Low-Cost, Lightweight, And Highly Efficient Holographic Solar Concentrators for Spectral Splitting and Concentration of Sunlight onto Multi-Junction Solar Cells and Nanowire/Nanopillar Solar Cells

Asghar Khan
Department of Physics, Karim City College, Jamshedpur, India- 831001

***Abstract*—Photovoltaic (PV) conversion is highly wavelength dependent and is most efficient when converting photons whose energy is close to the band gap energy of the PV cells. Spectral regions of solar radiation that do not match the band gap of the absorber material of the PV cells overheat the PV cells and reduce their efficiency and average lifetime. Current PV technology uses multiple bandgap PV cells for high efficiency. At present, multiple band gap triple-junction InGaAs photovoltaic (PV) cells have achieved the highestefficiency of 37%. On the other hand, innovative cost-effective architectures, such as laterally arranged multiple-bandgap nanowire and nanopillar solarcells, are extensively investigated for high efficiency. A typical nanowire solar cell requires 100 times less material to achieve the same level of absorption as required in thick crystalline silicon solar cells. This work presents the recording and analysis of two different types of holographic concentrators. The first is recorded using the photonic structure of an off-axis zone plate, while the second is recorded using a combination of a planar grating and an off-axis zone plate. These concentrators are designed to disperse and concentrate sunlight for multi-junction solar cells and nanowire/nano pillar solar cells, respectively. Their recording, playback geometry, and the spectrum of white light diffracted through these concentrators are presented. Further, the diffraction efficiencies of both concentrators were measured at three wavelengths: λ = 488 nm, λ = 543 nm, and λ = 633 nm.**

***Index Terms*—Holographic solar concentrators, Photovoltaic (PV), Diffractive optical elements, solar cells, spectrum splitting and concentration**

I. INTRODUCTION

Conventional solar power systems primarily rely on single-crystal silicon photovoltaic cells (PV Cells), which can achieve maximum efficiencies of about 20%. However, these cells generate significant heat during operation, and solar radiation increases the solar panel temperature to approximately 55 °C. It is well known that even a 1 °C rise in the temperature of a photovoltaic cell results in approximately a 0.5% drop in its conversion efficiency. Moreover, this relationship is not strictly linear—an increase of 10 °C can cause the efficiency to fall by nearly half. Cooling strategies using active components such as pumps or fans circulate a working fluid to remove heat, but they consume considerable power, demand regular maintenance, and negatively affect the overall reliability of the system. Passive cooling approaches are limited in their effectiveness and often fail to control the temperature of large-scale solar cell installations adequately [1].

To enhance the efficiency of PV systems, current PV technology uses multiple bandgap solar cells based on different semiconductor materials, such as indium gallium phosphide (InGaP with a bandgap of 1.86 eV), gallium arsenide (GaAs with a bandgap of 1.43 eV), indium gallium arsenide (InGaAs with a bandgap of 0.73 eV), etc. Currently, triple-junction InGaAs photovoltaic (PV) cells achieve the highest efficiency of 37% [2]. However, the widespread use of such high-efficiency solar cells is unattractive due to their high cost. On the other hand, considerable research is focused on developing alternative, cost-effective photovoltaic technologies utilizing nanomaterials. Conventional crystalline silicon solar cells require relatively thick silicon wafers (approximately 200 μm) to absorb most of the incident sunlight and achieve high efficiency. However, the fabrication of such

wafers is costly and contributes significantly to CO_2 emissions during the production process. In contrast, nanowire-based solar cells can attain similar light absorption performance while using nearly 100 times less material than traditional silicon solar cells. Nanostructured materials in various geometries, such as nanotubes [3-4], nanorods [5-6], and nanowires [7-9], are emerging elements in next-generation photovoltaic technologies. Among these, one-dimensional semiconductor nanowires present a particularly promising platform for realizing high-efficiency solar cells. Furthermore, wavelength-selective lateral multijunction nanowire solar cells have been proposed to improve overall performance.
These solar cells do not fully utilize the entire solar spectrum. This limitation occurs because a typical solar cell operates most efficiently only within specific regions of the spectrum where the photon energy closely matches its bandgap energy [10]. To address this issue, it is beneficial to disperse and concentrate solar radiation in photovoltaic (PV) systems. By splitting the spectrum and concentrating the solar radiation, we can strategically position solar cells with different band gaps to ensure that each cell aligns with the appropriate portion of the solar radiation spectrum [11-12].

The use of properly designed holographic solar concentrators has long been advantageous to reduce the cost of PV power generation by replacing a significant amount of expensive solar cell area with asmaller concentrator area while maintaining the same output [13-14]. These concentrators offer several significant advantages. Being diffractive optical elements, a typical holographic concentrator, a subset of holographic optical elements (HOEs), diffracts different wavelengths of light at different angles and focuses these wavelengths along its optic axis. Thus, using a properly designed holographic concentrator, both spectral splitting and concentration can be achieved for spatially separated solar cells of matching band gaps.

Furthermore, holographic concentrators can be designed for wavelength-selective performance, i.e., to filter out unwanted portions of the solar spectrum, reducing excess thermal load and thereby enhancing the operational lifetime of the solar cells. In addition, HOEs are lightweight, cost-effective, and relatively easy to fabricate. Because of the multifunctional characteristics of HOEs, extensive research efforts worldwide have been devoted to exploring various aspects of HOEs for solar concentrator applications [12-20]. In this work, two different types of holographic concentrators, one recorded with the photonic structure of an off-axis zone plate and the other recorded with the photonic structure of a planar grating and an off-axis zone plate, have been studied to disperse and concentrate sunlight for multi-junction solar cells and nanowire/nano pillar solar cells, respectively. Their recording and playback geometry, and the spectrum of white light passing through these concentrators, are presented. Furthermore, the diffraction efficiency of these concentrators was measured at three available wavelengths: λ = 488 nm, λ = 543 nm, and λ = 633 nm, and the results are shown.

II. EXPERIMENTAL

2.1. Recording of holographic concentrators with the photonic structure of an off-axis zone plate

To record the photonic structure of an off-axis zone plate, also known as a holographic lens, for holographic solar concentrators, two coherent waves derived from a single laser source are used [13-16]. A schematic of recording geometry is shown in Figure 1. Out of these two coherent waves, one is a plane wave, and the other is a spherical wave. The laser light (He-Ne laser of power 5mW) is allowed to fall on the beam splitter, which splits the incoming laser light into two parts. One part of the beam is transmitted, and the other part is reflected. The reflected beam strikes the mirror and is further reflected to pass through the pinhole of diameter 5 micrometersto generate a spherical wave, which falls on the holographic plate. At the same time, the other beam is directed on the recording plane (holographic plate) with the help of reflecting mirrors after proper expansion and collimation (rendering the beam parallel).

For the divergence of the beam and its collimation spatial filtering arrangement is used. Spatial filtering arrangement consists of a properly aligned pinhole to diverge the light beam and a converging lens kept at a distance equal to the focal length of the lens from the pinhole to render the light rays parallel. A plane wave front and spherical wave front fall on the holographic plate simultaneously to generate an off-axis zone plate, which acts as a holographic concentrator. The recording geometry for recording holographic concentrator is such that the path length of the transmitted beam and reflected beam from the beam splitter to the recording plate are the same. The holographic plate was PFG-01(film thickness d = 7 µm and average refractive index n = 1.61), which is sensitive to red colour [21].

The exposure time for maximum efficiency was optimised by recording holographic concentrators for various exposure times. The angle between the plane wave and the spherical wave at the time of recording was typically chosen to be 45º for high efficiency [15].

To prevent the formation of spurious grating, holographic concentratorswere recorded under index-matchedconditions. The exposed film was processed using standard procedure [21-22].

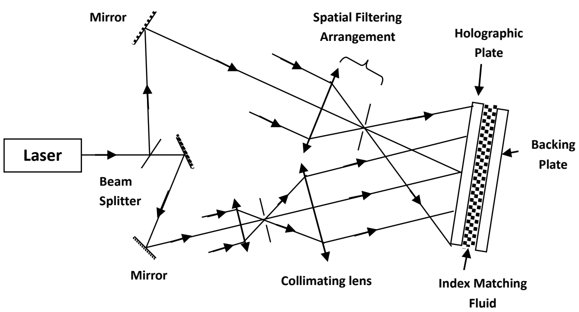


Fig. 1. Schematic of recording geometry for recording holographic concentrator having photonic structure of an off-axis zone plate.

2.2. Recording of holographic concentrators with a photonic structure of a planar grating and an off-axis zone plate

To record a holographic concentrator consisting of a planar grating and an off-axis zone plate photonic structure, first, a periodic fringe pattern (plane diffraction grating) formed by the superposition of two coherent plane waves is recorded on a high-resolution holographic plate [23-24]. The schematic geometry for recording the plane diffraction grating is shown in Figure 2.

Then, using the recording geometry shown in Figure 1, the photonic structure of the off-axis zone plate is recorded on the same holographic plate. The exposed plate is then developed following a standard procedure [21-22].

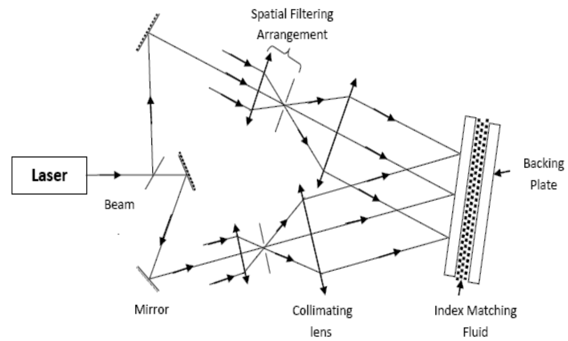


Fig. 2. Schematic of recording geometry for recording plane diffraction grating.

2.3. Playback of holographic concentrators

A schematic of the experimental setup for obtaining the spectrum of white light is shown in Figure 3. Figure 4 (a)and Figure 4 (b) show the photograph of the spectrum formation when a parallel beam of white light coming from a mercury vapour lamp is diffracted through holographic concentrators recorded with the photonic structure of an off-axis zone plate and holographic concentrators recorded with the photonic structure of a planar grating and an off-axis zone plate, respectively.

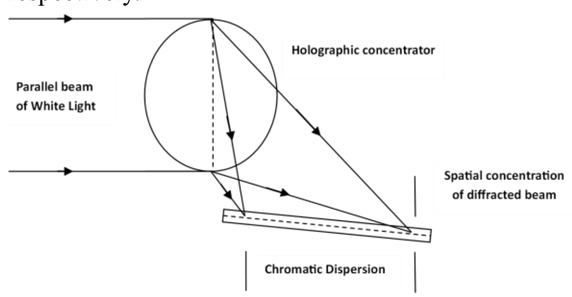
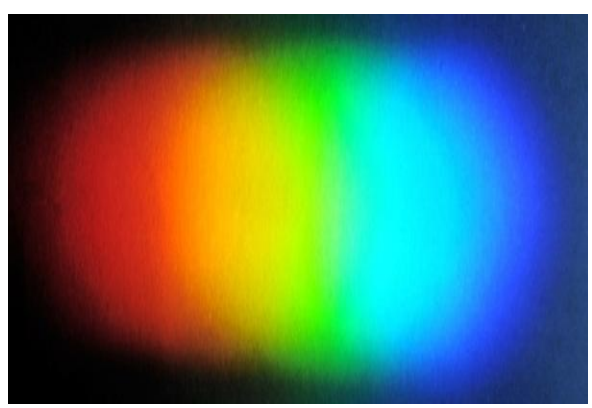
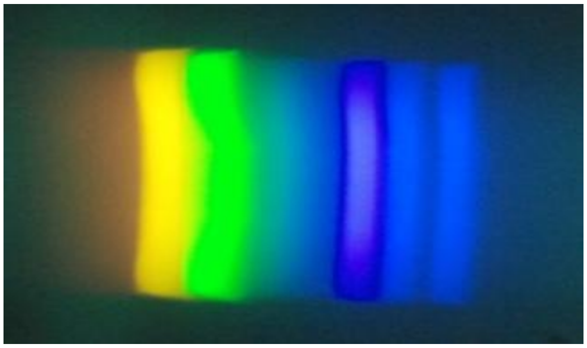


Fig. 3. Schematic of the playback geometry of holographic concentrators.



(a)



(b)

Fig. 4. Photograph of the spectrum of white light diffracted through holographic concentrators, (a) recorded with the photonic structure of an off-axis zone plate, (b) recorded with the photonic structure of a planar grating and an off-axis zone plate.

To show spectral responses of the recorded holographic concentrators, they were illuminated at optimum Bragg's position with three different laser sources emitting wavelengths, λ = 488 nm (blue colour), λ = 543 nm (green colour), and λ = 633 nm (red colour) and the output power in the first order was measured by an optical power meter. Figure 5 shows the variation of diffraction efficiency with wavelength for these concentrators. The diffraction efficiency was calculated using the relation: Diffraction efficiency = Output power / Input power. The variation of diffraction efficiencies of the recorded concentrator shows a good match with the theoretical diffraction efficiency given by Kogelnik's coupled wave theory [25].

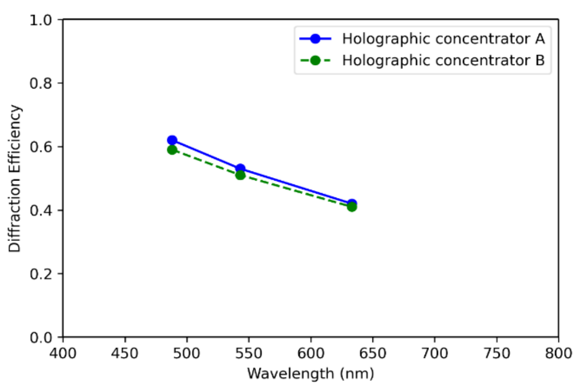


Fig. 5. Variation in diffraction efficiency with wavelength for the recorded holographic concentrators.

Holographic concentrator A is recorded with the photonic structure of an off-axis zone plate. Holographic concentrator B is recorded with the photonic structure of a planar grating and an off-axis zone plate.

III. DISCUSSION AND CONCLUSION

Based on the experimental results, it is concluded that the holographic concentrators can be recorded in different recording geometries to simultaneously disperse and concentrate solar radiation according to different types of PV solar cells. For nanowire solar cells, splitting of solar radiation into different wavelength components and a focused line spectrum, as shown in Figure 4 (b), is desirable. This can be achieved using a holographic concentrator where photonic structures of a plane diffraction grating and an off-axis zone plate are recorded on a high-resolution holographic plate (Figures 1 and 2). Whereas the spectrum shown in Figure 4 (a) is useful for multijunction solar cells. Such a spectrum can be obtained from a holographic concentrator where the photonic structure of an off-axis zone plate is recorded on a high-resolution holographic plate, as shown in Figure 1. Further, such concentrators are inexpensive and lightweight. In addition, holographic concentrators are flat in shape because they are recorded on high-resolution photographic films coated uniformly on optically flat glass plates. This provides ease of integration of holographic concentrators with PV panels. Mass production of holographic concentrators through the replication process provides an additional advantage over conventional concentrators.

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