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Solid State Lighting: A Summarization of Advancements

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***Abstract*— Solid State Lighting is a rapidly growing new technology in the field of lighting. By utilizing the concepts of solid-state physics and electronics, it generates light. Light emitting diodes and organic light emitting diodes pose several advantages over the current lighting technology but they still require development and research for using them to their full potential. In this paper the characteristics, sources of uncertainty, and market status of light emitting diode are reviewed to provide more suitable research directions for advancement in the field of solid-state lighting. Challenges faced by Light emitting diodes for maintaining color and visual comfort are also illustrated. Failure modes and environmental impact of light emitting diodes are also analysed. Quantum dot based solid state lightening is also presented to study the chromatic characteristics. Some critical factors of concern for broader application of light emitting diodes and additional enhancements in electrical, optical, temperature characteristic, high power output and color furnishing capabilities are also demonstrated in paper. Light emitting diodes wattage output and efficiency are also discussed for practical viability of solid state devices in emerging fields. The extension lead of current LED technology in evolving applications are considered as accumulation of numerous technologies such as wireless, communication, sensors and control engineering. Undoubtedly, LED engineering is contemporary and the price maybe unreasonable. Nevertheless, it will find its usage in very nearly all applications and the initiation of new techniques that might lessen the cost.**

***Keywords*— light emitting diode; organic light emitting diode; lighting; environmental impact; quantum dot.**

I. INTRODUCTION

Our world is rapidly advancing forward, newer technologies are appearing every day and the most simplest of processes are automated. The discovery of the light bulb by Thomas Edison revolutionized the concepts of lighting. The lighting industry has been growing ever since that day. Today, the market has to offer several different kinds of lamps and bulbs. The consumption of electricity is at an all-time high and scientists are looking for alternative and renewable sources of energy. New sources of lighting are also being discovered for more efficient consumption of power. Light sources hold a very important position in the world. Making them more efficient and improving, their performance is a priority nowadays. With Compact Fluorescent Lamps and incandescent lamps already in the market, a unique applied science area is emerging rapidly. This applied science technology is profusely called as solid state lightening (SSL). SSL is proving to be the future of conventional lighting sources. Features like longer lifetime, ability to generate a wider range of colors and superior energy conservation make it the preferable choice for using as a lighting source. Solid-state lighting utilizes the concepts of semiconductor electronics and the hole-electron dynamics for generation of light. Solid-state lightning (SSL) includes all those light sources which do not fit into the definition of the traditional light sources. Solid-state lighting has made rapid advances since the development of white Light Emitting diode (LED) and it has henceforth brought about changes in the lighting industry.

The basic concepts of the lighting systems are presently in the process of a vast makeover with the extensively developing lighting technology. This concept of solid-state lighting emerged around 5 decades back in 1962. SSL transforms electric current into detectable light with the help of semiconductors. SSL proves to be capable an energy conserving illumination system. In many aspects, SSL can be seen as the energy saving alternative of the fluorescent and incandescent lamps [1]. Progress in the development of inorganic and organic materials and nanostructure devices also, have made open a wide range of applications of LED and essentially pushed light emitting diodes (LEDs) towards the large scope of illumination with the white LED technology. These Light Emitting Diodes have lot of illumination, optimum color temperature, and immense color conditions to mirror natural light. It will soon replace fluorescent and incandescent illumination origin in the coming years. Ability and endurance of LEDs makes them a good choice for general applications over traditional lamps. In addition, LEDs have a good color control, excellent dimming capability, quick switching response time, and absolute compactness. They are environment friendly and do not emit any harmful radiations. In this paper, we reviewed the current progress in the field of solid-state lighting and analyzing what are the advantages and disadvantages that solid-state lighting possesses.

II. MATERIALS AND METHOD

A. *Basic Components of Solid State Lighting*

Let us understand the concepts lying behind the basic components, which make up a Solid State lighting System

1) Light Emitting Diode: As the name suggests solid state lighting is based on solid state physics. LED or a Light Emitting Diode is a basic component of most SSL systems. It is a simple semiconductor diode. A combination of a p-type semiconductor and an n-type semiconductor is used which together form a p-n junction. On application of a forward voltage to a p-n junction, these charge carriers move across the junction and recombine with each other. This recombination is conversion of excess energy and can lead to expulsion of energy in two forms; Radiative or Non-radiative [1]–[3]. Radiative recombination leads to emission of energy in the form of a photon which gives of light of a certain color depending on its wavelength. The energy of the photon is dependent on the band gap energy of the semiconductor. Non-radiative combination of a hole and electron leads to conversion of extra energy into vibrational energy of the lattice atoms. This is often termed as a phonon. Non-radiative combination does not produce any form of light and only adds to the temperature of the system. It increases the temperature of the LED. The temperature is an important factor for determining various properties such as efficacy, life span, luminous flux etc. of the LED [1].

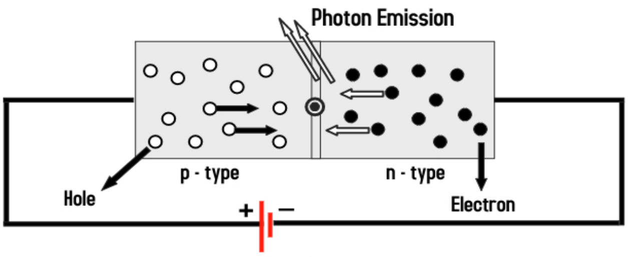

Fig. 1: Basic LED working [2]

In Fig. 1, basic working principle of LED is depicted. The temperature increase caused by the phonons needs to be carefully managed for achieving maximum life. Coating LEDs with lot of components enables obtaining the required wavelength of light [2], [4]. The advancement in LED technology has been extremely rapid and within a short span of time LEDs has gone from being considered a novelty item to an efficient light source [3], [5].

LEDs were not suitable for indoor lighting applications because of their poor chromatic reproduction. This creation led to the development of the white LED, which is a combination of the three LEDs (Red, Blue, and Green). With these advancements in the LED technology, it is not only powerful enough for streetlights but is also used in indoor lighting [5], [6].

2) Organic Light Emitting Diode: As the name suggests, an OLED employs an organic layer in it. The layer of organic material is sandwiched between two electrodes; an anode and a cathode. The cathode is made of a reflective metal contact. Materials like aluminum and silver can be used to make the cathode. A transparent electrode forms the anode of this arrangement. Most cases, Indium-Tin oxide (ITO) are used to make the anode. An application of voltage across the two electrodes, a potential difference is generated across the organic layer. Holes and electrons are injected into the organic layer. The anode is responsible for hole injection and the cathode injects the electrons [1], [3], [7].

By hopping through the highest unoccupied molecular orbitals of the organic layer molecules, the holes travel through the organic layer, moving in the direction of the electric field. Electrons utilize the lowest unoccupied molecular orbitals to move against the direction of the electric field, inside the organic layer. The holes and the electrons move in opposite directions in the organic layer and thus, they meet each other at a certain point, which depends on the mobility of the holes and the electrons. At this meeting point, the hole and electron recombine and relax their energy states. This leads to a radiative recombination process and light is generated [1], [7], [8]. Factors, which affect the OLED efficiency, are layer thickness, dopant concentration, and multilayer structures [5].

The product OLED film can be either clear or colored or opaque. The OLED films have the property of being rigid or flexible based on its construction. OLEDs are relatively expensive. There has been an increase in commercial applications of OLEDs. Several electronic companies have started using OLED panels in Televisions and mobile phone displays. With further developments and technological advancements, OLEDs are predicted to be the next big light source with a life of more than 2000 days and 100 luminous per watt (lm/W) [1], [9].

B. *SSL Characteristics*

LEDs possess several characteristics, which make them suitable for use. Some of these characteristics are shown in Fig. 2 and the important factors, which control the performance of light emitting diodes, are reviewed now.

1) Life: LEDs are estimated to run for approximately 100000-200000 hours or even longer, assuming that they are operated at or below the maximum junction temperature. The procedure to determine the LED lamp life is to test it time intervals i.e. to test its working for 6000 hours, 450 days or more. Measurements are taken every 45 days. This helps in keeping a track of the light output degradation with time [1], [10]. When testing the lifetime of LED, fixture factors like potential difference, flow of electrons, flow of air, temperature, and humidity are under supervision and controlled. Orientation of the LED unit majorly affects the junction temperature. On-off cycles severely affect conventional light sources but performance of LED remains unaffected by this factor. Hence, on off is usually excluded from consideration while testing lifetime of the LED fixture [1], [11].

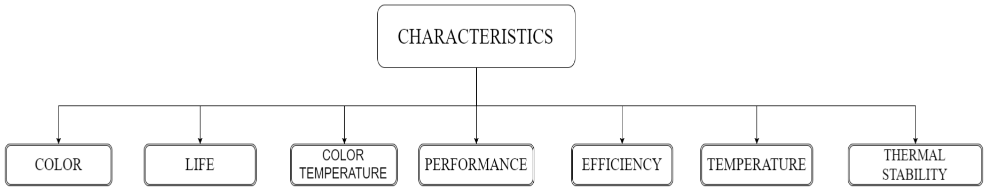

Fig. 2: Flow chart of characteristics

Fig. 3 is a bar chart which compares three different products namely Philips LED bulb (14W (100W), Cool daylight), Philips tornado CFL spiral bulb (32 W (150 W), Cool daylight) and Philips incandescent bulb (Softone, 100W). The brand Philips have been compared on the basis of the average life span mentioned in their specifications listed by the company [12],[13],[14] to illustrate the actual life span. Clearly, we can see that the LED lamp has an extremely long life of about 15000 hours. Proper maintenance can be achieved by knowing how long the fixture has been operating. The useful life of a LED fixture varies with the application of it. There is no visible indication as to when the LED product needs to be changed unlike the conventional lamps, which either fail or are stuck in an on/off cycle when they reach the end of their useful life [1].

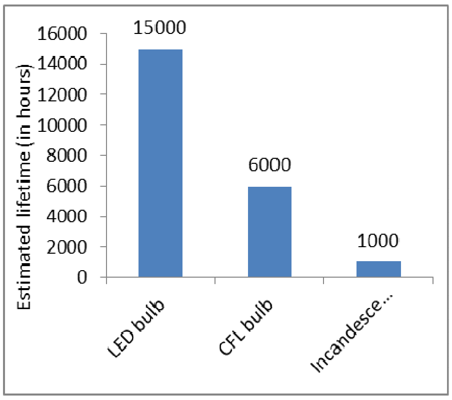

Fig 3. Estimated lifetime

2) Color: LEDs operate on the concept of emitting photons when holes and electrons recombine. The wavelength of the photon determines the color of the light emitted. This can be controlled by the thickness of the layer and infirmity of the material used. It is difficult to maintain the same value of these factors for LEDs used in a fixture, the color output of individual LEDs may vary. Thus, each LED produced is categorized according the chromaticity it delivers in the output. LEDs have a more detailed coloring effect as compared to conventional lamps where the color shift is minor [1], [15]. Color temperature is the temperature in Kelvin at which a blackbody radiator when operated gives the same chromaticity as the light source under testing. It helps in quantifying the property of color. In case of LEDs to test the characteristic, we use the correlated color temperature for measurement. LED lamps can operate in a range of 2700-6500K correlated color temperatures. The right color temperature affects various factors in the functioning of the LED and its applications. LEDs used in applications like airplanes and logos are set to the right color temperature to attract the customer or set the right mood. This quality is also important for indoor lighting applications [15] – [19].

3) Performance: Taking into consideration various factors, which affect the performance of the LED, the design of the fixture, can be altered and improved for enhanced performance. Some factors, which are used as performance metrics [1], are changes in the drive current, junction temperature, supply voltage, and intended ambient temperature. Factors like these can affect life and light output of the LED fixture positively or negatively. Traditional lamps use prescribed voltages and a gear controls configuration, the current supplied to the device. Thus, factors like supply voltage and current do not affect the design of the lamp. Incandescent lamps of same rating consume same amount of electricity and power, thus the brand and the construction does not affect performance [1], [10]. LED is an electronic circuit, thus, it is more vulnerable to facing issues with power output. Conventional lamps had better handle voltage fluctuations and power cuts as they are designed to operate in a wide voltage range. Low voltage supply may cause dimming of a LED but it does not damage the circuit. It cannot be said about a high voltage supply that can damage the chip. Thus, LEDs need to be equipped with surge protection to make their performance better in applications with low power [1], [10]. A constant current supply ensures a stable luminous flux from the LED. Thus, performance of LEDs can be improved by using constant current sources as the amount of light varies with supply current [20]. To illustrate the performance of LEDs better, the graph shown in Fig. 4 which draws a comparison between the Philips LED bulb (14W (100W), Cool daylight), Philips tornado CFL spiral bulb (32 W (150 W), Cool daylight) and Philips incandescent bulb (Softone,100W). The light output in lumen compared to the rated power gives us an idea that LEDs have a good light output making them highly competitive in the market.

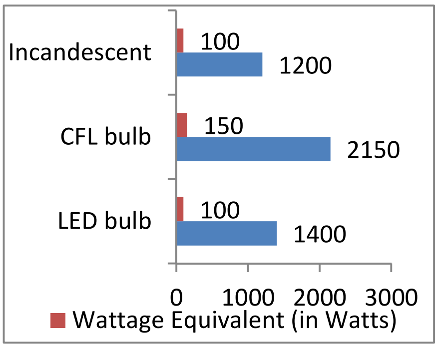

Fig. 4: Lumen output and power rating

4) Efficiency: Conventional light sources are omnidirectional and utilize reflectors and refractors to control the output light. This leads to reduced efficiency [1]. LED light sources are directional. The direction of the light will depend on the design of the fixture. In other terms, this can be understood as the photon being emitted in the direction where the design directs it. LED fixture is not made out of a single LED chip and it utilizes multiple chips [21]. This causes a more severe glare effect when compared with the conventional lamps. The selection of the right fixture makes all the difference in the efficiency. The application of the fixture affects its usage and thus selectivity is an important factor [1], [22]. LEDs have low energy consumption compared to the competition. If we compare LEDs and fluorescent lamps, fluorescent lamps consume about 2-3 times more power than LEDs, but then again to obtain the same level of luminance, more number of LEDs needs to be used [23]. LED lamp efficiency will depend on the LED chips used in the lamp. The generation of white light, the amount of current supplied and the color temperature are the three main aspects which influence the efficiency directly [22].For increasing the efficiency of the system and reducing energy consumption, the system should utilize the supplied energy fully. Thus, the power supply to the LED fixture should possess a high power factor and the total harmonic distortion in current should be low [1], [31].

5) Temperature: LEDs are characterized by a specific maximum operating temperature termed as the junction temperature. When the LED is made to operate at a temperature higher than the junction temperature, it provides better light output but life and efficiency of the LED fixture are compromised. As LED chips require an electronic device or a driver to operate it, we can pair the chip with different device or driver to alter the current supplied and the junction temperature to obtain a different efficacy, lumen output, and life according to the requirement. Conventional lamps generally run at high temperatures and LEDs are considered to run cooler than they do, but the junction temperature can be quite high for some designs [1], [25]. SSL devices face the issue of thermal stability. When the LED is supplied with a forward bias power supply, the device's internal resistance produces heat. Increase in the chip temperature leads to drop in efficiency as the impurities get excited and occupy the holes reducing the number of radiative electron-hole recombination. A red shift occurs in the output spectrum due to higher temperatures because the band gap of the material shrinks [25], [26]. An array type LED assembly requires thermal uniformity and similar light output from all the chips incorporated. The thermal uniformity can be tested by the method of mapping temperature differences across the entire assembly-elements.

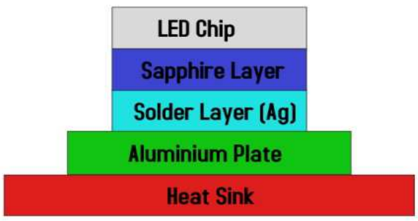

Fig. 5: Chip on plate assembly [4]

Chip on plate (COP) packaging is the current method used for enhanced thermal management. From figure 5, we can see that the heat spread downwards from the chip and is expelled to the environment through the heat sink [25]. In a COP packaged device, the heat spreads in all directions. Different elements have different compositions and their thermal resistances vary. This variation is caused by the difference in the thermal paths taken by the heat in the element. Change in elements results in chip temperature [25]–[27]. Non-uniform thermal behavior affects the color rendering, temperatures and lifetime of the SSL device. Thermal uniformity depends on final temperature distribution and thermal uniformity of the assembly. Maintaining uniform arrangement in the assembly and symmetry will reduce the undesired effects caused by higher chip temperatures and thermal instability [25], [27]. Chip temperature depends on factors like element layouts in the assembly and their arrangement, heat sink design and its measurements [26].

III. Results and Discussion

A. Challenges in LEDs

Solid-state lighting faces some challenges, which have been displayed in Fig. 6. The extremely important challenges faced by LED are reviewed in this section.

1) Issue of color maintenance: Color maintenance is a system failure which solid-state lighting technology faces. This problem is observed from the indication of the product after the product has been operated for many hours. The chromaticity at the beginning of the lamp's life changes over a time. This change in the chromaticity from the original value is defined as color maintenance. This color shift can be traced down to different reasons [17]–[19]. Factors causing lumen depreciation generally lead to color shift as well because light output degradation is never uniform. LEDs are encapsulated to protect them from the environmental factors like humidity and temperature. The encapsulates can be made of different materials like silicone or plastic. These materials may discolor over time and lead to a color shift. Phosphor materials used in LEDs cause a color shift over time because they degrade and their position with respect to LED changes with time. This leads to a variation for light emitted [28]. Being exposed to the surroundings, LEDs are susceptible to being contaminated by various sources [28]. Any kinds of coating or covering applied in the LED are worn off and may curl or crack. This results in a color shift of the output of the LED [28]. Parts of the LED can play an optical role by reflecting or transmitting light. Some of the examples of color shift causes are listed in Table 1.

TABLE I
Examples of Causes of Color Shift

Cause for color shift	Example of occurrence
Material Degradation	• Degradation of optical components in the LED • Degradation of reflective surfaces
External Contaminants	• Carbonization due to absence of oxygen • Browning of the optical

	path
Interface delamination	• Cracks in the materials joint together • Separation of materials inside the LED due to rough usage

2) Visual comfort provided by LEDs: All sources of lighting have to achieve the concept of visual comfort. Visual comfort is ensured by checking various factors like glare, veiling reflections, luminance levels, color rendering index and correlated color temperature [6], [29].

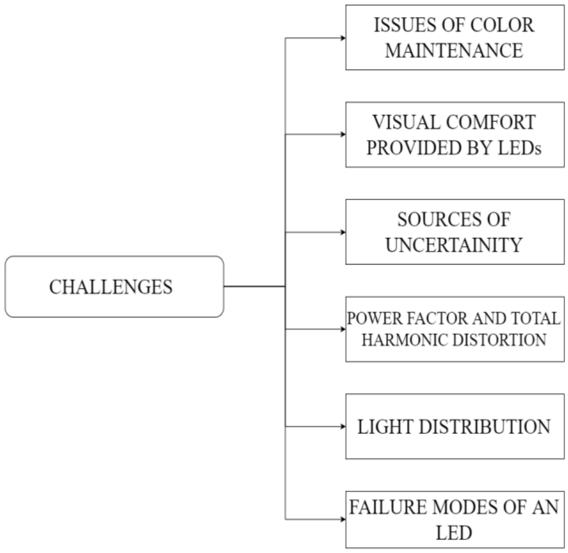

Fig. 6: Challenges in LED

In case of LEDs, the diffusion of light by means of lens can reduce the discomfort glare. Moreover keeping the same light source and luminance, the glare decreases on increasing the number of LEDs used. If we increase the area of the light source, the discomfort decreases. The magnitude of increase in area is more than the decrease in level of discomfort [30]. The use of diffusers and hiding the setup from direct view can assure better performance and reliability. Research on the glare provided by SSL is ongoing. The above-mentioned improvements can be used to improve performance [17], [30]. From Table 1, the occurrence of the root causes of color shift can be understood.

3) Sources of uncertainty: When performing traceable measurements on SSL fixtures to test their electrical parameters there are some sources of uncertainty. These sources can be listed as testing the power of the SSL product, which faces uncertainty from temperature of the chip, power supply distortions and stabilization. In addition, measurement of the root mean square current is made uncertain by the influence of power supply impedance, bandwidth error and the shunt resistor [31], [32].

4) Failure modes of LED: The LED may not live up to its expected lifetime due to certain failures. LEDs stop working efficiently as there is a moderate decrease in the decrease of light output. The difference in the construction marks the distinct failure modes of LEDs. Some of the failure modes are listed in Table 2. Reliability about thirty modes of failures has been recognized until date. A large amount of modes still remain unknown. Reliability of LEDs can be attributed to various levels.

TABLE II
FAILURE MODES

Level No.	**Led Part Failure**	**Failure Examples**
Level 0	Bare die	• LED catastrophic failure • Lumen output depreciation
Level 1	Packaged portion	• Yellowing of packaging materials • Electrostatic discharge • Failure of interconnects • Cracking of packaging materials • Delamination • Failure of wire bonds
Level 2	Substrate	• Cracks in substrate • Failure in solder • PCB metallization problem • Shorting (i.e. due to solder bridging)
Level 3	LED chip module	• Casing cracks • Failure in the driver • Degradation of optical components • ESD failures
Level 4	Functioning failures	• Failures caused by moisture • Corrosion due to water • Deposition of out gassing material on the optics
Level 5	LED Lighting system	• Failures in software with the lighting system • Electrical compatibility issues of the system

The important levels of failures modes are discussed in Table 2 [33].

5) Light distribution: LEDs run on the concept of emitting photons and thus they produce unidirectional light. Optical systems are utilized to make the light omnidirectional. The property of producing directional light of LEDs can be used in certain applications. This factor of LEDs needs to be considered when defining a lighting system. This factor also affects the decision of application of LED. Light distribution determines the area of illumination and thus, the design of LED fixture should be such that it suits the need of the application [6], [22].

6) Power factor and total harmonic distortion: Power factor is a ratio, which compares the power used by the device to the actual amount of power supplied. As it is a ratio, its value varies from 0-1 [22]. Total harmonic distortion (THD) is the reason for overheating, tripping of devices, resonance and other various issues [22], [32]. Ideally, power factor should be equal to 1 and the THD should be 0. LEDs may not have a power factor equal to 1 and THD may also not be zero, they remain similar to fluorescent lamps in these aspects. A proper filter on the power supply can easily mitigate the harmful effects of THD [22], [24].

B. *Impact on the Environment and Current Market Status*

LED lamps utilize several metals in their composition, which makes them more likely to impact human health and the ecosystem. The United Nations Environment Program (UNEP) concluded in a report that LEDs do not use toxic materials in their composition like mercury, which is present in fluorescent lamps. LEDs use an aluminum heat sink, which is the main cause of environmental degradation. If we aim at improving the luminous efficacy, improving electricity sources, designing structures, which improve efficacy; we can reduce the environmental impact of LED [5], [22], [34].

TABLE III
MERCURY CONTENT OF SOME BULBS

Type of Bulb	Mercury Content (in mg)
Philips LED Bulb (14W(100W))	0 mg
Philips Tornado CFL spiral bulb (32W(150W))	=<5 mg

In Table 3, we can observe that the mercury content of a commonly used LED bulb is 0mg whereas that of a commonly used CFL bulb is less than 5mg [12], [13]. The lack of mercury content makes LED bulbs safer to use and less harmful to the environment. LED technology has a growing market share in the lighting industry. LED lamps are still relatively new in the market. They have higher prices than the common incandescent lamps and compact fluorescent lamp. It is expected that with ongoing research into solid-state lighting, the prices of LED lamps will go down [22], [35].

1) Life cycle assessment: LEDs have been chosen over conventional lighting sources for the important reason of having a greater lifetime. LEDs are capable of lower environmental impacts mainly due to their high-energy efficiency [10]. On analysis of LEDs and CFL through all the stages of production to usage, we can find several results. LED luminaires have a lower environmental impact during the use stage in comparison to CFL. The use stage involves the main consumption of electricity and is the most important for determining a lamps environmental impact. A higher luminous efficacy is preferred on the lamps being used because this indicates that only a minimal amount of the electricity being consumed is being wasted. When producing the LED, it causes a greater environmental impact than other light sources. LED production uses electronic components and includes some hazardous substances as well [11].

TABLE IV
FACTORS FOR ENVIRONMENTAL IMPACT

Factors	Impact
Luminous Efficacy	Reduce Energy Consumption.
Design Modification	To deliver greater luminous flux.
Development of luminaries with large life time	Reduce replacement. Good illumination

As we aim to find lighting sources, which are highly efficient and safe to our environment, the areas, listed in Table 4 of the existing lighting technology to be explored for more innovation and research to reduce their environmental impact. Design of new Luminaires with larger lifetimes to reduce the frequent replacement and quantity of waste and new products [6], [11].

C. *Quantum Dot Based Solid State Lighting*

The introduction of quantum dots in place of phosphors makes the emission spectra size-tailorable. By altering quantum dot absorption or emission wavelengths and oscillator strengths using electric fields, the ability of real-time tuning of chromaticity can be obtained. Quantum dots have several advantages over phosphors. Quantum dots had better optimize the luminous efficacies and color rendering quality due to their narrow-line width emission. The emission wavelengths are easily tailorable through quantum size effects [15]. Quantum dots can allow the tuning of chromaticity in various ways. These methods are listed as absorption tuning (color rendering quality and luminous efficacies are maintained over a wider range of color temperature), wavelength tuning (color rendering quality is difficult to maintain) and power down conversion efficiency tuning (luminous efficacy is difficult to maintain). The properties of Quantum Dots can be effectively utilized to obtain different chromaticity’s for different changes in emission wavelength, absorption or power-down conversion efficiency [15]. The most recent application of commercial QLEDs has been in televisions.

D. *Emerging SSL Technology: Fipple*

FIPEL stands for field-induced polymer electroluminescent technology. This technology makes uses of three layers of polymers blended with carbon nanotubes. The whole arrangement glows and generates light when stimulated by electric current. FIPEL products can be molded into different shapes as they use polymers. The color can be varied in this type of technology. FIPEL is a competitor to LEDs in terms of efficacy. The technology still needs to be researched and basic standards for it are not available. FIPEL is under production and will soon have a place in the market [1].

IV. CONCLUSION

Analyzing the progress and the scope of SSL technology, we can say that the olden days luminous gas filled lamps and fluorescent lighting technologies will be replaced in the upcoming years in a phased manner. For broader application of light emitting diodes, additional enhancements in their electrical, optical, temperature characteristic, high power output, and color furnishing capabilities need to be looked into. The extension of present LED technology in emerging applications are viewed as conglomeration of various technologies like wireless, communication, sensors and control engineering and many more. No doubt, this LED engineering is modern and the price maybe exorbitant. However, it will find its usage in almost all applications and the advent of new techniques, processing will definitely reduce the cost.

Increased efficiencies, improved information, high light output, and lower production costs will help to pave the road for the commercial success of all LEDs. The future of SSL is wide open. In the coming years, around 200 lumens per watt efficiency will be crossed by profit making light emitting diodes. This efficiency level of commercial LEDS with respect to around 35 lumens per watt of luminous lamps proves that the prospective years are ahead for solid-state lighting is certainly vivid.

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