LED Applications and Driving Techniques

Chris Richardson
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• LED Applications
• LED Driving Techniques
• LED Dimming and Contrast Ratios
• Lighting Resources and Tools
LED Basics
What is an LED?

Light Emitted Forward

LED Chip

Reflector

PC Board

Cathode Lead

Anode Lead
LED Development

- **5mm Lamp**
  - 2-3 lumens
  - $I_F = 30mA$
  - 1970

- **SuperFlux**
  - 4-8 lumens
  - $I_F = 70mA$
  - 1992

- **Luxeon**
  - 20-40 lumens
  - $I_F = 350mA$
  - 1997

- **Lumileds**, **Osram**, **Cree**, **Seoul Semi**, **Avago**
  - $I_F = 700$ to $1.5A$
  - 2007
Structure of High Brightness LED

- Light Emitted Forward
- Plastic Lens
- Silicone Encapsulant
- InGaN Semiconductor Flip Chip
- Solder Connection
- Reflector Cup
- Heatsink Slug
- Gold Wire
- Cathode Lead
Materials used in color LEDs

White LED:
White light is generated by blue LED striking a phosphor coating
Many New Applications Have Emerged Because......

- **Typical spec. of HB LED**
  - 1 Watt LED
    - Full intensity 350mA, Maximum current 500mA
    - 2.8V Volt drop @ 350mA
  - 3 Watt LED
    - Full intensity 700mA, Maximum current 1A
    - 4.3V Volt drop @ 700mA
  - 5 Watt LED (multi-die package)
    - Full intensity 700mA, Maximum current 1A
    - 7.1V Volt drop @ 700mA
  - 5 Watt LED (single-die)
    - Full intensity 1.5A
Characteristics of LEDs

- Forward Voltage ($V_F$) drop across LED
  - Diodes are current driven!
- Wavelength variations
  - Crystal and junction growth defects
- Brightness variations
  - Crystal defects resulting formation of phonons and non-radiation energy transfer
- Temperature
  - Junction temperature of the device affects each of the parameters above
Temperature effect on LED Parameters

As Temperature increases:
• Light output decreases
• Wavelength gets longer
• Forward voltage decreases
LED Binning

• Manufacturers bin their devices for color/wavelength, brightness, and forward voltage

• Binning for all three characteristics is expensive, and forward voltage is often the specification that is allowed to vary the most
LED Applications
LED Applications

• Old days
  – Signal Indicators
  – Numeric and Alpha-numeric displays

• Nowadays
  – Automotive
  – Backlights
  – Flashlights for portable devices
  – General illumination
  – Projector Light Sources
  – Signage
  – Torch Lights
  – Traffic Lights
Backlight Applications

- Possible because of white LED development
- Almost all mobile phone color LCDs use white LED backlighting.
- Size of displays from smallest to largest
  - 1. Mobile phones, PDAs
  - 2. Automotive, aerospace infotainment
  - 3. Laptop displays
  - 4. Desktop PC monitors
  - 5. LCD televisions
LED Driving Techniques
Resistor Limiting, Linear Regulation

Resistor Limiting

Linear IC with Constant Current Source

Heat dissipation in resistor or linear IC
LED Driving Circuit ......

• Delivers a constant average current under all conditions (eg. input voltage change, temperature change, $V_F$ change......)

• Controls ripple current at acceptable level under all conditions

A LED driving circuit is a type of power conversion circuit that delivers constant current instead of constant voltage
Constant Voltage to Constant Current Conversion:

\[ V_O = V_{FB} \frac{R_{FB1} + R_{FB2}}{R_{FB1}} \]

\[ I_F = \frac{V_{FB}}{R_{FB}} \]
Average Current and Ripple Current

- $I_{av1} > I_{av2}$, thus $I_{av1}$ is brighter than $I_{av2}$ but color also changes.
- Human eye cannot detect the high frequency ripple current.
- Human eye cannot detect shift in average current of < 20%.
Buck LED Driving

- $V_O$ must be lower than $V_{IN}$
- Output capacitor is optional
- Typical Application: general lighting
Buck Driving – How it works

• If R4 = 5Ω, current passing through R4 = 0.5A. Current passing through the LED is also the same because FB is a high impedance pin.

• LED current setting can be done by R4.

Problem: Power dissipation at R4 = 1.25W!
Dedicated Buck LED Driver

- FB voltage is reduced to 200 mV
- Power dissipation at $R_{SNS} = 0.5A \times 0.2V = 0.1W$. 

![Diagram of Dedicated Buck LED Driver]

$V_{IN} \quad C_{IN} \quad R_{ON} \quad V_{CC} \quad L_{1} \quad D_{1} \quad I_{F} \quad 200mV \text{ Feedback Voltage}$

$C_{F} \quad R_{SNS}$

$\text{LM3402/02HV}$

$\text{VIN} \quad \text{BOOT} \quad \text{SW} \quad \text{DIM} \quad \text{GND}$

$\text{FB}$ voltage is reduced to 200 mV

Power dissipation at $R_{SNS} = 0.5A \times 0.2V = 0.1W$. 

$\text{Vin}$

$\text{Buck}$

$\text{Vcc}$

$\text{Dim}$

$\text{Gnd}$

$\text{Ron}$

$\text{L1}$

$\text{D1}$

$\text{IF}$

$\text{200mV Feedback Voltage}$

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Using Boost Regulator: Series LED Connection

- **Pros:**
  - Matching Guaranteed
  - Most efficient drive method
  - Easy to route (Only 1 or 2 connections between driver and LEDs)

- **Cons:**
  - High voltage output is needed
  - Output capacitor typically large due to voltage requirement

With external ballast

With internal current sink
Using Boost Regulator
Parallel LED Connection

• Pros
  – Workable with low-voltage semiconductor processes
  – Can work with common anode or common cathode module

• Cons
  – Good matching requires regulated current sources
  – Requires 1 connection per each LED i.e. driver IC requires more pins

Constant current source connection
Boost: Inductor based vs Charge Pump

<table>
<thead>
<tr>
<th>LED Connection</th>
<th>Charge Pump</th>
<th>Inductor Based</th>
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</thead>
<tbody>
<tr>
<td>Usually Parallel</td>
<td>Usually Series</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Depends on $V_{IN}$, $V_O$, and gain mode</th>
<th>Reduced dependence on $V_{IN}$ and $V_O$</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>PCB Space</th>
<th>Less</th>
<th>More</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Wide Vin – Vout Support</th>
<th>Not Practical</th>
<th>OK</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>EMI Generation</th>
<th>Less</th>
<th>More, due to presence of inductor</th>
</tr>
</thead>
</table>
Efficiency of a Charge Pump

- Charge pumps are very efficient if $V_{\text{IN}} \times \text{Gain}$ is close to target $V_O$
- Efficiency drops off as $V_{\text{IN}}$ increases.
- $1.5 \times$ mode is introduced to boost efficiency in conversion from one Li-ion battery to 5V $V_O$

LM2751 - $2\times$, $1.5\times$ charge pump (switched capacitor) white LED driver which can deliver up to 150mA at 725KHz switching frequency.
Charge Pumps with built-in Current Source

Built-in current source, better current matching in driving several LEDs.

LM2754 - 2×, 1.5× charge pump (switched capacitor) white LED driver which can deliver up to 800mA at 1MHz switching frequency.
Inductive vs Charge Pump Efficiency Comparison

LM3508 Inductive Boost Efficiency

<table>
<thead>
<tr>
<th>I_LED (mA)</th>
<th>EFFICIENCY (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>66</td>
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<tr>
<td>6</td>
<td>72</td>
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<tr>
<td>27</td>
<td>90</td>
</tr>
<tr>
<td>30</td>
<td>90</td>
</tr>
</tbody>
</table>

- \( V_{IN} = 4.2V \)
- \( V_{IN} = 3.6V \)
- \( V_{IN} = 2.7V \)

LM2751 2x/1.5x Efficiency vs. 2x Charge Pump Efficiency

<table>
<thead>
<tr>
<th>INPUT VOLTAGE (V)</th>
<th>EFFICIENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>60</td>
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<tr>
<td>3.0</td>
<td>50</td>
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<td>3.3</td>
<td>40</td>
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<td>3.6</td>
<td>30</td>
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<td>3.9</td>
<td>20</td>
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<tr>
<td>4.2</td>
<td>10</td>
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- \( V_{OUT} = 5.0V \)
- \( V_{OUT} = 4.5V \)

Typical 2x Only Pump

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True Shutdown Isolation

- **Method 1**
  - Add switch in return path.

  A switch is added to cut off leakage path during shutdown

- **Method 2**
  - Synchronous rectification.

  Diode is replaced by MOSFET and it is switched off during shutdown
Bucking and Boosting

- High power LEDs are being adopted into portable lamps (bicycle, mining, flashlight) with varying number and chemistry of batteries
- Low-voltage AC lighting (garden path) varies due to $I^2R$ loss
- Combine varying $V_{IN}$ with $V_F$ that changes with process and temperature
- Requires true buck-boost regulator
Buck Boost Efficiency

Buck: Input direct to output when power switch is on

Boost: Input direct to output when power switch is off

Buck-boost: input is never connected directly to output
Buck-Boost Driving: SEPIC Regulator

- Uses standard low-side regulator/controller
- Low-side or high-side current sensing
- Requires two inductors or coupled inductor
- Requires an output capacitor
Buck-Boost Driving: Cuk Regulator

- Uses low-side regulator/controller but requires negative FB pin
- Low-side or high-side current sensing

- Negative V<sub>O</sub> doesn’t matter in current drivers
- Requires two inductors or coupled inductor
- Can run without C<sub>O</sub>

Amplifier doubles as polarity inverter
‘Floating’ Buck-Boost Regulator

- Uses only one inductor
- $V_O$ is controlled WRT $V_{IN}$
- Requires high-side sensing for accurate $I_F$ control

$V_O = V_{IN} + V_F$
Floating Buck Boost with High-side Sense

[Diagram of a floating buck boost circuit with key components labeled, including VIN, NGATE, GND, FB, and a basic low-side MOSFET controller.]
LED Dimming and Contrast Ratios
Adjusting Light Level with LEDs

• “Analog Dimming”
  – Linear adjustment of current through LEDs
  – Causes shift in peak and dominant wavelength in monochromatic LEDs
  – Causes shift in Correlated Color Temperature (CCT) in white LEDs
  – Difficult to optimize driver efficiency
• “Digital Dimming” (PWM Dimming)
  – Drive at only one current level
  – Turn LEDs on and off at > 120Hz
  – Human eye integrated and averages light above this frequency
PWM Dimming Control

- PWM signal (EN/SD pin, FET, or special PWM pin)
  - “Average” Brightness proportional to Duty Cycle (D):
    \[ D = \frac{t_{\text{ON}}}{T} \]
Controlling Color

- Colored LEDs shift their peak/dominant wavelength as $I_F$ changes
- Requires control of $I_F$ and $\Delta I_F$
- Accuracy of $I_F$ is highly dependent on the application
Controlling CCT

- CCT provides the basis for “cool” white (more blue) and “warm” white (more red.)
- CCT shifts with $I_F$
- Much easier to see than with colored LEDs
White LED Structure

Human eye color sensitivity curve

BROAD RANGE PHOSPHOR

BLUE InGaN DIE

SUBSTRATE

From LED

From phosphor
CCT Shift

More Yellow

1W LED driven at 50 mA continuous

More Blue

Same 1W LED driven at 300 mA with 1/6th duty cycle (500Hz)
PWM Dimming with Switching Regulators

- Use buck regulator whenever possible
- Only the buck can eliminate the output capacitor*
- No RHP zero means fastest control loops (when using clocked regulators)
- Easy implementation of hysteretic and controlled on-time (COT) control
  – Even faster loops!
Contrast Ratio

• 1 : Wishful Thinking
• Contrast ratio is highly dependent on the external components
• Therefore, it is highly susceptible to specmanship
• One definition of contrast ratio is \( 1/D_{\text{DIM(MIN)}} \), where \( D_{\text{DIM(MIN)}} = \frac{2}{f_{SW}} \)
  – Circuit must be on DCM/CCM boundary
Frequency and Duty Cycle Limits

\[ T = \frac{1}{f_{PWM}} \]

\[ D_{\text{MIN}} = \frac{t_D + t_{SU}}{T} \]

\[ D_{\text{MAX}} = \frac{T - t_{SD}}{T} \]

Rise and fall times where \( I_F \) is between 0 and 100% cause further error.
LM3404 Eval Board

$V_{IN} = 6\text{V to } 42\text{V (LM3404)}$
$V_{IN} = 6\text{V to } 75\text{V (LM3404HV)}$

Drives a 1W white (InGaN) LED at 1A from 24V
LM3404 Delay, $t_D$

$t_D = 51$ ns

Bandgap, analog functions were already powered
LM3404 Slew Up, $t_{SU}$

$t_{SU} = 3 \, \mu s$

$\Delta i_L = \Delta i_F$ (no $C_O$)

$\Delta i_L = (V_{IN} - V_O) / L$

Limited by $t_{OFF-MIN}$

$t_{OFF-MIN} = 300 \, \text{ns}$
LM3404 Slew Down, $t_{SD}$

\[ \Delta I_L = -\frac{V_O}{L} \]

$t_{SU} = 8.4 \, \mu s$
Calculate the Contrast Ratios

\[ f_{\text{DIM}} = 500 \text{ Hz}, \ T_{\text{DIM}} = 2 \text{ ms} \]

- LM3404
- \( t_D + t_{SU} = 3.05 \mu s \)
- \( D_{\text{MIN}} = \frac{3.05}{2000} = 0.001525 \)
- \( CR = \frac{1}{D_{\text{MIN}}} = 655 : 1 \)
Low Frequency ( < 1 kHz)

• General and automotive applications
• More efficient: less transitions
• Duty cycle requirements not as strict: 10% to 90% is typical
• Usually achievable by using the DIM or EN pins
High Frequency ( > 10 kHz)

- Technical requirements force the users to high frequency
- Generation of white light from RGB in backlights, video projectors
- Machine vision and industrial inspection
  - Fast slew rates for light pulses that sync to sensors and cameras
- Loss of efficiency due to the transitions
- Usually requires a parallel dimming FET
Parallel FET Dimming

Continuous inductor current

$V_{IN} = 24V$

$\text{LM3404/04HV}$

$I_F = 1A$
Parallel FET Results

Ch1 Mean
892mA

Ch2 Freq
---.Hz
No period found

I_F

FET

GATE

17 Nov 2006
15:24:13

18.20 %
Parallel FET Results
CR Vs. $f_{DIM}$

• Circuit parameters placed a limit on the minimum dimming on-time, $t_{\text{MIN}} = D_{\text{MIN}} \times f_{DIM}$
New LED Driving Tools
Step 1 - Enter Design Inputs

Enter input voltage range

Enter Number of LEDs

Narrow LED choice by vendor and/or color

Select an LED from the list

Show Recommended Parts
Step 2 - Choose an LED Driver

Choose part

Recommended Devices
Switching Regulator
High efficiency regulator

LM3402
Start Your Design

Topology: BUCK
Max Current: 0.5 A
Typical Efficiency: 91%
On/Off Pin: Y
Error Pin: N
Price: $1.25
Frequency: 1800 kHz

Recommended Switching Regulators - BUCK Topology

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<td></td>
<td>$1.25</td>
<td>91%</td>
<td>Y</td>
<td>N</td>
<td>N</td>
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<td>N</td>
<td>1800</td>
<td>0.5A</td>
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<td>N</td>
<td>N</td>
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<td>$1.50</td>
<td>92%</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>1800</td>
<td>1.0A</td>
</tr>
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Step 3 – Optimize and Customize

Key operating values:
- Frequency
- Efficiency
- Peak to Peak $I_{\text{LED}}$
- Temperature

Optimization knob:
- No output cap
- Specify peak to peak LED ripple

Customize design for:
Optimize for Efficiency

Optimization for efficiency:
Lowers switching frequency, emphasizes low component power dissipation
Step 4 - Simulate Electrical Behavior

Spice simulation includes:
Steady state
Input transient
PWM dimming
Startup
View Waveforms

Add/delete waveforms

Click and drag mouse to zoom in on plot
Build It!

- Latest addition to LED WEBENCH® for LM3402/02HV and LM3404/04HV
- Generic evaluation board accepts a wide variety of external components
- User orders and receives a kit with blank PCB and all external components as selected through LED Webench
- Simply solder, connect to LEDs, and go
- Note: LEDs are not included
LED Reference Design Library

http://power.national.com

Customize

Modify

Custom datasheet of the resulting design