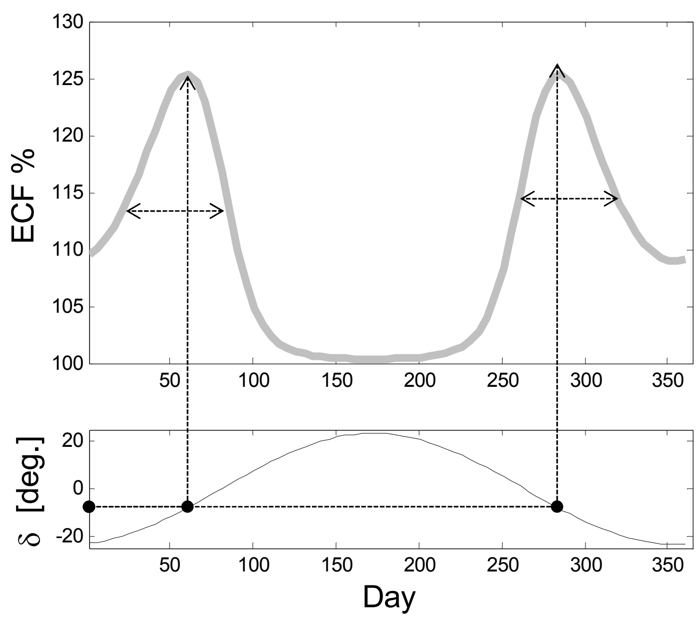

Figure 6: ECE obtained with a single holographic concentrator on one side of the PV cell.

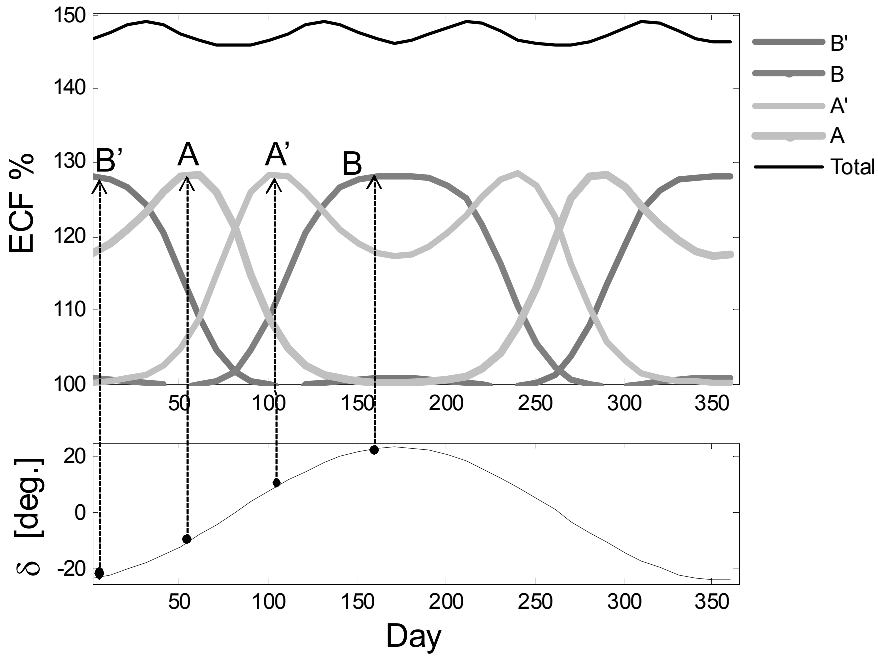

Figure 7: ECE obtained with two cascaded holograms (A,B) on the left side of the PV cell and (A',B') on the right side of the cell.

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