CCFL to LED Conversion Power Supply

National Semiconductor
RD-169
Product Applications Design Center
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1.0 Design Specifications

Inputs	Output #1
VinMin=8V	Vout1=20V
VinMax=16V	Iout1=0.06A

2.0 Design Description

Better backlight displays for portable devices - Two-Channel 60 mA Backlight LED Driver Design

Backlighting in portable device displays has historically utilized difficult-to-power cold cathode-fluorescent (CCFL) tubes. The tubes run on alternating current (AC) and need a large initial voltage of typically greater than 1 kV in order to fire them. Once they have fired, their operating voltage drops to under a kV. Because a notebook computer, for example, typically operates on low DC voltages (12V, 5V, 3.3V, etc.), a Royer oscillator must be used to transform this low voltage to the high-voltage AC required by the CCFL. The high voltages in the system are a potential safety hazard.

The CCFL to LED conversion power supply reference design replaces the backlight CCFLs with strings of light-emitting diodes (LEDs). LEDs operate at low voltages of 3V TO 4V each and are extremely durable. They produce a brighter light whose spectral content can be more easily custom tailored to the needs of the backlight. Their brightness can be easily controlled to compensate for changes in ambient light. Also in contrast to the glass-tubed CCFLs, the physically small LEDs can be mounted on flexible strips, allowing the display to be more tolerant of and resistant to sudden shocks.

The reference design, with National Semiconductor's LM3431 three-channel, constant-current LED driver, uses two strings of six series-connected LEDs at a current of 30 mA per string. Each LED has a forward voltage drop of about 3.5V, making the total voltage across each string between 21V and 27V. With a 12V power source, the LM3431 is configured as a boost converter to generate this 21V to 27V output voltage.

The design also includes a circuit utilizing a photodiode to make the brightness of the LEDs proportional to ambient light thus improving the readability of the display under all lighting conditions.

3.0 Features

- 8-16V input voltage range
- Two accurately regulated LED channels at 60mA each and 21-28V
- Expandable to 3 or more LED channels
- 500 kHz switching frequency for small size
- High efficiency (76%)
- LED PWM dimming proportional to ambient light

4.0 Schematic

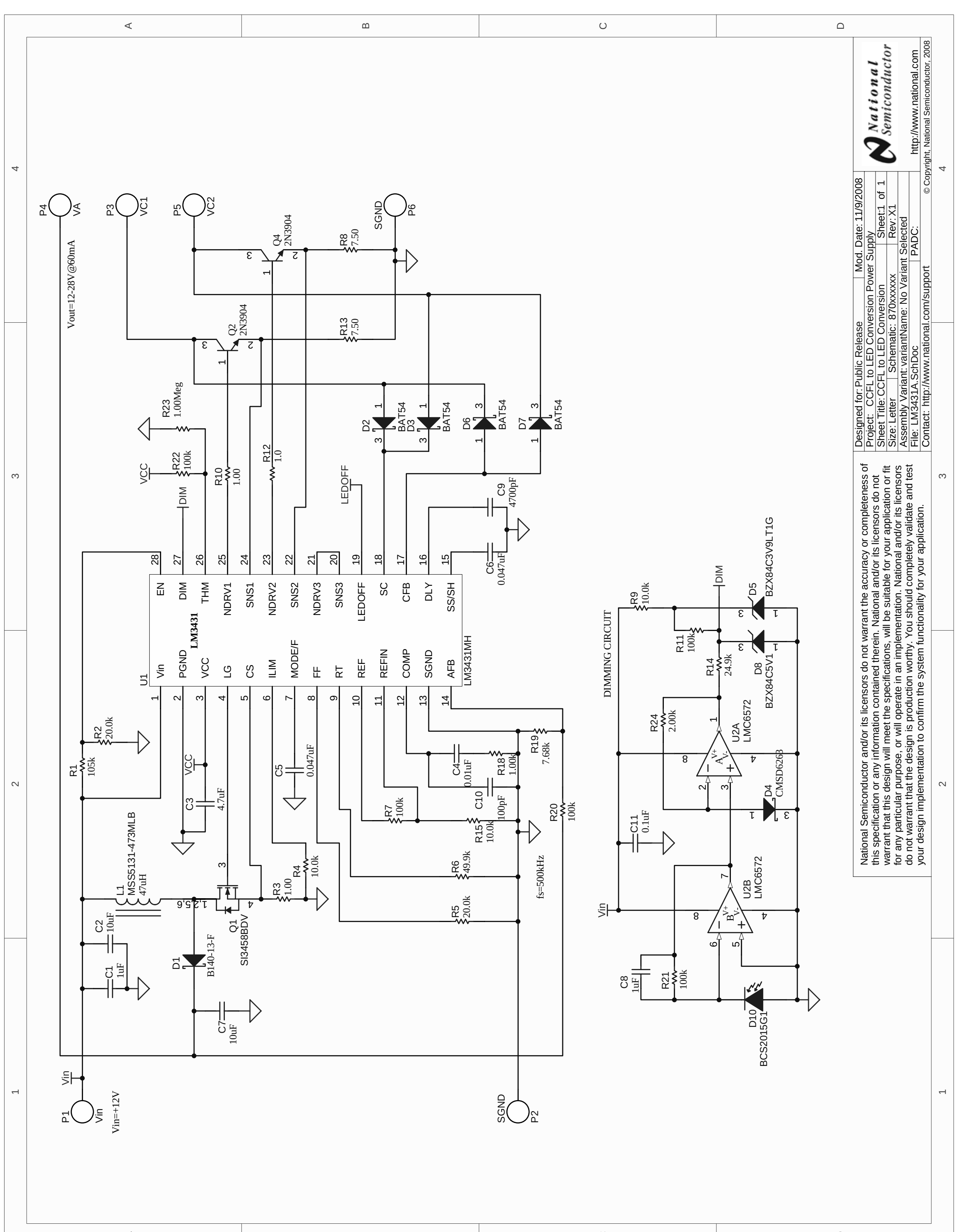


FIGURE 1. LED driver schematic

5.0 Bill of Materials

Designator	Value	PackageReference	Characteristics	Manufacturer	PartNumber	RoHS
C1	1uF	0805	Ceramic, X7R, 10V, 10%	TDK	C2012X7R1A105K	Y
C2	10uF	1206	Ceramic, X7R, 10V, 20%	TDK	C3216X7R1A106M	Y
C3	4.7uF	1206	Ceramic, X5R, 10V, 10%	TDK	C3216X5R1A475K	Y
C4	0.01uF	0805	Ceramic, C0G/NP0, 25V, 5%	TDK	C2012C0G1E103J	Y
C5, C6	0.047uF	0805	Ceramic, X7R, 100V, 10%	TDK	C2012X7R2A473K	Y
C7	10uF	1210	Ceramic, X7R, 25V, 20%	TDK	C3225X7R1E106M	Y
C8	1uF	0805	Ceramic, X7R, 10V, 20%	AVX	0805ZC105MAT2A	Y
C9	4700pF	0805	Ceramic, X7R, 100V, 20%	TDK	C2012X7R2A472M	Y
C10	100pF	0805	Ceramic, C0G/NP0, 50V, 5%	TDK	C2012C0G1H101J	Y
C11	0.1uF	0805	Ceramic, X7R, 50V, 10%	TDK	C2012X7R1H104K	Y
D1	0.5V	SMA	Vr = 40V, Io = 1A, Vf = 0.5V	Diodes Inc.	B140-13-F	Y
D2, D3, D6, D7	0.24V	SOT-23	Vr = 30V, Io = 0.2A, Vf = 0.24V	Diodes Inc.	BAT54-7-F	Y
D4	0.24V	SOT-323	Vr = 70V, Vf = 0.41V	Central Semiconductor	CMSD6263	O
D5	3.9V	SOT-23		ON Semiconductor	BZX84C3V9LT1G	Y
D8	5.1V	SOT-23		Diodes, Inc.	BZX84C5V1-7-F	Y
D10				TDK	BCS2015G1	Y
L1	47uH	MSS5131	Shielded Drum Core, 0.38A, 0.32 Ohm	Coilcraft Inc.	MSS5131-473MLB	Y
Q1	60V	TSOP_6	-3.6A, 3.5nC, rDS(on) @ 4.5V =0.105	Vishay-Siliconix	SI3458BDV	O
Q2, Q4	0.2V	TO-92	NPN, 0.2A, 40V	Central Semiconductor	2N3904	Y
R1	105k	0805	1%, 0.125W	Vishay-Dale	CRCW0805105kFKEA	Y
R2, R5	20.0k	0805	1%, 0.125W	Vishay-Dale	CRCW080520k0FKEA	Y
R3, R10	1.00	0805	1%, 0.125W	Vishay-Dale	CRCW08051R00FNEA	Y
R4, R9, R15	10.0k	0805	1%, 0.125W	Vishay-Dale	CRCW080510k0FKEA	Y
R6	49.9k	0805	1%, 0.125W	Vishay-Dale	CRCW080549k9FKEA	Y
R7, R11, R21, R22	100k	0805	1%, 0.125W	Vishay-Dale	CRCW0805100kFKEA	Y
R8, R13	7.50	0805	1%, 0.125W	Vishay-Dale	CRCW08057R50FNEA	Y
R12	1.0	0805	5%, 0.125W	Vishay-Dale	CRCW08051R00JNEA	Y
R14	24.9k	0805	1%, 0.125W	Vishay-Dale	CRCW080524k9FKEA	Y
R18	1.00k	0805	1%, 0.125W	Vishay-Dale	CRCW08051k00FKEA	Y
R19	7.68k	0805	1%, 0.125W	Vishay-Dale	CRCW08057k68FKEA	Y
R20	100k	0805	5%, 0.125W	Vishay-Dale	CRCW0805100kJNEA	Y
R23	1.00Meg	0805	1%, 0.125W	Vishay-Dale	CRCW08051M00FKEA	Y
R24	2.00k	0805	1%, 0.125W	Vishay-Dale	CRCW08052k00FKEA	Y
U1		MXA28A	3-Channel Constant Current LED Driver with Integrated Boost Controller	National Semiconductor	LM3431MH	Y
U2		M08A	Dual CMOS Low Voltage (2.7V and 3V) R-R Out Op Amp	National Semiconductor	LMC6572AIM	O

bom2

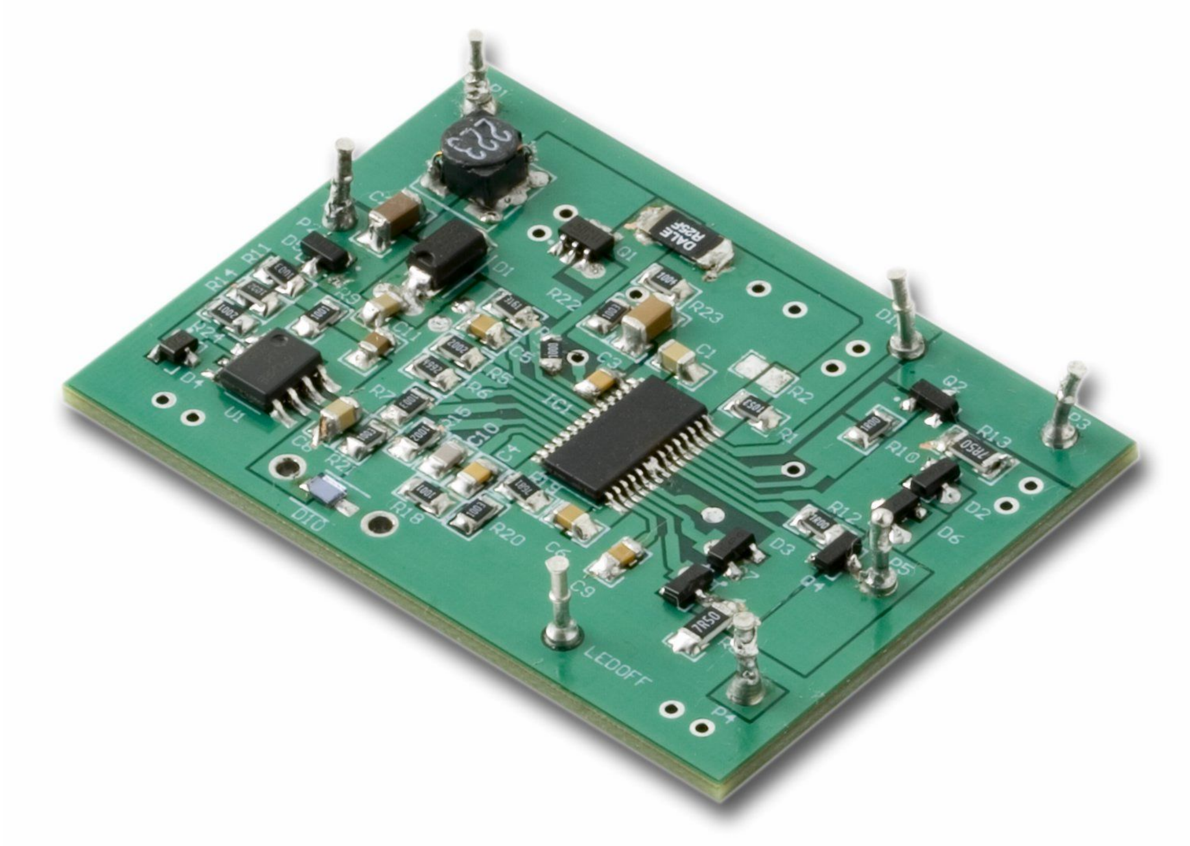
FIGURE 2. LED driver bill of materials

6.0 Other Operating Values

Operating Values

Description	Parameter	Value	Unit
Modulation Frequency	Frequency	500	KHz
Total output power	Pout	1.5	W
Steady State Efficiency	Efficiency	75	%
Peak-to-peak ripple voltage	Vout p-p	n/a	mV
Static load regulation	Static load	n/a	mV
Dynamic load regulation	Dynamic load	n/a	mV

7.0 Board Photos



boardphoto

FIGURE 3. LED driver board photograph

8.0 Quick Start

A photograph of the reference design is shown in Figure 3. To operate the board follow the steps outlined below.

1. Connect an LED string with an operating current of 30 mA and a rated voltage in the range 12-28V between the posts P4 (VA) and P3 (VC1). The anode side of the LED string should go to P4, and the cathode side to P3.
2. Connect a second LED string between posts P4 and P5 (VC2), again with polarity of anode to P4 and cathode to P5.
3. Apply an input voltage of 12V to the posts P1 (VIN) and P2 (SGND). The positive input voltage terminal should go to P1, and the negative terminal to P2.
4. The two LED strings should now be lighted.
5. To investigate the dimming function, shine a light more or less directly at the photodiode D10 on the board and notice how the LED strings brightens or dims according to whether there is more or less light falling on D10.
6. The equations 5, 6 and 7 given above can be used to fine tune the dimming function to conform to the characteristics of the display being used.

9.0 Hardware Description

The reference design schematic is shown in Figure 1. The boost converter consists of part of the LM3431, as well as C1, C2, C7, L1, Q1, R3 and D1 and produces an output voltage given by Eq. 1.

Equation 1 is derived as follows. One switching period consists of a time interval DT during which Q1 is on, and a complementary interval (1-D)T during which D1 is on. During Q1's on time the voltage across the inductor L1 is the input voltage, causing the inductor current to increase. When Q1 goes off the diode D1 turns on and the inductor current commutates into it to the output capacitor C7 and the LED strings. Under steady state conditions the output voltage, which appears across C7, is greater than the input voltage, so that during the (1-D)T interval the voltage across the inductor is equal to the difference between the output and input voltages. The net volt-seconds across the inductor are zero over one switching period, as given by Eq. 2

Rearranging Eq. 2 gives Eq. 1.

The currents flowing through the LED strings are set by the voltages at the SNS1, NDRV1, SNS2 and NDRV2 pins through the transistors Q2 and Q4. The voltages across the two diode strings are monitored at the SC and CFB pins of the LM3431 via diodes D2, D3, D6 and D7. The larger of the LED string voltages, i.e., the more negative one of the collector voltages of either Q2 or Q4, is used by the LM3431 to adjust the output voltage of the boost converter to a value that is just high enough for both LED strings to pass the right current, but no higher , in order to minimize the power dissipated in the transistors.

Each transistor Q2 or Q4 is configured as a linear voltage regulator with a fixed emitter voltage. The current through the diodes string connected to Q2 is given by Eq. 3

The current through the LED string connected to Q4 follows the same equation, but with R13 replaced by R8. With only very minor modifications to the components this board is capable of driving LED strings at significantly higher currents.

If there is a fault and the LED strings open, the resistors R19 and R20 limit the output voltage to a safe value that is set to be slightly greater than the highest normal operating voltage.

The LM3431's datasheet gives a complete description of all of the IC's functions.

The LM3431 supports either digital or analog dimming of the LEDs via the DIM pin. The present design uses analog dimming which is selected by connecting the mode pin to ground through a capacitor C5. An analog signal is applied to the DIM pin to cause the current through the LEDs to be PWM controlled at a frequency that is low relative to the switching frequency. The dimming PWM frequency, can be set to be as high as 25kHz, and is set by C5 according to Eq. 4.

It is recommended to use a dimming frequency in the 100-200Hz range. The duty ratio of the dimming signal increases proportionally from 0 to 100% as the analog voltage increases from 0.4V to 2.5V.

It is desirable for the brightness of the LEDs to be proportional to ambient light conditions so that the display is not too bright in dark conditions and is easy to view under bright light. A photodiode circuit comprising D10, op-amp U2 and associated components is used to implement this. If diode D4 is used the output voltage of this circuit appearing at pin 1 of U2 is exponentially proportional to the light intensity sensed by D10. If D4 is omitted and some of the resistors are re-sized, then U2A becomes a voltage follower and the output voltage of the circuit is simply directly proportional to the light intensity. A circuit comprising D5, R9, R11 and R14 applies an offset voltage to the dimming pin so that even if there is no ambient light the display retains a minimum brightness level.

The following equations can be used to calculate component values in the dimming circuit.

The output voltage of the photodiode amplifier appearing at pin 7 of U2 is given by Eq. 5

For the linear version of the dimming circuit (with D4 omitted) the output voltage at pin 1 is also equal to that at pin 7.

For the exponential version the voltage at pin 1 is given by Eq. 6. The exponential term in the expression for the diode current in Eq. 6 is typically much greater than unity, so that the equation reduces to Eq. 7. This equation is nearly exponential if R24 is made large so that the voltage across it is much greater than that across D4. The fraction of the voltage at pin 1 of voltage that appears at the DIM pin of the LM3431 is given by Eq. 8.

The offset voltage that ensures that some light is produced by the LED even when no light impinges on the photodiode is related to the breakdown voltage of zener diode D5 by Eq. 9.

The total voltage at the DIM pin of U1 is the sum of the voltages in equations 8 and 9 and is given by Eq. 10. The quantities in Eq. 10 can be adjusted to give the desired dimming behavior.

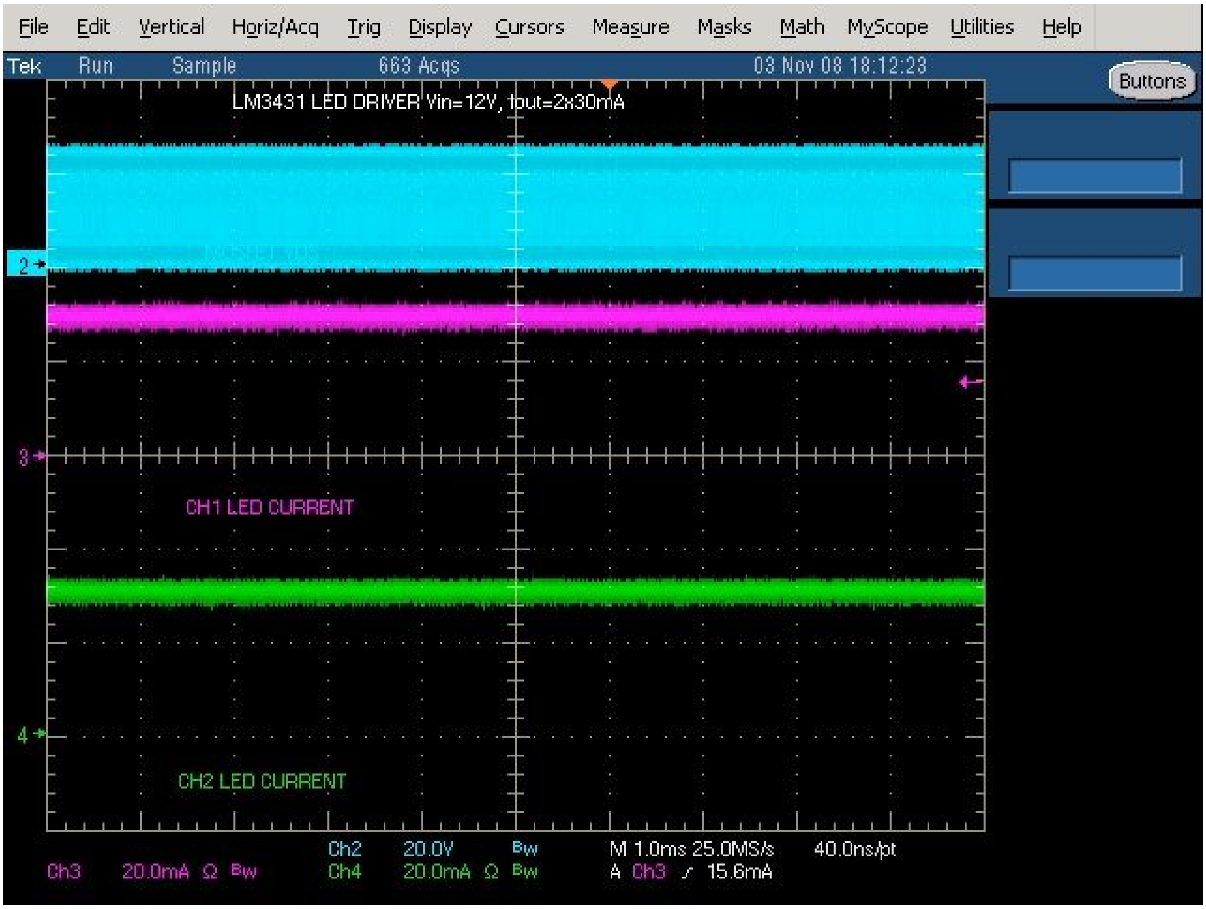
10.0 Test Results

— Figure 4 shows the currents in the two LED strings at maximum brightness. The currents are continuous at 30 mA. The trace is the drain-source voltage of Q1, and the bottom two traces are the currents in the two LED strings.

— Figure 5 shows the LED strings' currents when dimmed at a frequency of 200Hz to a duty ratio of about 20%. This condition corresponds to the minimum duty ratio for the LEDs when the photodiode is in the dark.

— Figure 6 shows the LED strings' currents at a duty ratio of 50%.

11.0 Waveforms



waveform

FIGURE 4. LED currents with no dimming and maximum ambient light

other

FIGURE 5. Fully dimmed LED currents with no ambient light

other1

FIGURE 6. Half dimmed LED currents

12.0 Appendix

Equations

$$V_{OUT} = \frac{V_{IN}}{1-D} \qquad \text{Eq. 1}$$

D is the duty ratio of Q1.

$$V_{IN} DT = (V_{OUT} - V_{IN})(1-D)T \qquad \text{Eq. 2}$$

$$I_{LED} = \frac{V_{REFIN}}{R_{13}} = \frac{V_{REF} R_{15}}{(R_7 + R_{15}) R_{13}} \qquad \text{Eq. 3}$$

$V_{REF} = 2.5V$ and V_{REFIN} are respectively the voltages at the REF and REFIN pins of the LM3431.

$$f_{DIM} = \frac{40\mu}{4.26 C_5} \qquad \text{Eq. 4}$$

$$V_P = I_P R_{21} \qquad \text{Eq. 5}$$

where I_P is the photodiode current.

$$V_1 = V_{D4} + i_{D4} R_{24} = V_{D4} + R_{24} i_{D4} \approx V_{D4} + R_{24} I_o \left(e^{\frac{V_{D4}}{0.026}} - 1 \right) \qquad \text{Eq. 6}$$

where V_{D4} and $I_{D4} = I_o \left(e^{\frac{V_{D4}}{0.026}} - 1 \right)$ are respectively the voltage across and the current in D4, and I_o is the diode's saturation current.

$$V_1 = V_{D4} + R_{24} I_o \, e^{\frac{V_{D4}}{0.026}} \qquad \text{Eq. 7.}$$

$$V_{DIMP} = \frac{V_1 R_{11}}{R_{11} + R_{14}} \qquad \text{Eq. 8}$$

$$V_{ofst} = \frac{V_{D5} R_{14}}{R_{11} + R_{14}} \qquad \text{Eq. 9}$$

image

FIGURE 7. Equations

Notes

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