ISSN No. 2456-0472

The Engineering Journal of Application & Scopes, Volume 3, Issue 1, May 2018

A REVIEW ON TRANSPARENT LUMINESCENT SOLAR CONCENTRATORS

Jayant Agarwal, Vishal Rai

Department of Mechanical Engineering, College of Engineering Roorkee, Roorkee, Haridwar, Uttarakhand – 247667

Department of Computer Science, College of Engineering Roorkee, Roorkee, Haridwar, Uttarakhand – 247667

jayantpkagarwal@gmail.com

Abstract–There is only one renewable energy source that can power the whole world today, i.e. Solar Energy. Solar energy has limitless potential but also has some major hurdles like the availability of land for installation of the solar power plant. If these solar cells are made transparent, they can be placed anywhere. A normal solar cell is opaque and absorbs maximum part of the sunlight falling on it. It absorbs light in all part of the spectrum and only 33% of the absorbed light is converted into electricity. A transparent solar cell is basically a thin film which can be placed on any surface, to extract energy from the Sun. These contractors let the visible spectrum of the light to pass through it and act as an opaque object for the UV and Near Infrared Spectrum Light. In the transparent Solar cells, if the visible part is cut out, still nearly 22% of the light is converted into electricity. There is a very vast application of this transparent solar cell. The most prominent application is the conversion of windows of skyscraper or any other building into a solar window. While utilizing the roof tops of the buildings, the vertical space of the buildings can also be utilized significantly for harvesting solar energy.

Keywords– Solar energy, Transparent Solar Cells, UV, NIR radiation.

I. INTRODUCTION

Due to the depleting natural resources like the fossil fuels, the researchers and scientists have been discovering various alternative sources of energy and ways to improve the efficiency of the existing mechanisms to capture energy from renewable energy sources. One such energy source is our solar system's star, Sun. The solar radiation from the sun has been converted into electricity for many decades using Photovoltaics (PV). The key motto in R&D of PV is to attain higher conversion efficiencies at lower costs. Still today, PV modules are quite costly and the deployment of the PV modules still requires financial support schemes such as investment subsidies. Nevertheless, the PV industry has experienced an average growth rate of 40% over the past 10 years [1].

To attain lower cost per installation capacity, many methods have been trailed all leading to complete and more use of the entire solar spectrum and not only the visible spectrum. All these routes are being referred to as the Third Generation PV[2, 3]. Examples of the third generation PV beingintermediate band-gap cells[4], quantum dot concentrators[5] and down- and up-converters[6, 7].

In the late 1970's, down conversion was proposed to be used in the Luminescent Solar Concentrators (LSC), also known as the fluorescent concentrators, to which solar cells were attached[8]. LSCs are transparent plastic slabs or waveguides, which consist of dispersed luminescent species, which are organic dye molecules or inorganic phosphors or quantum dots. These dye molecules absorb the incident solar light and emit it isotropically at longer wavelength with higher quantum efficiency. Internal reflection in the LSC ensures that the emitted light is concentrated at the edges of the waveguide, where small PV cells are attached which convert the emitted light into electricity.

The LSC is potentially more beneficial than silicon-based PV modules, especially in the built environment. The materials used for the manufacturing of LSC are relatively inexpensive and they also reduce the size of PV cells to more than 90%, hence utilizing the space more efficiently with lower modular costs. Since, plastic waveguides are lighter in weight than PV cells; therefore the reduction in weight makes LSC more feasible to mount on the buildings. LSC are better than PV cells in terms of collecting indirect sunlight as the sunlight can enter the waveguide surface form any angle. Due to thin shapes, LSC can be used to make curved surfaces.

II. LUMINESCENT SOLAR CONCENTRATORS (LSC)

Generally, two categories of concentrators are widely developed:

1) Focusing optical or thermal concentrators.
2) Luminescent concentrators.

A geometric focusing solar concentrator uses a reflective or refractive surface to redirect or focus the incident solar radiation onto PV cells or other energy harvesting systems. The most common focusing optics concentrators are – Parabolic troughs, Heliostatic arrays, Sterling dishes and Fresnel reflectors. These concentrators work well in few configurations but they also have two major limitations. One, the cost of robust elements is very high. Secondly, as they require solar trackingsystems to harvest the solar spectrum efficiently, it becomes unviable to be mounted on the buildings.

On the other hand, Luminescent Solar Concentrators (LSC) proves to be good option due to their simple design, easy integration and low cost. LSC is a plastic or glass waveguide embedded with chromophores which absorb the incident radiation and re-emit it at longer wavelengths and transmit these emitted radiations to the small PV cells mounted at the sides of the waveguides, which collect the light and generate electricity.

With recent advancements in the efficiencies of the phosphorescent and fluorescent luminophores, there has been an increment in the power conversion efficiency of the LSC modules to 7.1% using the multi-dye systems with GaAS photovoltaics[9]. The overall system conversion efficiency of the LSC modules is limited to less than 20%, in reality, due to the optical funneling[10]. Also optical funneling reduces the area of PV cells required bringing down the overall module cost[11-15].

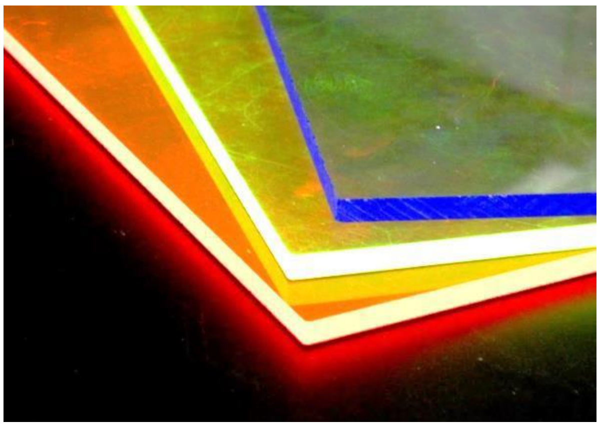

Fig. 1.Photograph of typical colorful luminescent solar concentrators highlighting the waveguided emission that is brightly focused at the edge.

Table 1: Efficiency of highest performing lsc's from the literature (note that metrics are for strongly colored (or black) lscs, which absorb and emit in visible spectrum)

Dye	Cell	LSC size (m x m)	Efficiency	Reference
Red305, CRS040	GaAs	0.05 x 0.05	7.1	[9]
BA241, BA856	GaInP	0.05 x 0.05	6.7	[34]
Rubrene, DCJTB	CdTe	0.1 x 0.1	4.7	[35]
CdSe/CdS /CdZnS/ZnS	Si	0.05 x 0.03	2.8	[36]
CdSe/CdS	GaAs	1.4 x 1.4	4.5	[37]
Red305, perylene perinone	Si	0.05 x 0.05	4.5	[38]
SrB4O7	Si	0.05 x 0.05	2.5	[38]
EuTT	Si	0.1 x 0.1	0.28	[39]

The molecules in LSC which absorb and re-emit photons are known as Luminophores. Chromophore is a molecule which is absorbs or emits light in generation of color whereas a luminophore does not necessarily impart color. The following requirements make a luminophore effective for the application of LSC [16]:

1) Should possess broad spectral absorption, i.e. it can absorb maximum key wavelengths of interest.
2) High quantum yields for luminescence.
3) Stokes shift should as large as possible so that the overlap of absorption and emission is very small or negligible.
4) Luminescence wavelength should match the solar cell spectral wavelength.

The key structure that supports the LSC module is the waveguide which is also used to transport the optical energy. The amount of light that can be transmitted within the waveguide using the phenomenon of Total Internal Reflection is given by the waveguide efficiency. The waveguide efficiency as a function of refractive index is given by the following expression[16].

$$\eta_{wav} = \sqrt{1 - \frac{1}{n^2}}$$

Low absorption coefficients lad to low reabsorption losses, which are significant when scaled up to larger areas. Figure 2 depicts the absorption coefficients for various waveguide materials.

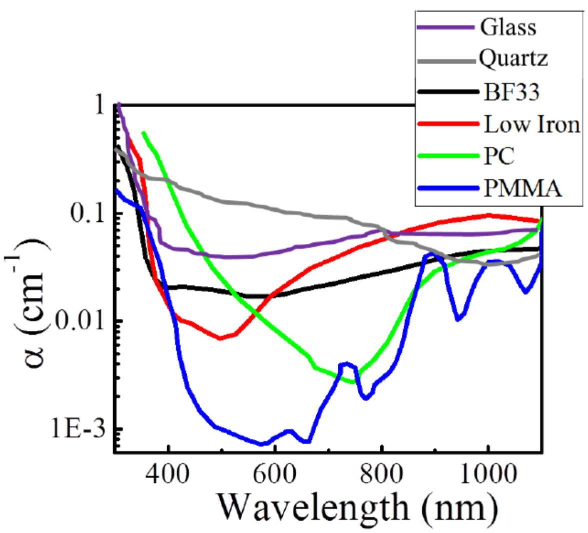

Fig. 2. Absorption coefficients of standard glass, quartz, BF33 glass, low iron glass, polycarbonate (PC) and poly(methyl methacrylate) (PMMA) as a function of wavelength[17].

The overall LSC efficiency depends upon following component efficiencies:

1) Solar spectrum absorption
2) Luminophore photoluminescence efficiency

3) Waveguide efficiency

4) Solar cell quantum efficiency

5) Transport and re-absorption efficiency

All these factors are used to formulate following expression for overall efficiency of LSC [18]:

$$\eta_{overall} = \eta^{*}_{PV}(1-R)\eta_{ABS}\,\eta_{PL}\,\eta_{trap}\,\eta_{RAE} \qquad (1)$$

where R is the fraction of front face reflection, η_{ABS} is the solar spectrum absorption efficiency of the luminophore, η_{PL} is the luminescence efficiency of the luminophore, η_{trap} is the waveguiding efficiency of the light, η^{*}_{PV} is the PV quantum efficiency and η_{RAE} is the efficiency of transporting photons without reabsorption loss[19]. For large area LSC modules, luminescence efficiency and re-absorption efficiency influence the most.

III. Transparent Luminescent Solar Concentrators (TLSC)

Under this section, the concept of transparent solar cells will be introduced. The discussion will be done on the working principle of the transparent solar cells, their types, range of applications where it can be used like the solar windows, mobile, electronics etc. and the theoretical limits of these transparent solar cells.

Transparent solar cells have opened a new path for the installation of solar harvesting surfaces to generate power while being completely blended in the environment. These surfaces selectively harvest either the UV or the Near Infrared (NIR) radiation which are completely invisible to naked eyes. These cells can be used to convert any normal surface into energy producing surface without any significant modifications to aesthetics and design. Previously many attempts were made to make transparent or semi-transparent solar cells, using following methods:

1) Optically thin PV with significant tinting or limited transmission[20, 21]or which have inherent adjustment between transparency and efficiency of the cell.

2) LSC's integrated with colored chromophores that absorb or emit radiation in visible spectrum, hence again generating significant tinting[22, 23].

3) Focusing optics concentrators using direct light only which need heavy solar tracking systems or optics[15, 24].

Due to the factors like the aesthetic properties, bulkiness or limited transparency, above mentioned methods have limited their applications only to windows and display parts. Recently, highly transparent PVs have been fabricated which selectively absorb near-infrared radiation by manipulating the exitonic character of the molecular and organic semiconductors with efficiencies of the range of 2-4% for small areas [25-27]. These transparent PVs possess the highest possible combination of conversion efficiency and transparency but also possess many challenges like strict defect tolerances, partial shading and different others to scale-up. In contrast to these, transparent LSCs with UV or NIR selective absorption, avoid aesthetic compromises and provide clear path for the scaling of larger area.

1) An ideal TLSC meets the following conditions:

2) The luminescence efficiency of the luminophore (η_{PL}) is maximum i.e. 100%.

3) The efficiency and quantum efficiency of the PV cell fixed at the edges must be equal to the Shockley-Queisser Limit.

4) Reflection losses are zero

5) Perfect light trapping takes places in the waveguide.

6) There is no reabsorption losses i.e. absorption and emission do not overlap.

7) There is no intensity dependence on the PV

8) The emission width (W) is narrow.

When all the above mentioned requirements are met by a TLSC, the efficiency limits to 20%, which is identical to the Transparent PV (TPV) cells.

A. *UV Absorbing TLSC:*

Transparent luminescent solar concentrator (TLSC) can absorb energy in different spectral ranges: in the UV or NIR. Even with the lower overall fraction of the solar spectrum in the UV (~6% photons, ~10% energy), there is significant potential in harvesting the UV in a transparent luminescent solar concentrator (TLSC) configuration up to 4% system energy conversion efficiency. TLSC employing novel nanocluster-polymer blends that allow for harvesting of selective ultraviolet light that results in a high degree of visible light transmittance demonstrating this pathway as a viable route to the production of transparent LSCs.

To efficiently convert the UV light, we focus on massive Stoke's shift (MSS) hexanuclear metal halide clusters of the form $M_6(II)X_{12}$.While the parent compounds of M = Mo and W, and X = Cl, Br, I etc. have been known for some time, their use has been limited to photophysical studies and oxygen sensors with quantum yields typically less than 20% [28]. These materials are highly stable, highly luminescent, US abundant, and non-toxic. Here, we have synthesized nanocluster complex-host blends with quantum yields > 75% and anticipate reaching near-unity quantum yields through further chemical and ligand modifications.

B. *NIR Absorbing TLSC:*

We exploit the structured absorption of organic excitonic semiconductors to produce near-infrared (NIR) LSC architectures that selectively harvest NIR photons by wave guiding deeper-NIR luminophore emission to high efficiency segmented solar cells. These transparent NIR LSCs can eliminate the visual impact and minimize the amount of expensive solar materials required while extending the photon harvesting range into the NIR.

The large phosphorescent Stokes shift and high quantum yield allowed for power conversion efficiency of > 0.5% over large module area (m^2) but these LSCs are ultimately limited toefficiencies up to 5% due to the limited UV fraction in the solar spectrum. To increase the overall potential of these systems, we look to selectively harvest NIR photons, where there is a substantially greater fraction of the solar photon flux (~74%). NIR fluorescent dyes, especially phthalocyanines, cyanines, and squaraine dyes have been widely used in fluorescence microscopy, bioimaging, organic light emitting diodes and other light emission applications. However, the quantum efficiency has mostly been limited to < 40% and most exhibit visible absorption[29-33].

Previous research on NIR-emitting LSCs employing inorganic compounds such as semiconducting quantum dots and nanocrystals as active materials typically have improved quantum yields but also present continuous band absorbance (with only minor excitonic features near the band edge). Accordingly, these systems all exhibit visible absorption or coloring despite emitting NIR. The NIR TLSCs based on organic salts provide an alternative strategy for transparent solar harvesting systems that can ultimately enhance the overall system efficiency of combined UV and NIR TLSCs.

IV. CONCLUSION

Integrating solar-harvesting systems into the built environment is a transformative route to capturing large areas of solar energy, lowering effective solar cell installation costs, and improving building efficiency. Indeed, the idea of luminescent solar concentrators (LSC), which were first introduced in the 1970s to reduce solar cell costs, are now regaining attention as low-cost solar harvesting systems to deploy around the building envelope. However, the visible absorption and emission of these LSCs result in highly colored systems that hamper their widespread adoptability in many applications, including windows.

The UV absorbing TLSC's are composed of the phosphorescent metal halide nanoclusters. The near perfect absorption cutoff at the edge of the visible spectrum (430nm) and the massive Stokes shift to the near-infrared (800nm) of these nanoclusters allows for efficient and selective harvesting of ultraviolet (UV) photons, improved reabsorption efficiency and non-tinted transparency in the visible spectrum. The NIR TLSC's selectively harvest the NIR photons based upon the fluorescent organic salts. These transparent NIR LSCs provide a new route to transparent light-harvesting systems with tremendous potential for high defect tolerances and processability.

V. FUTURE OUTLOOK

The aim of this work was to demonstrate transparent luminescent solar concentrators as a new pathway for widespread window deployment that can be scaled to commercial window products. Such a technology has the benefit of facile production, high defect tolerances, and exceptional scalability without many of drawbacks of scaling a transparent PV technology (resistive losses, partial shading losses, device yield, current matching, etc.). While the work presented so far has opened up an exciting new field and has demonstrated a key starting point for these new types of devices, there are a number of opportunities yet to be explored.

VI. REFERENCES

[1] W. G. J. H. M. Van Sark, G. W. Brandsen, M. Fleuster, and M. P. Hekkert, "Analysis of the silicon market: Will thin films profit?," Energy Pol. 35, 3121 (2007).

[2] M. A. Green, Third Generation Photovoltaics, Advanced Solar Energy Conversion (Springer Verlag, Berlin, Germany, 2003).

[3] A. Martí and A. Luque, eds. "Next Generation Photovoltaics, High Efficiency through Full Spectrum Utilization," in Series in Optics and Optoelectronics, R.G.W. Brown and E.R. Pike. eds. (Institute of Physics Publishing: Bristol, UK, 2004).

[4] A. Luque and A. Marti, "Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels," Phys. Rev. Lett. 78, 5014-5017 (1997).

[5] K. Barnham, J. L. Marques, J. Hassard, and P. O'Brien, "Quantum-dot concentrator and thermodynamic model for the global redshift," Appl. Phys. Lett. 76, 1197-1199 (2000).

[6] T. Trupke, M. A. Green, and P. Würfel, "Improving solar cell efficiencies by down-conversion of high-energy photons," J. Appl. Phys. 92, 1668-1674 (2002).

[7] T. Trupke, M. A. Green, and P. Würfel, "Improving solar cell efficiencies by up-conversion of sub-band-gap light," J. Appl. Phys. 92, 4117-4122 (2002).

[8] A. Goetzberger and W. Greubel, "Solar Energy Conversion with Fluorescent Collectors," Appl. Phys. 14, 123-139 (1977)

[9] L. H. Slooff, E. E. Bende, A. R. Burgers, T. Budel, M. Pravettoni, R. P. Kenny, E. D. Dunlop, A. Buchtemann, Physica Status Solidi-Rapid Research Letters 2008, 2, 257.

[10] F. Galluzzi, E. Scafe, Solar Energy 1984, 33, 501.

[11] W. H. Weber, J. Lambe, Applied Optics 1976, 15, 2299.

[12] A. Goetzberger, W. Greubel, Applied Physics 1977, 14, 123.

[13] Wittwer, W. Stahl, A. Goetzberger, Solar Energy Materials 1984, 11, 187.

[14] G. Smestad, H. Ries, R. Winston, E. Yablonovitch, Solar Energy Materials 1990, 21, 99.

[15] W. G. J. H. M. van Sark, K. W. J. Barnham, L. H. Slooff, A. J. Chatten, A. Buchtemann, A. Meyer, S. J. McCormack, R. Koole, D. J. Farrell, R. Bose, E. E. Bende, A. R. Burgers, T. Budel, J. Quilitz, M. Kennedy, T. Meyer, C. D. M. Donega, A. Meijerink, D. Vanmaekelbergh, Opt Express 2008, 16, 21773.

[16] M. G. Debije, P. P. C. Verbunt, Advanced Energy Materials 2012, 2, 12.

[17] L. R. Wilson, Ph.D. Thesis, Heriot-Watt University, May 2010.

[18] R. Kinderman, L. H. Slooff, A. R. Burgers, N. J. Bakker, A. Buchtemann, R. Danz, J. A. M. van Roosmalen, Journal of Solar Energy Engineering-Transactions of the Asme 2007, 129, 277.

[19] L. R. Wilson, B. S. Richards, Applied Optics 2009, 48, 212.

[20] J. S. Batchelder, A. H. Zewail, T. Cole, Applied Optics 1981, 20, 3733.

[21] M. J. Currie, J. K. Mapel, T. D. Heidel, S. Goffri, M. A. Baldo, Science 2008, 321, 226.

[22] J. M. Drake, M. L. Lesiecki, J. Sansregret, W. R. L. Thomas, Applied Optics 1982, 21, 2945.

[23] J. Yoon, L. F. Li, A. V. Semichaevsky, J. H. Ryu, H. T. Johnson, R. G. Nuzzo, J. A. Rogers, Nature Communications 2011, 2, 343.

[24] A. M. Hermann, Solar Energy 1982, 29, 323.

[25] L. H. Slooff, R. Kinderman, A. R. Burgers, A. Buechtemann, R. Danz, T. B. Meyer, A. J. Chatten, D. Farrell, K. W. J. Barnham, J. A. M. van Roosmalen, Photonics for Solar Energy Systems 2006, 6197.

[26] M. G. Debije, P. P. C. Verbunt, P. J. Nadkarni, S. Velate, K. Bhaumik, S. Nedumbamana, B. C. Rowan, B. S. Richards, T. L. Hoeks, Applied Optics 2011, 50, 163.

[27] R. Reisfeld, M. Eyal, V. Chernyak, R. Zusman, Solar Energy Materials 1988, 17, 439.

[28] V. Shrotriya, G. Li, Y. Yao, T. Moriarty, K. Emery, Y. Yang, Advanced Functional Materials 2006, 16, 2016

[29] V. J. Pansare, S. Hejazi, W. J. Faenza, R. K. Prud'homme, Chemistry of Materials 2012, 24, 812.

[30] J. O. Escobedo, O. Rusin, S. Lim, R. M. Strongin, Current Opinion in Chemical Biology 2010, 14, 64.

[31] G. M. Fischer, M. Isomaki-Krondahl, I. Gottker-Schnetmann, E. Daltrozzo, A. Zumbusch, Chemistry-a European Journal 2009, 15, 4857.

[32] R. Weissleder, Nature Biotechnology 2001, 19, 316.

[33] J. C. Ostrowski, K. Susumu, M. R. Robinson, M. J. Therien, G. C. Bazan, Advanced Materials 2003, 15, 1296.

[34] J. C. Goldschmidt, M. Peters, A. Bosch, H. Helmers, F. Dimroth, S. W. Glunz, G. Willeke, Solar Energy Materials and Solar Cells 2009, 93, 176.

[35] M. A. Faist, T. Kirchartz, W. Gong, R. S. Ashraf, I. McCulloch, J. C. de Mello, N. J. Ekins-Daukes, D. D. C. Bradley, J. Nelson, Journal of the American Chemical Society 2012, 134, 685.

[36] J. Bomm, A. Buchtemann, A. J. Chatten, R. Bose, D. J. Farrell, N. L. A. Chan, Y. Xiao, L. H. Slooff, T. Meyer, A. Meyer, W. G. J. H. M. van Sark, R. Koole, Solar Energy Materials and Solar Cells 2011, 95, 2087.

[37] G. Smestad, C. Bignozzi, R. Argazzi, Solar Energy Materials and Solar Cells 1994, 33, 253.

[38] L. Desmet, A. J. M. Ras, D. K. G. de Boer, M. G. Debije, Optics Letters 2012, 37, 3087.

[39] T. X. Wang, J. Zhang, W. Ma, Y. H. Luo, L. J. Wang, Z. J. Hu, W. X. Wu, X. Wang, G. Zou, Q. J. Zhang, Solar Energy 2011, 85, 2571.