Off-axis holographic lens spectrum splitting photovoltaic system for direct and diffuse solar energy conversion

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A high-efficiency spectrum splitting PV module is described that uses an off-axis volume holographic lens to focus and disperse incident solar illumination to a rectangular shaped high bandgap indium gallium phosphide cell surrounded by strips of silicon cells. The holographic lens design allows for efficient collection of both direct and diffuse illumination to maximize energy yield. Volume diffraction characteristics are modeled using rigorous coupled wave analysis, and system performance is simulated using non-sequential raytracing and PV cell data from the literature. Under AM 1.5 illumination conditions the simulated module obtains 30.6% conversion efficiency. This efficiency is a 19.7% relative improvement compared to the more efficient cell in the system (silicon). The module is also simulated under a typical meteorological year of direct and diffuse irradiance in Tucson, AZ and Seattle, WA. Compared to a flat panel silicon module, the holographic spectrum splitting module obtains a relative improvement in energy yield of 17.1% in Tucson and 14.0% in Seattle. An experimental proof-of-concept volume holographic lens is also fabricated in dichromated gelatin to verify the main characteristics of the system. The lens obtains an average first-order diffraction efficiency of 85.4% across the aperture at 532 nm.

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1. INTRODUCTION

An ongoing goal of photovoltaic (PV) research is to maximize power output by increasing system conversion efficiency. Significant efficiency gains can be achieved by using PV systems with a variety of cell bandgap energy values [1]. Multijunction (MJ) PV systems typically utilize optical concentration to reduce the area of expensive MJ PV cells. Such concentrating PV (CPV) systems have restricted acceptance angles which reject some fraction of diffuse light, counteracting these efficiency gains. For example, as the geometric concentration of a rotationally-symmetric tracking CPV system increases from 1X to 100X, its optical efficiency decreases from 100% to 75% in Tucson and from 100% to 54% in Seattle due to not collecting the diffuse component of solar illumination [2].

In addition to instantaneous power output, PV engineers must consider the energy yield produced over the course of a year. A significant percentage of the incident solar insolation is diffuse, therefore its capture is a major concern to maximize energy yield. For instance, the standard AM 1.5G spectrum contains just 10% diffuse light, while solar insolation is 25.4% diffuse in Tucson, AZ and 46.4% diffuse in Seattle, WA [3].

Recently, Yamada and Okamoto designed a broadband CPV module that can operate under diffuse illumination [4]. In their system, direct light is focused by a Fresnel lens onto a high efficiency MJ cell while diffuse light is collected by a silicon cell in the surrounding area. The addition of the silicon cell provided 1.19x greater power output in sunny conditions (82% direct, 18% diffuse) and 37.3x greater power output in cloudy conditions.

In this work, a 2-bandgap holographic spectrum splitting system is presented. Under direct illumination, this system is designed to achieve high conversion efficiency from multiple bandgap operation. Under diffuse illumination, a fully-populated lateral arrangement of PV cells ensures light collection for maximum energy yield.
2. OFF-AXIS HOLOGRAPHIC LENS SPECTRUM SPLITTING SYSTEM

Volume holograms are useful for spectrum splitting because they can diffract nearly all incident light into a single diffraction order [5]. In the proposed design, the Bragg selectivity of a volume grating allows diffraction of direct normal irradiance (DNI) into a specified angle and allows light at other angles of incidence that are not Bragg matched (diffuse irradiance) to pass through the hologram. A holographic lens brings the diffracted light to a focus by varying the lateral grating period across its aperture. This allows the incident solar illumination to be concentrated at the PV cell surface and enables sharp transitions between diffracted spectral bands.

Several holographic lens-based spectrum splitting PV systems have been proposed. Some designs include vertically-oriented PV cells which add complexity and bulk to the system [6, 7]. Another concept focuses spectral bands onto PV cells with 1225x geometric concentration, reducing acceptance angle and rejecting diffuse light [8].

The spectrum splitting system in this work consists of a holographic lens array placed above a horizontal arrangement of PV cells that are encapsulated in a dielectric material such as glass and bonding cements (Fig 1) [9]. To achieve high DE in a single diffraction order; the hologram aperture must be split into two off-axis lenses. A sharp spectral transition is accomplished by designing the hologram to focus the absorption cut-off wavelength of the high bandgap cell to a position that separates high and low bandgap cells. This wavelength is defined as the “transition wavelength” λT.

Assuming normal incidence, the first-order diffraction angle is determined based on the grating equation:

\[ \theta_d = \sin^{-1}\left(\frac{\lambda}{n_d \Lambda_x}\right) \]  

where \( \lambda \) is wavelength, \( n_d \) is refractive index in the medium following the grating, and \( \Lambda_x \) is lateral grating period. This equation determines the raytracing properties of the hologram.

In order to realize high DE in a single diffraction order; the volume grating condition must be satisfied. Kogelnik provides an approximate form for this condition using a “Q-parameter” [5]:

\[ Q = \frac{2\pi \lambda_d d}{n \Lambda^2} \]  

where \( \lambda_d \) is the minimum wavelength satisfying the volume condition for a fixed set of parameters, \( d \) is holographic film thickness, \( \Lambda \) is the volume grating period (indicated in Fig. 2), and \( n \) is index of refraction of the film. In order to satisfy the volume grating condition, \( Q \geq 10 \).

In general, grating fringes in a volume hologram are slanted with respect to the surface normal. The grating slant angle, \( \phi \), can be adjusted to shift the peak diffracted wavelength as determined by the Bragg condition:

\[ \cos(\phi - \theta) = \frac{\lambda_d}{2n\Lambda} \]  

where \( \theta \) is incident angle, \( \lambda_d \) is peak diffracted wavelength, and \( \Lambda \) is volume grating period. The grating slant angle and incident angle for a volume grating are indicated in Fig. 2. For a fixed grating period, \( \lambda_d \) can be increased by reducing \( \phi \) and vice versa.

Fig. 2. Diagram of angles used in Bragg condition equation (Eq. 3). Also shown is the volume grating period \( \Lambda \).

The peak diffracted wavelength is selected for different locations along the lens aperture. Light that is not diffracted will be collected by the PV cell directly below. Thus, diffracted wavelengths should be tuned to the spectral response of the appropriate PV cell by adjusting \( \phi \). Sections of the holographic lens directly above the low bandgap PV cell diffract wavelengths <\( \lambda_T \) to the high bandgap PV cell with high efficiency. Sections of the holographic lens directly above the high bandgap PV cell diffract wavelengths >\( \lambda_T \) to the low bandgap PV cell with high efficiency.

2. System Geometry

The relations in Section 2.A.1 are used to determine system dimensions. The design process begins by selecting \( \lambda_d \) the hologram film thickness and refractive index. Substituting these parameters into Eq. 2, the maximum grating period for volume operation is determined:

A. Design Procedure

The holographic lens has several degrees of freedom: for a fixed incident angle, i) lateral grating period determines diffraction angle; ii) grating slant angle determines peak diffracted wavelength; iii) peak modulation of the refractive index within the film and film thickness determine peak diffraction efficiency. Diffraction properties of slanted gratings are described in Section 2.A.1, and a design procedure for the holographic lens is provided in Section 2.A.2.

1. Grating Parameters
The grating with this period is located at the center of the unit cell (yellow asterisks in Fig. 3).

![Diagram of a unit cell of the holographic lens spectrum splitting array.](image)

**Fig. 3.** Cross section of a unit cell of the holographic lens spectrum splitting array. \( W_L \) is width of the high bandgap cell, \( W_H \) is width of the low bandgap cell, \( H \) is system height, \( \theta_{T-min} \) is minimum diffraction angle for the transition wavelength, and \( \theta_s \) is diffraction angle of the shortest wavelength at the outer edge of the lens.

The next step is to determine the width of the high bandgap PV cell \( (W_H) \). This parameter is based on the diffraction angle of the transition wavelength at the center of the unit cell, \( \theta_{T-min} \) (Fig. 3). To find the value of \( \theta_{T-min} \) using the grating equation, \( \Lambda_{max} \) must be specified. Lateral grating period is not yet known, but can be calculated based on volume grating period \( \Lambda_{max} \) and \( \phi \) at the center of the unit cell. Slant angle is determined by specifying the desired peak diffracted wavelength using the Bragg-matching equation (Eq. 3):

\[
\phi = \cos^{-1}\left(\frac{\lambda_p}{2n\Lambda_{max}}\right)
\]

Peak diffracted wavelength in this section of the holographic lens should fall in the center of the range \( (\lambda_L, \lambda_T) \) where \( \lambda_L \) is the wavelength corresponding to the bandgap energy of the low bandgap cell. By choosing this peak diffracted wavelength, light with energy below the bandgap of the high bandgap cell will be diffracted to the low bandgap cell. With \( \phi \) specified, the lateral grating period is determined:

\[
\Lambda_{x-max} = \frac{\Lambda_{max}}{\sin \phi}
\]

After calculating \( \Lambda_{x-max} \), diffraction angle of the transition wavelength \( \lambda_T \) is determined using the grating equation:

\[
\theta_{T-min} = \sin^{-1}\left(\frac{\lambda_T}{n_j\Lambda_{x-max}}\right)
\]

Finally, for a fixed system height \( H \), the high bandgap PV cell width is calculated:

\[
W_H = 2H \tan \theta_{T-min}
\]

Maximum width of the holographic lens occurs when the grating diffracts a specified minimum wavelength \( \lambda_s \) to the near-edge of the high bandgap cell (magenta star in Fig. 3). The grating equation and geometric system relations are used to derive the following two equations for lateral grating period at the edge of the unit cell as a function of total unit cell width:

\[
\Lambda_{x-edge} = \frac{\lambda_T}{2H} \left(\frac{W_H + W_L}{n_j \tan^{-1}\left(\frac{W_H + W_L}{2H}\right)}\right)
\]

\[
\Lambda_{x-edge} = \frac{\lambda_T}{2H} \left(\frac{W_H - W_L}{n_j \tan^{-1}\left(\frac{W_H - W_L}{2H}\right)}\right)
\]

where \( W_{tot} \) is unit cell width and \( \Lambda_{x-edge} \) is lateral grating period at the edge of the unit cell. These two parameters are then found by simultaneously solving Eqs. 9 and 10.

### 3. DESIGN EXAMPLE

The process in Section 2 is used to design an off-axis holographic lens spectrum splitting system. The following sections describe the process of selecting PV cells and system parameters for a specific design.

#### A. Selection of PV Bandgaps

Different combinations of PV cells for a spectrum splitting system can be evaluated using a parameter called the spectral conversion efficiency (SCE) [10], which is defined as:

\[
SCE(\lambda) = FF \cdot V_{oc} \cdot SR(\lambda)
\]

where FF is fill factor, \( V_{oc} \) is open-circuit voltage, and \( SR(\lambda) \) is spectral responsivity.

The two bandgaps chosen in this example are indium gallium phosphide (InGaP) and silicon (Si) because they provide a near-ideal combination for maximum 2-junction system efficiency [11]. Parameters for a 25.6% efficient silicon (Si) cell and a 20.8% efficient indium gallium phosphide (InGaP) cell are taken from the literature [12-14]. The SCE plots of these two cells, shown in Fig. 4, indicate that InGaP is more efficient than Si at wavelengths shorter than 663 nm and drops to zero for longer wavelengths. This determines a transition wavelength \( \lambda_T \) of 663 nm.

![SCE plots of InGaP and Si cells selected for the spectrum splitting module simulation.](image)

### B. Selection of Holographic Film Material
Dichromated gelatin (DCG) was chosen for the simulation due to its high refractive index modulation capability and resulting high diffraction efficiency [15]. The maximum refractive index modulation of DCG is 0.1, and film thickness can typically be varied from 5-30 μm with low scatter and good adhesion properties.

C. System Parameters

The design process in Section 2 is carried out to determine geometric parameters of the holographic lens spectrum splitting system. The results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holographic film thickness</td>
<td>20 μm</td>
</tr>
<tr>
<td>Refractive index modulation</td>
<td>0.077-0.084</td>
</tr>
<tr>
<td>System height</td>
<td>1 cm</td>
</tr>
<tr>
<td>Unit cell width</td>
<td>1.29 cm</td>
</tr>
<tr>
<td>System f/#</td>
<td>f/0.77</td>
</tr>
<tr>
<td>InGaP PV cell width</td>
<td>0.53 cm</td>
</tr>
<tr>
<td>Si PV cell width</td>
<td>0.76 cm</td>
</tr>
<tr>
<td>Geometric concentration on InGaP PV cell</td>
<td>2.43X</td>
</tr>
<tr>
<td>Geometric concentration on Si PV cell</td>
<td>1.70X</td>
</tr>
</tbody>
</table>

4. SYSTEM SIMULATION

The system is modeled using rigorous coupled wave analysis (RCWA) using DiffractMOD software [16]. The diffraction efficiency analysis is combined with non-sequential raytracing software FRED from Photon Engineering [17]. Two-axis tracking is assumed for most of the simulation process, but the angular tolerance for one-axis tracking performance is discussed in Section 4D.

A. Diffraction Efficiency Across the Holographic Lens Aperture

The holographic lens is approximated as a set of planar gratings with varied slant angle across the aperture of the hologram [18]. Refractive index modulation and grating slant angle are also modified along the depth direction of the film to model attenuation and swelling effects encountered with DCG. A sample of refractive index profiles and corresponding spectral diffraction efficiency curves along the holographic lens aperture are shown in Fig. 5. Rigorous coupled wave analysis indicates that a small amount of light is diffracted into the -1, +2, and +3 orders in addition to the 0 and +1 order. For accuracy, all orders from -1 to +3 are simulated. At each point on the hologram aperture, the DE is calculated over a full range of incident angles, a full range of solar wavelengths, and for both polarization states that are averaged to provide unpolarized DE.

B. Ray Tracing Simulation

Fig. 5. Schematic showing simulation of sampled regions along the holographic lens. Top: Modulation of film refractive index in each sampled region is plotted. Bottom: DE(λ) in all significant diffracted orders (normal incidence). The bandgap energy of InGaP and Si are indicated with vertical blue and red dotted lines on the plots, respectively. Sections of the lens located above the Si cell diffract 350-663 nm light to the InGaP cell. Sections of the lens above the InGaP cell diffract 663-1100 nm light to the Si cell.
Non-sequential raytracing software is used to model ray trajectories for the holographic lens spectrum splitting system. The holographic lens is modeled as a discrete set of planar grating surfaces which are each given a lateral grating period. Each ray that interacts with the grating is split into various diffracted orders with the appropriate DE distribution as determined by RCWA in Section 4A. A schematic raytrace for three distinct wavelengths is shown in Fig. 6.

![Raytrace showing normally incident light at three distinct wavelengths diffracted by the holographic lens onto the PV cell array.](image)

Fig. 6. Raytrace showing normally incident light at three distinct wavelengths diffracted by the holographic lens onto the PV cell array. The opacity of each ray indicates the amount of power it contains.

Direct and diffuse light sources are also modeled. Each source consists of rays placed randomly along an x-y plane just above the top of the module. Direct source rays are incident for the range of angles subtended by the solar disk (+/-0.26° with respect to normal incidence), while diffuse rays are cover a full range of angles between +/-90° with respect to normal incidence. The spectrum splitting module is simulated for three cases: i) AM 1.5 direct and diffuse irradiance; ii) annual insolation in Tucson, AZ; and iii) annual insolation in Seattle, WA. In the first simulation, AM 1.5 direct and diffuse spectra and power values are assigned to the sources. Typical Meteorological Year 3 data for direct and diffuse insolation is used for the annual energy yield simulations. Insolation spectra are generated using the SMARTS2 simulation software [19]. Specifically, 16 direct and 16 diffuse spectra are generated for each location: four times during the day (8:00 AM, 10:45 AM, 1:30 PM, and 4:15 PM) and four seasonal samples (summer and winter solstice, spring and fall equinox).

C. Simulation Results: Conversion Efficiency and Improvement over Best Bandgap

Conversion efficiency values for the three simulation groups are summarized in Table 2. In addition, the spectrum splitting module is compared to a flat-panel module that is fully-populated by the more efficient PV cell (Si in this case). The relative improvement in conversion efficiency and energy yield is also listed in Table 2, and the spectral filtering properties of the modeled holographic lens are shown in Fig. 7.

![Spectral optical efficiency of the holographic lens for light reaching the InGaP (blue) and Si (red) cells in the spectrum splitting system under AM 1.5D irradiance. The addition of diffuse light reduces spectral filtering from this ideal case.](image)

Fig. 7. Spectral optical efficiency of the holographic lens for light reaching the InGaP (blue) and Si (red) cells in the spectrum splitting system under AM 1.5D irradiance. The addition of diffuse light reduces spectral filtering from this ideal case.

<table>
<thead>
<tr>
<th>AM 1.5 Irradiance</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Total Incident Irradiance</td>
<td>1001.07 W/m²</td>
</tr>
<tr>
<td>Single Bandgap (Si): Converted Irradiance</td>
<td>256.27 W/m²</td>
</tr>
<tr>
<td>Single Bandgap (Si): Conversion Efficiency</td>
<td>25.6%</td>
</tr>
<tr>
<td>Spectrum Splitting: Converted Irradiance</td>
<td>306.66 W/m²</td>
</tr>
<tr>
<td>Spectrum Splitting: Conversion Efficiency</td>
<td>30.6%</td>
</tr>
<tr>
<td>Relative Improvement over Best Bandgap</td>
<td>19.7%</td>
</tr>
</tbody>
</table>

Annual Energy Yield in Tucson, AZ

| Total Incident Insolation (2-axis tracking) | 3074.87 kW-hr |
| Single Bandgap (Si): Converted Insolation | 773.98 kW-hr |
| Spectrum Splitting: Converted Insolation | 906.51 kW-hr |
| Relative Improvement over Best Bandgap | 17.1% |

Annual Energy Yield in Seattle, WA

| Total Incident Insolation (2-axis tracking) | 1739.59 kW-hr |
| Single Bandgap (Si): Converted Insolation | 445.94 kW-hr |
| Spectrum Splitting: Converted Insolation | 508.55 kW-hr |
| Relative Improvement over Best Bandgap | 14.0% |

D. Tracking Tolerance

The in-plane and out-of-plane tracking tolerance is evaluated in the simulation by varying the angular incidence of rays illuminating the hologram aperture and evaluating spectrum splitting conversion efficiency. Tracking tolerance in the system is defined as the range of incident angles over which there is a positive ionBB compared to the flat panel Si module without spectrum splitting. As shown in Fig. 8a-b, in-plane tracking tolerance is +/-11° and out-of-plane tracking tolerance is +/-19°. This means that the spectrum splitting module on a fixed latitude tilt 1-axis tracker would still improve energy yield compared to a Si flat panel of the same area. However, a trade-off exists between the cost-savings of this 1-axis tracker and reduced performance due to seasonal changes in sun angle.
5. EXPERIMENTAL HOLOGRAPHIC LENS PROTOTYPE

An off-axis holographic lens is fabricated in DCG to verify off-axis focusing and diffraction efficiency values.

A. Recording Setup

The volume holographic lens recording geometry is shown in Fig. 9. A converging wavefront is formed using a 1.2 cm wide, 20 cm focal length cylindrical lens. In order to keep the volume Q condition (Eq. 2) $>10$ across the entire hologram aperture, the interbeam angle between the focused and reference beam is set equal to 35°. Emulsion swelling during processing rotates the grating slant angle. Therefore in order to obtain peak DE at normal incidence the effect of swelling is compensated by rotating the hologram an additional 7.0° with respect to normal. This value was found by characterizing the DCG exposure and development process. In this setup, the holographic lens has a peak diffraction efficiency at the recording wavelength (532 nm). Methods for tuning the peak diffracted wavelength are discussed in Section 6.

B. Film Preparation, Exposure, and Development

Dichromated gelatin is mixed in a ratio of [1:6:50] [Ammonium Dichromate:Gelatin:Water] by weight. The film is formed using a molding technique on a glass substrate and dried for 24 hours. The film is then stored in a dry environment (9% relative humidity) for an additional 24 hours before recording. The resulting initial film thickness is 16.0 μm.

The hologram is recorded with an exposure of 754 mJ/cm² at a wavelength of 532 nm. In order to form two side-by-side off-axis lenses, one exposure is made and then the film is rotated 180° in the same recording geometry for the second exposure. The exposed film is then developed in a fixer bath, a water bath, and three dehydrating baths of water with increasing concentrations of isopropanol (50%, 75%, and 100%). The hologram is then baked in an oven at 70°C for 10 minutes to remove any residual water. The final film thickness after swelling is 20.0 μm.

Fig. 9. Recording setup for the prototype off-axis holographic lens. A 532 nm laser is used to record the hologram. The interfering beams are recorded in a conjugate arrangement so that the cylindrical lens does not block the reference beam.

C. Experimental Holographic Lens Properties

Diffraction efficiency across the holographic lens aperture is evaluated using laser illumination. The holographic lens is measured at 5 lateral positions across the aperture (Fig. 10a). Three lasers (457 nm, 532 nm, and 633 nm) are used to illuminate the lens, and diffracted light is measured directly with a power meter. Measurements show that the holographic lens satisfies the volume condition. The results show that 95.70% of incident power is diffracted into the 0 and +1 order, 0.66% is diffracted into the -1 order, and 3.64% is scattered or absorbed in the film. Peak diffraction efficiency in the +1 order for each laser wavelength across the holographic lens is plotted in Fig. 10b.

Film transmittance is also measured using a broadband light source and a spectrometer. Average scattering and absorption in the film between 375-1050 nm is 3.64%. Finally, the measured peak DE values are applied to the holographic lens model simulated in Section 4. A quadratic fit to the peak DE for 532 nm light is used to determine peak DE continuously across the lens aperture. These peak values are used to scale DE values in the holographic lens simulation. After performing a raytrace on the updated holographic lens spectrum splitting system, the following relative Improvement over Best Bandgap (IoBB) values are obtained: 15.0% IoBB under AM 1.5 irradiance, 12.9% IoBB under annual insolation in Tucson, and 10.5% IoBB under annual insolation in Seattle.

6. FUTURE WORK

The prototype holographic lens in Section 5 was recorded using 532 nm light and a cylindrical lens. This hologram obtains peak DE centered at 532 nm across the aperture. The outer and inner sections of the unit cell should have different peak diffracted wavelengths based
on the PV bandgap located below each section. It is possible to record such a hologram using a single laser wavelength by varying the construction angles. For a particular section of the holographic lens, if the desired grating period along x and z directions (Λx and Λz) are known, recording angles (θ1 and θ2) in the film can be determined for a particular recording wavelength $\lambda_R$ according to:

$$\theta_1 = \cos^{-1} \left( \frac{a^2b + \sqrt{-a^4 + 2a^3b + 4a^2 - a^2b^2 + 4a^2b^2}}{2(a^2 + b^2)} \right)$$  \hspace{0.5cm} (12)$$

$$\theta_2 = \sin^{-1} |\sin \theta_1 - a|$$  \hspace{0.5cm} (13)$$

where $a = \lambda_R/(n\cdot\Lambda_X)$, $b = \lambda_R/(n\cdot\Lambda_Z)$, and n is film refractive index. This optimization will be performed in future design and experimental work.

Fig. 10. (a) Sampling locations for measurement of DE across fabricated off-axis holographic lens. (b) Peak DE into the first diffracted order for each sampled location and three laser wavelengths.

### 7. CONCLUSION

An off-axis holographic lens module is described for two-bandgap photovoltaic spectrum splitting. Increased conversion efficiency from spectrum splitting occurs under direct normally incident solar illumination, and rays that are not Bragg matched to the volume holographic lens pass through without being diffracted. The non-Bragg matched rays correspond to diffuse illumination, and by covering the receiver plane with PV cells, the collection of diffuse illumination is ensured. The ability to collect direct light with higher efficiency in addition to diffuse insolation leads to a higher overall energy yield.

The holographic lens has several properties that allow it to approach ideal spectrum splitting conversion. First, light is diffracted off-axis to achieve high diffraction efficiency in a single order. Next, the bandgap wavelength for the high-bandgap cell is focused to the boundary between cells for a sharp spectral transition. Finally, the grating slant angle is adjusted in each region of the holographic lens to select a diffracted wavelength band that matches the spectral response of the appropriate PV cell.

The holographic lens diffraction efficiency is modeled using rigorous coupled wave analysis and ray trajectories are simulated with non-sequential raytracing software. Under AM 1.5 conditions, the spectrum splitting module achieves conversion efficiency of 30.6%, which is a 19.7% relative improvement compared to the efficiency of the best bandgap PV cell in the system with the same aperture. The module also provides improvement in annual energy yield despite increased diffuse illumination. In Tucson, AZ with 25.6% diffuse insolation, the spectrum splitting module demonstrates 17.1% relative improvement in energy yield. In Seattle, WA with 46.4% diffuse insolation, 14.0% relative improvement is achieved.

A prototype of the off-axis volume holographic lens was fabricated in dichromated gelatin. When illuminated with 532 nm light (the same wavelength used for exposure), the peak DE ranged from 74.4% to 94.4% across the aperture, with an average value of 85.4%. Average film absorption and scatter in the prototype holographic lens was 3.64% for wavelengths ranging from 375-1050 nm. Applying the measured peak DE values to the simulated holographic lens model, a conversion efficiency of 29.4% was achieved under AM 1.5 illumination conditions. A relative improvement over best bandgap of 15.0% was achieved under AM 1.5 illumination conditions. 12.9% IoBB was achieved for Tucson, AZ, and 10.5% IoBB was achieved for Seattle, WA.

Future work in this system includes continued improvement in peak DE values, reduction of absorption and scattering in the film, and incorporation of wavelength tuning of the peak DE. Peak DE values can be improved by optimizing exposure energy across the holographic lens. This could be achieved using a graded neutral density filter, for example. Scattering can be reduced by adjusting the film fabrication and development process. Slanted transmission gratings in DCG have demonstrated a peak DE as high as 98.4% with average scatter and absorption as low as 1.4% (discounting Fresnel reflection loss), so there is significant potential for improvement in optical performance [20]. Finally, a set of equations has been provided to determine recording angles for a particular laser wavelength to obtain an arbitrary slanted grating in the film. This capability will allow tuning of the peak diffracted wavelength in different sections of the holographic lens.

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