IALA

IALA GUIDELINE

1048

LED TECHNOLOGIES AND THEIR USE IN SIGNAL LIGHTS

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Association Internationale de Signalisation Maritime

DOCUMENT REVISION

Revisions to this IALA Document are to be noted in the table prior to the issue of a revised document.

Date	Page / Section Revised	Requirement for Revision

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1. INTRODUCTION

Over the past 10 years, advances in high intensity LEDs have made their use preferable to incandescent lamps for many signalling applications. Among the special advantages of LEDs, in comparison with incandescent lamps, are:

- longer expected operational lifetime;
- higher electro-optic efficiency, particularly for coloured light;
- improved colour purity;
- shock and vibration resistance;
- low service cost.

As LED light deployments have increased, end users increasingly have become concerned with issues which impact performance, expected operational life and measurement standards.

1.1. OBJECTIVE

The purpose of this Guideline is to provide interested persons with an understanding of the unique optical, thermal and electrical properties of LEDs and LED lights.

The Guideline provides a brief overview of current LED technology and identifies specific issues of interest related to the design, specification and use of high intensity LEDs in signal lights.

2. LED LIGHT

2.1. DESCRIPTION OF OPERATION

LEDs are electronic semiconductor devices that produce near monochromatic light. The semiconductor junction is typically encapsulated in a clear plastic housing that usually incorporates a lens. Several LEDs may be grouped together in a cluster or an array to provide a light source of the required size and intensity to replace a lamp or lamp and lens system. New high power LEDs allow short range lanterns using a single LED.

LEDs operate from a low voltage DC supply. Correct operation depends on accurate control of the supply current.

An LED is not a lamp, but rather a solid-state light source that emits monochromatic radiation in the infrared, near ultra-violet or visible spectrum when a current is passed. Spectral power distribution is narrow in the order of 50nm, except for white. There are two main types of white LED: those with a combination of different coloured LEDs (typically red, green and blue) that appear white when viewed together; and those consisting of a blue or UV LED chip that activates a broadband phosphor - so-called phosphor-conversion LEDs or pcLEDs (see section 3.3).

When compared with incandescent technology, red and green LEDs are much more efficient than incandescent lights with filters, yellow and white are presently a little more efficient.

LEDs require integrated thermal management and drive circuitry that can vary in efficiency. Within an LED, about 15% of the energy is emitted as light and the remaining 85% as heat. Unlike conventional light sources, which dissipate heat by radiation, convection and conduction, all heat from the LEDs must be conducted away by the luminaire.

Typically, each LED has an integrated lens. Secondary lenses may be used to produce a desired light beam.

2.2. ADVANTAGES AND DISADVANTAGES IN COMPARISON WITH FILAMENT LAMPS

There are specific advantages and disadvantages when compared with filament lamps:

2.2.1. ADVANTAGES

- energy efficient, rugged, robust, shock-resistant, no mechanical moving parts;
- long life depending on driving techniques, thermal management, environmental conditions, duty cycles and type of LED (see section 3.5), rarely catastrophic failures, but continues lumen depreciation.;

  Lamp changers are not considered necessary.
- LED groups or arrays can substantially reduce the probability of total lamp failure;
- light produced in saturated signal colours therefore coloured filters not needed;

  LEDs maintain the colour through whole lifetime.
- instantaneous on-off switching of light;
- presently demonstrating improved conspicuity for the same light output possible due to the colour purity (narrow spectral distribution) and rectangular-wave flash profile;
- does not have a high inrush current;
- no shadows created by filament supports;
- no complex maintenance requirements for LED lanterns;
- LED technology is advancing rapidly.

2.2.2. DISADVANTAGES

- generally difficult to match to existing optics;
- LED colours vary and may be outside the new CIE (2001) colour regions and therefore may have to be sorted;
- LED colours also shifts with operation temperature (about 2nm per 1°C for red and yellow);
- white pcLEDs will be very inefficient with red and green filters used with existing incandescent light sources and it is better to replace the lamp and filter with coloured LEDs, where possible;
- depending on drive circuitry, the light output can vary with ambient temperature but this variation may be compensated by controlling the current;
- individual LEDs can vary greatly in the distribution of their light output, affecting beam pattern;
- long term experience with LED lanterns is limited;
- light output degrades over operating time;
- complex electronic control needed to achieve long life and consistent performance;
- LEDs technology is not yet suitable for long range lights;
- there is a gap between phosphide and nitride technologies and this is in the yellow region, therefore some colours of yellow are not available.

2.3. OPERATIONAL, ENVIRONMENTAL AND FINANCIAL ISSUES

2.3.1. OPERATIONAL ISSUES

- minimal guidelines needed for LED lanterns since they are largely maintenance free;
- reduces complexity of maintenance and, therefore less technical competence is required;
- photometric performance may need to be verified but is difficult to quantify;
- efficacy (lumens/watt) is improving steadily, so LED lanterns will continue to improve in efficiency;

- large number in use (in the order of hundreds of thousands of LED lights are in use);
- region-specific safety labelling requirements.

2.3.2. Environmental Issues

- LED lanterns present no more environmental issues than other lanterns;
- elf-contained LED lanterns that contain a battery can present disposal problems;

  It is recommended that they be returned to the manufacturer for recycling.
- less power consumption leads to less batteries, solar panels, fuel requirements, etc. possibly resulting in smaller buoys and smaller moorings;

  These factors reduce the environmental impact of the aids to navigation to which LEDs are fitted.
- less frequent servicing reduces impact on environment from ships, aircraft etc.;
- LED itself is better than a lamp in terms of toxic materials.

  The very tiny amount of solid-state electronics involved is encased in epoxy or silicon, and there are no discarded lamps during life of lantern.

2.3.3. Financial Issues

- very long operating life and low power requirement may reduce maintenance expense;
- LEDs allow the production of small, self-contained lanterns;
- purchase cost depends on range and features. Low cost lights available for low intensity, up to high intensity where the initial purchase cost can be higher than incandescent lamp lanterns.

3. LED TYPES

There are many types of LEDs, differing in packaging methods, but sharing the same basic technology. LEDs can be generally divided into two groups by power: low power and high power.

3.1. LOW POWER LEDS

Low power LEDs (sometimes called indicator LEDs) often are used for direct viewing in arrays in signs and signal lights. The most popular are the 5 mm precision optical performance LED and the Super Flux LED.

3.1.1. T-1 3/4 or 5 mm LED

The 5 mm package is one of two original packaging configurations adopted from the incandescent lamp industry designated, T-1 and T-1 ¾. (the number indicates lamp diameter in 1/8ths of an inch). Thus, the T-1 ¾ has a diameter of approximately 5mm.

Details of the 5mm lamp are shown in Figure 1. The cathode lead, which mounts a small reflecting cup holding the LED chip, is used both, for electrical path and heat extraction. The upper surface serves as a lens, projecting light into the forward direction. This package is popular due to low cost and ease of incorporation into an array for signage or other high flux applications.

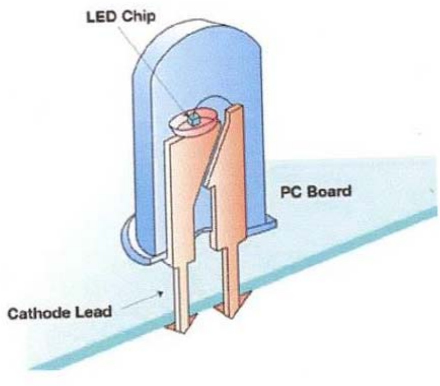

Figure 1 T-1 3/4 or 5 mm LED

(Source: LumiLeds)

3.1.2. Superflux LEDs

The Superflux LED package is constructed using double lead frames for reduced thermal resistance and improved ruggedness. Improved heat removal, along with a larger die area, permits a power rating of twice that of the 5mm device. Light is projected through a 3mm diameter convex lens on the top surface of the package.

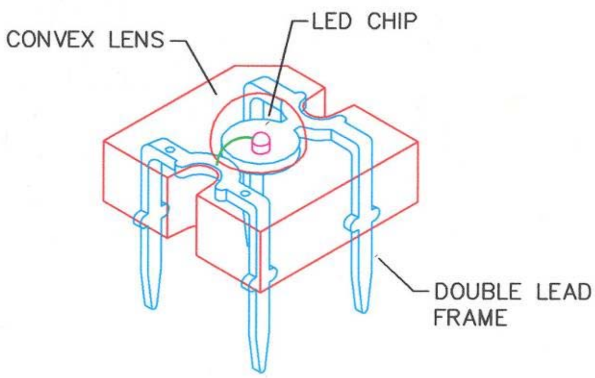

Figure 2 Superflux LED

3.2. HIGH POWER LEDS

High power or illumination LEDs are used to illuminate other objects or as high intensity, concentrated light sources.

The high power LED, Figure 3, employs a large metal slug for heat conduction with electrical leads isolated from the thermal path. This structure dramatically improves heat transfer, supporting greater die size and increased operating current.

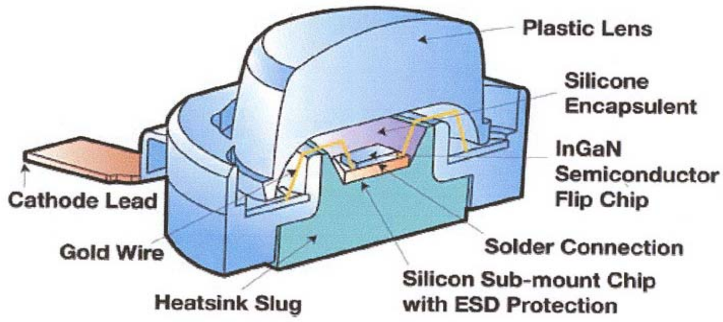

Figure 3 High Power LED

(Source: LumiLeds)

Other improvements include the use of an ultraviolet resistant silicone encapsulant as an optical coupling medium between the die and transparent epoxy outer package, greatly attenuating yellowing of the epoxy. In addition, the silicone material, being pliable, results in reduced mechanical and thermal stresses acting upon the die structure and electrical leads. Improved phosphor conformance coating provides greater uniformity in correlated colour temperature (CCT) for white LEDs. These advances have virtually eliminated severe lumen depreciation and colour variation, which are notorious in 5 mm LEDs.

3.3. COLOUR

The material composition determines emitted light colour. Variations in alloy composition produce differences in band gap energy and, in turn, different characteristic light colour. Currently, two classes of materials are used in most high brightness LEDs.

3.3.1. AlInGaP MATERIAL

Red, orange and yellow are produced by a four alloy structure of aluminium, indium, gallium and phosphorous (AlInGaP).

Hewlett-Packard, after a decade of research, mastered the technique of the complex OMVPE growth process (see definitions) allowing growth of the four alloy structure on GaAs substrates, leading to commercialization of high brightness red and yellow LEDs in 1990.

3.3.2. InGaN MATERIAL

Blue, green and white are produced by an alloy of indium, gallium nitride (InGaN). Researchers at Nichia Chemical and Nagoya University perfected the growth process for this alloy structure on a sapphire substrate, completing the full colour range of LEDs.

3.3.3. WHITE LED SOURCE

Currently two approaches are used to create a white LED source. The first uses colour mixing from an array of red, green and blue dies. This complex technique requires precise control of the LED driver including a feedback system ensuring colour integrity. This source type is used mostly in television back lighting. A second simpler approach uses phosphors deposited onto a blue LED die; achieving acceptable colour rendition.

In early 5mm LEDs, during the encapsulation process, a measured quantity of phosphor and epoxy in slurry form was deposited into the containment cup surrounding a blue die. This process resulted in variations as large as 700°K in CCT with viewing angle. (The human eye can detect a change of the order of 50-100°K.)

Colour variation with viewing angle along with colour shift with die temperature and time result in small variation in chromaticity.

3.4. LUMINOUS EFFICIENCY OF LEDS

With a goal of producing a viable high intensity light source for signal lights, LED manufacturers have focused on developments in:

- heat extraction;
- luminous efficiency;
- overall electro-optic efficiency;
- cost.

3.4.1. HEAT EXTRACTION

The balance between heat generation and dissipation is a key limitation on power handling capacity. Manufacturers specify a maximum die temperature consistent with acceptable service lifetime. A thermal resistance stated in °C/Watt specifies the rise of die temperature above that of the LED mounting contact point or surface. Maintaining acceptable temperature is process of balancing:

- environmental conditions, i.e. ambient temperature from direct sunlight, lantern size vs. power, etc.;
- driving power;
- heat sink design.

Recent designs have emphasized intimate thermal contact between LED die and external mount. Thermal resistance has been reduced to between 10-15°C/Watt in high power devices in comparison with 100-150°C/Watt for low power LEDs.

3.4.2. LUMINOUS EFFICIENCY

For all practical purposes, luminous efficiency is determined by internal quantum efficiency and extraction efficiency.

3.4.2.1. Internal quantum efficiency

Internal quantum efficiency depends on several factors such as material impurity, optimisation of crystal layers, crystal growing technique, etc.

- AlInGaP (red, orange and yellow) is the most widely understood material;

  Consequently, its internal quantum efficiency approaches nearly 100% which means that every electron-hole pair creates a photon.

- InGaN (green, blue and white) is less well understood at the present time.

  Typical internal quantum efficiency of the green device is 20 to 40% with blue 40 – 60%.

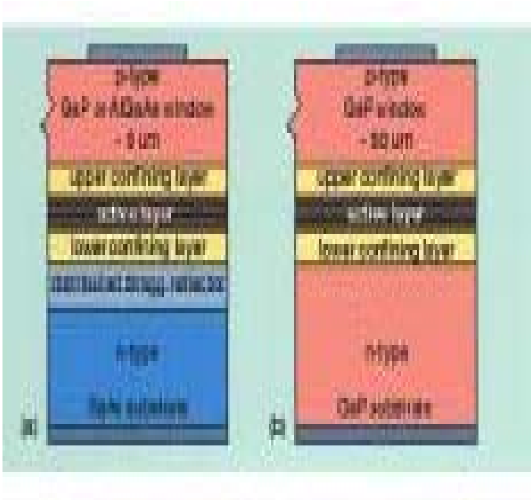

Figure 4 Typical Structure of AlInGaP Die

(Source: Compoundsemiconductor Magazine –.'AlGaInP LEDs break performance barriers' by Mari Holcomb, Pat Grillot, Gloria Hfler, M. Krames, Steve Stockman - April 2001.)

3.4.2.2. Extraction efficiency

Once photons are created, it is necessary to transport them out of the die, a process called light extraction. Extraction efficiency depends on absorption within the substrate material, chip geometry, and relative refractive indices of the die, optical coupling material and transparent package.

1 Boundary reflections.

The refractive index of the die material is extremely large in comparison with that outside of the die. This large discontinuity produces strong reflections, trapping the light within the die. Extraction efficiency is improved by an encapsulant of intermediate refractive index, which acts as a bridge between the die and external medium.

The extraction process for a rectangular solid die with epoxy encapsulant is shown in Figure 5. Photons within the die are generated and propagate in all directions. However only a small fraction is able to pass through the boundary within the small cone, with the remainder reflected from the surface. Outside of the critical cone angle, photons experience total internal reflection and do not contribute to useful light.

2 Absorption by substrate material (internal absorption).

Photons generated within the die structure must propagate within the die to reach boundary walls. Substrate materials are chosen with due consideration for minimizing absorption along this path.

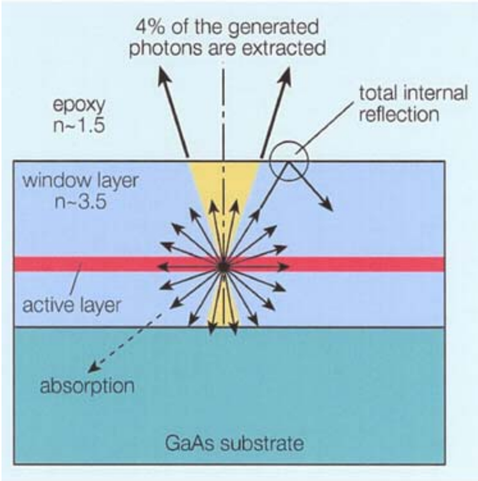

Figure 5 Showing the Extraction Process

(Source: Compound Semiconductor: Article 'Buried Micro-reflectors Boost Performance of AlGaInP LEDs' by Stefan Illek.)

3 Die geometry has a large impact upon extraction efficiency.

To date, the most efficient geometry is the truncated inverted pyramid (Figure 6), which minimizes internal reflections. To date, the highest extraction efficiency is 55% at 650nm.

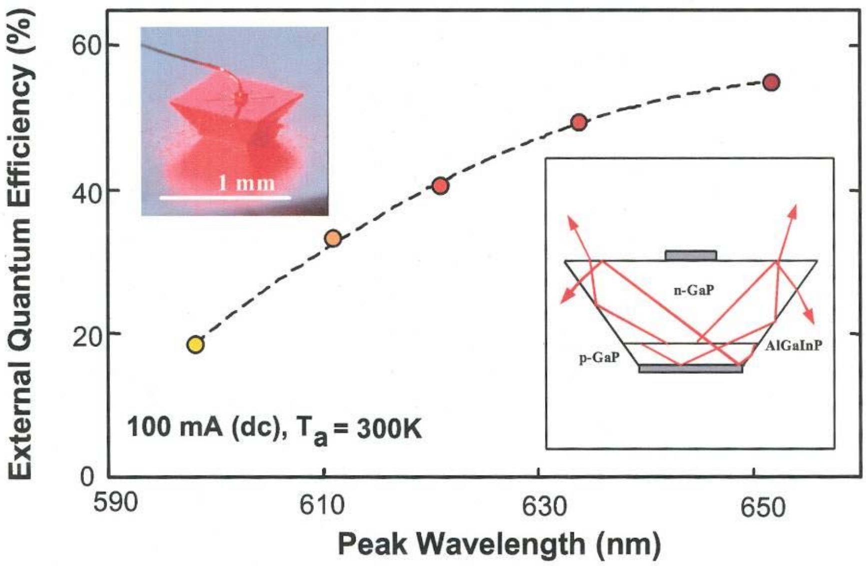

Figure 6 AlInGaP/GaP Truncated-Inverted-Pyramid (TIP) Die

(Source : LumiLeds)

3.5. LIFE AND LUMEN DEPRECIATION

Life expectancy of LEDs is a misleading claim by some manufacturers. Traditional light sources such as incandescent lamps have a life defined as the time at which 50% of test samples have burned out. Currently, there is no corresponding standard definition for LED lamp life. In analogy to a mercury or metal halide lamp, an LED seldom fails catastrophically, but instead slowly degrades in light output over time. This process is called alternately lumen maintenance or lumen depreciation.

Generally, a light level reduction over a short time is not noticeable until the level reaches 80% of its initial value (Kryszczuk and Boyce.) Figure 7 shows range reduction in nautical miles versus initial visual range with percent intensity degradation of the light source as a parameter.

IALA, to date, has not addressed this issue or recommended a source replacement scheme for AtoN signal lights based on degradation levels. Some of the administrations accept a 20% degradation before replacing lantern while IALA Recommendation on the determination of the luminous intensity of a marine aid-to-navigation light quotes 75% as 'service conditions allowance' for reduction in intensity.

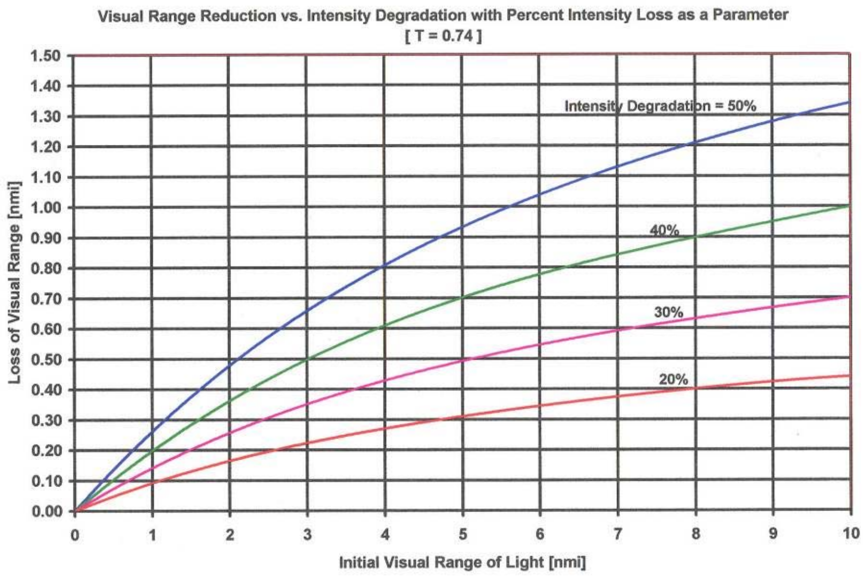

__Figure 7__ *__Range Reduction vs. Initial Visual Range in Nautical Miles__*

Lumen degradation depends upon the following factors:

- packaging (discussed above);
- Die operating temperature;
- drive current;
- colour.

3.5.1. LUMEN DEPRECIATION OF LOW POWER LEDS (OR 5MM PACKAGE)

Due to packaging methods discussed in section 3.1.1, the lumen degradation of 5mm LEDs is greater than that of high power LEDs mainly due to poor heat transfer and epoxy yellowing of the package.

Different colour LEDs have different rates of degradation since they are manufactured with different semiconductor materials with different degradation properties. Figure 8 shows typical lumen degradation of red, green, blue and white indicator type LEDs operating at rated current of 20mA.

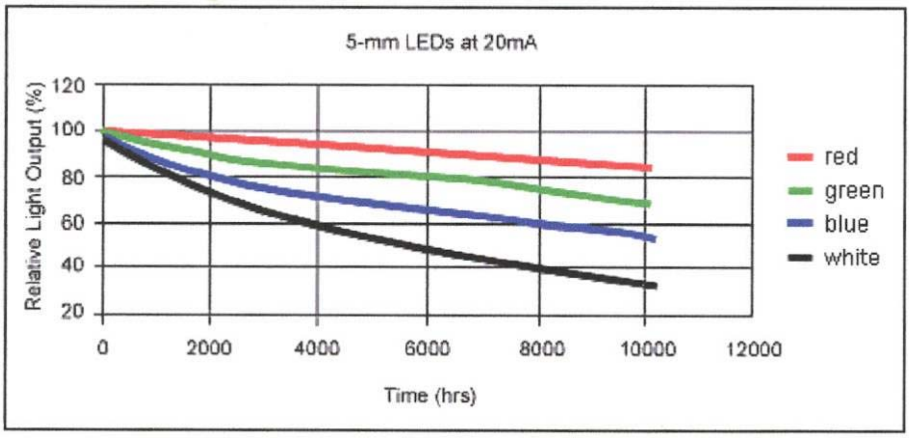

Figure 8 Lumen Degradation of Red, Green, Blue and White Indicator LEDs (5mm)

(Data based on literature of Lighting Research Center)

3.5.1.1. White Indicator type (5mm) LED degradation

The primary cause of degradation of white indicator type LEDs is yellowing of the epoxy encapsulant, caused by several factors:

- excessive junction temperature;
- photodegradation of the epoxy material subjected to short wavelength radiation.

Figure 9 shows typical lumen degradation of white 5mm LEDs for several drive currents.

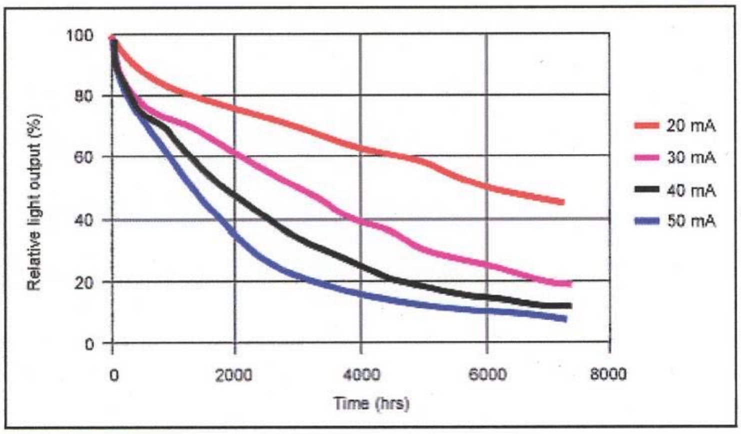

Figure 9 Degradation of the 5mm LED with different drive currents

(Data based on Literature of Lighting Research Center)

As seen in the figure above, indicator type white LEDs reach 75% lumen maintenance around 2000 hours when operated at rated current (20mA). Degradation is detailed in the test report entitled 'Solid-State Lighting: Failure Analysis of White LEDs' by N. Narendran at Lighting Research Center, Troy, NY.

3.5.1.2. Lumen degradation due to Pulsed Drive

It is common practice for many AtoN light manufacturers to employ a pulsed drive technique in an effort to obtain increased light output. However, due to declining electro-optic efficiency with increasing drive current, the average light output is less than that produced by a constant current of comparable power. In addition, increased peak current comes at a price of light output degradation, as shown in Figure 10.

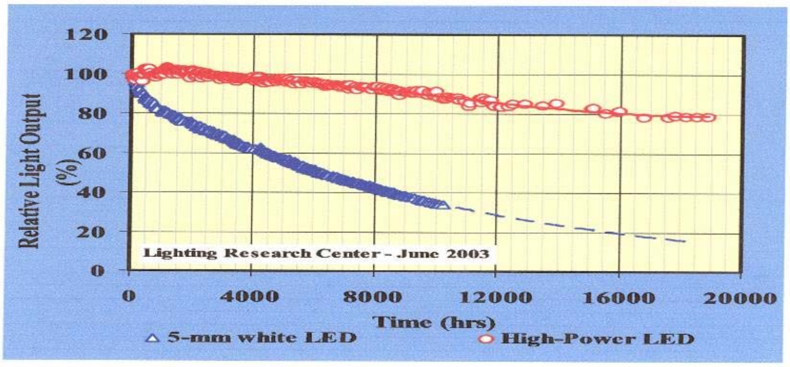

Figure 10 Projected Long Term Light Output Degradation for Pulse Drive Condition with The LED On Time Duty Cycle Adjusted to Provide an Average Current IAvg = 30mA

(Source: Agilent Application Brief I-024)

3.5.2. LUMEN DEPRECIATION OF HIGH POWER LEDs

Due to improvements in packaging as described above, manufacturers of high power LEDs claim to retain over 70% average lumen output over 50,000hours.

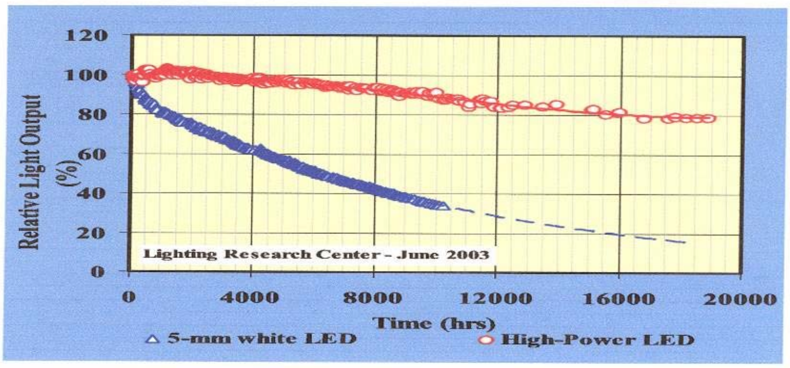

Figure 11 On Going Test Data From the RPI Lighting Research Center – Troy, NY

3.5.2.1. Lumen Degradation of High Power White LEDs

The use of silicone as the coupling material, along with improved techniques in phosphor coating, enable high power white LEDs to retain excellent light output degradation characteristics as shown in Figure 12.

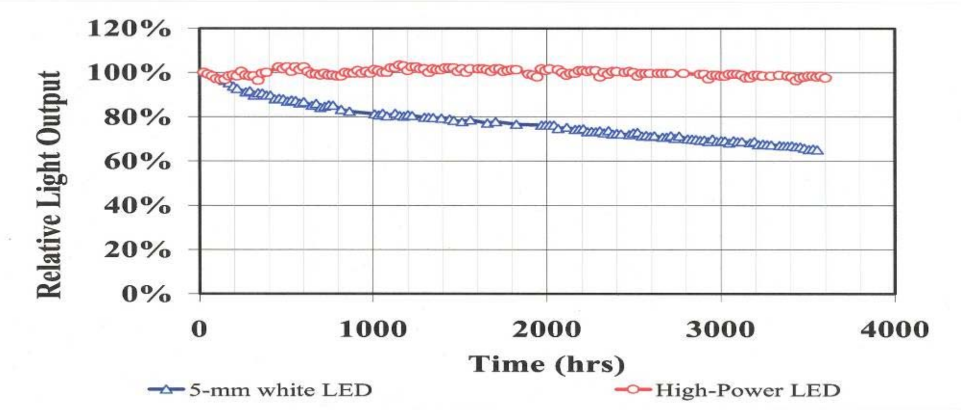

Figure 12 Ongoing test data from the RPI Lighting Research Center –Troy, NY

3.6. TEMPERATURE COMPENSATION

The electro-optic efficiency of LEDs is temperature dependent. In general, output flux decreases with increasing temperature under constant drive current conditions. This effect is most pronounced for the AlInGaP series, although all colours experience the effect to some degree.

Thus, in order to maintain a constant luminous output over the nominal range of operating temperatures, it is necessary to adjust the drive current, due care being taken to avoid thermal run-away. In addition, the drive current vs. temperature algorithm must be designed in such a way that maximum junction temperature and maximum drive current limits are not exceeded at high ambient temperature and with large duty factors.

3.7. IMPORTANT FACTORS TO BE CONSIDERED WHEN EVALUATING A LED LIGHT

Based upon information from the above overview, LED light specifiers and end-users should consider the following issues:

- luminous intensity should be specified over operational temperature range;
- horizontal consistency of intensity should be specified, noting that IALA E-122 recommends the 10th percentile figure of horizontal intensity be quoted;
- required angle of vertical divergence and beam location, noting that IALA Recommendation E-122 recommends that vertical divergence be quoted at 50% of maximum intensity;
- lifetime expectation depends on correct LED current and junction temperature;
- efficiency of beacon is proportional to total luminous flux versus power used;
- required working hours of the light;
- power source requirements, including power consumption when light is on and off;
- the operational effect of the reduction in intensity with time;
- temperature effect on peak intensity and temperature compensation to maintain constant luminous output;
- voltage effect on intensity, pulse or DC-driven;
- effect of loss of a single LED or group of LEDs;
- method of control i.e. current controlled, voltage controlled or power controlled, series or parallel;
- compliance of LED with the IALA Colours for Signal Lights, noting that colour may change with character exhibited;

- CE standard for Electromagnetic Interference/Immunity and Electromagnetic Compatibility, or other national standards;
- additional lightning protection may be required if not included;
- requirements for mechanical vibration/ shock;
- process at the end of useful life:
  - LED module or array replacement?
  - discard and replace with new light?
  - are life and colour performance specifications being met?

3.8. LED EYE SAFETY

LED eye safety issue has been discussed in many LED manufacturers' application notes and publications. Guidelines can be found in IEC document (IEC-825-1). Due to the intense, concentrated source, it is recommended to avoid direct viewing of LED sources at short distance where possible.

4. CURRENT AND EMERGING APPLICATIONS OF LEDS IN AIDS TO NAVIGATION

LEDs are being used in almost all AtoN equipment. These include LED lanterns for buoys, small beacons, range lights and illuminated 'day boards' which may be encased sealed units. The typical nominal range for LED omni-directional beacons is 1 to 15 nautical miles, with greater ranges beginning to appear for directional lanterns.

4.1. SECTOR LIGHT

Light-emitting diodes revolutionize the light signalling of all areas of traffic at the moment. For many applications (e.g. traffic lights, braking lights, sea lanterns) solutions have already been worked out in LED technology and used in practice.

The sector lights using the projection principle represent a special signal type of lights that is exclusively used in AtoN.

The development of high power LEDs (typically 1 watt, standard LEDs 0.1 watt) could be useful in the development of LED projectors.

In principle the lamp of a projector could be replaced by LEDs (Figure 13). However, the use of red and green filters in conjunction with an LED light source would severely reduce the intensity of the red and green sectors.

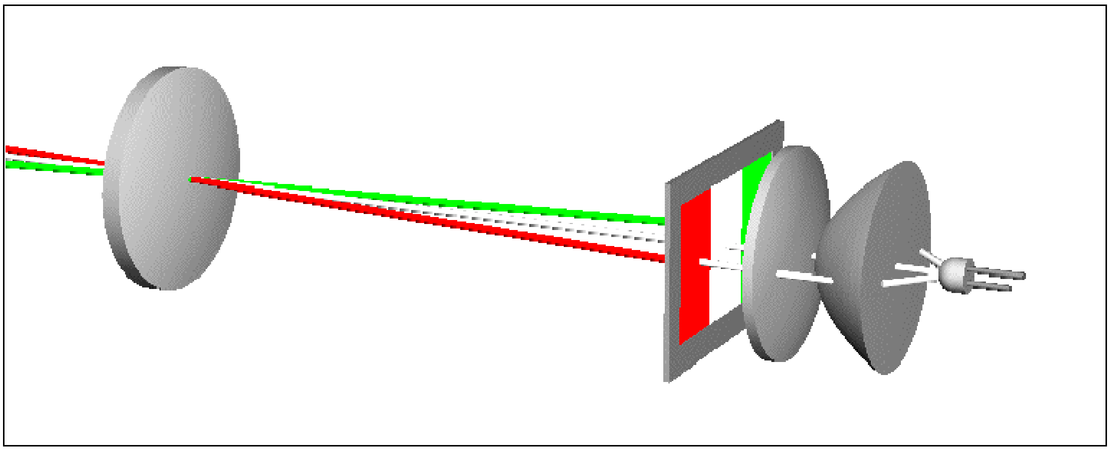

Figure 13 General principal of a projector

The light gain (emitted luminous flux per electrical power) of white diodes is only comparable with that of incandescent lamps. The projector in Figure 13 then would correspond to a sector light with a 1 watt incandescent lamp. It would be a very weak light and unsuitable for most applications.

An improvement is possible by using an own projector for every sector (Figure 14). The luminous intensity of the coloured sectors could clearly be raised since the colour doesn't arise from filtration any more.

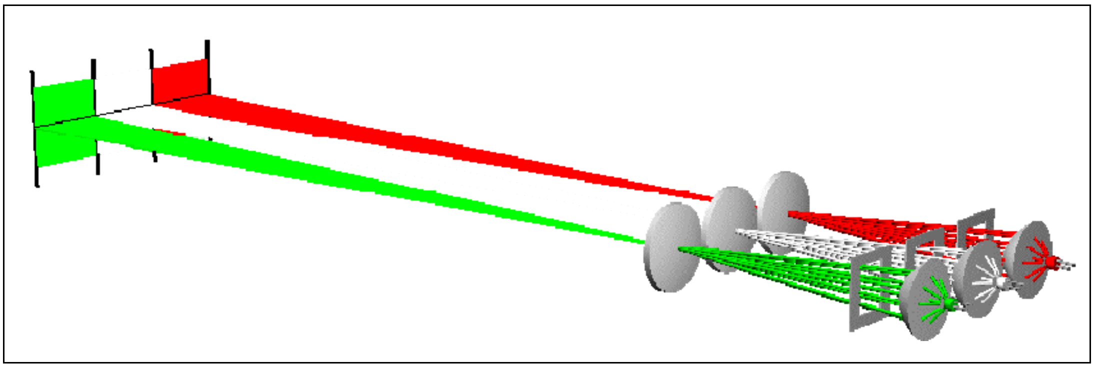

Figure 14 Beam arrangement for 3 projectors

However, this construction has two disadvantages:

Adjustment of the sector limits is complex and difficult. It is almost impossible to adjust the sectors on-site. Since the white LEDs are of lower intensity (at same electrical power) in comparison with the coloured, either the power of the coloured diodes must be reduced or a lower intensity white sector must be accepted.

To avoid these disadvantages, the white sector can be made by colour mixture from green and red (Figure 15). To produce the colour white by so called additive colour mixture, it is necessary to mix the three colours red, green and blue.

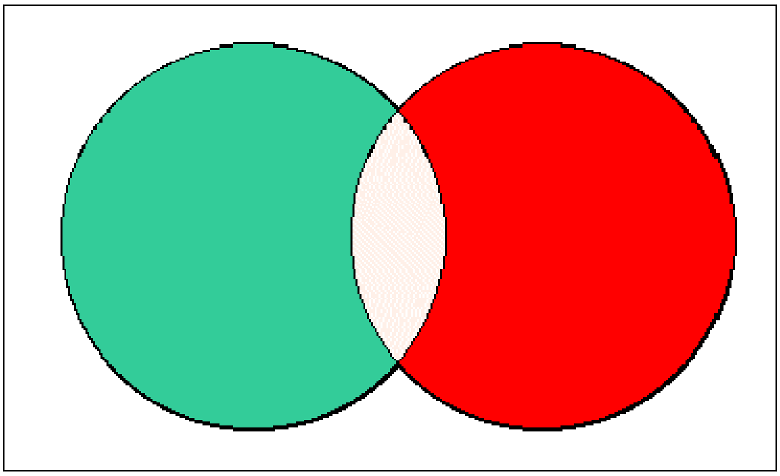

Figure 15 Colour addition

The green colour used in the traffic signals is always one bluish green and contains therefore also blue colour shares. A skilful choice of the luminous intensity of red and green a warm white arises, which fulfils the requirements for white signal lights (Figure 16).

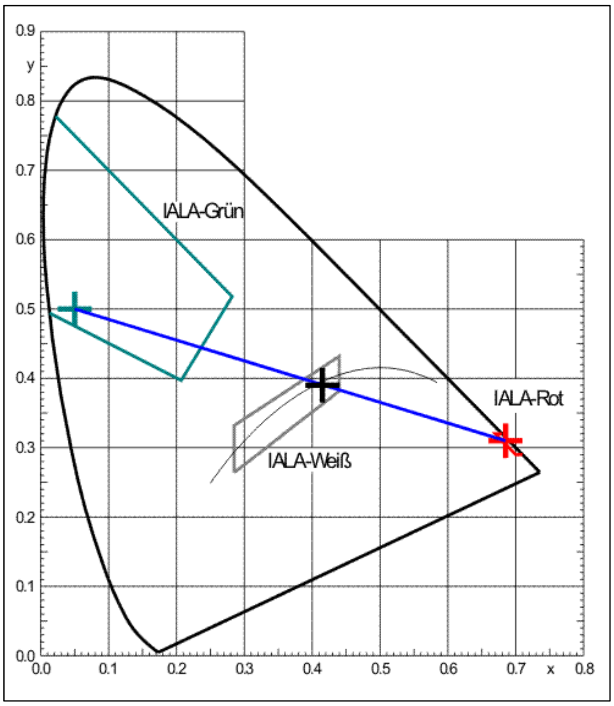

Figure 16 Colour diagram

To create the white sector, let overlap the two coloured sectors. This can be made by the use of two projectors (Figure 17).

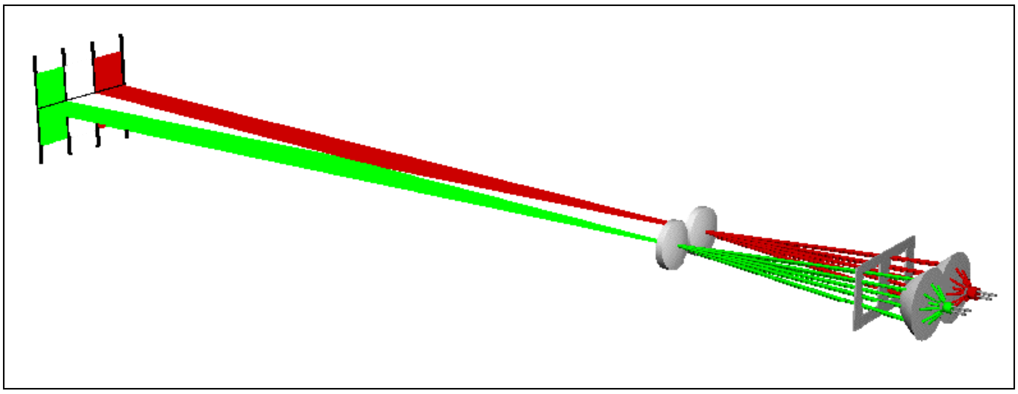

Figure 17 Beam arrangement for 2 projector

In some cases (e.g. at small distances or if the projection lens gets very great) it is advisable to mix the light already in the projector. A colour factor can be used for this.

A colour factor is a semi permeable mirror which reflects the light or lets through depending on colour. The colour factor used here is designed to an angle of 45° to reflect red light and to pass blue/green through. It is put between the frame for the sector limits and the projection optics. The two light sources are ordered at the colour factor that both rays are brought together again in the projection objective (Figure 18).

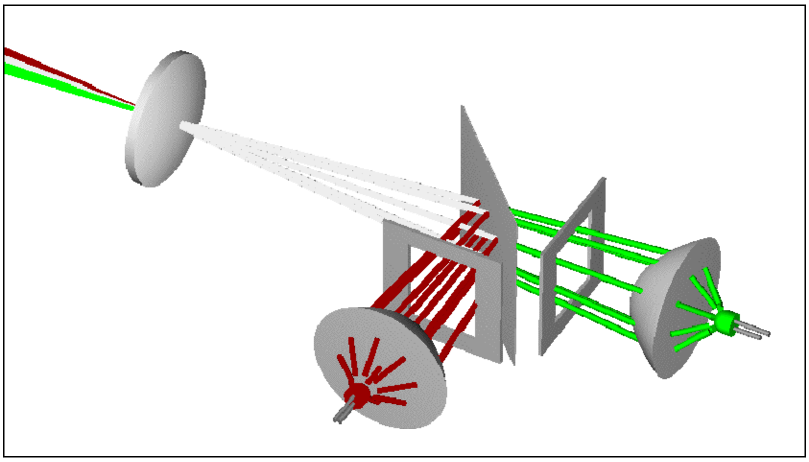

Figure 18   Beam arrangement for 1 projector

The following comparison is from the measures between a commercial sector light in incandescent lamp technology and the described experiment construction.

Table 1   Incandescent lamp technology compared with LED technology

Parameter	Incandescent lamp technology	LED-technology
Electrical Power	5 Watts	2 Watts
Luminous intensity (white)	1500 cd	1300 cd
Luminous intensity (red)	300 cd	650 cd
Luminous intensity (green)	300 cd	650 cd

By further improvements at the visual system as well as at the LEDs it is foreseeable that the luminous intensity is gradable (with an increased power consumption) around the factor 10. It then would be possible to replace sector lights with up to 50watts by LEDs with half of the power consumption.

4.2. TRADITIONAL OPTICS

IALA Guideline 1049 on the Use of Modern Light Sources in Tradition Lighthouse Optics provides further information on applications of LEDs in AtoN lights.

5. INTENSITY

LED marine lanterns are sometimes reported as having intense colours and ranges longer than the current IALA calculation method would suggest. Current work by IALA is investigating this.

6. CONCLUSION

Recently, several independent institutions have developed programs dedicated to research, testing, and evaluation of LEDs. Information from LED manufacturers and independent sources enables engineers and end users to gain a better understanding of design and operational requirements.

LED manufacturers have made great strides toward improving efficiencies and power capacities of new generations of high power LEDs. These improvements render great design opportunities for new AtoN signal lights. Many high power LEDs fitted with special lenses, offer flexibility in designing light sources for retrofitting in existing marine optics, realizing considerable savings for AtoN signal light end-users.

More research and development has to be done in other issues as vertical divergence, horizontal uniformity, spectral characteristics, measurement of intensity.

7. DEFINITIONS

The definition of terms used in this Guideline can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) at http://www.iala-aism.org/wiki/dictionary.

It is suggested that the definitions of correlated colour temperature, organo-metallic vapour phase epitaxy, colour temperature, colour purity, colour rendition, die chip are relevant to this guideline.

8. ACRONYMS

AlInGaP	Aluminium, Indium, Gallium and Phosphorous
AtoN	Aid(s) to Navigation
CCT	Correlated Colour Temperature
cd	candela
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
DC	Direct Current
ESD	Electrostatic discharge
GaP	Gallium and Phosphorous
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities - AISM
IAVG	Average current
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society
InGaN	Indium Gallium Nitride
LED	Light-Emitting Diode
mA	milliamp(s)
mm	millimetre(s)
nm	nanometre(s)
NY	New York
OMVPE	Organometallic vapor phase epitaxy
PC	Personal Computer
pcLED	LED strips
TIP	Truncated-Inverted-Pyramid
UV	Ultra Violet (light) (10 – 380 nm)
vs	versus
°C	degrees Centigrade
°K	degrees Kelvin

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