

AN-1839 LM3402/LM3404 Fast Dimming and True Constant LED Current Evaluation Board

1 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.

2 Circuit Performance with LM3404

This evaluation board (see [Figure 1](#)) uses the LM3404 to provide a constant forward current of 700 mA $\pm 10\%$ 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.

3 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 θ_{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](#).

4 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.

5 Low Power Shutdown

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

6 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.

$$D = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{t_{ON}}{T_S} = t_{ON} \times f_{SW} \quad (1)$$

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

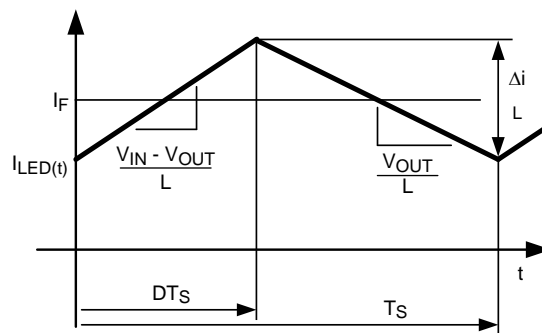
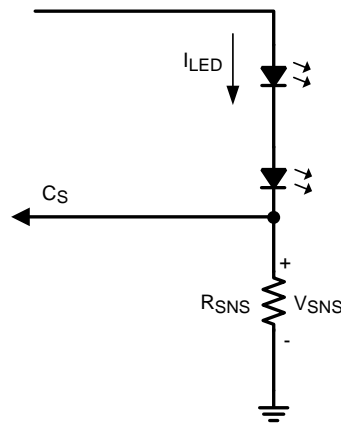


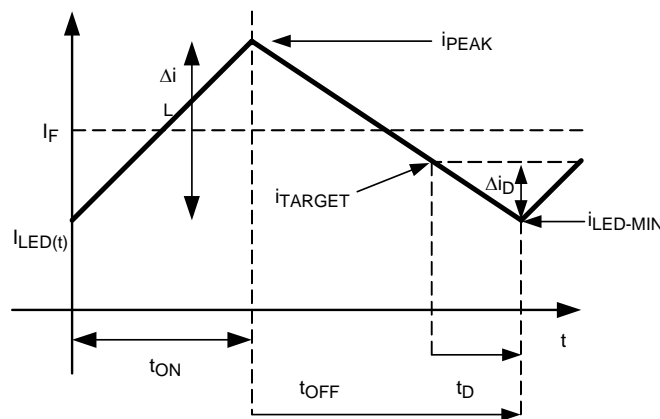
Figure 3. Buck Converter Inductor Current Waveform

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

6.1 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 [Figure 3](#) and [Figure 5](#) and the equations of a line, calculate $I_{LED-MIN}$.

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

(2)

Where

$$I_F = I_{LED-Average} \quad (3)$$

The delta of the inductor current is given by:

$$\frac{\Delta i}{2} = \left(\frac{V_{IN} - V_{OUT}}{2L} \right) \times t_{ON} \quad (4)$$

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.

$$I_{TARGET} = I_F - \frac{\Delta i}{2} + \Delta i_D \quad (5)$$

Δi_D is the magnitude of current beyond the target current and equal to:

$$\Delta i_D = \left(\frac{V_{OUT}}{L} \right) t_D \quad (6)$$

Therefore:

$$i_{TARGET} = I_F - \left(\frac{V_{IN} - V_{OUT}}{2L} \right) \times t_{ON} + \left(\frac{V_{OUT}}{L} \right) \times t_D \quad (7)$$

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

$$i_{TARGET} \times R_{SNS} = 0.20V \quad (8)$$

Therefore:

$$0.2V = R_{SNS} \left(I_F - \left(\frac{V_{IN} - V_{OUT}}{2L} \right) \times t_{ON} + \left(\frac{V_{OUT}}{L} \right) \times t_D \right) \quad (9)$$

Finally R_{SNS} can be calculated.

$$R_{SNS} = \frac{0.20V}{\left(I_F - \left(\frac{V_{IN} - V_{OUT}}{2L} \right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L} \right) \right)} \quad (10)$$

7 Standard On-Time Set Calculation

The control MOSFET on-time is variable, and is set with an external resistor R_{ON} (R2 from [Figure 1](#)). On-time is governed by the following equation:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN}} \right) \quad (11)$$

Where

$$k = 1.34 \times 10^{-10} \quad (12)$$

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.

8 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

- $V_{IN} = 48V (\pm 20\%)$
- Driving three HB LEDs with $V_F = 3.4V$
- $V_{OUT} = (3 \times 3.4V + 200 \text{ mV}) = 10.4V$
- $I_F = 500 \text{ mA}$ (typical application)
- Estimated efficiency = 82%
- $f_{SW} = \text{fast as possible}$
- 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.

$$\Delta i_L = 500 \text{ mA} \times 0.50 = 250 \text{ mA}$$

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

Calculate t_{ON} , t_{OFF} and R_{ON}

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

$$t_{OFF} \text{ minimum} = 300 \text{ ns}$$

$$t_{ON} \text{ minimum} = 300 \text{ ns}$$

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

A quick guideline for maximum switching frequency allowed versus input and output voltages are in [Figure 6](#) and [Figure 7](#).

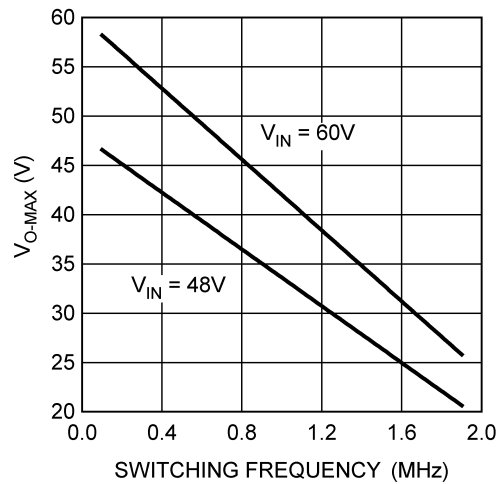


Figure 6. $V_{OUT-MAX}$ vs f_{SW}

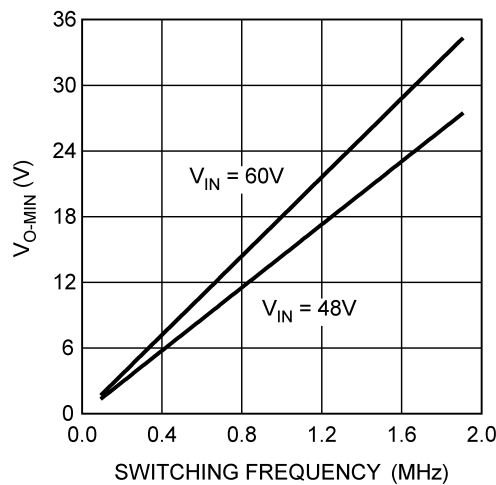


Figure 7. $V_{OUT-MIN}$ vs f_{SW}

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN}} \right) \tag{13}$$

$R_{ON} = 135 \text{ k}\Omega$ (use standard value of $137 \text{ k}\Omega$)

$t_{ON} = 306 \text{ ns}$

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

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

$t_{ON} = 510 \text{ ns}$

We know that:

$$D = \frac{V_{OUT}}{V_{IN} \times \eta} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \tag{14}$$

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

$$t_{OFF} = t_{ON} \left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1 \right) \tag{15}$$

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

Table 1. Example 1 ON and 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:

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

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

Table 2. Example 1 Ripple Current

V_{IN} (V)	V_{OUT} (V)	Δi_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.

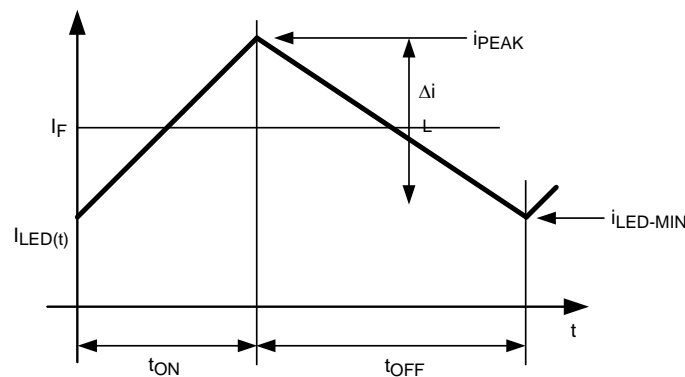


Figure 8. Inductor Current Waveform

- $I_F = 500$ 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:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) \left(\frac{k \times R_{ON}}{V_{IN}}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)} \quad (16)$$

 Therefore: $R_{SNS} = 467 \text{ m}\Omega$

Calculate Average LED current (I_F)

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

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{V_{IN} - V_{OUT}}{2L}\right) (t_{ON}) - \left(\frac{V_{OUT} \times t_D}{L}\right) \quad (17)$$

Table 3. 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).

- $V_{IN} = 48V$ ($\pm 20\%$)
- Driving 3, 4, or 5 HB LEDs with $V_F = 3.4V$
- $I_F = 500 \text{ mA}$ (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.

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

Calculate t_{ON} , t_{OFF} and 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 $t_{ON} = 300 \text{ ns}$:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN}}\right) \quad (18)$$

$$R_{ON} = 137 \text{ k}\Omega, t_{ON} = 306 \text{ ns}$$

 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 $R_{ON} = 137 \text{ k}\Omega$ calculate t_{ON} from the above equation:

$$t_{ON} = 510 \text{ ns}$$

$$\frac{V_{IN} \times \eta}{V_{OUT}} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \quad (19)$$

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

$$t_{OFF} = t_{ON} \left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1 \right) \quad (20)$$

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

Table 4. Example 2 On and Off Time

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

Calculate Switching Frequency

The switching frequency will only change with output voltage.

$$f_{SW} = \frac{V_{OUT}}{V_{IN} \times \eta \times t_{ON}} \quad (21)$$

Substituting equations:

$$f_{SW} = \frac{V_{OUT}}{\eta \times k \times R_{ON}} \quad (22)$$

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}} \quad (23)$$

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

Calculate Inductor Value

$$L = \left(\frac{V_{IN} - V_{OUT}}{\Delta i} \right) \times t_{ON} \quad (24)$$

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

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

Calculate Δi for $V_{IN} = 36\text{V}$, 48V , and 60V with $L = 68 \mu\text{H}$.

Table 5. Example 2 Ripple Current

V _{IN} (V)	V _{OUT} (V)	Δi _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

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L} \right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L} \right)} \quad (25)$$

$$R_{SNS} = 446 \text{ m}\Omega$$

Calculate Average Current through LED

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

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{V_{IN} - V_{OUT}}{2L} \right) (t_{ON}) - \left(\frac{V_{OUT} \times t_D}{L} \right) \quad (26)$$

Table 6. 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.

9 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:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}} \right) \quad (27)$$

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.

10 Modified Application Circuit Design Example 3

Design Example 1

- $V_{IN} = 48V$ ($\pm 20\%$)
- 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.

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

Calculate t_{ON} , t_{OFF} and 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:

$$R_{ON} = t_{ON} \left(\frac{V_{IN} - V_{OUT}}{k} \right) \quad (28)$$

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

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

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

$$t_{ON} = 806$$
 ns

$$t_{OFF} = t_{ON} \left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1 \right) \quad (29)$$

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

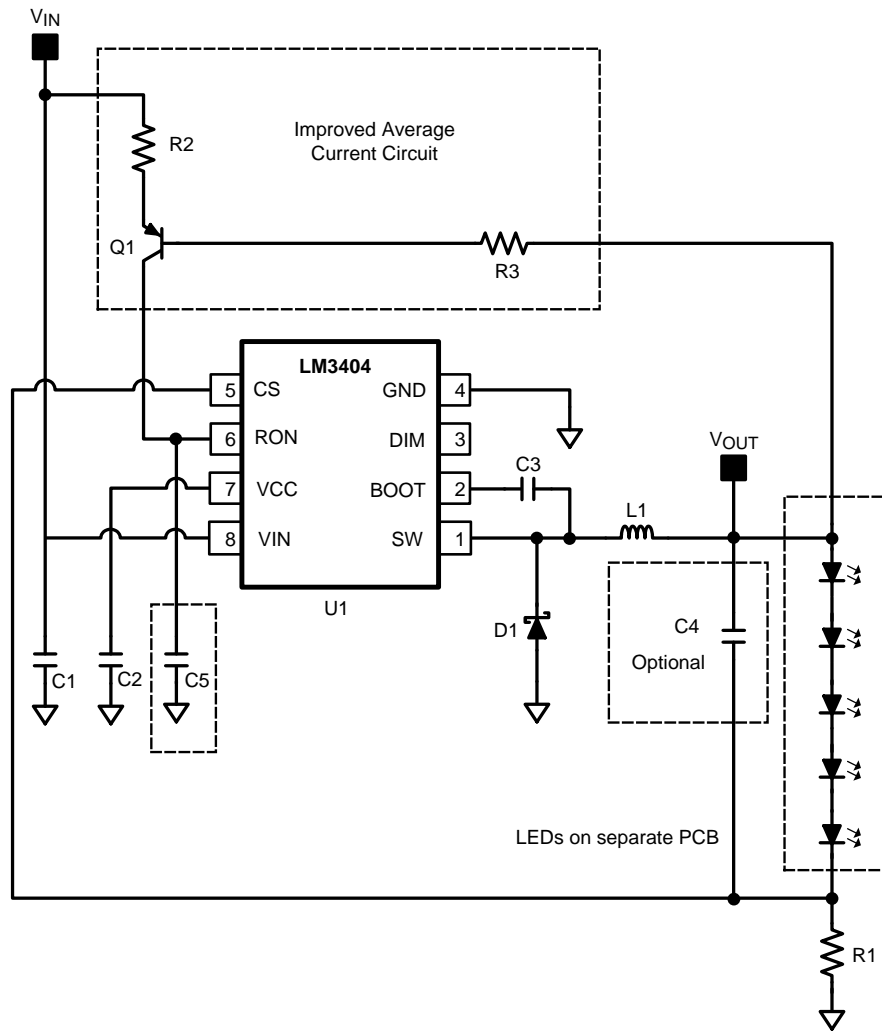


Figure 9. Improved Average LED Current Application Circuit

Table 7. Example 3 On and Off Times

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

Calculate Switching Frequency

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

Or:

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

(30)

Table 8. 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

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

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

(31)

Therefore:

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

(32)

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)
- Δi_L = 250 mA (target)
- R_{ON} = 113 kΩ
- L = 59 μH (68 μH standard value)
- Δi_L = 223 mA (L = 68 μH all combinations)

Calculate R_{SNS}

Original R_{SNS} equation:

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

(33)

Substitute improved circuit t_{ON} calculation:

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

(34)

Simplified:

$$R_{\text{SNS}} = \frac{0.20\text{V}}{(I_F) - \left(\frac{k \times R_{\text{ON}}}{2L}\right) + \left(\frac{V_{\text{OUT}} \times t_D}{L}\right)} \quad (35)$$

Typical Application:

- $V_{\text{OUT}} = 13.8\text{V}$
- $I_F = 500\text{ mA}$
- $R_{\text{ON}} = 113\text{ k}\Omega$
- $L = 68\text{ }\mu\text{H}$
- $t_D = 220\text{ ns}$

$$R_{\text{SNS}} = 462\text{ m}\Omega$$

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.

$$I_F = \frac{0.20\text{V}}{R_{\text{SNS}}} + \left(\frac{V_{\text{IN}} - V_{\text{OUT}}}{2L}\right) \left(\frac{k \times R_{\text{ON}}}{V_{\text{IN}} - V_{\text{OUT}}}\right) - \left(\frac{V_{\text{OUT}} \times t_D}{L}\right) \quad (36)$$

Simplified:

$$I_F = \frac{0.20\text{V}}{R_{\text{SNS}}} + \left(\frac{k \times R_{\text{ON}}}{2L}\right) - \left(\frac{V_{\text{OUT}} \times t_D}{L}\right) \quad (37)$$

Table 9. 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.

11 Modified Application Circuit Design Example 4

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

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

- $V_{\text{OUT}} = 3 \times 3.4\text{V} + 200\text{ mV} = 10.4\text{V}$

- $V_{OUT} = 4 \times 3.4V + 200 \text{ mV} = 13.8V$
- $V_{OUT} = 5 \times 3.4V + 200 \text{ mV} = 17.2V$

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

Calculate t_{ON} , t_{OFF} and R_{ON}

$$t_{ON} = \left(\frac{V_{OUT}}{V_{IN} \times \eta} \right) \left(\frac{1}{f_{SW}} \right) \quad (38)$$

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

$$t_{ON} \cong 705 \text{ ns}$$

$$R_{ON} = \left(\frac{t_{ON}}{k} \right) (V_{IN} - V_{OUT}) \quad (39)$$

$R_{ON} \cong 179 \text{ k}\Omega$ (use standard value of 182 k Ω)

Calculate Inductor Value

$$L = \left(\frac{R_{ON}}{\Delta i} \right) \times k \quad (40)$$

- $I_F = 500 \text{ mA}$
- $\Delta i_L = 250 \text{ mA}$ (target)
- $R_{ON} = 182 \text{ k}\Omega$
- $L = 100 \text{ }\mu\text{H}$

Calculate Δi_L with $L = 100 \text{ }\mu\text{H}$ ($V_{IN} = 48V$, $V_{OUT} = 13.8V$)

$\Delta i_L = 241 \text{ mA}$ (all combinations)

Calculate Switching Frequency

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

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}} \quad (41)$$

Table 10. 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}

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{k \times R_{ON}}{2L}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)} \quad (42)$$

- $V_{OUT} = 13.8V$
- $V_{IN} = 48V$
- $I_F = 500 \text{ mA}$
- $t_D = 220 \text{ ns}$
- $\eta = 0.85$
- $L = 100 \mu\text{H}$

$$R_{SNS} = 488 \text{ m}\Omega$$

Calculate Average Current through LED

$$I_F = \frac{0.20V}{R_{SNS}} + \left(\frac{k \times R_{ON}}{2L}\right) - \left(\frac{V_{OUT} \times t_D}{L}\right) \quad (43)$$

Table 11. 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**.

12 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.

13 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.

For illustrations, see Figure 10. 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 $\frac{1}{2}$ 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.

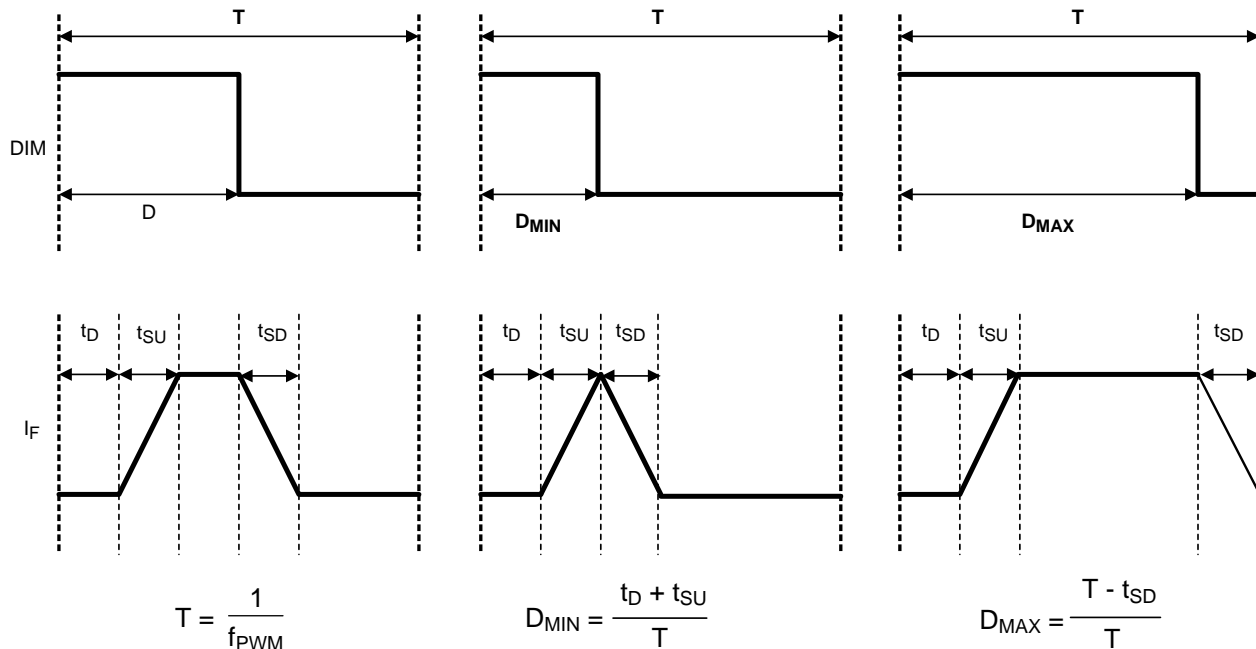


Figure 10. Contrast Ratio Definitions

14 Contrast Ratio Definition

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

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

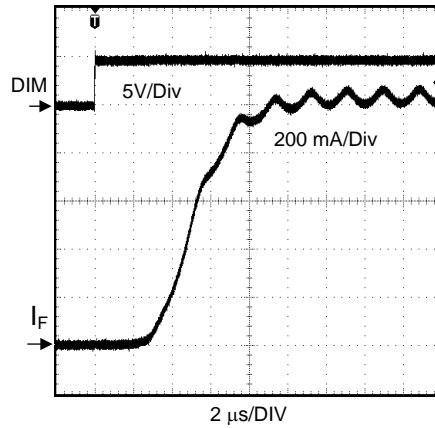


Figure 11. t_D and t_{SU} (DIM Pin)

15 External MOSFET Dimming and Contrast Ratio

MOSFET Q4 and its drive circuitry are provided on the demonstration PCB (see [Figure 12](#)). When MOSFET Q4 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. For typical delays and rise time for external MOSFET dimming, see [Figure 13](#) - [Figure 15](#).

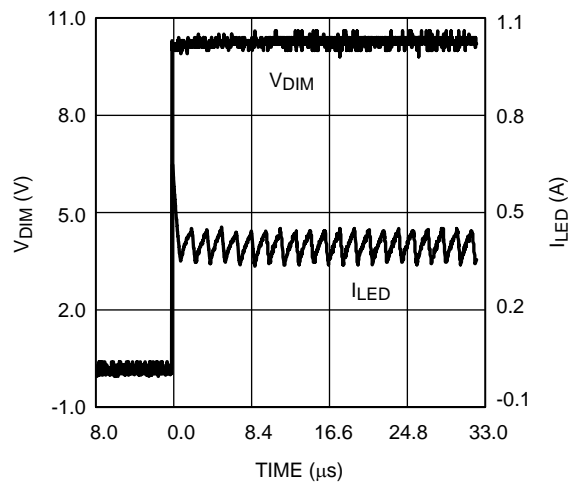
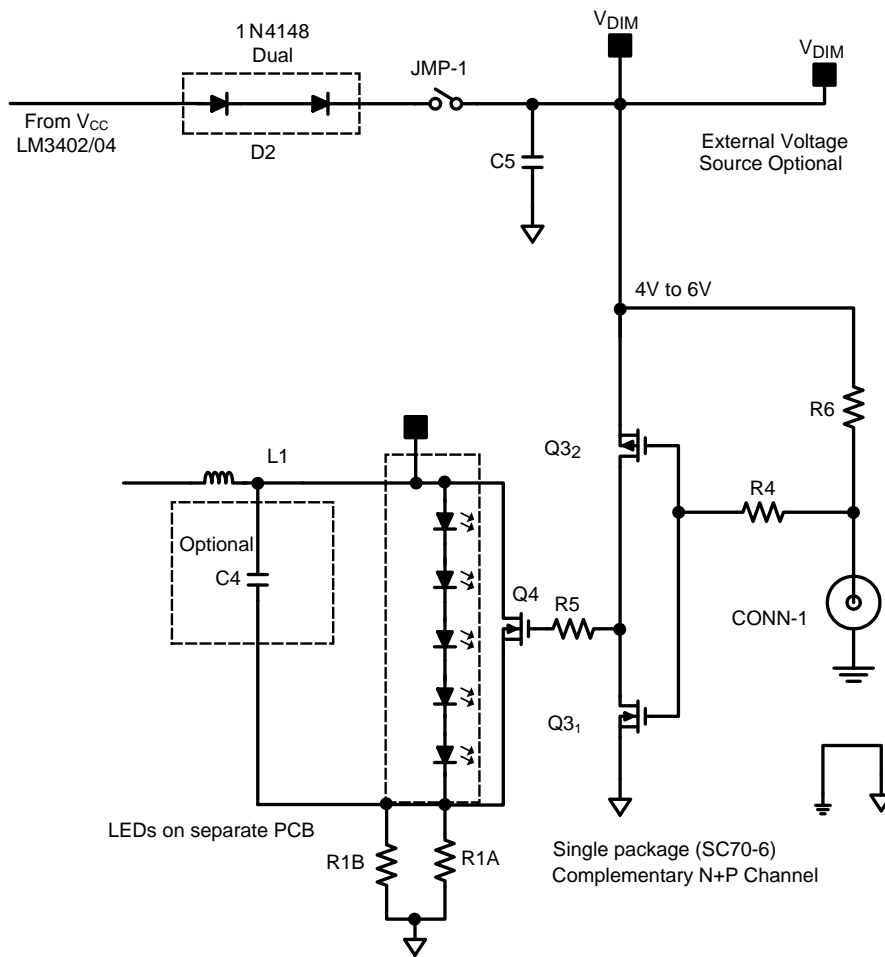


Figure 12. $V_{IN} = 24V$, 3 series LEDs @ 400mA

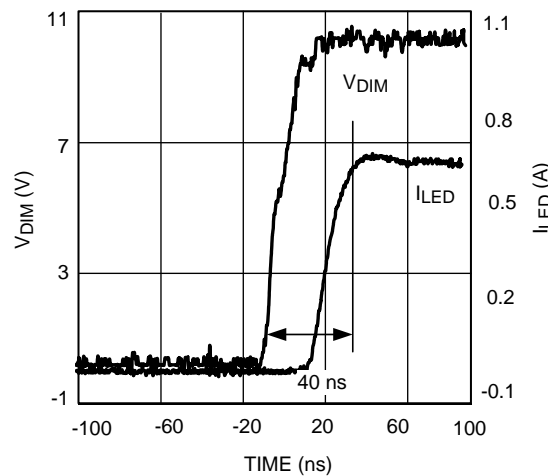


Figure 13. $t_D + t_{SU}$ Graph

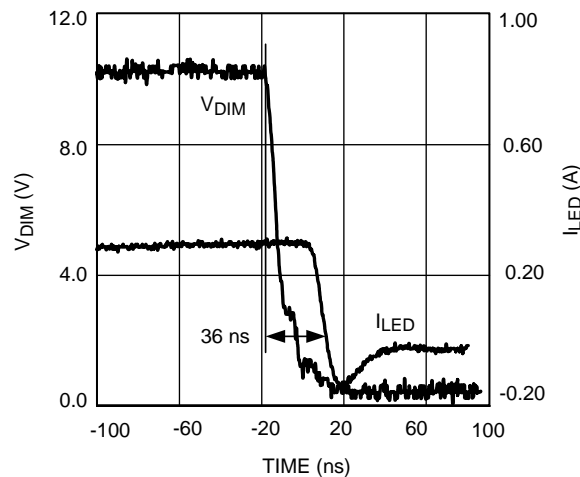


Figure 14. $t_D + t_{SD}$ Graph

16 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 Q4 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} :

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}} \right) \quad (44)$$

t_{ON} equation becomes:

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - 0.2V} \right) \quad (45)$$

when Q4 shunt MOSFET is on during fast dimming.

t_{OFF} equation during normal operation is:

$$t_{OFF} = t_{ON} \left(\frac{V_{IN} \times \eta}{V_{OUT}} - 1 \right) \quad (46)$$

t_{OFF} equation then becomes:

$$t_{OFF} = t_{ON} \left(\frac{V_{IN} \times \eta}{0.2V} - 1 \right) \quad (47)$$

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 Q4 turns off current flows through the LED string.

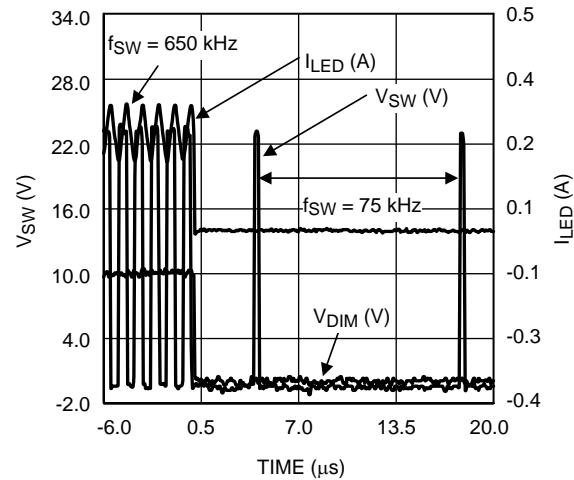


Figure 15. Improved Avg I_{LED} Circuit + Fast Dimming

17 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).

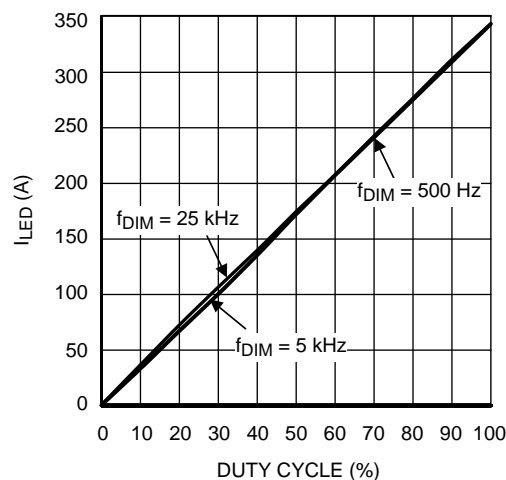


Figure 16. Linearity With Fast Dimming

18 LM3404 Improved ILED Average and Fast Dimming Demonstration Board

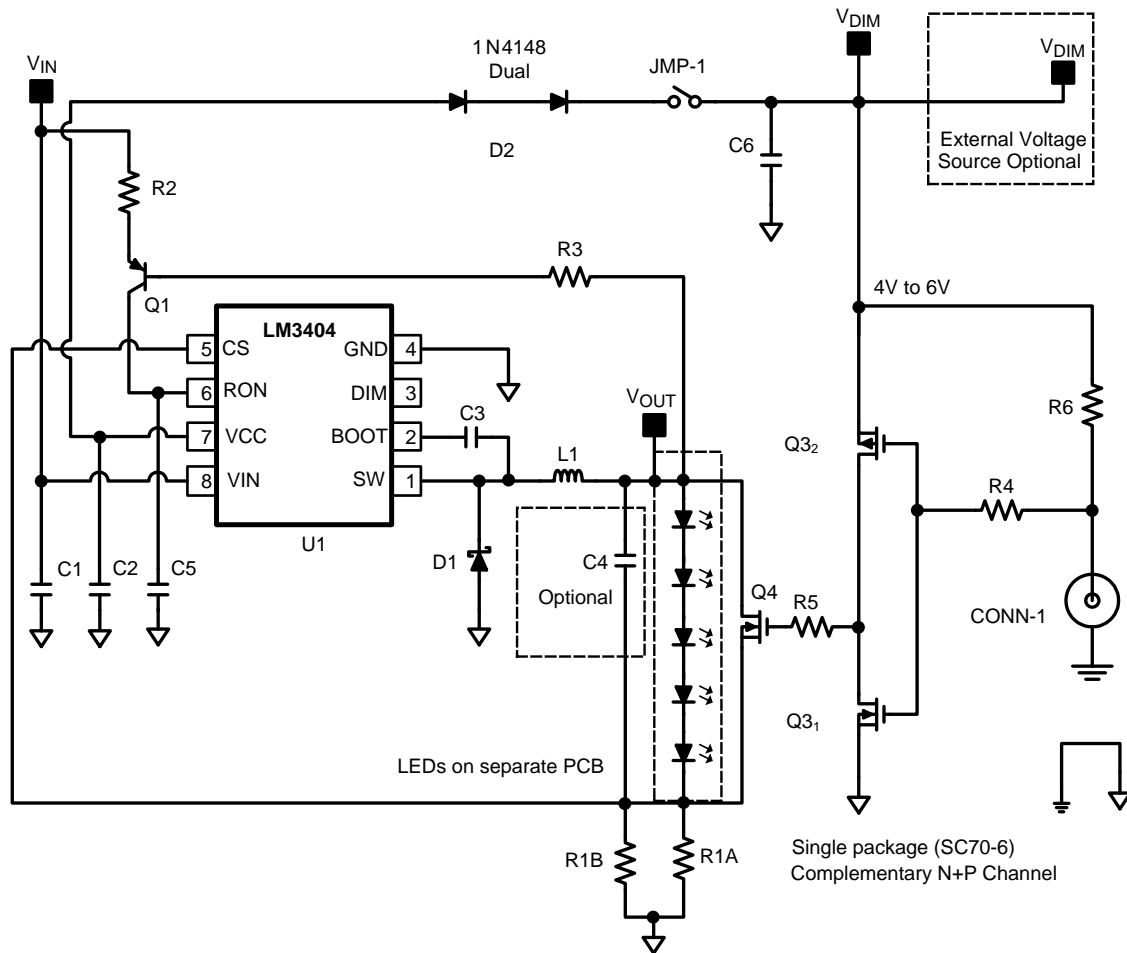
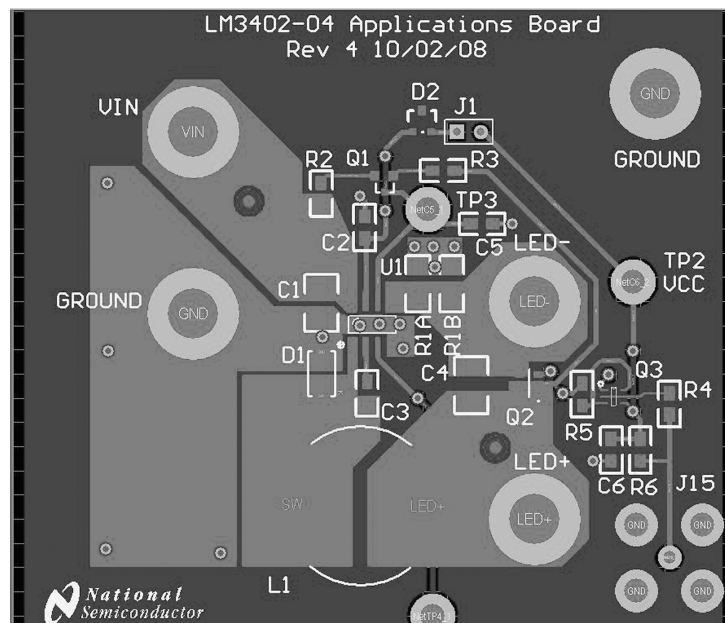


Figure 17. $V_{IN} = 9V$ to $18V$, $I_{LED} = 700$ mA, 3 x 3.4V White LED Strings ($f_{sw} \approx 500$ kHz)

19 Bill of Materials

Part ID	Part Value	Mfg	Part Number
U1	1A Buck LED Driver PSOP pkg	NSC	LM3404
C1, Input Cap	10 μ F, 25V, X5R	TDK	C3225X5R1E106M
C2, C6 Cap	1 μ F, 16V, X5R	TDK	C1608X5R1C105M
C3, V _{BOOST} Cap	0.1 μ F, X5R	TDK	C1608X5R1H104M
C4 Output Cap	10 μ F, 25V, X5R (Optional)	TDK	C3225X5R1E106M
C5, V _{RON} Cap	0.01 μ F, 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 μ H	CoilCraft	D01813H-333
R1A, R1B	0.62 Ω 1% 0.25W 1206	ROHM	MCR18EZHFLR620
R2	47.5 k Ω 1%	Vishay	CRCW08054752F
R3	1.0 k Ω , 1%	Vishay	CRCW08051001F
R4, R5	1 Ω , 1%	Vishay	CRCW08051R00F
R6	10 k Ω , 1%	Vishay	CRCW08051002F
Q1	SOT23 PNP	Diodes INC	MMBT3906
Q4	SOT23-6 N-CH 2.4A, 20V	ZETEX	ZXMN2A01E6
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
J15	50 Ω BNC	Amphenol	112538

20 Layout



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