GREEN PHOTONICS – A BROAD OVERVIEW

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Abstract: The importance of Green Photonics or understanding how optics can be used for applications that help protect the environment is brought out. The paper gives an overview of Green Photonics and covers aspects such as Photonics for Clean Energy Generation and Solid State Lighting as well as applications of Photonics Technology in Energy Loss Reduction and Environmental Sensing. The importance of the knowledge of optics in spreading awareness about the Greenhouse Effect as well as the little discussed but important issue of Light Pollution are also touched upon. At the end an interesting possibility of 'Artificial Photosynthesis' is brought out.

1. INTRODUCTION

With the last summer's power crisis fresh in our memory and Delhi still generating only 15-18 % of its own energy requirement, it is essential to look at innovative methods for mitigating the power shortage. Additional growth of coal-based power is not desirable both financially and environmentally. It is 'green' solutions that one needs to look at now. We also need to act on the presumption – 'Power saved is power generated' [1].

The National Action Plan on Climate Change (NAPCC) released by the Prime Minister on 30th June 2008 outlines the national strategy to meet the challenge of Climate Change. Eight National Missions, form the core of the National Action Plan, representing multi-pronged, long term and integrated strategies for achieving key goals in the context of climate change [2].

These missions include [3]

1. National **Solar Mission** to increase the share of solar energy for decentralized distribution and to create affordable and convenient solar power systems.
2. National Mission for **Enhanced Energy Efficiency** to introduce cost effectiveness and shift to energy efficient appliances.

The Infrastructural Agencies in general agreed to adopt the following concepts in making Clean Development Program (CDM) projects:

1) Energy Conservation
2) Use of CFL and Electric Chokes
3) Solar Water Heating Systems
4) Efficient Street-lighting
5) Efficient use of water pumps
6) Energy efficient buildings
7) Promotion of LEDs
8) Solar Air-conditioning, etc
9) Afforestation [3]

Many of these concepts will require the application of 'Green Photonic Technology'.

Reducing greenhouse gas emission requires action in various sectors viz. power, transport, buildings, land-use, agriculture, and industry. As we transition to an information-driven society, photonics will play a key role in green IT, communications and information display.

'Green Photonics' impacts energy generation (photovoltaics), lighting (solid state lighting and displays), and communications. The contribution of photonics is considered "green" if it generates or conserves energy, reduces pollution, yields an environmentally sustainable outcome or improves public health [4].

The growing importance of this area in photonics has lead to organization such as OIDA (Opto-Electronics Industry Development Association) and OSA (Optical Society of America), organizing special conferences in the area and bringing out specific reports on the Green Photonics share of the opto-electronic market.

As per OIDA, while the CAGR (Compounded Annual Growth Rate) for global optoelectronics is forecast to be 3.4% the Green Photonics share is forecast to be very encouraging 19.6%. This translates into revenue of $493 billion for optoelectronics components by 2020, of which $261 billion or 53% is the green photonics market share [5 a].

Table 1. Different types of Photonics technologies and their impact [5 b].

Technology	Underlying Technology	Application	Impact
Photovoltaics	xSi, pSi, aSi, CdTe,	Power generation	Renewable energy, reduced carbon emissions, reduced pollution
Solid State Lighting	LEDs, OLEDs	Illumination, Displays	Reduced energy consumption, reduced mercury pollution
UV Disinfection	UV LEDs	Water purification	Improved drinking water quality, reduced mercury pollution
High Efficiency Optical Transceivers	VCSELs, PIN detectors, Si electronics	IT data centers	Reduced energy consumption
Optical Sensors	Fiber optics, Bragg gratings, Detectors	Energy extraction, Gas sensing, environmental monitoring,	Reduced energy consumption, Reduced pollution, Reduced green house gas emission
Low Power Displays	OLEDs, LEDs, MEMs, Electrophoretics, LCDs	Info. and Entertainment Display	Reduced energy consumption
Green Optoelectronic Manufacturing	Many	Many	Reduced energy consumption, reduced water consumption, Reduced pollution, Reduced green house gas emission

2. MAJOR AREAS OF IMPACT

The areas of impact of 'Green Photonics' would include:

1. Clean Energy through Photovoltaic Technology
2. Solid-State Lighting for Energy Saving
3. Photonic Technology for decreasing energy consumption in Optoelectronic Systems
4. Photonics for Environmental Sensing
5. Optics Education as an enabler for appreciating the Greenhouse Effect and other problems
6. Light Pollution and its prevention

2.1 Clean Energy Generation through Solar Technology – Photovoltaics

The most environmental friendly source of energy is undoubtedly the Sun. In one hour, the sun deposits 13.6 TW of radiation on earth – more energy than is consumed in a whole year (13 TW) [6]. Solar Technology has been around for a long time but its relevance is more today than it was ever before.

In 1950s, scientists at Bell Laboratories serendipitously discovered that Silicon doped with certain impurities is very sensitive to light [8]. This discovery led to photovoltaics as a source of energy for space. With the consensus that continued reliance on fossil fuels result in global warming, solar technology has become very relevant [9].

The critical question remains the economic viability. Research which is continuing at a frantic pace in exotic areas such as Nanophotonics, Photonic Crystals [7] and Plasmonics may provide new answers.

Silicon Photovoltaic (PV) cells include those based on single crystal, multi crystalline and amorphous thin film. Growing single crystals consumes considerable time and energy. The crystals when grown have a circular shape which does not match the standard square cell module. Cutting is required which creates a lot of wastage. Alternately, circular slices of crystal can be attached to the square module. Here, the price is paid in efficiency. Inspite of these disadvantages, the majority of today's PV cells are monocrystalline [8]. Multi-crystalline silicon cells are formed by pouring silicon into a large molding container. Multi-crystalline cells have efficiency of 13 to 17 percent.

Solar cells have evolved from single crystal based cells to thin film planar solutions. This leads to cost reduction. The efficiency can also be improved by the use of optics for concentrating the solar energy **Figure 1**.

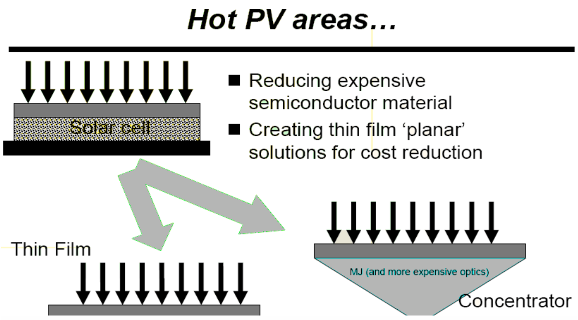


Fig 1. Evolution of Solar (PV) cells

A major route to improving solar cell efficiencies is by improving the light trapping in solar absorber layers. The basic aim is to increase the number of photons absorbed by the solar cell and to use the maximum efficiency of each photon. Photonic Technology is very important for this.

Traditional light trapping schemes involve a textured metallic back reflector that also introduces losses at optical wavelengths. Efficiency can be enhanced by the use of photonics crystals and diffractive grating structure. Such a design and preliminary fabrication results have been described in [10]. The structure incorporates 1-D Photonic crystals as band pass filters that reflect short light wavelengths 400-1100 nm and transmit longer wavelengths at the interface between two adjacent cells. Nanostructured diffractive gratings are incorporated to redirect incoming waves and increase the optical path length of the light within the solar cell.

Thin film devices with efficient light trapping schemes have a number of advantages.
1. The amount of high quality silicon needed in manufacturing each solar cell is significantly reduced.
2. The reduction in cell thickness improves the collection efficiency of electron–hole pairs.
3. Thin film technology has the added advantage of increasing the size of the unit of manufacturing, i.e., the unit size is not constrained to the area of a silicon wafer.

Light trapping in silicon solar cells mainly falls into two categories, the first being the reduction of front surface reflection and the second involves increasing the optical path length of light within the cell. The concept of reducing the surface reflectivity by introducing intermediate transparent layers has been known since the early 1800's. These intermediate layers serve to 'buffer' the drastic refractive index changes between low index and higher index materials [10].

Various photonic concepts can be applied to help in increasing the optical efficiency of the PV systems. Three such methods which use optical principles for increasing efficiency have been described in [11]. These are spectral selectivity, angular selectivity and diffractive gratings.

1.**Spectral Selectivity**: Sunlight consists of various wavelengths. The efficiency of absorption of a particular wavelength can vary depending on the exact material of the solar cell. This varying sensitivity to different parts of the spectrum is applied, for example, to split the light and guide different parts of the spectrum to different solar cells. Or it is used to trap light after a spectral shift. This spectral shift is used to increase the light guiding efficiency.

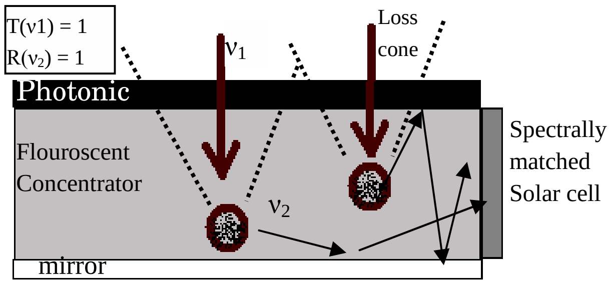


Fig.2: The fluorescent concentrator: an example of how spectral selectivity is used to increase the efficiency of a photovoltaic (PV) system. The spectral shift of light inside the fluorescent concentrator is used. The light is trapped via the application of a filter which is transparent for the spectral absorption range of the fluorescent dye and is a perfect mirror for the dye's emission range.

2. **Angular Selectivity**: Angular confinement of the light rays can also be used to increase efficiency. The angle at which the light is incident on the surface of the solar cell affects a photovoltaic system in several ways. For maximum absorption of light inside the solar cell, diffuse internal

radiation is helpful. The correct angular incidence of the light will ensure that we get efficient light trapping. Angular confinement also affects the balance of radiation exchange with its surroundings, and may be used to create a conservative system.

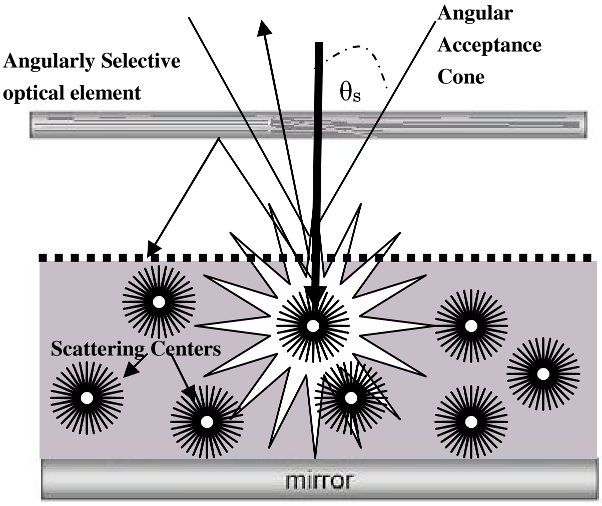


Fig.3: Schematic sketch of the photonic light trap. An angularly selective optical element is placed on top of the light trap. The angular confinement is defined by an angular acceptance range θ_s. The optical element shall be transparent for all light incident within that range and shall be a perfect mirror for light incident from all other directions. Inside the photovoltaic system, scattering centers diffuse the internal radiation. Because of the angular confinement, the fraction $L=1/\sin^2 \theta_s$ of this diffused light is trapped.

3. **Diffractive Gratings**: Gratings are used to achieve a defined change of the direction of the internal radiation. This results in a pathlength enhancement of the internal light, and consequently in an increased absorption and quantum efficiency.

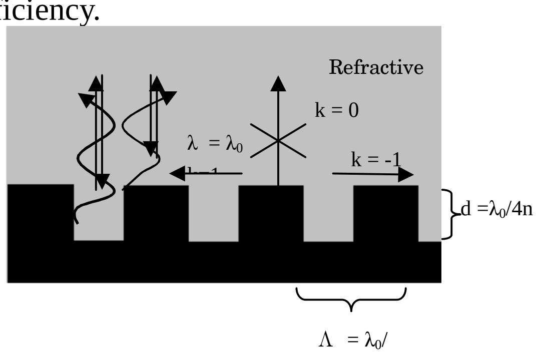


Fig.4: Schematic sketch of the concept of the reflective λ/4 grating. In a first scalar approach, this grating should redirect all light with a design wavelength λ_0 into a direction parallel to the photovoltaic system. In a vectoral approach we find that this is not possible, however, the basic idea may be used to design gratings which redirect at least a fraction of the incident light into directions close to parallel.

Recently, novel light trapping designs have been applied to stand alone and multiple junction thin film silicon solar cells. Various special structures such as Photonic Crystals have been designed.

A Photonic Crystal is a periodic arrangement of dielectric or metallic material with a lattice constant comparable to the wavelength of an electromagnetic wave. In the construction of the 1D-PhC (One – Dimensional Photonic Crystal), alternating layers of material with different refractive indices are stacked to form a structure that is periodic along one direction. The parameters that determine the band structure are the refractive index contrast and thicknesses of the constituting layers. Nano structured diffractive gratings formed by photonic crystals have been designed to increase the optical path length of light within the solar cell. [10]

In India, Solar Energy Programme for urban areas encompass solar water heating systems for domestic, industrial and commercial establishments; solar air heating/ steam generating systems for community cooking and industrial applications; solar buildings incorporating active systems and passive designs, the National rating system for green buildings, GRIHA to promote solar/green buildings; **Akshay Urja** Shops for sale and servicing of solar energy and other renewable energy products; solar photovoltaic products and devices for street-lighting, hoardings, traffic signals, power packs etc. in cities and towns; and development of Solar Cities.[19]

The table given below specifies the solar radiation exposure at different parts of the country as per a study conducted by Ministry of New and Renewable Energy. [21]

Table 2. Mean Monthly Global Solar Radiant Exposure (Mega Joules per sq m per day) over India [12].

Station	**Annual (MJm^{-2}/day)**
Srinagar	**15.40**
NewDelhi	**18.25**
Jodhpur	**19.97**
Jaipur	**19.42**

Varanasi	**17.68**
Patna	**17.25**
Shillong	**16.27**
Ahmedabad	**19.30**
Bhopal	**18.65**
Ranchi	**16.39**
Kolkata	**16.17**
Bhavnagar	**20.99**
Nagpur	**18.34**
Mumbai	**18.25**
Pune	**19.51**
Hyderabad	**20.34**
Visakhapatnam	**18.51**
Panjim	**20.00**
Chennai	**19.34**
Bangalore	**19.70**
PortBlair	**17.27**
Minicoy	**18.34**
Thiruvananthapuram	**19.45**

This study shows that solar radiance over India is good and solar power plant at any place in India would yield good results. Figure 5 shows the solar power plant at Bhavnagar, Gujarat. Much of Southern India would be good for solar power plants as that region is exposed to optimum solar radiance through out the year.

Figure 5. 3,000 LPD Solar Water Heating System installed at a Govt. Medical College Hostel in Bhavnagar, Gujarat,

Fig.6 Solar Street Lighting

Over 10,000 Solar Photovoltaic systems for various applications have been sanctioned by the Govt. in India. Many of these have been for solar street lights (Fig 6) [12].

A solar power plant is a good option for electrification in areas that are located away from the gridline or where other sources are neither available nor can be harnessed in a techno-economically viable manner. Solar power plants are free from recurring cost on fuel to provide clean energy [13].

Table 3 Renewable Energy [14] – Estimated Potential & Cumulative Achievement in India as on 31.12.2007

S.NO.	Type	Estimated Potential	Cumulative Achievement
I	Solar Photovoltaic Programme	50 MW /sq. km.	110 MWp
1	Solar Street Lighting System	-	69549 nos.
2	Home Lighting System	-	3,63,399nos.
3	Solar Lantern	-	5,85,001 nos.
4	Solar Power Plants	-	2.18 MWp
II	Solar Thermal Power Plant	-	
1.	Solar Water Heating System	140 million sq. collector area	2.15 million sq. collector area
2.	Solar Cooker	-	6.17 lakh

Research & development efforts of the Ministry of New and Renewable Energy are directed to lead to cost reduction, improvement of efficiency, reliability, long-life and manufacture of complete systems. R&D projects in Solar Photovoltaics, Solar Concentrators, Stirling Engine, Biogas, Hydrogen, Fuel cells and Solar Thermal Refrigeration and other Research & development activities have been taken up with national laboratories, universities, scientific & educational institutions & industry. [15].

The Solar Energy Centre, a research & technology evaluation facility has upgraded the existing sun simulator for testing of solar PV modules of dimensions up to 150 x 70 cms. [15].

A thermal power plant in Asanol, Jamurai at

Raniganj in West Bengal has been converted to a solar plant. This is perhaps the only instance in the world where *a high-carbon power unit has been replaced by a zero-carbon one*. The plant gives an output of two MW, enough for 2,000 homes. The estimated investment is around Rs. 36 crore. This has been hailed as empowerment of India in green energy and demonstrates the country's intent and ability to be climate responsive in the energy sector. Sh. Gon Chaudhuri, Managing Director of the West Bengal Green Energy Development Corporation is a well known figure in the Indian solar area and has won the Ashden Award, better known as 'Green Oscar'[16].

With the use of nanotechnology, the cost of setting up a solar power plant will be reduced by half, thereby negating the argument that mass producing solar power is cost prohibitive. Capital investment in a solar plant is around Rs 15-18 crore per mega watt – which is four times that of thermal energy at Rs 4-5 crore/ MW. The cost is expected to be slashed by half and efficiency doubled when nano technology is integrated in solar cells in 4-5 years [16].

2.2 Solid-State Lighting (SSL)

A large proportion of our energy consumption is for Lighting. The traditional light sources such incandescent, HID and fluorescent have evolved over 60 to 100 years. Only marginal improvements in their efficiency are possible. SSL technologies such as LEDs (Light Emitting Diodes) and OLEDs (Organic Light Emitting Diodes) have potential for a large improvement over present efficacy levels [18].

In order to replace 60 W incandescent bulbs, US Dept. of Energy has started 'Bright Tomorrow Lighting Prize' (L Prize) competition. Philips has been the first entrant in that. Intended to spur development of efficient LED replacements for incandescent bulbs, L Prize comes with a handsome reward--$10 million to the first group or individual to develop a 60 W replacement. The competition was inspired by the Energy Independence & Security Act of 2007, which sounded the death knell for incandescent bulbs [19]. To replace the 60 W bulb, the lighting product must have an efficacy of 90 lm/W. Efficacy of 123 lm/W is needed to replace halogen lamps [18].

Philips claims to have developed an LED light bulb that uses *one-sixth* the energy of a standard 60-watt incandescent bulb. The company says the bulbs meet all the criteria of the contest, which specifies a bulb that reproduces the same amount and color of light made by a 60-watt incandescent bulb, but uses only 10 watts of power. The bulb must also last for more than 25,000 hours — about 25 times longer than a standard light bulb [20].

CFLs Vs LEDs

* LEDs can save upto six times energy in a year as compared to CFLs
* LEDs have better colour refractions and luminous power than CFLs
* The loss of power transmission is less in LEDs than CFLs
* LEDs do not depend on mercury, a harmful metal that pollutes the environment and is difficult to recycle
* LEDs have more longevity than CFLs [22]

In the 1950 British experiment on semiconductor GaAs led to the creation of the first modern light emitting diode (LED). This emitted in the infrared region. General electrics created the first practical visible spectrum LED in 1962. Red LEDs using GaAsP and green LEDs using GaP were subsequently produced. The blue LED (GaN) only emerged in 1990. Combining the red, green, and blue LEDs or coating the blue LEDs with a yellow phosphor led to the creation of white LEDs, a promising, high-efficiency technology for general illumination. Parallel to efforts to create white LEDs, researchers have been working to improve the efficacy of the technology. Present day LED commercial packages have reached efficacies of 101 lm/W. This is comparable to the efficacies of fluorescent and certain HID lamps. [18]

Dr. Ching Tang at Eastman Kodak discovered that sending an electrical impulse through a carbon compound caused such materials to glow. This led to development of the first Organic Light-Emitting Diode (OLED). OLED researchers have developed white OLEDs that have reached efficacies of upto 102 lm/W in the laboratory. Currently only OLEDs used for display purposes are sold commercially. Companies are conducting research in white OLEDs as commercial products for general illumination purposes.

Technologically LEDs are discrete semiconductor devices with a narrow-band emission that can be manufactured to emit in the ultraviolet (UV), visible or infrared regions of the spectrum (Fib.7). These LED dies cannot produce the white light which is necessary for general illumination application. To transform the narrow spectral band of the LED emission there are two common approaches. (a) Phosphor conversion and (b) Discrete colour mixing (fig.8.). There are also some hybrid LED luminaries that generate white light using a combination of these two methods.

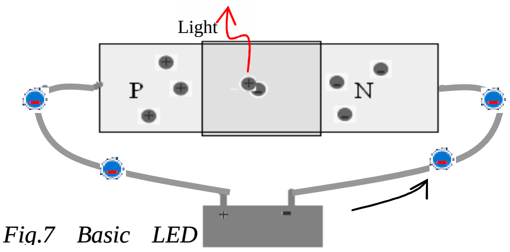
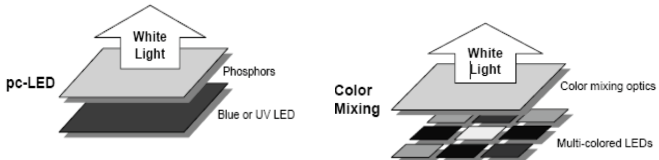


Fig.7 Basic LED

In phosphor conversion the LED die emits at around 460 nm. Some of this light is emitted directly and some of it is down converted by the phosphor to longer wavelength with white band emissions that blend with the blue to produce white light LED packages. These have been produced on a commercial scale since 1997. However, one of the problems is the difficulty of maintaining consistent light quality due to natural variations in LED (blue of UV) wavelength and the phosphor. The white light is susceptible to variations in LED optical power, peak emission wavelength, temperature, optical characteristic etc. This may lead to variations in colour from piece to piece which can cause serious problem in lighting applications. Besides this Stokes loss (due to down conversion of wavelength by the phosphor) is a fundamental limitation to the efficiency in Phosphor Conversion based white LEDs.

Colour mixing LED packages can potentially give higher efficacy devices. However, the manufacturing process is more complex and hence less economical. The process requires multi-die mounting, sophisticated optics and may also require colour control feedback circuitry to address the different degradation and thermal characteristic of the discrete LED dies. The other challenge is the absence of efficient emitters in green. [18]



(a) Phosphor-Conversion LED (pc-LED) (b) Color-Mixing LED

Figure 8. General types of white LED packages

OLEDs are thin-film multi-layer devices based on organic carbon molecules or polymers. They consist of: 1) a substrate foil, film or plate (rigid or flexible), 2) an electrode layer, 3) layers of active materials, 4) a counter electrode layer, and 5) a protective barrier layer. At least one of the electrodes must be transparent to light. (Figure 9). The materials used in OLEDs have broader emission spectra. By slight changes in the chemical composition it may be possible to tune the emission peak. This leads to the anticipation that good quality white light from OLEDs may be possible. OLED technologies for general illumination application is at an infant and yet critical stage for development. The prediction is commercialization of white light OLED sources would be possible by 2015/2020.

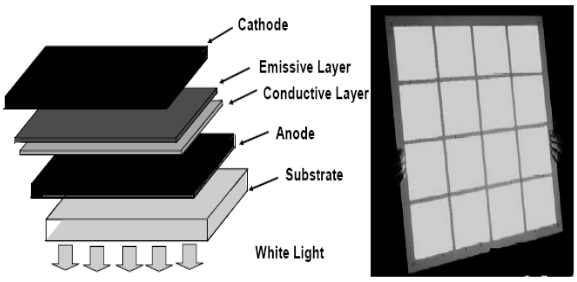


Figure 9: Diagram of OLED Device Structure and Photo of OLED Panel (source: GE)

Considerable work on OLEDs is also going on in countries like China, Japan, Korea, Taiwan etc. Researchers in Taiwan have developed OLEDs with full range of colour temperature to mimic the sunlight spectrum which could be useful. This sunlight-style OLED is said to have a relatively simple design consisting of nanometer thick layers of various colour emitting material, electron transport layer and electron injection layer. However, as in all OLEDs, short life and degradation with time is a major challenge. [26]

In the research areas too considerable innovative work is continuing. LEDs that have Photonic Crystals etched on them can direct the emission of light at preferred angles and enhance brightness without consuming more power. With affordable production techniques under development, these devices have the potential to revolutionize the lighting industry and spur adoption of environmentally friendly lighting solution [27].

The introduction of quantum wells that could confine charge carriers so that they could recombined more efficiently was one of the first major changes in LED structure. Beside the increase in the number of internally generated photons the brightness also depends on surface texturing so that the internally generated light does not remain confined because of the refractive index variation between the semiconductor material and the surrounding air. GaN used for blue LEDs has RI of 2.3 at 450 nm. This large RI leads to effectively trapping light through total internal reflection at semiconductor-air inter faces. Typically less then 20% gets out leading to low external quantum efficiency.

Surface texturing by creating facets – surface angles on external faces to increase the change that the light ray will strike the facet at an angle at which it can escape is generally used for commercial devices. However, many LED application may require particular angular distribution of light intensity and can benefit from ordered patterning of the light emitting face. This is being done by producing Photonic Crystal structure on top of the LED to increase the surface brightness and influence the spatial emission profile. [27]

Commercial LED devices have the potential to surpass the efficacy of conventional light sources. Although the range in efficacy for commercial LEDs is currently 63 to 101 lm/W, research may raise the efficacy of LEDs to approximately 230 lm/W. Laboratory efficacies for OLEDs are beginning to surpass efficacies of conventional technologies. The best laboratory efficacy for an OLED device is currently around 102 lm/W. More research needs to be done to realize the potential of this technology for creating efficient white light.

SSL (Solid State Lighting) has the potential to reduce lighting energy use by 50%, to revolutionize the efficiency, appearance and quality of lighting and to save millions of metric tones of greenhouse gas emissions. President Obama's Energy and Environment agenda calls for the deployment of the cheapest, cleanest, fastest energy source – energy efficiency. Lighting in the USA is projected to consume nearly 10 quads of primary energy by 2012 (One Quad is equivalent to the amount of energy contained in 171-172 barrels of oil, approx. 10^{15} BTUs of energy). A nation-wide move towards SSL for general illumination could save a total of 32.5 quads between 2012 and 2027. Guided by govt– industry partnership the mission is to create a new US-led market for high-efficiency, general illumination products through the advancement of semiconductor technologies, to save energy, reduce costs and enhance the quality of the lighted environment [18].

World wide SSL is no longer the illumination technology for the future. It is already the technology for today. Large numbers of companies are involved in production. Every week, new products are developed and new milestones are achieved.

An important and serious practical constraint in shifting to this energy-efficient technology is that often the decision on purchase of lighting system is made by building contractors and developers who may not be the ones who pay the electricity bill finally. Thus, the low first-cost lighting may often get chosen instead of more expensive but energy-efficient lighting products that would cost the consumer less over the long term

To prevent a recurrence of the mistakes made in the CFL market introduction an initiative named SSL Quality Advocates has been setup to improve the quality and develop guidelines for labeling product performance in a uniform manner. The label will provide essential performance information in 5 categories: lumen output, luminaire efficacy, power input, correlated color temperature, and color rendering index. DOE (Department of Energy, USA) has planned a voluntary pledge program to build a growing community of SSL Quality Advocates across the lighting supply chain. Participating manufacturers will agree to follow the guidelines and use the label. Participating partners (retailers, utilities, contractors, designers, and other buyers) will agree to look for and purchase products with this label [18].

Over the past few months there has been a lot of progress towards the commercialization of OLED lighting technology. All the major lighting companies such as Philips Lighting, Osram, GE, Panasonic and Thorn Lighting are actively developing OLED lighting technology that is expected to be available commercially this year (2010). Two Plenary talks were given by Philips Lighting UK, Mike Simpson, Technical Director and Takuya Komoda, Research Director, Panasonic emphasizing the importance of OLED lighting technology [24].

In India too, work is going on in SSL at various levels. In January 2009, BPL techno vision unveiled a rechargeable study lamp called 'StudyLite'. This lamp has been developed in collaboration with Sankara Nethralaya, the Chennai-based eye hospital, to provide what it called ideal lighting for students. The light source used in StudyLite is 24 set of light-emitting-diode (LED) bulbs to provide flicker free, white light, with no ultra violet infra red radiations. Further, LEDs typically use only ten percent of the power consumed by ordinary light bulbs which makes it highly efficient. LEDs also last up to 50 times longer than conventional compact fluorescent lamp (CFL) or incandescent light bulbs. Study Lite uses a dual power source. It can be powered either via mains power supply or through a solar panel that BPL provides as an additional accessory. Priced at Rs.1,690, the lamp was first made available in Chennai and Bangalore. It is now available across India. [23].

Another innovative LED-based Indian company Lucifer Lights has achieved many benchmarks in the lighting industry. The latest of these being the report of efficiency from Central Power Research of India (CPRI). Development of in-house technology, to use the advantages of LEDs in functional lighting, has allowed Lucifer to deliver high energy-efficient products. Constant price reductions of products have been one major marketing policy, beneficial for mass usage of their products. [25]

There is keen interest in Solid State Lighting at the Government level. Research in LED & OLEDs has been going on at several institutions. All major lighting companies have expressed interest in moving into SSL. Companies in the Display Technology sector already familiar with LED and OLEDs manufacture will also be competing with them.

2.3. Green Photonic for Energy efficient Photonic Systems

2.3.1. Silicon Photonics: Silicon Photonics has been included in the new Green Photonics energy efficiency initiative by OIDA. Dr. Lebby, OIDA President predicted that the future of Silicon Photonics will be in energy efficient Photonic integrated circuits and not the super high data rates being demonstrated by the research community. He emphasized the importance of products for datacom and consumer applications where lower power consumption is a key attribute [31].

Silicon Photonics may provide the answer to the problem of rapid growth of energy requirement as Bandwidth needs increase exponentially [32].

In the first technology transfer organized by Nature Photonics in Tokyo in October 2007 to discuss questions about the future of optical communication [33] one point raised by most of the speakers was the urgent need to address the electrical power consumption of routers and find more energy-efficient, compact and cooler methods for directing the flow of optical data-bits. It was brought out that by 2015 routers would consume 9% of Japan’s electricity. In terms of energy efficiency of transmission we need to go from using around 100 pJ per bit to just 10 pJ per bit. Photonic Technology, which supports this, needs to be looked into urgently.

The fast growing internet traffic has resulted in a large increase in power consumption. To speed up communication replacement of electrical interconnects by optical interconnects for shorter and shorter distances has been suggested. Given that computing related power usage accounts for 15% of the electricity consumption in a country like USA, the energy efficiency of photonic components is very important [32].

Silicon is becoming the material of choice for photonic components because of the material and process compatibility with microelectronic technology. Active device such as modulators, amplifiers, photo detectors can be integrated on chip. Silicon optical interconnects could also replace the copper interconnects. However, the energy consumption and heat dissipation are likely to be the main factors influencing the choice.

The operation of silicon photonic devices such as amplifiers and wavelength converters is based on third order optical nonlinearities such as Kerr & Raman effects. These require high optical intensity which leads to considerable energy dissipation due to two-photon absorption and free carrier absorption.

The two-photon photovoltaic effect in silicon has been described in detail by Bahram Jalali et al [32]. He suggests that harvesting the optical energy lost to two-photon absorption in silicon devices may enable reducing of optical losses and the simultaneous generation of electrical power.

2.3.2. Fiber Lasers :- Energy efficiency and environmental aspects will be the differentiators in future between different technologies for photonic systems. For example fibre lasers, which are not chemical-reactant based, and are highly efficient at converting electronic to photons are likely to replace conventional lasers in many areas [34]. Their operation is claimed to be 15 times efficient than conventional laser. These also require less cooling and minimize electricity used.

2.4. Sensing

While Photovoltaics, SSL and Energy savings in Communication are the well known aspects of Green Photonics, there are many lesser known but very interesting application in sensing, optics education and light pollution.

For over forty years, there have been expectations that optical sensors, especially fiber–optic based sensors will become very important. However, despite extensive research, not many have fulfilled the raised expectations. In Green Photonics, however, a new window of opportunity is opening. Sensing for the environment is utilizing various and very varied optical technologies.

The need to acquire reliable scientific data for environmental sensing is leading to sophisticated monitoring programmes. The aim is to detect ecological changes that are occurring because of climate change. Monitoring programmes which give data meeting specific scientific standard and quality control procedure are needed. Government spending world wide in the sensor research activity has greatly increased. In USA, the 2009 Economic Recovery Act provides substantial funding for research on environmental monitors and sensors. [36].

The global market for environmental sensing and monitoring technologies is expected to increase to $13 billion in 2014 from $ 9.1 billion in 2008 and an estimated $ 10.1 billion in 2009 according to a report published in June 2009 by BCC research [36].

Based on the rate of growth in revenues the fastest growing emerging areas include the application of photonic based sensor for water processing and waste water treatment as well as photonic devices for bio sensing. In this multi-angle lights scattering and other photonic techniques are preferred. These methods can detect and classify bacteria and spores as well as chemical, bio-toxic and radiation agents. The application of photonics leads to real time warning in water treatment whereas standard laboratory test can take upto 72 hours.

In remote sensing new technologies include photonic advances such as silicon photonic integrated circuits. Significant investment have been made in developing optical methods for remote or stand-off detection of trace chemicals, environmental, pollutants etc. these techniques involve advanced laser remote sensing based on Raman scattering or laser induced fluorescence from a target sample.

The use of certain classes of nano-particles which have very good photostability in fluorescence emission enables new types of sensors to be devised with very long operational lifetime.

Photonic based technologies hold the key for sensing air pollution and networking of multiple units to measure air pollution. In Germany, Siemens have developed a laser supported technique for measuring carbon monoxide concentration which is much more reliable then conventional sensors. [36].

An interesting idea of an 'Artificial nose' which can detect Toxins is described by Kenneth Suslick [37]. This is based on the simplest photonic principle of colorimetry. The sensor array is similar to a dotted postage stamp and could be useful in detecting exposure to chemicals which pose serious health risks. The device is described as a digital multi dimensional extension of litmus paper. It consists of a 6x6 array of different Nanoporous pigments whose colour change depends on the chemical environment. The pattern of the colour change identifies the toxic gas and its concentration.

Over the last four decades, space-borne lidar instruments have evolved beyond their original application-altimetry. They are now also used for tracking glacier melting, gauging wind speeds and spotting snow on Mars. [38]. A properly working lidar system on a space craft will enable researchers to study changes over time periods and track how a variable surface such as a multi glacier changes its heights with time etc [38].

The laser is also being thought of as a possible weapon for designing a "Photonic Fence" that will distinguish mosquitoes from other useful insects and kill them. The prototype fence uses a retro-reflective backing to image mosquitoes 100 ft. away from the high speed CMOS camera sensor. The specific height, speed, trajectories as well as the characteristic wing-beat speed of a mosquito can be distinguished by the imaging system. [39].

A few Photonic related sensor technology:

1. Laser induced incandescence for monitoring vehicular emission by UV and IR techniques
2. A multiparameter fibre optic sensing system using sapphire fiber grating as the sensing element for monitoring combustion of fossil fuels.
3. In agriculture for monitoring pollution, Raman spectroscopy detector can be used which can detect specific chemical groups.
4. For industrial and mine waste disposal, the use of optical fiber mounted porous silicon photonic crystal for remote sensing of environmental toxics has been taken up.
5. For ocean spill and dumping IR/UV microwave radiometers and imaging laser fluorosensors can be used.
6. For monitoring climate change–optical spectroscopic methods to measure trace amounts of a particular atom or molecule, such as oxygen, carbon dioxide or water vapour, are of relevance. [36].

2.5. Optics Education

The basic technology for understanding and finding solutions to problems such as the Green house effect; Increasing the light collection and hence efficiency for Solar Energy generation; Power saving through solid-state lighting and Less power-hungry optoelectronic systems is Optics. Optical engineering would form a large part of the design for 'Green Building' [40]. The rapid growth in importance of all segments of Green Photonics should lead to emphasis on Optics Education.

When the earth's surface is warmed by the sun, some of this energy is reradiated in the form of Infrared light. Certain gases in the atmosphere absorb this light, keeping the energy from escaping into space. A delicate balance between the radiation of energy by the earth and the reflection back keeps our earth a comfortable inhabitable ecosystem.

An interesting school level experiment is reported in [41]. The greenhouse effect is brought home to young students with simple equipment such as plastic bags, balloons, a few clear glasses or glass panes and infra red camera. While visible and infra red light will pass through the plastic bags and balloons, the water container will absorb the infra red light and appear black on the camera screen. The glass panes will transmit visible light but reflect infrared light.

2.6. Light Pollution

While a lot of thought has gone into issues like air pollution, water pollution, noise pollution etc. the concept of light pollution is relatively new.

Light pollution can be defined as unnecessary or intrusive light that human generates. There are three main types of light pollution [42].

1. Sky Glow: Light emitted upward into the atmosphere that is scattered by clouds or particles in the atmosphere. In this way air pollution also contributes to light pollution by causing enhanced scattering.

2. Light Trespass: Light from a source on your property infringes on someone else's property.

3. Glare: Lighting which is bright enough to cause viewing discomfort, or reduced night vision.

Light pollution affects several areas of science such as biology, engineering, and astronomy.

It is estimated that 30% of outdoor lighting is wasted due to over illumination or photons directed upwards into the atmosphere [44]. In USA alone, this works out to a waste of $10.4 billion per year and corresponds to 38 million tones of unnecessary carbon dioxide produced [44]. Green Photonics can provide answers to this problem by the proper design of energy efficient low light pollution outdoor lighting fixtures[43].

An energy efficient low light pollution outdoor light should emit light within the angle defined by the nadir (which is the line perpendicular to the ground) and the astronomical horizon. Any light emitted or reflected above this astronomical horizon is considered light pollution [43].

An interesting summary w.r.t. the problems caused by light pollution and some simple solutions are mentioned in reference [45].

What's the Problem with Light Pollution?

- Unshielded light shining into eyes reduces vision and that's dangerous. A good light fixture shows you the scene, but can't be seen
- Misdirected light shining into eyes, off property, or into the night sky is wasted electricity. That means higher electric bills and unnecessary air pollution
- Misdirected light shining onto someone else's property is a nuisance. Too much light can create clutter, the visual equivalent of dueling boom boxes, and gives the community an industrial look.
- Excessively bright lighting makes it difficult to see into nearby darker areas. A highly illuminated background makes foreground objects turn into silhouettes. Eyes readjust slowly from bright light to lower light levels, temporarily diminishing vision.
- An overly lighted business is as intrusive as an oversized sign and creates a prison yard look.
- Light shining upward into the night sky destroys our view of half of our natural environment. Artificially brightened night skies diminish the usefulness of astronomical observatories and deprive us all of the calming and inspiring wonder of the heavens

Simple Light Pollution Solutions

- Use only lighting fixtures that direct light downward and not upward or into your eyes. Fixtures creating dangerous glare should be shielded or removed.

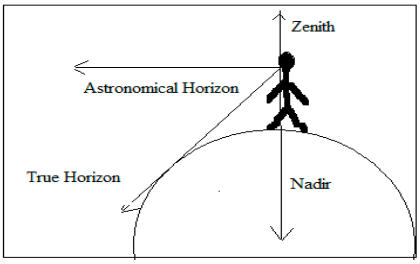


Figure 10. Geometrical Extent for outdoor illumination

- Large capital outlays can be avoided by initially requiring that these better lighting standards apply only to new fixtures, existing fixtures as they require repair, and hazardous lighting
- Re-aim moveable fixtures to reduce glare and light directed off property or upward
- Set limits on how bright lights can be
- Require lighting designs that allow unneeded lights to be turned off
- Use motion detector activated lighting for security needs

2.7 Artificial Photosynthesis

Artificial photosynthesis is an innovative concept which uses synthetic material to replace chlorophyll molecule and create an "Artificial Leaf" Power generation from artificial photosynthesis is a green dream beginning to grow tall. Grass and all green plants get all their energy by using sunlight to convert chlorophyll, carbon dioxide and water into sugar (giving off oxygen as a by-product). The possibility of replicating it as a source of power has always been exciting.

Scientists have discovered two new catalysts that could turn CO_2 into fuel efficiently, with only the power of the sun. The new catalyst uses ruthenium (Ru) and rhenium (Re), two elements not found in an average leaf. However, they allow for the same first step (CO_2 to CO) that plants use. In fact, it's considerably more efficient and simpler than the way plants do photosynthesis. [46]

The main concept behind this technique is:
1. Ru catalyst helps to absorb the light. It does this very efficiently in the visible spectrum,
2. The Re catalyst is used to actually take the electron produced and knock one of the oxygen molecule off the CO_2. The Re complex has a quantum efficiency of 0.62,

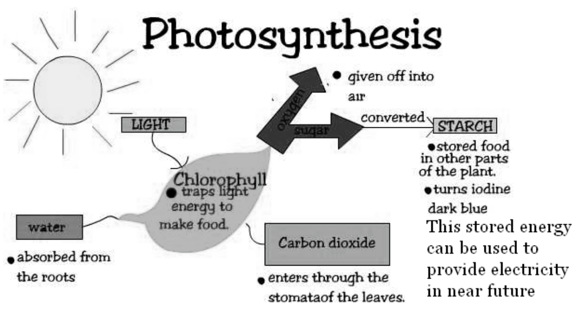


Fig.11. Artificial Photosynthesis

which means it actually uses 62% of the electrons it gets from the Ru catalyst to reduce the CO_2. This number is extremely high.

The main problem remaining is to ensure that the catalyst is stable and doesn't degrade over time. If this can be achieved it would be quite feasible to implement this technique. [47]

A technology for artificial photosynthesis based on using Nanoparticles is also described in [49]. A Biotech company called Dyesol in Queanbean, Australia is developing a photo-reactive dye to replace chlorophyll. The dye must include molecules to capture photons and transfer the electrons produced. The main efforts are towards developing a Solar Cell having nano particulate titanium dioxide, a photoactive chlorophyll analogue (such as a ruthenium-based compound) and an iodide based reduction – oxidation compound. Ultimately the company sees the so-called dye-sensitized panels as overtaking even photo-voltaic Solar Technology.

One of the main advantages brought out is the energy payback period for these dye sensitized panels, which is around two to six months against a energy payback time of three to eight years for the traditional photovoltaic panels.

Artificial photosynthesis opens a new area for the production of liquid fuels. It offers the promise of a renewable and carbon-neutral source of transportation energy. It would not contribute to the global warming that results from the burning of oil and coal. The idea is to improve upon the process that has long-served green plants and certain bacteria by integrating into a single platform light-harvesting systems that can capture solar photons and catalytic systems that can oxidize water - in other words, an ‘artificial leaf’. [48]

3. CONCLUSION

In this paper an attempt has been made to present a broad overview of Green Photonics. The importance of Green Photonics world wide has been brought out and a few examples of activity in India mentioned. Work in some segments such as energy generation through photovoltaic effect and use of LEDs for lighting has been initiated in the country. The appreciation of Green Photonics technology for these and the other segments as a whole is still to be built up. A paper on “Green Photonics” was recently presented at ICOP 2009-International Conference on Optics and Photonics. [50]

The aspects of Green Photonics discussed above include - clean energy generation through photovoltaic technology. Here the advantages of using photonics to improve internal and external efficiency and hence the economics of production was brought out. In India considerable work is ongoing in photovoltaic technology under Ministry of New & Renewal Energy. However, more synergy between photonics technology and this work is desirable.

The other aspects discussed include silicon photonics and the need to work on more energy efficient photonics systems especially for data communication and consumer applications. Fiber Lasers are definitely more "Green" than any of their conventional counterparts and will be the lasers for the future. Work in fiber lasers is going on, atleast at the R&D level, in India also.

The paper also brings out the concept that environmental sensing may prove to be the long awaited driver to take Photonic sensors to the market in a big way. Several types of sensors are described. Considerable research work especially in photonic sensors based on optical fiber technology has been initiated in India. However, the growth of the application market in the country is needed before wider commercialization can be expected.

Optical education as a part of "Green Photonics" is briefly discussed. This is especially important to note in the Indian context. Unfortunately the trends nationally are towards decreasing the component of optics in the general syllabus especially in engineering colleges. This could lead to a severe shortage of knowledgeable people for environmentally sound engineering.

The details presented on light pollution and the various ways of alleviating the problem can be implemented directly in designing light fixtures especially for outdoor illumination.

Solid State Lighting has been recognized as the future of lighting world wide. In India also the National Manufacturing Competitive Council has identified LEDs as one of the thrust areas. The Ministry of Power set up a core group to study the possibility of stimulating LED lighting in India through proper demand management. Some R&D work in LEDs and OLEDs has also been ongoing at CSIR laboratories, IISc, IITs etc. However, these activities are being undertaken in isolation. There is need to coordinate the research work, the industrial views and the need for power saving in the country as a whole. At the recent meeting of the Working Group of Photonics of DIT in December 2009 Green Photonics was presented as a thrust area and the Working Group has recommended the formation of a sub-group on Green Photonics with special emphasis on Solid State Lighting to start with. A detailed study of this segment of "Green Photonics" area is now planned and will be published subsequently.

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