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Optical design and characterization of holographic solar concentrators for photovoltaic applications

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ABSTRACT

In present work, different possible aspects of holographic PV concentrators like wide acceptance angle, wavelength selectivity and maximum efficiency operation have been investigated by controlling different processing parameters like depth of refractive index modulation, film thickness and fringe spacing. We have discussed and analyzed individual as well as cumulative effect of processing parameters on angular selectivity, wavelength selectivity and efficiency. In addition, we are also reporting optimized value of the processing parameters for designing high efficiency holographic concentrator.

1. Introduction

Energy crisis and depletion of fossil fuels has increased attention towards use of clean and renewable energy. Over consumption of traditional fossil fuels causes serious energy crisis and environmental pollutions. Photovoltaic can produce safe and clean renewable energy and replace current electricity generation. This may relieve energy crisis and environmental pollution [1]. Unfortunately, their use is limited due to high price of the photovoltaic modules.

In the first generation, the most developed PV solar cells that fully dominated the market are crystalline silicon solar cells [2]. In the second generation, there were modification and development of the PV systems which had lowered manufacturing cost, improved efficiency etc. However, third generation includes technological development, such as Concentrated Photovoltaic (CPV) [3] and organic PV cells that are still in the development stage [4]. Concentrated Photovoltaic technology is one of the ways to reduce the cost of PV power generation by replacing the costly solar cell area with a relatively cheap concentrator area [5,6]. Concentrated Photovoltaic (CPV) systems can be distinguished from each other with respect to several features such as concentration ratio, type of optics and tracking requirements. Based on their concentration ratios, CPV systems are generally classified as low, medium and high concentration [3,7]. Unfortunately, as the concentration goes on increasing the tracking requirement of the daily movement of the sun becomes more involved. The major hindrances at medium and high concentration are increase in cell temperature and requirement of accurate sun tracking system which reduces the efficiency and increases overall cost of the system respectively [8]. Low concentration PV systems are less demanding in terms of tracking accuracy as compared to high concentration systems [9,10]. Holography is a promising optical tool that can advantageously be implemented in low concentration photovoltaic systems. Ludman [11], for the first time proposed the use of holographic concentrator (holocon) for PV power generation. Then after a lot of work have been carried out by many

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researchers to investigate different aspects of holographic solar concentrators [12–21]. Wavelength selective properties are required for solar cells by matched band gap applications [22–24] whereas wide acceptance angle concentrating system is required for reducing tracking requirement of the daily movement of the sun [25].

In the present work dependence of angular selectivity, wavelength selectivity and diffraction efficiency of holographic concentrators on processing parameters like depth of refractive index modulation, film thickness and fringe spacing have been discussed and analyzed. For achieving maximum diffraction efficiency, we have optimized the processing parameters. In order to realize maximum diffraction efficiency at first order, four holocons have been recorded with different spatial frequency of fringes and another four with fixed fringe spacing but different depth of refractive index modulations.

2. Theory

2.1. Kogelnik coupled wave theory

The formula for diffraction efficiency (η) of thick phase transmission holograms, which takes into account the angular deviation from Bragg's angle in the reconstruction, is given by Kogelnik coupled wave theory [26], assuming refractive index variation to be sinusoidal as:

$$\eta = \frac{\sin^2\left\{\left(\xi^2+\upsilon^2\right)^{\frac{1}{2}}\right\}}{\left(1+\frac{\xi^2}{\upsilon^2}\right)} \tag{1}$$

Where parameters ξ and υ are defined by the relation $\xi = \delta\frac{2\pi n}{\lambda}d\sin\theta$ and $\upsilon = \frac{\pi n_1 d}{\lambda\cos\theta}$

Where n_1 is the depth of refractive index modulation, d is the film thickness, n is the average refractive index of the medium, λ is the free space wavelength of the reconstruction light beam and δ is the angular deviation in radians with respect to Bragg's angle (θ).

Bragg angle (θ) is related to the fringe spacing (Λ) recorded in the hologram through the relation

$$\sin\theta = \frac{\lambda}{2n\Lambda} \text{ and } \cos\theta = \left\{1\text{-}\left(\frac{\lambda}{2n\Lambda}\right)^2\right\}^{\frac{1}{2}}$$

When the illumination is made at Bragg's angle (i.e. $\delta = 0$) we have from (1), $\eta = \sin^2 v$

Thus, for illumination at Bragg's angle reconstruction, diffraction efficiency can be given as

$$\eta = \sin^2\left(\frac{\pi n_1 d}{\lambda\left\{1-\left(\frac{\lambda}{2n\Lambda}\right)^2\right\}^{\frac{1}{2}}}\right) \tag{2}$$

While drawing the curves care has been taken to ensure that criteria for thick phase transmission hologram are fulfilled for which Eqs. (1) and (2) holds good [27]. A hologram is said to be thick if its Q parameter $\left(Q = \frac{2\pi\lambda d}{n\Lambda^2}\right)$ is greater or equal to 10 [28].

2.2. Fringe spacing inside the recording medium

When two recording beams intersect in free space (air) having wavelength λ_a and inter beam recording angle $2\theta_a$ then corresponding fringe spacing is given by $\Lambda_a = \lambda_a/\left(2\sin\theta_a\right)$. When these two recording beams are incident into a medium the corresponding fringe spacing is given by $\Lambda_m = \lambda_m/\left(2\sin\theta_m\right)$ where λ_m is the wavelength of light and θ_m is the half inter beam recording angle inside the medium. Wavelengths and half inter beam recording angles in the two media are related as $\lambda_m = \lambda_a/n$ and $\sin\theta_m = \sin\theta_a/n$. Hence fringe spacing remains same irrespective of change of medium.

2.3. Optimization of inter-beam recording angle for maximum diffraction efficiency at first order

For designing holocons to diffract most of the light into only one particular order (maximum efficiency at first order) and almost negligible efficiency at the rest of the orders, theoretically it has been found that recording should be done with inter-beam recording angle $2\theta \approx 40^\circ$ [29,30].

3. Optical design

3.1. Holographic concentrator

Holographic PV concentrators have been recorded using two coherent waves derived from the same laser source. Out of two coherent waves one is diverging spherical wave and another is a plane wave. Schematic of the recording geometry has