Light harvesting using solar cells and luminescent solar concentrators

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Luminescent solar concentrators (LSCs) are panels made of polymers which are doped with fluorescent dye or quantum dots. In space-limited urban areas where deploying solar cells on a large scale is inconvenient, LSC panels can be installed on vertical structures to collect maximum solar radiation. These structures which collect solar radiation, guide the light towards edges of the panel where solar converters are located. Solar converters for large-scale deployment make use of photovoltaic or nano-antenna technology. The latter has the advantage of being able to work at night-time by making use of infrared radiation re-emitted by earth. It is possible to increase the efficiency of LSCs by employing novel approaches which make use of stimulated emission. In this manner, LSCs can increase the share of solar energy use in urban areas.

Keywords: Light harvesting, luminescent solar concentrators, nano-antennas, photovoltaics, solar radiation.

WITH depletion in oil and gas reserves, and global warming caused due to increasing use of fossil fuels, major economies of the world are opting for renewable energy to meet a share of their energy needs. Solar radiation is a major source of renewable energy. Researches on solar cells are continuing to increase the efficiency of these devices. With over 1 kW of radiation falling per square metre, this is a major resource to be tapped for energy requirements of the future. The energy produced by a photovoltaic device depends on the intensity of light falling on it. Devices which can increase the intensity of light before it falls on a solar converter are called solar concentrators. There are various types of lens and mirror structures which can concentrate light towards a solar converter. Alternatively, large panels spread over a wide area can be used for collecting light. These panels known as luminescent solar concentrators (LSCs) or fluorescent solar collectors (FSCs) are made of glass or plastic doped with fluorescent material[1]. They are attached to the walls or roofs of buildings to collect light and guide it by total internal reflection towards the edges of panels where the solar cells are located. This method of light collection is found to be useful for increasing the efficiency of the installed system, since the expensive solar cells are used judiciously to increase the power production capacity of the system. In this article, the role of LSC in solar power-generating systems is considered.

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Solar radiation

Intensity of solar radiation reaching the earth's surface gets reduced due its passage through the atmosphere[2]. This happens due to the absorption and scattering of radiation by various gases present in the atmosphere. Solar radiation outside the earth's atmosphere has an intensity of 1367 W/m^2, also known as the solar constant[3]. This value decreases by an amount proportional to the thickness of the earth's atmosphere through which the radiation traverses[4]. It is expressed in terms of a unit called air mass (AM), which is defined as the ratio of thickness of the atmosphere through which solar radiation traverses to the local thickness of the earth's atmosphere[5]. Figure 1 illustrates calculation of air mass. Air mass can be conveniently expressed as $1/\cos\phi$, where ϕ is the angle

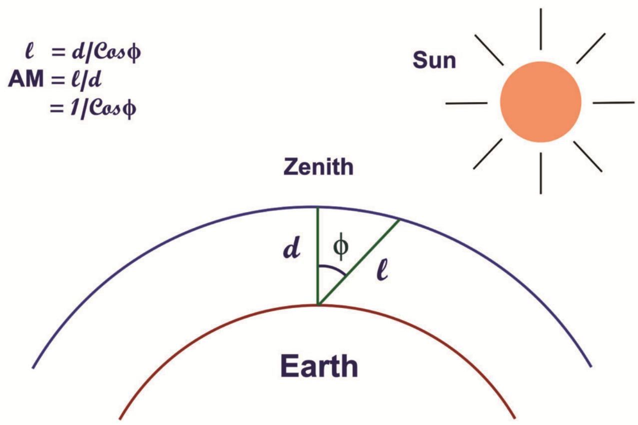

Figure 1. Estimation of air mass from the position of sun and zenith.

between position of the sun and zenith. Air mass value in the outer space is denoted by AM0, and is equivalent to the solar constant. Terrestrial irradiation when position of the sun is at this zenith is denoted by AM1. For measurement purposes, irradiation which is made at an angle 48° with the zenith, denoted by AM1.5 is adopted as the standard. This corresponds to an intensity of 1000 W/m^2. Solar irradiance varies with wavelength, and its distribution outside the earth's atmosphere resembles the blackbody radiation spectrum. Figure 2 shows the spectral irradiance for AM0. As it can be noticed, visible and infrared regions account for 90% of spectral irradiance[6]. Hence, most of the materials used for solar cell fabrication operate in this spectral range.

Solar cell technology

Solar energy can be converted into electricity by various means. Considering the economic aspect of conversion, it is worthwhile to consider two technologies which have the potential for scaling up – photovoltaics and nano-antennas.

Photovoltaics

In case of the photovoltaic effect, a potential is developed across dissimilar materials when electromagnetic waves are incident on them. After the semiconductor revolution in the 1950s, silicon-based p–n junction solar cells are the most commonly employed photovoltaic cells. Figure 3 shows the basic structure of a p–n junction solar cell. Here, the n region is thin compared to the p region. This design allows light falling on the n region to reach the p–n junction, where the photons interact with lattice atoms to create electron–hole pairs. Due to presence of the depletion region, the electrons created drift towards the n region, whereas the holes created drift towards the p region. In this way, a solar cell is able to produce a potential difference across the n and p regions. When an external circuit is connected, the electrons follow through it to produce a current. The amount of current generated is proportional to the intensity of light falling on a solar cell. So, it is essential to increase the intensity of light falling on a solar cell to draw maximum current from it. LSCs can be used for achieving this goal. To reduce the light lost by reflection, the front surface of a solar cell has an antireflection coating. It also contains ohmic contact in the form of fingers to draw current. This design helps retain the light-falling area of the solar cell by allowing minimum obstruction[3]. Solar cells are connected together to form solar panels which generate enough power to run electric devices. The power produced from a solar cell is direct current (DC) whereas most of electrical appliances run on alternating current (AC). Due to this reason; DC is converted to AC using an inverter before it is supplied to an appliance[7].

Nano-antennas

Just like antennas which operate in the microwave and radio wave frequencies, it is possible to construct antennas which operate in infrared and visible regions of the electromagnetic spectrum. These antennas which are considerably smaller in dimension are known as nano-antennas (abbreviated as nantennas)[8]. The AC generated from nano-antennas should be converted to DC before it can be stored in a battery. For conversion from AC to DC, a rectifier (diode) is attached along with the antenna. This combination of antenna and diode is usually referred to as rectenna[9]. Nano-antennas can be connected together to generate enough power required for running electrical devices. Figure 4 shows an array of square spiral nano-antennas which can serve this purpose. The central part of the nano-antenna consists of a metal–insulator–metal

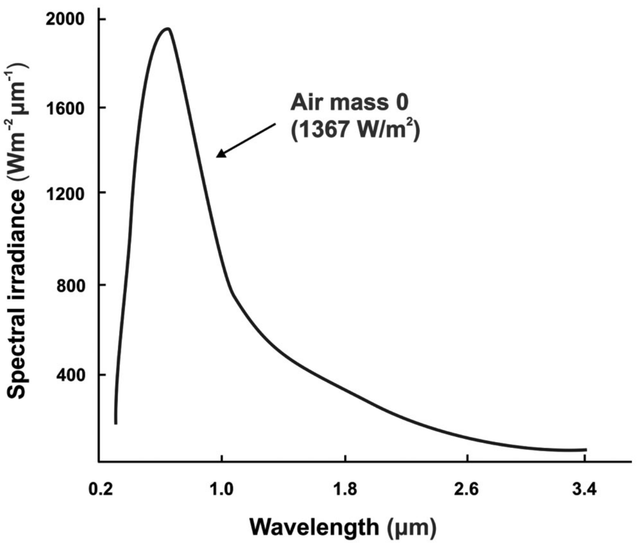

Figure 2. Spectral irradiance for air mass in outer space (AM0) which resembles the blackbody radiation spectrum.

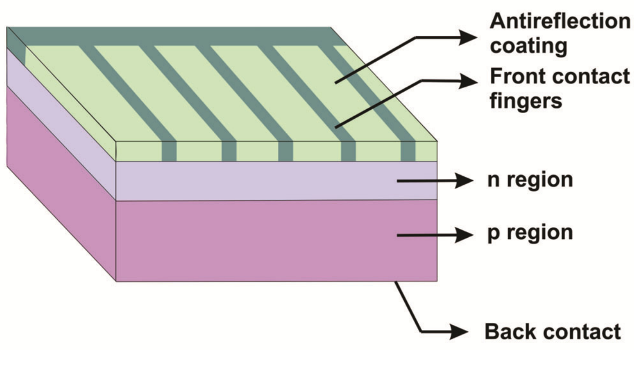

Figure 3. Basic structure of a p–n junction solar cell.

(MIM) diode[10]. This diode whose operation is based on quantum mechanical tunnelling offers faster rectification required in the optical frequency range. Compared to photovoltaics which operate only during daytime, nano-antennas designed for infrared frequency range can also operate during night by making use of longwave infrared radiation emitted by the earth[11]. In this way, nano-antennas offer a viable technological front for round-the-clock energy harvesting. Moreover, compared to photovoltaics which have a maximum efficiency of 30%, this technology has a theoretical conversion efficiency of 100%. Efforts are under way to make use of this technology to transform wasted heat energy into electricity.

Luminescent solar concentrators

From an economical perspective, light harvesting becomes effective only when large areas are covered for solar energy conversion. It is not cost-effective to deploy solar convertors for large areas. An alternative would be the use of LSCs[12]. This device consists of panels made of plastic such as polymethyl-methacrylate (PMMA), which is doped with fluorescent dyes or quantum dots. When solar radiation falls on these panels, fluorescent dye is excited which results in fluorescence emission. Due to the presence of air medium outside, a part of the fluorescent radiation which undergoes total internal reflection reaches the edges of the panels where the solar cells are located[13]. These transparent panels which can collect solar radiation from large areas such a vertical structures of buildings are useful for making solar power economical[14]. Based on band gap of the luminescent material, the colour of the panel will be different. This adds to the aesthetic appeal as for collecting light from different parts of the solar spectrum. Figure 5 is a schematic representation of the working of a LSC. Due to small Stokes shift, i.e. the separation between absorption and emission peaks, fluorescent dyes have the disadvantage of reabsorption of emitted light. Though quantum dots are able to overcome this limitation, their quantum yields are not appreciable. Efforts are under way to increase the quantum yield and Stokes shift required for a suitable LSC material.

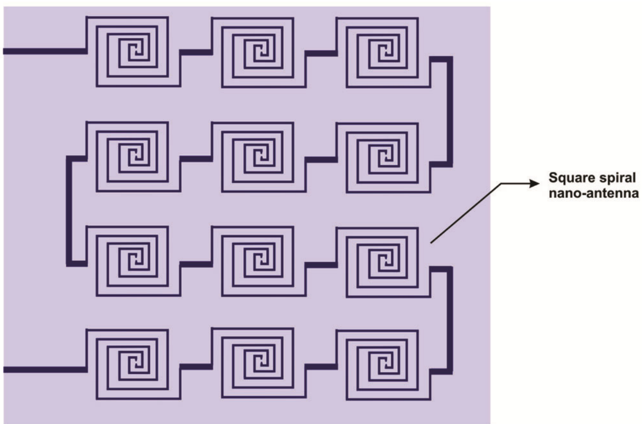

Figure 4. An array of square spiral nano-antennas.

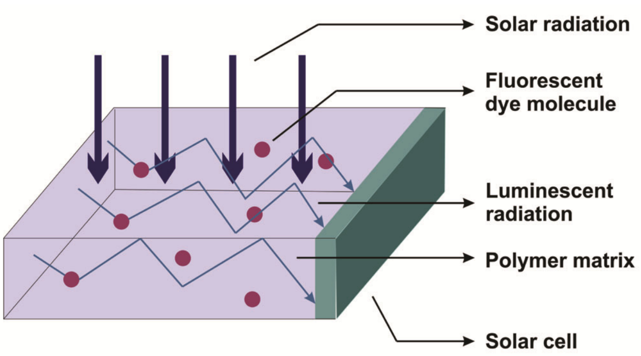

Figure 5. Guidance of luminescent radiation in luminescent solar concentrator by total internal reflection.

Novel approaches for increasing efficiency

In order to rectify the drawbacks of LSCs, novel approaches are being adopted. In one such effort, stimulated emission is used to reduce reabsorption. In this technique, a diode laser is used to overcome the spontaneous emission process in favour of stimulated emission. The laser diode has emission corresponding to the emission peak of the dye molecule in a LSC. When solar radiation falls on the LSC, the efficiency can be significantly increased if the emission is stimulated. The laser diode acts as a mediator here for converting the process from spontaneous to stimulated emission. Since stimulated emission produces coherent radiation, the intensity is very high. This helps in increasing the efficiency of the LSC. A part of the output power from the solar cell can be used for working of the laser diode, which makes the system self-sufficient[15].

Conclusion

With increase in energy demand, major economies of the world are now considering solar power for their energy needs. For converting solar energy into electricity, the technologies employed should have considerable efficiency to compete with fossil fuels. Two widely adopted scalable technologies in this regard are photovoltaics and nano-antennas. As of now, the cost of solar power is quite high when compared to non-renewable energy. This can be considerably reduced by deploying LSCs. These planar structures doped with fluorescent dye or quantum dots have the ability to concentrate light towards solar converters located at the edges of the panels. Compared to solar converters, these polymer structures can be manufactured at a fraction of the cost. Moreover, they can be installed in vertical structures in urban areas to collect maximum solar radiation from the available space. Thus, this technology will be useful for adopting solar power in a big way by reducing the cost of installing solar cells.

1. Christie, R. M., *Colour Chemistry*, Royal Society of Chemistry, Cambridge, UK, 2015.
2. Andrews, J. and Jelley, N., *Energy Science: Principles, Technologies, and Impacts*, Oxford University Press, New York, USA, 2007.
3. Sze, S. M. and Lee, M. K., *Semiconductor Devices: Physics and Technology*, John Wiley, New York, USA, 2012.
4. Smestad, G. P., *Optoelectronics of Solar Cells*, SPIE Press, New York, USA, 2002.
5. Eicker, U., *Solar Technologies for Buildings*, John Wiley, New York, USA, 2003.
6. Da Rosa, A. V., *Fundamentals of Renewable Energy Processes*, Academic Press, New York, USA, 2009.
7. Hantula, R., *How Do Solar Panels Work?* Infobase Publishing, New York, USA, 2010.
8. Sangster, A. J., *Electromagnetic Foundations of Solar Radiation Collection: A Technology for Sustainability*, Springer, New York, USA, 2014.
9. Nozik, A. J., Conibeer, G. and Beard, M. C., *Advanced Concepts in Photovoltaics*, Royal Society of Chemistry, New York, USA, 2014.
10. Moddel, G. and Grover, S., *Rectenna Solar Cells*, Springer, New York, USA, 2013.
11. Mescia, L., Losito, O. and Prudenzano, F., *Innovative Materials and Systems for Energy Harvesting Applications*, IGI Global, Hershey, USA, 2015.
12. Goetzberger, A., *High-Efficient Low-Cost Photovoltaics: Recent Developments*, Springer, Berlin, Germany, 2009.
13. Lifante, G., *Integrated Photonics: Fundamentals*, John Wiley, New York, USA, 2003.
14. Debije, M., Renewable energy: better luminescent solar panels in prospect. *Nature*, 2015, **519**, 298–299.
15. Kaysir, M. R., Fleming, S., MacQueen, R. W., Schmidt, T. W. and Argyros, A., Luminescent solar concentrators utilizing stimulated emission. *Opt. Express*, 2016, **24**, A497–A505.

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