TI Designs: TIDA-01586
IR LED Illumination and ICR Control Reference Design for IP Network Cameras With Day/Night Vision

TEXAS INSTRUMENTS

Description

This reference design showcases an Infrared LED illumination sub-system for Internet Protocol (IP) network cameras with day and night vision. The system features a cut filter control, LED dimming, ambient light measuring and ballasting for the current of each IR LED string. Ballasting is an alternative for driving multi-string LED arrays with a single string LED driver while maintaining uniform illumination under low-light conditions. The OPT3001 Ambient Light Sensor (ALS) with precise visible light measuring and good IR rejection, is an ideal preferred replacement for photodiodes, photoresistors or other ambient light sensors.

Resources

|	
TIDA-01586	Design Folder
TPS54202	Product Folder
TPS54201	Product Folder
TPS61169	Product Folder
TLV700	Product Folder
DRV8837C	Product Folder
CSD25402Q3A	Product Folder
OPT3001	Product Folder
MSP430FR2311 LaunchPad™	Tool Folder

ASK Our E2E™ Experts

Features

- Incorporates Current Ballasting to Equalize IR LED Currents Between Strings in a Multi-String LED Array While Using a Single-String LED Controller
- Offers Firmware-Adjustable Ambient Light Level Thresholds and Ambient Light Measurement Modes
- Offers PWM-Adjustable Illumination Brightness Levels
- Offers ICR Open or Close Control for Day and Night Vision by Using a Simple Motor Driver
- Incorporates the Ability to Operate From Either a 12-V or 5-V Power Supply
- Designed With Headers Compatible With BoosterPack™ Plug-in Module Ecosystem With Software Designed to Work With MSP430FR2311 MCU LaunchPad™

Applications

- IP Network Camera
- Analog Security Camera
- Video Doorbell

IR LED Illumination and ICR Control Reference Design for IP Network Cameras With Day/Night Vision
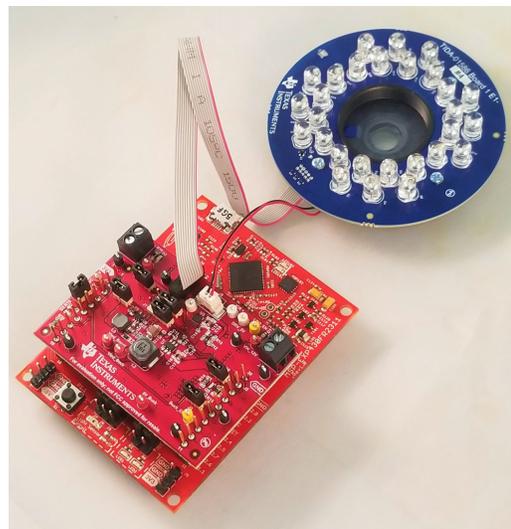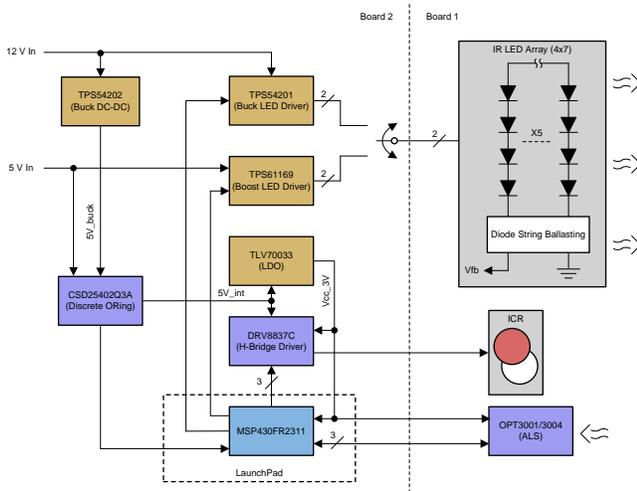
An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Description

Cameras are becoming more common in low-cost security applications. The ability to add functionality without affecting cost is attractive to manufacturers. TI's product offerings for the IR LED illumination sub-system of IP network camera systems used in video surveillance end equipment meet the low cost and small-size constraints of this application while adding features.

The low cost and small-size constraints make the use of multi-channel LED drivers prohibitive for large-array LED illumination. The problem is how to drive a large LED array with a single string LED driver while maintaining uniform illumination using low-cost (non-matched) LEDs. Ballasting is an alternative for driving multi-string LED arrays with a single string LED driver while maintaining uniform illumination without significant increases to cost and size.

Use of the OPT3001 device as the ambient light sensor (ALS) eliminates the need for analog signal-chain components and calibration when compared to techniques using LDRs as the ALS device.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Power supply voltage	12 V ±10% or 5 V ±10%	Section 2.4.1
IR LED array total current	180 mA	Section 3.2.2.2
IR LED minimum illumination	0.01 lux at (F1.2 AGC ON)	Section 3.2.2.2
IR LED string current matching	< 5%	Section 3.2.2.2
IR LED wavelength	850 nm	Section 2.4.2
ICR transition duration	< 500 ms	Section 3.2.2.4
Average power dissipation	< 2.5 W	Section 2.4.1
Operation temperature	–40°C to 85°C	Section 2.3

2   System Overview

2.1   Block Diagram

Figure 1 illustrates the TIDA-01586 block diagram.
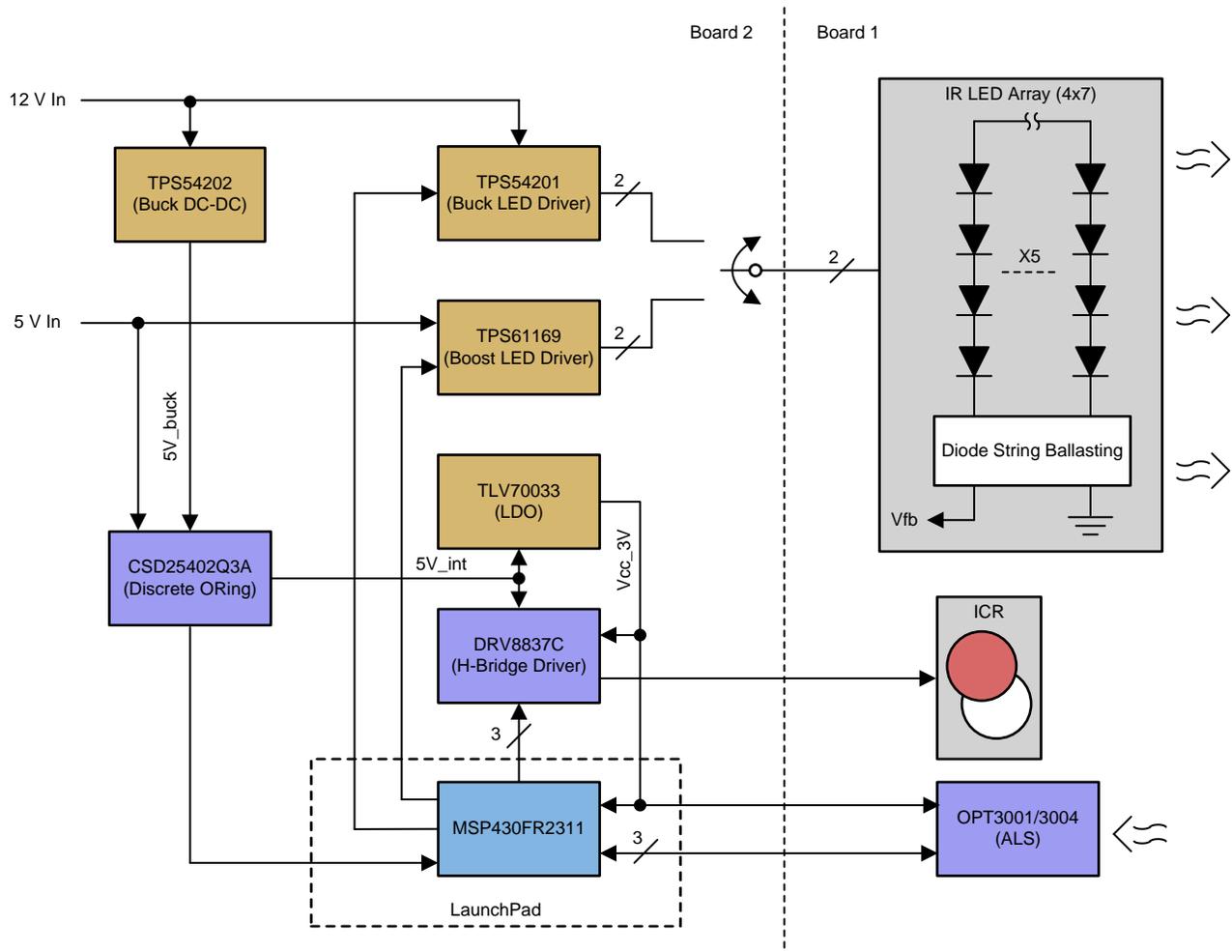
Figure 1. TIDA-01586 Block Diagram

2.2   Design Considerations

The low cost and small size constraints make the use of multi-channel LED drivers prohibitive for large array LED illumination. The problem is how to drive a large LED array with a single string LED driver while maintaining uniform illumination using low cost (non-matched) LEDs. Ballasting is an alternative for driving multi-string LED arrays with a single string LED driver while maintaining uniform illumination without significant increases to cost and size.

The camera can capture good images through the opening or closing of infrared cut-off removal (ICR) to change the intensity of light that comes into the camera, and adjusting the IR LEDs dimming pulse-width modulation (PWM) duty cycle based on the ambient light levels.

Several considerations are taken into account for this particular design:

* LED size, numbers, and ways of connecting for meeting the requirement of IR lighting range
* Uniform illumination for multi-string LED arrays
* LED smoothly implementing dimming control
* Adjustable ambient light threshold setting for ICR action and LED dimming

- Adjustable ambient light hysteresis setting to avoid ICR frequent action

These considerations apply to most video surveillance end equipment with day and night vision designs in some way, but the designer must decide the particular considerations to take into account for a specific design.

2.3 Highlighted Products

2.3.1 MSP430FR2311 LaunchPad™

The MSP430FR231x ferroelectric RAM (FRAM) microcontrollers (MCUs) are part of the MSP430™ MCU value line sensing family. The devices integrate a configurable low-leakage transimpedance amplifier (TIA) and a general-purpose operational amplifier. The MCUs feature a powerful 16-bit RISC CPU, 16-bit registers, and a constant generator that contributes to maximum code efficiency. The digitally-controlled oscillator (DCO) also allows the device to wake up from low-power modes to active mode typically in less than 10 μs. The feature set of these MCUs are well suited for applications ranging from smoke detectors to portable health and fitness accessories.

The ultra-low-power MSP430FR231x MCU family consists of several devices that feature embedded nonvolatile FRAM and different sets of peripherals targeted for various sensing and measurement applications. The architecture, FRAM, and peripherals, combined with extensive low-power modes, are optimized to achieve extended battery life in portable and wireless sensing applications. FRAM is a nonvolatile memory technology that combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash at lower total power consumption.

The MSP430FR231x MCUs are supported by an extensive hardware and software ecosystem with reference designs and code examples to get your design started quickly. Development kits include the *MSP430FR2311 LaunchPad Development Kit* and the MSP-TS430PW20 20-pin Target Development Board. TI provides free MSP430Ware™ software, available as a component of the Code Composer Studio™ IDE desktop and cloud versions within TI Resource Explorer. The MSP430 MCUs are also supported by extensive online collateral, training, and online support through the E2E Community Forum.

The MSP430FR2311 MCU is the next device in TI's new ultra-low-power FRAM technology platform. FRAM is a cutting-edge memory technology, combining the best features of flash and RAM into one nonvolatile memory.

The device features include:
- 1.8-V to 3.6-V Operation
- 16-bit RISC Architecture With up to 16-MHz System Clock and 8-MHz FRAM Access
- Optimized Low-Power Modes (at 3 V)
  - Active Mode: 126 μA/MHz
  - Standby: Real-Time Clock (RTC) Counter (LPM3.5 With 32768-Hz Crystal): 0.71 μA
  - Shutdown (LPM4.5): 32 nA Without SVS
- Low-Power Ferroelectric RAM (FRAM)
  - Up to 3.75KB of Nonvolatile Memory
  - Built-In Error Correction Code (ECC)
  - Configurable Write Protection
  - Unified Memory of Program, Constants, and Storage
  - 1015 Write-Cycle Endurance
  - Radiation Resistant and Nonmagnetic
- 8-Channel 10-bit ADC
- Operational Amplifier Supporting Multiple Modes
- Transimpedance Amplifier
- Clock System (CS)
  - On-Chip 32-kHz RC Oscillator (REFO)
  - On-Chip 16-MHz Digitally-Controlled Oscillator (DCO) With Frequency Locked Loop (FLL) : ±1%

Accuracy With On-Chip Reference at Room Temperature
  – On-Chip Very Low-Frequency 10-kHz Oscillator (VLO)
  – On-Chip High-Frequency Modulation Oscillator (MODOSC)
  – External 32-kHz Crystal Oscillator (LFXT)
  – External High-Frequency Crystal Oscillator up to 16 MHz (HFXT)
  – Programmable MCLK Prescalar of 1 to 128
  – SMCLK Derived From MCLK With Programmable Prescalar of 1, 2, 4, or 8
- Three Timers
- Direct Memory Access
- General I/O and Pin Functionality
  – 16 I/Os on a 20-pin Package
  – 12 Interrupt pins (8 pins of P1 and 4 pins of P2) can Wake the MCU From LPMs
  – All I/Os are Capacitive Touch I/Os
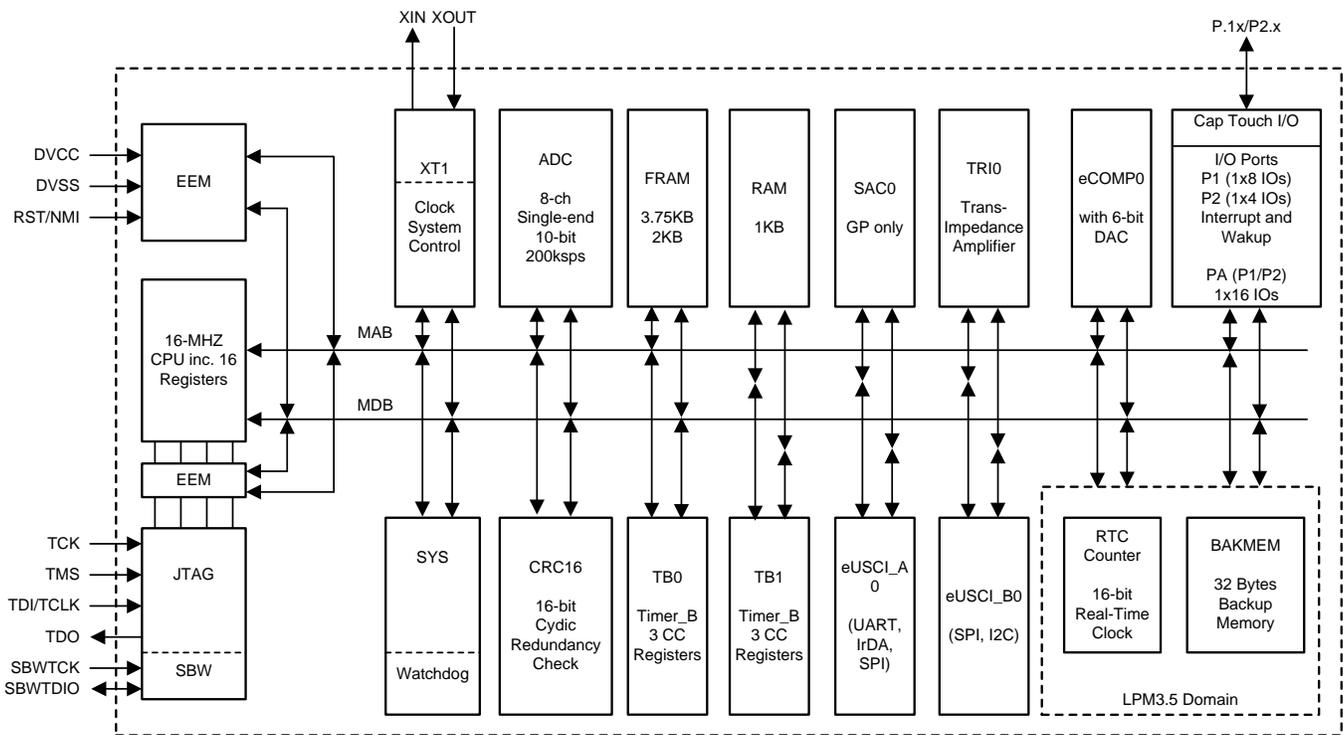
Figure 2. MSP430FR231x Functional Block Diagram

2.3.2   TPS54201

The TPS5420x device is a 1.5-A synchronous buck LED driver with up to 28-V input. Current-mode operation provides fast transient response. The optimized internal compensation network minimizes the external component counts and simplifies the control-loop design.

A fixed 600-kHz switching frequency is chosen for a good tradeoff between efficiency and size.

The integrated 150-mΩ high-side MOSFET and 70-mΩ low-side MOSFET allow for the high-efficiency LED driver with continuous output currents up to 1.5 A.

The TPS5420x device supports deep dimming in both analog and PWM dimming mode. In analog dimming mode, the internal reference voltage is changed proportional to the duty cycle of PWM signal in the 1% to 100% range. In PWM dimming mode, the LED is periodically turned on and off according to the PWM duty cycle. For higher efficiency, the internal reference will be halved to 100 mV.

The cycle-by-cycle current limit in high-side MOSFET protects the converter in an overload condition and is enhanced by a low-side MOSFET freewheeling current limit which prevents current runaway. There is a low-side MOSFET sinking current limit to prevent excessive reverse current. For safety and protection, the TPS54200 and TPS54201 devices include LED open and short protection, sense resistor open and short protection, and device thermal protection. The TPS54200 device implements shutdown-and-latch mode protection, while the TPS54201 device adopts hiccup-mode protection.

The device features include:

- Integrated 150-mΩ and 70-mΩ MOSFETs for 1.5-A, Continuous Output Current
- SOT23-6 Compact Package
- Precision Analog Dimming by PWM Input
- 4.5-V to 28-V Wide Input Range
- Low, 2-μA Shutdown Current
- Fixed 600-kHz Frequency
- Peak Current Mode with Internal Compensation
- LED Open and Short Protection
- Sense Resistor Open and Short Protection
- Shutdown-and-Latch Mode Protection (TPS54200) and Hiccup Mode Protection (TPS54201)
- Thermal Shutdown

Figure 3 shows the TPS54201 functional block diagram.
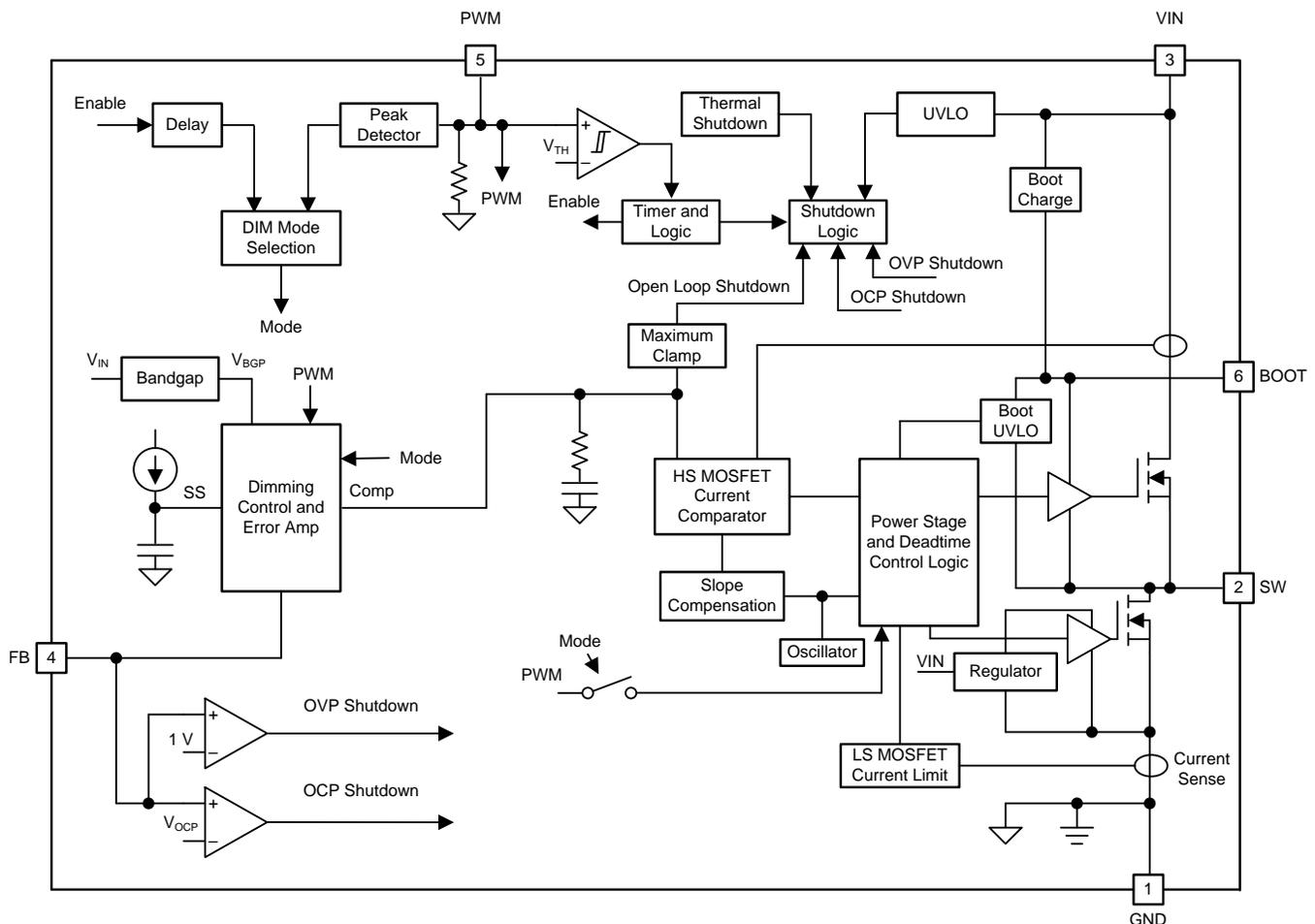
Figure 3. TPS54201 Functional Block Diagram

2.3.3 TPS61169

The TPS61169 is a high-efficiency, high-output voltage boost converter in small package size. The device integrates a 40-V, 1.8-A switch FET and is designed for output voltage up to 39 V with a switch peak current limit of 1.2 A minimum. Its large driving capability can drive single or parallel LED strings for small to large size panel backlighting.

The TPS61169 device operates in a current mode scheme with quasi-constant frequency. It is internally compensated for maximum flexibility and stability. The switching frequency is 1.2 MHz, and the minimum input voltage is 2.7 V. During the on-time, the current rises into the inductor. When the current reaches a threshold value set by the internal GM amplifier, the power switch MOSFET is turned off. The polarity of the inductor changes and forward biases the Schottky diode which lets the current flow towards the output of the boost converter. The off-time is fixed for a certain V_{IN} and V_{OUT}, and therefore maintains the same frequency when varying these parameters.

However, for different output loads, the frequency slightly changes due to the voltage drop across the $R_{DS(on)}$ of the power switch MOSFET, this has an effect on the voltage across the inductor and thus on tON (tOFF remains fixed). The fixed off-time maintains a quasi-fixed frequency that provides better stability for the system over a wider range of input and output voltages than conventional boost converters. The TPS61169 topology has also the benefits of providing very good load and line regulations, and excellent line and load transient responses.

The feedback loop regulates the FB pin to a low reference voltage (204 mV typical), reducing the power dissipation in the current sense resistor.

The device features include:

- 1.2-A Minimum Switch Current Limit
- 5-pin SC70 Package
- PWM Brightness Control
- 1.2-MHz Switching Frequency
- 2.7-V to 5.5-V Input Voltage
- Integrated 40-V, 1.8-A MOSFET
- Up to 90% Efficiency
- Drives LED String up to 38 V
- Internal Compensation
- Open LED Protection
- Undervoltage Protection
- Built-in Soft-Start
- Thermal Shutdown

Figure 4 shows the TPS61169 functional block diagram.

Figure 4. TPS61169 Functional Block Diagram

2.3.4 DRV8837C

The DRV883x family of devices provides an integrated motor driver solution for cameras, consumer products, toys, and other low-voltage or battery-powered motion control applications. The device can drive one dc motor or other devices like solenoids. The output driver block consists of Nchannel power MOSFETs configured as an H-bridge to drive the motor winding. An internal charge pump generates needed gate-drive voltages.

The DRV883x family of devices can supply up to 1.8 A of output current. It operates on a motor power supply voltage from 0 to 11 V, and a device power supply voltage of 1.8 V to 7 V.

The DRV8837C device has a PWM (IN1-IN2) input interface; the DRV8838 device has a PH-EN input interface. Both interfaces are compatible with industry-standard devices.

These devices greatly reduce the component count of motor driver systems by integrating the necessary driver FETs and FET control circuitry into a single device. In addition, the DRV883x family of devices adds protection features beyond traditional discrete implementations: undervoltage lockout, overcurrent protection, and thermal shutdown.

The device features include:
- H-Bridge Motor Driver:
  - Drives a DC Motor or Other Loads
  - Low MOSFET On-Resistance: HS + LS 280 mΩ
- 1.8-A Maximum Drive Current
- Small Package and Footprint:
  - 8-Pin WSON With Thermal Pad

- – 2.0 × 2.0 mm
- Separate Motor and Logic Supply Pins:
  - – Motor VM: 0 to 11 V
  - – Logic VCC: 1.8 to 7 V
- PWM or PH-EN Interface:
  - – DRV8837C: PWM, IN1 and IN2
  - – DRV8838: PH and EN
- Low-Power Sleep Mode With 120-nA Maximum Sleep Current
- Protection Features:
  - – VCC Undervoltage Lockout (UVLO)
  - – Overcurrent Protection (OCP)
  - – Thermal Shutdown (TSD)

Figure 5 illustrates the DRV8837C functional block diagram.
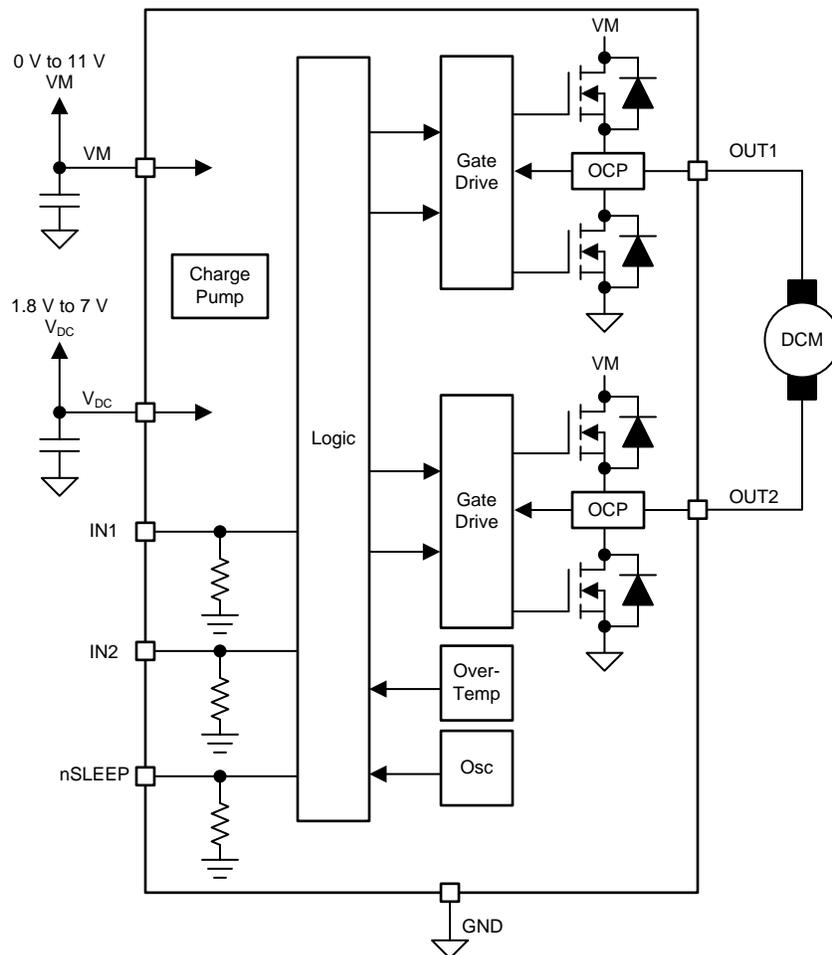
Figure 5. DRV8837C Functional Block Diagram

IR LED Illumination and ICR Control Reference Design for IP Network
Cameras With Day/Night Vision

2.3.5 OPT3001

The OPT3001 device measures the ambient light that illuminates the device. This device measures light with a spectral response very closely matched to the human eye, and with very good infrared rejection.

Matching the sensor spectral response to that of the human eye response is vital because ambient light sensors are used to measure and help create ideal human lighting experiences. Strong rejection of infrared light, which a human does not see, is a crucial component of this matching. This matching makes the OPT3001 especially good for operation underneath windows that are visibly dark, but infrared transmissive.

The OPT3001 device is fully self-contained to measure the ambient light and report the result in lux digitally over the I^{2}C bus. The result can also be used to alert a system and interrupt a processor with the INT pin. The result can also be summarized with a programmable window comparison and communicated with the INT pin.

The OPT3001 device can be configured into an automatic full-scale, range-setting mode that always selects the optimal full-scale range setting for the lighting conditions. This mode frees the user from having to program their software for potential iterative cycles of measurement and readjustment of the full-scale range until optimal for any given measurement. The device can be commanded to operate continuously or in single-shot measurement modes.

The device integrates its result over either 100 ms or 800 ms, so the effects of 50-Hz and 60-Hz noise sources from typical light bulbs are nominally reduced to a minimum.

The device starts up in a low-power shutdown state, such that the OPT3001 device only consumes active-operation power after being programmed into an active state.

The optical filtering system of the OPT3001 device is not excessively sensitive to non-ideal particles and micro-shadows on the optical surface. This reduced sensitivity is a result of the relatively minor device dependency on uniform density optical illumination of the sensor area for infrared rejection. Proper optical surface cleanliness is always recommended for best results on all optical devices.

The device features include:
- Precision Optical Filtering to Match Human Eye:
  - Rejects > 99% (typ) of IR
- Automatic Full-Scale Setting Feature Simplifies Software and Ensures Proper Configuration
- Interrupt Operation, INT Pin, and Interrupt Reporting Mechanisms
- Compatibility With Both I^{2}C and SMBus Interfaces
- Measurements: 0.01 Lux to 83 k Lux
- 23-Bit Effective Dynamic Range With Automatic Gain Ranging
- 12 Binary-Weighted Full-Scale Range Settings:
  - < 2% (typ) Matching Between Ranges
- Low Operating Current: 1.8 µA (typ)
- Operating Temperature Range: –40°C to +85°C
- Wide Power-Supply Range: 1.6 V to 3.6 V
- 5.5-V Tolerant I/O
- Flexible Interrupt System
- Small-Form Factor: 2.0 mm × 2.0 mm × 0.65 mm

Figure 6 illustrates the OPT3001 functional block diagram.
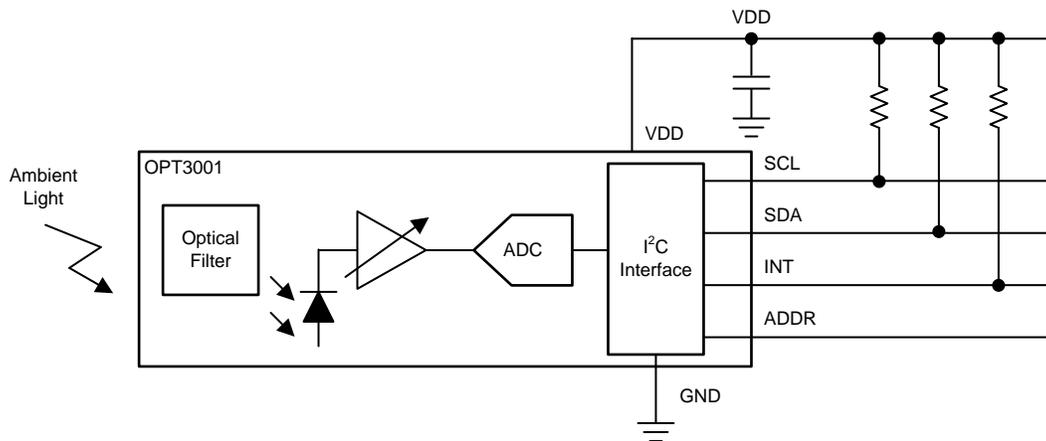
Figure 6. OPT3001 Functional Block Diagram

2.4 System Design Theory

2.4.1 Power Supply Design Theory

Generally, 5-V or 12-V supplies are provided for IR LEDs in end equipment like IP network cameras, analog security cameras, or video doorbells. This reference design showcases a solution that has compatibility for 5-V and 12-V input voltages, to supply a reference design for the customer in either of these two input voltages. Consider that the output voltage of the LED array is about 8 V, when setting 12 V as the input voltage, there need a buck LED driver, while setting 5 V as the input voltage, there need a boost LED driver. And an ORing circuit is designed to supply the power for other parts of the system.

Figure 7 shows the ORing circuit using two CSD25402Q3A PMOS. When giving a 12-V input, Q2 is "OFF", Q3 is "ON" since VIN_5V is open and the Q3 gate is pulled down to 0-V by R9. Output DRV_5V is driven by the 5v_buck rail generated by the 12-V input. Inversely, when giving a 5-V input, Q3 is "OFF", Q2 is "ON" since VIN_12V is open and the Q2 gate is pulled down to 0-V by R8. Output DRV_5V is driven by the vin_5vor rail generated by the 5-V input.
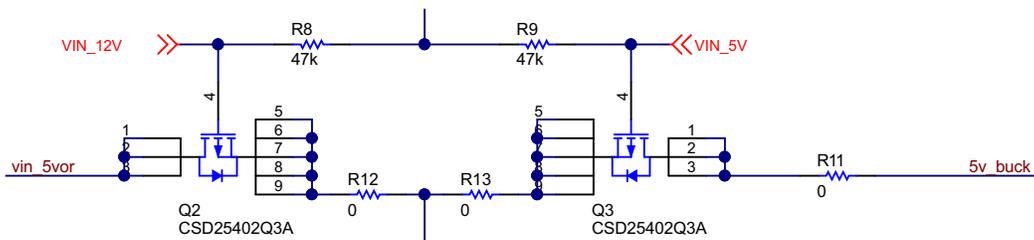
Figure 7. ORing Circuit for 12-V and 5-V Input

2.4.2 LED-String Array and Uniform Illumination Design Theory

IR LED power which is proportional to LED forward current, determines the LED illumination range. Based on the customer requirement for the IR illumination range, the total LED current can be known. The high power LEDs are not suitable for this design because of their high cost and bigger in size. Meanwhile, if connecting all LEDs to a single string, the voltage of which may exceed the regular output voltage range of LED drivers, this may increase the cost and difficulty of the system design. Multi-string LED arrays with a suitable output voltage will be a good method which cannot only balance the single LED current and LED string output voltage, but also improve the uniform coverage for a specific lighting area.

This design shows a method to drive 28 IR LEDs with a single LED driver. Assume the required total current of all the LEDs is 700 mA for this design, so the single LED forward current is 25 mA. Meanwhile, the output voltage is designed to about 8.5 V to meet the output voltage of the buck LED driver, the boost LED driver, and the worst-case output voltage for these two LED drivers.

Before deciding on the number of LEDs in each string, introduce the ballasting current mirror circuit to give an additional voltage drop for each string of LEDs. Because of material defects and processing technology errors, the parameters and performance of LEDs are not exactly the same, which will cause the slight difference for V-I curves among the LEDs. Current mirror ballasting is an alternative for driving multi-string LED arrays with a single string LED driver while maintaining uniform illumination. A current mirror is a circuit designed to copy a current through one active device by controlling the current in another active device of a circuit, keeping the output current constant regardless of loading.

Figure 8 shows an IR LED array with current mirror ballasting. Transistor Q1 is used to supply the base current for Q8, Q2, Q3, Q4, Q5, Q6, and Q7. Observing the first two strings, for example, the bipolar transistors base of Q8 is directly connected to the base of Q2, because Q8 and Q2 have the same resistor value connected between emitter and ground. Assuming their Vbe value is the same, the mirror collector current of Q2 will be the same as the collector current of Q8, as long as β and early voltage Va of the transistor being used are both large. The voltage drop across Q8 is V_{BE-Q1} + V_{BE-Q8}, which is nearly 1.2 V.

By using 8.5-V output voltage minus the Q8 voltage drop of 1.2 V and a reference voltage 0.2 V, the voltage for the LED string is 7.1 V, which is larger than the voltage of 4 of the LEDs string in series but smaller than the voltage of 5 LEDs string in series. So, the LEDs number in one string are 4 and there will be 7 strings in parallel. Figure 8 shows the design of the LED arrays.
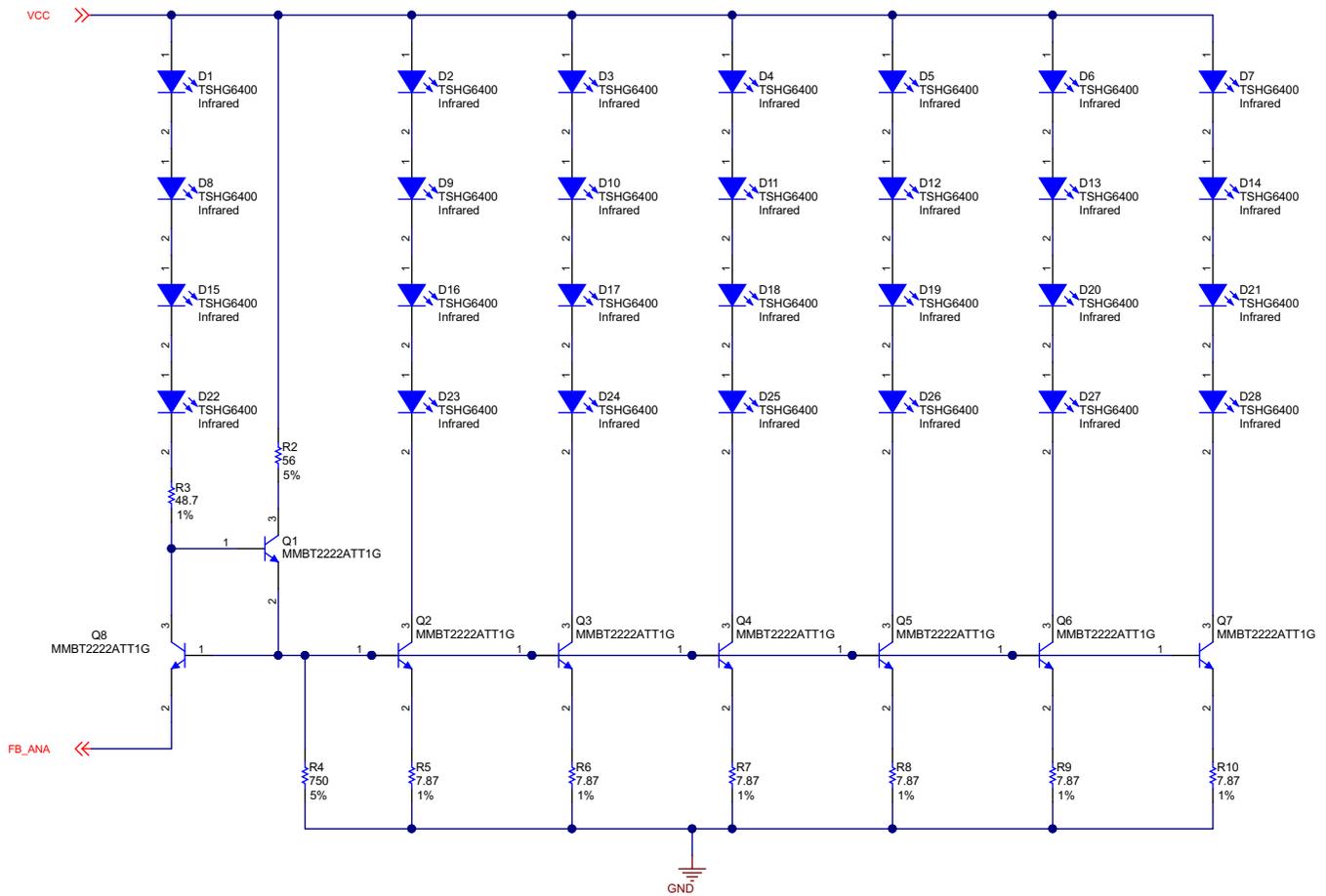
Figure 8. IR LED Arrays With Ballasting

Figure 9 shows the simulation without current mirror ballasting. The LEDs in the simulation circuit have the same parameters and the TPS54200 and TPS54201 have the same transient model. The input voltage is set to 12 V and the PWM control pin receives a 3.3-V voltage. The inductor is set to 180 µH with a resistance of 0.75 Ω. V4, V5, V6, and V7 are added to simulate the difference in forward voltage versus forward current for LEDs in the left two strings, and AM1, AM2, and AM3 are the current sensors. Figure 10 shows the simulation result when setting V4 = 0.5 V and V7 = 0.5 V..

IR LED Illumination and ICR Control Reference Design for IP Network Cameras With Day/Night Vision
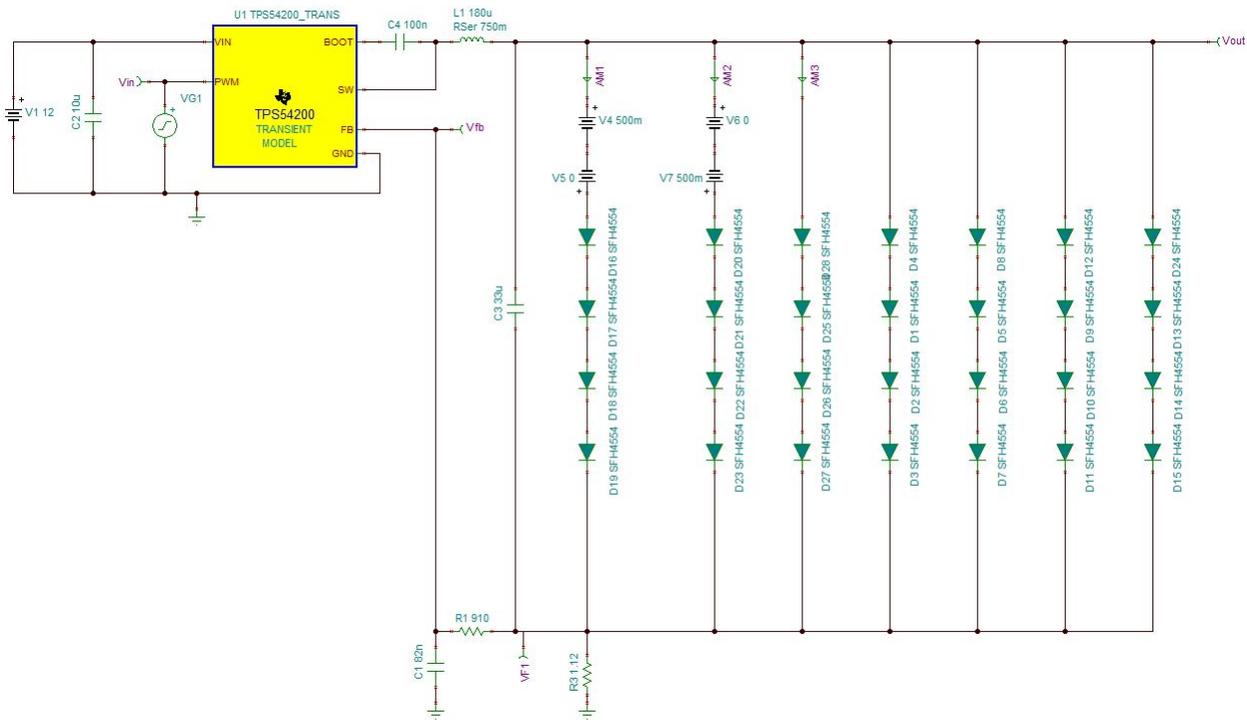
Figure 9. Simulation Circuit Without Channel Ballasting

The current in the left three strings of the circuit are 2.7 mA, 63.9 mA and 22.4 mA in the simulation curves, they have a large difference which comes from the unbalance of the LED string. Ballasting is required to match each string in any condition.
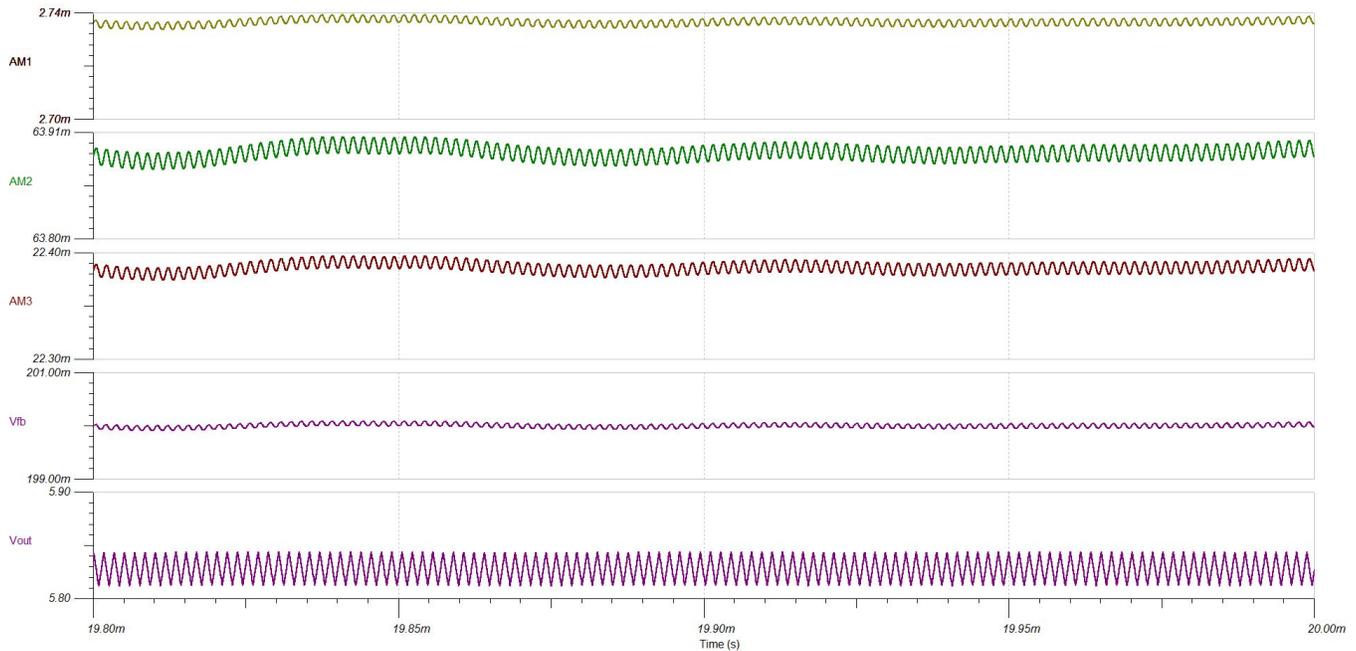
Figure 10. Simulation Results Without Channel Ballasting

Figure 11 shows the simulation with current mirror ballasting. BJTs and sensor resistors are used on each LED string. Figure 12 shows the simulation result.
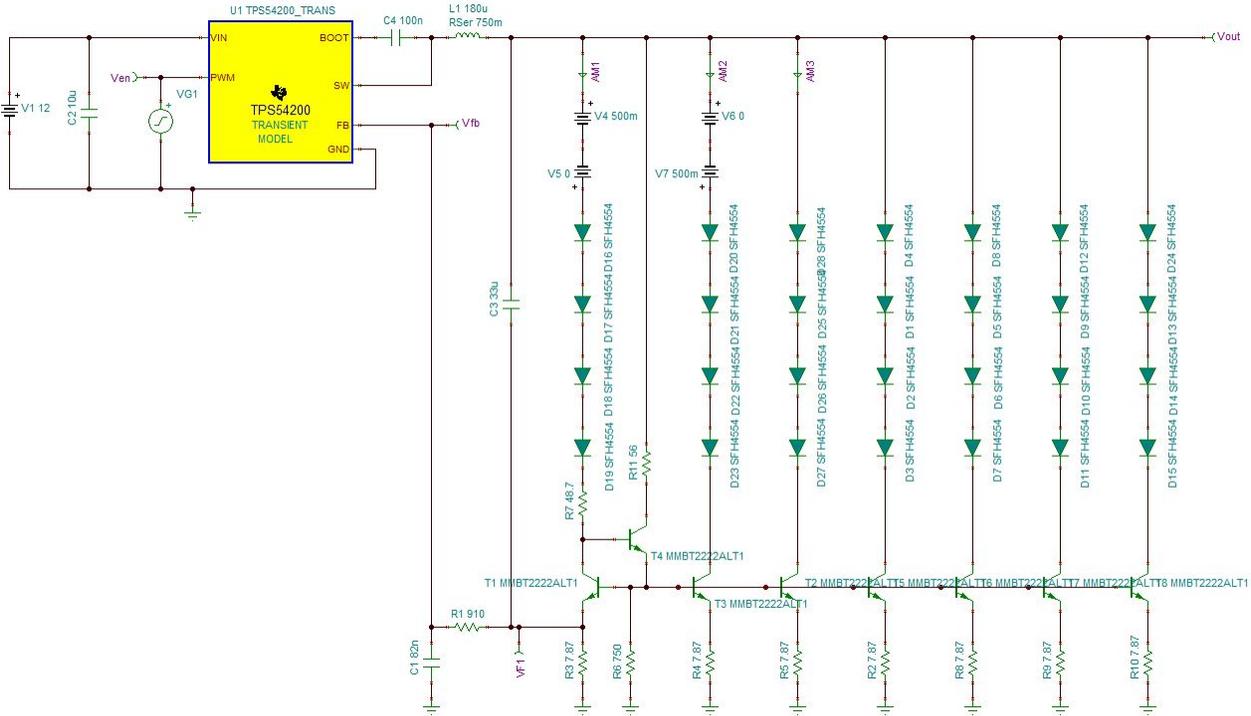
Figure 11. Simulation Circuit With Channel Ballasting

The current in the left three strings of the circuit are 25 mA, 25.5 mA and 25.5 mA in the simulation curves. It can be concluded that the output current of each LED string is nearly the same, the ballasting circuit can realize the current by copying from one string to the others.
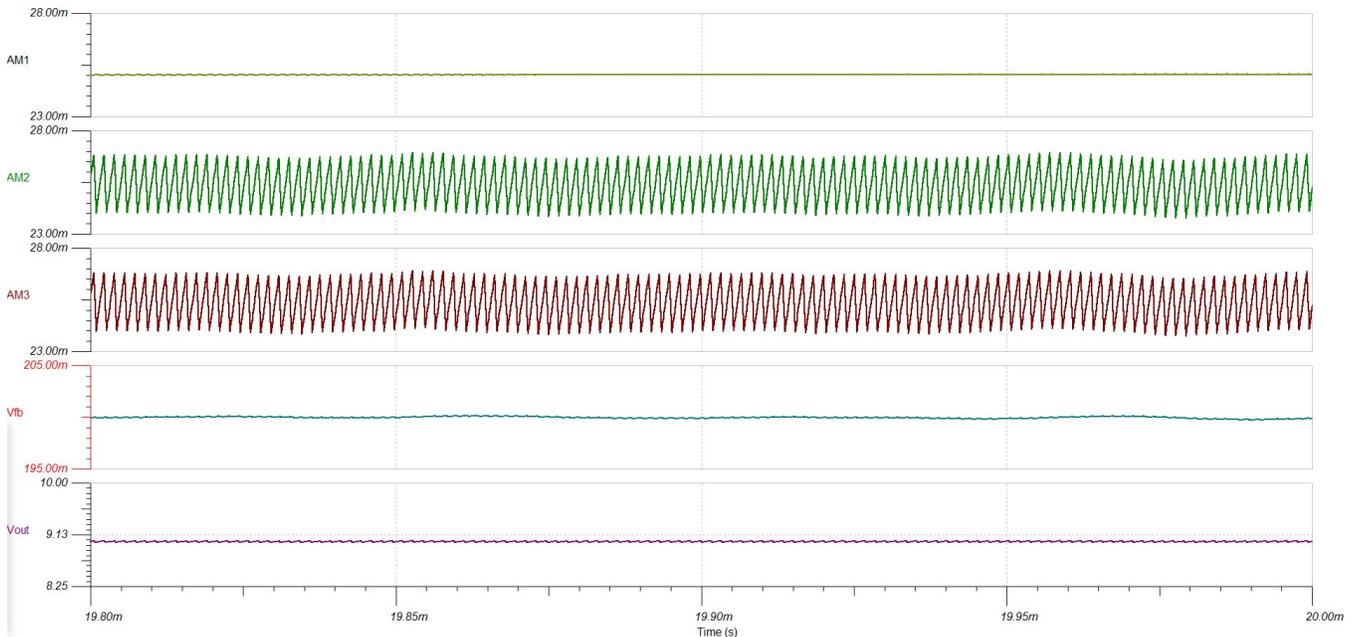
Figure 12. Simulation Results With Channel Ballasting

2.4.3 IR LED Driver Circuit Design Theory

There are two LED drivers designed to control LED illumination, but at the same time, only one part is enabled, which is based on the input voltage. When giving 5-V input voltage, the circuit works in boost mode, the TPS61169 device is enabled and the TPS54201 device is disabled. Inversely, when giving 12-V input voltage, the circuit works in buck mode, the TPS54201 device is enabled and the TPS61169 device is disabled.

2.4.3.1 *TPS54201 Design Theory*

2.4.3.1.1 *Inductor Selection*

According to the system parameters, the TPS54201 device input voltage is 12 V with smaller than ±10% error, the maximum LED current is 25.4 mA, and the minimum switch frequency is 480 kHz.

Use Equation 1 to calculate the minimum value of the output inductor (L_{min}).

$$L_{MIN} = \frac{V_{OUT} \times \left(V_{IN(min)} - V_{OUT} \right)}{V_{IN(max)} \times K_{IND} \times I_{LED} \times F_{SW}}$$

where

- K_{IND} is a coefficient that represents the amount of inductor ripple current relative to the maximum LED Current
- I_{LED} is the maximum LED current
- V_{OUT} is the sum of the voltage across LED-string, ballasting BJT voltage drop and the voltage across the sense resistor

(1)

In general, the value of K_{IND} is suggested between 0.2 and 0.4. For the application choosing the $K_{IND} = 0.2$ to get a small enough LED current ripple.

With the chosen inductor value, the actual inductor current ripple is calculated with Equation 2.

$$I_{L(ripple)} = \frac{V_{OUT} \times \left(V_{IN(max)} - V_{OUT} \right)}{V_{IN(max)} \times L \times F_{SW}}$$

(2)

The inductor RMS current and saturation current ratings must be greater than those seen in the application. This ensures that the inductor does not overheat or saturate. During power-up, transient conditions, or fault conditions, the inductor current can exceed its normal operating current. For this reason, the most conservative approach is to specify an inductor with a saturation current rating equal to or greater than the converter current limit. This is not always possible due to application size limitations. The peak inductor current and the RMS current equations are shown in Equation 3 and Equation 4 .

$$I_{L(peak)} = I_{LED} + \frac{I_{L(ripple)}}{2}$$

(3)

$$I_{L(rms)} = \sqrt{I_{LED}^2 + \frac{I_{L(ripple)}^2}{12}}$$

(4)

In this design, choose $K_{IND} = 0.2$. According to the data sheet of the LED manufacturer, the IR LED has 1.4-V forward voltage at 25.4-mA current. $V_{OUT} = (1.4 \times 4 + 0.0254 \times 48.7 + 0.6 \times 2 + 0.2)$ V = 8.24 V, the calculated inductance is 179.2 μH. A 180-μH inductor (part number is ELL-6UH181M from Panasonic) is chosen. With this inductor, the ripple, peak, and RMS current of the inductor is 35.8 mA, 197.9 mA, and 180.3 mA, respectively. The chosen inductor has ample margin.

2.4.3.1.2   Input Capacitor Selection

The device requires an input capacitor to reduce the surge current drawn from the input supply and the switching noise from the device. Ceramic capacitors with X5R or X7R dielectrics are highly recommended because of their low ESR and small temperature coefficients. For most applications, a 10-µF capacitor is enough. An additional 0.1-µF capacitor from VIN to GND is optional to provide additional high-frequency filtering. The input-capacitor voltage rating must be greater than the maximum input voltage and have a ripple-current rating greater than the maximum input-current ripple of the converter. The RMS input-ripple current is calculated in Equation 5, where D is the duty cycle (output voltage divided by input voltage).

$$I_{CIN(rms)} = I_{LED} \times \sqrt{D \times (1-D)}$$

(5)

Use Equation 6 to calculate the input ripple voltage, where ESR_{CIN} is the ESR of input capacitor. Ceramic capacitance tends to decrease as the applied DC voltage increases. This depreciation must be accounted for when calculating input ripple voltage.

$$V_{IN(ripple)} = \frac{I_{LED} \times D \times (1-D)}{C_{IN} \times F_{SW}} + I_{LED} \times ESR_{CIN}$$

(6)

In this design, a 10-µF, 35-V X7R ceramic capacitor, part number GRM32ER7YA106KA12L, from Murata is chosen. This yields around 30-mV input ripple voltage. The calculated RMS input ripple current is 76 mA, well below the ripple current rating of the capacitor.

2.4.3.1.3   Output Capacitor Selection

The output capacitor reduces the high-frequency ripple current through the LED string. Various guidelines disclose how much high-frequency ripple current is acceptable in the LED string. Excessive ripple current in the LED string increases the RMS current in the LED string, and therefore the LED temperature also increases.

1. Calculate the total dynamic resistance of the LED string (R_{LED}) using the data sheet of the LED manufacturer.

2. Calculate the required impedance of the output capacitor (Z_{OUT}) given the acceptable peak-to-peak ripple current through the LED string, $I_{LED(ripple)}$. $I_{L(ripple)}$ is the peak-to-peak inductor ripple current as calculated previously in inductor selection.

3. Calculate the minimum effective output capacitance required.

4. Increase the output capacitance appropriately due to the derating effect of applied DC voltage.

$$R_{LED} = \frac{\Delta V_F}{\Delta I_F} \times \# \text{ of LEDs}$$

(7)

$$Z_{COUT} = \frac{R_{LED} \times I_{LED(ripple)}}{I_{L(ripple)} - I_{LED(ripple)}}$$

(8)

$$C_{OUT} = \frac{1}{2\pi \times F_{SW} \times Z_{COUT}}$$

(9)

Once the output capacitor is chosen, Equation 10 is used to estimate the peak-to-peak ripple current through the LED string.

$$I_{LED(ripple)} = \frac{Z_{COUT} \times I_{L(ripple)}}{Z_{COUT} + R_{LED}}$$

(10)

OSRAM IR LED SFH4715A is used here. The dynamic resistance of this LED is 0.25 Ω at 1.5-A forward current. In this design, a 10-µF, 35-V X7R ceramic capacitor is chosen, the part number is GRM32ER7YA106KA12L, from Murata. The calculated ripple current of the LED is about 20 mA.

2.4.3.1.4 FB Pin RC Filter Selection

The RC filter, RF and CF, connected between the sense resistor and FB pin is used to generate a pole for the purpose of loop stability. Moving this pole can adjust the loop bandwidth. The suggested frequency of the pole is 2 kHz in analog dimming mode, and 4 kHz in PWM dimming mode. Use Equation 11 to choose RF and CF. Due to the DC offset current of the internal amplifier, use RF less than 1 kΩ to minimize the effect on LED current regulation accuracy.

$$C_F = \frac{1}{2\pi \times R_F \times f_{POLE}}$$

(11)

Analog dimming mode is implemented in this design. The design choose the pole at around 2 kHz, and 910 Ω as the filter resistor, then the calculated filter capacitance is 87 nF. A 82 nF is chosen for this filter.

2.4.3.1.5 Sense Resistor Selection

The maximum target LED current at 100% PWM duty cycle is 25.4 mA, the corresponding VREF is 200 mV. The calculated sense resistance is 7.87 Ω. Pay close attention to the power consumption of the sense resistor in this design at 5.08 mW, make sure the chosen resistor has enough margin in power rating.

2.4.3.2 TPS61169

2.4.3.2.1 Inductor Selection

The selection of the inductor affects power efficiency, steady state operation, as well as transient behavior and loop stability. These factors make it the most important component in power regulator design. There are three important inductor specifications: inductor value, DC resistance, and saturation current. Considering inductor value alone is not enough. The inductor value determines the inductor ripple current. Choose an inductor that can handle the necessary peak current without saturating. Follow Equation 12 to Equation 14 to calculate the peak current of the inductor. To calculate the current in the worst case, use the minimum input voltage, maximum output voltage, and maximum load current of the application. In a boost regulator, the input DC current is calculated as Equation 12.

$$I_{LED} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times \eta}$$

where

- V_{OUT} = boost output voltage
- I_{OUT} = boost output current
- V_{IN} = boost input voltage
- η = power conversion efficiency

(12)

The inductor current peak-to-peak ripple is calculated using Equation 13:

$$I_{L(ripple)} = \frac{1}{L \times \left(\dfrac{1}{V_{OUT} - V_{IN}} + \dfrac{1}{V_{IN}} \right) \times F_S}$$

where

- $I_{L(ripple)}$ = inductor peak-to-peak ripple
- L = inductor value
- F_S = boost switching frequency
- V_{OUT} = boost output voltage
- V_{IN} = boost input voltage

(13)

Therefore, the peak current $I_{L(ripple)}$ seen by the inductor is calculated with Equation 14:

$$I_{L(peak)} = I_{LED} + \frac{I_{L(ripple)}}{2}$$

(14)

Inductor values can have ±20% tolerance with no current bias. When the inductor current approaches saturation level, its inductance can decrease 20% to 35% from the 0-A value depending on how the inductor vendor defines saturation current. Using an inductor with a smaller inductance value forces discontinuous PWM when the inductor current ramps down to zero before the end of each switching cycle. This reduces the maximum output current of the boost converter, causing large input voltage ripple and reducing efficiency. A large inductance value provides much more output current and higher conversion efficiency. However, a large value inductor has a large package which will occupy a lot of the board. For these reasons, a 4.7-µH to 10-µH inductor value range is recommended, and a 4.7-µH inductor is recommended for higher than 5-V input voltage by considering inductor peak current and loop stability. In this design, a 4.7 µH IFSC1515AHER4R7M01 is used.

2.4.3.2.2   Schottky Diode Selection

The TPS61169 demands a low forward voltage, high-speed, and a low capacitance Schottky diode for optimum efficiency. Ensure that the diode average and peak current rating exceeds the average output current and peak inductor current. In addition, the diode reverse breakdown voltage must exceed the open LED protection voltage. ONSemi NSR0240 is recommended for the TPS61169 device.

2.4.3.2.3   Output Capacitor Selection

The output capacitor is mainly selected to meet the requirement for the output ripple and loop stability. This ripple voltage is related to capacitor capacitance and its equivalent series resistance (ESR). Assuming a capacitor with zero ESR, the minimum capacitance needed for a given ripple is calculated with Equation 15:

$$C_{OUT} = \frac{(V_{OUT} - V_{IN}) \times I_{OUT}}{V_{OUT} \times F_S \times V_{(ripple)}}$$

(15)

The additional part of the ripple caused by ESR is calculated using $V_{ripple\_ESR} = I_{OUT} \times R_{ESR}$.

Due to its low ESR, V_{ripple_ESR} could be neglected for ceramic capacitors, a 4.7-µF capacitor is recommended for this application.

2.4.3.2.4   LED Current Set Resistor

The FB voltage is regulated by a low 204-mV reference voltage. The LED current is programmed externally using a current-sense resistor in series with the LED-string array. The value of the R_{SET} is calculated using Equation 16:

$$R_{SET} = \frac{V_{FB}}{I_{LED}}$$

(16)

The output current tolerance depends on the FB accuracy and the current sensor resistor accuracy. From Equation 16, a 7.87-Ω, 1% accuracy resistor is used in this design.

2.4.4   Firmware Control

Figure 13 describes the MSP430FR2311 operation in this TI Design. The MSP430FR2311 MCU starts by initializing and configuring the OPT3001, DRV8837C, TPS54201, and TPS61169 devices to their lowest power state. Afterward, the MSP430FR2311 device checks the state of the S1 switch button on the LaunchPad. If the S1 switch is in the default state, the MSP430FR2311 MCU configures the OPT3001 device in interrupt reporting mechanism mode; otherwise, if it has been pushed down, the MSP430FR2311 configures the OPT3001 device in automatic full-scale setting mode.

START

Initialization
1) OPT3001 in sleep mode
2) DRV8837C in sleep mode
3) disable LED Drivers
4) check state of Launchpad S1

Default 1 ← Launchpad S1 → Press 0

Configure OPT3001
Interrupt Reporting
Mechanism Modes

Configure OPT3001
Automatic Full-Scale
Setting Mode

Set the value of
a=Highest Light Level,
b=Dark Threshold High,
c=Dark Threshold Low,
d=Lowest Light Level

Set the value of
a=Dark Threshold High,
b=Dark Threshold Low,
c=LED Threshold DisH,
d=LED Threshold DisL
e=Dark Threshold EnH,
f=Dark Threshold EnL

Configure threshold
High-Limit=b and Low-
Limit registers= d

Timer
interrupt

Low Power
mode(LMP3)
Until timer out

Low Power
mode(LMP3)
Wait for next event

External
interrupt

Read OPT3001 result
register and convert to
Lux

Read OPT3001
Configuration register

No ← Lux>a → Yes

No ← Flag high field=1 → Yes

No ← Lux<b → Yes

No ← Flag low field=1 → Yes

Open ICR

Close ICR

Open ICR

Close ICR

12 V ← Input 12 V / 5 V? → 5 V

Close ICR

No ← Lux>c → Yes

Disable LED Drivers

Enable Buck
TPS54201, 100%
dimming

Enable Boost
TPS61169, 100%
dimming

Disable LED Drivers

Configure threshold
High-Limit=a and Low-
Limit registers= c

Yes ← Lux<d &&Lux>e → No

Disable LED Drivers

Configure threshold
High-Limit=b and Low-
Limit registers= d

Convert Lux
to PWM duty

Yes ← Lux<f → No

12 V ← Input 12 V / 5 V? → 5 V

12 V ← Input 12 V / 5 V? → 5 V

Enable Buck
TPS54201, PWM
duty dimming

Enable Boost
TPS61169, PWM
duty dimming

Enable Buck
TPS54201, 100%
dimming

Enable Boost
TPS61169, 100%
dimming

Figure 13. Firmware

2.4.4.1 OPT3001 in Interrupt Reporting Mechanism Mode

The MSP430FR2311 interrupt is triggered by the event of the OPT3001 INT pin in interrupt reporting mechanism mode. First, set the values of the low-limit register (offset = 02h) and high-limit register (offset = 03h), then set the configuration register to interrupt reporting mechanism mode and continuous conversions mode to enable interrupt.

However, if setting the low-limit register to the dark threshold value, when the detected ambient light is lower than this value, the OPT3001 device will constantly output the interrupt until the detected ambient light is higher than the dark threshold value. Similarly, if setting the high-limit register to the dark threshold value, when the detected ambient light is higher than the value, the OPT3001 device will also constantly output the interrupt until the detected ambient light is lower than the dark threshold value. Also, when the detected ambient light approaches the dark threshold value, the ICR will frequently open and close, and the MSP430FR2311 timers used to produce the PWM signal will also frequently start and end with the detected ambient light lower and higher than the dark threshold value.

This presents two main problems, (1) the OPT3001 device must enable and work all the time, (2) the ambient light will always be higher or lower than the dark threshold value during the day or night, the constant interrupt takes lots of resources, meanwhile causing the high power dissipation and heavy workload for the MSP430FR2311.

Figure 14 shows a method to solve the constant interrupt problem. Area 1 and Area 3 represent the day light area and the night light area, the highest light level is settled to the maximum value of the high-limit register, and the lowest light level is settled to the minimum value of the low-limit register. The dark threshold line is the ambient light level that distinguished day from night, the bold red line is the intensity of the visible ambient light.

At the beginning, set the high-limit register to the value of the dark threshold, and set the low-limit register to the value of the lowest light level. When the intensity of the ambient visible light is higher than the dark threshold level (in Area 1), the OPT3001 device produces an interrupt to notify the MSP430FR2311 MCU that the light is bright enough, close the ICR, and disable the LED driver. The OPT3001 device then reloads the high-limit register and low-limit register to the value of highest light level and dark threshold. The OPT3001 device does not produce the interrupt until the intensity of the ambient visible light is lower than the dark threshold level (from Area 1 to Area 3), the MSP430FR2311 MCU senses the light is dark enough, the ICR opens, and LED driver is enabled.
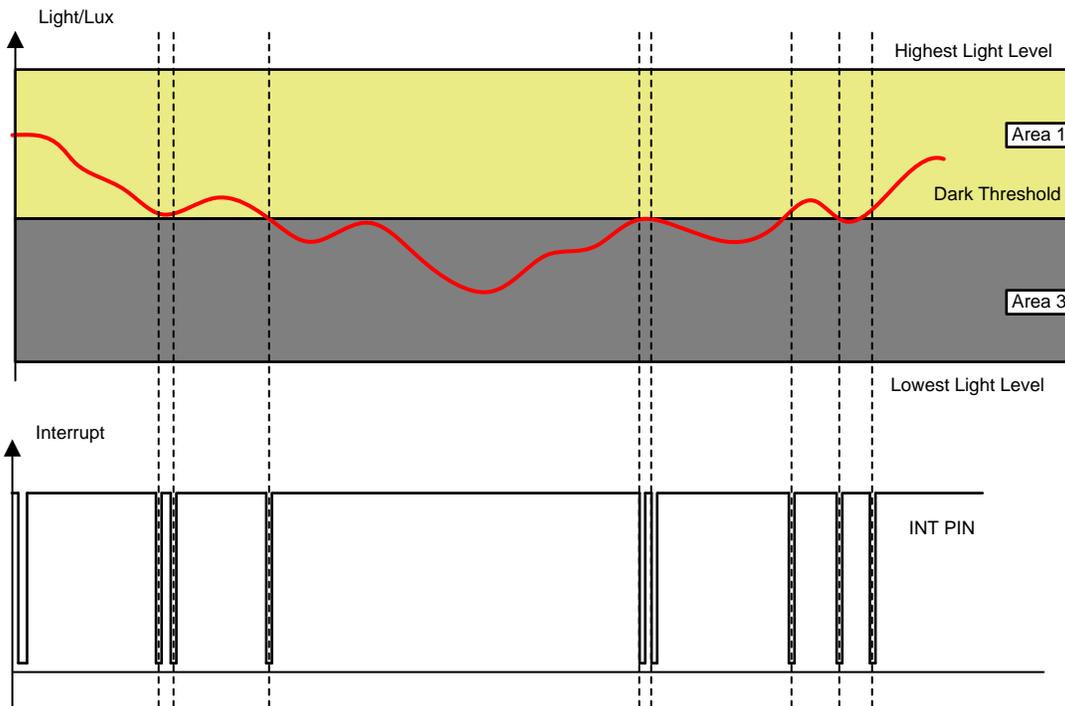
Figure 14. OPT3001 Interrupt Control Method Without Light-Level Hysteresis

It seems the problem has been solved, but when the ambient light level is approach to dark threshold value, the interrupt may frequently happen with the ambient light level higher and lower than dark threshold value in a specific light level such as sunrise or sunset time. and this will lead to frequently action of the ICR and timers, which will cause high power dissipation and heavy workload for the MSP430FR2311.

Figure 15 shows a method to solve this problem. the Area 1, Area 2 and Area 3 represent the day light area, excessive area between day and night and the night light area, the highest light level is settled the maximum value of the high-limit register, and the lowest light level is settled the minimum value of the low-limit register, and the dark threshold high and dark threshold low lines are the ambient light level that distinguished from day and night, the bold red line is the intensity of the visible ambient light. and the bold yellow line is the dark threshold value between day and night.

At the beginning, set the high-limit register to the value of dark threshold high, and set the low-limit register to the value of lowest light level. When the intensity of the ambient visible light higher than dark threshold high level (in Area 1), OPT3001 will produce a interrupt so as to inform the MSP430FR2311 that the light is brightness enough, the ICR should be closed and LED driver should be disabled. Then reload the high-limit register and low-limit register to the value of highest light level and dark threshold low. OPT3001 will not produce the interrupt later until the intensity of the ambient visible light lower than dark threshold level low (From Area 1 to Area 3), MSP430FR2311 will know that the light is darkness enough, the ICR should be open and LED driver should be enabled. And then reload the high-limit register and low-limit register to the value of highest light level and dark threshold low . OPT3001 will not produce the interrupt later until the intensity of the ambient visible light lower than dark threshold level low (From Area 3 to Area 1).
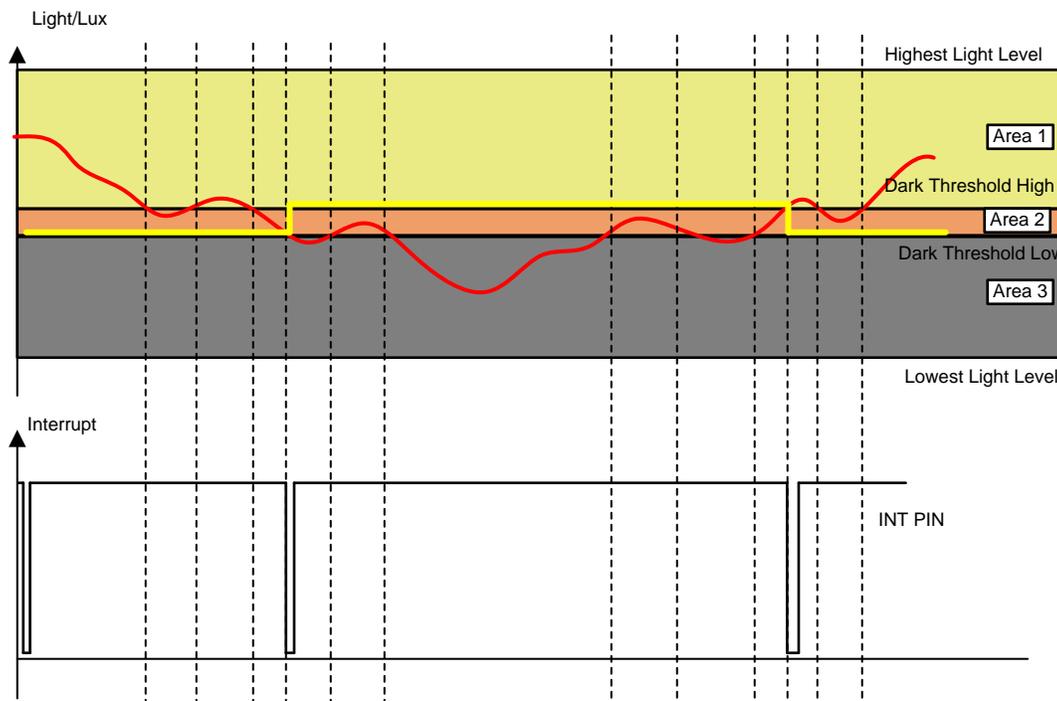
Figure 15. OPT3001 Interrupt Control Method With Light-Level Hysteresis

Table 2 shows the threshold ambient light level setting in interrupt mode.

Table 2. Threshold Ambient Light Level Setting in Interrupt Mode

PARAMETERS	REGISTER VALUES	LUX VALUES
Highest light level	0xBFFF	83865.60
Threshold light high	0x2FA0	160
Threshold light low	0x2E6A	150

Table 2. Threshold Ambient Light Level Setting in Interrupt Mode (continued)

PARAMETERS	REGISTER VALUES	LUX VALUES
Lowest light level	0x0000	0

2.4.4.2   OPT3001 in Automatic Full-Scale Setting Mode

The OPT3001 has an automatic full-scale-range setting mode that eliminates the need for a user to predict and set the optimal range for the device. This mode is entered when the configuration register range number field (RN[3:0]) is set to 1100b.

The first measurement that the device takes in auto-range mode is a 10-ms range assessment measurement. The device then determines the appropriate full-scale range to take its first full measurement.

For subsequent measurements, the full-scale range is set by the result of the previous measurement. If a measurement is towards the low side of full-scale, the full-scale range is decreased by one or two settings for the next measurement. If a measurement is towards the upper side of full-scale, the full-scale range is increased by one setting for the next measurement.

If the measurement exceeds the full-scale range, resulting from a fast increasing optical transient event, the current measurement is aborted. This invalid measurement is not reported. A 10-ms measurement is taken to assess and properly reset the full-scale range. Then, a new measurement is taken with this proper full-scale range. Therefore, during a fast increasing optical transient in this mode, a measurement can possibly take longer to complete and report than indicated by the configuration register conversion time field (CT).

Figure 16 shows the ICR and LED driver action in automatic full-scale setting mode of the OPT3001 device. If the ambient light higher than dark threshold high, the MSP430FR2311 executes the action to close the ICR; else if the ambient light lower than dark threshold low, the MSP430FR2311 executes the action to open the ICR; if the ambient light is between the dark threshold high and dark threshold low, the MSP430FR2311 executes the action to keep the former state for ICR. the ICR will not be frequently open and closed in a specific light level such as sunrise or sunset time.

To have a stable camera light at the condition of the changing ambient light, smooth dimming for IR LED is needed, so change the LED PWM duty cycle based on the intensity of ambient light. when the ambient light high than LED threshold DisH, the MSP430FR2311 executes the action to disable LED driver, when the ambient light lower than LED threshold DisL but higher than dark threshold ENH, the MSP430FR2311 executes the action to adjust the PWM duty cycle of LED driver control PIN, when the ambient light lower than dark threshold EnL, the MSP430FR2311 executes the action to set control Pin high for full PWM duty cycle. and when ambient light is between LED threshold DisH and LED threshold DisL or between dark threshold EnH and dark threshold EnL, the MSP430FR2311 executes the action to keep the former state for LED driver for avoiding of the PWM generator frequently enabled and disabled.
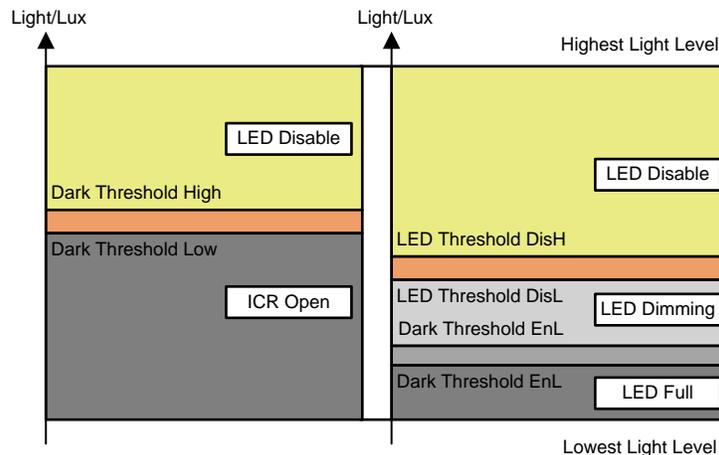
Figure 16. OPT3001 ICR and LED Driver Action in Automatic Full-Scale Setting Mode

23

Table 3 shows threshold ambient light level setting in automatic full-scale setting mode.

**Table 3. Threshold Ambient Light Level Setting in
Automatic Full-Scale Setting Mode**

PARAMETERS	LUX VALUES
Highest Light Level	Automatic
Lowest Light Level	Automatic
Dark Threshold High	210
Dark Threshold Low	200
LED Threshold DisH	160
LED Threshold DisL	150
Dark Threshold EnH	50
Dark Threshold EnL	40

The MSP430FR2311 will go into standby mode while waiting for the counter to time out, and then wake up for the next conversion of OPT3001.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The following sections describe the quickest way to get the reference design board up and running for evaluation.

3.1.1 Hardware

Figure 17, Figure 18, and Figure 19 show the design boards. Board-1 (the blue color) is the IR LED array board with ICR and the OPT3001 device, board-2 (the red color) is the power supply and control board. Board-2 is meant to be used with TI's MSP430FR23xx series LaunchPad development kits and connected using the integrated board headers. Board-2 also has multiple jumper pin placements to allow the choice of the input voltage and the power schedule for the system. Table 4 shows the main jumpers used in this reference design along with their respective components being supplied power.
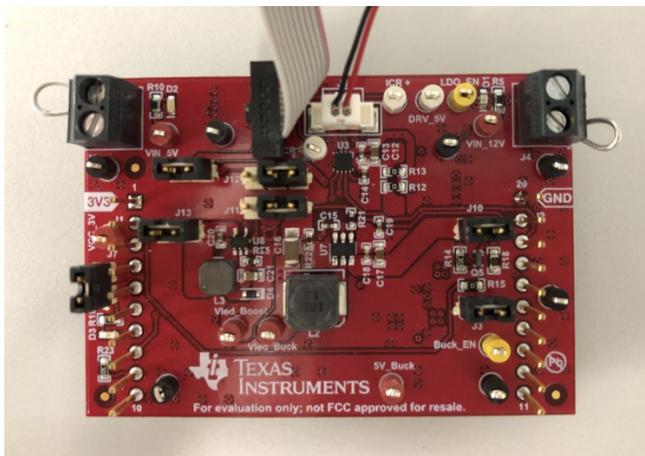
Figure 17. Power and Control Board (Board-2) Front Side
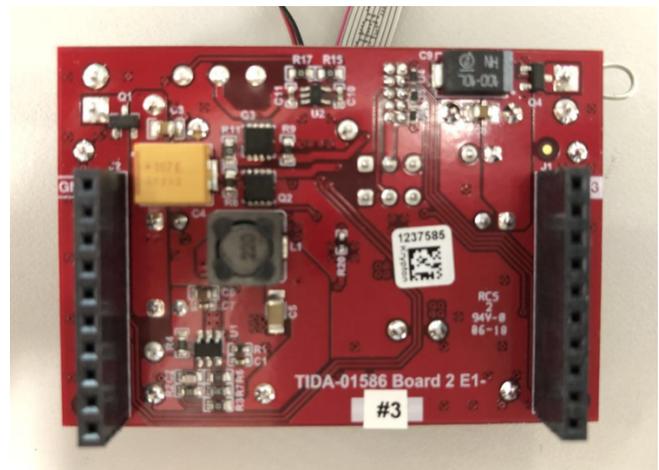
Figure 18. Power and Control Board (Board-2) Back Side

Figure 19. IR LED Array and ALS Board (Board-1)

Table 4. Power Jumper Configuration and Function

JUMPER	FUNCTION
J11	(1) Jump PIN 1 and PIN 2 to feedback from the LED array to the buck LED driver (2) Jump PIN 3 and PIN 2 to feedback from the LED array to boost the LED driver
J12	(1)Jump PIN 1 and PIN 2 to connect the LED array to the output of the buck LED driver. If choosing this configuration, J11 should also be configured to (1) (2) Jump PIN 3 and PIN 2 to connect the LED array to the output of the boost LED driver. f choosing this configuration, J11 should also be configured to (2)
J10	Enable TPS54201 power supply
J13	Enable TPS61169 power supply
J3	Enable 12-V input power supply
J6	Enable 5-V input power supply

After ensuring the jumpers are correctly placed, the design board can be placed on the MSP430FR2311 LaunchPad through the use of the headers provided on both boards.

3.1.2 Software

The following section describes the process for bringing the design firmware online and deploying it to the MSP430 device.

First, install the firmware from TI.com. After obtaining the file, import it into Code Composer Studio (CCS) as a zipped project. Once the code is loaded successfully, compile and build it. Figure 20 shows the building of the design firmware in CCS.
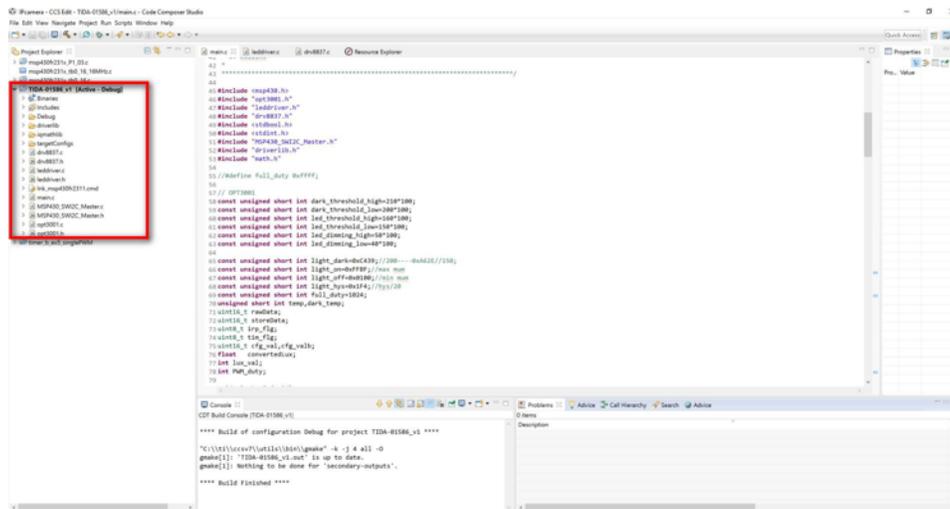
Figure 20. Building the TIDA-01586 Code in CCS

After the firmware is successfully built and the board is properly connected to the computer, it is next debugged and deployed to the target device. Figure 21 shows this process.
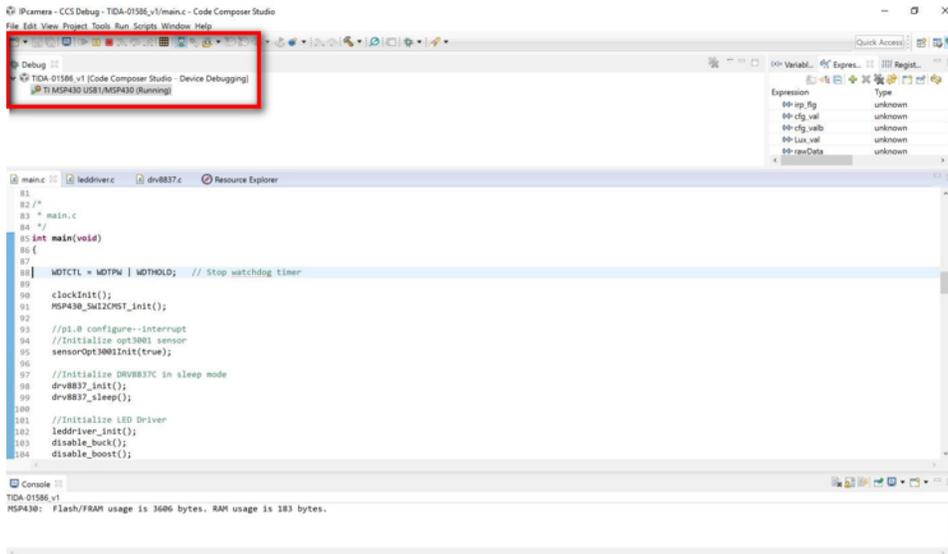
Figure 21. Debugging and Deploying the TIDA-01586 Firmware

3.2 Testing and Results

The following sections describe the setup used for testing as well as their respective results. Some of the test setups are not followed with a unique result in the results section; these results are detailed in Section 3.2.2.

3.2.1 Test Setup

Figure 22 shows the setup used for the initial testing of the board. A DC power supply is connected to the VIN and GND test points of the test load section of the board. The board is connected to a computer through the LaunchPad located on the bottom of the design and connected to the headers. The DC power supply slowly increases up to the limit value of 12 V (in buck mode) or 5 V (in boost mode).
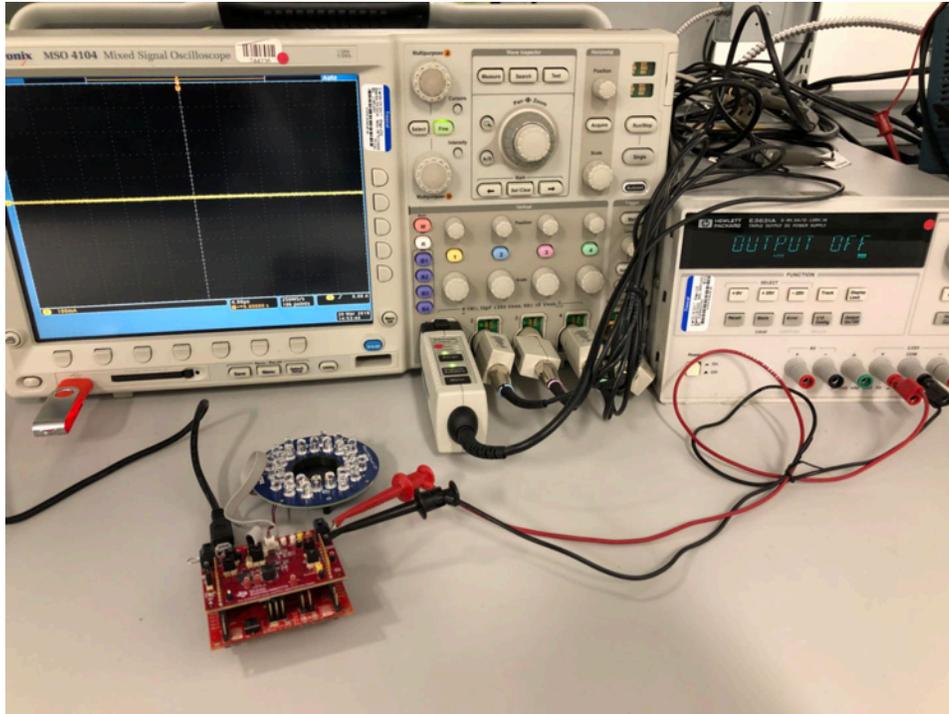
Figure 22. Test Setup of IR LED Array Board (Board-1), Control Board (Board-2) and LaunchPad™

3.2.2 Test Results

The following section describes the test results. The test contents include function verification, characterization of ambient light level versus threshold, LED driver startup waveforms, LED string current ballasting, LED dimming, motor driver currents, and waveforms.

3.2.2.1 LED Driver and Motor Driver Action With Ambient Light Level

The MSO-4104 is a mixed signal oscilloscope with 4 channels, it is used to detect the voltage and current based on the probe.

3.2.2.1.1 Input Voltage at 12 V and OPT3001 in Interrupt Mode Conditions

Figure 23 and Figure 24 show the curves when the system is working with a 12-V input voltage and the OPT3001 devices is working in interrupt mode by defaulting the S1 button at the start. Channel-1 connects to the OPT3001 INT pin, channel-2 and channel-3 connect to IN2 and IN1 pin of the DRV8837C device, and channel-4 connects to the PWM pin of the TPS54201 device.

When ambient light is from dark to bright, the waveforms are shown in Figure 23. First, the OPT3001 device produces an interrupt, then the MSP430FR2311 receives the interrupt signal and reads the OPT3001 configuration register, when the configuration register is read, the OPT3001 device will end the interrupt and set the INT pin to high (channel-1 curve) , Later, the MSP430FR2311 executes the actions to close the ICR (channel-2 and channel-3 curves) and disable the LED driver (channel-4).
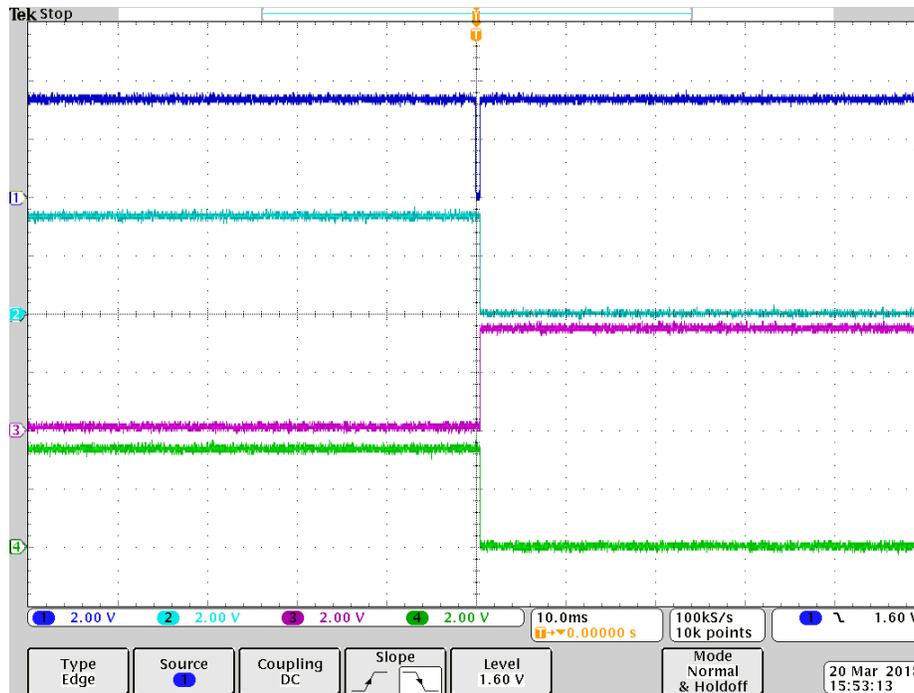

Figure 23. Ambient Light From Dark to Bright

Similarly, when ambient light is from bright to dark, the waveforms are shown in Figure 24, First, the OPT3001 device produces an interrupt, then the MSP430FR2311 receives the interrupt signal and reads the OPT3001 configuration register. When the configuration register is read, the OPT3001 device will end the interrupt and set the INT pin to high (channel-1 curve) , Later, the MSP430FR2311 executes the actions to open the ICR (channel-2 and channel-3 curves) and enable the LED driver (channel-4).
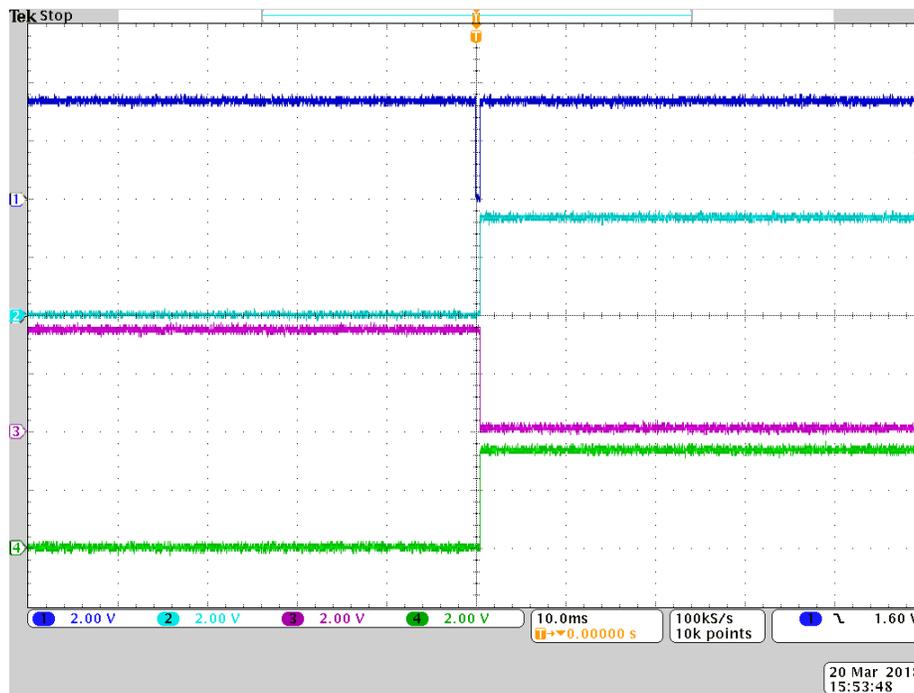
Figure 24. Ambient Light From Bright to Dark

3.2.2.1.2   *Input Voltage at 12 V and OPT3001 in Automatic Full-Scale Setting Mode Conditions*

Figure 25, Figure 26, and Figure 27 show the curves when the system is working with a 12-V input voltage and the OPT3001 device works in automatic full-scale setting mode by pushing the S1 button down at the start. Channel-1 connects to the OPT3001 INT pin (does not matter in this mode), channel-2 and channel-3 connect to the IN2 and IN1 pins of the DRV8837C device, and channel-4 connects to the PWM pin of the TPS54201 device.

Figure 16 shows the ambient light level bound for the action of the ICR and LED driver, and Figure 25 shows the waveform when the ambient light level is from the LED full to LED dimming area, the ICR is open (channel-2 and channel-3) and the LED driver output is from full current to adjustable current, based on the PWM duty cycle (channel-4).
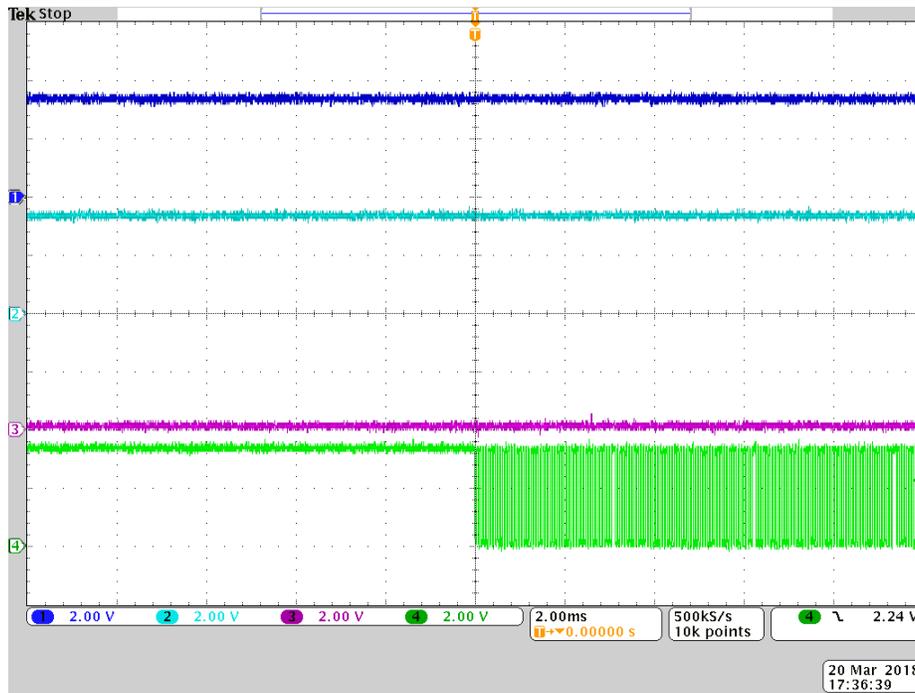
Figure 25. Ambient Light Level From LED Full to LED Dimming Area

Figure 26 shows the waveform when the ambient light level is from the LED dimming area to the LED disabled area, the ICR is open (channel-2 and channel-3) and the LED driver output is from adjustable current to disabled state (channel-4).
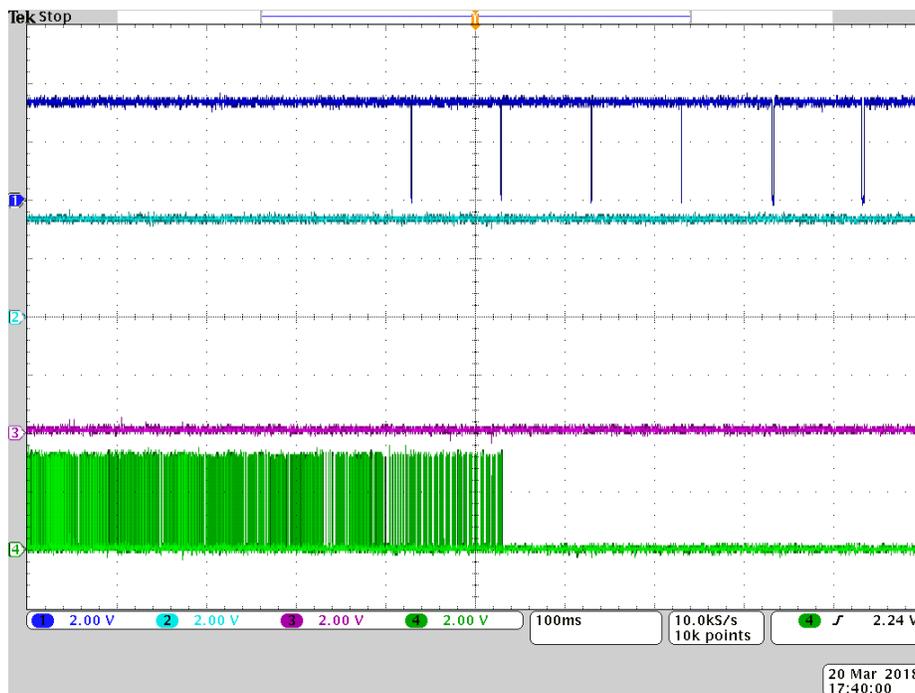

Figure 26. Ambient Light Level From LED Dimming Area to LED Disabled Area

Figure 27 shows the waveform when the ambient light level is from the LED disabled area to the ICR closed area, the ICR is closed (channel-2 and channel-3) and the LED driver output keeps the disabled state (channel-4) .
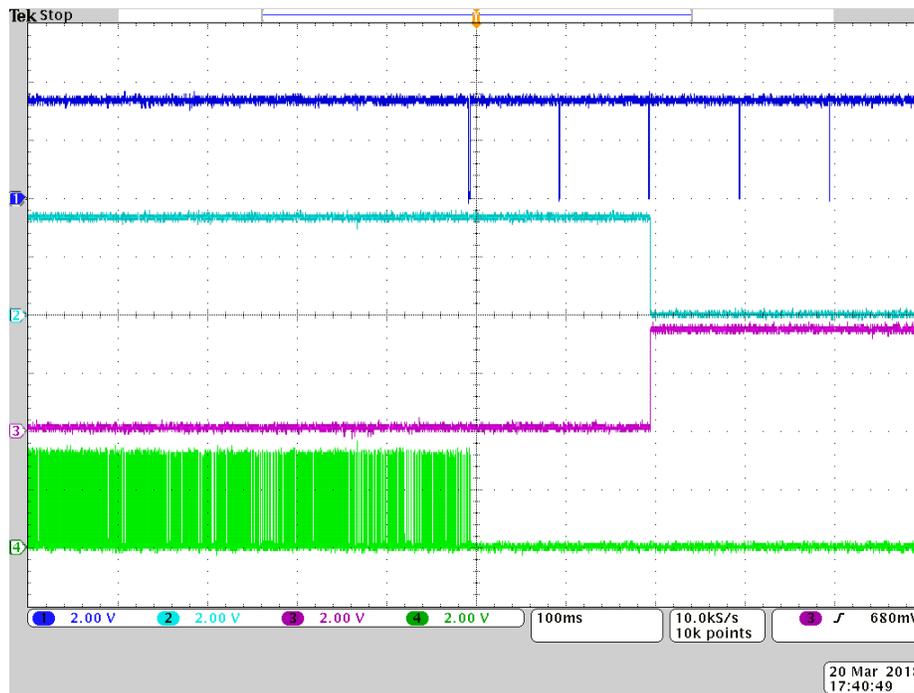
Figure 27. Ambient Light Level From LED Disabled Area to ICR Closed Area

3.2.2.1.3   *Input Voltage at 5 V and OPT3001 in Interrupt Mode Conditions*

Figure 28 and Figure 29 show the curves when the system is working with a 5-V input voltage and the OPT3001 device works in interrupt mode by defaulting the S1 button at the start. Channel-1 connects to the OPT3001 INT pin, channel-2 and channel-3 connect to the IN2 and IN1 pin of the DRV8837C device, and channel-4 connects to the PWM pin of the TPS54201 device.

The waveforms in Figure 28 show when ambient light is from dark to bright. First, the OPT3001 device produces an interrupt, then the MSP430FR2311 receives the interrupt signal and reads the OPT3001 configuration register, when the configuration register is read, the OPT3001 device will end the interrupt and set the INT pin to high (channel-1 curve) , Later, the MSP430FR2311 executes the actions to close the ICR (channel-2 and channel-3 curves) and disable the LED driver (channel-4).
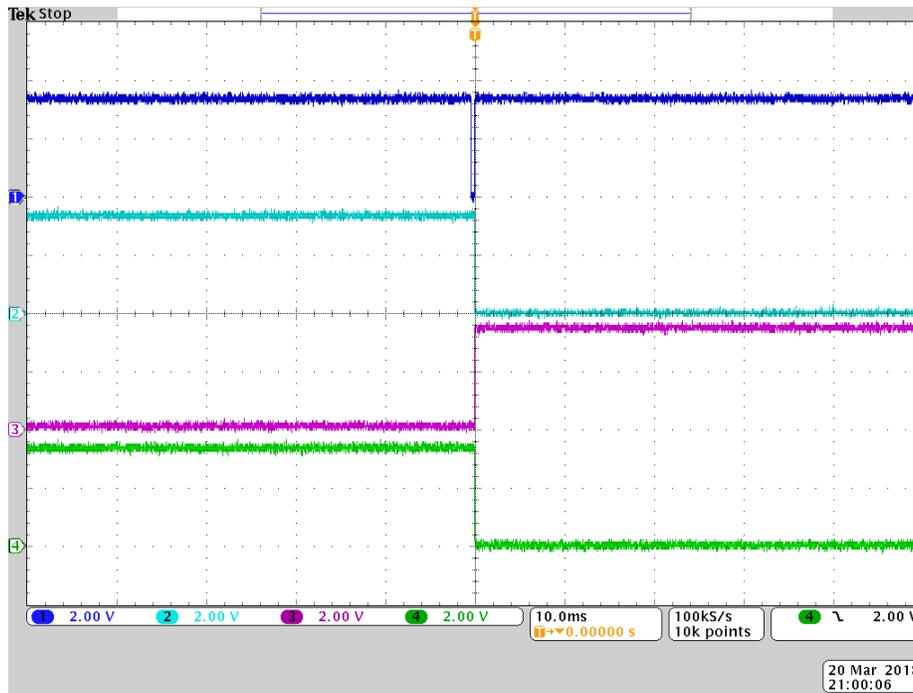
Figure 28. Ambient Light From Dark to Bright

Similarly, the waveforms in Figure 29 show when ambient light is from bright to dark. First, the OPT3001 device produces an interrupt, then the MSP430FR2311 receives the interrupt signal and reads the OPT3001 configuration register, when the configuration register is read, the OPT3001 device will end the interrupt and set the INT pin to high (channel-1 curve). Later, the MSP430FR2311 executes the actions to open the ICR (channel-2 and channel-3 curves) and enable the LED driver (channel-4).
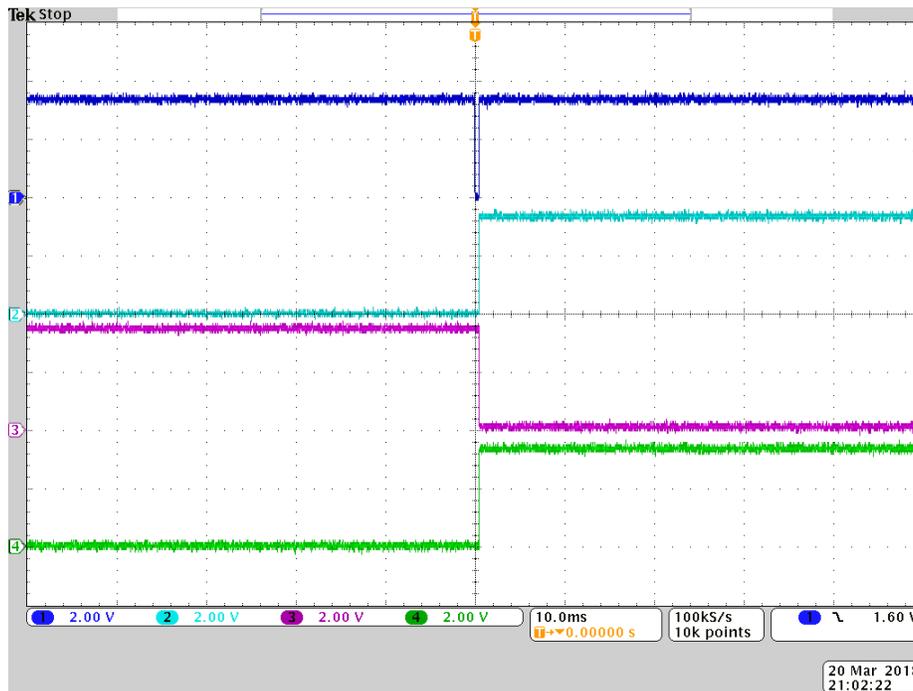
Figure 29. Ambient Light From Bright to Dark

3.2.2.1.4 *Input Voltage at 5 V and OPT3001 in Automatic Full-Scale Setting Mode Conditions*

Figure 30, Figure 31, and Figure 32 show the curves when the system is working with a 5-V input voltage and the OPT3001 device works in automatic full-scale setting mode by pushing S1 button down at the start. Channel-1 connects to the OPT3001 INT pin (does not matter in this mode), channel-2 and channel-3 connect to the IN2 and IN1 pin of the DRV8837C device, and channel-4 connects to the PWM pin of the TPS54201 device.

Figure 16 shows the ambient light level bound for the action of the ICR and LED driver. Figure 25 shows the waveform when the ambient light level is from LED full to LED dimming area, the ICR is open (channel-2 and channel-3), and the LED driver output is from full current to adjustable current, based on the PWM duty cycle (channel-4).
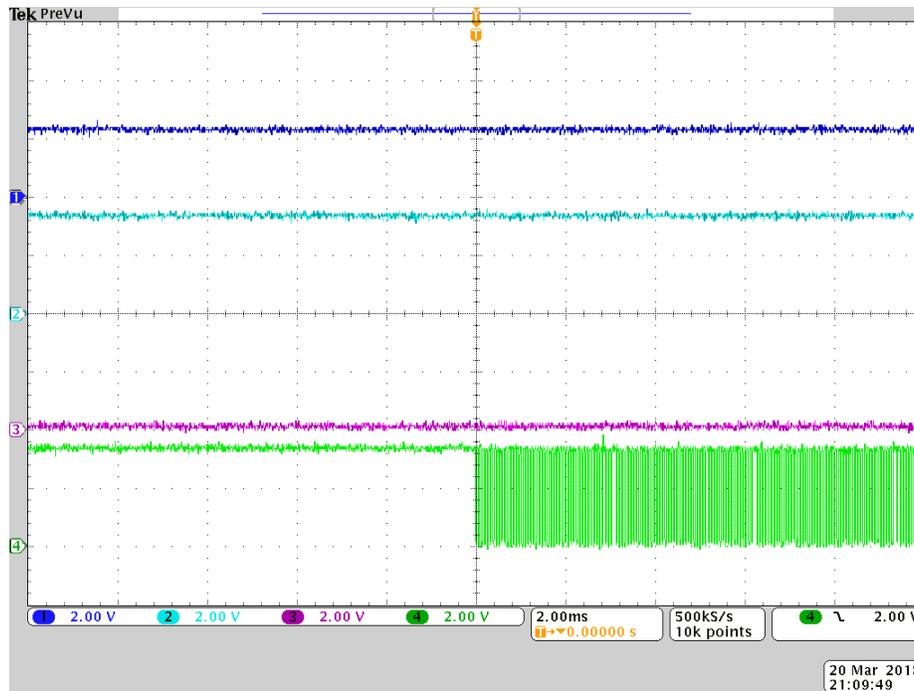
Figure 30. Ambient Light Level From LED Full to LED Dimming Area

Figure 31 shows the waveform when the ambient light level is from the LED dimming area to the LED disabled area, the ICR is open (channel-2 and channel-3), and the LED driver output is from adjustable current to disabled state (channel-4).
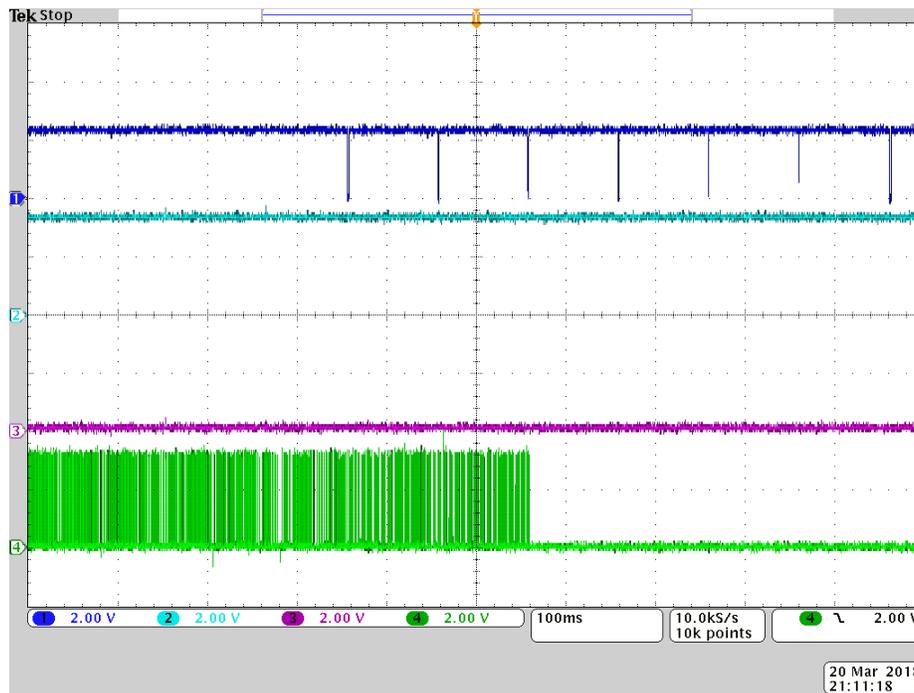
Figure 31. Ambient Light Level From LED Dimming Area to LED Disabled Area

Figure 32 shows the waveform when the ambient light level is from the LED disabled area to the ICR closed area, the ICR is closed (channel-2 and channel-3), and the LED driver output keeps the disabled state(channel-4) .
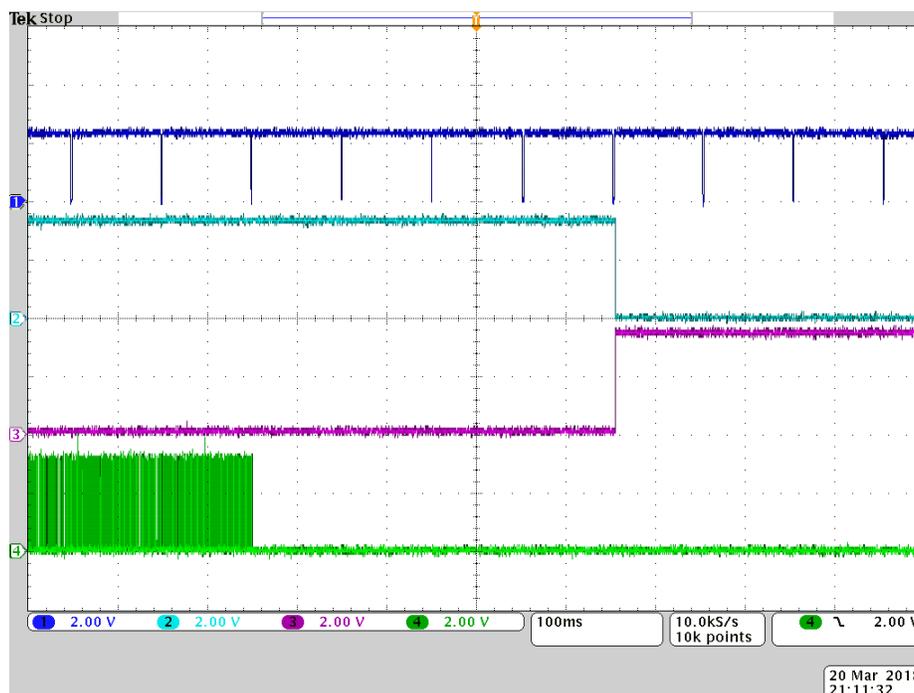
Figure 32. Ambient Light Level From LED Disabled Area to ICR Closed Area

3.2.2.2   *LED String Current Ballasting*

Figure 33 shows the IR LED illumination without ballasting. Some LEDs are bright and some LEDs are dark which means the current of each string is different.
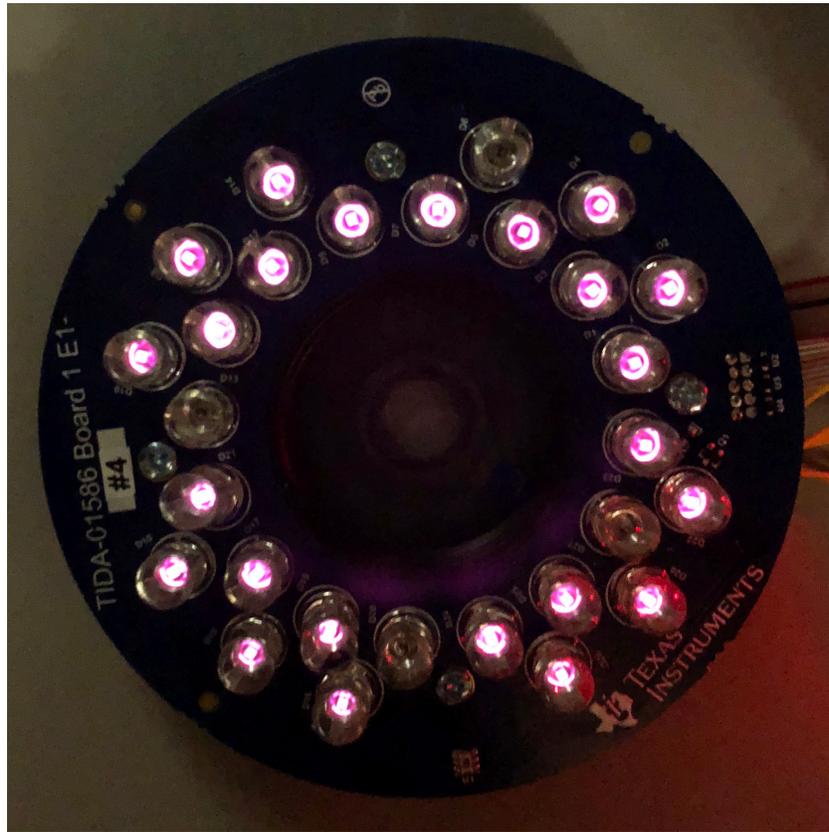
Figure 33. IR LEDs illumination Without Ballasting

The specific current of each LED string can be acquired through measuring the voltage and the value of each sense resistor connecting between the emitter of transistor and GND, this method does not influence the circuit and test results. Table 5 shows the test results of the current of each LED string when using 12 V as the supply voltage, and enabling the TPS54201 buck LED driver with 100% duty cycle in analog dimming mode.

Table 5. Current of Each LED String

	STRING-1 (REFERENCE STRING)	STRING-2	STRING-3	STRING-4	STRING-5	STRING-6	STRING-7
R_{sense}(ohm)	7.855	7.865	7.853	7.887	7.838	7.859	7.835
U_{sense}(mV)	205.5	224.4	223.3	235.9	231.5	229.6	231.9
I_{sense}(mA)	26.16	28.53	28.43	29.91	29.54	29.25	29.60

From the data in Table 5, the reference string has a lower current than the other strings. This is because the reference string has a lower collector-emitter voltage than the other strings. The easiest solution is to adjust the value of R3 (series resistance in reference string) of Figure 8 since this is where most of the difference comes from, but at the risk of having a string of high V_f LEDs being completely off in production. Obviously, in a real design, there would need to be a significant statistical analysis conducted to determine the optimum value of R3.

As for string 2 to string 7, they have the similar current with an error of no more than 5%, which can verify the success of the ballasting circuits.

Figure 34 shows the IR LED with a uniform illumination result. Comparing to Figure 33, the IR LEDs in the array nearly have the same brightness with the help of ballasting circuits.
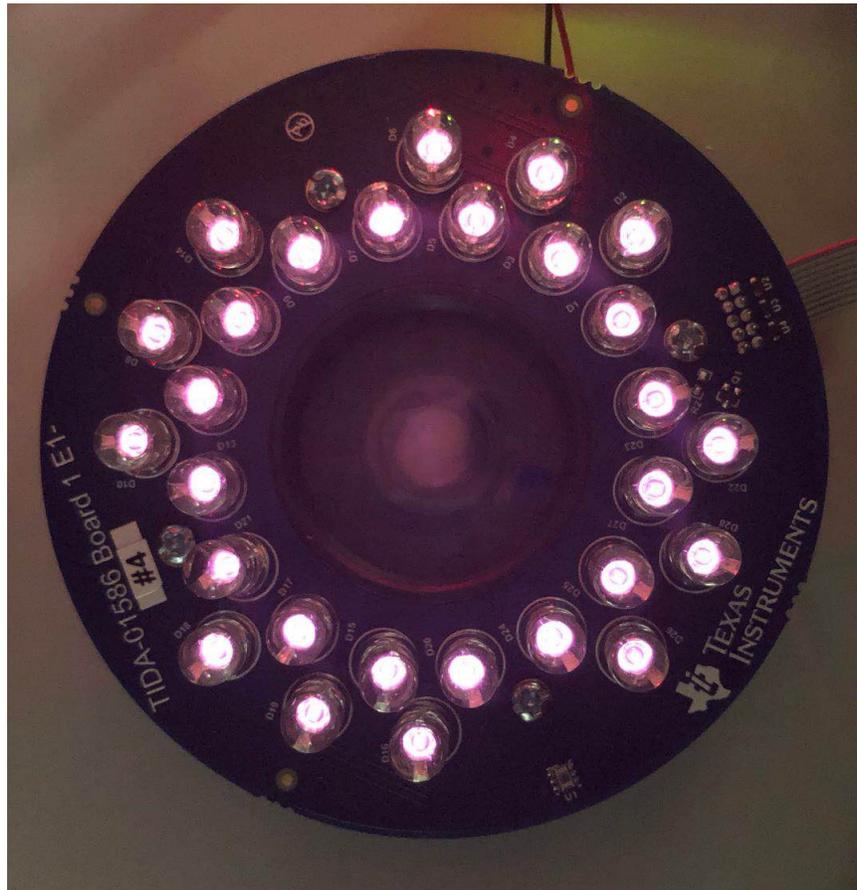
Figure 34. Ballasting Effect for IR LEDs Uniform Illumination

3.2.2.3   LED Dimming

3.2.2.3.1   Input Voltage at 12 V and OPT3001 in Interrupt Mode Conditions

Figure 35, Figure 36, Figure 37, and Figure 38 are the curves of the TPS54201 buck LED driver dimming signals with the PWM duty cycle 1%, 50%, 99% and disable state. The blue curve of channel-1 represents the PWM duty cycle for TPS54201 device control PIN, and the green curves of channel-4 represent the output current of TPS54201 LED drivers.

The figures show that the TPS54201 average output currents are about 3 mA, 100 mA, and 200 mA with the PWM duty cycle of 1%, 50%, and 99%, which is consistent with the theory. Figure 38 shows the PWM control signal and the changes of the output current with ambient light from brightness to darkness.
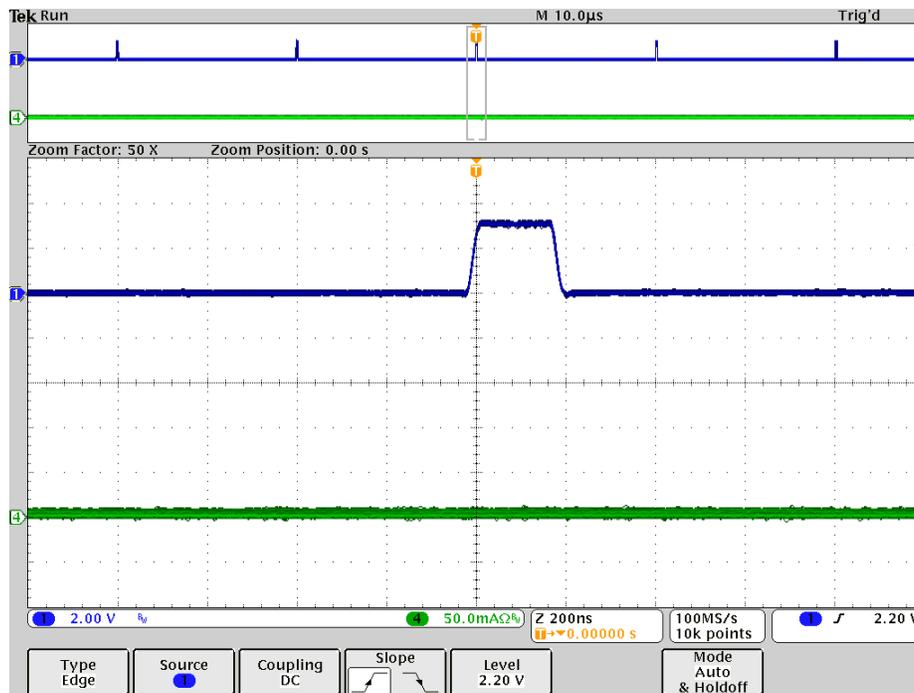
Figure 35. PWM Duty Cycle at 1% for Buck LED Driver

Figure 36. PWM Duty Cycle at 50% Buck LED Driver
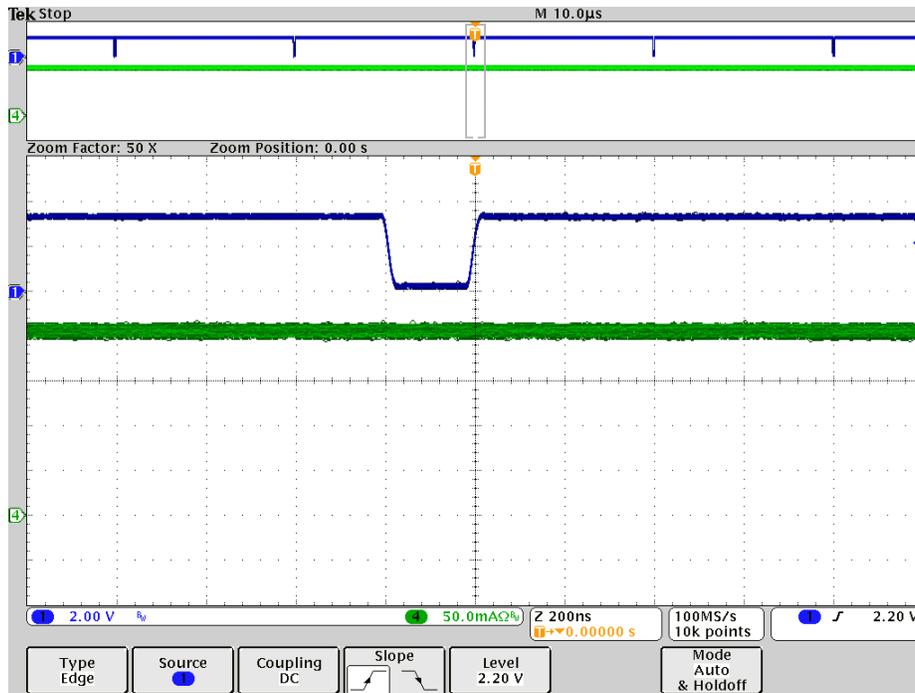
Figure 37. PWM Duty Cycle at 99% Buck LED Driver
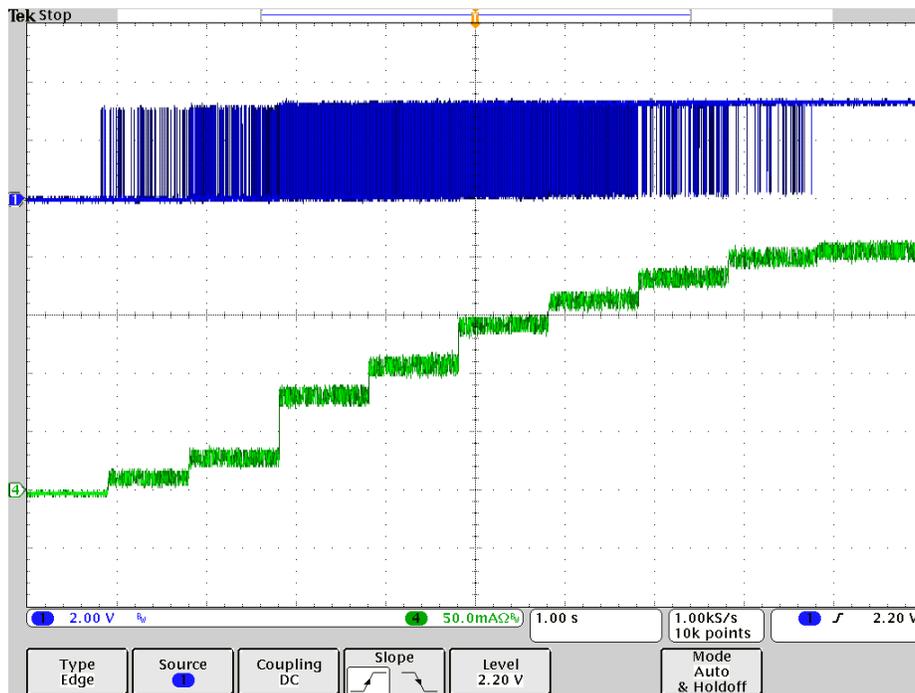
Figure 38. Buck LED Driver From Disable to 100% Duty Cycle

3.2.2.3.2   *Input Voltage at 5 V and OPT3001 in Interrupt Mode Conditions*

Figure 39, Figure 40, Figure 41 and Figure 42 are the curves of the TPS61169 boost LED driver dimming signals with the PWM duty cycle 1%, 50%, 99% and disable state. The blue curve of channel-1 represents the PWM duty cycle for the TPS61169 device control PIN, and the green curves of channel-4 represent the output currents of the TPS61169 LED drivers.

The figures show that the TPS61169 average output currents are about 5 mA, 110 mA, and 220 mA with the PWM duty cycle 1%, 50% and 99%, which is consistent with the theory. Figure 42 shows the PWM control signal and the changes of the output current with ambient light from brightness to darkness.
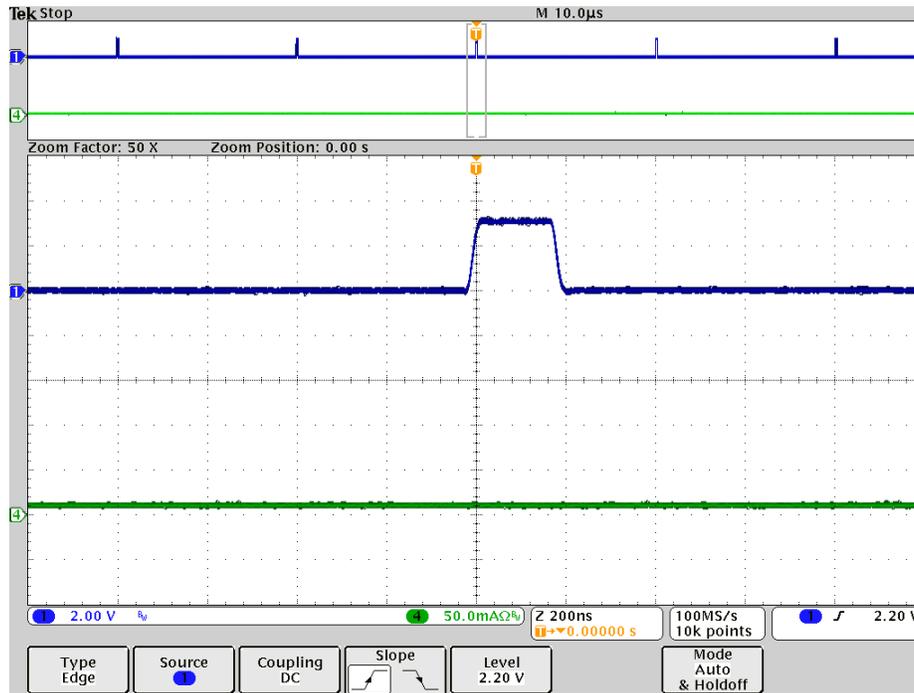
Figure 39. PWM Duty Cycle at 1% for Boost LED Driver
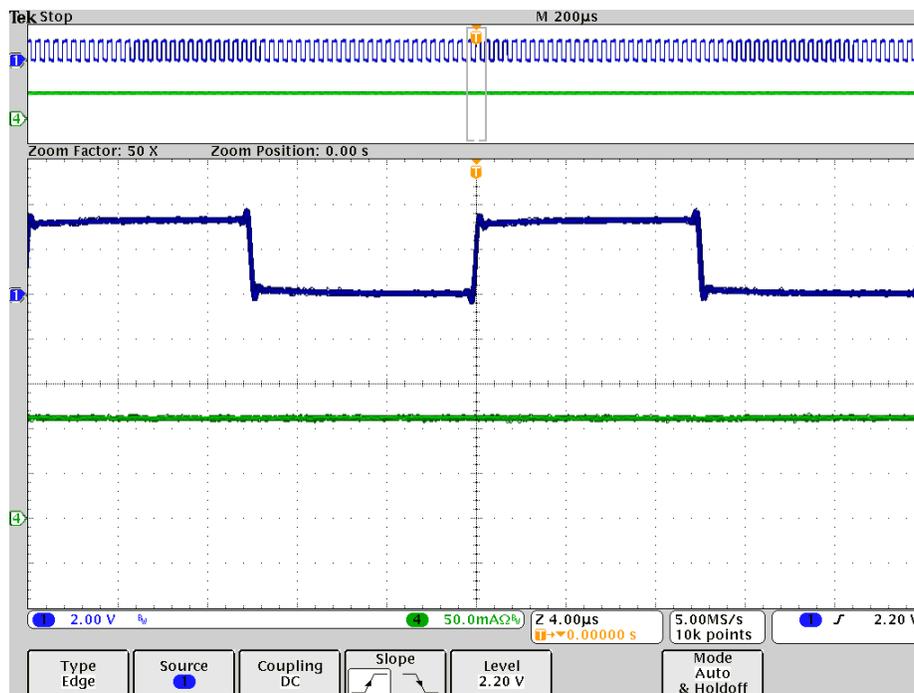
Figure 40. PWM Duty Cycle at 50% for Boost LED Driver
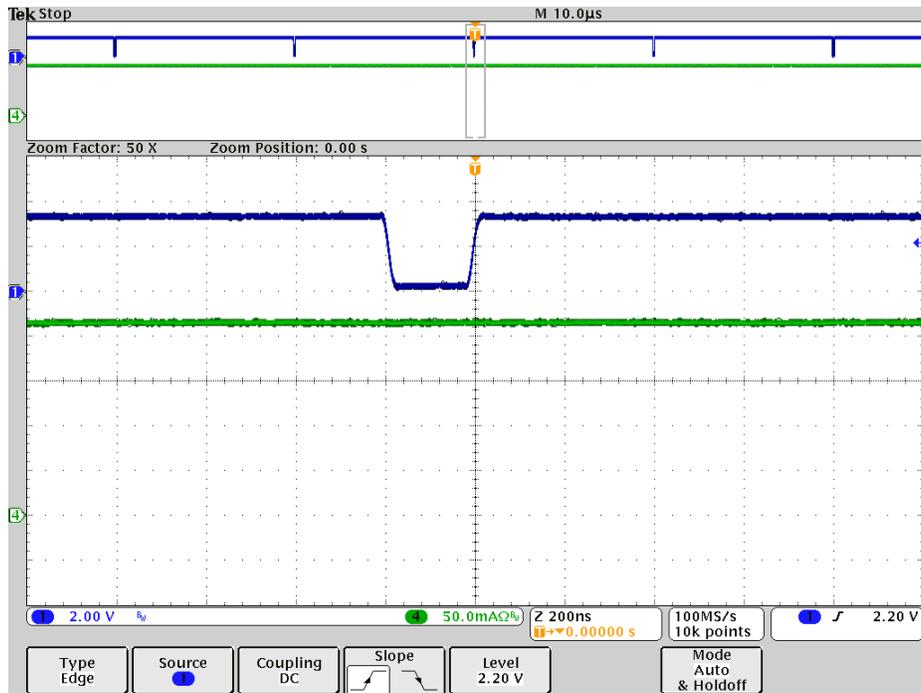
Figure 41. PWM Duty Cycle at 99% for Boost LED Driver
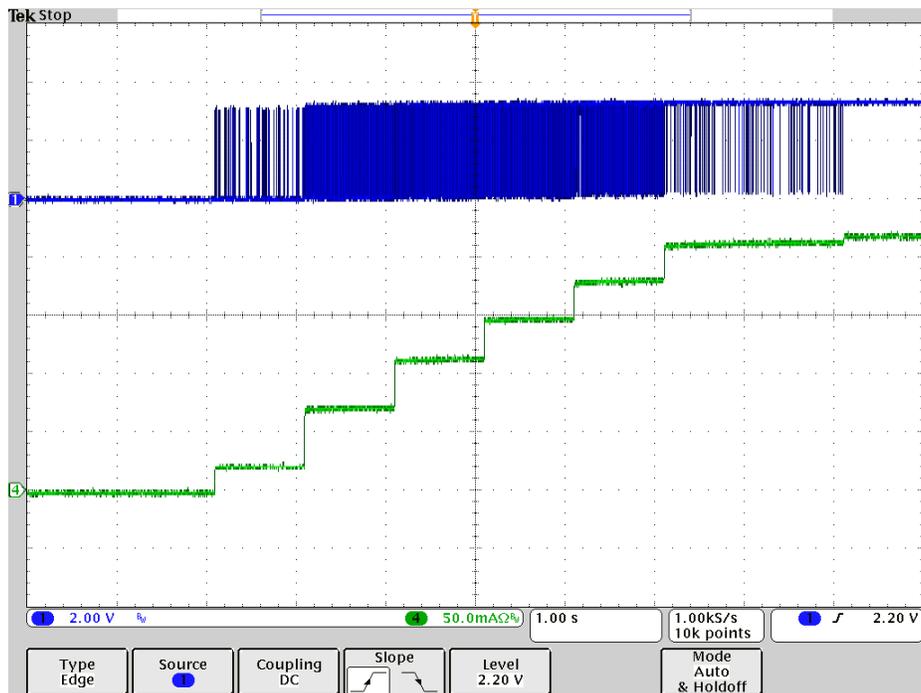
Figure 42. Boost LED Driver From Disable to 100% Duty Cycle

3.2.2.4 Motor Driver

Figure 43 and Figure 44 show the curves of the motor driver used to open and close ICR. Channel-1 used a current probe to detect the IN2 current of the DRV8837C device, channel-2 and channel-3 connect to the IN2 and IN1 pin of the DRV8837C, and channel-4 connects to the PWM pin of the TPS54201 device.

The direction of current through the IR filter coil can be controlled by using a sample PWM interface(IN1 and IN2) on the DRV8837C device. Figure 43 shows an example of the bidirectional current control using the DRV8837C. The DRV8837C is applying about 75 mA in two different directions in relation to the IR filter coil. This application causes the IR filter to open and shut, depending on the direction of current through the coil.
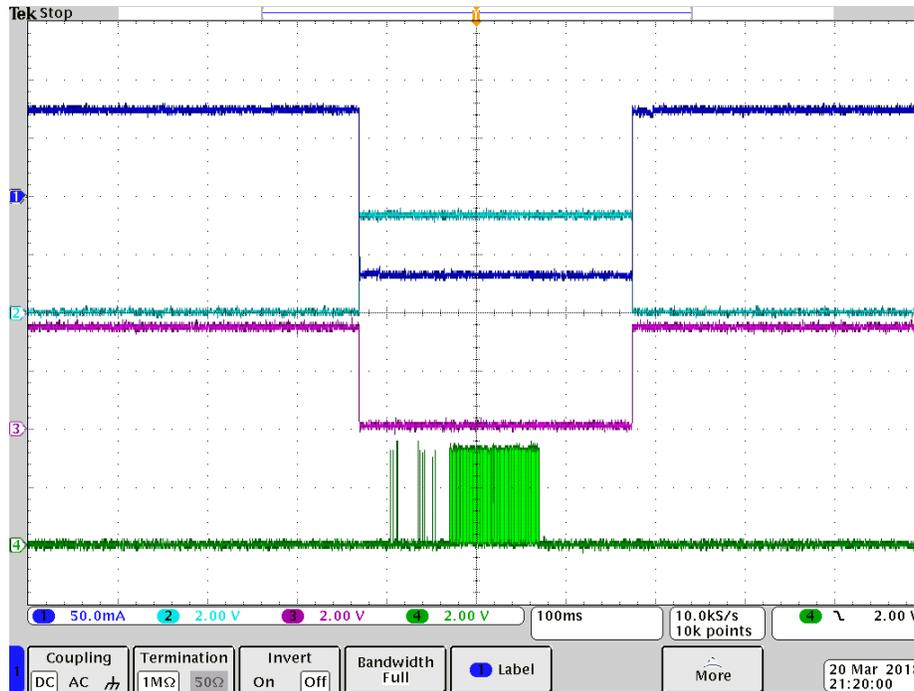
Figure 43. Bidirectional Current Control Using the DRV8837C

When the device is not opening or closing the IR filter, the device can be put into a low-power sleep mode where the driver will turn off the internal H-bridge into a high-impedance state and turn off all unnecessary logic. Figure 44 shows an example of the difference in sleep current and coil current consumption.

When the voltage on the nSLEEP pin of the DRV8837C is low, the device will stay in a low-power sleep state and no current drives through the IR filter coil. In this design, the nSLEEP pin on the DRV8837C device is tied to the output of an OR gate connected to both input pins on the DRV8837C. When either input pin is pulled high, the DRV8837C device comes out of its low-power sleep state and responds to the logic state on either of its input pins. Figure 44 shows this operation with 83 mA of current flowing through the coil while the device outputs are on and then the resulting 1 mA of current while the device is in its low-power sleep state.
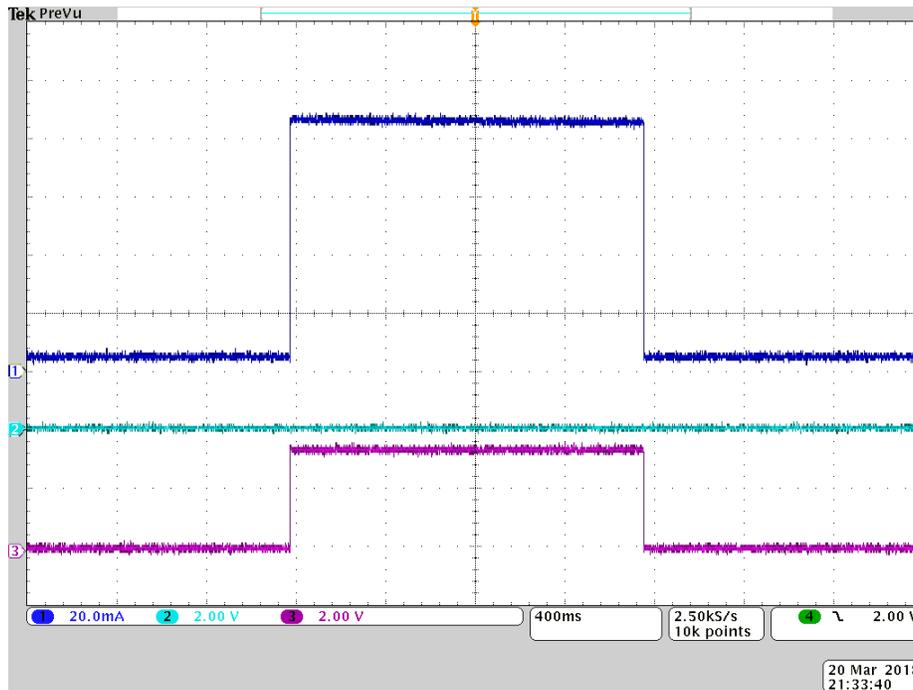
Figure 44. Current Consumption Difference in Sleep Current and Coil Current

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01586.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01586.

4.3 PCB Layout Recommendations

The key to estimating the ambient temperature accurately is to ensure an optimized PCB layout. Pay attention to where the sensors are placed as well as ensure a good heat dissipating plane near the heat load and farther from the main temperature sensing device.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01586.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01586.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01586.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01586.

5 Software Files

To download the software files, see the design files at TIDA-01586.

6 Related Documentation

1. Texas Instruments, *MSP430FR2311 LaunchPad™ Development Kit (MSP-EXP430FR2311) User Guide*
2. Texas Instruments, *TPS54200, TPS54201 4.5-V to 28-V Input Voltage, 1.5-A Output Current, Synchronous Buck WLED Driver Data Sheet*
3. Texas Instruments, *TPS61169 38-V High Current-Boost WLED Driver With PWM Control Data Sheet*
4. Texas Instruments, *OPT3001 Ambient Light Sensor Data Sheet*
5. Texas Instruments, *DRV883x Low-Voltage H-Bridge Driver Data Sheet*
6. Texas Instruments, *TPS54202 4.5-V to 28-V Input, 2-A Output, EMI Friendly Synchronous Step Down Converter Data Sheet*
7. Texas Instruments, *CSD25402Q3A –20 V P-Channel NexFET™ Power MOSFET*
8. Texas Instruments, *200mA Low-Iq Low-Dropout (LDO) Regulator for Portable Devices*

6.1 Trademarks

LaunchPad, E2E, BoosterPack, MSP430, MSP430Ware, Code Composer Studio, NexFET are trademarks of Texas Instruments.

7 About the Author

SHAWN DING is a systems designer at Texas Instruments, where he is responsible for developing reference designs in the industrial segment. Shawn earned his bachelor of science in electrical engineering (BSEE) degree from Hefei University of technology, Hefei, Anhui, China and a master of science in instrument and meter engineering (MSIME) degree from Zhejiang University at Hangzhou, Zhejiang, China.

DAVID STOUT is a systems designer at Texas Instruments, where he is responsible for developing reference designs in the industrial segment. David has over 18 years of experience designing Analog, Mixed-Signal, and RF ICs with more than 14 years focused on products for the industrial semiconductor market. David earned his bachelor of science in electrical engineering (BSEE) degree from Louisiana State University, Baton Rouge, Louisiana and a master of science in electrical engineering (MSEE) degree from the University of Texas at Dallas, Richardson, Texas.