Solar Holography—A Potential High Efficiency Green Energy Solution

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Abstract Two impediments that acted globally against the progress and popularity of solar electricity were low efficiency and high price of traditional Silicon photovoltaic (PV) panels. Though mass manufacturing and large scale competition between manufacturers have resulted in per Watt price of about 0.3–0.5 USD, low efficiency of these panels still remains as a major hurdle. Concentrator Photovoltaics (CPV) with spectral splitting ability gained worldwide research interest during the recent decades. This paper presents an overview of activities in this highly emerging green energy avenue, some of our work and future design possibilities of relevance.

1 Introduction

Globally there is an increasing and pressing need for the production of green energy. Energy from Sun is not only green but is bestowed free of cost and perpetual also. This is especially relevant for tropical countries that are blessed with abundant sunshine during major part of a year. Due to drastic reduction in price per Watt and aggressive promotional efforts of governments of various countries, recent years witnessed an increase in global popularity of one Sun solar panels. Matured technology, mass manufacturing and increased global competition were other reasons that fuelled the above reduction in price. These PV panels are made of either monocrystalline or polycrystalline Silicon materials. Optimum conversion efficiency under standard test conditions claimed by leading Silicon cell manufacturers is about 18% and this figure reduces to about 12% under true field level conditions. Second generation multi-junction thin film panels are also becoming

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popular now. Leading commercial brands of multi-junction thin film panels have Copper, Indium and Selenium (CIS) as the main ingredients, and include Gallium and Sulphur in the semiconductor layer (CIGS). These panels claim about 14% conversion efficiency and better overall performance under real world conditions where fluctuations in both temperature and solar insolation are realities. Under peak sunshine hours, if we assume an insolation of about 1 kW/m^2, both of the above commercially available panels, in real field conditions, will practically yield only about 120 W/m^2 output. Thus, though the price is affordable, low conversion efficiency still remains as the main impediment for wider global acceptance of PV systems.

Concentrator PV systems use large sun-following reflecting or refracting optical elements to focus intense white light on to multi-junction (MJ) high efficiency cells of about 42% conversion efficiency and are highly attractive due to their high overall output. Currently there are several of such functioning solar plants with large traditional concentrators. The technology of MJ concentrator cells is highly emerging and these cells have already demonstrated an optimum conversion efficiency of over 45% and theoretical predictions of further higher values make it more attractive. However, traditional concentrator optical elements focus heat radiation also on to the cell and this drastically affects the efficiency. Hence special filters and cooling mechanisms are required.

2 Holographic Energy Couplers

Holographic Optical Elements (HOEs) are now effectively applied in a variety of scientific, industrial and Defense applications. High efficiency wavelength filters and dispersive elements, beam combiners and aim sight elements, beam shapers and diffusers, free space wavelength multiplexers and de-multiplexers are just a few examples to mention. Possibility of using HOEs as solar concentrators (Fig. 1) was proposed [1, 2] in the eighties and since then the technology gained increasing attention [3–6] and various module architectures [7] are under consideration. Traditional reflecting and refracting solar concentrator elements focus intense white light on to a MJ cell or MJ arrays, so that various spectral regions pass through the layers of junctions of different spectral sensitivity (Fig.2). On the other hand, Holographic Solar Concentrators (HSCs) are diffractive elements and hence have high spectral selectivity. Spectral response of an HSC under direct sunlight is shown in Fig. 3. Unlike traditional concentrators, HSCs can spectrally split, concentrate and properly direct the solar insolation to specific junctions of different spectral selectivity, resulting in higher and optimum conversion efficiency. HSCs can be designed in such a way that specific infrared wavelengths are diffracted away and the issue of overheating can also be effectively addressed. Thus, HSCs can function as sophisticated energy couplers. Continued improvements in MJ cell

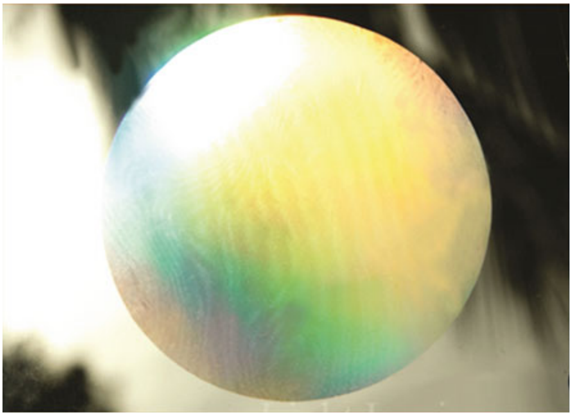

Fig. 1 A holographic solar element set against Sun

Fig. 2 A Multi-junction concentrator cell under white light illumination

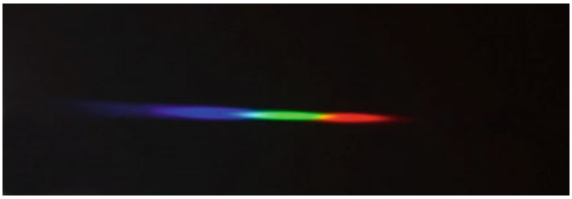

Fig. 3 Spectral response of a transmission type HSC

technology [8] with more number of spectrally selective junctions is a truly encouraging aspect that fuels active research in the development of HSCs and related concentrator modules. Along with this, availability of matured commercial grade photopolymer materials with near 100% diffraction efficiency offer lots of possibilities in recording optimum HSCs for next generation PV applications.

3 Design, Recording and Configuration

A standard optical scheme for recording a transmission HSC is shown in Fig. 4. Coherent light from a laser is split into two beams and both the beams are filtered and expanded to the desired size. Depending upon the spectral sensitivity of the photopolymer material, various recording wavelengths can be chosen. We have used commercial grade red sensitive photopolymer film of 15 μm thickness and homemade photopolymer plates of various thicknesses, coated with Polygrama green sensitive photopolymer emulsion. DPSS lasers of wavelength 639 and 532 nm respectively, were applied to record HSCs of various sizes and properties. Concentration ratio is an important parameter that decides the overall efficiency of a MJ concentrator cell. Along with high spectral selectivity, HOEs have high angular selectivity too. This demands Sun following architecture to effectively and continuously reap the solar insolation. Selection of transmission or reflecting geometry, material thickness, refractive index modulation, selection of substrate material, cost effective copying of the HCS, sealing of the emulsion, encapsulation etc. are essential practical aspects that are to be addressed to achieve commercially acceptable and viable designs. HOEs have high spectral selectivity and multi-function capability. Concentration and spread of each spectral region must match with the cell arrangement and parameters, to facilitate optimum energy coupling. Though photopolymers have lots of advantages over other holographic materials, they demand relatively longer exposure time. This imposes practical limits in recording large format photopolymer HOEs of extremely high concentration ability. However, availability of lasers with abundant power in the green region is a solution to the issue and there are matured photopolymer materials with relatively good response in the green region.

To have a practical HSC system that can yield a sizable electrical output, it is essential to design, develop and incorporate arrays of HOEs that, along with the multi-junction cells, form a holographic concentrator module. Figure 5 shows field

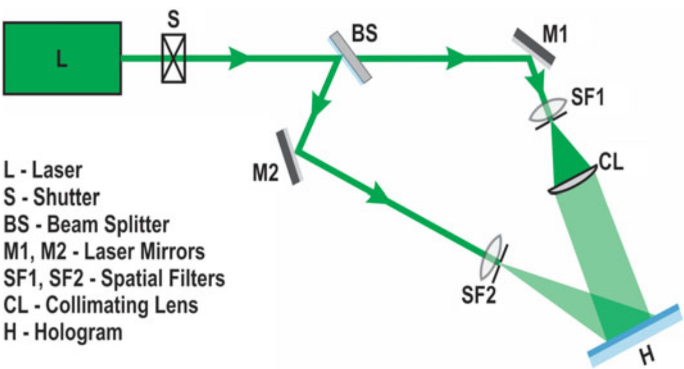

Fig. 4 Optical scheme for recording a transmission type HSC

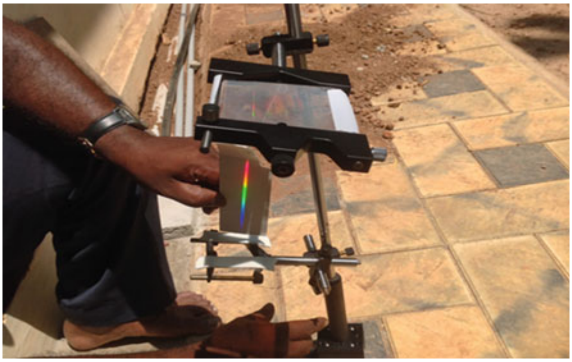

Fig. 5 Field level spectral splitting and concentration response of one of the photopolymer HSCs

level response of one of the photopolymer HSCs we recorded. Advanced simulation and R&D on optimization of parameters to exactly match with ideal MJ cell arrays and viable module formation are further progressing.

4 Possibilities and Challenges

In sharp deviation from traditional concentrator system architecture, HSCs demand laterally arranged junctions (Fig. 6). Possibility of designing and recording HSCs of wide bandwidth with desired spectral response, higher energy coupling efficiency and lower price in comparison with other competing technologies etc. are added advantages of HSC modules. Possible collection of diffuse radiation component, frequency up conversion and passive breadboard type modules can also bring in revolutionary results. Compared to concentrator modules, one Sun modules demand larger collection area. As in any concentrator based system, HSCs also help to derive maximum energy yield from a minimum area. Weight of HSC based modules is much less than traditional concentrator modules. Possibility of mass copying of HSCs and lower cost of photopolymer materials, compared to silicon panels, are other added advantages. On the other side, per Watt price of MJ cells has to come down further in order to achieve development of commercially viable modules.

Though Sun tracking can improve the output yield, one Sun solar modules do not demand Sun tracking. Also, they are warranted for rated output for about 25 years. Hence, achieving stable long-term performance and freedom from Sun tracking are some of the challenges to be addressed with regard to HSC based module design and development.

Solar holography is emerging and getting matured as a subject of its own space and relevance [9, 10]. National Research Council, Institute for Microelectronics and Microsystems, Italy is one of the centers that conduct R&D in this avenue [11]. There are commercial modules [12] that use holographic planar concentrator films

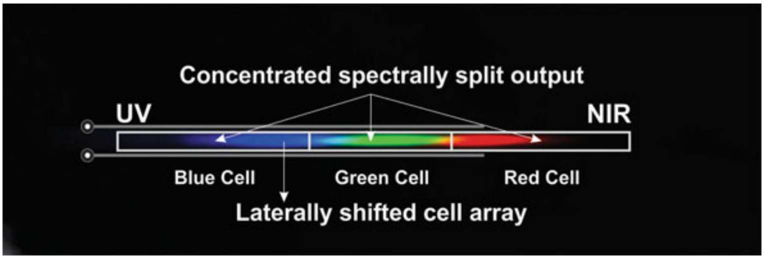

Fig. 6 Schematic of the cell arrangement

in conjunction with bifacial N-type silicon cells and here the architecture is different and the cells used are not multi-junction concentrator cells. Modules made of high efficiency MJ cells with three or more junctions, coupled with matching high efficiency HSCs, can yield exceptionally high energy output from unit area, that too for a lesser cost. However to address the above challenges, holography and semi-conductor technology companies/ laboratories must function hand in hand and in close coherence.

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