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Operational Considerations for LED Lamps and Display Devices

Application Note 1005

Introduction

In the design of a drive circuit for an LED lamp, an LED light bar, or an LED 7-segment display, the objective is to achieve optimum light output, power dissipation, reliability, and operating life. The performance capabilities of each LED device are presented in the device data sheet. The data sheet contains tabular data and graphs that describe the optical and electrical characteristics of the LED device, and Absolute Maximum Ratings which are the maximum operating capabilities of the device. A thorough understanding of how to use this information is the basis for achieving an optimum design.

This application note presents an in-depth discussion of the use of the optical and electrical information contained in an LED device data sheet. Design examples for dc and pulsed operation are presented. The calculated results for each example are in **Bold Type** for identification.

Typical Data Sheet Information

Data sheets typically contain three tables of data. Usually for LED lamp devices the first table is titled **Device Selection Guide** or **Axial Luminous Intensity and Viewing Angle at T_A = 25°C** and presents the basic optical characteristics of the devices listed in the data sheet. The luminous intensity, I_V, both minimum and typical values, are listed in this table. This table is used as a device selection guide.

The next table is titled **Absolute Maximum Ratings at T_A = 25°C**, containing maximum peak, dc and average currents, maximum transient current, operating and storage temperature range, and the absolute maximum LED junction temperature. These are the maximum allowed operating conditions for all the devices in the data sheet.

The third table, titled **Electrical/Optical Characteristics at T_A = 25°C**, contains the electrical data, and some optical data, that are used to determine the operating conditions for the device. The forward voltage, V_F, and device thermal resistance, $R\theta_{J\text{-}PIN}$, used in operating condition calculations, are listed in this table.

The graphs usually contained in a lamp data sheet used to determine operational conditions are:

Figure 1. Relative Intensity vs. Wavelength. (not shown here)

Figure 2. Forward Current vs. Forward Voltage.

Figure 3. Relative Luminous Intensity vs. DC Forward Current.

Figure 4. Relative Efficiency vs. Peak Current. (This figure is not included on all data sheets.)

Figure 5. Maximum Forward DC Current vs. Ambient Temperature.

Figure 6. Maximum Average Current vs. Peak Forward Current.

Figure 7. Relative Luminous Intensity vs. Angular Displacement. (not shown here)

Design Criteria

The two criteria that establish the operating limits are the maximum

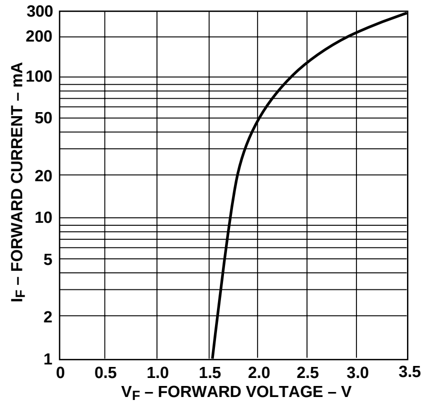

Figure 2. Forward Current vs. Forward Voltage.

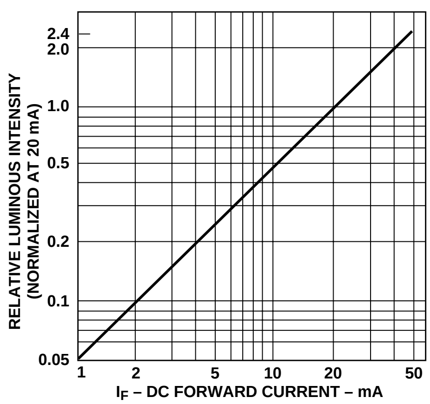

Figure 3. Relative Luminous Intensity vs. DC Forward Current.

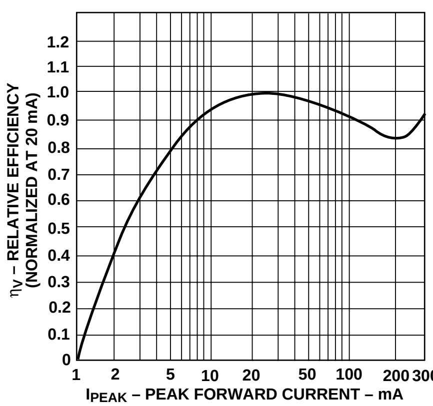

Figure 4. Relative Efficiency vs. Peak Forward Current.

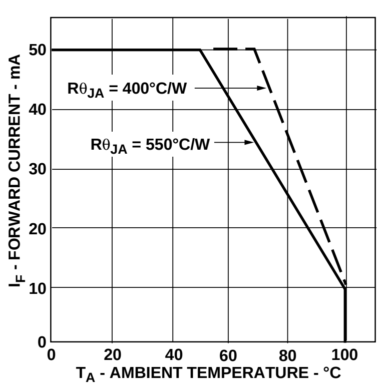

Figure 5. Maximum Forward DC Current vs. Ambient Temperature. Derating Based on T_JMAX = 110°C.

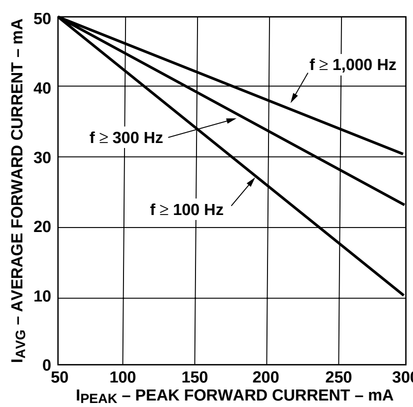

Figure 6. Maximum Average Current vs. Peak forward Current.

drive currents and the absolute maximum LED junction temperature, T_JMAX. The maximum drive currents have been established to ensure long operating life. The absolute maximum LED junction temperature is a device package limitation that must not be exceeded.

Thermal Resistance

The LED junction temperature, T_J(°C), is the sum of the ambient temperature, T_A(°C), and the temperature rise of the LED junction above ambient, ΔT_J(°C), which is the product of the power dissipated within the LED junction, P_D(W), and the thermal resistance LED junction-to-ambient, $R\theta_{J\text{-}A}$(°C/W).

$$T_J = T_A + \Delta T_J$$
$$T_J = T_A + P_D \times R\theta_{J\text{-}A} \qquad (1)$$

The cathode leads (pins) of a typical LED device are the primary thermal paths for heat dissipation from the LED junction to the surrounding environment. The exceptions are TS AlGaAs lamps, that use flip chip technology (anode die attach), where the anode lead is the primary thermal path. The data sheet lists the thermal resistance LED junction-to-pin, $R\theta_{J\text{-}PIN}$(°C/W), for each device type listed. This device thermal resistance is added to the pc board mounting assembly thermal resistance-to-ambient, $R\theta_{PC\text{-}A}$(°C/W), to obtain the overall thermal resistance LED junction-to-ambient, $R\theta_{J\text{-}A}$(°C/W).

$$R\theta_{J\text{-}A} = R\theta_{J\text{-}PIN} + R\theta_{PC\text{-}A} \qquad (2)$$

$R\theta_{J\text{-}A}$ is on a per LED chip basis for lamps, light bars, and 7-segment displays, and on a per device basis for displays with on-board ICs.

For reliable operation, it is recommended that the value of $R\theta_{PC\text{-}A}$ be designed low enough to achieve the lowest possible $R\theta_{J\text{-}A}$ to ensure the LED junction temperature does not exceed the absolute maximum value when the device is operated in the maximum surrounding ambient temperature.

Maximum Power Calculation

The maximum allowed power that may be dissipated within an LED junction, P_{MAX}, is determined by multiplying the maximum rated dc current by the forward voltage for that current, determined from Figure 2.

$$P_{MAX} = I_{DC}MAX \times V_F \qquad (3)$$

Derating vs. Temperature

The drive current derating vs. temperature, Figure 5, is a function of drive current, T_JMAX, and $R\theta_{J\text{-}A}$. Typically derating curves are given from two ambient temperatures, T_A = 50°C (solid line) and 70°C (dashed line). The derating curves are lines of T_JMAX with slopes equal to the specific maximum $R\theta_{J\text{-}A}$ values indicated, intersecting the temperature axis at the maximum LED junction temperature point with zero current. Operation of the LED device at a particular drive current should be at or below a derating curve with a thermal resistance-to-ambient at or less than the maximum value indicated for that curve.

Current Limiting

An LED is a current operated device, and therefore, requires some kind of current limiting incorporated into the drive circuit. This current limiting typically takes the form of a current limiter resistor, R, placed in series with the LED. The forward voltage characteristic of Figure 2 is used to calculate the value of the series current limiter resistor.

$$R = \frac{V_{CC} - V_{SAT} - V_F}{I_{PEAK}} \qquad (4)$$

Where:
- V_{CC} = Power supply voltage.
- V_{SAT} = Saturation voltage of driver transistor(s).
- V_F = Forward voltage of the LED at I_{PEAK}.
- I_{PEAK} = The peak drive current through the LED.

Light Output

The luminous intensity at T_A = 25°C for a particular dc drive condition is determined using the relative luminous intensity factor from Figure 3.

I_V (dc) = [I_V(25°C)] [Relative Intensity Factor] (5)

Where: I_V (25°C) is obtained from the data sheet.

For pulsed drive conditions, the time average luminous intensity is determined from the relative efficiency characteristic, η_V, presented in Figure 4. (Note: Not all data sheets include relative efficiency data.)

I_V (time average) = [I_V (25°C)] [I_{AVG}/I_F] [η_V] (6)

Where:
- I_V (25°C) = Data sheet luminous intensity value.

I_{AVG} = The time average operating current.

I_F = The current where the data sheet luminous intensity is specified.

η_V = Relative efficiency factor for the peak drive current, I_{PEAK}.

The calculated luminous intensity value at T_A = 25°C can be adjusted for a different operating ambient temperature by the following exponential equation, and using the k factor for the specific LED.

$$I_V(T_A) = I_V(25°C)e^{[k(T_A - 25°C]} \quad (7)$$

LED	k
Standard Red	-0.0188/°C
High Efficiency Red	-0.0131/°C
Yellow	-0.0112/°C
Green	-0.0104/°C
DH AS AlGaAs	-0.0095/°C
TS AlGaAs	-0.0130/°C
AlInGaP	-0.0100/°C
TS AlInGaP	-0.0100/°C

Pulsed Operation vs. DC Operation

When operating an LED device under dc drive conditions, the LED junction temperature is a linear function of the dc power dissipation multiplied by $R\theta_{J-A}$. The light output is proportional to the dc drive current by the luminous intensity factor of Figure 3 and as expressed in Equation 5.

For best pulsed operation and overall light output performance, a rectangular current waveform with a refresh rate equal to or greater than 100 Hz is strongly recommended. Sinusoidal waveforms are not generally recommended, as the rms power will exceed that of a rectangular current waveform with the same peak current value. If a sinusoidal current waveform is used, the peak current should not exceed the maximum dc current rating. Sinusoidal waveforms produce less than two thirds the light output of an equivalent rectangular pulse, and at 50 or 60 Hz, are not fast enough to prevent observable flicker.

When operating an LED device in pulsed current mode, it is the peak junction temperature, not the average junction temperature, that governs the performance of the device. At refresh rates below 1000 Hz (the number of times per second a device is pulsed), the peak junction temperature is higher than the average junction temperature. As a result, the allowed time average currents for refresh rates between 100 Hz and 1000 Hz are less than those permitted at 1000 Hz, as can be seen by the 100 Hz and 300 Hz curves of Figure 6.

Design Steps

In order to determine the derated drive conditions from the data sheet for an elevated ambient temperature, the value for $R\theta_{J-A}$ must be determined. Once the value for $R\theta_{J-A}$ has been established, the required current derating can be determined for safe operation at the elevated temperature directly from Figure 5. The basic design steps are:

1. Determine $R\theta_{J-A}$.
2. Calculate the required value for $R\theta_{PC-A}$ for the pc board mounting configuration.
3. Determine the maximum allowable dc drive current for the operating ambient temperature.
4. Calculate the LED chip power dissipation to be sure it will not cause T_J to exceed the absolute maximum value.
5. Calculate the value of the current limiting resistor.
6. Determine the luminous intensity at 25°C and at the elevated ambient temperature.

The example calculations in this application note use representative data typically contained in LED lamp data sheets. The purpose of the calculations is to ensure reliable operation of an LED lamp when operated at an elevated ambient temperature. For the example calculations, a sample T-1 3/4 LED lamp is used, with 0.45 mm (0.018 in.) square leads and the following data sheet parameters:

Typical Luminous Intensity at 20 mA, I_V (25°C) = 2.0 cd (candela).
Maximum Peak Forward Current = 300 mA.
Maximum Average Forward Current = 30 mA (I_{PEAK} = 300 mA).
Maximum dc Forward Current = 50 mA.
Maximum LED Junction Temperature = 110°C.
$R\theta_{J-PIN}$ = 260°C/W

DC Design Example

In this example, the operating ambient temperature is assumed to be T_A = 60°C.

Step 1. For this example, the value for $R\theta_{J-A}$ has been established to be 500°C/W.

Step 2.
From Equation 2:
$R\theta_{PC-A}$ = (500 - 260°C/W)
$R\theta_{PC-A}$ = **240°C/W**

The pc board mounting assembly should be designed to provide this value of thermal resistance to ambient, or less, for reliable operation of the LED device.

Step 3.
From Figure 5, the following are determined:
1) $R\theta_{PC-A}$ at 500°C/W is less than the maximum $R\theta_{PC-A}$ shown for the solid line derating curve.
2) The maximum allowable dc current at T_A of 60°C = **42 mA**.

Step 4.
Calculation of the power dissipation for 42 mA drive current using Equation 3.
From Figure 2, V_F (42 mA) = 1.95 volts.
P(W) =
(0.042 A) (1.95 V) = 0.082 W
P(W) = **82 mW**

Using Equation 1 for LED junction temperature:

T_J = 60°C + (0.082 W)(500°C/W)
T_J = **101°C**, less than the maximum allowable 110°C.

Step 5.
Equation 4 is used to calculate the value of the current limiting resistor. A 5 volt power supply is used. One switching transistor is used to drive the LED lamp with a saturation of 0.1 volts.

$$R = \frac{5.0\text{ V} - 0.1\text{ V} - 1.95\text{ V}}{0.042\text{ A}}$$

R = **70 Ω**

Resistor power rating should be 2x the actual power dissipation:

$P_R = I^2 \times R = (0.042\text{ A})^2 \times 70\ \Omega$
P_R = **0.123 W**

Thus, use a 1/4 watt 70 Ω resistor.

Step 6.
The luminous intensity at T_A = 25°C is determined from Figure 3 and Equation 5:

From Figure 3, the relative luminous intensity factor at 42 mA = 2.0.

I_V (25 °C) = (2.0 cd) (2.0)
I_V (25 °C) = **4.0 cd**

At the operating temperature of 60°C, the luminous intensity is calculated using Equation 7 and the appropriate k value. For this example, k = -0.0130/°C

I_V (60°C) =
$(4.0\text{ cd})\ e^{-0.0130/°C(60 - 25°C)}$
I_V (60°C) = (4.0 cd) (0.634)
I_V (60°C) = **2.54 cd**

DC parameter summary:
T_A = 60°C
$R\theta_{PC-A}$ = 240°C/W
I_F (dc) = 42 mA
T_J = 101°C
R = 70 Ω, 1/4 W
I_V (25°C) = 4.0 cd
I_V (60°C) = 2.54 cd

Pulsed Mode Design Example
In this example, T_A = 50°C, and the above LED lamp is to be pulsed with a refresh rate of 1000 Hz at 200 mA peak drive current.

Steps 1 and 2. The $R\theta_{J-A}$ and $R\theta_{PC-A}$ values are the same as determined in the above DC Design Example.

Step 3.
From Figure 6, at a refresh rate of 1000 Hz and I_{PEAK} of 200 mA, the maximum allowable time average current, I_{AVG} , = **38 mA**.

The on-time duty factor, DF is:
DF = I_{AVG} / I_{PEAK}
DF = 38 mA / 200 mA = 0.190
DF = **19.0%**

Step 4.
From Figure 2, V_F (200 mA) = 2.8 volts. The time average power is:

P = I_{PEAK} x V_F (I_{PEAK}) x DF
P = (0.200 A) (2.8 V) (0.190)
P = **0.106 W**

Using Equation 1 for LED junction temperature:
T_J =
50°C + (0.106 W) (500°C/W)
T_J = **103°C**, less than the maximum allowable 110°C.

Step 5.
At 200 mA, the driver transistor saturation is 0.2 volts.

$$R = \frac{5.0\text{ V} - 0.2\text{ V} - 2.8\text{ V}}{0.200\text{ A}}$$

R = **10 Ω**

Resistor power rating should be 2x the time average power dissipation:

$P_R = (I_{PEAK})^2 \times R \times DF$
$= (0.200\text{ A})^2 (10\ \Omega)(0.190)$
P_R = **0.076 W**

Thus, use a 1/4 watt 10 Ω resistor.

Step 6.
The time average luminous intensity at T_A = 25°C is determined using Equation 6 and the relative efficiency factor from Figure 4.

From Figure 4,
η_v (200 mA) = 0.82.
I_V (25°C) =
[2.0 cd] [38 mA/20 mA] [0.82]
I_V (25°C) = [2.0 cd] [1.56]
I_V (25°C) = **3.12 cd**

I_V (50°C) =
(3.12 cd) $e^{-0.0130/°C(50 - 25°C)}$
I_V (50°C) = (3.1 cd) (0.723)
I_V (50°C)) = **2.26 cd**

Pulsed parameter summary:
T_A = 50°C
$R\theta_{PC-A}$ = 240°C/W
I_{PEAK} = 200 mA
I_{AVG} = 38 mA
f = 1000 Hz; DF = 19.0%
T_J = 103°C
R = 10 Ω, 1/4 W
I_V (25°C) = 3.12 cd
I_V (60°C) = 2.26 cd

DC Operation is Better than Pulsed Operation for Light Output

It is always better to drive an LED device with a high dc current to obtain the necessary light output to be viewed by a human observer than to pulse drive the LED. Using a high peak current and a low duty factor to pulse drive an LED device produces less time average light output than by using a high dc drive current.

There are only two reasons for pulse driving an LED device:
1) To strobe an LED array to form messages of changing characters or symbols to be viewed by human observers.
2) To obtain a peak pulse of light to be received by a photodetector in a non-visual emitter/ detector application. In this case, the high peak pulse of light produces a high peak photocurrent output from the photodetector.

Operation Without Current Derating

LED lamp and display devices may be operated in elevated ambient temperatures without current derating only when the pc board mounting configuration is designed for a sufficiently low thermal resistance-to-ambient. The criterion is that the LED junction temperature must not exceed the T_JMAX value for the device. This low thermal resistance design may include such items as a maximum metalized pc board and possible heat sinking to ensure adequate heat dissipation. Operation above the Absolute Maximum Current Ratings is not recommended.

The necessary thermal resistance requirements for operation without current derating are calculated for the maximum power dissipation using the Absolute Maximum DC Current.

1. Calculate the maximum power dissipation, if not provided on the data sheet.

2. Using Equation 1, calculate the allowable ΔT_J rise above the elevated ambient temperature.

3. Calculate the required thermal resistance LED junction-to-ambient, $R\theta_{J-A}$.

$$R\theta_{J-A} = \Delta T_J / P_{MAX} \qquad (8)$$

4. Calculate the allowable thermal resistance pc board-to-ambient using Equation 2.

Using the above sample LED lamp, the following example calculations determine the thermal resistance requirements for operating at T_A = 80°C without dc current derating.

Step 1.
V_F (50 mA) = 2.05 V.

From Equation 3:
P_{MAX} = (0.050 A) (2.05 V)
P_{MAX} = **0.103 W**

Step 2.
From Equation 1:
ΔT_J = 110°C - 80°C
ΔT_J = **30°C**

Step 3.
Using Equation 8:
$R\theta_{J-A}$ = 30°C / 0.103 W
$R\theta_{J-A}$ = **291°C/W**

Step 4.
From Equation 2:
$R\theta_{PC-A}$ = 291°C/W - 260°C/W
$R\theta_{PC-A}$ = **31°C/W**

To obtain this low a value for the pc board thermal resistance-to-ambient necessitates the use of a maximum metalized pc board, may require special heat sinking attached to the device leads, and forced air cooling. This means considerable cost is added to the design to allow for operation at 80°C without current derating.

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Data subject to change.

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