User's Guide
SNVA342E – July 2008 – Revised April 2013

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 ±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.

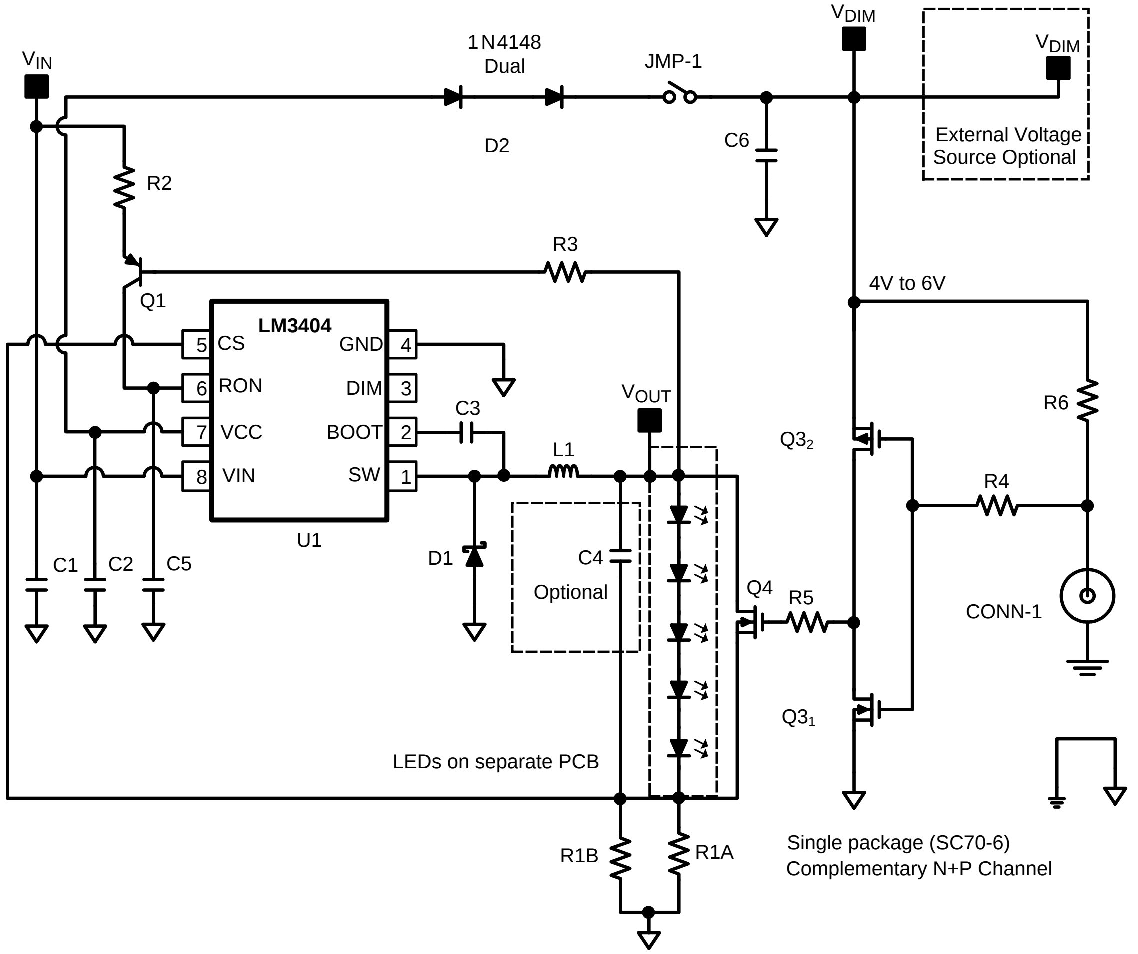


Figure 1. LM3402 / 04 Schematic

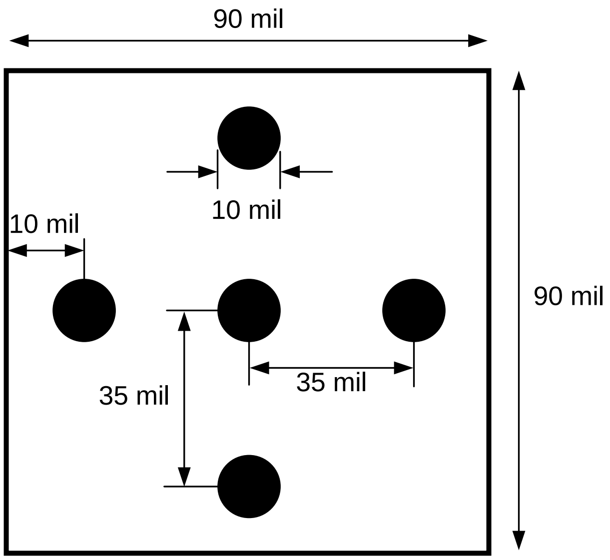


Figure 2. LM3402/04 PSOP Thermal PAD and Via Layout

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 µA) 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.

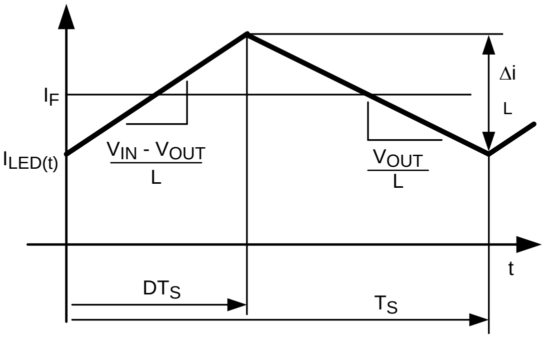


Figure 3. Buck Converter Inductor Current Waveform

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}.

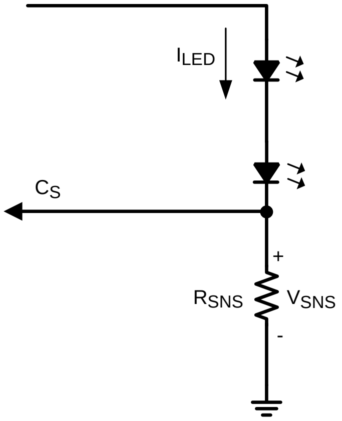


Figure 4. V_{SNS} Circuit

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.

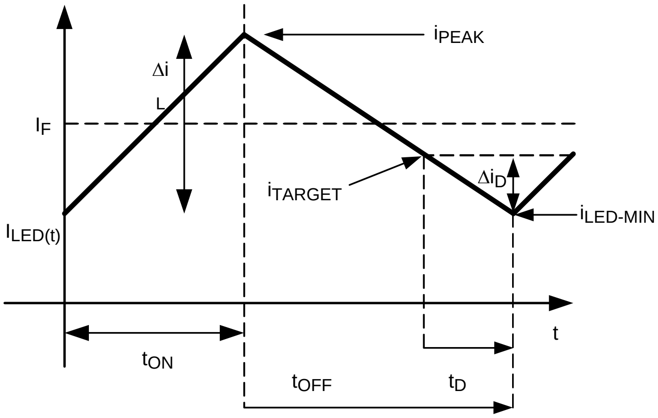


Figure 5. I_{SENSE} Current Waveform

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

$$I_{LED\text{-}MIN} = I_F - \frac{\Delta i_L}{2} \quad (2)$$

Where

$$I_F = I_{LED\text{-}Average} \tag{3}$$

The delta of the inductor current is given by:

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

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.

$$I_{TARGET} = I_F - \frac{\Delta i_L}{2} + \Delta i_D \tag{5}$$

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

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

Therefore:

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

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

$$i_{TARGET} \times R_{SNS} = 0.20V \tag{8}$$

Therefore:

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

Finally R_{SNS} can be calculated.

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

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:

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

Where

$$k = 1.34 \times 10^{-10} \tag{12}$$

At the conclusion of t_{ON} the control MOSFET turns off for a minimum OFF time ($t_{OFF\text{-}MIN}$) of 300 ns, and once $t_{OFF\text{-}MIN}$ 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 (±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.

Δi_L = 500 mA x 0.50 = 250 mA

I_{PEAK} = 500 mA + 125 mA = 625 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} 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 in Figure 6 and Figure 7.

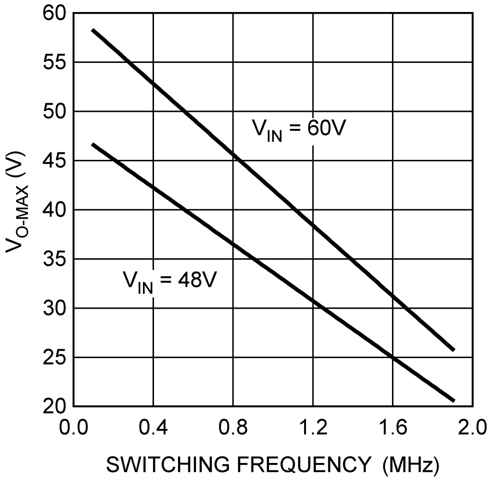


Figure 6. $V_{OUT-MAX}$ vs f_{SW}

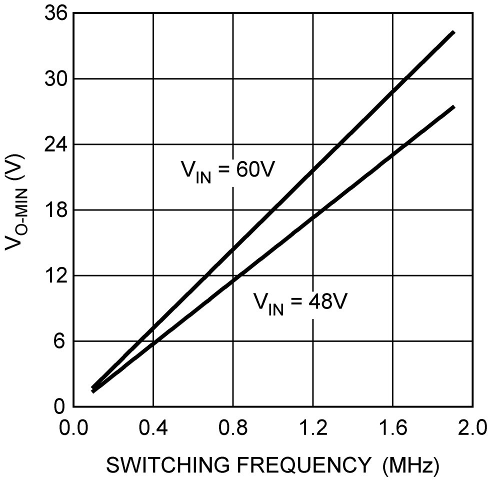


Figure 7. $V_{OUT-MIN}$ vs f_{SW}

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

R_{ON} = 135 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:

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

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 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
- Δi_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.

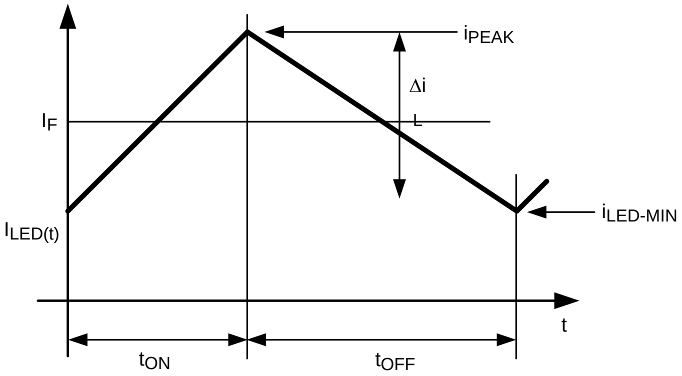


Figure 8. Inductor Current Waveform

- 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 mΩ

Calculate Average LED current (I_F)

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

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

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 (±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} 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 ns:

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

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

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

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

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

t_{OFF} = 365 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 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.

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

Substituting equations:

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

Or:

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

- 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

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

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

- I_{AVG} = 500 mA
- Δi_L = 250 mA (target)
- L = 53 µH (68 uH standard value)

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

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

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

R_{SNS} = 446 mΩ

Calculate Average Current through LED

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

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

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:

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

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 (±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} 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:

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

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

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

t_{OFF} = 577 ns (satisfied)

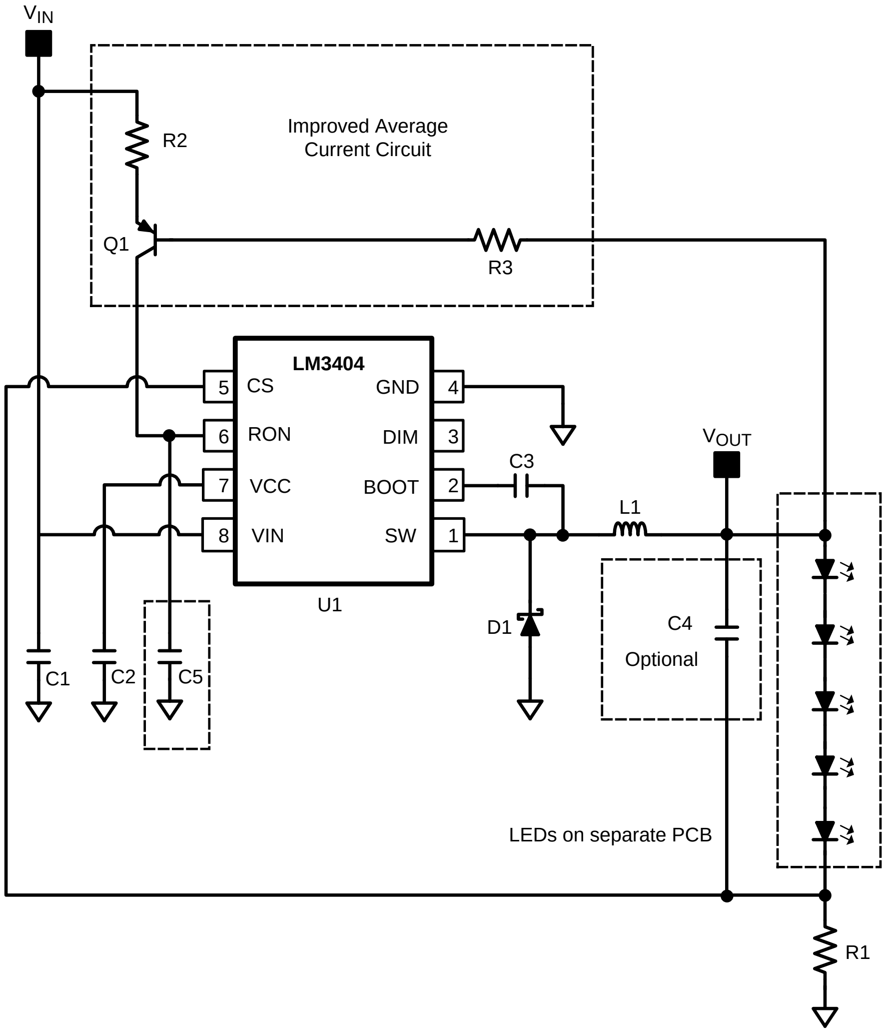


Figure 9. Improved Average LED Current Application Circuit

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 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:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}} \quad (30)$$

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

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

$$t_{ON} = k \times \left(\frac{R_{ON}}{V_{IN} - V_{OUT}}\right) \quad (31)$$

Therefore:

$$L = \left(\frac{R_{ON}}{\Delta i}\right) \times k \quad (32)$$

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:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right) \times t_{ON} + \left(\frac{V_{OUT} \times t_D}{L}\right)} \quad (33)$$

Substitute improved circuit t_{ON} calculation:

$$R_{SNS} = \frac{0.20V}{(I_F) - \left(\frac{V_{IN} - V_{OUT}}{2L}\right)\left(k \times \frac{R_{ON}}{V_{IN} - V_{OUT}}\right) + \left(\frac{V_{OUT} \times t_D}{L}\right)} \quad (34)$$

Simplified:

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

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.

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

Simplified:

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

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_{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} and R_{ON}

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

- 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

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

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

Calculate Inductor Value

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

- I_F = 500 mA
- Δi_L = 250 mA (target)
- R_{ON} = 182 kΩ
- L = 100 µH

Calculate Δi_L with L = 100 µH (V_{IN} = 48V, V_{OUT} = 13.8V)

Δi_L = 241 mA (all combinations)

Calculate Switching Frequency

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

Or:

$$f_{SW} = \frac{1}{t_{ON} + t_{OFF}} \tag{41}$$

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}

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

- 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

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

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

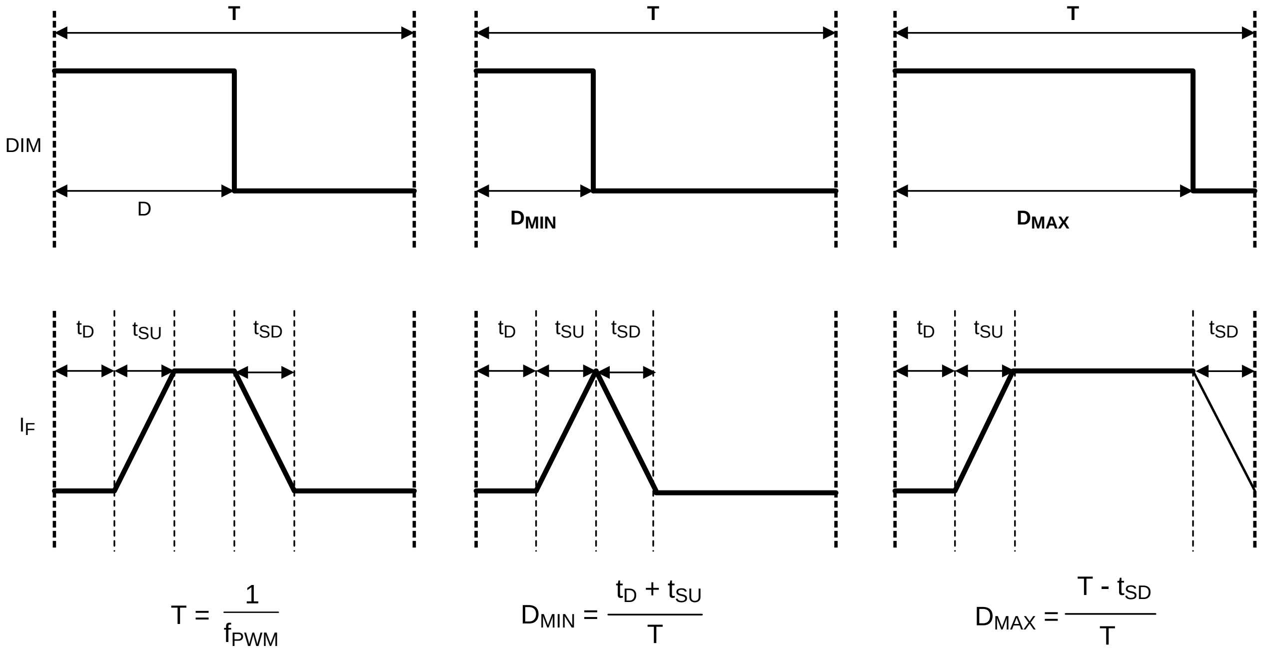
The DIM pin of the LM3402/04 is a TTL compatible input for low frequency pulse width modulation (PWM) dimming of the LED current. Depending on the application, a contrast ratio greater than what the LM3402/04 internal DIM circuitry can provide might be needed. This demonstration board comes with external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



$$T = \frac{1}{f_{PWM}} \qquad D_{MIN} = \frac{t_D + t_{SU}}{T} \qquad D_{MAX} = \frac{T - t_{SD}}{T}$$

Figure 10. Contrast Ratio Definitions

14 Contrast Ratio Definition

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

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

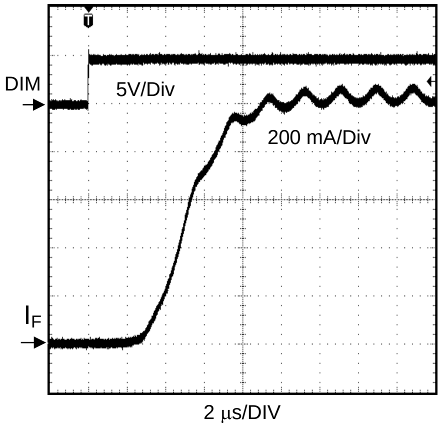
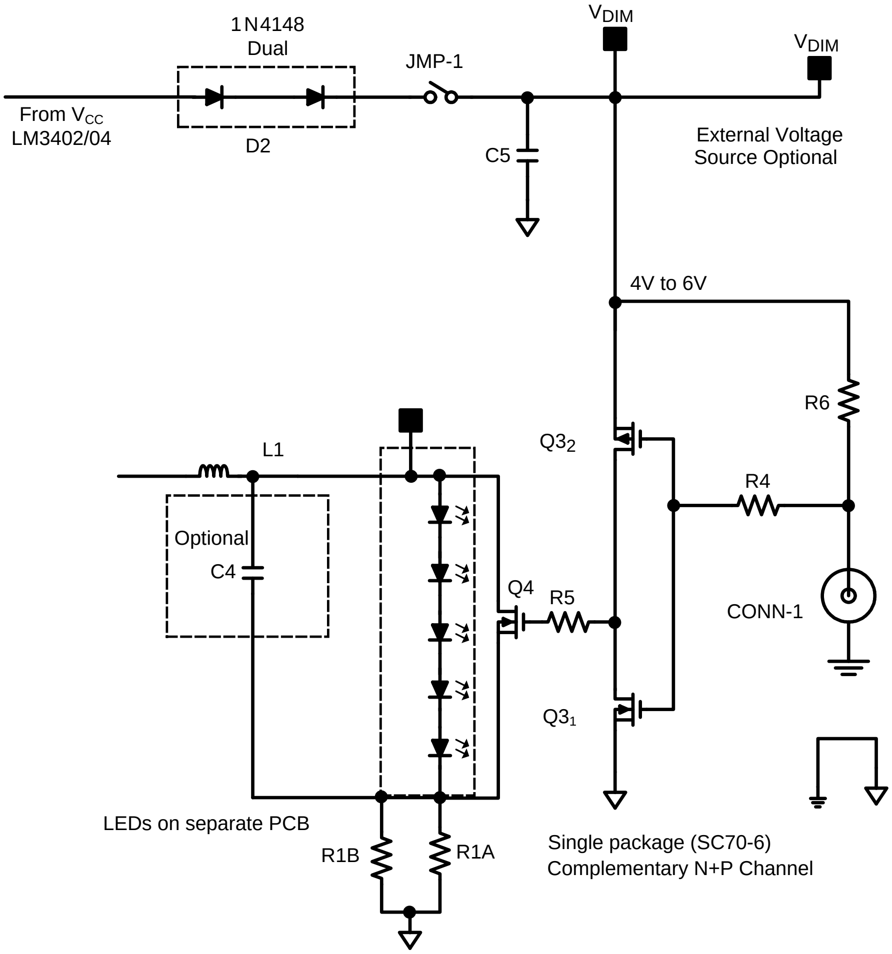


Figure 11. t_D and t_{SU} (DIM Pin)

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.



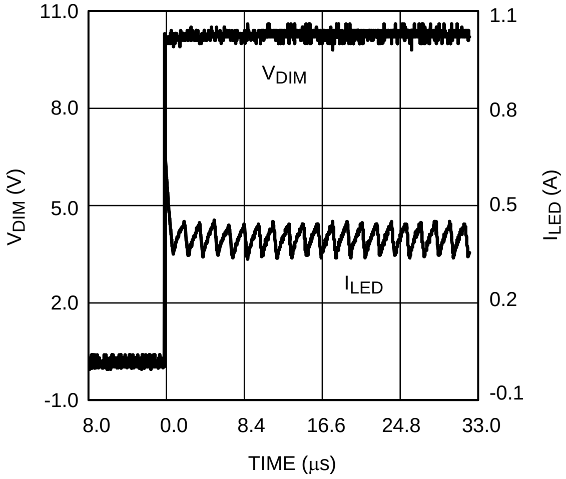


Figure 12. V_{IN} = 24V, 3 series LEDs @ 400mA

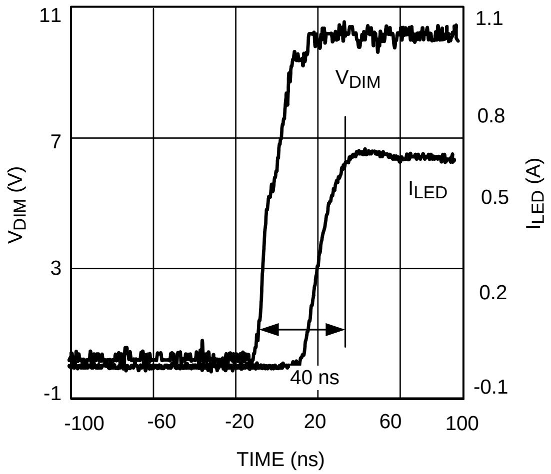


Figure 13. $t_D + t_{SU}$ Graph

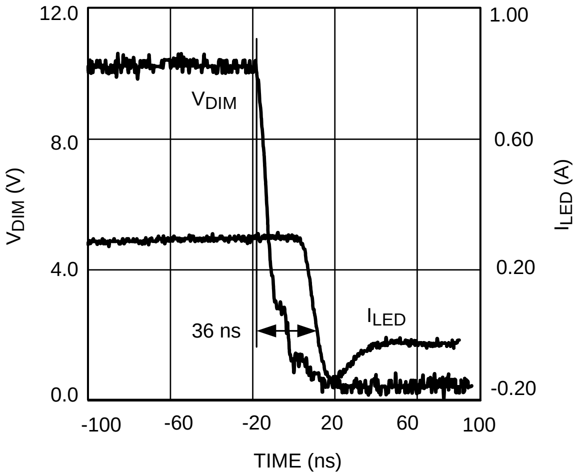


Figure 14. $t_D + t_{SD}$ Graph

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}:

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

t_{ON} equation becomes:

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

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.

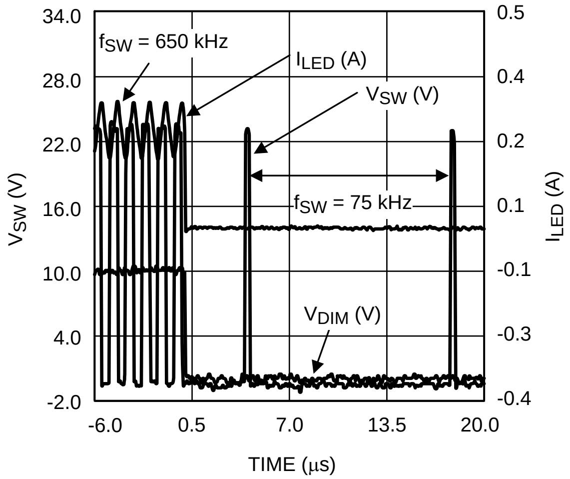


Figure 15. Improved Avg I_{LED} Circuit + Fast Dimming

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).

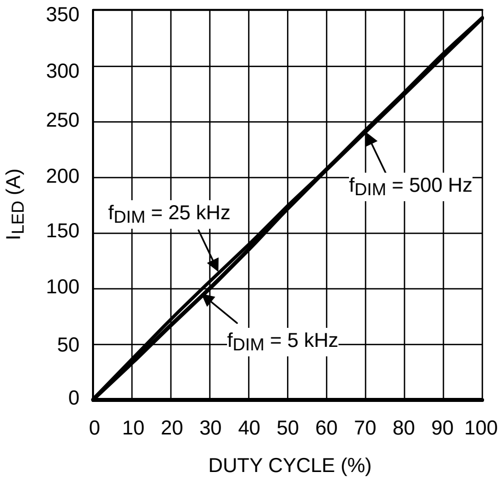


Figure 16. Linearity With Fast Dimming

18 LM3404 Improved ILED Average and Fast Dimming Demonstration Board

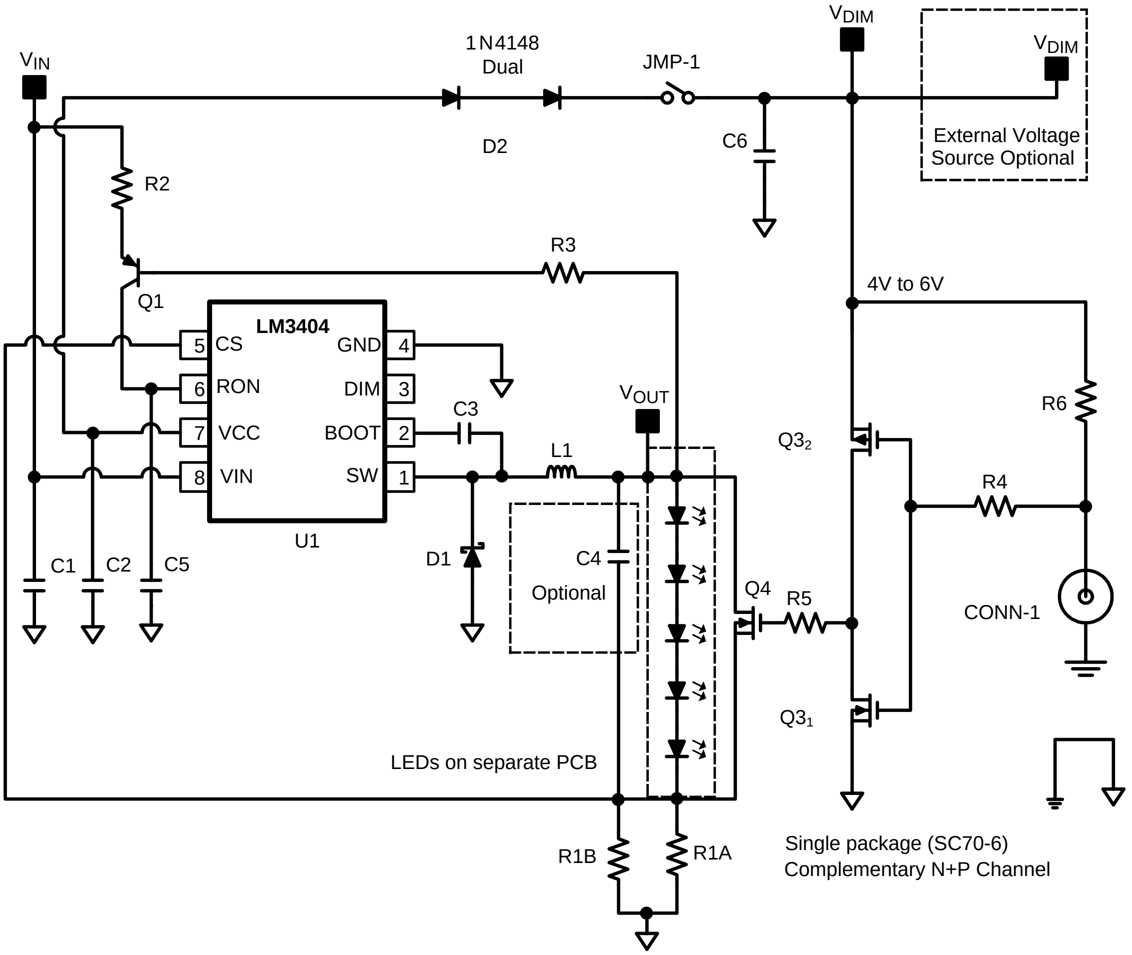
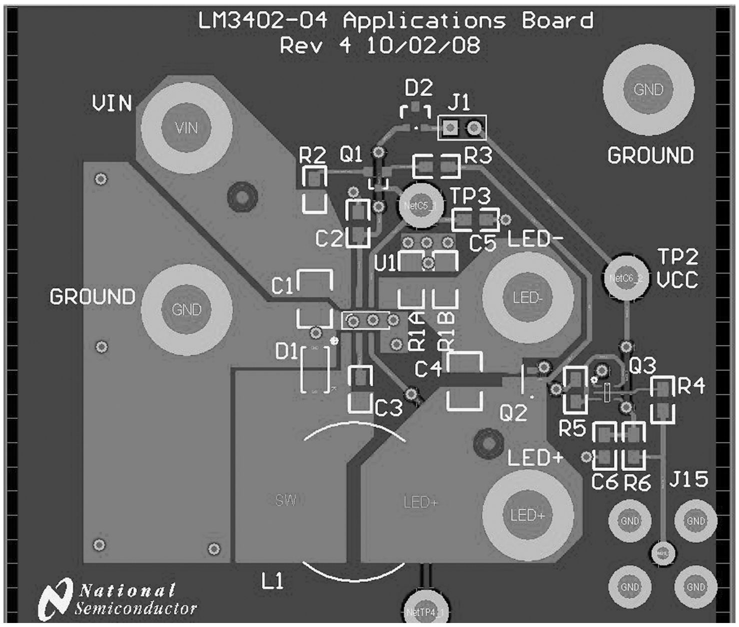


Figure 17. V_{IN} = 9V to 18V, I_{LED} = 700 mA, 3 x 3.4V White LED Strings (f_{SW} ≅ 500 kHz)

19 Bill of Materials

Part ID	Part Value	Mfg	Part Number
U1	1A Buck LED Driver SO PowerPAD pkg	NSC	LM3404
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	0.62Ω 1% 0.25W 1206	ROHM	MCR18EZHFLR620
R2	47.5 kΩ 1%	Vishay	CRCW08054752F
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
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	50Ω BNC	Amphenol	112538

20 Layout



STANDARD TERMS FOR EVALUATION MODULES

1. *Delivery:* TI delivers TI evaluation boards, kits, or modules, including any accompanying demonstration software, components, and/or documentation which may be provided together or separately (collectively, an “EVM” or “EVMs”) to the User (“User”) in accordance with the terms set forth herein. User's acceptance of the EVM is expressly subject to the following terms.
   1.1 EVMs are intended solely for product or software developers for use in a research and development setting to facilitate feasibility evaluation, experimentation, or scientific analysis of TI semiconductors products. EVMs have no direct function and are not finished products. EVMs shall not be directly or indirectly assembled as a part or subassembly in any finished product. For clarification, any software or software tools provided with the EVM (“Software”) shall not be subject to the terms and conditions set forth herein but rather shall be subject to the applicable terms that accompany such Software

   1.2 EVMs are not intended for consumer or household use. EVMs may not be sold, sublicensed, leased, rented, loaned, assigned, or otherwise distributed for commercial purposes by Users, in whole or in part, or used in any finished product or production system.

2 *Limited Warranty and Related Remedies/Disclaimers*:

   2.1 These terms do not apply to Software. The warranty, if any, for Software is covered in the applicable Software License Agreement.

   2.2 TI warrants that the TI EVM will conform to TI's published specifications for ninety (90) days after the date TI delivers such EVM to User. Notwithstanding the foregoing, TI shall not be liable for a nonconforming EVM if (a) the nonconformity was caused by neglect, misuse or mistreatment by an entity other than TI, including improper installation or testing, or for any EVMs that have been altered or modified in any way by an entity other than TI, (b) the nonconformity resulted from User's design, specifications or instructions for such EVMs or improper system design, or (c) User has not paid on time. Testing and other quality control techniques are used to the extent TI deems necessary. TI does not test all parameters of each EVM. User's claims against TI under this Section 2 are void if User fails to notify TI of any apparent defects in the EVMs within ten (10) business days after delivery, or of any hidden defects with ten (10) business days after the defect has been detected.

   2.3 TI's sole liability shall be at its option to repair or replace EVMs that fail to conform to the warranty set forth above, or credit User's account for such EVM. TI's liability under this warranty shall be limited to EVMs that are returned during the warranty period to the address designated by TI and that are determined by TI not to conform to such warranty. If TI elects to repair or replace such EVM, TI shall have a reasonable time to repair such EVM or provide replacements. Repaired EVMs shall be warranted for the remainder of the original warranty period. Replaced EVMs shall be warranted for a new full ninety (90) day warranty period.

WARNING

Evaluation Kits are intended solely for use by technically qualified, professional electronics experts who are familiar with the dangers and application risks associated with handling electrical mechanical components, systems, and subsystems.

User shall operate the Evaluation Kit within TI’s recommended guidelines and any applicable legal or environmental requirements as well as reasonable and customary safeguards. Failure to set up and/or operate the Evaluation Kit within TI’s recommended guidelines may result in personal injury or death or property damage. Proper set up entails following TI’s instructions for electrical ratings of interface circuits such as input, output and electrical loads.

NOTE:

EXPOSURE TO ELECTROSTATIC DISCHARGE (ESD) MAY CAUSE DEGREDATION OR FAILURE OF THE EVALUATION KIT; TI RECOMMENDS STORAGE OF THE EVALUATION KIT IN A PROTECTIVE ESD BAG.

3 *Regulatory Notices:*

3.1 *United States*

3.1.1 *Notice applicable to EVMs not FCC-Approved:*

FCC NOTICE: This kit is designed to allow product developers to evaluate electronic components, circuitry, or software associated with the kit to determine whether to incorporate such items in a finished product and software developers to write software applications for use with the end product. This kit is not a finished product and when assembled may not be resold or otherwise marketed unless all required FCC equipment authorizations are first obtained. Operation is subject to the condition that this product not cause harmful interference to licensed radio stations and that this product accept harmful interference. Unless the assembled kit is designed to operate under part 15, part 18 or part 95 of this chapter, the operator of the kit must operate under the authority of an FCC license holder or must secure an experimental authorization under part 5 of this chapter.

3.1.2 *For EVMs annotated as FCC – FEDERAL COMMUNICATIONS COMMISSION Part 15 Compliant:*

CAUTION

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

FCC Interference Statement for Class A EVM devices

NOTE: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

FCC Interference Statement for Class B EVM devices

NOTE: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- *Reorient or relocate the receiving antenna.*
- *Increase the separation between the equipment and receiver.*
- *Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.*
- *Consult the dealer or an experienced radio/TV technician for help.*

3.2 *Canada*

3.2.1 *For EVMs issued with an Industry Canada Certificate of Conformance to RSS-210 or RSS-247*

Concerning EVMs Including Radio Transmitters:

This device complies with Industry Canada license-exempt RSSs. Operation is subject to the following two conditions:

(1) this device may not cause interference, and (2) this device must accept any interference, including interference that may cause undesired operation of the device.

Concernant les EVMs avec appareils radio:

Le présent appareil est conforme aux CNR d'Industrie Canada applicables aux appareils radio exempts de licence. L'exploitation est autorisée aux deux conditions suivantes: (1) l'appareil ne doit pas produire de brouillage, et (2) l'utilisateur de l'appareil doit accepter tout brouillage radioélectrique subi, même si le brouillage est susceptible d'en compromettre le fonctionnement.

Concerning EVMs Including Detachable Antennas:

Under Industry Canada regulations, this radio transmitter may only operate using an antenna of a type and maximum (or lesser) gain approved for the transmitter by Industry Canada. To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that necessary for successful communication. This radio transmitter has been approved by Industry Canada to operate with the antenna types listed in the user guide with the maximum permissible gain and required antenna impedance for each antenna type indicated. Antenna types not included in this list, having a gain greater than the maximum gain indicated for that type, are strictly prohibited for use with this device.

Concernant les EVMs avec antennes détachables

Conformément à la réglementation d'Industrie Canada, le présent émetteur radio peut fonctionner avec une antenne d'un type et d'un gain maximal (ou inférieur) approuvé pour l'émetteur par Industrie Canada. Dans le but de réduire les risques de brouillage radioélectrique à l'intention des autres utilisateurs, il faut choisir le type d'antenne et son gain de sorte que la puissance isotrope rayonnée équivalente (p.i.r.e.) ne dépasse pas l'intensité nécessaire à l'établissement d'une communication satisfaisante. Le présent émetteur radio a été approuvé par Industrie Canada pour fonctionner avec les types d'antenne énumérés dans le manuel d’usage et ayant un gain admissible maximal et l'impédance requise pour chaque type d'antenne. Les types d'antenne non inclus dans cette liste, ou dont le gain est supérieur au gain maximal indiqué, sont strictement interdits pour l'exploitation de l'émetteur

3.3 *Japan*

3.3.1 *Notice for EVMs delivered in Japan:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_01.page 日本国内に輸入される評価用キット、ボードについては、次のところをご覧ください。

https://www.ti.com/ja-jp/legal/notice-for-evaluation-kits-delivered-in-japan.html

3.3.2 *Notice for Users of EVMs Considered “Radio Frequency Products” in Japan:* EVMs entering Japan may not be certified by TI as conforming to Technical Regulations of Radio Law of Japan.

If User uses EVMs in Japan, not certified to Technical Regulations of Radio Law of Japan, User is required to follow the instructions set forth by Radio Law of Japan, which includes, but is not limited to, the instructions below with respect to EVMs (which for the avoidance of doubt are stated strictly for convenience and should be verified by User):

1. Use EVMs in a shielded room or any other test facility as defined in the notification #173 issued by Ministry of Internal Affairs and Communications on March 28, 2006, based on Sub-section 1.1 of Article 6 of the Ministry’s Rule for Enforcement of Radio Law of Japan,
2. Use EVMs only after User obtains the license of Test Radio Station as provided in Radio Law of Japan with respect to EVMs, or
3. Use of EVMs only after User obtains the Technical Regulations Conformity Certification as provided in Radio Law of Japan with respect to EVMs. Also, do not transfer EVMs, unless User gives the same notice above to the transferee. Please note that if User does not follow the instructions above, User will be subject to penalties of Radio Law of Japan.

【無線電波を送信する製品の開発キットをお使いになる際の注意事項】 開発キットの中には技術基準適合証明を受けていないものがあります。 技術適合証明を受けていないもののご使用に際しては、電波法遵守のため、以下のいずれかの措置を取っていただく必要がありますのでご注意ください。

1. 電波法施行規則第6条第1項第1号に基づく平成18年3月28日総務省告示第173号で定められた電波暗室等の試験設備でご使用いただく。
2. 実験局の免許を取得後ご使用いただく。
3. 技術基準適合証明を取得後ご使用いただく。

なお、本製品は、上記の「ご使用にあたっての注意」を譲渡先、移転先に通知しない限り、譲渡、移転できないものとします。

上記を遵守頂けない場合は、電波法の罰則が適用される可能性があることをご留意ください。 日本テキサス･インスツルメンツ株式会社
東京都新宿区西新宿６丁目２４番１号
西新宿三井ビル

3.3.3 *Notice for EVMs for Power Line Communication:* Please see http://www.tij.co.jp/lsds/ti_ja/general/eStore/notice_02.page

電力線搬送波通信についての開発キットをお使いになる際の注意事項については、次のところをご覧ください。https://www.ti.com/ja-jp/legal/notice-for-evaluation-kits-for-power-line-communication.html

3.4 *European Union*

3.4.1 *For EVMs subject to EU Directive 2014/30/EU (Electromagnetic Compatibility Directive)*:

This is a class A product intended for use in environments other than domestic environments that are connected to a low-voltage power-supply network that supplies buildings used for domestic purposes. In a domestic environment this product may cause radio interference in which case the user may be required to take adequate measures.

4 *EVM Use Restrictions and Warnings:*

4.1 EVMS ARE NOT FOR USE IN FUNCTIONAL SAFETY AND/OR SAFETY CRITICAL EVALUATIONS, INCLUDING BUT NOT LIMITED TO EVALUATIONS OF LIFE SUPPORT APPLICATIONS.

4.2 User must read and apply the user guide and other available documentation provided by TI regarding the EVM prior to handling or using the EVM, including without limitation any warning or restriction notices. The notices contain important safety information related to, for example, temperatures and voltages.

4.3 *Safety-Related Warnings and Restrictions:*

4.3.1 User shall operate the EVM within TI's recommended specifications and environmental considerations stated in the user guide, other available documentation provided by TI, and any other applicable requirements and employ reasonable and customary safeguards. Exceeding the specified performance ratings and specifications (including but not limited to input and output voltage, current, power, and environmental ranges) for the EVM may cause personal injury or death, or property damage. If there are questions concerning performance ratings and specifications, User should contact a TI field representative prior to connecting interface electronics including input power and intended loads. Any loads applied outside of the specified output range may also result in unintended and/or inaccurate operation and/or possible permanent damage to the EVM and/or interface electronics. Please consult the EVM user guide prior to connecting any load to the EVM output. If there is uncertainty as to the load specification, please contact a TI field representative. During normal operation, even with the inputs and outputs kept within the specified allowable ranges, some circuit components may have elevated case temperatures. These components include but are not limited to linear regulators, switching transistors, pass transistors, current sense resistors, and heat sinks, which can be identified using the information in the associated documentation. When working with the EVM, please be aware that the EVM may become very warm.

4.3.2 EVMs are intended solely for use by technically qualified, professional electronics experts who are familiar with the dangers and application risks associated with handling electrical mechanical components, systems, and subsystems. User assumes all responsibility and liability for proper and safe handling and use of the EVM by User or its employees, affiliates, contractors or designees. User assumes all responsibility and liability to ensure that any interfaces (electronic and/or mechanical) between the EVM and any human body are designed with suitable isolation and means to safely limit accessible leakage currents to minimize the risk of electrical shock hazard. User assumes all responsibility and liability for any improper or unsafe handling or use of the EVM by User or its employees, affiliates, contractors or designees.

4.4 User assumes all responsibility and liability to determine whether the EVM is subject to any applicable international, federal, state, or local laws and regulations related to User's handling and use of the EVM and, if applicable, User assumes all responsibility and liability for compliance in all respects with such laws and regulations. User assumes all responsibility and liability for proper disposal and recycling of the EVM consistent with all applicable international, federal, state, and local requirements.

5. *Accuracy of Information:* To the extent TI provides information on the availability and function of EVMs, TI attempts to be as accurate as possible. However, TI does not warrant the accuracy of EVM descriptions, EVM availability or other information on its websites as accurate, complete, reliable, current, or error-free.

6. *Disclaimers:*

6.1 EXCEPT AS SET FORTH ABOVE, EVMS AND ANY MATERIALS PROVIDED WITH THE EVM (INCLUDING, BUT NOT LIMITED TO, REFERENCE DESIGNS AND THE DESIGN OF THE EVM ITSELF) ARE PROVIDED "AS IS" AND "WITH ALL FAULTS." TI DISCLAIMS ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, REGARDING SUCH ITEMS, INCLUDING BUT NOT LIMITED TO ANY EPIDEMIC FAILURE WARRANTY OR IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF ANY THIRD PARTY PATENTS, COPYRIGHTS, TRADE SECRETS OR OTHER INTELLECTUAL PROPERTY RIGHTS.

6.2 EXCEPT FOR THE LIMITED RIGHT TO USE THE EVM SET FORTH HEREIN, NOTHING IN THESE TERMS SHALL BE CONSTRUED AS GRANTING OR CONFERRING ANY RIGHTS BY LICENSE, PATENT, OR ANY OTHER INDUSTRIAL OR INTELLECTUAL PROPERTY RIGHT OF TI, ITS SUPPLIERS/LICENSORS OR ANY OTHER THIRD PARTY, TO USE THE EVM IN ANY FINISHED END-USER OR READY-TO-USE FINAL PRODUCT, OR FOR ANY INVENTION, DISCOVERY OR IMPROVEMENT, REGARDLESS OF WHEN MADE, CONCEIVED OR ACQUIRED.

7. *USER'S INDEMNITY OBLIGATIONS AND REPRESENTATIONS.* USER WILL DEFEND, INDEMNIFY AND HOLD TI, ITS LICENSORS AND THEIR REPRESENTATIVES HARMLESS FROM AND AGAINST ANY AND ALL CLAIMS, DAMAGES, LOSSES, EXPENSES, COSTS AND LIABILITIES (COLLECTIVELY, "CLAIMS") ARISING OUT OF OR IN CONNECTION WITH ANY HANDLING OR USE OF THE EVM THAT IS NOT IN ACCORDANCE WITH THESE TERMS. THIS OBLIGATION SHALL APPLY WHETHER CLAIMS ARISE UNDER STATUTE, REGULATION, OR THE LAW OF TORT, CONTRACT OR ANY OTHER LEGAL THEORY, AND EVEN IF THE EVM FAILS TO PERFORM AS DESCRIBED OR EXPECTED.

8. *Limitations on Damages and Liability:*
    - 8.1 *General Limitations*. IN NO EVENT SHALL TI BE LIABLE FOR ANY SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL, OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF THESE TERMS OR THE USE OF THE EVMS , REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. EXCLUDED DAMAGES INCLUDE, BUT ARE NOT LIMITED TO, COST OF REMOVAL OR REINSTALLATION, ANCILLARY COSTS TO THE PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES, RETESTING, OUTSIDE COMPUTER TIME, LABOR COSTS, LOSS OF GOODWILL, LOSS OF PROFITS, LOSS OF SAVINGS, LOSS OF USE, LOSS OF DATA, OR BUSINESS INTERRUPTION. NO CLAIM, SUIT OR ACTION SHALL BE BROUGHT AGAINST TI MORE THAN TWELVE (12) MONTHS AFTER THE EVENT THAT GAVE RISE TO THE CAUSE OF ACTION HAS OCCURRED.
    - 8.2 *Specific Limitations.* IN NO EVENT SHALL TI'S AGGREGATE LIABILITY FROM ANY USE OF AN EVM PROVIDED HEREUNDER, INCLUDING FROM ANY WARRANTY, INDEMITY OR OTHER OBLIGATION ARISING OUT OF OR IN CONNECTION WITH THESE TERMS, , EXCEED THE TOTAL AMOUNT PAID TO TI BY USER FOR THE PARTICULAR EVM(S) AT ISSUE DURING THE PRIOR TWELVE (12) MONTHS WITH RESPECT TO WHICH LOSSES OR DAMAGES ARE CLAIMED. THE EXISTENCE OF MORE THAN ONE CLAIM SHALL NOT ENLARGE OR EXTEND THIS LIMIT.

9. *Return Policy.* Except as otherwise provided, TI does not offer any refunds, returns, or exchanges. Furthermore, no return of EVM(s) will be accepted if the package has been opened and no return of the EVM(s) will be accepted if they are damaged or otherwise not in a resalable condition. If User feels it has been incorrectly charged for the EVM(s) it ordered or that delivery violates the applicable order, User should contact TI. All refunds will be made in full within thirty (30) working days from the return of the components(s), excluding any postage or packaging costs.

10. *Governing Law:* These terms and conditions shall be governed by and interpreted in accordance with the laws of the State of Texas, without reference to conflict-of-laws principles. User agrees that non-exclusive jurisdiction for any dispute arising out of or relating to these terms and conditions lies within courts located in the State of Texas and consents to venue in Dallas County, Texas. Notwithstanding the foregoing, any judgment may be enforced in any United States or foreign court, and TI may seek injunctive relief in any United States or foreign court.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you fully indemnify TI and its representatives against any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale, TI’s General Quality Guidelines, or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products. Unless TI explicitly designates a product as custom or customer-specified, TI products are standard, catalog, general purpose devices.

TI objects to and rejects any additional or different terms you may propose.

Copyright © 2026, Texas Instruments Incorporated

Last updated 10/2025