TI Designs

Using LDO for LED Control and Brightness Matching

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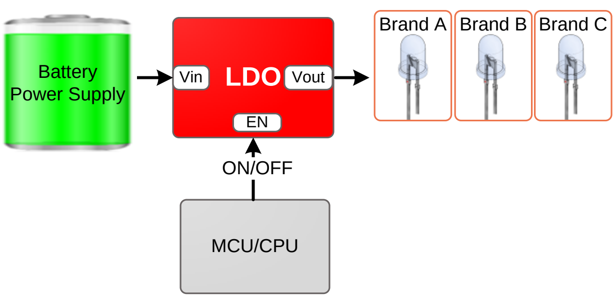
Design Resources

TIDA-00526	Design Folder
LP38693MPX-ADJ	Product Folder
TPD4E1U06	Product Folder

TI E2E™ Community

- Ask The Analog Experts
- Linear Regulators - Forum
- WEBENCH® Design Center

High level Block Diagram



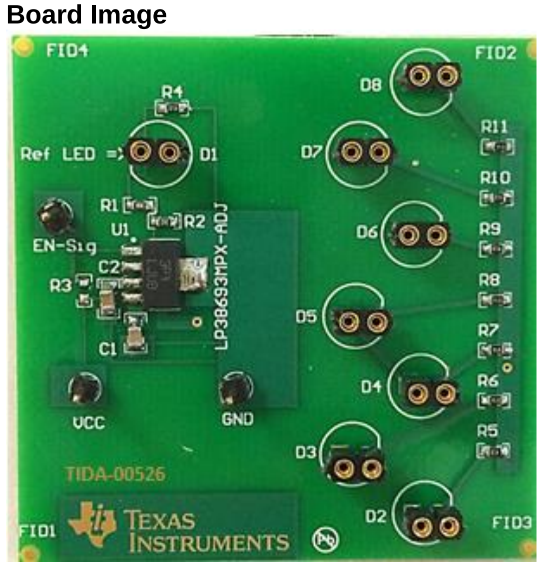
Design Features

- Cost optimized LED brightness matching solution
- Small foot print with few compensation components
- Tunable for a wide range of LED types
- Dimmable brightness control feature
- Enable/Disable feature

Featured Applications

- Battery-power devices
- Backlight
- Indicator LEDs
- Fun-lights for toys

Board Image



1 System description

This document describes how LDO can be used as a white LED continuous current source for consistent brightness. This design provides higher power efficiency and brightness matching than discrete solutions. All of this in an affordable, small foot print, and easy to implement design.

1.1 Design Overview

In todays market there is a wide range of applications that utilize white light emitting diodes (LED) for illumination, indication, decoration and many other applications. A known issue with white LEDs is that their I-V characteristics fluctuate from brand to brand and part to part. The variation in the current drawn by the LED is directly proportional with the luminous intensity or millicandela (mcd), which is the standard unit to measure brightness intensity. Having various LED suppliers and variation in the manufacturing process make it difficult to obtain consistent and satisfactory results using just a limiting resistor. If a passive circuitry is implemented the limiting resistor will have to be adjusted for each LED.

Brightness mismatch could be perceived by customers or users as a poorly made design. This issue can be avoided by implementing a constant current source to each LED using a lightning management unit like LP3952, however if the application requires to power multiple LEDs and cost is an obstacle a low cost, low dropout linear regulator like LP38693-ADJ can be implemented as a current controlled source which will do an excellent job of matching the brightness of the LEDs and controlling the light intensity.

This TI design provides all the design files and supporting documentation (schematic, layout, and test data).

1.2 Benefits

If cost is of great concern and the application is sensitive to noise created by power switchers a low noise, low cost, easy to implement low dropout linear (LDO) regulator is a great solution. LDOs offer a consistent current supply for color and brightness accuracy over the manufacturing life of the device. Furthermore, it will provide the following extra features to the system:

- High load/line transient regulation and high power supply rejection minimizes noise from source power.
- Small foot print with no need of bulk components like inductors or external FETs.
- Adjustable LDO output gives flexibility to tune the design for various types of LEDs.
- Enable/Disable capability will prolong battery operation.
- High current and low IQ maximizes battery life.
- Brightness dimming control via PWM.
- Fold-back current limiting.

2 Block Diagram

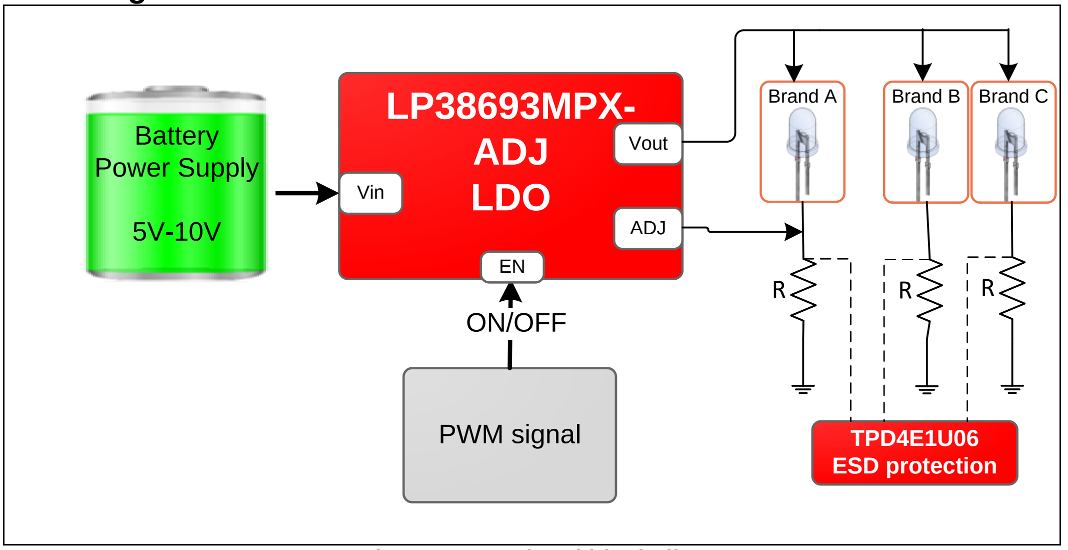


Figure 1 Functional block diagram

3 Component Selection

This LED brightness matching design features the following parts:

- LP38693MPX-ADJ : 500mA Low Dropout CMOS Linear Regulators with Adjustable Output Stable with Ceramic Output Cap.
- TPD4E1U06: Quad Channel High Speed ESD Protection Device
- LEDs: 3.5V Forward voltage white LEDs

3.1 LP38693MPX-ADJ

The LP38691/3-ADJ low dropout CMOS linear regulators provide 2.0% precision reference voltage, extremely low dropout voltage (250mV @ 500mA load current, V_{OUT} = 5V) and excellent AC performance utilizing ultra low ESR ceramic output capacitors.

The low thermal resistance of the WSON and SOT-223 packages allows the full operating current to be used even in high ambient temperature environments.

The use of a PMOS power transistor means that no DC base drive current is required to bias it allowing ground pin current to remain below 100 µA regardless of load current, input voltage, or operating temperature.

Alternative Adjustable output power LDOs:

- LP2951 (ADJ) not functional equivalent - wider Vin/Vout
- LP38501-ADJ not functional equivalent - Higher current supply
- LP38691-ADJ equivalent functionality -not enable/disable capability

For more alternatives visit ti.com/LDO

3.2 TPD4E1U06

The TPD4E1U06 is a quad channel unidirectional Transient Voltage Suppressor (TVS) based Electrostatic Discharge (ESD) protection diode with ultra low capacitance. This device can dissipate ESD strikes above the maximum level specified by the IEC 61000-4-2 international standard. Features ultra low leakage current of 10nA (max). Its 0.8-pF line capacitance makes it suitable for a wide range of applications.

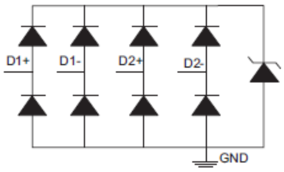


Figure 2 TPD4E1U06 Block Diagram

3.3 LEDs

The LEDs chosen for this design are from leading LED manufacturers. If more affordable LEDs from other manufactures are used then the brightness mismatch might be grater if they are driven with a passive circuitry.

3.3.1 LED Brand A

Brand: LUMEX
Reference number AND720HW

Table 1 LED Brand A

CHARACTERISTICS	SYMBOL	RATING TYPICAL	UNIT
Forward Current	IF	20	mA
Forward Voltage	VR	3.5	V
Package Type	Thru-Hole T1-3/4	5	mm
Luminous Intensity	LI	9000	mcd

3.3.2 LED Brand B

Brand: AND
Reference number SSL-LX5093UWC/G

Table 2 LED Brand B

CHARACTERISTICS	SYMBOL	RATING TYPICAL	UNIT
Forward Current	IF	20	mA
Forward Voltage	VR	3.5	V
Package Type	Thru-Hole T1-3/4	5	mm
Luminous Intensity	LI	11000	mcd

4 System Design Considerations and component selection

In order to have a consistent forward current (IF) across the set of LEDs the LP38693-ADJ LDO is used in a current regulation mode, dependent on one of the LEDs forward voltage drop. The LDO will source current to compensate for the forward voltage across the reference LED. This will allow the other non-matching LEDs connected in parallel to have a constant current flow equal to the reference LED forward current (FI).

This design drives eight LEDs four from brand A and four from brand B, their datasheet specifies a forward voltage drop of 3.5V at 20mA. The LP38693-ADJ is able to drive up to 24 LEDs at 20mA per LED

The design considerations on this section apply to the given parameters. If your design requires other parameters than the stated in this document, it is necessary to review the ratings on the datasheet of mentioned devices or consider using an alternative part from section 3 or perform an easy parametric search at www.ti.com/ldo

Table 3 Design Parameters

DESIGN PARAMETERS	VALUE
Input voltage	5.2V to 10V
Output voltage	5V
Maximum output current	500 mA
White LED forward voltage	3.5V

4.1 Input Voltage Considerations

The input voltage should be higher than the combine voltage of LDO dropout voltage (250mV), LED voltage drop and LED reference voltage (explained in section 4.3.1).

Minimum input voltage = V_{DO} +V_{LED}+V_{LED_REF} = 250mV+ 3.5V + 1.49V = 5.2V

An input capacitor of at least 1µF is required (ceramic recommended). The capacitor must be located not more than one centimeter from the input pin and returned to a clean analog ground.

4.2 Capacitor selection consideration

Input output capacitors are necessary for loop stability and eliminate high frequency noise; the following recommendations were taken into account:

- To ensure tolerance and variation with temperature X7R or X5R ceramic capacitors were used
- Input/output caps must be located less than 1cm from the input/output pins
- ± 20% tolerance of nominal over full operating ratings
- Output capacitor ESR must not exceed 100mΩ
- Output minimum capacitance of 1 µF
- Input minimum capacitance of 1 µF

4.3 Output voltage configuration

The LP38693-ADJ is an adjustable regulator; the output voltage is typically set by an external resistor divider at the adjustable pin.

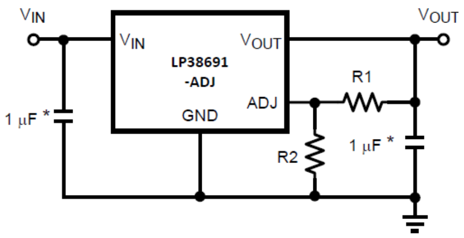


Figure 3 typical configuration

Equation 1 $\boldsymbol{Vout} = \boldsymbol{V_{ADJ}}^{*} \times (\mathbf{1} + \frac{\boldsymbol{R1}}{\boldsymbol{R2}})$

LP38693-ADJ datasheet specifies that V_{ADJ} is typically 1.25V from ADJ pin to ground

The typical model of setting the output voltage could not used in this design, because in order to match the brightness of the array of LEDs the LDO needs to monitor the forward current of one of the LEDs (Reference LED).

Various circuit configurations were assessed; the top two configurations were evaluated using the LP38693-ADJ low dropout regulator.

Circuit configuration A

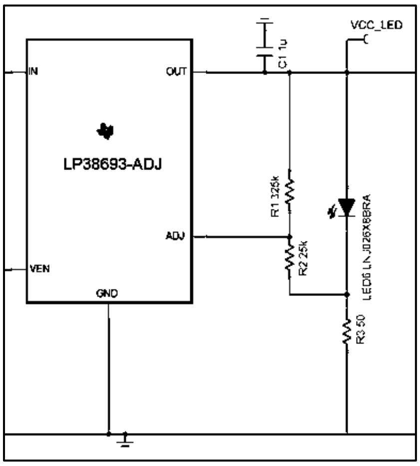


Figure 4 Circuit Configuration A

PROS:
Requires lower input voltage; the voltage divider at the ADJ pin permits a lower voltage drop at the biasing resistor R3 in this case.

CONS:
In this case the LP38693 takes more time to reach steady state and the output voltage accuracy is affected by minimal changes in the LED (i.e. LED rising temperature due to prolonged operation).

This approach works with most LDO architectures; however, it is recommended to check for stability before implementing design topology

Circuit configuration B

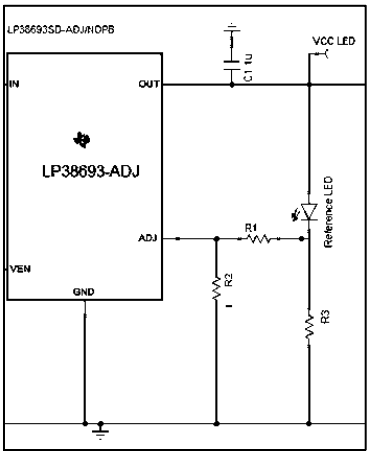


Figure 5 Circuit Configuration B

PROS:

The LDO reaches steady state faster than configuration A, and delivers a superior current matching among all the LEDs.

CONS:

Due to a higher voltage drop across R3 it requires higher input voltage than circuit B.

Next section will explain how to calculate the resistor values on configuration B.

4.3.1 Resistor value selection

LDO automatically adjust the output voltage to compensate for the voltage drop on the LED. The resistive network has to be adjusted to regulate the forward current of the LED.

Resistor R1, R2 and R3 on **Figure 5** determine the current across the LED. As a conservative approach 12KΩ was selected for R2 in order to meet the minimum load current requirement of 100uA; a maximum Ohmic value of 100kΩ is recommended for R2.
The voltage across R3 will define the LED current; a 100Ω was selected to simplify the calculations. An Ohmic value for R1 was calculated such as 2 volts are delivered across R3.
Equation 2 was used to determine the Ohmic value for R1.

Equation 2 $$\boldsymbol{R1} = \left(\frac{2}{V_{ADJ}} - 1\right) \times \boldsymbol{R2} = \left(\frac{2}{1.25} - 1\right) \times 12k\Omega = 7.2k\Omega$$

$V_{ADJ:}$ The datasheet specifies that The LDO develops a 1.25V reference voltage between the adjustable pin and ground (V_{ADJ} varies for other LDOs architectures).

Table 4 LDO Feedback network values

COMPONENT	VALUE (SMD-0603 1% STANDARD)
R1	7.32KΩ
R2	12kΩ
R3	100Ω

4.4 Safety

If the final product is intended to have the LEDs exposed to any possible source of electro static discharge (ESD), it is recommended to implement a voltage transient suppressor. The overvoltage and over current transients could totally damage the LEDs or it might permanent disturb their normal functionality.

The TPD4E1U06 with its low clamping voltage, ultra low leakage current, and tiny foot print makes it a great safety solution to avid failure due to ESD.

The ESD protection was not implemented in the evaluation module. To implement in your design just follow the following guidelines:

- The optimum placement is as close to the connector as possible.
  - EMI during an ESD event can couple from the trace being struck to other nearby unprotected traces, resulting in early system failures.
  - The PCB designer needs to minimize the possibility of EMI coupling by keeping any unprotected traces away from the protected traces which are between the TVS and the connector.
- Route the protected traces as straight as possible.
- Eliminate any sharp corners on the protected traces between the TVS and the connector by using rounded corners with the largest radii possible.
  - Electric fields tend to build up on corners, increasing EMI coupling.

5 Test setup and results

5.1 Passive circuit vs LDO constant current supply

Since LED brightness intensity is directly dependent on how much current it draws, we measured the voltage across the limiting resistor and calculated the current through the LEDs. Two test setups were made to quantify the benefits of using and LDO over a fix bias voltage with a limiting resistor:
The first setup used a fix voltage supply and a simple limiting resistor to limit the current drawn by the array of eight LEDs.
The second setup used the same array of eight LEDs, but in this case the current through the LEDs was regulated by a LDO. Then the results from the two scenarios were compared to determine which setup yield a better LED current matching. A tighter LED current matching means that the brightness intensity will be better matched among the array of LEDs.

Table 5 Test Equipment

EQUIPMENT	DEVICE NUMBER	FUNCTION
Voltage supply	Agilent E3631A	Constant voltage supply $5.2V_{DC}$ For uniformity consistent power supply was used instead of a battery.
Digital Voltmeter	Agilent 34401A	Used to measure voltage across the limiting resistor in order to calculate the LED forward current

5.1.1 Passive circuit test setup and results

From the information on the datasheet of the LEDs we take the assumption that the typical forward voltage (LED_{VF}) is 3.5V at 20mA. Taking 3.5V as reference the required limiting resistance (R_{LIM}) was calculated with Equation 3.

Equation 3

$$R_{LIM} = \frac{Power\ Supply\ voltage - LED_{VF}}{LED_{IF}} = \frac{5.2V - 3.5V}{20mA} = 85\Omega$$

Four LEDs from brand **A** and four LEDs from brand **B** were connected in parallel from the continuous voltage source.

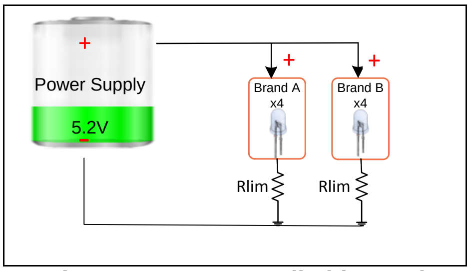


Figure 6 Test Setup - limiting resistor

The LED forward current on **Table 6** and **Table 7** was calculated by measuring the voltage across the limiting resistor and using ohms law to calculate the LED forward current.

Table 6 Limiting resistor Test results

LED Brand #umber	Limiting resistor [Ω]	Voltage across R_{LIM} [Volts]	LED forward current [mA]	Average	Standard deviation
A#1	82	1.98	24.09	24.05	0.38
A#2	82	2.02	24.59		
A#3	82	1.95	23.80		
A#4	82	1.95	23.74		
B#1	82	1.87	22.78	22.96	0.29
B#2	82	1.87	22.80		
B#3	82	1.87	22.85		
B#4	82	1.92	23.39		
			Standard Deviation	0.776	
			Average		0.34

The total input current for the passive circuit was 189mA and the input voltage was 5.2V, which yields a total input power of 982.8mW

5.1.2 LDO constant current supply – test setup and results

Figure 7 represents the test setup for the constant current supply circuit. All the resistor values were calculated using the equations in section 4.3.1. It was assume that the forward voltage of the LEDs is 3.5V at a 20mA forward current.

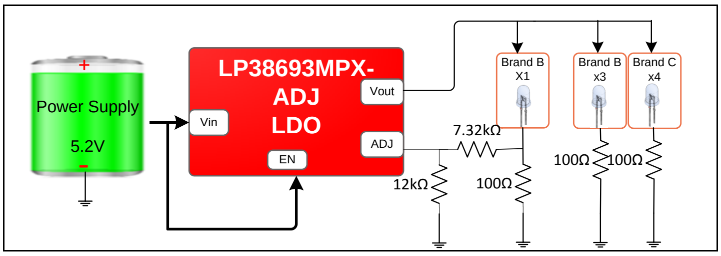


Figure 7 Test setup – LDO Current source

Table 7 LDO Constant current supply - test results

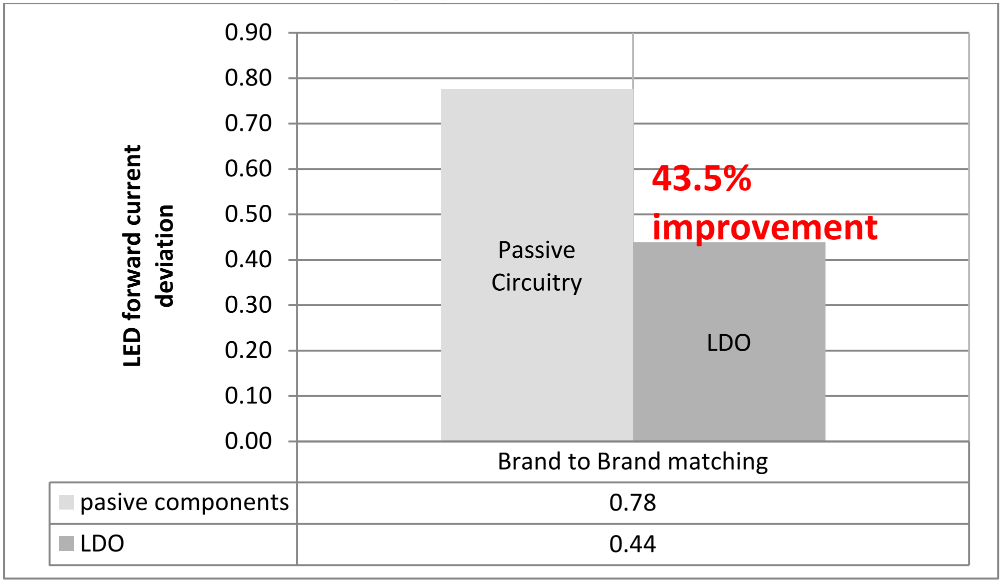
LED BRAND #NUMBER	LIMITING RESISTOR [Ω]	VOLTAGE ACROSS R_{LIM} [VOLTS]	LED FORWARD CURRENT [MA]	AVERAGE	STANDARD DEVIATION
A#1	100	1.99	19.91	19.87	0.33
A#2	100	2.03	20.3		
A#3	100	1.97	19.74		
A#4	100	1.95	19.52		
B#1	100	1.91	19.13	19.25	0.22
B#2	100	1.91	19.13		
B#3	100	1.92	19.16		
B#4	100	1.96	19.57		
			Standard Deviation	0.438	
			Average		0.27

The total input current of the LDO is 159mA and the input voltage is 5.2V, which yields a total input power of 826.8mW

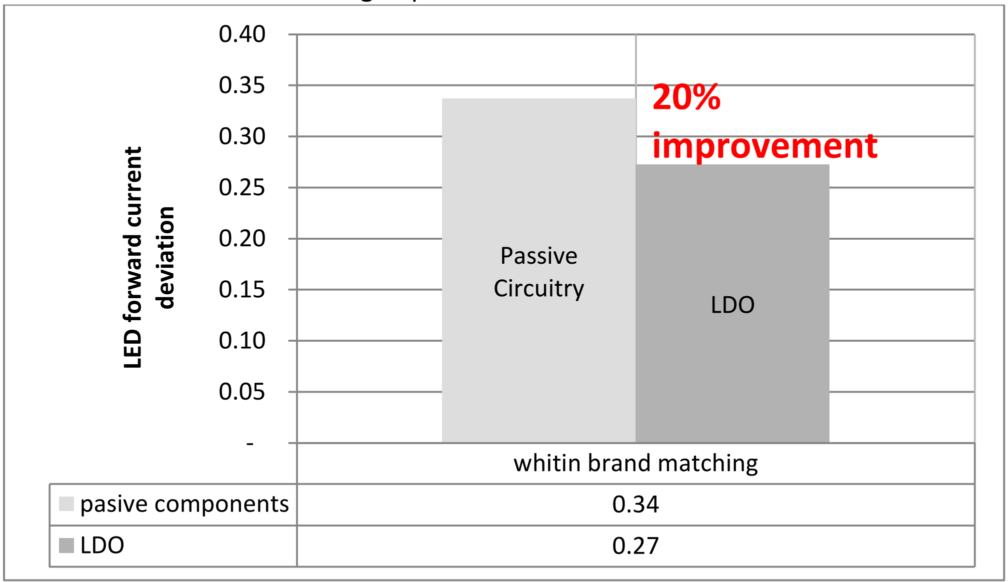
5.1.3 Comparison

By comparing **Table 6** and **Table 7** we can conclude the following advantages of using LDO over passive circuitry:

- Brand to brand current matching improved by 43.5%



- Within brand current matching improvement of 20%



- LDO is more accurate at delivering the desired LED forward current of 20mA. Passive circuitry delivered an average of 23.51mA when the LDO did a better job with an average of 19.56mA forward current per LED.
- The LDO prolongs battery operation by using <u>156mW</u> less than the passive circuit approach.
  LDO total input power = V_{IN} x I_{IN} = 5.2V X 63mA = 826.8mW
  Passive circuit total input power =V_{IN} x I_{IN} = 5.2V X 91mA = 982.8mW

5.2 Dimmable brightness

This test demonstrates the ability of dimming LED brightness by applying a PWM signal at the enable pin of the LDO. This dimmable ability is directly related with the architecture design of the enable feature it is necessary to verify functionality on the bench if other LDO, PWM frequency, or PWM voltage is intended to be used for a similar design.

The signal at the enable pin must not go lower than ground potential or higher than Vin. The enable pin has no internal pull-up or pull-down, it must never be left floating otherwise it will have an undetermined behavior.

Table 8 Equipment used in dimmable brightness test

TEST EQUIPMENT	PART NUMBER	FUNCTION
Oscilloscope	Agilent MSO7034B	Measure the waveform signals of the system
Voltage supply	Agilent E3631A	Supply DC voltage
Function generator (square signal generator)	Agilent 33220A	Signal: Square wave Frequency: 1KHz High level: 2.5 Low level: 0V Duty cycle: 20% - 80%

A square signal with variable duty cycle was applied to the enable pin of the LP38693-ADJ.**Figure 8** represents the dimmable brightness test setup, the feedback network components were calculated using the equation in section 4.3.1

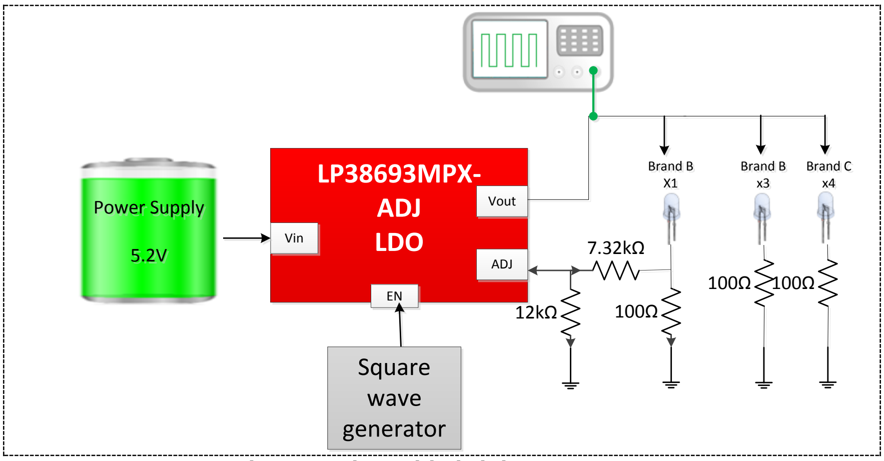


Figure 8 Dimmable brightness test setup

The LED brightness softens when the current through the LED drops. **Table 9** shows how the LEDs forward current drops by adjusting the duty cycle of the input signal on the enable pin.

Table 9 Dimmable Brightness Test Results

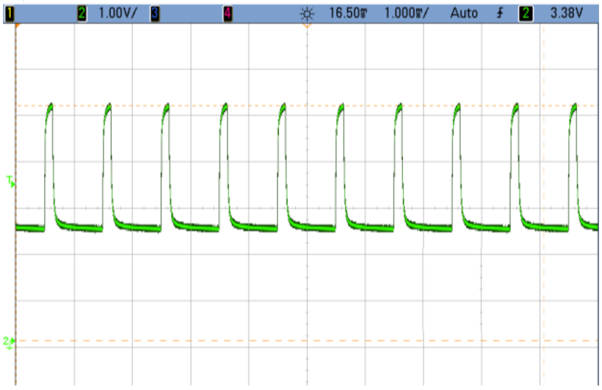
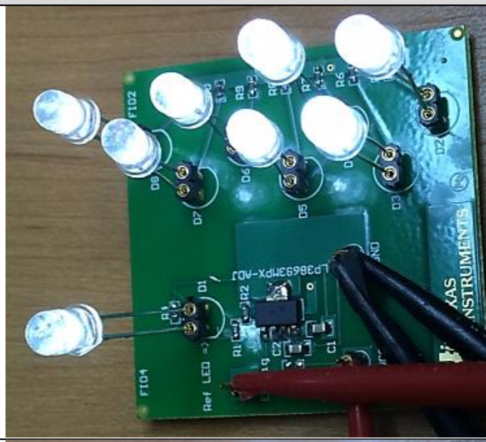
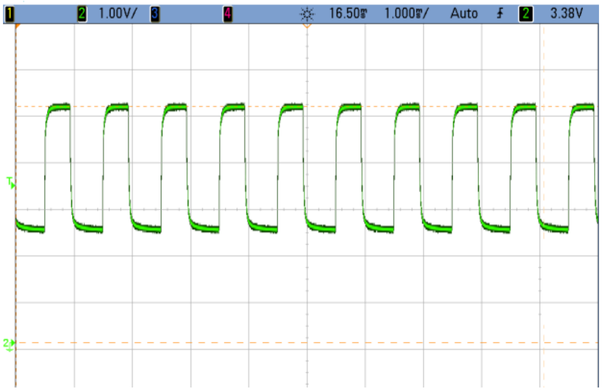
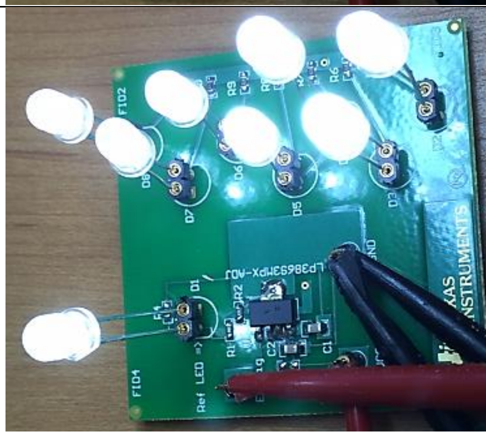
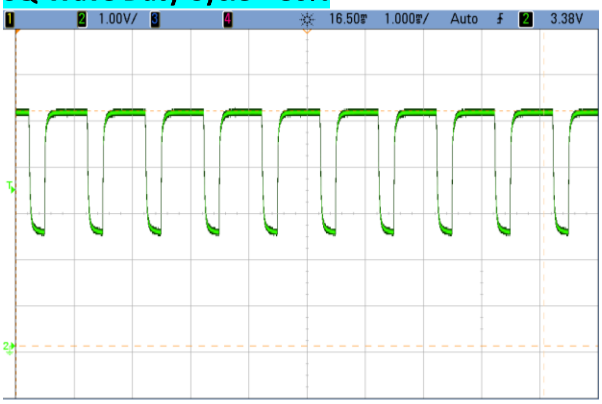
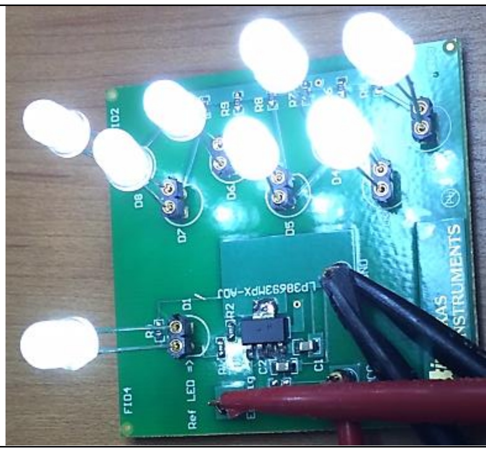
DUTY CYCLE	VOLTAGE ACROSS R_{LIM} [VOLTS]	LED FORWARD CURRENT [AMPS]
20%	60mV	0.6 mA
50%	112mV	1.12mA
80%	1.06V	10.6mA

Brightness is directly related with LED forward current. **Table 10** shows a comparison between the pulsed output voltage charging and discharging the output cap and LED brightness.

Test setup:

DC coupled probe capture waveform at V_{OUT} PIN
Time division: 2ms\DIV time division
Voltage: 2V\DIV

Table 10 Dimmable Brightness Comparison Test Results (Part 2)

SCOPE SHOTS AT V_{OUT} PIN	BOARD PICTURE
SQ-Wave Duty Cycle = 20% 	
SQ-Wave Duty Cycle = 50% 	
SQ-Wave Duty Cycle = 80% 	

6 Design Files

6.1 Schematics

To download the Schematics for each board, see the design files at http://www.ti.com/tool/TIDA-00526

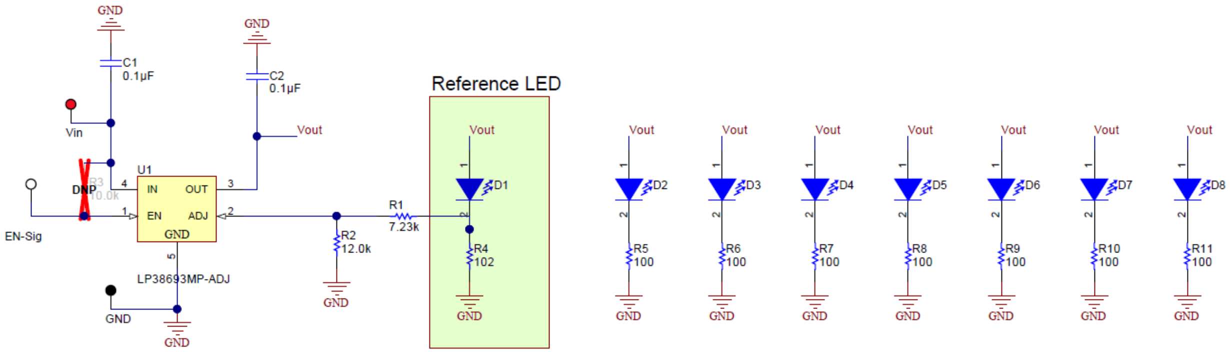


Figure 9: Schematic

6.2 Bill of Materials

To download the Bill of Materials for each board, see the design files at http://www.ti.com/tool/TIDA-00526

Table 11: Bill of Materials

Item #	Designator	Quantity	Value	Part Number	Manufacturer	Description	Package Reference
1	!PCB	1		TIDA-00526	Any	Printed Circuit Board	
2	C1, C2	2	0.1uF	C0805C104K3RACTU	Kemet	CAP, CERM, 0.1 µF, 25 V, +/-10%, X7R, 0805	0805
3	D1, D2, D3, D4, D5, D6, D7, D8	8		C503D-WAN-CCBDB232	CREE	LED, White, TH	
4	EN-Sig	1	White	5002	Keystone	Test Point, Miniature, White, TH	White Miniature Test point
5	FID1, FID2, FID3, FID4	4		N/A	N/A	Fiducial mark. There is nothing to buy or mount.	Fiducial
6	GND	1	Black	5001	Keystone	Test Point, Miniature, Black, TH	Black Miniature Test point
7	H1, H2, H3, H4	4		SJ61A1	3M	Bumpon, Cylindrical, 0.312 X 0.200, Black	Black Bumpon
8	R1	1	7.23k	RT0603DRE077K23L	Yageo America	RES, 7.23 k, 0.5%, 0.1 W, 0603	0603
9	R2	1	12.0k	RC0603FR-0712KL	Yageo America	RES, 12.0 k, 1%, 0.1 W, 0603	0603
10	R4	1	102	CRCW0603102RFKEA	Vishay-Dale	RES, 102, 1%, 0.1 W, 0603	0603
11	R5, R6, R7, R8, R9, R10, R11	7	100	RC0603FR-07100RL	Yageo America	RES, 100, 1%, 0.1 W, 0603	0603
12	U1	1		LP38693MP-ADJ	Texas Instruments	500mA Low Dropout CMOS Linear Regulators, 5-pin SOT-223	MP05A
13	Vin	1	Red	5000	Keystone	Test Point, Miniature, Red, TH	Red Miniature Test point
14	R3	0	10.0k	CRCW060310K0FKEA	Vishay-Dale	RES, 10.0 k, 1%, 0.1 W, 0603	0603

6.2.1 Layout Prints

To download the Layout Prints for each board, see the design files at
http://www.ti.com/tool/TIDA-00526

Figure 10 Top Silkscreen

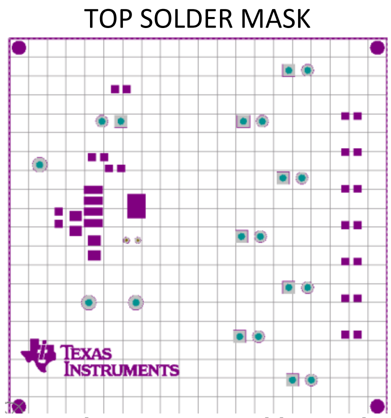


Figure 11 Top Solder Mask

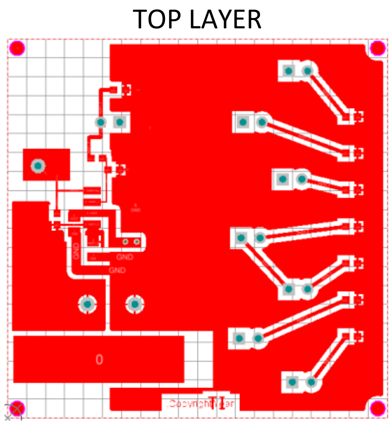


Figure 12 Top Layer

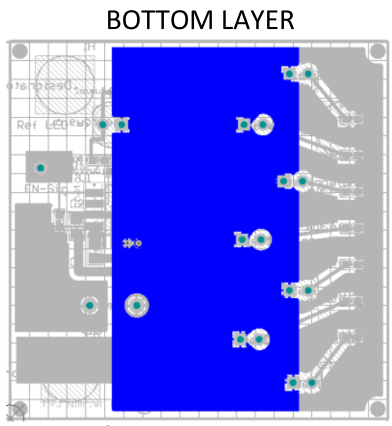


Figure 13 Bottom Layer

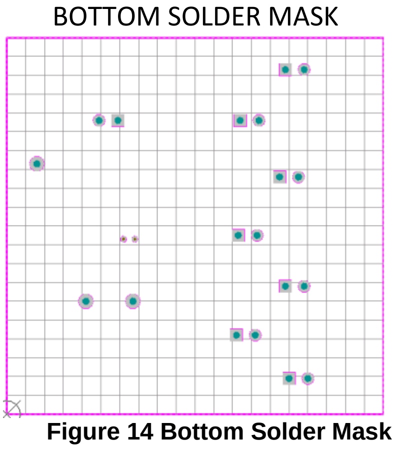


Figure 14 Bottom Solder Mask

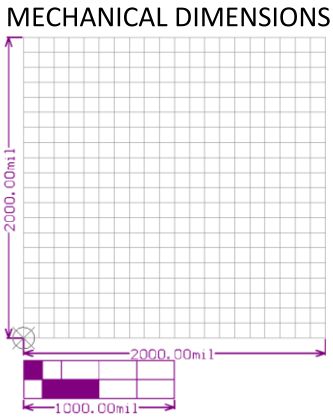


Figure 15 Mechanical Dimensions

6.3 Altium Designer Project

To download the Altium project files for each board, see the design files at
http://www.ti.com/tool/TIDA-00526

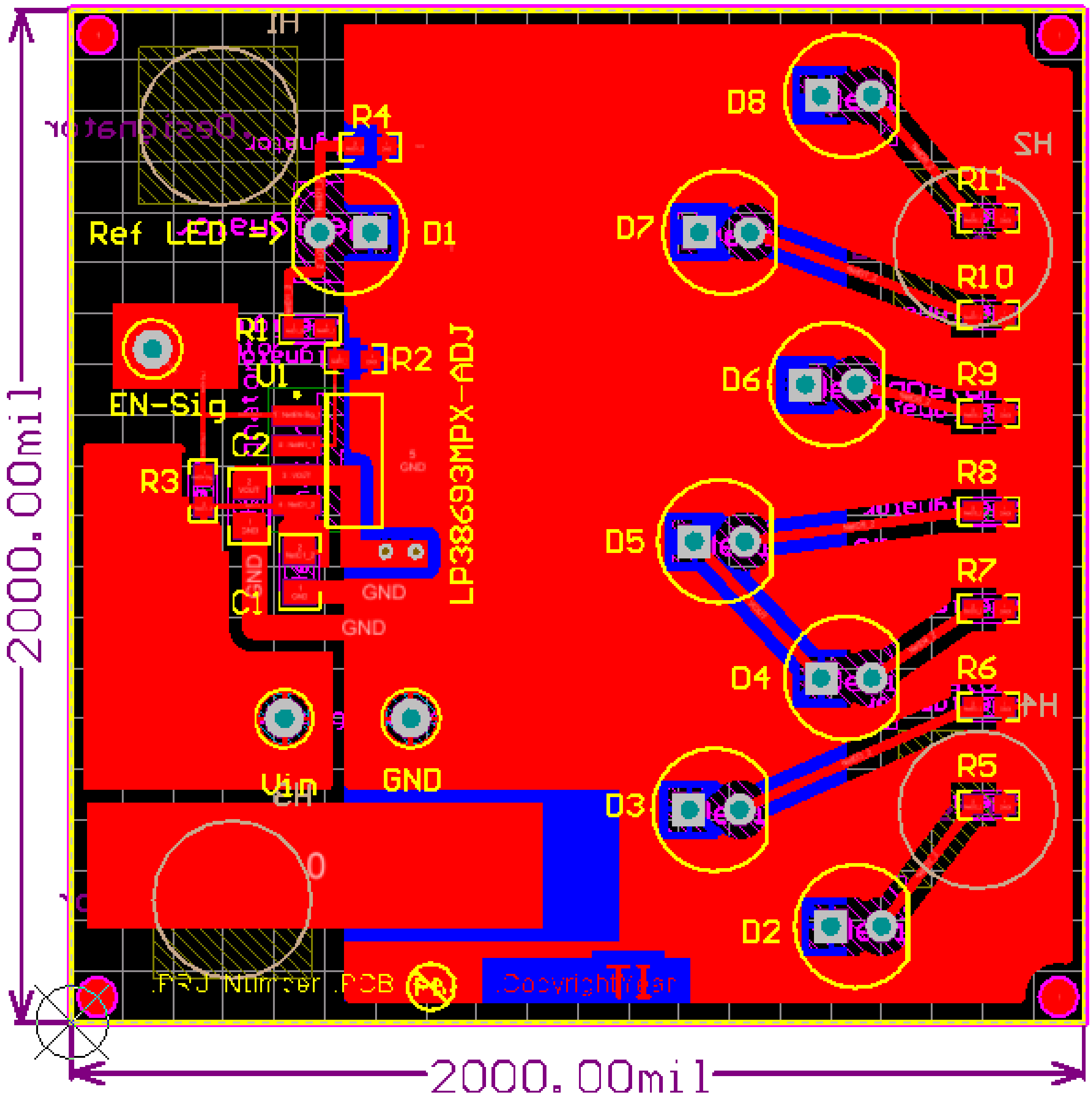


Figure 16 Altium Screenshot

6.4 Layout Guidelines

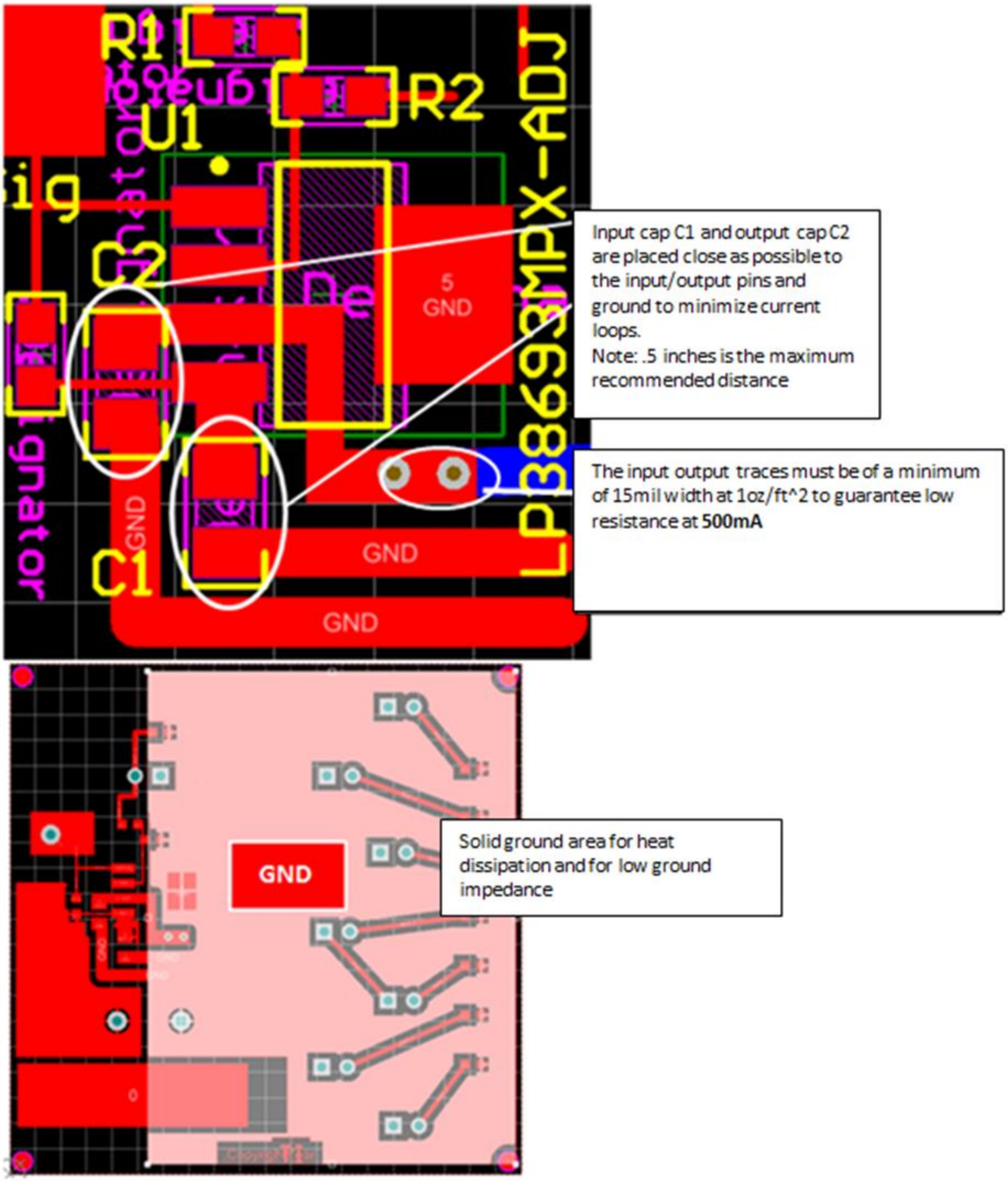


Figure 17 Layout hints

6.5 Gerber files

To download the Gerber files for each board, see the design files at http://www.ti.com/tool/TIDA-00526

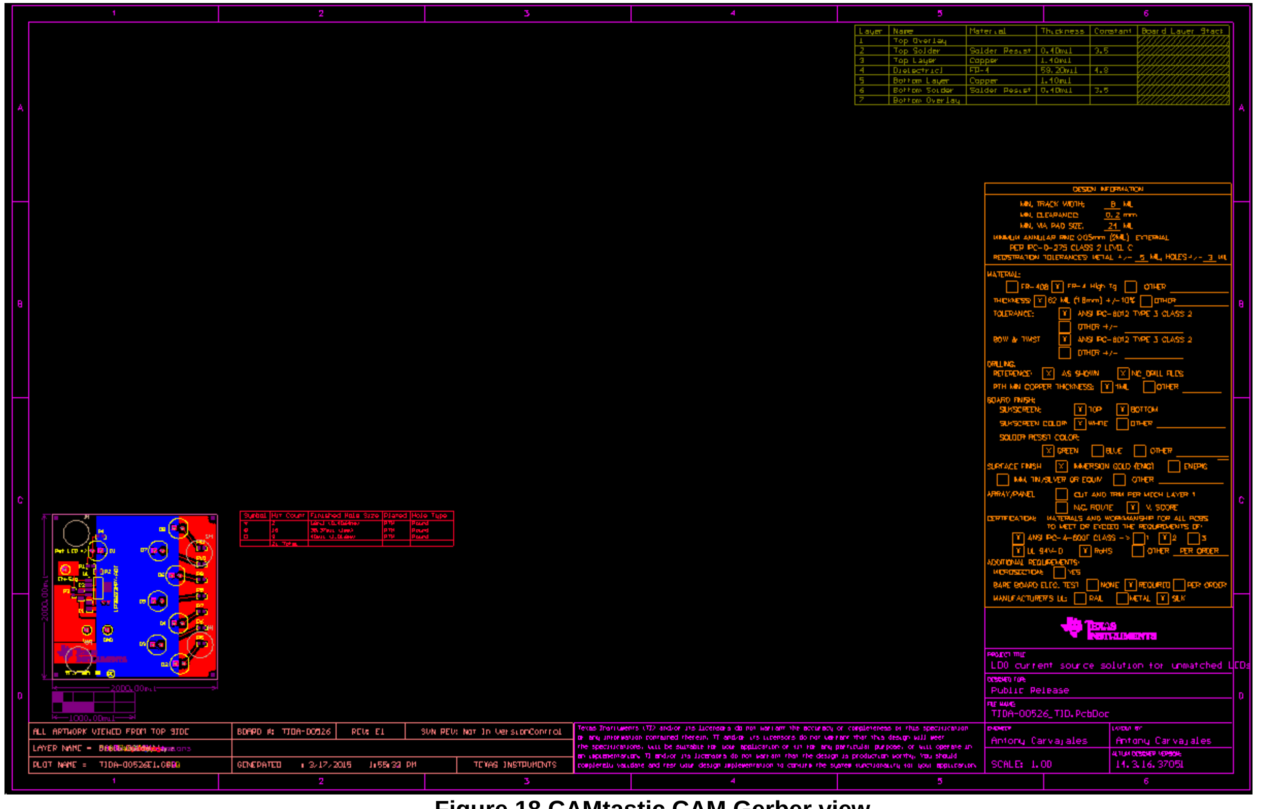
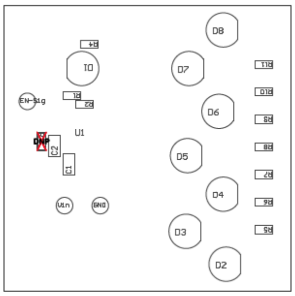


Figure 18 CAMtastic.CAM Gerber view

6.6 Assembly Drawings

To download the Assembly Drawings for each board, see the design files at http://www.ti.com/tool/TIDA-00526

222 ■These assemblies are ESD sensitive, ESD precautions shall be observed.
223 ■These assemblies must be clean and free from flux and all contaminants. Use of no clean flux is not acceptable.
224 ■These assemblies must comply with workmanship standards IPC-A-610 Class 2, unless otherwise specified.



COMPONENTS MARKED 'DNP' SHOULD NOT BE POPULATED.
ASSEMBLY VARIANT: 001

PCB VIEWED FROM TOP SIDE	BOARD #: TIDA-00526	REV: E1	SVN REV: Not In VersionControl	
PLOT NAME = Top Assembly Drawing	GENERATED : 3/17/2015 3:03:34 PM			TEXAS INSTRUMENTS

Figure 19 Top Assembly Drawings

7 About the Author

Antony Pierre Carvajales

Is an Applications Engineer on the mobile power devices RF power group at Texas Instruments. Antony has worked in various business units expanding his knowledge on analog circuitry to help customers solve their design challenges using TI technologies.

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