1. INTRODUCTION

Once limited to simple status indicators, light emitting diodes (LEDs) are now widely used in backlighting, panel indication, decorative illumination, emergency lighting, animated signage, etc. LED lights for commercial and residential buildings are also emerging.

It was the low light output and a lack of colour options that had limited the use of earlier LEDs. However, new LED materials and improved production processes have resulted in brighter LEDs in colours throughout the visible spectrum with efficacies greater than incandescent lamps. These brighter, more efficient and colourful LEDs are finding more and more lighting applications.
2. WHAT IS LED?

2.1 AN OVERVIEW

LED stands for Light Emitting Diode. An LED is a semiconductor chip that converts electrical energy into light. The conversion of energy into light happens on the quantum level within the molecular makeup of the semiconductor chip. The process begins with the chip acting as a diode with two terminals, a P (Positive hole carrier) and N (Negative electron) region in its basic structure, which allow the chip to conduct in one direction for operation. In addition, there are added chemical layers called epitaxy layers that enhance the ability of the device to emit light (Photons).

As electrical energy passes through the P and N regions of the LED, electrons move to higher energy levels called band gap potentials. To meet the conservation of energy law, the electron's excess energy, gained while moving energy levels, will then produce a photon that our eye will perceive as light. At this point, the band gap potentials equal the energy of the photon created when the electron that was moving energy levels comes back to the ground state. The colour of the light emitted directly relates to the size of the band gap potentials or the amount of energy the photons produce. Since different colours occur at different band gap potentials, or energy levels, this explains why different colour LEDs exhibit different forward voltages to operate.

Recent advances in LED technology have led to brighter LEDs due to higher quantum efficiencies and higher chip extraction efficiencies.

Another recent development of a blue color LED has led to RGB (Red Green Blue) white lighting as well as Phosphor on Blue to form white LEDs. The technique of Phosphor coating on Blue has shown that in the near future, white lighting from solid-state sources is a possibility, which has led to a lot of excitement.
2.2 BRIGHT LEDS FOR OUTDOOR APPLICATIONS

The first LEDs bright enough for use in outdoor applications were made of aluminium-gallium arsenide (AlGaAs). These red LEDs appeared as high mount-stop lights on automobiles and in a limited number of traffic lights. The recent advent of efficient green, blue and white LEDs may lead to more applications.

Aluminium-gallium-indium phosphide (AlGaInP) and indium-gallium-nitride (InGaN) LEDs have succeeded AlGaAs as the brightest available LEDs. AlGaInP LEDs range in colour from red to amber and produce about 3 lumens with efficacies greater than 20 lumens per electrical watt, although green and yellow AlGaInP LEDs have much lower efficacies. Hewlett-Packard plans to release AlGaInP LEDs with a light output of more than 10 lumens per LED.

The Nichia Chemical Company in 1993 introduced InGaN LEDs with efficacies more than 100 times that of earlier blue and green LEDs. Other companies, including Hewlett-Packard and Panasonic, offer similar InGaN LED products.

Green InGaN LEDs have efficacies exceeding 30 lumens per watt, and blue InGaN LEDs have efficacies of 10 lumens per watt. InGaN technology also makes possible the first white LEDs.

3. LEDS VS INCANDESCENT LAMPS

For many applications, LED lamps are superior to incandescent lamps. Their efficiency is the most apparent in applications requiring colour. Unlike incandescent bulbs that give off the full spectrum of light in a spherical pattern, LEDs emit a focused beam of a single wavelength (colour) in only one direction, in a variety of angles. The composition of the materials in the semiconductor chip determines the wavelength and, therefore, the specific colour of the light. Lenses, reflectors and diffusers can be integrated
into the package to achieve the desired spatial radiation characteristics. The beam patterns on the lamps change when we select different diffusers.

Since incandescent lamps emit the full spectrum of light, these require a filtering system to produce light of a specific colour. This, in turn, reduces their light output. For example, a red-filtered incandescent lamp is as much as ten times less visible than a red LED. The filtering of the light greatly reduces the efficiency of the lamp to only a few lumens per watt. Colored LEDs do not have the same problem since they produce light in a single colour and at higher efficiencies than white LEDs. To get around this issue with white LEDs the lamps are blue LEDs with a yellow phosphor coating to produce white light, making them much more efficient and therefore requiring less LEDs to do the job. The job in this case would be decorative lighting, landscape lighting, accent lighting, wall washing and special effects. These type applications tend to be the most suitable for LEDs in the lighting world today.

The blue-white light from an LED array looks 'cold' compared to the yellow glow from a filament lamp. For example, the yellow bias of a halogen bulb flatters mud, sand and 'stal' in caves whereas the green/blue bias of a white LED is better for the outdoors. Experiments are going on with introducing some yellow or orange LEDs to a white LED array to shift its colour balance to better suit caves, and this may also reduce the overall cost.

We need to talk about the light efficiency of a conventional incandescent lamp. These range from around 12-17 lumens per watt (depending on the rated life). LED's on the other hand, have efficiencies that vary with the color of the light. If we are talking white only, the efficiency of the LED that we use is between 29-42 lumens per watt. We can increase this efficiency even more by designing a range of products to be spot lamps that concentrate the light in a smaller area without any significant losses in lumens per watt.

New ‘doping’ technologies have increased the LED light output by as much as 20 times over earlier generations and allowed the production of daylight-visible LEDs in
virtually any colour of the spectrum. In addition to red, yellow and amber/orange, LEDs are now available in many colours from leaf green to ultra blue. LEDs produce sharp, vibrant colours. Even pure white light, long thought to be an impossibility, is now available in three different shades. Since lamps are LED based, they provide saturated colors.

Now about the power requirement. Typical pin spot fixtures use 30-50 watt lamps with colored filters to project a colored spot of light. With LED lamps, the power requirements would be only 2.5 Watts of power! LED lamps also have the power supply built in so they screw directly into a standard lighting socket.

While LEDs deliver 100 per cent of their energy as colored light, incandescent bulbs waste 90 per cent or more of their energy in light blocked by the colored lens or filter. Incandescent bulbs also waste 80 to 90 per cent of their energy on heat generation to reach the temperature (in Kelvins) for which they are designed. LED lamps produce very little heat. Less heat is important for a couple of reasons; firstly, we can reduce air-con loading and electric bills and secondly, we don't have to worry about the fire hazards involved with flammable material touching the surfaces of the lamps.

True, for general lighting applications in homes, factory floors, etc, an incandescent bulb generates more visible light per watt than an equivalent LED, which makes an incandescent bulb better suited to this job. However, in specific power-critical applications (car brake lights, display panels, industrial controls and traffic signals), energy-efficient LEDs outshine incandescent lamps.

LED lamps have better visual effects. LED lamps can be used for decoration and are point source devices meant to be viewed by the observer. With painted lamps, light escapes from the back of the globe as well as the front. This has the negative effect of lowering the contrast of the point source and the immediate background, because the light that escapes, lights up the background and weakens the effect. Secondly, when this type of install is on glass the painted lamps have a tendency to light up the inside of people's offices, which has been a source of complaints from the buildings occupants.
Using LED lamps in place of painted bulbs rids you of both of these effects. As the lamps are point sources in this application, which does not "paint" the rear surface with light and drastically increases the contrast. At the same time, this also overcomes the problem of lighting up the occupants' office space.

LED lamps have got visibility during the day. Painted lamps must be on during the day if the colors are to be seen because they look black when turned off. LED lamp has overcome this problem by designing the lamp to glow in its original color, which is activated by the Ultra Violet content from the sun. This also means that you can also choose to power down the lamps during the day and yet still see the colors, which adds more cost savings on your energy bills.

LEDs with standard lamp bases once only competed with tiny miniature and sub-miniature bulbs called the T1 or 3mm ‘grain-of-wheat’ bulbs. Today, LED lamps in a variety of standard lamp bases, in sizes ranging from the grain-of-wheat T1 (3mm) to medium-screw G30 (25mm) bulbs and larger.

LED lamps are rugged and durable, and have a lifespan far exceeding that of incandescent lamps. Flashlight bulbs contain a fragile incandescent filament that can easily be broken. In this respect LEDs are much more rugged.

A high-power flashlight bulb might have a lifetime of only 20 hours, but even the longer-lasting bulbs have a lifetime of only a few thousand hours; compared with this, LEDs will last 'forever'. However, it is important to realise that this does not mean that your caving lamp is going to last for 100,000 hours. What it means, of course, is that when your caving lamp finally breaks (for example, you smash the housing, the contacts corrode, the cable falls off, or the electronics fails) then the LEDs will still be OK. It seems that the phosphor in the LEDs may start to degenerate well before the 100,000-hour point, changing the colour of the light, although this is probably not significant.

Vacuum-filled tungsten filament lamps (i.e. not krypton, xenon or halogen types) that are designed as low-current pilot bulbs can be very inefficient - as low as 1 lm/W.
Under-running your main-beam (perhaps using a commercial 'dimmer' circuit that is available for bicycle lamps) is equally inefficient. LEDs, on the other hand, can be under-run with no loss of efficiency - in fact, they are more efficient at low currents. Thus a dimmable LED lamp would allow you to choose the illumination level appropriate to the conditions and consequently to save battery life.

LEDs come with their own built-in micro-reflector that produces a pure, even beam without the need for any external optics that can become damaged, dirty or corroded. However, you still need a waterproof box or conventional headpiece to protect the LEDs from damage.

We can also produce Festival lights that are direct replacements for colored lamps. The Festival lights can replace a typical 60-watt painted incandescent bulb with only 2.5 watts of power including the complex figure of merit, power factor.

LED lamps withstand shocks, vibrations, frequent switching and temperature extremes that rapidly incapacitate fragile incandescent lamps. LED lamps are 10 to 50 times more energy-efficient, thus reducing the operating costs by up to 90 per cent. They have 100 to 1000 times faster response than incandescent lamps, so there’s no flicker.

The new LED spotlamp's precision optics provides collimated beams of light. The light then goes into micro diffuser optic that "bends" the light into a predetermined shape. The "bending" of the light occurs without any appreciable loss of the light due to the special design of the diffuser. The diffuser works by shaping the light into various spherical patterns as well as elliptical patterns.

You now have the ability to tailor the light onto the target without the need for pin spots, gobos or filters to achieve this function, saving costs and increasing the light usage efficiency. Diffusers come in both spherical shaped as well as elliptical shaped patterns.

4. ABOUT THE LED LAMPS
4.1 ADVANTAGES

Typical use of LED lamps would be anywhere there are white or colored spot lamps, such as for architectural, landscape, accent or general lighting. Imagine lighting up your palm trees and walls with amazing saturated colors. The LED lamps can be direct replacements for pin spot fixtures and deliver huge savings on power and material costs when replacing the standard lamps with color filters.

Some of the important advantages of replacing the standard lamps with LED lamps are:

1. Power Savings.
2. Optional Beam patterns.
3. Saturated Colors.
4. Low heat generation.
5. They can be dimmed effectively.
6. No need of reflector or focusing assembly.
7. More rugged than filament lamps.
8. Lifetime of 100,000 hours.
10. versatility.
11. More energy efficient.

4.2 LIMITATIONS

Most LED lamps on the market today use a 5mm LED device, which consists of either a single device or multiple devices combined to form a unit. These 5mm devices consist of clear or colored epoxy that forms a basic optic. The optic works to focus the light into a beam that has a beam spread ranging from 16 degrees up to 30 degrees.

When used as a general lighting source, the 5mm LED device has several drawbacks as opposed to when it is a point source and viewed directly. The optic in the
device is only about 30% efficient, which is acceptable for a point source, but will not perform well in a general lighting application.

Using high efficiency optics it is possible to achieve state of the art extraction efficiencies making the lights brighter and more efficient.

Another major drawback with 5mm LED devices is the different expansion rates between the metal and epoxy parts within the device. The different rates of expansion between the parts cause the eventual failure of the 5mm LED device and a shortening of the life of the device to approximately 8 or 9 thousand hours.

There is a device with a single die that is approximately 9 times larger than the 5mm die. LED devices are surrounded by optical gels, which allow the device to overcome the problem with different expansion rates and makes the lifetime of the devices much, much longer.

LEDs can get very hot during operation. Local overheating can lead to an imbalance in the current, with the result that the hot LEDs get still hotter. This process is called 'thermal runaway' and, if not checked, will cause the LEDs in the lamp to fail one by one. For the larger lamps, careful thermal design is required, as well as control electronics that can detect the fault condition or, ideally, prevent any hazardous situation arising in the first place.

All light-producing devices work by converting electric current (not voltage) to light. LEDs require a controlled current supply. If we connect them to a voltage source without a 'ballast' to limit the current they are in danger of burning out. The current can be limited with a resistor, but this is only really suitable for smaller lamps, as it can be inefficient. A more sophisticated control uses a current regulator; and more advanced still is a power converter, known as a 'switch-mode' supply. This takes some expertise to implement well, and there is the attendant problem of designing reliable cave-proof electronics.

The light from an LED is almost a point source. This means that there is a very high
power density, and when this spot is focused onto our retina, there is the potential to cause eye damage. The situation is not as bad as with laser diodes, but it is still a cause for concern. Perhaps some form of diffuser would be advantageous.

Additional drawbacks include the use of resistive/capacitive supplies, which are inexpensive, but are not electrically efficient and may develop problems when a large number of the LED devices are driven from a transformer.

Another drawback is that when a capacitive supply is used with multiple 5mm LEDs in a series, that when a single LED fails, the whole lamp will fail. We can incorporate proprietary electronics that use switched mode power supply technology to control both the current and temperature supplying the LED. This technology insures a long life, high electrical efficiency and safe operating conditions.

5. A LOOK INTO WHITE LED

5.1 STRUCTURE

A white LED is basically a blue LED surrounded by a phosphorescent dye that glows white when it is struck by blue light. This process is similar to that in flourescent
lamps, where the coating glows white when it is irradiated by the ultraviolet light that the tube generates internally. A white LED has a continuous spectrum similar to daylight, i.e. slightly ‘blue’. This coupled with the fact that the beam is pure, is why the light can look slightly ‘unusual’ underground.

The light has a color temperature of 6500 degrees, which is similar to noonday sun. If you look at the spectrum through a prism, you will get a mostly complete and well-proportioned rainbow. This is why the LED has a very good color-rendering index of 85. Many other white light sources, such as a fluorescent light have just a few widely spaced spectral lines and as a result have a poor color-rendering index.

White LEDs currently offer an efficiency of around 20 lumens per watt, which is higher than of incandescent light bulbs, but not high enough to compete with fluorescent lights, which have an efficiency of 60 to 100 lumens per watt.

There are two kinds of single-chip white LEDs, viz, gallium nitride-based diodes with an InGaN active layer. One version combines a blue LED with a yellow phosphor. It generates white light by mixing blue with the yellow light emitted by the phosphor. The combination of an ultraviolet LED with red, green and blue phosphors generates white light, just as fluorescent lamps do. Ultraviolet light excites the phosphors to generate visible light.

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5.2 SPECTRUM

LEDs are monochromatic (one color) devices. The color is determined by the bandgap of the semiconductor used to make them. Red, green, yellow and blue LEDs are fairly common. White light contains all colors and cannot be directly created by a single LED. The most common form of "white" LED really isn't white. Its a Gallium Nitride blue LED coated with a phosphor that, when excited by the blue LED light, emits a broad range spectrum that in addition to the blue emission, makes a fairly white light. The actual light has a blue cast and is similar in color to a mercury vapor street lamp.

On the curve shown, the peak at the left is the shortest wavelength blue light from the LED. The lump of emission to the right is the longer wavelength emission of the phosphor.
5.3 IV CHARACTERISTICS

This IV curve is log-normal up to about 20 mA. After that, it saturates, the voltage goes up but the current does not go up fast enough. This indicates that the diode is screaming in pain. The power dissipation and therefore the temperature of the LED is increasing rapidly.

5.4 FORWARD IV CHARACTERISTICS

The LED generates light when current passes through it in the "forward" direction. The important thing to note is that the red, green and yellow diodes are all Gallium Arsenide devices and all have about the same forward voltage drop. All their red, green and yellow cousins will be about the same. The white LED is a Gallium Nitride device and has a considerably higher forward voltage drop. All other white LEDs of the same technology
5.5 REVERSE IV CHARACTERISTICS

When the diode is reverse biased, no current should flow. However all diodes have an avalanche or breakdown voltage. This is the highest voltage that the diode can stand before it starts to conduct in the reverse direction. Reverse conduction is very hard on any diode not designed for it. Whatever current does flow will do so with high voltage...
impressed across the diode and the dissipation will be very high and could result in rapid thermal destruction of the diode.

Most of the white LEDs are rated for a $V_r$ (reverse voltage) of just 5 volts. This is not high enough to cause the diode to block reverse currents.

6. WHITE LEDS BECOMING POPULAR

6.1 APPLICATIONS

White LEDs are beginning to be used in lighting for offices and automotives, and photographic flashes, replacing incandescent bulbs, fluorescent bulbs and xenon lamps. At the same time, market requirements have changed. It no longer requires merely white lights, but brighter lights, or lights that match the colour of sunlight. As a result, equipment manufacturers, who formerly left everything up to the LED chipmakers, have begun to control white LED functionality. The white LED has assumed a new importance in equipment’s aesthetic and functional design.

White LEDs are making steady progress as photographic flashes for camera-equipped mobile phones, enabling video photography even in dim light. This is possible because of the continuous emission capabilities of the white LED. The flashes from commonly used xenon lamps for cameras are pulses, and can not be kept ‘on’ continuously. The dimensions of the white LEDs are also advantageous: they do not need the drive capacitors that the xenon lamp requires.

6.2 TRUE EFFICACY OF LED LAMPS

Light sources perform well when used in a suitable environment. The lumens per watt, the SI unit commonly used for measuring the total amount of light emitted by a light source per energy input, does not accurately reflect the true efficacy of LED light sources. An LED is a directional light source and emits little or no spherical light, whereas lumen-per-watt takes into account all light emissions, including spherical, from a light
source and not just what is actually accomplishing the required illumination task.

Placed under a lens, an LED lamp cluster can suffer a 20 to 30 per cent reduction in brightness depending on the specific and thickness of the lens. The lighter the lens pigmentation, the brighter the LED lamp appears.

7. WHITE LIGHT FROM LEDS

7.1 HOW IT IS PRODUCED?

While the introduction of white-light LEDs has increased interest in using LED lighting, this has raised an equal number of questions concerning what white-light LEDs can and cannot illuminate and how they can be used. To understand the potential of white LEDs, it is helpful to examine the methods used to produce white light from LEDs.

White lights from LEDs can be produced by combining red, green and blue (RGB) LED chips in one discrete package or cluster LED lamp, or by coating blue InGaN LED chips with phosphorus.

The technique of mixing red, green and blue LED chips is used in signage because RGB LEDs can be combined to create 256 colours, making it a cost-effective and efficient solution. If a lighting application requires a rainbow of colours from a single-point light source, an RGB LED is the answer.
In the second method, blue light from an InGaN LED chip filters through the phosphorus to generate a cold white or fluorescent light. InGaN technology results in superior reliability and colour integrity.

InGaN LEDs would be used, for example, in elevator panel lights because illumination of only one colour is needed. The brightness and colour purity of InGaN white LEDs depend on the amount of phosphorus coating.

Three shades of InGaN white LEDs exist: cool white, pale white and incandescent white. Cool white has the least amount of phosphorus, incandescent white has the maximum amount of phosphorus pale white is somewhere between the two. Cool white is brightest, incandescent is the dimmest and pale white holds the middle ground.

One issue with all phosphor-coated white LEDs is the Stokes shift, which is the difference in energy between the UV or blue light from the pump LED chip and the longer-wavelength (lower-energy) light emitted by the phosphor. UV-based white LEDs experience larger Stokes losses than those pumped using blue chips. However, the superior
Many think that InGaN white LEDs can illuminate a lens of any colour, thereby simplifying lighting requirements and designs. But it is wrong. Since red colour is not represented in the white LED, white LEDs can only be used behind a clear or milky white lens or panel. Place a white LED behind a red lens and the light produced is pink, a yellow lens turns lemon-lime, green lens shifts to aqua and orange lens becomes yellow.

To maintain accurate and brilliant colours, it is imperative to match the LED colour with the lens colour. In short, white LEDs made from a blue chip cannot be used as a general backlighting light source for different coloured lenses and panels.

### 7.2 RELIABILITY OF WHITE LEDS

The first and greatest contribution of the new white LEDs is their reliability. These LED bulbs are solid state Light Emitting Diodes and have an expected lifetime of around 100,000 hours. That's over 11 years of continuous operation.

If you look at one of these bulbs closely you will see there are some wires and a little block of material completely encased in clear plastic. The little block of material is the part that is generating all the light. It is almost impossible for the LED bulb to fail because of physical abuse unless you smash the plastic or break the wire leading to it. Putting the LED on a cement floor and hitting it with a hammer is one way to break it. So realistically, as long as you can get power to the bulbs, you will never be in the dark.

The way these bulbs fail under normal conditions is to slowly generate less light. You can expect the light output to drop about 3% for every 1000 hours of operation at full power (25 degrees C, 20mA). At reduced power settings, the percentage drop per 1000 hours gets very small indeed.
Like all solid state devices, the failure rate goes up with the junction temperature. Increased ambient temperatures and increased current will drive up the junction temperatures. Putting a large number of LEDs into an array has the same affect as raising the ambient temperature so extra caution must be used for large arrays. But since there is no easy way for you to measure the junction temperature, be sure to stick to the manufacturer's published limitations or reliability will suffer.

7.3 BRIGHTNESS OF WHITE LEDS

Light output is the total amount of light the little block of material generates. Luminous intensity is how brightly a surface is illuminated. If you spread the same amount of light over twice the area, the luminous intensity will be half. And if you move the light source twice as far away from the surface it will illuminate four times the area.

They are plenty bright -- if you use more than one. You will need an array of 12 LEDs for smaller passages or light colored passages, what I will call the typical caving condition. You will need an array of 25 LEDs for darker or larger passages. 50 LEDs are only needed for very dark passageways, such as large lava tubes. These numbers assume you are using the best quality devices at normal drive currents.

The above numbers also assume the LEDs you are using have a half-angle of about 15 degrees (i.e., the brightness has dropped to half by 15 degrees off the center axis) and produce an optimum beam pattern. Which leads us into the optical properties of LEDs. Each LED has its own lens. For most flashlight and headlamp applications, a beam of light is desired. However, for optimum usefulness, the beam intensity should fall off smoothly from the center of the beam to the edge of the beam. Such a beam will provide a smoothly lit path from your feet to where you are looking if the beam is aimed about 5 paces in front of you. You will find that the beam patterns change from one manufacturer to the next and so careful selection is needed for best results. You may have to combine LEDs with different optical properties to get the desired beam pattern.

The beam pattern from an incandescent light with parabolic reflector is a narrow 15
degree beam. From the center of the beam to just outside of the beam is contrast ratio of 6 f-stops - a very harsh contrast ratio indeed. However, the beam pattern of an LED array using superior optics has no discernable beam because of the smooth transition from the central bright area to the dimmer edge areas. A visual cone of over 45 degrees is well illuminated and we still have not reached the 6 f-stop contrast point. We have traded the brighter peak luminous intensity (almost 2 f-stops) with its harsh viewing conditions for a smoothly lit scene that is safer to more around in and more pleasant to look at.

The following photographs will illustrate this point.

Beam pattern from a 24-LED array, 1.4W (left) and two-cell headlamp with 2.5V 500mA halogen bulb, 1.4W (right)
This scene is looking at a saguaro cactus about 30 feet (9 meters) away. The lamp is pointed about half way up the cactus. The left photo used a 24-LED array; the right photo used a two-cell headlamp with halogen bulb.

This scene is looking at a streambed with the lamp pointed about 15 feet (4.5 meters) ahead. The left photo used a 24-LED array; the right photo used a two-cell headlamp with halogen bulb.

Now on the subject of how much light is needed to perform a task. For instance, when we are using an array of 12 LEDs for small to average size passage, it is for providing enough light to clearly see interesting things on the floor, walls and ceiling. If all we want to do is traverse a passage without falling into a hole, a single LED will do fine. It's like the difference between hiking a beautiful mountain trail in daylight versus on a dark night -- following the trail is different from seeing all the scenery.

**8. EFFICIENCY OF LEDS**

When we consider the overall performance of a lighting system, there are three major considerations in addition to the beam pattern. First, our eyes are able to adapt to a wide range of light levels with relatively small changes in visual acuity. As long as we can still see colour, there is enough light for high visual acuity. Below this level, your visual acuity drops rapidly. Of course, fatigue, altitude and illness can have an adverse affect of
your visual acuity and increase your need for light.

Second, our eyes respond to light in a non-linear (logarithmic) fashion. What this means is that the light level has to change dramatically for you to notice a slight change in illumination. If you change the light level by 20% you may not even notice the difference.

Finally, LEDs can efficiently produce a wide range of light output. Roughly, light output is proportional to power input. For this discussion, we can assume a linear relationship.

Combining these characteristics allows us to build a lamp system that is super efficient because we can reduce the power consumption by allowing the eyes to adapt to a comfortable level of light. The important thing here is the ability to generate the correct amount of light needed for a task and to do so efficiently. And because of the way your eyes work, when we reduce the power we are reducing it to 25% at each reduction. Going the other way, we are increasing the power by 4 times for a significant increase in light output. This is the reason bright lights must consume so much power.

For best results, the different light settings should be spaced about 2 f-stops apart which corresponds to a power change of about 4:1. This keeps the total number of settings to 3 or 4 which has several advantages over continuously variable dimming. First, it makes it easy for the user to know exactly which setting is being used and hence keep track of power consumption. Second, it makes it easy to adapt to lower light levels because the next lower level is always within a comfortable range of your eyes. Finally, with a continuously variable setting, the user tends to make slight increases without realizing the total cumulative effect and thus tends to use more power.

The white LEDs have advanced to the point where they are now more efficient than the low power (less than 2 watt) incandescent light bulbs. They are just about as efficient as the higher power bulbs (3 to 5 watts) incandescent light bulbs. Within another year they will have passed the higher power bulbs in efficiency.

The efficiency of the white LEDs changes depending on how much power you are
running through them. If you take 20mA as the starting point (100%), adding power reduces the efficiency while reducing power increases the efficiency. At the high power extreme, increasing power by 7.5 times only results in 3 times the light output for a staggering drop in efficiency. At a low power extreme, dropping the power by 80% still yields 30% of the light for a substantial increase in efficiency. The moral to this story is if you need more light, add more LEDs, don't increase the power per LED.

9. LED VARIATIONS

Speaking of LED variations, it is probably worth taking a few moments to talk about the differences between individual LEDs. If we make 50 identical parts on the same wafer, all 50 parts will be different. In fact, we have to test each part to figure out what the part is. In the case of white LEDs, the voltage curve, the efficiency and the color all vary from one LED to the next. As a result vendors sort the parts into separate bins and sell them at different prices. The best LEDs are the most expensive.

Now about combining red, green and blue LEDs in order to get white. Surely it would be more efficient than using a blue LED with the phosphorescent materials. And indeed it is more efficient. But given the LED to LED variations, it is almost impossible to produce a consistent white light. Each color of LED has its own family of characteristics. It is a very difficult engineering problem to compensate for the 6 major variables and eliminate the color fringing.

Purchasing white LEDs from a single bin that have been tested to close tolerances is a simpler way to run a production line. In the end, the product will be less expensive and perhaps just as efficient.

10. CONTROLLING LEDS

10.1 NEED FOR CONTROLLING

LEDs have a very steep voltage/current curve. What this means is if
we change the voltage by a small amount the current will change by a large amount. This also means that LEDs need to be tightly controlled in order to achieve consistent results. LEDs need control circuitry in order to operate safely and efficiently. A sophisticated controller, using a switched-mode power supply will allow us to dim the LEDs to save power, and it will allow you to extract the maximum amount of energy from your battery. At the other end of the scale, we can simply not bother with any sort of current control - you might get away with it.

The stages of sophistication can be split into five broad categories.

10.2 NO CURRENT CONTROLLER

The simplest way to control LEDs is to connect them to a battery that does not have enough voltage to drive them to normal current levels. All small LED flashlights that use two alkaline batteries use this method. There is no inherent power loss but the LEDs are always dimly lit because they cannot draw full power.

We can connect LEDs directly to the batteries. This is simple, but very restrictive of battery voltage, reliability and useful battery life. Using modern electronics, these power supplies are small, light weight, reliable and highly efficient. We might do it for a single LED key-fob, but it would be foolish to try it with a multi-LED lamp, since it could be an expensive lesson. The drawback to using constant voltage power supplies is that the supply voltage must be carefully matched to the LEDs.

The voltage across a single white LED, running at 20mA varies between about 3.3V and 4.0V depending on temperature and manufacturing tolerances. If we happen to be using a diode at the lower end of that scale, and we connect a 3.6V battery across it then it will over-run considerably because - unlike a filament lamp - the current in an LED is exponentially proportional to voltage. As the over-run diode gets hot the current will increase further, leading to thermal runaway and damage. There is a particular problem if you try to connect multiple diodes in parallel unless they are 'matched'.
10.3 RESISTOR AS CURRENT LIMITER

The most common way to control LEDs is to add a resistor in series with the LED. The resistor acts to limit the current flow by causing a voltage drop across the resistor. You can use the internal resistance of the batteries themselves and this what is done for all the small flashlights that use 3 alkaline batteries. However, even with well-chosen values, the tolerances are sloppy. The solution is very inexpensive but has the problem of wasting a lot of power in the resistor. Power losses of 15% to 25% are typical.

When we connect LEDs to battery via a resistor that allows us to regulate the current in a crude way. But you are still limited to a small variation in battery voltage. But when the battery voltage drops the light would dim to nearly nothing - unless we short the resistor. In summary - we are wasting power in the resistor, and we are only able to use a fraction of the available battery power.

10.4 LINEAR CURRENT REGULATOR

We can see from the above that what is required is a series resistor that can be dynamically adjusted. This is, in fact, the principle behind the standard series-pass transistor voltage regulator. The difference is that here we require current regulation instead of voltage regulation. The block diagram of a typical circuit would be as in Figure.

Figure - block diagram of a linear current regulator. The complete circuit uses only a few more components than shown here.
The reference voltage is compared with the voltage across the current-sense resistor, and the resultant error voltage controls a series-pass transistor. It is not necessary to use a MOSFET; in fact a good quality bipolar transistor will work better. By altering the reference voltage we can dim the lamp.

Depending on the relative voltages of your battery and the LEDs, this circuit can be quite efficient. When the battery voltage drops below 10.5V the circuit comes out of regulation, but the LEDs will still be illuminated, and will now perform as if they were directly connected to a battery of a 'safe' and gradually falling voltage.

10.5 A SWITCHING REGULATOR

A switching regulator, or switched-mode power supply (SMPS) can be thought of as a 'transformer' that converts one voltage to another with minimal losses. The series-pass transistor of Figure above is replaced by an SMPS module (Figure below) and, again, current feedback serves to maintain the voltage across the diodes at exactly the right point for safe operation.

Figure - block diagram of a switching current regulator. The controller IC switches its output transistor at a high frequency, and the current pulses are smoothed by the external inductor, diode and capacitor. Current feedback from the sense resistor requires more components than shown here, but the basic principle is
the same. The current is compared with a reference and the output of the regulator and the output of the regulator adjusts itself to keep the LED current constant despite falling battery voltage or rising LED temperature.

The disadvantage of switching regulators is that they are not straightforward to design, and are more costly than the other options discussed here. Using a published design - such as the one(s) that we will be discussing in future articles - solves the first problem. And the additional cost is not a large fraction of the overall cost of the lamp - especially if you are going to use a lot of LEDs.

10.6 COMPUTER CONTROL

Computer control may seem to be a bit of a gimmick but, if we do not trust a microprocessor-controlled lamp, then our designs will work without it. But if we do want some additional features, a small 'PIC' processor (from Arizona Microchip) makes it easy to add them.

We could, for example, arrange for the lamp to switch off after an hour or two, so that the battery will be saved if we accidentally leave it on. (Obviously, it should not just switch off without any warning, but it is not necessary to discuss such sophistication here - it should be self-evident that aspects such as this will be catered for in the software which is, in any case, easy to modify to suit the requirements). Another option is to implement a 'fuel gauge', where the lamp can give you an indication that it only has a few hours' life left.

One attraction of a computer-controlled lamp is that it could be controlled by a simple push-to-make low-current switch. Because the switch does not have to carry a high current, nor provide multiple functions it can easily be made totally waterproof. Functions such as dimming the lamp, blinking SOS and so on, are all achieved by clicking or double-clicking the switch.

11. REGARDING THE COST

High quality white LEDs are still expensive. The manufacturers are tending to
keep the price constant while improving the efficiency. In the last two years there has been a significant increase in efficiency and color consistency while the price has remained unchanged.

Given the relatively high cost of LED lamps, the issue of an LED flashlight or headlamp quickly becomes one of utility. People accept the fact that it will produce a useful if limited amount of light. If damaged, it's not a great expense. To purchase something that will be a primary source of light is going to be an investment, so we want the lamp to last a lifetime.

To last a lifetime, the lamp must be well built, rugged and tolerant of water, mud and dust. And while we're at it, it should be very reliable, have multiple brightness settings and be efficient. Over the next couple of years the LED unit price may drop by 20% to 30%, this will make a slight change in the overall lamp cost.

Opto-electronics is an exciting area and white LEDs in a few years time may be powerful and cheap enough for house and street lighting when they move from being maximum 100mW devices to several watts each.

White LED lamps which contain 36 or 48 LEDs and which incorporate 'smart' power supplies to implement dimming and allow the lamps to operate from all common caving batteries (e.g. FX5/Kirby pack down to two AA cells). More recently, produced a seven-LED pilot light with a simple built-in regulator, which enhances its performance without adding much to the cost.

Now, LED lamp is designed to glow in its original color, which is activated by the Ultra Violet content from the sun. This also means that you can also choose to power down the lamps during the day and yet still see the colors, which adds more cost savings on your energy bills.
12. CONCLUSION

However, given the remarkable technological innovation of the past few years, it is expected that market expansion will bring further improvements in LED luminous efficiency, and further cost reductions. The range of uses will surely continue to increase, not only for white LEDs but also for LEDs of other colors, within the context of saving energy and the need for thinner designs. The LED, the new "light" of the 21st century, will surely serve as a key technology for social infrastructure, such as traffic systems, as well as many industrial sectors, such as electronics and automobiles. LEDs will also bring a diverse array of innovations to our daily lives and provide a powerful means for saving energy for the future.
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