



Description

This local dimming backlight design conserves power, extends the life of liquid-crystal displays (LCDs), and enhances automotive display quality through high dynamic range (HDR) or localized dimming technology. Seven multi-channel constant-current LED drivers allow for 144-zone localized dimming via pulse-width modulation (PWM) on-time and current-level brightness configuration. A single serial interface allows daisy-chaining of the LED drivers for brightness and configuration programming. Temperature and ambient light sensors enable sensing of the surrounding conditions to protect from overtemperature scenarios and adjust the global brightness based on ambient brightness.

Resources

| | |
|------------------------------|----------------|
| TIDA-020001 | Design Folder |
| TLC6C5724-Q1 | Product Folder |
| TLC6C5716-Q1 | Product Folder |
| LM74700-Q1 | Product Folder |
| LMR14030-Q1 | Product Folder |
| OPT3001-Q1 | Product Folder |
| TPS22918-Q1 | Product Folder |
| TPS7A5201-Q1 | Product Folder |
| LMT87-Q1 | Product Folder |



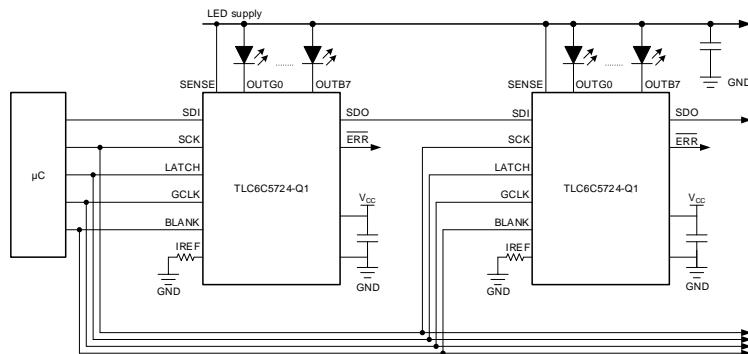
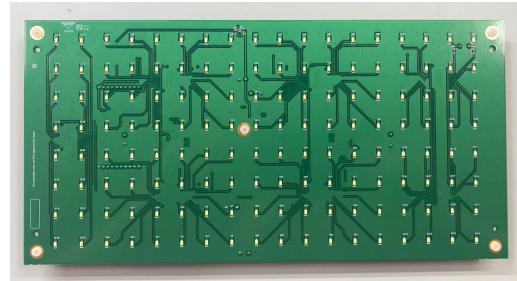
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Features

- Individually dim backlight zones saves power, prevents backlight bleed, and realizes HDR and local dimming solutions
- High-voltage transient and reverse battery protection
- Ambient light sensing with excellent human eye spectral response matching with strong IR rejection (<1%)
- Dynamically adjusts backlight brightness on logarithmic scale based on human eye and perception of brightness
- Direct-lit backlight configuration
- Single-chip sensing solutions without thermistors or photo-diodes

Applications

- Automotive display module
- Automotive center stack display
- Automotive cluster display
- Other automotive displays



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1 System Description

LCD-based displays require an external light source to illuminate the image formed from the liquid crystals. Center stack, cluster, eMirror, head-unit, and other automotive displays implement this with LEDs located behind or on the edges of the LCD panels. An LED backlight driver controls the brightness of these LEDs. LED backlight systems have two configurations, edge-lit and direct-lit. Edge-lit allows all the LEDs to be placed on the outer edge of the LCD, then have the light uniformly disperse through light-guides. Direct-lit configuration has all LEDs directly behind the display in an array configuration.

Commonly, the LED control scheme for both edge-lit and direct-lit delivers the same amount of current to all LEDs for a uniform brightness across the display. A major drawback for this type of control is that the LEDs are still on in areas where the display is dark, this creates light leakage and consumes power. When in the direct-lit LED configuration, an alternative control scheme can be used called local-dimming. Local dimming allows for individual zones or LEDs to be controlled independently via current limiting or PWM on-time adjustment.

1.1 Key System Specifications

Table 1. Key System Specifications

| PARAMETER | SPECIFICATIONS | DETAILS |
|---|--------------------------------------|-----------------------------------|
| Input voltage | 13.5 V | Section 2.3.1.1 |
| Input current (30 mA / LED, all on) | 1.7 A | Section 2.3.1.1 |
| Operating temperature | -40°C to 125°C | Section 2.2 |
| Number of LEDs | 144 LEDs | Section 2.3.3 |
| LEDs per string | 1 LED | Section 2.3.3 |
| Maximum current per string (current-limit resistor) | 30 mA | Section 2.3.3.2.3 |
| Serial peripheral interface (SPI) frequency | 390 kHz | Section 2.3.2.2 |
| GS clock frequency | 4 MHz | Section 2.3.2.2 |
| LED channel dimming ratio (GS dimming only) | 12 bits, 4096:1 | Section 2.3.3.2.5 |
| LED bias buck converters | 2 (U1 and U6) | Section 2.3.1.4 |
| LED bias voltage | 4 V | Section 2.3.1.4 |
| LED bias switching frequency | 2.2 MHz | Section 2.3.1.4 |
| Buck converter efficiency (U6) | 80.1% (4 V _{OUT} at 3.25 A) | Section 2.3.1.4 |
| LED bias currents (30 mA / LED, all on) | 1.92 A (U1) and 2.4 A (U6) | Section 2.3.1.4 |
| Ambient light sensor IR rejection | > 99% | Section 2.3.2.4 |
| Ambient light sensor dimming ratio | 32,000:1 | Section 2.3.2.4 |
| Board size | 140 mm x 280 mm | Section 3.1.1 |

2 System Overview

2.1 Block Diagram

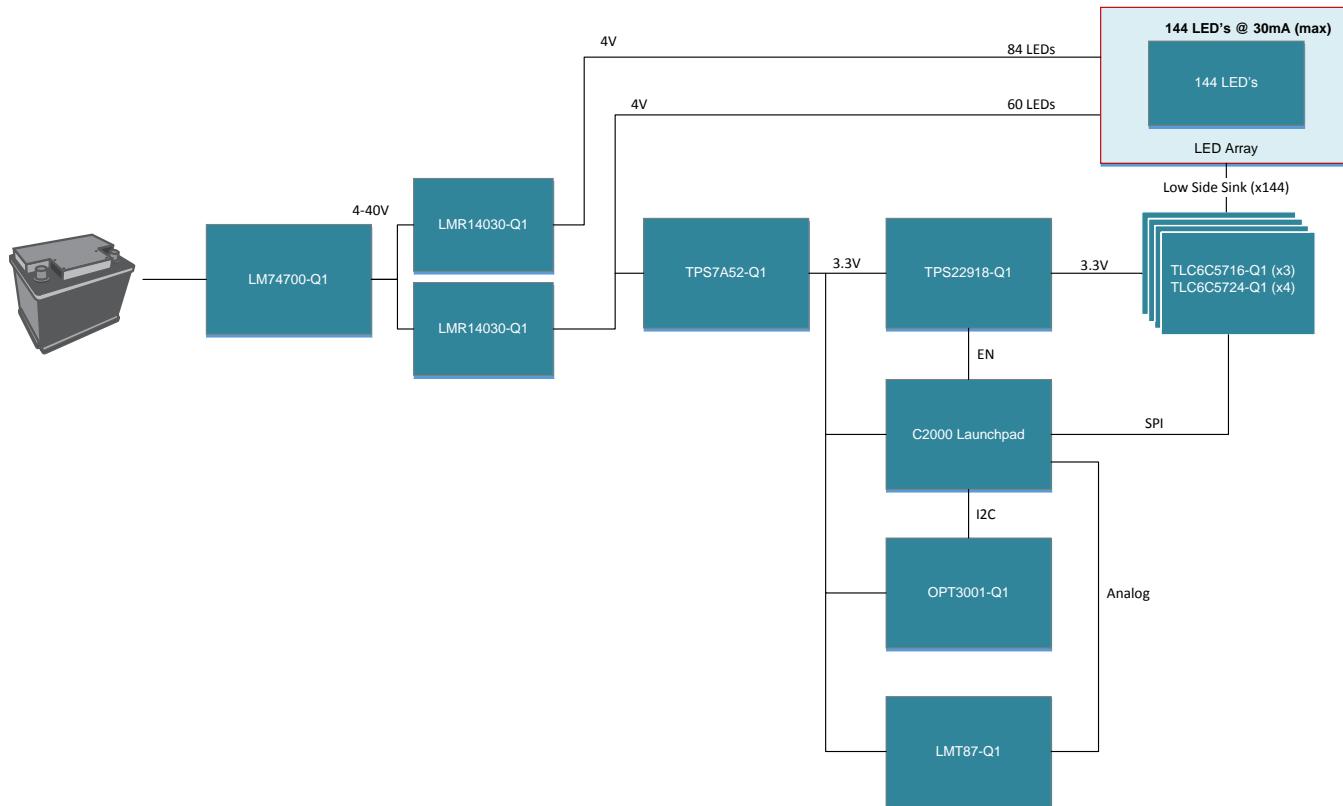


Figure 1. TIDA-020001 Block Diagram

2.2 Highlighted Products

2.2.1 LM74700-Q1

The LM74700-Q1 is a smart diode controller that operates in conjunction with an external N-channel MOSFET as an ideal diode rectifier for low-loss reverse polarity protection. The wide supply input range of 3 V to 65 V allows control of many popular DC bus voltages. The device can withstand and protect the loads from negative supply voltages down to -65 V. With a low $R_{DS(ON)}$ external N-channel MOSFET, this device can achieve a very-low forward voltage while minimizing the amount of power dissipated in the MOSFET. For low-load currents, the forward voltage is regulated to 20 mV to enable graceful shutdown of the MOSFET. TI recommends external MOSFETs with a 5 V or lower threshold voltage. With the enable pin low, the controller is off and draws approximately 3 μ A of current.

The LM74700-Q1 controller provides a charge pump gate drive for an external N-channel MOSFET. The high-voltage rating of the LM74700-Q1 helps to simplify system designs for automotive ISO7637 protection. Fast response to reverse current blocking makes the device suitable for systems with output voltage holdup requirements during ISO7637 pulse testing as well as power fail and brownout conditions. The LM74700-Q1 is also suitable for ORing applications or AC rectification.

Features:

- Qualified for automotive applications
- AEC-Q100 qualified with the following results:
 - Device temperature grade 1:
-40°C to +125°C ambient operating temperature range

- Device human body model (HBM) electrostatic discharge (ESD) classification level 2
- Charge device model (CDM) ESD classification level C4B
- 3-V to 65-V input range
- –65 V reverse voltage rating
- Charge pump for external N-Channel MOSFET
- 20-mV ANODE to CATHODE forward-voltage drop regulation
- Enable pin feature
- 3- μ A shutdown current (EN = low)
- 30- μ A operating quiescent current (EN = high)
- 1.5-A peak gate turnoff current
- Fast response to reverse current blocking:
 $< 2 \mu\text{s}$
- Meets automotive ISO7637 transient requirements with a suitable transient-voltage-suppression (TVS) diode
- –40°C to +150°C operating junction temperature
- 6-pin SOT 23-6 package (3 mm x 3 mm)

Figure 2 shows the LM74700-Q1 functional block diagram.

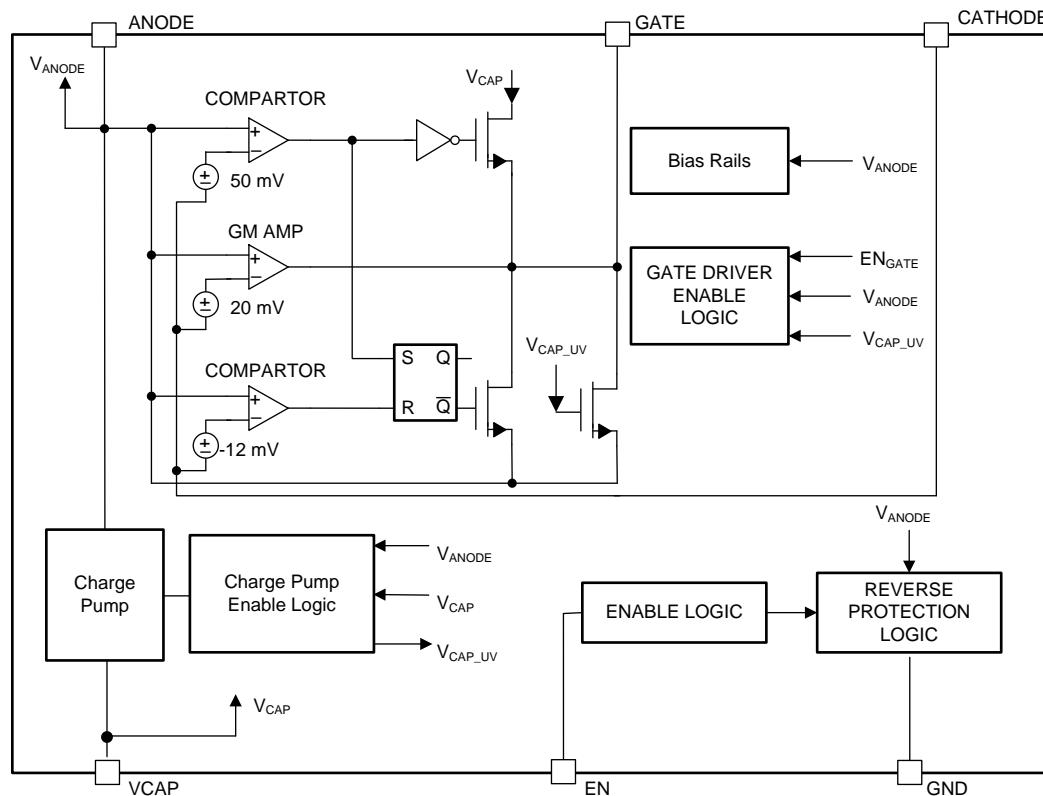


Figure 2. LM74700-Q1 Functional Block Diagram

2.2.2 TLC6C57xx-Q1

In automotive indicator and local dimming backlighting applications, the demand for multi-channel constant-current LED drivers is increasing to achieve uniformity of LED brightness and color temperature. System-level safety considerations require fault-detection capability and device self-check features.

The TLC6C5724-Q1 device is an automotive 24-channel constant-current RGB LED driver with LED diagnostics. The TLC6C5724-Q1 device provides up to 50-mA output current set by an external resistor. The current can be adjusted by 7-bit dot correction with two subranges for individual output and an 8-bit brightness control for the outputs of each color group. The brightness can be adjusted individually for each channel through a 12-, 10-, or 8-bit grayscale control. Fault-detection circuits are available to detect system faults including LED faults, adjacent-pin short faults, reference-resistor faults, and more. Negate bit toggle and LOD-LSD self-test provide a device self-check function to improve system reliability. Configurable slew-rate control optimizes the noise generation of the system and improves the system EMC performance. Output-channel group delay helps to reduce inrush current to optimize the system design. The SDI and SDO pins allow more than one device to be connected in a daisy chain for control through one serial interface.

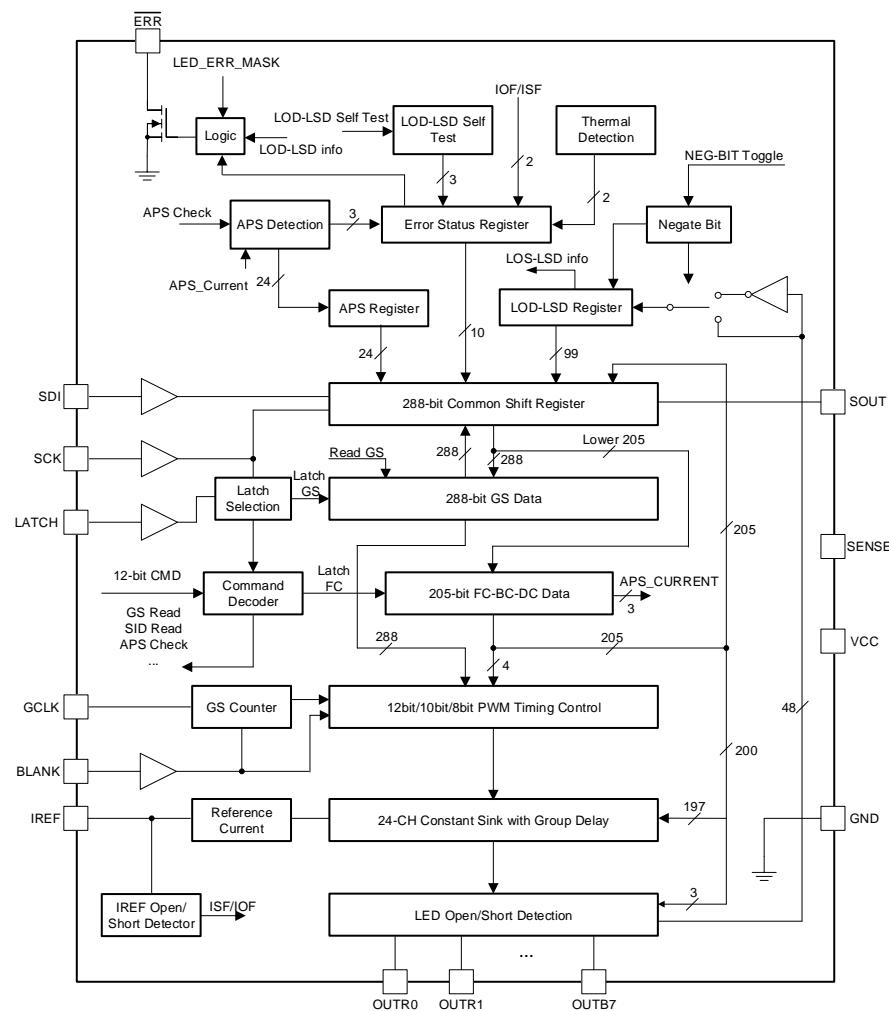


Figure 3. TLC6C57xx-Q1 Functional Block Diagram

2.2.3 TPS22918-Q1

The TPS22918-Q1 is a single-channel load switch with both configurable rise time and configurable quick-output discharge. The device contains an N-channel MOSFET that can operate over an input voltage range of 1 V to 5.5 V and can support a maximum continuous current of 2 A. The switch is controlled by an ON and OFF input, which is capable of interfacing directly with low-voltage control signals.

The configurable rise time of the device reduces inrush current caused by large bulk load capacitances, thereby reducing or eliminating power supply droop. The TPS22918-Q1 features a configurable quick output discharge (QOD) pin, which controls the fall time of the device to allow design flexibility for power down and sequencing.

The TPS22918-Q1 is available in a small, leaded SOT-23 package (DBV) which allows to visually inspect solder joints. The device is characterized for operation over the free-air temperature range of -40°C to $+105^{\circ}\text{C}$.

- AEC-Q100 qualified
- Integrated single-channel load switch
- Qualified for automotive applications:
 - Device temperature grade 2: -40°C to $+105^{\circ}\text{C}$ ambient operating temperature range
- Input voltage range: 1 V to 5.5 V
- Low ON-resistance (R_{ON})
 - $R_{\text{ON}} = 52 \text{ m}\Omega$ (typical) at $V_{\text{IN}} = 5 \text{ V}$
 - $R_{\text{ON}} = 53 \text{ m}\Omega$ (typical) at $V_{\text{IN}} = 3.3 \text{ V}$
- 2-A maximum continuous switch current
- Low quiescent current
 - $8.3 \mu\text{A}$ (typical) at $V_{\text{IN}} = 3.3 \text{ V}$
- Low-control input-threshold enables use of 1 V or higher general-purpose input/output (GPIO)
- Configurable quick-output discharge (QOD)
- Configurable rise time with CT pin
- Small SOT23-6 package (DBV)
 - $2.9 \text{ mm} \times 2.8 \text{ mm}$, 0.95-mm pitch,
1.45-mm height (with leads)
- ESD performance tested per AEC Q100
 - $\pm 2\text{-kV HBM}$ and $\pm 750\text{-V CDM}$

[Figure 4](#) shows the TPS22918-Q1 functional block diagram.

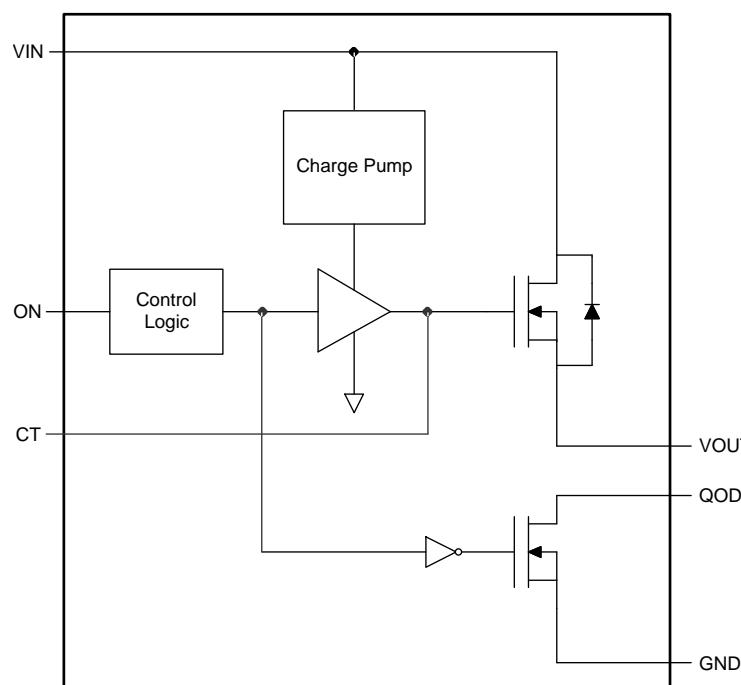


Figure 4. TPS22918-Q1 Functional Block Diagram

2.2.4 LMT87-Q1

The LMT87-Q1 device is a precision CMOS integrated-circuit temperature sensor with an analog output voltage that is linearly and inversely to temperature. The LMT87-Q1 features make it suitable for many general temperature sensing-applications. The device can operate down to a 2.7-V supply with a 5.4- μ A power consumption. Package options, which include the through-hole TO-92 package, allow the designer to mount the LMT87-Q1 on the board, off the board, to a heat sink, or on multiple unique locations in the same application. A class-AB output structure gives the LMT87-Q1 a strong output source and a sink current capability that can directly drive up to 1.1-nF capacitive loads. This quality means the device is well suited to drive an ADC sample-and-hold with its transient load requirements. The LMT87-Q1 accuracy is specified in the operating range of -50°C to 150°C . The accuracy, three-lead package options, and other features also make the LMT87-Q1 an alternative to thermistors.

The main features of this device are as follows:

- Very accurate: $\pm 0.3^{\circ}\text{C}$ typical
- Wide temperature range of -50°C to 150°C
- Low 5.4- μ A quiescent current
- Sensor gain of $-13.6 \text{ mV}/^{\circ}\text{C}$
- Output is short-circuit protected
- Push-pull output with 50- μ A source current capability
- Cost-effective alternative to thermistors

2.2.5 OPT3001-Q1

The OPT3001 device is a sensor that measures the intensity of light. The spectral response of the sensor is tightly matched to the photopic response of the human eye and includes significant infrared rejection. The OPT3001 is a single-chip lux meter, measuring the intensity of light as seen by the human eye. The precision spectral response and strong IR rejection of the device enables the OPT3001 to accurately measure the intensity of light regardless of its source. The strong IR rejection also aids in maintaining high accuracy when industrial design calls for mounting the sensor under dark glass for aesthetics. The OPT3001 is designed for systems that create light-based experiences for humans and is an ideal, preferred replacement for photodiodes, photoresistors, or other ambient light sensors with less human eye matching and IR rejection. The small form factor ($2.0 \times 2.0 \times 0.65 \text{ mm}$) allows the device to fit almost anywhere.

Features:

- Precision optical filtering to match human eye
 - Rejects >99% (typ) of IR
- Automatic full-scale setting feature simplifies software and ensures proper configuration
- Measurements: 0.01 lux to 83k lux
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted full-scale range settings: <0.2% (typ) matching between ranges
- Low operating current: 1.8 μ A (typ)
- Operating temperature range: -40°C to 85°C
- Wide power-supply range: 1.6 to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system
- Small-form factor: $2.0 \text{ mm} \times 2.0 \text{ mm} \times 0.65 \text{ mm}$

[Figure 5](#) shows the OPT3001 functional block diagram.

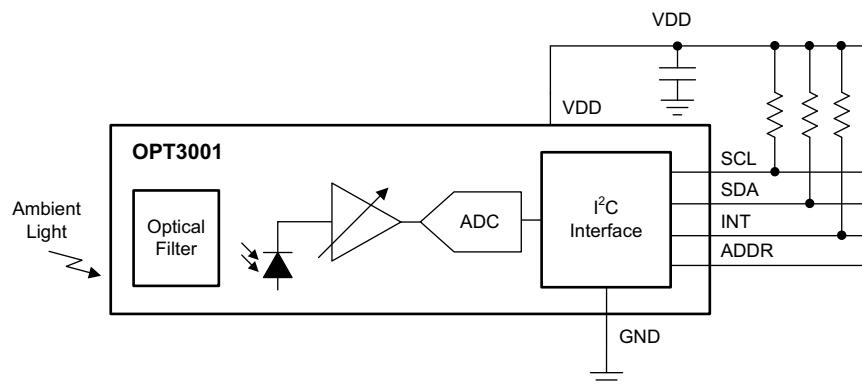


Figure 5. OPT3001 Functional Block Diagram

2.2.6 TPS7A52-Q1

2.2.6.1 Overview

The TPS7A52-Q1 is a high-current (2 A), low-noise ($4.4 \mu\text{V}_{\text{RMS}}$), high accuracy (1%) low-dropout linear voltage regulator with an input range of 1.1 V to 6.5 V, an output voltage range of 0.8 V to 5.2 V. The TPS7A52-Q1 has an integrated charge pump for ease of use, and an external bias rail to allow for the lowest dropout across the entire output voltage range. [Table 2](#) categorizes the functions shown in [Figure 6](#). These features make the TPS7A52-Q1 a robust solution to solve many challenging problems by generating a clean, accurate power supply in a variety of applications.

Table 2. Device Features

| VOLTAGE REGULATION | SYSTEM START-UP | INTERNAL PROTECTION |
|-----------------------------|---|------------------------|
| High accuracy | Programmable soft start | Foldback current limit |
| Low-noise, high-PSRR output | No sequencing requirement between BIAS, IN, and EN | Thermal shutdown |
| Fast transient response | Power-good output Start-up with negative bias on OUT | |

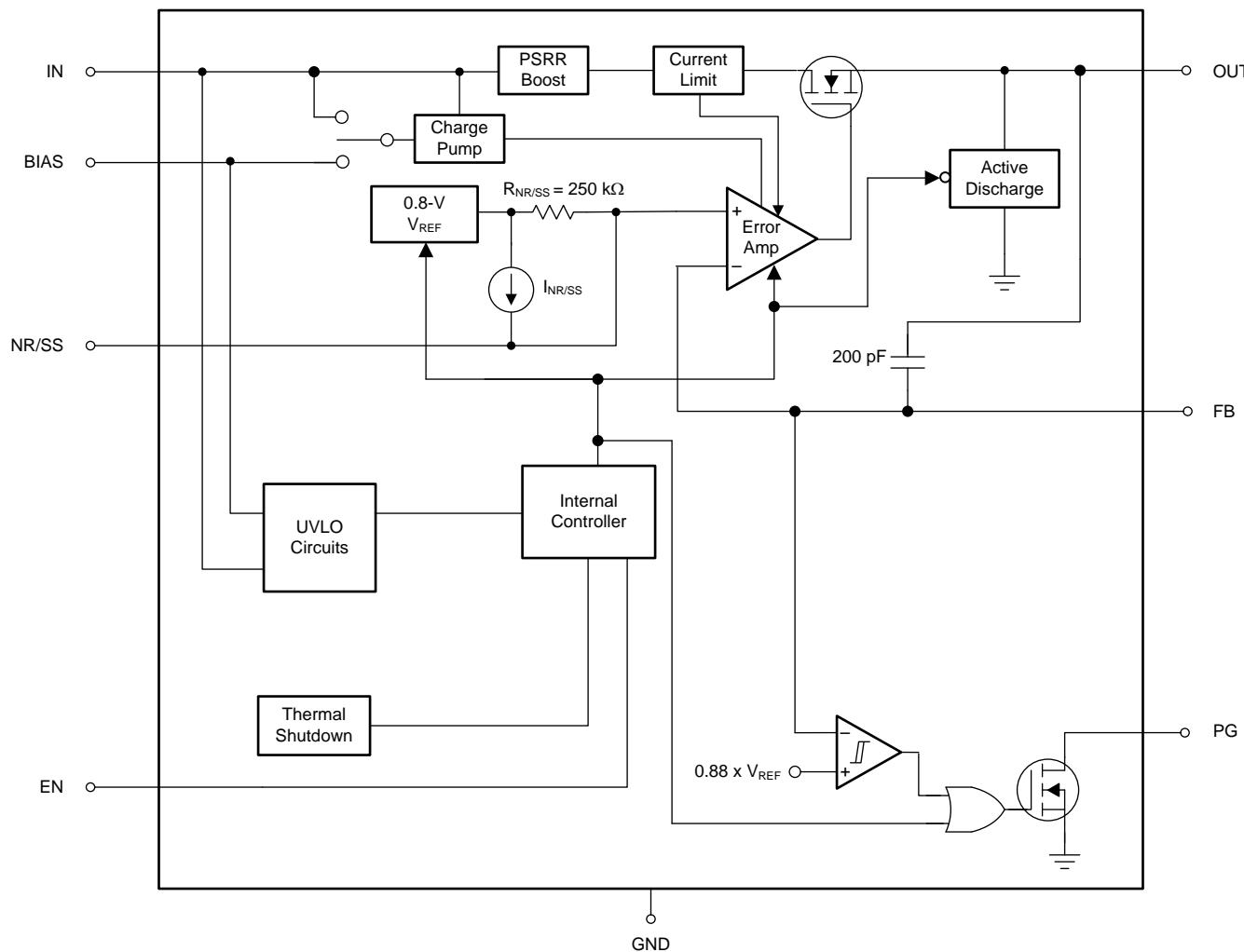


Figure 6. TPS7A52-Q1 Functional Block Diagram

2.3 Design Considerations

2.3.1 Power Management

2.3.1.1 Reverse Battery Protection

Reverse battery protection is a requirement for every electronic subsystem in a vehicle recognized by original equipment manufacturer (OEM) standards as well as load dump protection standards ISO 16750-2. The LM74700 device is used to control the negative-channel field-effect transistor (NFET) to protect the load in a negative polarity condition. This device is used to emulate an ideal diode by using an NFET in series with the battery supply. This configuration has the advantage of a highly effective and efficient substitute for reverse battery protection to the traditional rectifier. The LM74700 device has a low typical I_Q of 30 μA and standby current of 3 μA that is drawn from the battery. Additionally, the voltage drop across the field-effect transistor (FET) is so inconsequential that it allows the system to operate at even lower battery input voltages. This property is an advantage for scenarios such as cold crank when the battery voltage temporarily drops to as low as 3.5 V. A traditional diode solution usually has a 700-mV voltage drop, so the LDO would not be able to maintain the minimum 3-V system voltage. With the smart diode solution, the LDO and boost converter still receive close to 5 V during this condition and can continue to operate.

2.3.1.2 MOSFET and TVS Diodes

[LM74700-Q1 Low I_D Always ON Smart Diode Controller](#) details the MOSFET selection for the LM74700-Q1 device. The following items are important characteristics to design around:

- Continuous drain current (I_D)
- Maximum drain-to-source voltage ($V_{DS(MAX)}$)
- Gate-to-source threshold voltage ($V_{GS(TH)}$)
- Drain-to-source on resistance ($R_{DS(ON)}$)

Additionally, the rating for I_D must exceed the system current ($I_D > I_{LOAD}$), which is less than 2.5 A in this system. This ideal diode controller is paired with a SQJ412EP-T1 MOSFET.

[Table 3](#) lists the TVS diode parameters.

Table 3. TVS Diode Parameters

| PARAMETER | COMMENTS | MIN | TYP | MAX | UNIT |
|------------------|--------------------------|------|------|------|------|
| D1SMBJ28A | | | | | |
| V_{RWM} | Reverse standoff voltage | — | 28.0 | — | V |
| V_C | Clamping voltage | — | — | 45.4 | V |
| V_{BR} | Breakdown voltage | 31.1 | — | 35.8 | V |
| D2SMBJ14A | | | | | |
| V_{RWM} | Reverse standoff voltage | — | 14 | — | V |
| V_C | Clamping voltage | — | — | 23.2 | V |
| V_{BR} | Breakdown voltage | 15.6 | — | 17.9 | V |

The diode breakdown voltages must be chosen such that the transients are clamped at the voltages that protect the MOSFET and the remainder of the system. In [Table 3](#), the positive clamping diode D1 clamps above the double battery (jump-start) and clamped load dump voltages, but lower than the maximum operating voltage of the downstream devices. In this case, the positive clamping diode starts to clamp around 28 V, but has a maximum clamp voltage just below 40 V (ideally, somewhere around 36 V), which is why D1 is chosen for its maximum clamping voltage (see [Figure 7](#)).

The reverse clamping diode D2 must clamp all negative voltages greater than the battery voltage so that it does not short out during a reverse-battery condition. Because the battery voltage is likely to be 14 V, D2 is selected to block all negative voltages greater than this voltage.

Regarding the power levels for the TVS diodes, the particular package used is SMBJ, which supports 600-W peak power levels. This package is sufficient for ISO 7637-2 pulses and suppressed load dump case (ISO-16750-2 pulse B). Unsuppressed load dumps (ISO-16750-2 pulse A) may require higher-power TVS diodes such as SMCJ or SMDJ. For more information about designing the TVS diodes for this application, see [LM74700-Q1 Low I_D Always ON Smart Diode Controller](#).

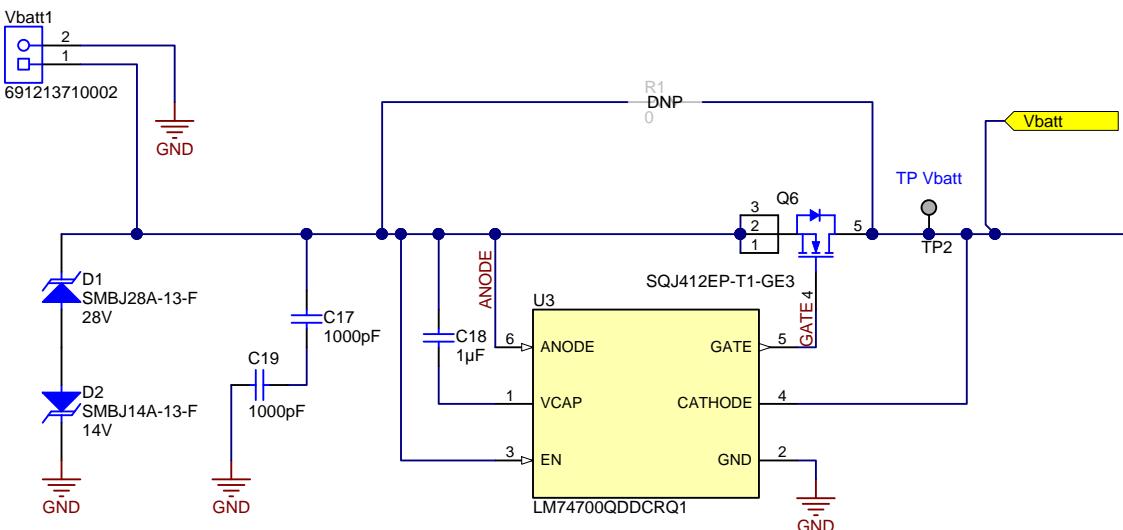


Figure 7. TIDA-020001 Schematic: Input Protection

2.3.1.3 LC Filter and Input Capacitors

After the LM74700 setup, an LC filter is used for two main functions: prevent EMI and prevent high-frequency voltage on the power line from passing through to the power supply of the regulator.

For EMI filter designs, determining the attenuation and appropriate cutoff frequency is important to properly calculate the capacitor and inductor values. For further clarification, see [AN-2162 Simple Success With Conducted EMI From DC-DC Converters](#).

The regulator performs switching at 2.2 MHz; therefore, TI recommends to set the cutoff frequency to be approximately $1/10 f_{sw}$. The cutoff frequency is set as follows in [Equation 1](#).

$$f_c = 220\text{kHz} = \frac{1}{(2\pi\sqrt{LC})} \quad (1)$$

The values chosen for C25 and L1 are 0.47 μF and 1 μH, respectively, for a cutoff frequency of 190 kHz. Place C30 and R31 after the filter to increase the impedance of the PI filter and prevent stability problems between the filter and converter (see [Figure 8](#)).

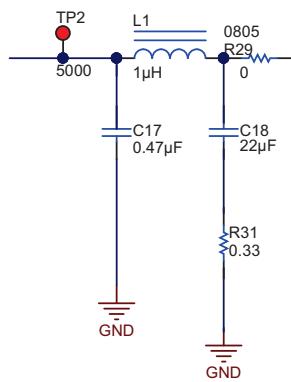


Figure 8. TIDA-020001 Schematic: PI Filter

2.3.1.4 Off-Battery Buck Converters

Two LMR14030-Q1 off-battery buck converters are used to supply the two 4-V bias voltage rails for the 144 LEDs. One of the two buck converters (U6) also supplies power to an LDO for a 3.3-V rail for the MCU, logic, and signaling.

The LMR14030-Q1 device only requires a few external components to convert from a wide voltage range supply to a fixed output voltage. [Figure 9](#) shows a schematic of 4 V at 3.5-A application circuit based on the LMR14030-Q1 device in a SO-8 package. The external components have to fulfill the needs of the application, but also the stability criteria of the control loop of the device.

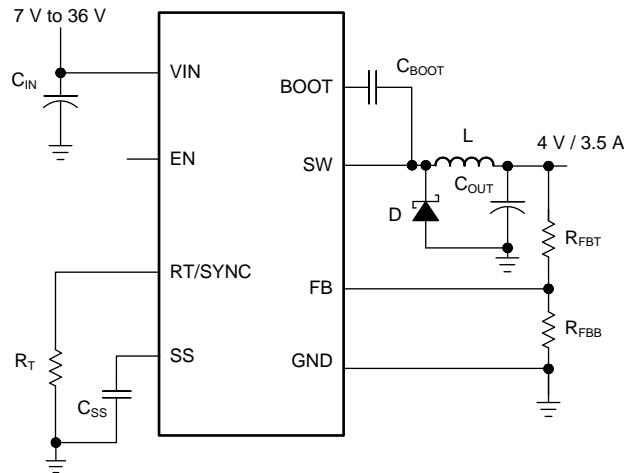


Figure 9. Application Circuit, 4-V Output

Table 4. Buck Converter Configuration and Components

| PARAMETER | SPECIFICATIONS | COMPONENT OR PIN | DETAILS |
|---------------------------|-----------------------|----------------------------------|-----------------------------------|
| Boost frequency | 2.2 MHz | RT/SYNC = 10 kΩ | Section 2.1 |
| V _{OUT} | 4 V | R _{FB1} = 100 kΩ | Section 2.3.1 |
| | | R _{FB2} = 23.2 kΩ | |
| Soft-start | Approximately 5 ms | C _{SS} = 0.022 μF | |
| Buck converter #1 (U1) | | | |
| Output current | 2.5 A | 84 LEDs | |
| Buck converter #2 (U6) | | | |
| Output current | 2 A | 60 LEDs, MCU, 3.3-V rail | |
| BUCK CONVERTER COMPONENTS | VALUE AND PART NUMBER | DESCRIPTION | DETAILS |
| Input capacitance | 4.7 μF | CERM, 50 V, 10%, X7R | Section 2.3.1.4.4 |
| | 0.1 μF | CERM, 50 V, 20%, X5R | |
| Inductor | 1.5 μH | I _{SAT} 8.5 A, 0.0151 Ω | Section 2.3.1.4.3 |
| Diode | PDS560-13 | 60 V, 5 A, PowerDI5 | Section 2.3.1.4.5 |
| Output capacitance | 10 μF(x 2) | CERM, 16 V, 10%, X7R | Section 2.3.1.4.4 |
| | 2.2 μF | CERM, 16 V, 10%, X7R | |

2.3.1.4.1 Output Voltage

The output voltage of the LMR14030-Q1 device is externally adjustable using a resistor divider network. The divider network is comprised of top feedback resistor R_{FBT} and bottom feedback resistor R_{FBB}. The output voltage of the LMR14030-Q1 device is set by [Equation 2](#):

$$R_{FBT} = \frac{V_{OUT} - 0.75}{0.75} \times R_{FBB} \quad (2)$$

A value of 681 kΩ is chosen for R_{FBT}, and the recommended value of 100 kΩ is chosen for R_{FBB}.

2.3.1.4.2 Switching Frequency Selection

The LMR14030-Q1 buck converter supports a wide range of switching frequencies from 200 kHz to 2.2 MHz. A switching frequency of 2.2 MHz is chosen due to EMI considerations such as being above the AM band. The frequency of the LMR14030-Q1 device is set with [Equation 3](#):

$$R_T(k\Omega) = 42904 \times f_{SW}(\text{kHz})^{-1.088} \quad (3)$$

A value of 10 kΩ is chosen to set the frequency to 2.2 MHz.

2.3.1.4.3 Inductor Selection

The most critical parameters for the inductor are the inductance, saturation current, and the RMS current. The inductor ripple to maximum current coefficient is chosen to be 30% in this design. Therefore, an inductor is chosen with 1.5 μH, 8.1 I_{RMS}, and 8.5 I_{SAT}.

For additional information on selecting an inductor based on the desired ripple coefficient and inductor parameters, see the *Output Inductor Selection* section of the [LMR14030 SIMPLE SWITCHER® 40 V 3.5 A, 2.2 MHz Step-Down Converter with 40 μA I_Q](#) data sheet.

2.3.1.4.4 Input and Output Capacitor Selection

The LMR14030-Q1 device requires high frequency input decoupling capacitors and a bulk input capacitor, depending on the application. The typical recommended value for the high-frequency decoupling capacitor is 4.7 μF to 10 μF. A high-quality ceramic capacitor type X5R or X7R with sufficiency voltage rating is recommended. A 4.7-μF and 0.1-μF capacitor is placed at the input of each buck converter.

Two 10-μF capacitors and a 2.2-μF capacitor are chosen for the output capacitance. Output capacitance determines the output ripple of the buck converter. [Figure 28](#) shows the output ripple performance of the LMR14030-Q1 buck converters.

For more information on the input and output capacitance selection, see the *Output Capacitor Selection* section of the [LMR14030 SIMPLE SWITCHER® 40 V 3.5 A, 2.2 MHz Step-Down Converter with 40 μA I_Q](#) data sheet.

2.3.1.4.5 Diode Selection

The breakdown voltage rating of the diode is preferred to be 25% higher than the maximum input voltage. The current rating for the diode should be equal to the maximum output current for best reliability in most applications. This design uses a 60-V, 5-A rated diode.

2.3.1.5 3.3-V LDO

In this design, the MCU, LED drivers, and sensors have an input voltage of 3.3 V. A linear regulator is used to create the 3.3 V from the 4-V LED bias voltage created by the buck converters. The TPS7A5201-Q1 LDO (U#) is connected to buck converter #1 (U#).

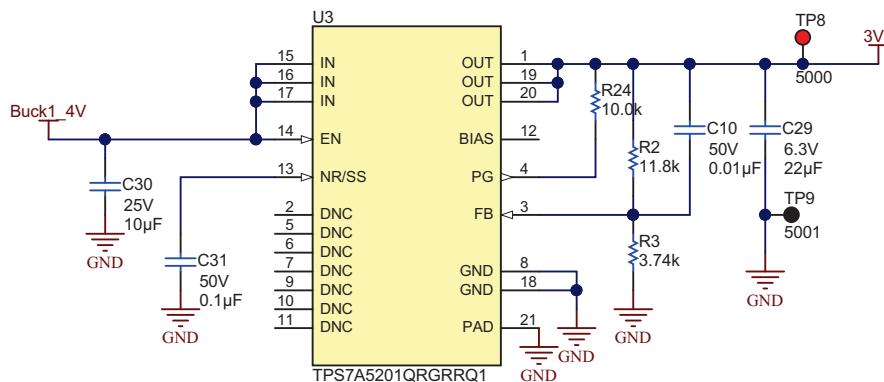


Figure 10. TIDA-020001 LDO

2.3.1.6 Load Switch

A TPS22918-Q1 load switch is used to connect the VCC pin of the LED driver to the LDO. When the backlight is turned off, all 7 backlight drivers pull a 110 μ A of quiescent current. In order to limit the amount of power loss, a load switch is used inline between the 3.3-V rail and VCC pins to limit any quiescent current from being consumed.

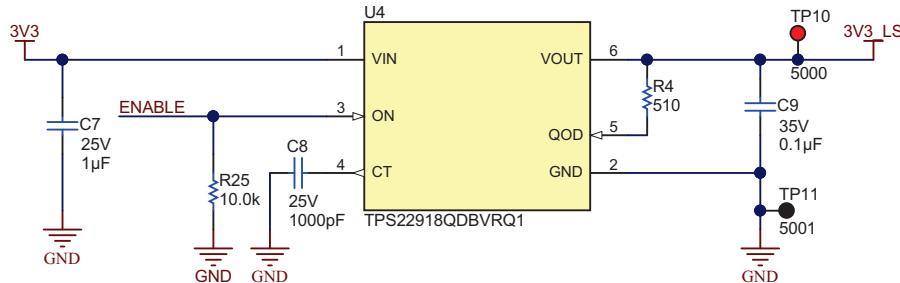


Figure 11. TIDA-020001 Load Switch

2.3.2 MCU, Interface, and Sensing

This reference design utilizes a C2000™ LaunchPad to execute the local-zone dimming, smart backlight algorithm, and interface with the various user inputs, sensors, and power devices.

2.3.2.1 C2000 Launchpad

A TMS320F28379D micro-controller (MCU) attaches to the LaunchPad headers on this TI design. The MCU executes an animation and dimming algorithm to control the LED drivers through SPI interface. Along with SPI, the I²C, ADC, and GPIO peripherals of the MCU are also utilized. I²C is used to communicate with the digital ambient light sensor. The integrated analog-to-digital converter within the MCU is used to convert an analog temperature voltage to interpret an over- or under temperature condition.

2.3.2.2 Interface

I²C and SPI interfaces are used for communication between the MCU, LED drivers, and sensors.

The I²C interface is used to communicate to the digital ambient light sensor. The I²C operates at 195-kHz frequency, and is polled by the C2000 every animation frame. 10-k Ω pullup resistors are placed on the SDA and SCL lines of the I²C bus.

The SPI interface is used to communicate from the MCU to the 7 LED drivers. All 144 LEDs are individually controlled via SPI and 288-bit common shift registers in each of the LED drivers. This TI design used a SPI clock frequency of 390 kHz. SPI speeds up to 4 MHz can be realized, which allow the LEDs to be updated within a video frame. For more information on the SPI interface registers and control, see [Section 3.1.4](#).

2.3.2.3 Temperature Sensing

Due to the tight temperature tolerances of LCD panels, one or more temperature sensors are typically needed to ensure operation within the allowable temperature range. This TI design senses the temperature through an analog-out temperature sensor that is read and converted by the MCU. When operating conditions exceed the allowable temperature threshold of 85°C, the backlight will shutdown.

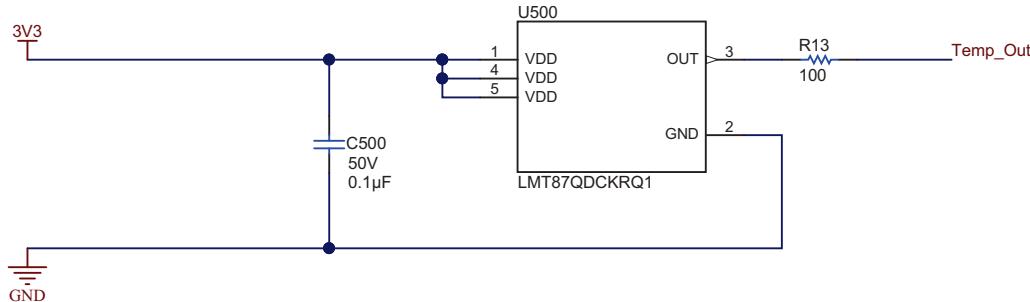


Figure 12. TIDA-020001 Temperature Sensor

2.3.2.4 Optical Light Sensing

The OPT3001 ambient light sensor is used to measure the ambient light level exposed to the display. The only hardware recommendation for the OPT3001 sensor is a bypass capacitor on the VDD pin to ensure stable, low-noise input power. The digital interface pins require pullup resistors. The OPT3001 has an open-drain interrupt and interrupt reporting system that allows the processor connected to the I²C bus to enter sleep mode, or otherwise ignore the device results, until a user-defined event occurs that requires possible action. Two major interrupt reporting modes are available: latched-window comparison mode and transparent hysteresis-style comparison mode. This reference design has the interrupt connected to the MCU but does not use these interrupt modes. I²C read calls are used to read the data from the device. For more information on the modes and use of the interrupt pin, see [OPT3001 Ambient Light Sensor \(ALS\)](#).

The light level is read from a 16-bit register that has two fields: a 4-bit exponent (E[3:0]) and 12-bit mantissa (R[11:0]). The exponent field is based on the full-scale range and sets the least significant bit (LSB) size for one lux. This design used the auto-scaling feature of the device and calculated the resulting lux in [Equation 4](#).

$$\text{lux} = 0.01 \times (2^{E[3:0]}) \times R[11:0] \quad (4)$$

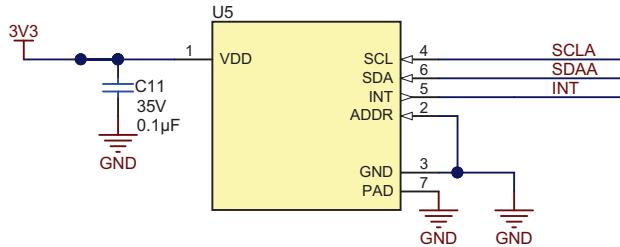


Figure 13. TIDA-020001 Ambient Light Sensing

2.3.3 LEDs and Drivers

This reference design represents a direct-lit backlight configuration with 144 LEDs. The LEDs are uniformly placed in an array for a 12-inch display. The design and implementation is scalable for larger amounts of LEDs or zones by increasing the amount of LED drivers or multiplexing the outputs using high-side drivers.

There are trade-offs when determining the number of LEDs for a display. When a low quantity of LEDs are used with larger displays, the physical location of the backlight array needs to be further from the LCD to realize homogenous spread across the LCD. While this design has 144-zones, up to several thousand zones might be required to realize the visual enhancement of HDR technology for large displays (>15 in.).

2.3.3.1 LEDs

OSRAM KW DNLS31.RA LEDs are used in this reference design. These LEDs have more of a square, less rectangular form factor than other LEDs, allowing them to provide a more uniform and homogeneous spread of light in a direct-backlight array. These LEDs have a maximum current rating of 80 mA, and luminous flux of 20 lm at 80 mA. The typical forward voltage of these LEDs is 3.05 V.

2.3.3.2 LED Drivers

2.3.3.2.1 LED Drivers Configuration

This reference design has 144-zones that are controlled by 7 TLC7C54xx LED drivers, four 24-channel and three 16-channel devices. One serial interface is used to connect the 7 LED drivers in a daisy chain configuration. A larger or smaller amount of LEDs is also possible by cascading 16-channel and 24-channel devices in a design.

The 144-zones each have one LED per zone, therefore 144 individual channels are utilized. The maximum output voltage for each channel is 8 V, allowing more than one LED to be connected to a single channel.

2.3.3.2.2 LED Bias Voltage

The LED drivers provide constant-current-sink channels to control LEDs. Therefore, each LED needs to be biased individually to a power source. Two buck converters with integrated switches provide the 4-V bias power for the 144 LEDs.

2.3.3.2.3 Current Sink Limit

The constant-current-sink channels on the LED drivers are capable of sinking 50 mA of current. In this reference design, the maximum current was limited to 30 mA due to thermal constraints of the buck converters. The lower maximum current also lowers the overall brightness of the design to ensure a comfortable viewing experience during bench evaluation. This design is capable of delivering 13 W of backlight power, consistent with the typical needs of displays of this size. R_{IREF} is set to 1.6 k Ω using [Equation 5](#).

2.3.3.2.3.1 Maximum Constant-Sink-Current Setting

LED full-scale current can be programmed using an external resistor connected between the IREF pin and GND. The R_{IREF} resistor value is calculated with the following formula:

$$R_{IREF} = K \times \frac{V_{IREF}}{I_{(OUT)max}}$$

where

- V_{IREF} is the reference voltage
 - K is the IREF current to output current ratio
 - $I_{(OUT)max}$ is full-scale current for each output
- (5)

2.3.3.2.4 Output Current Using Brightness Control and Dot Correction

The TLC6C5724-Q1 device implements an 8-bit group brightness control (BC) and 7-bit individual dot correction (DC) to calibrate the output current. The 24 output channels are divided into three groups: OUTRn, OUTGn, and OUTBn. Each group contains 8 output channels. There are two configurable ranges for the DC value of each group. One is the low DC range with output current from 0 to 66.7% $I_{(OUT)max}$. The other is the high DC range with output current from 33.3% $I_{(OUT)max}$ to 100% $I_{(OUT)max}$. The IREF resistor, BC, DC, and DC range together determine the channel output current, as shown in [Figure 14](#), [Equation 6](#) and [Equation 7](#) are the detailed output current calculation formulas.

[Equation 6](#) determines the output sink current for each color group when DC is in the high adjustment range.

$$I_{OUT} = \left(\frac{1}{3} \times I_{(OUT)max} + \frac{2}{3} \times I_{(OUT)max} \times \frac{DC}{127} \right) \times \frac{BC}{255} \quad (6)$$

[Equation 7](#) determines the output sink current for each color group when DC is in the low adjustment range.

$$I_{OUT} = \frac{2}{3} \times I_{(OUT)max} \times \frac{DC}{127} \times \frac{BC}{255} \quad (7)$$

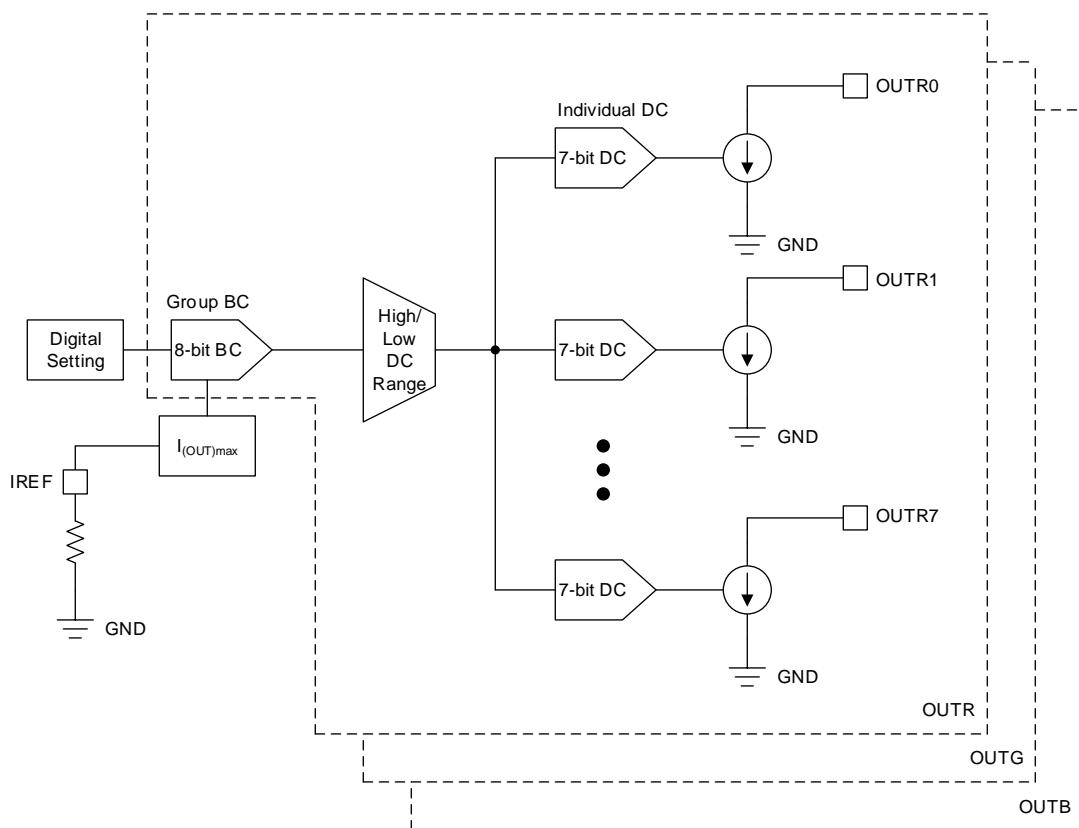
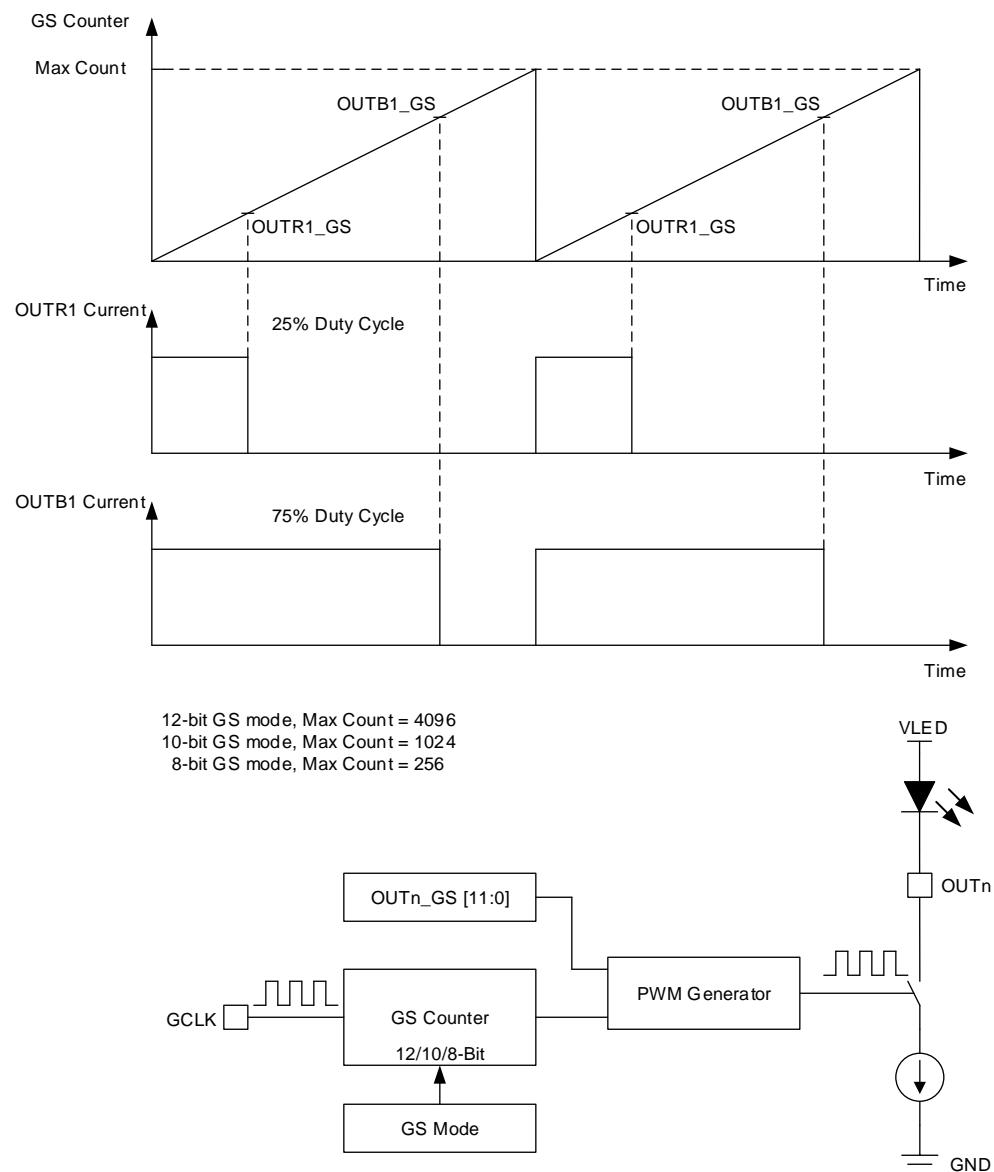


Figure 14. Brightness Control and Dot Correction Block Diagram

2.3.3.2.5 Grayscale Control

The TLC6C5724-Q1 device implements a grayscale configuration function to realize the individual PWM dimming function for the output channels. The grayscale has three global configuration modes, 12 bit, 10 bit and 8 bit. The GCLK input provides the clock source for the internal PWM generator. The GS counter counts the GCLK number and compares the number with the channel grayscale register value. The output channel turns off when the GS counter value reaches the grayscale register value. [Figure 15](#) shows the detailed block diagram of the PWM generator.

To restart a new PWM cycle, use two methods. One is to toggle the BLANK pin after the GS counter reaches the maximum count value, because BLANK low resets the GS counter and BLANK high restarts the GS counter. Another is to pull BLANK high and set the AUTO_REPEAT&TIMING_RESET register bit to 1. The PWM starts a new cycle automatically after the GS counter reaches the maximum count value.


Figure 15. PWM Generator

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The LEDs and ambient light sensor is located on the top side of the board. All other components are located on the back of the board. [Figure 16](#) shows the top side of the design board.

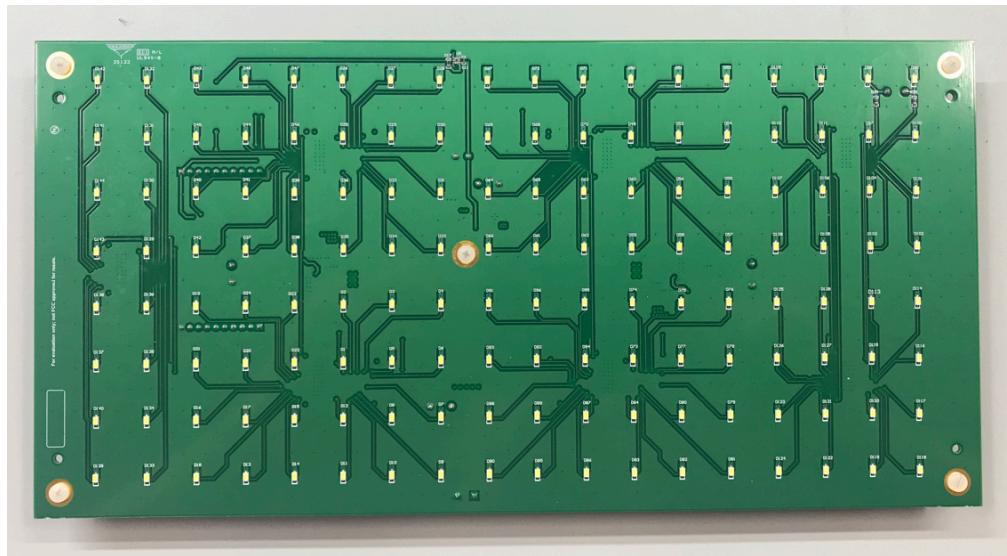


Figure 16. TIDA-020001 Board Top

The 144 LEDs are evenly distributed in 18 columns across the top side of the board. The ambient light sensor is placed on the top side of board at the top of the LED array, or where the display would be.

Aside from the ambient light sensor and LEDs, all ICs and circuitry are located on the bottom side of the board (see [Figure 17](#)).

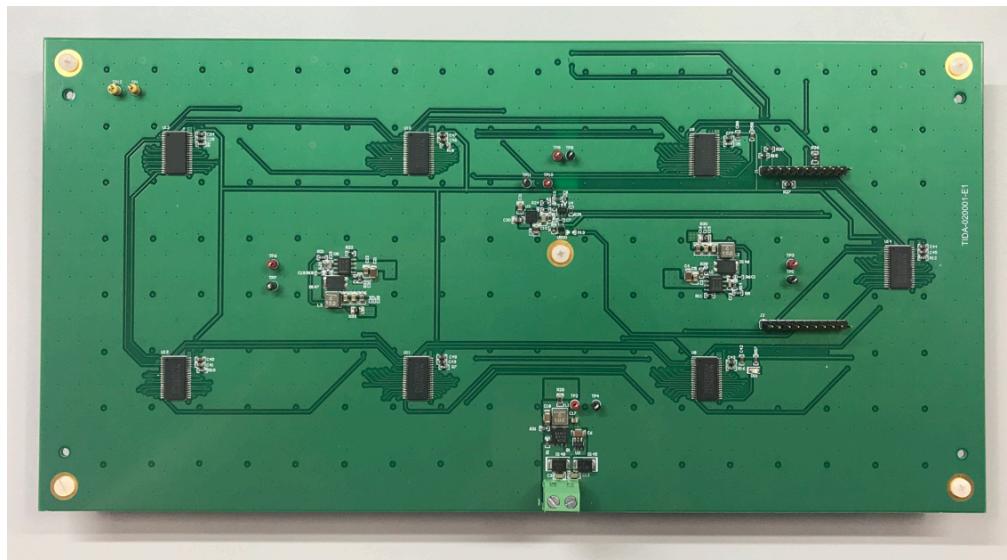


Figure 17. TIDA-020001 Board Bottom

The LED drivers are spread-out on the bottom side of the PCB to be positioned locally to a set of 24 LEDs. This keeps the return paths from the LEDs to the LED driver sink pins short. The input power connector and accessory filtering and protection are located at the bottom of the PCB. LaunchPad headers allow a C2000 LaunchPad to be connected to the board and provide control and timing signals to the LED drivers.

WARNING



Hot Surface. Contact may cause burns. Do not touch!

3.1.1.1 LED Brightness Attenuation

In this reference design, the backlight does not have an LCD panel, diffuser, or the rest of the LCD stack-up. In a real application, LCDs will typically have less than 10% transmissivity. For the purpose of testing and demonstration, a piece of tinted acrylic is mounted above the LED array to attenuate some of the illumination of the backlight. [Figure 18](#) shows the acrylic mounted on the board.

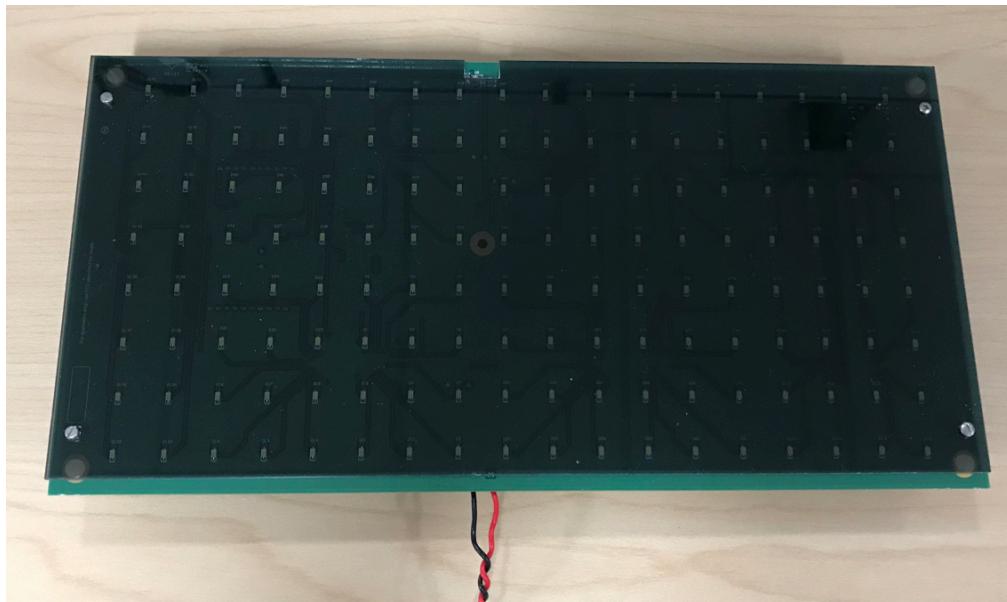


Figure 18. TIDA-020001 With Acrylic Light Attenuator

3.1.2 Software

To evaluate performance and provide demonstration, this reference design utilizes a C2000 LaunchPad to provide LED driver instruction and read the sensors. C200 peripherals, such as SPI, ADC, and GPIO, are used to interface with the LED drivers and sensors.

3.1.3 LED Driver Programming

3.1.3.1 Register Write and Read

The TLC6C5724-Q1 device is programmable via serial interface. It contains a 288-bit common shift register to shift data from SDI into the device. The register LSB connects to SDI and the MSB connects to SDO. On each SCK rising edge, the data on SDI shifts into the register LSB and all 288 data bits shift towards the MSB. The data appears on SDO when the 288-bit common shift register overflows.

The TLC6C5724-Q1 data write command contains 288-bit data. According to the following different criteria, there are three types of data write commands: FC-BC-DC write, GS data write, and special command.

- When LATCH is high at the 288th SCK rising edge, and the 12 MSBs of the 288-bit data are 0, the 205 LSBs of 288-bit data shift to the function control (FC), brightness control (BC) and dot correction (DC) registers on the LATCH rising edge. This is illustrated in the *Function Control, Brightness Control, and Dot Correction Data (FC-BC-DC) Write* image in the [TLC6C5724-Q1 Automotive 24-Channel, Full Diagnostics, Constant-Current RGB LED](#) data sheet.
- When LATCH is low at the 288th SCK rising edge, all 288-bit data shifts into the grayscale (GS) configuration registers on the LATCH rising edge. This is illustrated in the *Grayscale (GS) Data Write* image in the [TLC6C5724-Q1](#) data sheet.
- When LATCH is high at the 288th SCK rising edge, and the 12 MSBs of the 288-bit data match any of the eight 12-bit command codes, the device executes the corresponding command after the LATCH rising edge. For more details, see the *Special Command Function* section in the [TLC6C5724-Q1](#) data sheet.

When the device powers on, the default value of the 288-bit common shift register is 0.

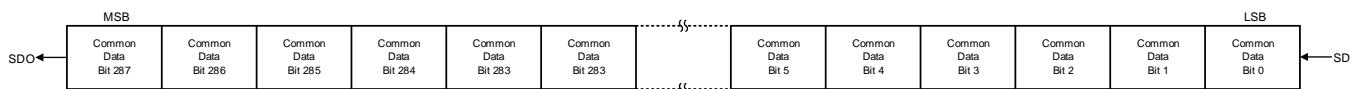


Figure 19. TLC6C5724-Q1 Common Register

See the *Register Write and Read* section of the [TLC6C5724-Q1 Automotive 24-Channel, Full Diagnostics, Constant-Current RGB LED](#) data sheet for more information pertaining to the writing of FC-BC-DC and GS registers.

3.1.4 Cascaded Data Write

Per [Section 3.1.3](#), each frame update 288 bits of GS data must be sent to each LED driver to adjust the brightness (LED PWM on-time). Additionally, if global current or individual dot-correction adjustment is desired, then 288 bits for the FC-BC-DC update is also sent. This design uses daisy chain connection to control all 7 LED drivers through one serial interface, as [Figure 20](#) shows.

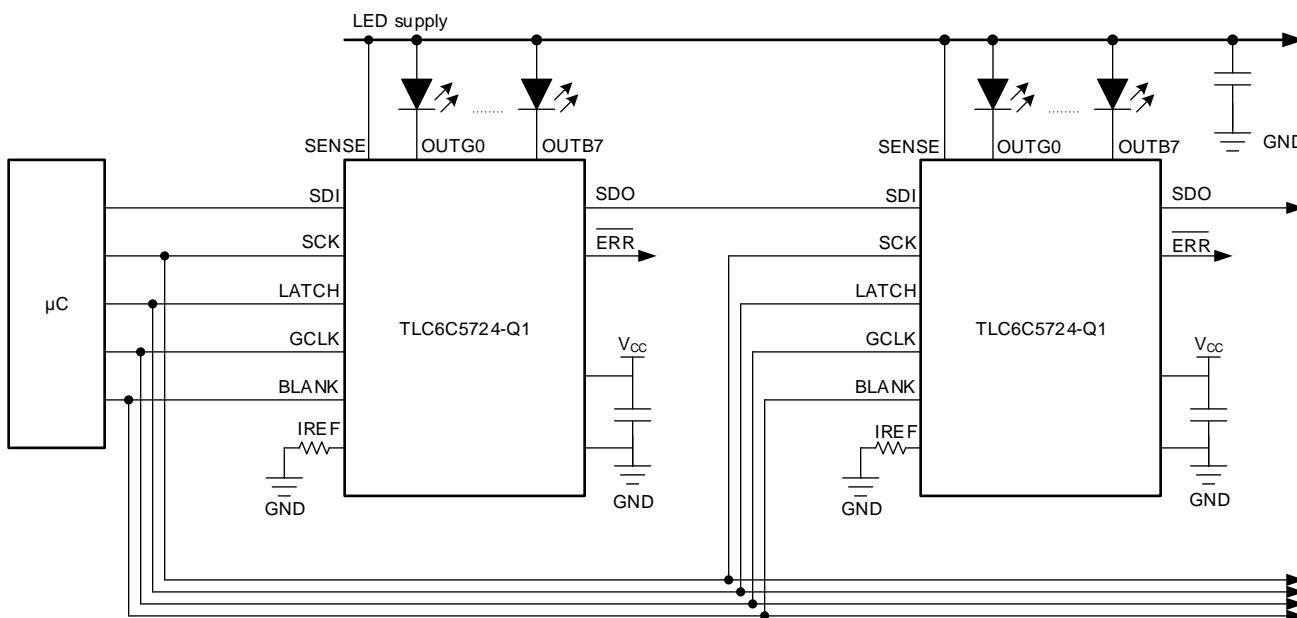


Figure 20. Typical Block Diagram for Local Dimming

This design rewrites both GS and DC data every frame. The number of bits and corresponding refresh time for one frame is calculated with [Equation 8](#) and [Equation 9](#).

$$\text{Bits} = (288 + 288) \times \text{LED Drivers} \quad (8)$$

$$\text{Refresh Time} = \text{Bits} \times \text{SPI Frequency} \quad (9)$$

If BC or DC does not get adjusted frame by frame, the refresh rate is cut in half since only 288 bits need to be loaded per LED driver instead of 576 bits. Other ways to increase refresh rates are to increase the SPI frequency or have multiple serial interfaces.

3.1.5 Animation and Brightness Control Scheme

This TI design loops through animations to demonstrate individual brightness and current adjustment. Several images and gradients, such as a line, circle, all-on gradient, and TI logo are animated and moved across the backlight array. Grayscale values are saved into an image array that defines the on-pixels and individual brightness of each image. Since each image pixel needs to be mapped to an individual channel and register setting, look-up tables are used to correlate pixel location to the LED driver number and channel. This mapping is specific to this TI design, depending on the order of serial communication, channel number, and location of the LED.

3.1.5.1 Ambient Lux to Brightness Algorithm

This TI design measures ambient brightness on a frame-by-frame basis, then modifies the global brightness of the backlight.

3.1.5.1.1 Input Lux to Backlight Brightness

Determining the best backlight brightness based on ambient light levels can vary from personal preference and application. The backlight levels of this design are based on a study completed by Microsoft®, [Understanding and Interpreting Lux Values](#), which discusses how humans perceive ambient light in an almost logarithmic function.

[Figure 21](#) shows the ambient input lux to backlight brightness curve used for this design.

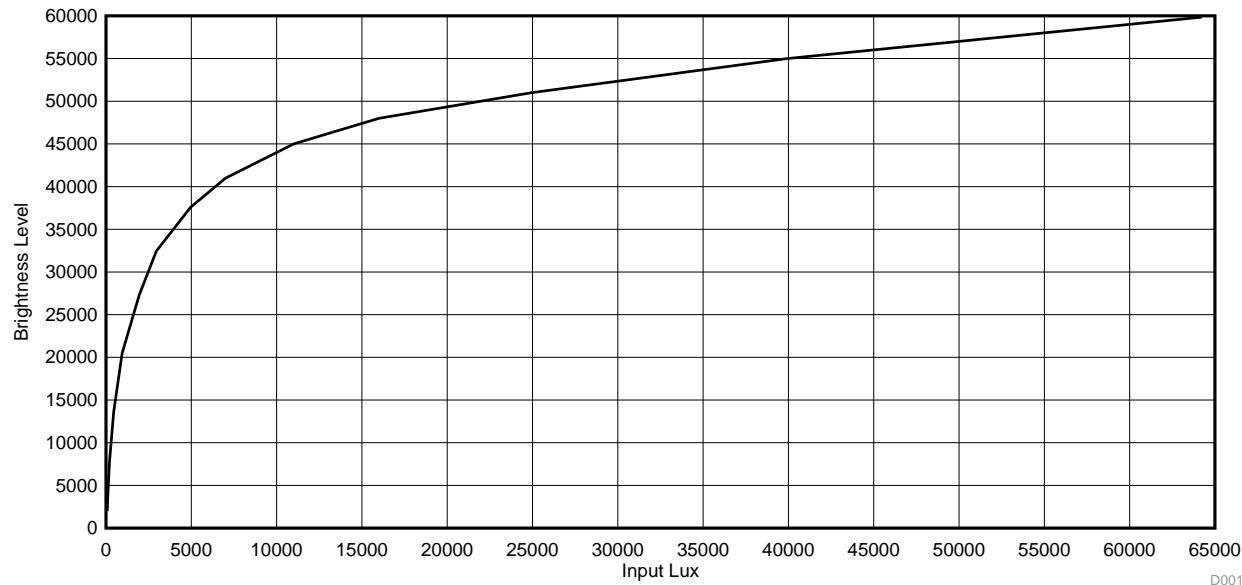


Figure 21. TIDA-020001 Ambient Lux to Backlight Brightness

The grayscale value (on-time brightness) set point defined in the image array is scaled based on the ambient-brightness to backlight-brightness curve in [Figure 21](#).

3.2 Testing and Results

Testing was performed on the major LED and power components in the system, including the TLC6C57xx-Q1 LED drivers and buck converters. [Section 3.2.1](#) describes the test setup and procedures for the tests performed. View the test results in [Section 3.2.2](#).

3.2.1 Test Setup

[Figure 22](#) shows the test setup for the TIDA-020001 reference design. The C2000 is connected to the LaunchPad headers on the bottom side of the board.

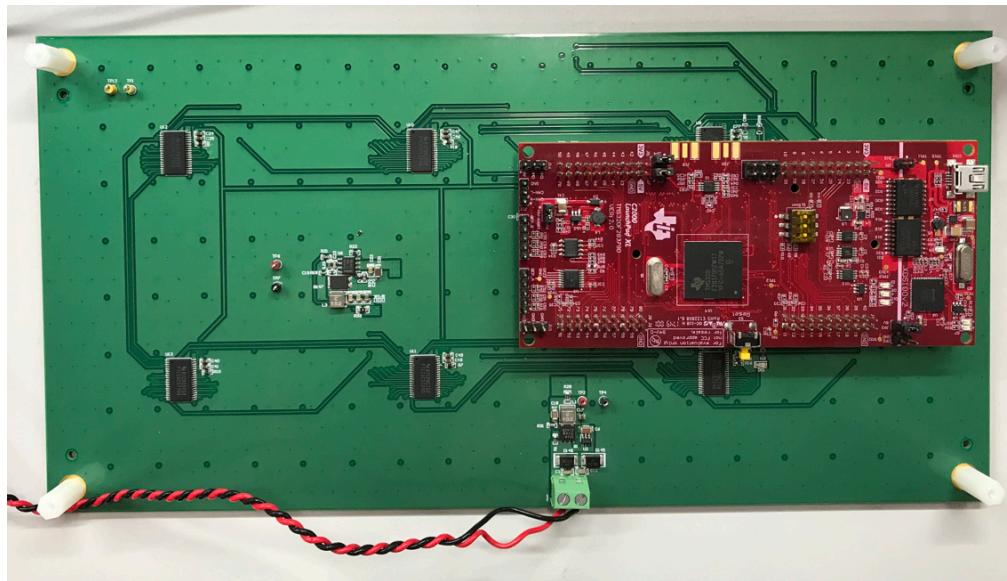


Figure 22. TIDA-020001 Test Setup

This reference design has individual channel control by looping through a series of animations. [Figure 23](#) through [Figure 25](#) present the different images that the LEDs create. The ball and line animation shows a gradient that demonstrates the individual on-time adjustment capability of the LEDs.

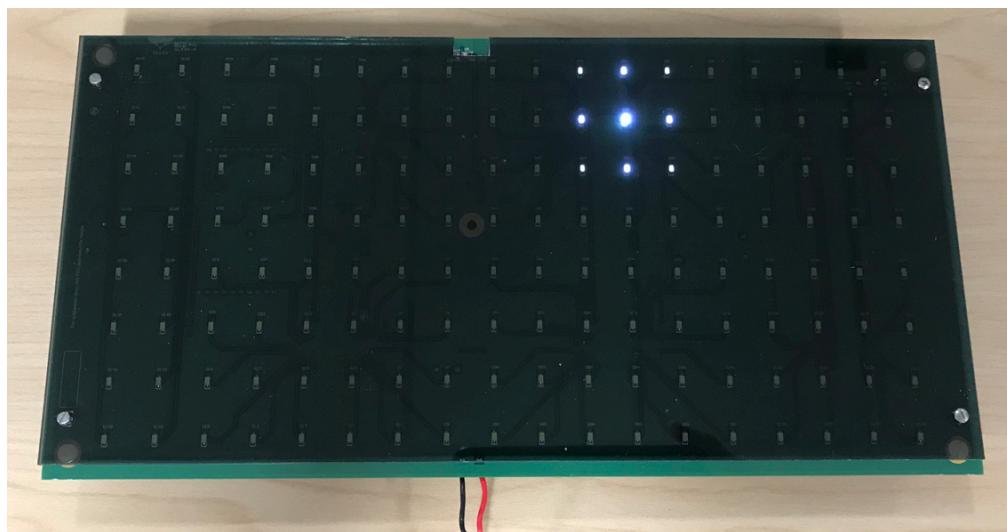


Figure 23. TIDA-020001 Animation - Ball

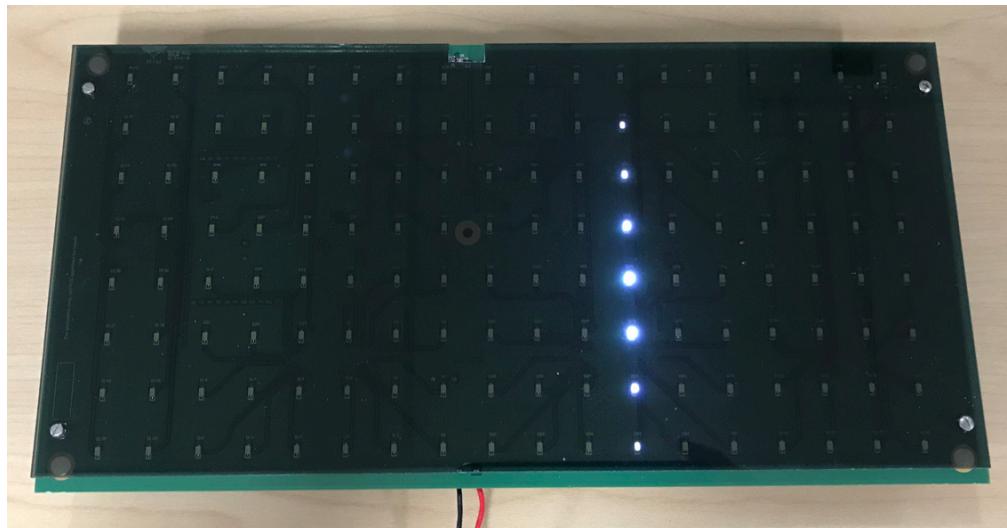


Figure 24. TIDA-020001 Animation - Line

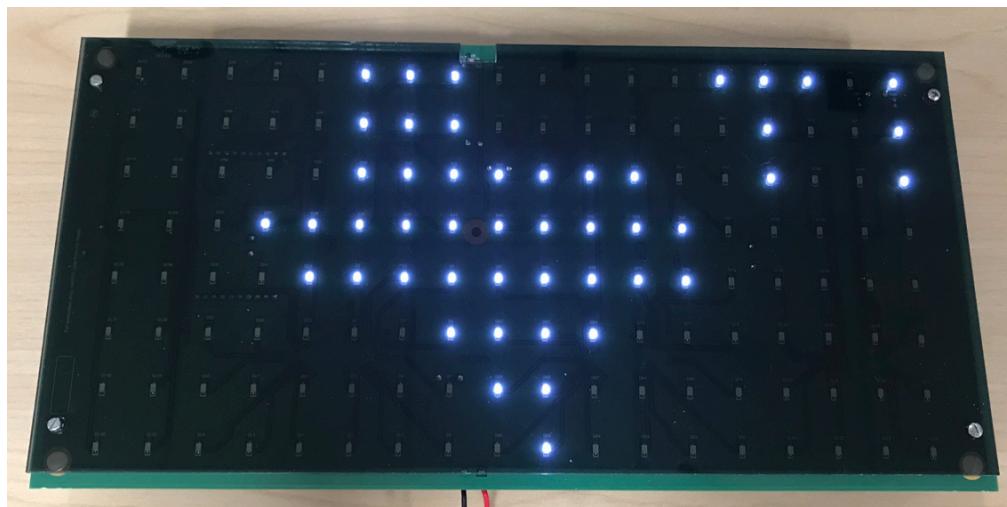


Figure 25. TIDA-020001 Animation - TI Logo

3.2.2 Test Results

This section highlights the test results of this reference design. Since the two buck converters in this design (U1 and U6) have the same schematic and marginal layout differences, the buck converter test results are only shown for U1 when the LEDs were disconnected from the output.

3.2.2.1 Buck Converter Switch Node

Figure 26 and Figure 27 show the switch node of the buck converter.

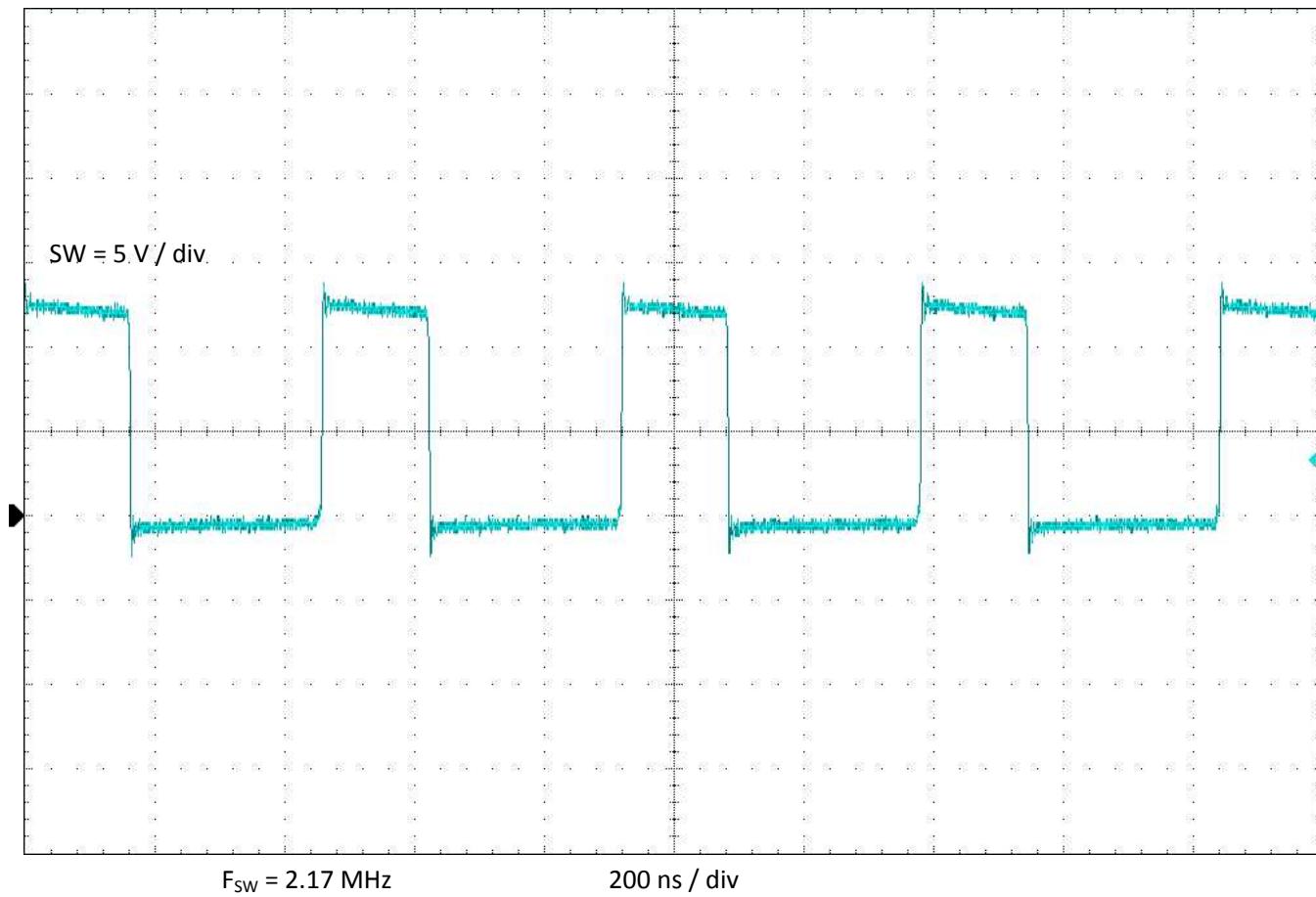


Figure 26. TIDA-020001 Switch Node

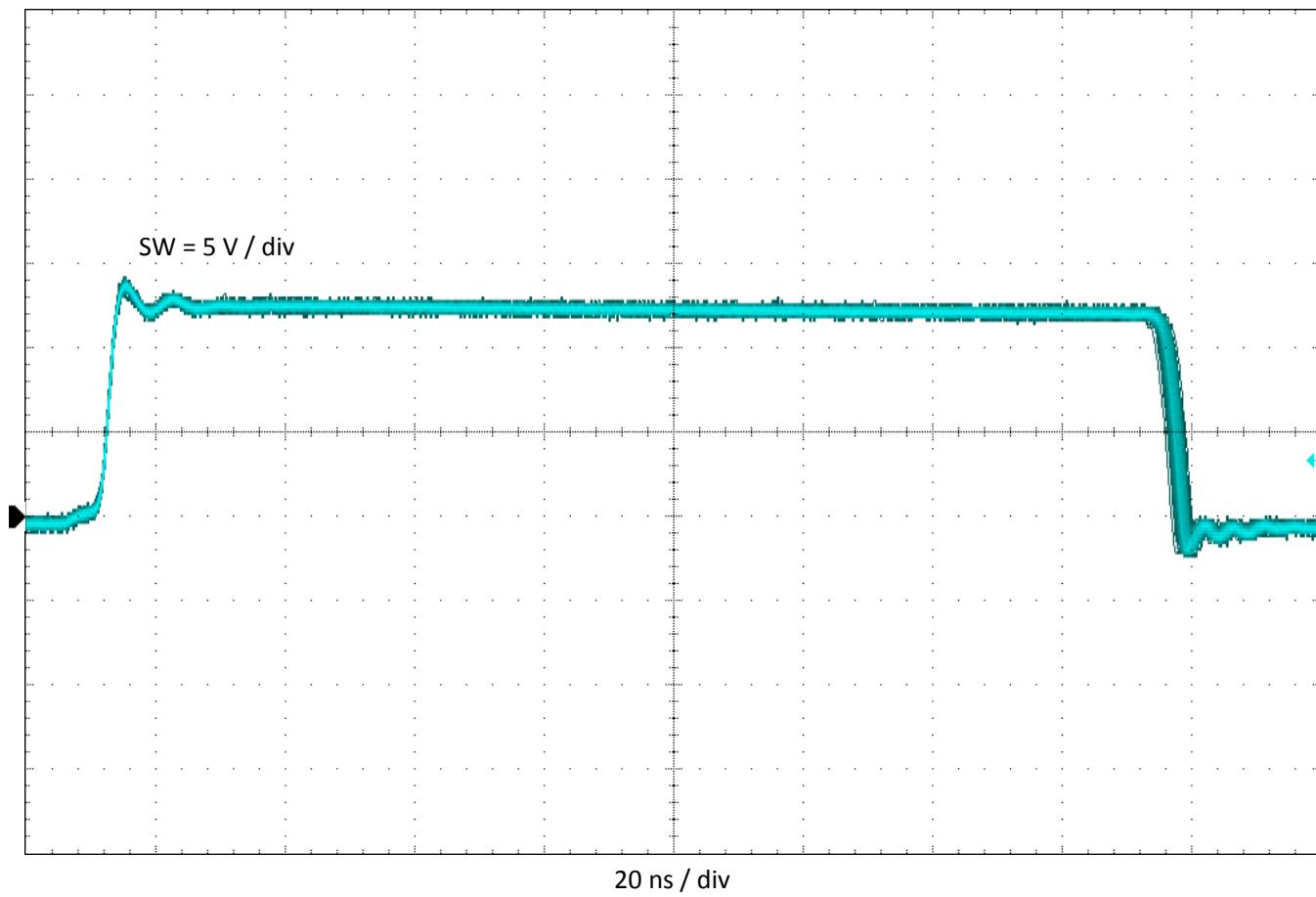


Figure 27. TIDA-020001 Switch Node Persistence

3.2.2.2 Buck Converter Output Ripple

Figure 28 shows the output ripple of the buck converter.

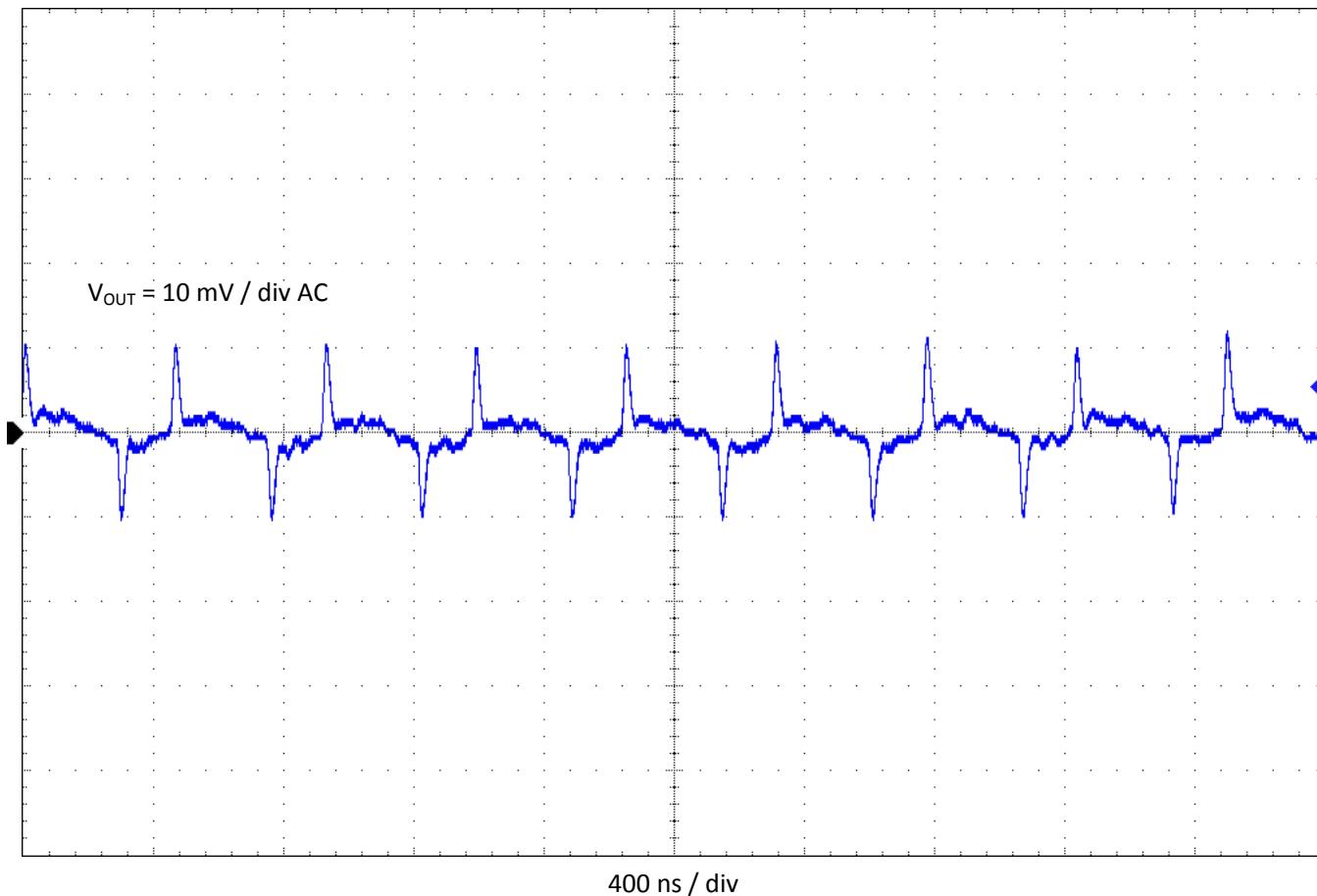


Figure 28. TIDA-020001 Output Ripple

3.2.3 Buck Converter Load Transient

Figure 29 shows the load transient of the buck converter.

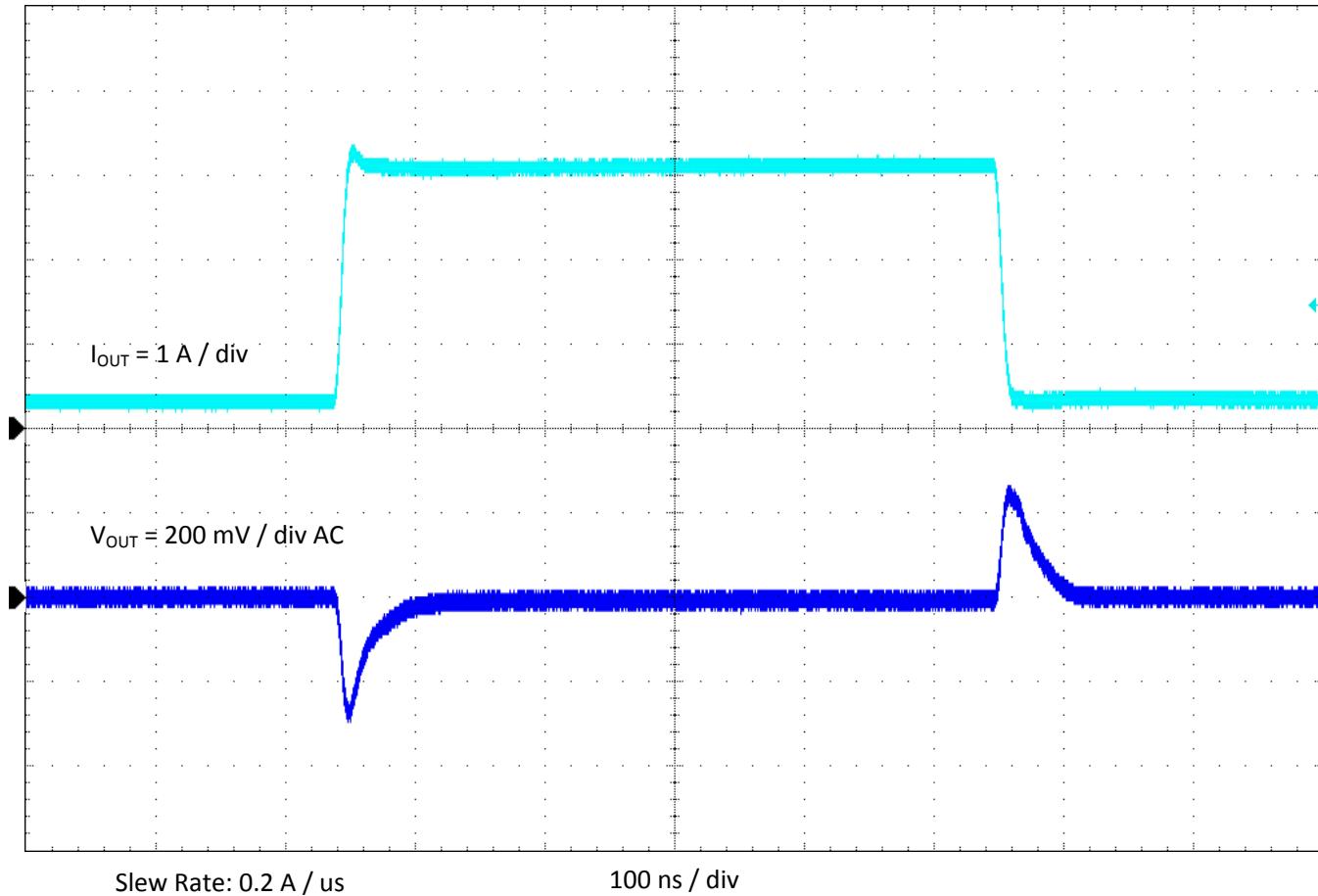


Figure 29. TIDA-020001 Load Transient

3.2.4 LED Driver Channel Control

The TLC6C724-Q1 LED drivers allow individual channel control of current and PWM on-time. Figure 30 demonstrates the adjustment of BC/DC (current) and grayscale (on-time) on two LEDs. The on-time and current set points are individually controlled for D98 (OUTB0/4 on U12) and D99 (OUTA1 on U12).

The LED frequency is 488 Hz, or 2.048 ms.

The grayscale (on-time) set point for D98 and D99 are both set to 33% with a value of 1365 in the 12-bit GS register, which corresponds to an on-time of 0.665 ms.

The 8-bit global brightness registers (BC) are all set to full brightness at 256. The dot-correction (DC) adjustment range is set to high, which corresponds to 33.3%–100% set points. The D98 current is set to 50% of the external current limiting resistor set point. The 7-bit DC register is set to 64. D99 current is set to 100% of the external current limiting resistor set point. The 7-bit DC register is set to 128. The measured current through D99 is 29.6 mA.

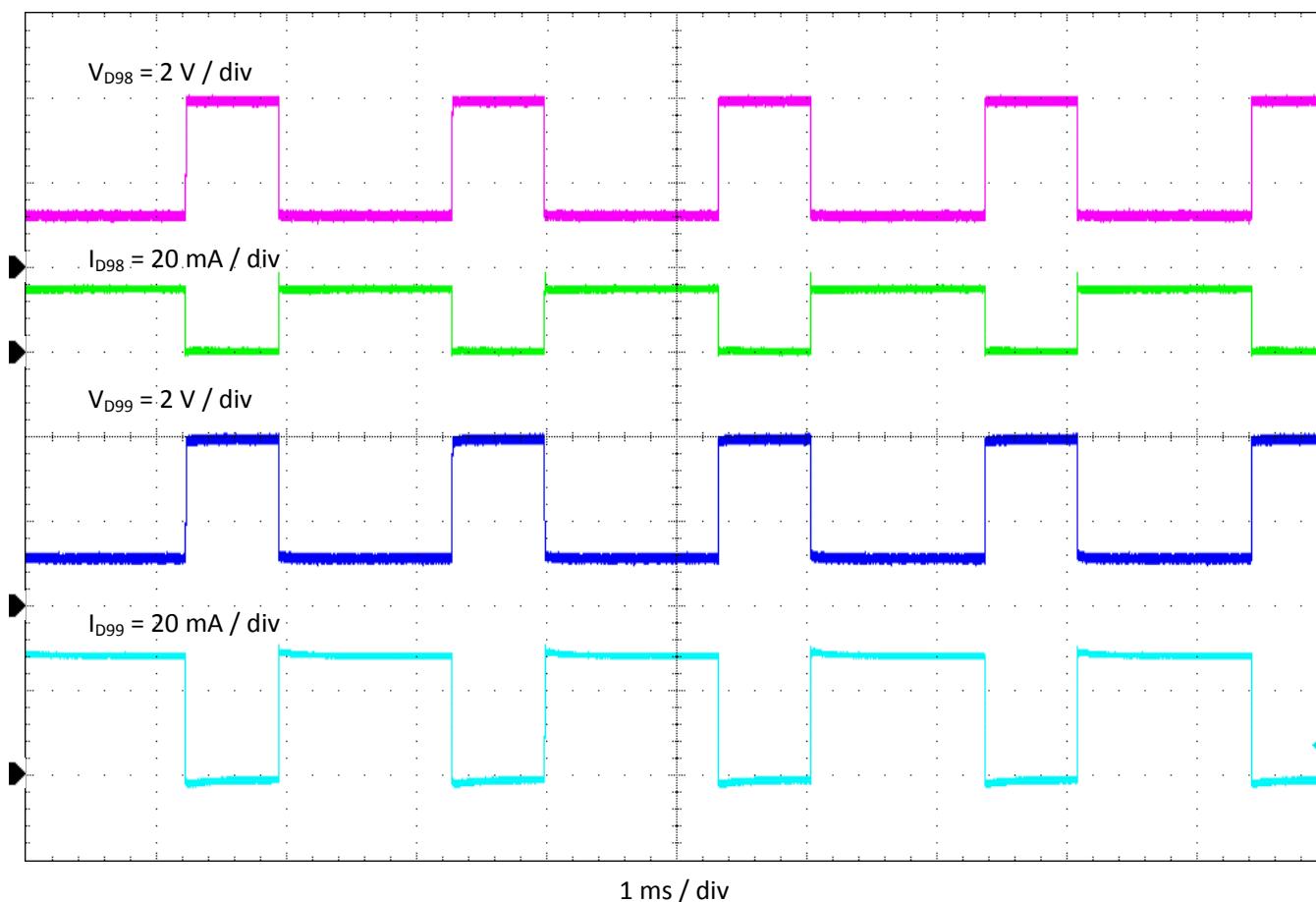


Figure 30. TIDA-020001 50% and 100% Current, 33% On-Time

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-020001](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-020001](#).

4.3 PCB Layout Recommendations

This reference design has four copper layers. Four layers allow routing on the internal layers and also an internal ground layer, which improves noise and thermals. Careful consideration was taken with the component placement in this design. All bypass capacitors are placed as close to the device pins as possible.

Each buck converter is placed centrally on each half of the PCB to limit the length of routing required to the LEDs. An internal layer is dedicated for the two 4 V bias power rails.

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-020001](#).

4.4 Altium Project

To download the Altium Designer® project files, see the design files at [TIDA-020001](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-020001](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-020001](#).

5 Software Files

To download the software files, see the design files at [TIDA-020001](#).

6 Related Documentation

1. Texas Instruments, [TLC6C5724-Q1 Automotive 24-Channel, Full Diagnostics, Constant-Current RGB LED Driver Data Sheet](#)
2. Texas Instruments, [TLC6C5716-Q1 Automotive 24-Channel, Full Diagnostics, Constant-Current RGB LED Driver Data Sheet](#)
3. Texas Instruments, [TPS22918-Q1, 5.5-V, 2-A, 52-mΩ On-Resistance Load Switch Data Sheet](#)
4. Texas Instruments, [OPT3001-Q1 Ambient Light Sensor \(ALS\) Data Sheet](#)
5. Texas Instruments, [LM74700-Q1 Low \$I_Q\$ Reverse Polarity Protection Ideal Diode Controller Data Sheet](#)
6. Texas Instruments, [LMR14030 SIMPLE SWITCHER® 40 V 3.5 A, 2.2 MHz Step-Down Converter with 40 \$\mu\text{A}\$ \$I_Q\$ Data Sheet](#)
7. Texas Instruments, [TPS7A52-Q1 2-A, High-Accuracy, Automotive-Grade, Low-Noise, LDO Voltage Regulator Data Sheet](#)
8. Texas Instruments, [LMT87-Q1 2.7-V, SC70, Analog Temperature Sensors With Class-AB Output Data Sheet](#)
9. Microsoft.com, [Understanding and Interpreting Lux Values](#)

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