# LM3402/LM3404 Fast Dimming and True Constant LED Current Evaluation Board

National Semiconductor
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## Introduction

The LM3402/02HV and LM3404/04HV are buck regulator derived controlled current sources designed to drive a series string of high power, high brightness LEDs (HBLEDs) at forward currents of up to 0.5A (LM3402/02HV) or 1.0A (LM3404/04HV). This evaluation board demonstrates the enhanced thermal performance, fast dimming, and true constant LED current capabilities of the LM3402 and LM3404 devices.

## Circuit Performance with LM3404

This evaluation board (figure 1) uses the LM3404 to provide a constant forward current of 750 mA ±10% to a string of up to five series-connected HBLEDs with a forward voltage of approximately 3.4V each from an input of 18V to 36V.

## Thermal Performance

The PSOP-8 package is pin-for-pin compatible with the SO-8 package with the exception of the thermal pad, or exposed die attach pad (DAP). The DAP is electrically connected to system ground. When the DAP is properly soldered to an area of copper on the top layer, bottom layer, internal planes, or combinations of various layers, the $\theta_{JA}$ of the LM3404/04HV can be significantly lower than that of the SO-8 package. The PSOP-8 evaluation board is two layers of 1oz copper each, and measures 1.25" x 1.95". The DAP is soldered to approximately 1/2 square inch of top and two square inches of bottom layer copper. Three thermal vias connect the DAP to the bottom layer of the PCB. A recommended DAP/via layout is shown in figure 2.

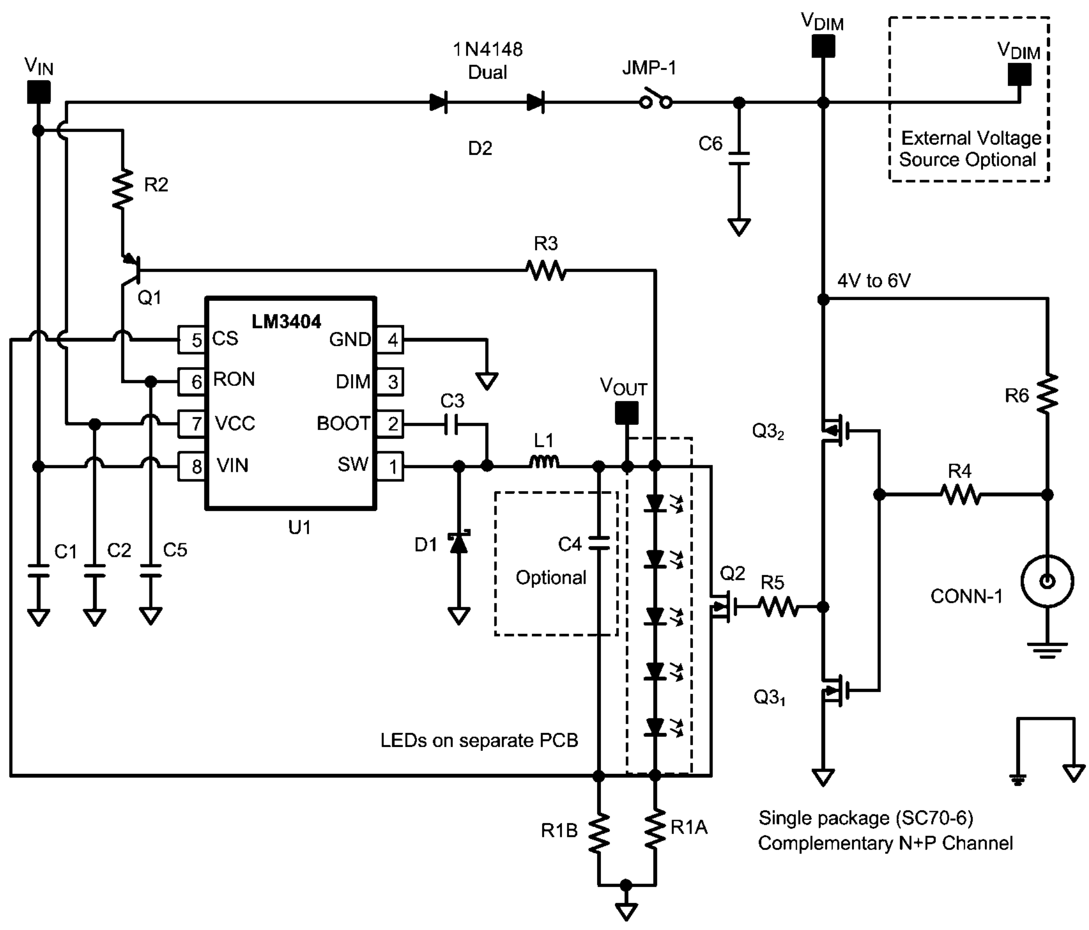



**FIGURE 1. LM3402 / 04 Schematic**



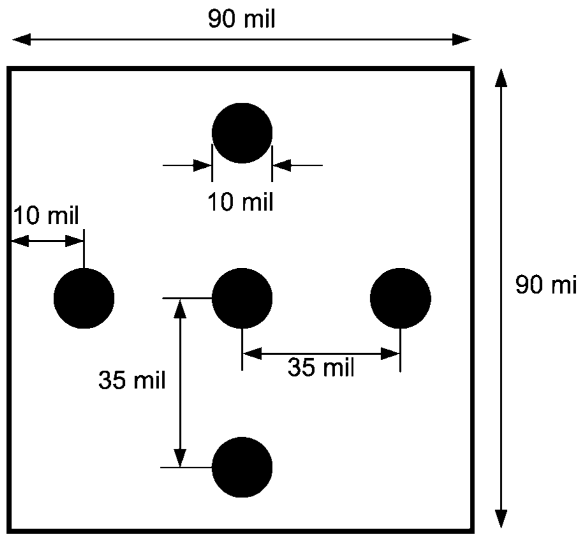



**FIGURE 2. LM3402/04 PSOP Thermal PAD and Via Layout**

## Connecting to LED Array

The LM3402 / 04 evaluation board includes two standard 94 mil turret connectors for the cathode and anode connections to a LED array.

## Low Power Shutdown

The LM3402/04 can be placed into a low power shutdown state ($I_Q$ typically 90 µA) by grounding the DIM terminal. During normal operation this terminal should be left open-circuit.

## Constant On Time Overview

The LM3402 and LM3404 are buck regulators with a wide input voltage range and a low voltage reference. The controlled on-time (COT) architecture is a combination of hysteretic mode control and a one-shot on-timer that varies inversely with input voltage. With the addition of a PNP transistor, the on-timer can be made to be inversely proportional to the input voltage minus the output voltage. This is one of the application improvements made to this demonstration board that will be discussed later (improved average LED current circuit).

The LM3402 / 04 were designed with a focus of controlling the current through the load, not the voltage across it. A constant current regulator is free of load current transients, and has no need for output capacitance to supply the load and maintain output voltage. Therefore, in this demonstration board in order to demonstrate the fast transient capabilities, I have chosen to omit the output capacitor. With any Buck regulator, duty cycle (D) can be calculated with the following equations.

$$D = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{t_{ON}}{T_S} = t_{ON} \times f_{SW}$$

The average inductor current equals the average LED current whether an output capacitor is used or not.

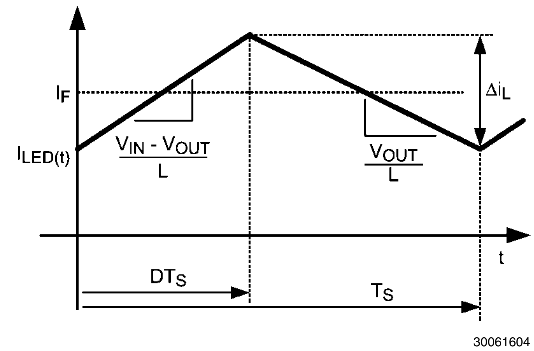



**FIGURE 3. Buck Converter Inductor Current Waveform**

A voltage signal, $V_{SNS}$, is created as the LED current flows through the current setting resistor, $R_{SNS}$, to ground. $V_{SNS}$ is fed back to the CS pin, where it is compared against a 200 mV reference ($V_{REF}$). A comparator turns on the power MOSFET when $V_{SNS}$ falls below $V_{REF}$. The power MOSFET conducts for a controlled on-time, $t_{ON}$, set by an external resistor, $R_{ON}$.

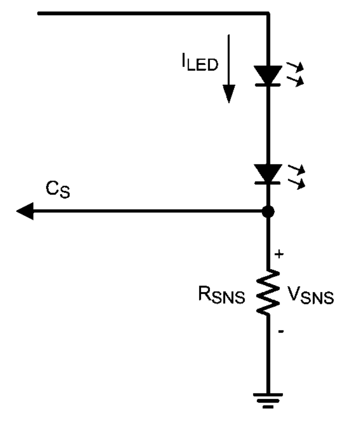



**FIGURE 4. $V_{SNS}$ Circuit**

### SETTING THE AVERAGE LED CURRENT

Knowing the average LED current desired and the input and output voltages, the slopes of the currents within the inductor can be calculated. The first step is to calculate the minimum inductor current (LED current) point. This minimum level needs to be determined so that the average LED current can be determined.

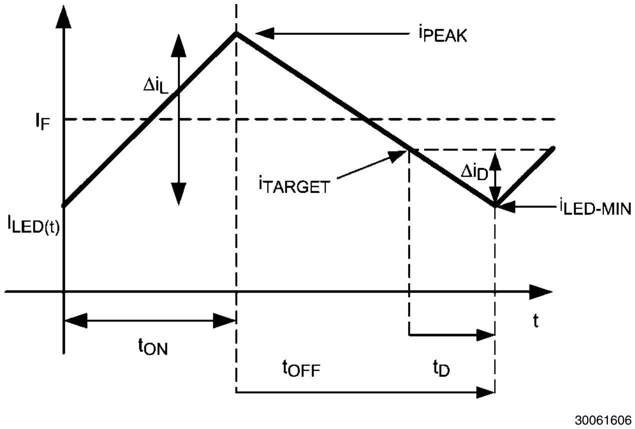



**FIGURE 5. $I_{SENSE}$ Current Waveform**

Using figures 3 and 5 and the equations of a line, calculate $I_{LED-MIN}$.

$$I_{LED-MIN} = I_F - \frac{\Delta i_L}{2}$$

Where

$$I_F = I_{LED-Average}$$

The delta of the inductor current is given by:

$$\frac{\Delta i}{2} = \left(\frac{V_{IN} - V_{OUT}}{2L}\right) x\ t_{ON}$$

There is a 220 ns delay ($t_D$) from the time that the current sense comparator trips to the time at which the control MOSFET actually turns on. We can solve for $i_{TARGET}$ knowing there is a delay.

$$I_{TARGET} = I_F - \frac{\Delta i_L}{2} + \Delta i_D$$

$\Delta i_D$ is the magnitude of current beyond the target current and equal to:

$$\Delta i_D = \left(\frac{V_{OUT}}{L}\right) t_D$$

Therefore:

$$i_{TARGET} = I_F - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) x\ t_{ON} + \left(\frac{V_{OUT}}{L}\right) x\ t_D$$

The point at which you want the current sense comparator to give the signal to turn on the FET equals:

$$i_{TARGET}\ x\ R_{SNS} = 0.20V$$

Therefore:

$$0.2V = R_{SNS}\left(I_F - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) x\ t_{ON} + \left(\frac{V_{OUT}}{L}\right) x\ t_D\right)$$

Finally $R_{SNS}$ can be calculated.

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) x\ t_{ON} + \left(\frac{V_{OUT}\ x\ t_D}{L}\right)}$$

## Standard On-Time Set Calculation

The control MOSFET on-time is variable, and is set with an external resistor $R_{ON}$ (R2 from Figure1). On-time is governed by the following equation:

$$t_{ON} = k\ x \left(\frac{R_{ON}}{V_{IN}}\right)$$

Where

$$k = 1.34\ x\ 10^{-10}$$

At the conclusion of $t_{ON}$ the control MOSFET turns off for a minimum OFF time ($t_{OFF-MIN}$) of 300 ns, and once $t_{OFF-MIN}$ is complete the CS comparator compares $V_{SNS}$ and $V_{REF}$ again, waiting to begin the next cycle.

The LM3402 / 04 have minimum ON and OFF time limitations. The minimum on time ($t_{ON}$) is 300 ns, and the minimum allowed off time ($t_{OFF}$) is 300 ns.

Designing for the highest switching frequency possible means that you will need to know when minimum ON and OFF times are observed.

Minimum OFF time will be seen when the input voltage is at its lowest allowed voltage, and the output voltage is at its maximum voltage (greatest number of series LEDs).

The opposite condition needs to be considered when designing for minimum ON time. Minimum ON time is the point at which the input voltage is at its maximum allowed voltage, and the output voltage is at its lowest value.

## Application Circuit Calculations

To better explain the improvements made to the COT LM3402 / 04 demonstration board, a comparison is shown between the unmodified average output LED current circuit to the improved circuit. Design examples 1 and 2 use two original LM3402 / 04 circuits. The switching frequencies will be maximized to provide a small solution size.

Design example 3 is an improved average current application. Example 3 will be compared against example 2 to illustrate the improvements.

Example 4 will use the same conditions and circuit as example 3, but the switching frequency will be reduced to improve efficiency. The reduced switching frequency can further reduce any variations in average LED current with a wide operating range of series LEDs and input voltages.

**Design Example 1**

- $V_{IN}$ = 48V (±20%)
- Driving three HB LEDs with $V_F$ = 3.4V
- $V_{OUT}$ = (3 x 3.4V +200 mV) = 10.4V
- $I_F$ = 500 mA (typical application)
- Estimated efficiency = 82%
- $f_{SW}$ = fast as possible
- Design for typical application within $t_{ON}$ and $t_{OFF}$ limitations

LED (inductor) ripple current of 10% to 60% is acceptable when driving LEDs. With this much allowed ripple current, you can see that there is no need for an output capacitor. Eliminating the output capacitor is actually desirable. An LED connected to an inductor without a capacitor creates a near perfect current source, and this is what we are trying to create.

In this design we will choose 50% ripple current.

$\Delta i_L$ = 500 mA x 0.50 = 250 mA

$I_{PEAK}$ = 500 mA + 125 mA = 625 mA

**Calculate $t_{ON}$, $t_{OFF}$ & $R_{ON}$**

From the datasheet there are minimum control MOSFET ON and OFF times that need to be met.

$t_{OFF}$ minimum = 300 ns

$t_{ON}$ minimum = 300 ns

The minimum ON time will occur when $V_{IN}$ is at its maximum value. Therefore calculate $R_{ON}$ at $V_{IN}$ = 60V, and set $t_{ON}$ = 300 ns.

A quick guideline for maximum switching frequency allowed versus input and output voltages are shown below in the two graphs (figures 6 & 7).

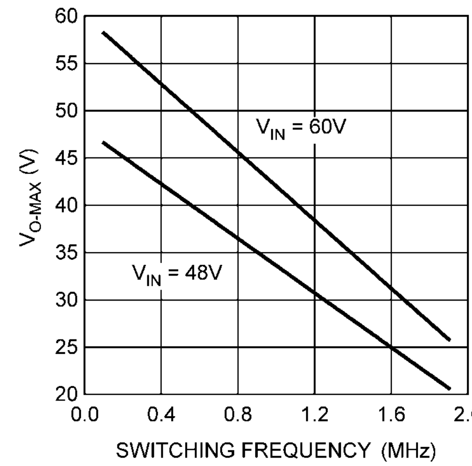



**FIGURE 6. $V_{OUT-MAX}$ vs $f_{SW}$**

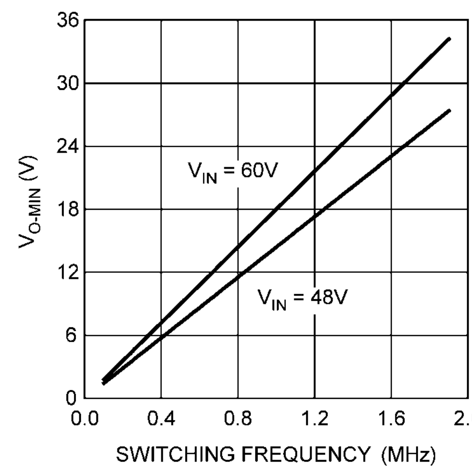



**FIGURE 7. $V_{OUT-MIN}$ vs $f_{SW}$**

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN}}\right)$$

$R_{ON}$ = 135 kΩ (use standard value of 137 kΩ)

$t_{ON}$ = 306 ns

Check to see if $t_{OFF}$ minimum is satisfied. This occurs when $V_{IN}$ is at its minimum value.

At $V_{IN}$ = 36V, and $R_{ON}$ = 137 kΩ calculate $t_{ON}$ from previous equation.

$t_{ON}$ = 510 ns

We know that:

$$D = \frac{V_{OUT}}{V_{IN} \times \eta} = \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

Rearranging the above equation and solving for $t_{OFF}$ with $t_{ON}$ set to 510 ns

$$t_{OFF} = t_{ON}\left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1\right)$$

$t_{OFF}$ = 938 ns (satisfied)

**Example 1 ON & OFF Times**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $t_{ON}$ | $t_{OFF}$ |
|---|---|---|---|
| 36 | 10.4 | 5.10E-07 | 9.38E-07 |
| 48 | 10.4 | 3.82E-07 | 1.06E-06 |
| 60 | 10.4 | 3.06E-07 | 1.14E-06 |

**Calculate Switching Frequency**

$V_{IN}$ = 36V, 48 and 60V.

Substituting equations:

$f_{SW}$ = 691kHz ($V_{IN}$ = 36V, 48V, & 60V)

**Calculate Inductor Value**

With 50% ripple at $V_{IN}$ = 48V

- $I_F$ = 500 mA
- $\Delta i_L$ = 250 mA (target)
- L = 57 µH (68 µH standard value)

Calculate Δi for $V_{IN}$ = 36V, 48V, and 60V with L = 68 µH

**Example 1 Ripple Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $\Delta i_L$ (A) |
|---|---|---|
| 36 | 10.4 | 0.192 |
| 48 | 10.4 | 0.211 |
| 60 | 10.4 | 0.223 |

**Calculate $R_{SNS}$**

Calculate $R_{SNS}$ at $V_{IN}$ typical (48V), and average LED current ($I_F$) set to 500 mA.

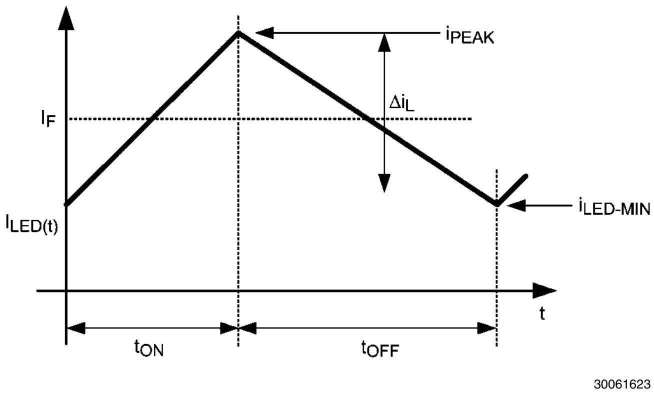



**FIGURE 8. Inductor Current Waveform**

- $I_F$ = 500 mA
- $V_{IN}$ = 48V
- $V_{OUT}$ = 10.4V
- L = 68 µH
- $t_D$ = 220 ns
- $t_{ON}$ = 382 ns

Using equations from the COT Overview section, calculate $R_{SNS}$.

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

Or:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right)\left(\frac{k \times R_{ON}}{V_{IN}}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

Therefore: $R_{SNS}$ = 467 mΩ

**Calculate Average LED current ($I_F$)**

Calculate average current through the LEDs for $V_{IN}$ = 36V and 60V.

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{V_{IN} - V_{OUT}}{2L}\right)(t_{ON}) - \left(\frac{V_{OUT} \times t_D}{L}\right)$$

**Example 1 Average LED Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $I_F$ (A) |
|---|---|---|
| 36 | 10.4 | 0.490 |
| 48 | 10.4 | 0.500 |
| 60 | 10.4 | 0.506 |

**Design Example 2**

Design example 2 demonstrates a design if a single Bill of Materials (Bom) is desired over many different applications (number of series LEDs, $V_{IN}$, $V_{OUT}$ etc).

- $V_{IN}$ = 48V (±20%)
- Driving 3, 4, or 5 HB LEDs with $V_F$ = 3.4V
- $I_F$ = 500 mA (typical application)
- Estimated efficiency = 82%
- $f_{SW}$ = fast as possible
- Design for typical application within $t_{ON}$ and $t_{OFF}$ limitations

The inductor, $R_{ON}$ resistor, and the $R_{SNS}$ resistor is calculated for a typical or average design.

- $V_{OUT}$ = 3 x 3.4V + 200 mV = 10.4V
- $V_{OUT}$ = 4 x 3.4V + 200 mV = 13.8V
- $V_{OUT}$ = 5 x 3.4V + 200 mV = 17.2V

**Calculate $t_{ON}$, $t_{OFF}$ & $R_{ON}$**

In this design we will maximize the switching frequency so that we can reduce the overall size of the design. In a later design, a slower switching frequency is utilized to maximize efficiency. If the design is to use the highest possible switching frequency, you must ensure that the minimum on and off times are adhered to.

Minimum on time occurs when $V_{IN}$ is at its maximum value, and $V_{OUT}$ is at its lowest value.

Calculate $R_{ON}$ at $V_{IN}$ = 60V, $V_{OUT}$ = 10.4V, and set $t_{ON}$ = 300 ns:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN}}\right)$$

$R_{ON}$ = 137 kΩ, $t_{ON}$ = 306 ns

Check to see if $t_{OFF}$ minimum is satisfied:

$t_{OFF}$ minimum occurs when $V_{IN}$ is at its lowest value, and $V_{OUT}$ is at its maximum value.

At $V_{IN}$ = 36V, $V_{OUT}$ = 17.2V, and $R_{ON}$ = 137 kΩ calculate $t_{ON}$ from the above equation:

$t_{ON}$ = 510 ns

$$\frac{V_{IN} \times \eta}{V_{OUT}} = \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

Rearrange the above equation and solve for $t_{OFF}$ with $t_{ON}$ set to 510 ns

$$t_{OFF} = t_{ON}\left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1\right)$$

$t_{OFF}$ = 365 ns (satisfied)

**Example 2 On & Off Time**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $R_{ON}$ | $t_{ON}$ | $t_{OFF}$ |
|---|---|---|---|---|
| **Three Series LEDs** | | | | |
| 36 | 10.4 | 137 kΩ | 5.10E-07 | 9.38E-07 |
| 48 | 10.4 | 137 kΩ | 3.82E-07 | 1.06E-06 |
| 60 | 10.4 | 137 kΩ | 3.06E-07 | 1.14E-06 |
| **Four Series LEDs** | | | | |
| 36 | 13.8 | 137 kΩ | 5.10E-07 | 5.81E-07 |
| 48 | 13.8 | 137 kΩ | 3.82E-07 | 7.08E-07 |
| 60 | 13.8 | 137 kΩ | 3.06E-07 | 7.85E-07 |
| **Five Series LEDs** | | | | |
| 36 | 17.2 | 137 kΩ | 5.10E-07 | 3.65E-07 |
| 48 | 17.2 | 137 kΩ | 3.82E-07 | 4.93E-07 |
| 60 | 17.2 | 137 kΩ | 3.06E-07 | 5.69E-07 |

**Calculate Switching Frequency**

The switching frequency will only change with output voltage.

$$f_{SW} = \frac{V_{OUT}}{V_{IN} \times \eta \times t_{ON}}$$

Substituting equations:

$$f_{SW} = \frac{V_{OUT}}{\eta \times k \times R_{ON}}$$

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}}$$

- $f_{SW}$ = 691 kHz ($V_{OUT}$ = 10.4V)
- $f_{SW}$ = 916 kHz ($V_{OUT}$ = 13.8V)
- $f_{SW}$ = 1.14 MHz ($V_{OUT}$ = 17.2V)

**Calculate Inductor Value**

$$L = \left(\frac{V_{IN} - V_{OUT}}{\Delta i}\right) \times t_{ON}$$

With 50% ripple at $V_{IN}$ = 48V, and $V_{OUT}$ = 10.4V

- $I_{AVG}$ = 500 mA
- $\Delta i_L$ = 250 mA (target)
- L = 53 µH (68 uH standard value)

Calculate Δi for $V_{IN}$ = 36V, 48V, & 60V with L = 68 µH.

**Example 2 Ripple Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $\Delta i_L$ (A) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 0.192 |
| 48 | 10.4 | 0.211 |
| 60 | 10.4 | 0.223 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 0.166 |
| 48 | 13.8 | 0.192 |
| 60 | 13.8 | 0.208 |
| **Four Series LEDs** | | |
| 36 | 17.2 | 0.141 |
| 48 | 17.2 | 0.173 |
| 60 | 17.2 | 0.193 |

**Calculate $R_{SNS}$**

Calculate $R_{SNS}$ at $V_{IN}$ typical (48V), with four series LEDs (13.8V = $V_{OUT}$), and average LED current ($I_F$) set to 500 mA.

- $I_F$ = 500 mA
- $V_{IN}$ = 48V
- $V_{OUT}$ = 13.8V
- L = 68 µH
- $t_D$ = 220 ns
- $t_{ON}$ = 382 ns

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

$R_{SNS}$ = 446 mΩ

**Calculate Average Current through LED**

All combinations of $V_{IN}$, $V_{OUT}$ with $R_{SNS}$ = 446 mΩ

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{V_{IN} - V_{OUT}}{2L}\right)(t_{ON}) - \left(\frac{V_{OUT} \times t_D}{L}\right)$$

**Example 2 Average LED Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $I_F$ (A) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 0.511 |
| 48 | 10.4 | 0.521 |
| 60 | 10.4 | 0.526 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 0.487 |
| 48 | 13.8 | 0.500 |
| 60 | 13.8 | 0.508 |
| **Five Series LEDs** | | |
| 36 | 17.2 | 0.463 |
| 48 | 17.2 | 0.479 |
| 60 | 17.2 | 0.489 |

In this application you can see that there is a difference of **63 mA** between the low and high of the average LED current.

## Modified COT Application Circuit

With the addition of one pnp transistor and one resistor (Q1 and R3) the average current through the LEDs can be made to be more constant over input and output voltage variations. Refer to page one figure 1. Resistor $R_{ON}$ (R2) and Q1 turn the $t_{ON}$ equation into:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}}\right)$$

Ignore the PNP transistor's $V_{BE}$ voltage drop.

Design to the same criteria as the previous example with the improved application and compare results.

## Modified Application Circuit Design Example 3

**Design Example 1**

- $V_{IN}$ = 48V (±20%)
- Driving 3, 4, or 5 HB LEDs with $V_F$ = 3.4V
- $I_F$ = 500 mA (typical application)
- Estimated efficiency = 82%
- $f_{SW}$ = fast as possible
- Design for typical application within $t_{ON}$ and $t_{OFF}$ limitations

The inductor, $R_{ON}$ resistor, and the $R_{SNS}$ resistor are calculated for a typical or average design.

- $V_{OUT}$ = 3 x 3.4V + 200 mV = 10.4V
- $V_{OUT}$ = 4 x 3.4V + 200 mV = 13.8V
- $V_{OUT}$ = 5 x 3.4V + 200 mV = 17.2V

**Calculate $t_{ON}$, $t_{OFF}$ & $R_{ON}$**

Minimum ON time occurs when $V_{IN}$ is at its maximum value, and $V_{OUT}$ is at its lowest value.

Calculate $R_{ON}$ at $V_{IN}$ = 60V, $V_{OUT}$ = 10.4V, and set $t_{ON}$ = 300 ns:

$$R_{ON} = t_{ON}\left(\frac{V_{IN} - V_{OUT}}{k}\right)$$

$R_{ON}$ = 111 kΩ (113 kΩ) $t_{ON}$ = 306 ns

Check to see if $t_{OFF}$ minimum is satisfied.

At $V_{IN}$ = 36V, $V_{OUT}$ = 17.2V, and $R_{ON}$ = 113 kΩ calculate $t_{ON}$:

$t_{ON}$ = 806 ns

$$t_{OFF} = t_{ON}\left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1\right)$$

$t_{OFF}$ = 577 ns (satisfied)

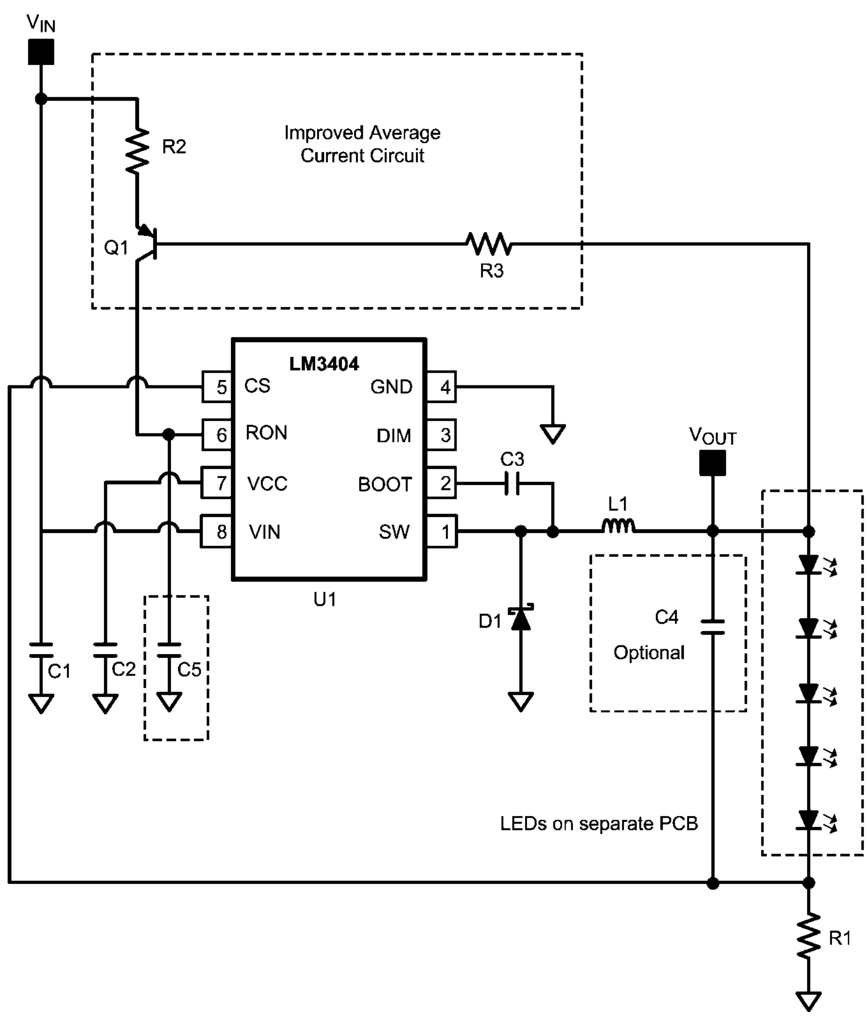



**FIGURE 9. Improved Average LED Current Application Circuit**

**Example 3 On & Off Times**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $R_{ON}$ | $t_{ON}$ | $t_{OFF}$ |
|---|---|---|---|---|
| **Three Series LEDs** | | | | |
| 36 | 10.4 | 113 kΩ | 5.92E-07 | 1.09E-07 |
| 48 | 10.4 | 113 kΩ | 4.03E-07 | 1.12E-06 |
| 60 | 10.4 | 113 kΩ | **3.06E-07** | 1.14E-06 |
| **Four Series LEDs** | | | | |
| 36 | 13.8 | 113 kΩ | 6.83E-07 | 7.78E-07 |
| 48 | 13.8 | 113 kΩ | 4.43E-07 | 8.21E-07 |
| 60 | 13.8 | 113 kΩ | 3.28E-07 | 8.41E-07 |
| **Five Series LEDs** | | | | |
| 36 | 17.2 | 113 kΩ | 8.06E-07 | **5.77E-07** |
| 48 | 17.2 | 113 kΩ | 4.92E-07 | 6.34E-07 |
| 60 | 17.2 | 113 kΩ | 3.54E-07 | 6.59E-07 |

**Calculate Switching Frequency**

$$f_{SW} = \frac{V_{OUT}}{V_{IN} \times \eta \times t_{ON}}$$

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}}$$

**Example 3 Switching Frequency**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $f_{SW}$ (kHz) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 595 |
| 48 | 10.4 | 656 |
| 60 | 10.4 | 692 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 685 |
| 48 | 13.8 | **791** |
| 60 | 13.8 | 855 |
| **Five Series LEDs** | | |
| 36 | 17.2 | 723 |
| 48 | 17.2 | 888 |
| 60 | 17.2 | 987 |

**Calculate Inductor Value**

$$L = \left(\frac{V_{IN} - V_{OUT}}{\Delta i}\right) \times t_{ON}$$

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}}\right)$$

Therefore:

$$L = \left(\frac{R_{ON}}{\Delta i}\right) \times k$$

You can quickly see one benefit of the modified circuit. The improved circuit eliminates the input and output voltage variation on RMS current.

- $I_F$ = 500 mA (typical application)
- $\Delta i_L$ = 250 mA (target)
- $R_{ON}$= 113 kΩ
- L = 59 µH (68 µH standard value)
- $\Delta i_L$ = 223 mA (L = 68 µH all combinations)

**Calculate $R_{SNS}$**

Original $R_{SNS}$ equation:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

Substitute improved circuit $t_{ON}$ calculation:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right)\left(k \times \frac{R_{ON}}{V_{IN} - V_{OUT}}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

Simplified:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{k \times R_{ON}}{2L}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

Typical Application:

- $V_{OUT}$ = 13.8V
- $I_F$ = 500 mA
- $R_{ON}$= 113 kΩ
- L = 68 µH
- $t_D$ = 220 ns

$R_{SNS}$ = 462 mΩ

This equation shows that only variations in $V_{OUT}$ will affect the average current over the entire application range. These variations should be very minor even with large variations in output voltage.

**Calculate Average Current through LED**

Modified application circuit average forward current equation.

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{V_{IN} - V_{OUT}}{2L}\right)\left(\frac{k \times R_{ON}}{V_{IN} - V_{OUT}}\right) - \left(\frac{V_{OUT} \times t_D}{L}\right)$$

Simplified:

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{k \times R_{ON}}{2L}\right) - \left(\frac{V_{OUT} \times t_D}{L}\right)$$

**Example 3 Average LED Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $I_F$ (A) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 0.511 |
| 48 | 10.4 | 0.511 |
| 60 | 10.4 | 0.511 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 0.500 |
| 48 | 13.8 | 0.500 |
| 60 | 13.8 | 0.500 |
| **Five Series LEDs** | | |
| 36 | 17.2 | 0.489 |
| 48 | 17.2 | 0.489 |
| 60 | 17.2 | 0.489 |

In this application you can see that there is a difference of **22 mA** between the low and high of the average LED current.

## Modified Application Circuit Design Example 4

- $V_{IN}$ = 48V (±20%)
- Driving 3, 4, or 5 HB LEDs with $V_F$ = 3.4V
- $I_F$ = 500 mA (typical application)
- Estimated efficiency = 82%
- $f_{SW}$ = 500 kHz (typ app)

The inductor, $R_{ON}$ resistor, and the $R_{SNS}$ resistor are calculated for a typical or average design.

- $V_{OUT}$ = 3 x 3.4V + 200 mV = 10.4V
- $V_{OUT}$ = 4 x 3.4V + 200 mV = 13.8V
- $V_{OUT}$ = 5 x 3.4V + 200 mV = 17.2V

Reduce switching frequency for the typical application to about 500 kHz to increase efficiency.

**Calculate $t_{ON}$, $t_{OFF}$ & $R_{ON}$**

$$t_{ON} = \left(\frac{V_{OUT}}{V_{IN} \times \eta}\right)\left(\frac{1}{f_{SW}}\right)$$

- $V_{OUT}$ = 13.8V
- $V_{IN}$ = 48V
- $I_F$ = 500 mA
- $t_D$ = 220 ns
- η = 0.85
- $f_{SW}$ = 500 kHz

$t_{ON}$ ≅ 705 ns

$$R_{ON} = \left(\frac{t_{ON}}{k}\right)(V_{IN} - V_{OUT})$$

$R_{ON}$ ≅ 179 kΩ (use standard value of 182 kΩ)

**Calculate Inductor Value**

$$L = \left(\frac{R_{ON}}{\Delta i}\right) \times k$$

- $I_F$ = 500 mA
- $\Delta i_L$ = 250 mA (target)
- $R_{ON}$ = 182 kΩ
- L = 100 µH

Calculate $\Delta i_L$ with L = 100 µH ($V_{IN}$ = 48V, $V_{OUT}$ = 13.8V)

$\Delta i_L$ = 241 mA (all combinations)

**Calculate Switching Frequency**

$$f_{SW} = \frac{V_{OUT}}{V_{IN} \times \eta \times t_{ON}}$$

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}}$$

**Example 4 Switching Frequency**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $f_{SW}$ (kHz) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 374 |
| 48 | 10.4 | 412 |
| 60 | 10.4 | 435 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 430 |
| 48 | 13.8 | 497 |
| 60 | 13.8 | 537 |
| **Five Series LEDs** | | |
| 36 | 17.2 | 454 |
| 48 | 17.2 | 558 |
| 60 | 17.2 | 620 |

**Calculate $R_{SNS}$**

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{k \times R_{ON}}{2L}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)}$$

- $V_{OUT}$ = 13.8V
- $V_{IN}$ = 48V
- $I_F$ = 500 mA
- $t_D$ = 220 ns
- η = 0.85
- L = 100 µH

$R_{SNS}$ = 488 mΩ

**Calculate Average Current through LED**

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{k \times R_{ON}}{2L}\right) - \left(\frac{V_{OUT} \times t_D}{L}\right)$$

**Example 4 Average LED Current**

| $V_{IN}$ (V) | $V_{OUT}$ (V) | $I_F$ (A) |
|---|---|---|
| **Three Series LEDs** | | |
| 36 | 10.4 | 0.507 |
| 48 | 10.4 | 0.507 |
| 60 | 10.4 | 0.507 |
| **Four Series LEDs** | | |
| 36 | 13.8 | 0.500 |
| 48 | 13.8 | **0.500** |
| 60 | 13.8 | 0.500 |
| **Five Series LEDs** | | |
| 36 | 17.2 | 0.493 |
| 48 | 17.2 | 0.493 |
| 60 | 17.2 | 0.493 |

In the reduced frequency application you can see that there is a difference of 14 mA between the low and high of the average current.

If the original $t_{ON}$ circuit was used (no PNP transistor) with the switching frequency centered around 500 kHz the difference between the high and low values would be about **67 mA**.

## Dimming

The DIM pin of the LM3402/04 is a TTL compatible input for low frequency pulse width modulation (PWM) dimming of the LED current. Depending on the application, a contrast ratio greater than what the LM3402/04 internal DIM circuitry can provide might be needed. This demonstration board comes with external circuitry that allows for dimming contrast ratios greater than 50k:1

## LM3402 / 04 DIM Pin Operation

To fully enable and disable the LM3402 / 04, the PWM signal should have a maximum logic low level of 0.8V and a minimum logic high level of 2.2V. Dimming frequency, $f_{DIM}$, and duty cycle, $D_{DIM}$, are limited by the LED current rise time and fall time and the delay from activation of the DIM pin to the response of the internal power MOSFET. In general, $f_{DIM}$ should be at least one order of magnitude lower than the steady state switching frequency in order to prevent aliasing.

Refer to figure 10 for illustrations. The interval $t_D$ represents the delay from a logic high at the DIM pin to the onset of the output current. The quantities $t_{SU}$ and $t_{SD}$ represent the time needed for the LED current to slew up to steady state and slew down to zero, respectively.

As an example, assume a DIM duty cycle $D_{DIM}$ equal to 100% (always on) and the circuit delivers 500mA of current through the LED string. At $D_{DIM}$ equal to 50% you would like exactly ½ of 500 mA of current through your LED string (250 mA). This could only be possible if there were no delays ($t_D$) between the on/off DIM signal and the on/off of the LED current. The rise and fall times ($t_{SU}$ and $t_{SD}$) of the LED current would also need to be eliminated. If we can reduce these times, the linearity between the PWM signal and the average current will be realized.

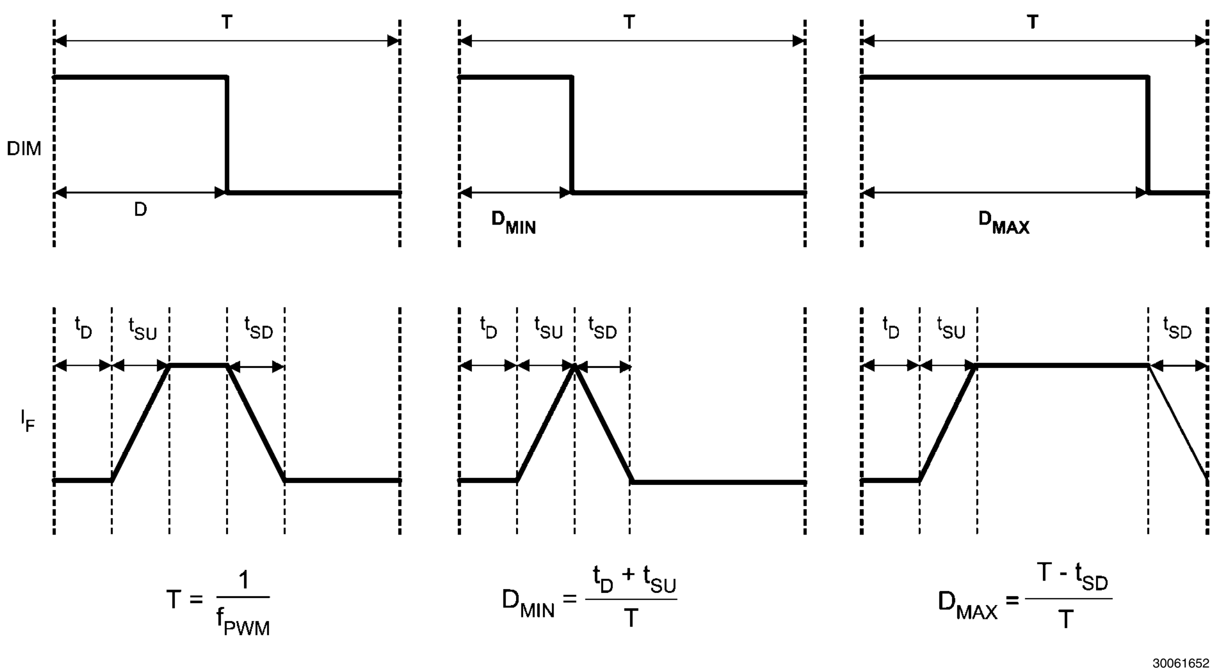



**FIGURE 10. Contrast Ratio Definitions**

## Contrast Ratio Definition

Contrast Ratio (CR) = $1/D_{MIN}$

$D_{MIN} = (t_D + t_{SU}) \times f_{DIM}$

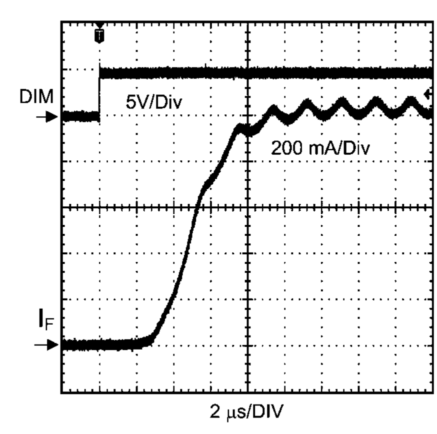



**FIGURE 11. $t_D$ & $t_{SU}$ (DIM Pin)**

## External MOSFET Dimming and Contrast Ratio

Refer to figure 12. MOSFET Q2 and its drive circuitry are provided on the demonstration PCB. When MOSFET Q2 is turned on, it shorts LED+ to LED-, therefore redirecting the inductor current from the LED string to the shunt MOSFET. The LM3402 / 04 is never turned off, and therefore become a perfect current source by providing continuous current to the output through the inductor (L1). A buck converter with an external shunt MOSFET is the ideal circuit for delivering the highest possible contrast ratio. Refer to figures 13-15 for typical delays and rise time for external MOSFET dimming.

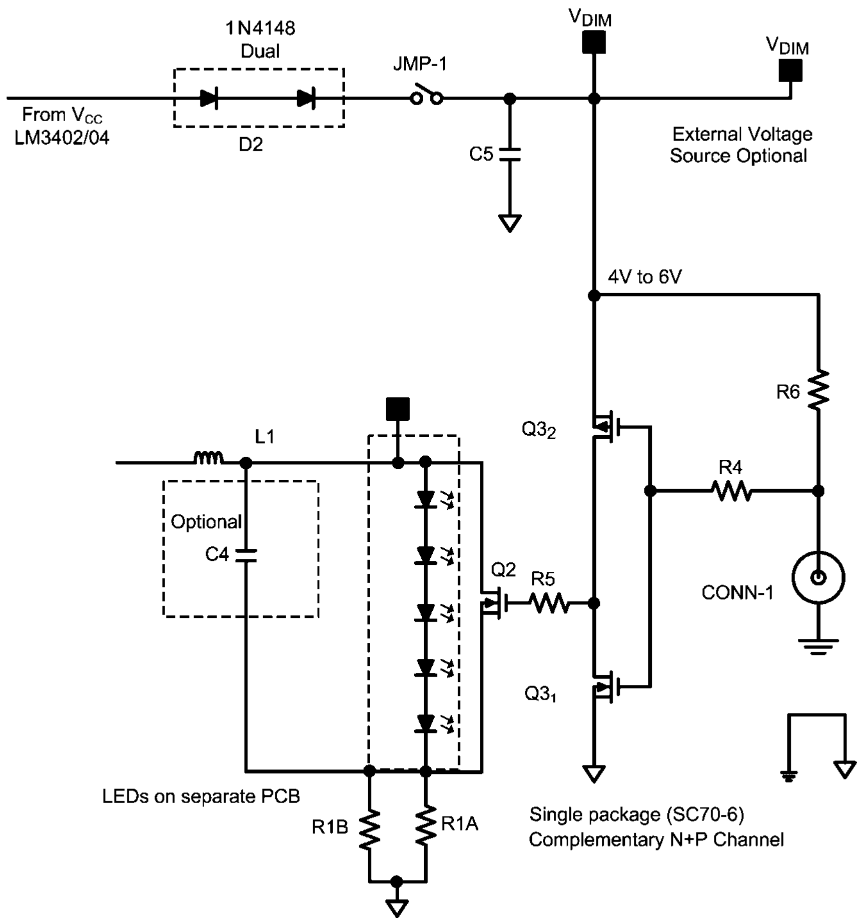



**FIGURE 12.**

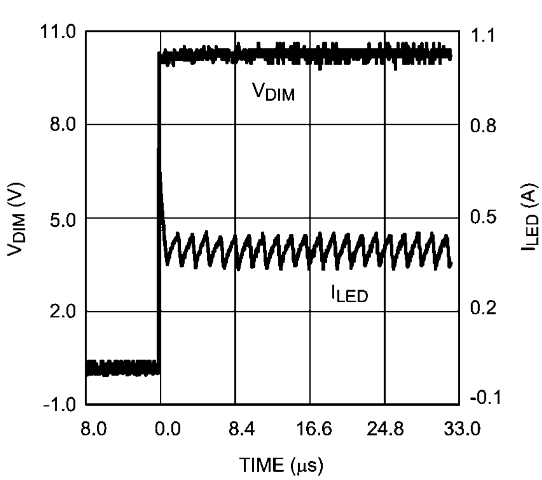



**FIGURE 13.** $V_{IN}$ **= 24V, 3 series LEDs @ 400mA**

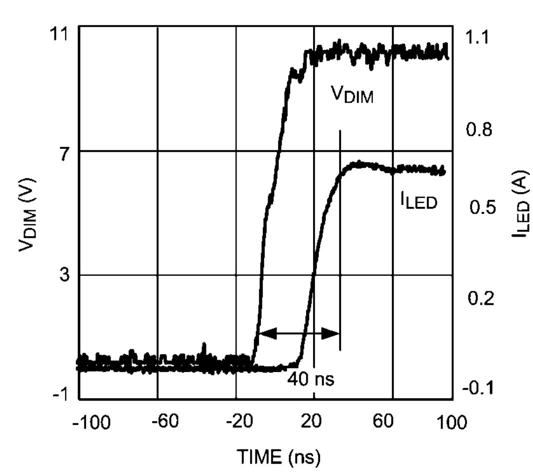



**FIGURE 14.** $t_D + t_{SU}$ **Graph**

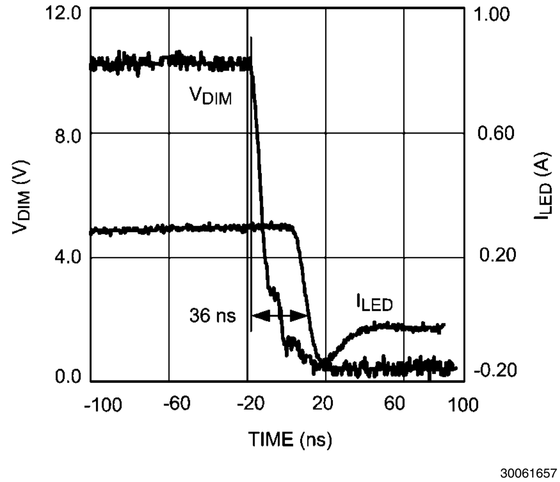



**FIGURE 15. $t_D + t_{SD}$ Graph**

## Fast Dimming + Improved Average Current Circuit

Using both the Improved Average LED current circuit and the external MOSFET fast dimming circuit together has additional benefits. If $R_{ON}$ and the converter's switching frequency ($f_{SW}$) is determined and set with the improved average LED current circuit, the switching frequency will decrease once $V_{OUT}$ is shorted during fast dimming. With MOSFET Q2 on, $V_{OUT}$ is equal to $V_{FB}$ (200 mV). The $t_{ON}$ equation then becomes almost identical to the original unmodified circuit equation.

Setting $t_{ON}$ and $R_{ON}$:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}}\right)$$

$t_{ON}$ equation becomes:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - 0.2V}\right)$$

when Q2 shunt MOSFET is on during fast dimming.

$t_{OFF}$ equation during normal operation is:

$$t_{OFF} = t_{ON}\left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1\right)$$

$t_{OFF}$ equation then becomes:

$$t_{OFF} = t_{ON}\left(\frac{V_{IN} \times \eta}{0.2V} - 1\right)$$

when Q2 shunt MOSFET is OFF during fast dimming.

This is an added benefit due to the fact that $t_{OFF}$ is greatly increased, and therefore the switching frequency is decreased, which leads to improved efficiency (see figure 16). Inductor L1 still remains charged, and as soon as Q2 turns off current flows through the LED string.

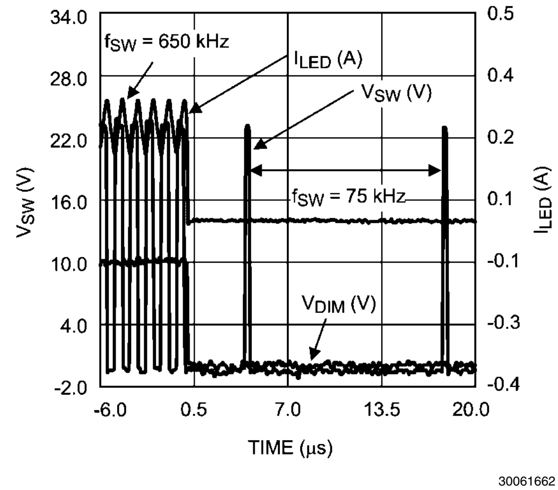



**FIGURE 16. Improved Avg $I_{LED}$ Circuit + Fast Dimming**

## Linearity with Fast Dimming

Once the delays and rise/fall times have been greatly reduced, linear average current vs, duty cycle ($D_{DIM}$) can be achieved at very high dimming frequencies ($f_{DIM}$) (see figure 17).

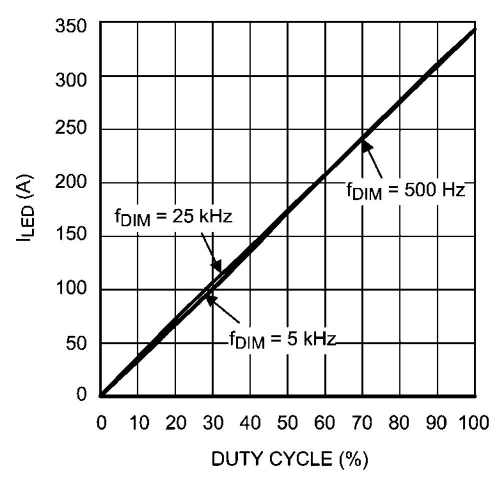
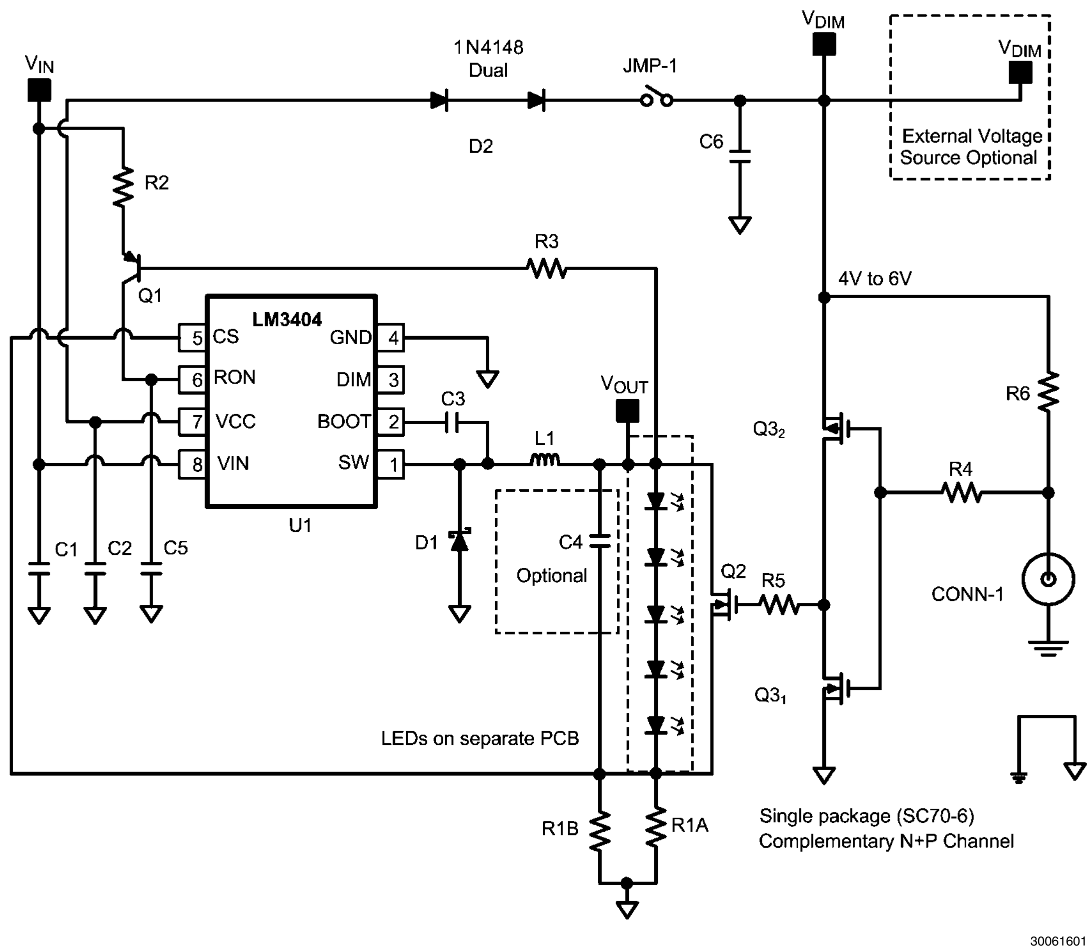



**FIGURE 17. Linearity with Fast Dimming**

# LM3402 Improved ILED Average & Fast Dimming Demonstration Board

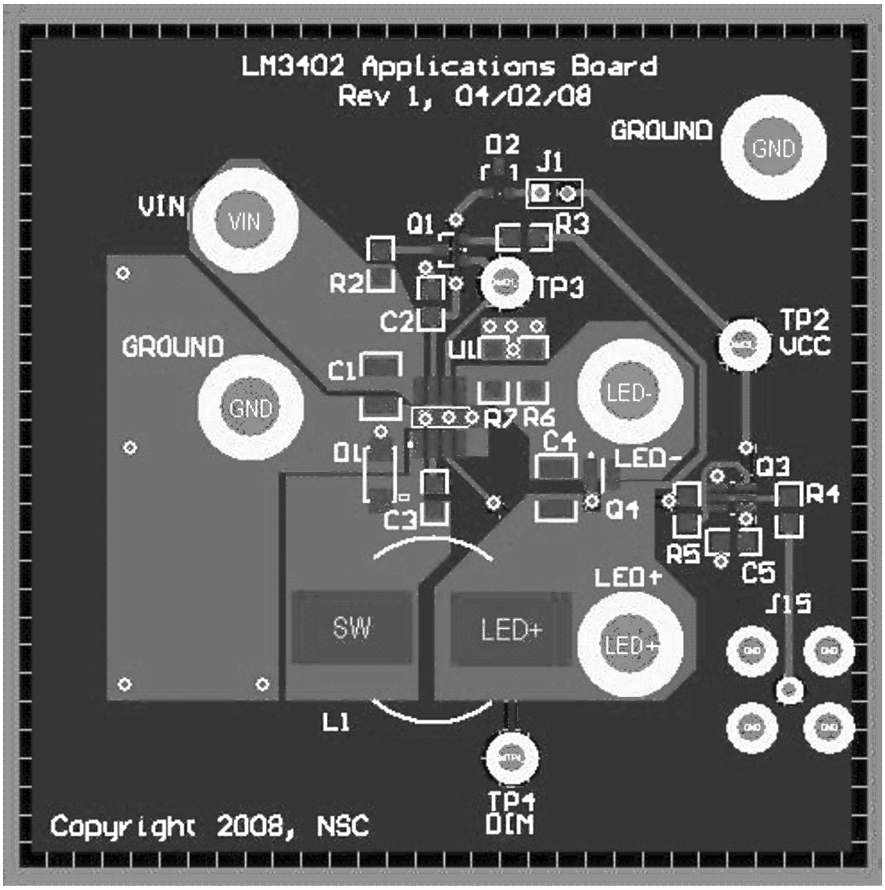



$V_{IN}$ = 9V to 18V, $I_{LED}$ = 500 mA, 3 x 3.4V White LED Strings ($f_{SW} \cong$ 750 kHz)

## Bill of Materials

| Part ID | Part Value | Mfg | Part Number |
|---|---|---|---|
| U1 | 0.5A Buck LED Driver PSOP pkg | NSC | LM3402 |
| C1, Input Cap | 10 µF, 25V, X5R | TDK | C3225X5R1E106M |
| C2, C6 Cap | 1 µF, 16V, X5R | TDK | C1608X5R1C105M |
| C3, $V_{BOOST}$ Cap | 0.1 µF, X5R | TDK | C1608X5R1H104M |
| C4 Output Cap | 10 µF, 25V, X5R (Optional) | TDK | C3225X5R1E106M |
| C5, $V_{RON}$ Cap | 0.01 µF, X5R | TDK | C1608X5R1H103M |
| D1, Catch Diode | $0.5V_f$ Schottky 2A, $30V_R$ | Diodes INC | B230 |
| D2 | Dual SMT small signal | Diodes INC | BAV199 |
| L1 | 33 µH | CoilCraft | D01813H-333 |
| R1A, R1B | 1Ω 1% 0.25W 1206 | Panasonic | ERJ-8RQF1R0V |
| R2 | 64.9 kΩ 1% | Vishay | CRCW08056492F |
| R3 | 1.0 kΩ, 1% | Vishay | CRCW08051001F |
| R4, R5 | 1Ω, 1% | Vishay | CRCW08051R00F |
| R6 | 10 kΩ, 1% | Vishay | CRCW08051002F |
| Q1 | SOT23 PNP | Diodes INC | MMBT3906 |
| Q2 | SOT23-6 N-CH 2.4A, 20V | ZETEX | ZXM2A01E6CT |
| Q3 | SC70-6, P + N Channel | Vishay | Si1539DL |
| Test Points | Connector | Keystone | 1502-2 |
| VIN, GND, LED+, LED- | Connector | Keystone | 575-8 |
| JMP-1 | Jumper | Molex | 22-28-4023 |

## Layout

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