Ambient Light Adaptive LED Driver

National Semiconductor
RD-168
Applications Design Center
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1.0 Design Specifications

Inputs	Output #1
VinMin=6V	Vout1=20V
VinMax=12V	Iout1=0.1A

2.0 Design Description

The ambient light adaptive LED driver automatically adjusts display brightness for changing ambient light conditions, providing a more viewable display with better contrast. The design drives five series connected LEDs from an input voltage of 4.5V to 12V. The LED current is nominally 100 mA and the output voltage is 15 to 20V.

The heart of the design is National's PowerWise® LM3423 LED driver which has all the features needed to implement a boost converter with output current regulation and PWM dimming of the current. The LM3423 achieves output current regulation by sensing and appropriately adjusting the voltage across a resistor connected in series with the LED string.

Dimming or brightening the backlight of a display in response to ambient light condition can greatly increase the life of batteries in portable devices, and improves the visibility of the display under different viewing conditions. In this design a photodiode circuit is used to measure ambient light and provide a signal for dimming the LEDs.

PWM dimming is the preferred method of dimming because it allows the light's color temperature to remain constant irrespective of its intensity. PWM dimming is done by keeping the amplitude of the LED current constant, but periodically turning the LED driver on and off, thus varying the LEDs' average current and light intensity. The switching is at done at a low frequency, but one which is high enough for the human eye to sense only changes in the light's average intensity. Linear dimming, where the amplitude of the current in the LEDs is modulated, is not suitable because the LEDs' light color temperature is sensitive to the current's amplitude.

The dimming range of the average LED current is from 20 to nearly 100% percent of its nominal value as ambient light conditions increase from dark to bright. To reduce power consumption and prolong battery life the output current is clamped to no more than 50% of the nominal value when the input (battery) voltage falls below a predetermined level.

3.0 Features

- 4.5-12V battery input voltage range
- 100 mA Constant current LED at 15-20V
- High switching frequency
- High efficiency (85%)
- PWM LED dimming up to 25kHz
- LED brightness limited to less than 50% of maximum at low input voltage to prolong battery life
- LED brightness proportional to ambient light

4.0 Schematic

schematic2

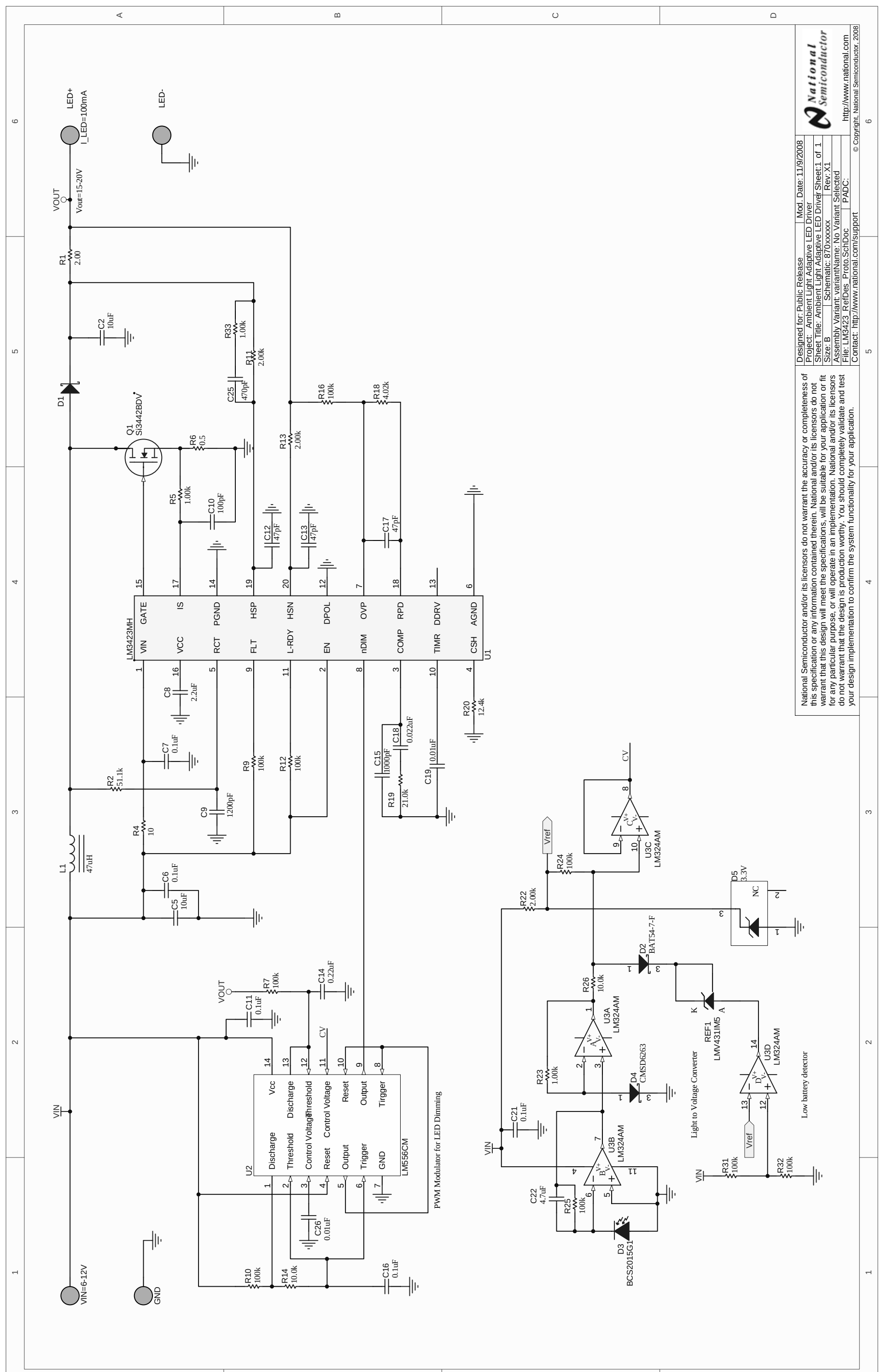


FIGURE 1. LED Driver Board Schematic

5.0 Bill of Materials

Designator	Value	PackageReference	Characteristics	Manufacturer	PartNumber	RoHS
C2	10uF	1206	Ceramic, X5R, 25V, 20%	Taiyo Yuden	TMK316BJ106ML-T	
C5	10uF	1210	Ceramic, X7R, 25V, 20%	TDK	C3225X7R1E106M	Y
C6	0.1uF	1206	Ceramic, X7R, 50V, 10%	Yageo America	12062R104K9B20D	
C7, C11, C21	0.1uF	0805	Ceramic, X7R, 25V, 10%	AVX	08053C104KAT2A	Y
C8	2.2uF	0805	Ceramic, X5R, 16V, 10%	AVX	0805YD225KAT2A	Y
C9	1200pF	0805	Ceramic, X7R, 100V, 10%	AVX	08051C122KAT2A	Y
C10	100pF	0805	Ceramic, C0G/NP0, 100V, 1%	AVX	08051A101FAT2A	Y
C12, C13	47pF	0805	Ceramic, C0G/NP0, 100V, 5%	AVX	08051A470JAT2A	Y
C14	0.22uF	0805	Ceramic, X7R, 25V, 20%	AVX	08053C224MAT2A	Y
C15	1000pF	0805	Ceramic, X7R, 100V, 10%	AVX	08051C102KAT2A	Y
C16	0.1uF	0805	Ceramic, X7R, 25V, 10%	TDK	C2012X7R1E104K	Y
C17	47pF	0805	Ceramic, C0G/NP0, 100V, 10%	AVX	08051A470KAT2A	Y
C18	0.022uF	0805	Ceramic, X7R, 100V, 10%	AVX	08051C223KAT2A	Y
C19, C26	0.01uF	0805	Ceramic, X7R, 50V, 10%	AVX	08055C103KAT2A	Y
C22	4.7uF	0805	Ceramic, X7R, 10V, 20%	TDK	C2012X7R1A475M	Y
C25	470pF	0805	Ceramic, X7R, 50V, 10%	AVX	08055C471KAT2A	Y
D1	0.5V	SMA	Vr = 25V, Io = 1.5A, Vf = 0.5V	Vishay-Semiconductor	BYS10-25-E3/TR	Y
D2	0.65V	SOT-23	Vr = 30V, Io = 0.2A, Vf = 0.65V	Diodes Inc.	BAT54-7-F	Y
D3				TDK	BCS2015G1	Y
D4	0.24V	SOT-323	Vr = 70V, Vf = 0.41V	Central Semiconductor	CMSD6263	O
D5	3.3V	SOT-23	0.225W	ON Semiconductor	BZX84C3V3ET1G	Y
GND, I_LED=100mA, LED-, VIN=6-12V	Double		Terminal, Turret, TH, Double	Keystone Electronics	1503-2	Y
L1	47uH	MSS1038	Shielded Drum Core, 1.6A, 0.128 Ohm	Coilcraft Inc.	MSS1038-473MLB	Y
Q1	30V	SOT23-6		Vishay	Si3442BDV	Y
R1	2.00	0805	1%, 0.125W	Vishay-Dale	CRCW08052R00FNEA	Y
R2	51.1k	0805	1%, 0.125W	Vishay-Dale	CRCW080551k1FKEA	Y
R4	10	0805	5%, 0.125W	Vishay-Dale	CRCW080510R0JNEA	Y
R5, R23, R33	1.00k	0805	1%, 0.125W	Vishay-Dale	CRCW08051k00FKEA	Y
R6	0.5	1206	1%, 0.25W	Susumu Co	RL1220S-R47-F	Y

bom2

FIGURE 2. LED Driver Board BOM Page 1 of 2

Designator	Value	PackageReference	Characteristics	Manufacturer	PartNumber	RoHS
R7, R9, R10, R12, R16, R24, R25, R31, R32	100k	0805	1%, 0.125W	Vishay-Dale	CRCW0805100kFKEA	Y
R11, R13, R22	2.00k	0805	1%, 0.125W	Vishay-Dale	CRCW08052k00FKEA	Y
R14, R26	10.0k	0805	1%, 0.125W	Vishay-Dale	CRCW080510k0FKEA	Y
R18	4.02k	0805	1%, 0.125W	Vishay-Dale	CRCW08054k02FKEA	Y
R19	21.0k	0805	1%, 0.125W	Vishay-Dale	CRCW080521k0FKEA	Y
R20	12.4k	0805	1%, 0.125W	Vishay-Dale	CRCW080512k4FKEA	Y
REF1		MF05A	Low-Voltage (1.24V) Adjustable Precision Shunt Regulator	National Semiconductor	LMV431IM5	O
U1		MXA20A	N-Channel Controllers for Constant Current LED Drivers	National Semiconductor	LM3423MH	Y
U2		M14A	Dual Timer	National Semiconductor	LM556CM	O
U3		M14A	Low Power Quad Operational Amplifier	National Semiconductor	LM324AM	O

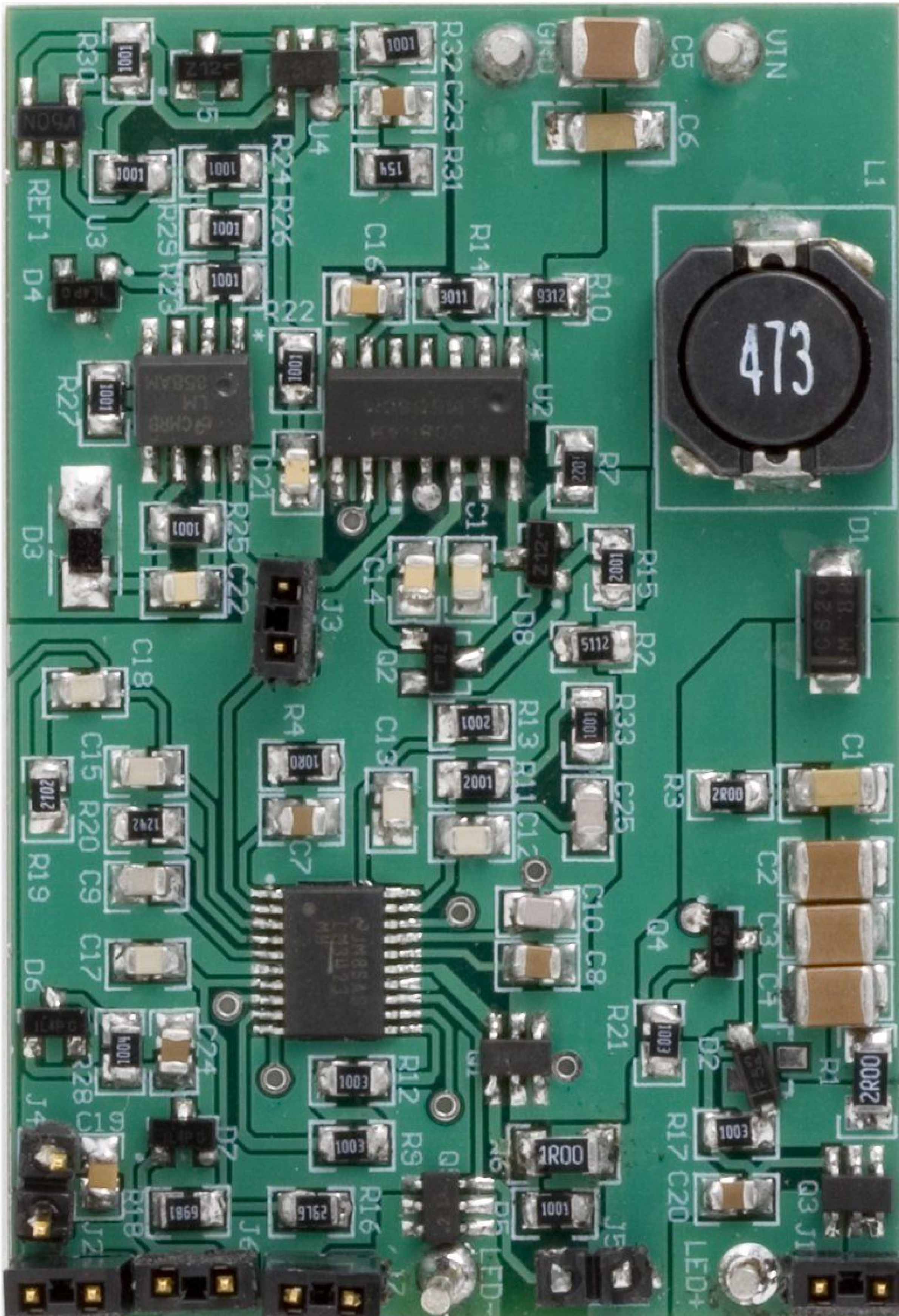
FIGURE 3. LED Driver Board BOM Page 2 of 2

6.0 Other Operating Values

Operating Values

Description	Parameter	Value	Unit
Modulation Frequency	Frequency	300	KHz
Total output power	Pout	2	W
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
Steady state efficiency	Efficiency	85	%

7.0 Board Photos



boardphoto

FIGURE 4. 4_LED_Driver_2482

8.0 Quick Start

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

1. Connect an LED string with a rated current of 100 mA at a voltage in the 15-20V range between the LED+ (anode side) and LED- posts (cathode side)
2. Apply a 9V battery to the VIN and GND pins which are adjacent to each other
3. The LED string should now be lighted.
4. To investigate the dimming function, shine a light more or less directly at the photodiode D4 on the board and notice how the Leeds brighten or dim according to whether there is more or less light falling on D4.
5. The equations 5, 6 and 7 given above can be used to fine tune the dimming function to conform to the characteristics of the application being designed for.
6. To investigate the battery life-extending function, replace the battery with an adjustable power supply set at 9V, ensure that a bright light is shining on the photo diode, and observe that the LEDs are on.
7. Now reduce the power supply voltage, and notice that when the voltage falls to about 6V, the LEDs' brightness drops to about 50% and stays there. Notice also that the brightness can fall below this value if the light falling on the photodiode decreases, but it cannot increase above 50%.
8. The equations 8 through 10 can be used to select the voltage level at which the brightness changes.

9.0 Hardware Description

The reference design schematic is shown in Figure 1 and the bill of materials is shown in Figures 2 and 3. A battery input voltage powers a boost converter comprising U1 and the power components C5, C6, L1, Q1, D1 and C2. The output voltage of the boost converter, which appears across C2, is given by Eq .1.

Eq. 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 and the LED string. Under steady state conditions the output voltage 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 output current of the boost converter flows to the LEDs through a high side sense resistor R1. High side sensing reduces the number of wires in a system with many parallel LED strings because the cathodes of all the LEDS share a common ground. The sense resistor's voltage is applied via the HSP and HSN pins to a current amplifier within the LM3423 and used to regulate the LED current to a value given by Eq. 3. The LM3423's datasheet derives Eq. 3 and explains all of the IC's features.

If there is a fault and the LED strings open, the resistors R16 and R18 limit the output voltage to a safe value that is set to be somewhat greater than the highest normal operating voltage.

The LM3423 supports dimming of the LEDs via the nDIM pin. A PWM signal applied to the nDIM pin turns the boost converter on and off, allowing and interrupting LED current flow, thus achieving dimming. If faster dimming than is possible by this method is desired, it can be implemented by switching on and off with a signal from the DDRV pin (this signal is derived from that at the nDIM pin) a MOSFET placed in the LED current path. See application note AN1872 for details on exactly how to do this.

It is also 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 D3, op-amp U3A and U3B and associated components is used to implement this. If diode D4 is used the output voltage of this circuit appearing at pin 7 of U3B is exponentially proportional to the light intensity sensed by D3. If D4 is omitted then U3B becomes a voltage follower and the output voltage of the circuit is simply directly proportional to the light intensity. A circuit comprising D5, R22, R24 and R26 applies an offset voltage to the dimming voltage so that even if there is no ambient light a minimum voltage representing a minimum brightness level remains at pin 10 of UC3C

A comparator circuit built around U3D monitors the input battery voltage. If the battery voltage falls below about 6.6V the output of U3D goes low, and a clamping voltage of about 2V created by reference REF1 and diode D2 is imposed on pin 10 of U3C. Thus no matter what the ambient light conditions are the voltage at pin 10 can not go above 2V, though it if free to assume any value below 2V. The 2V represents a maximum dimming duty ratio of about 50%. Limiting the maximum duty ratio in this way extends battery life under bright light conditions.

The voltage at pin 8 of voltage follower buffer U3C is the control voltage to which dimming duty ratio of the LEDs is proportional. The PWM dimming signal is generated by a PWM modulator built around an LM556 timer, U2. The left-hand side of U2 is configured as an astable multivibrator that generates a clock of narrow negative pulse and determines the dimming frequency. The dimming frequency is given by Eq. 4. The astable multivibrator's output voltage is used as the clock for a PWM modulator built around the right-hand side of U2. Each time the astable multivibrator's output (pin 5) produces a negative pulse the PWM modulator starts a new switching cycle. The output voltage of the modulator at pin 9 goes high and the timing capacitor C14 starts charging from zero to the output voltage through R7 according to Eq. 5. The output voltage of the dimming circuit at pin 8 of U3C is applied as a control voltage to the PWM modulator at pin11 of U2 (Note that U3C is a buffer which is required between the dimming circuit and the control pin of the PWM modulator, which has a low impedance.). When the rising voltage across capacitor C14 intersects this control voltage the output of the modulator appearing at pin 9 of U2, and applied to the nDIM pin of U1, goes low, and stays low until the multivibrator starts a new switching cycle. Consequently the dimming duty ratio is proportional to the voltage produced by the dimming circuit built around U3.

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

The output voltage of the photodiode amplifier at pin 1 of U1 is given by Eq. 6

For the linear version of the dimming circuit i.e., with D4 omitted, the output voltage at pin 7 is equal to that at pin 1.

For the exponential version the voltage at pin 7 is given by Eq. 7. The exponential term in the expression for the diode current in Eq. 7 is typically much greater than unity, so that the equation reduces to Eq. 8. This equation is nearly exponential if R23 is made large so that the voltage across it is much greater than that across D4.

The fraction of the voltage at pin 7 of U3B voltage that appears at pin 10 of U3C is given by Eq. 9.
The offset voltage that ensures that some light is produced by the LEDs even when no light impinges on the photodiode is related to the breakdown voltage of zener diode D5 by Eq. 10.

The total voltage at pin 10 of U3C is the sum of the voltages in equations 8 and 9 and is given by Eq. 11. The quantities in Eq. 11 can be adjusted to give the desired dimming behavior.

10.0 Test Results

— Figure 5 shows the LED current in the two strings at maximum brightness. The current is almost continuous at 100 mA. The duty ratio is slightly less than 100% because of way in which the LM556 PWM dimming works.
— Figure 6 shows the LEDs dimmed to the minimum possible dimmed brightness of about 20%, obtained when there is no ambient light and the input voltage is above 6.6V.
— Figure 7 shows the current in the LEDs defaulting to a maximum dimmed value of 50% when the input voltage falls below 6.6V while the photodiode is in bright light.
— Figure 8 shows the current in the LEDs when the input voltage is below 6.6V and there is no ambient light. Thus under low voltage conditions the circuit adjusts correctly to light conditions that correspond to dimming duty ratios less than 50%.

11.0 Waveforms

waveform

FIGURE 5. Vin =9_ diode current @max. light

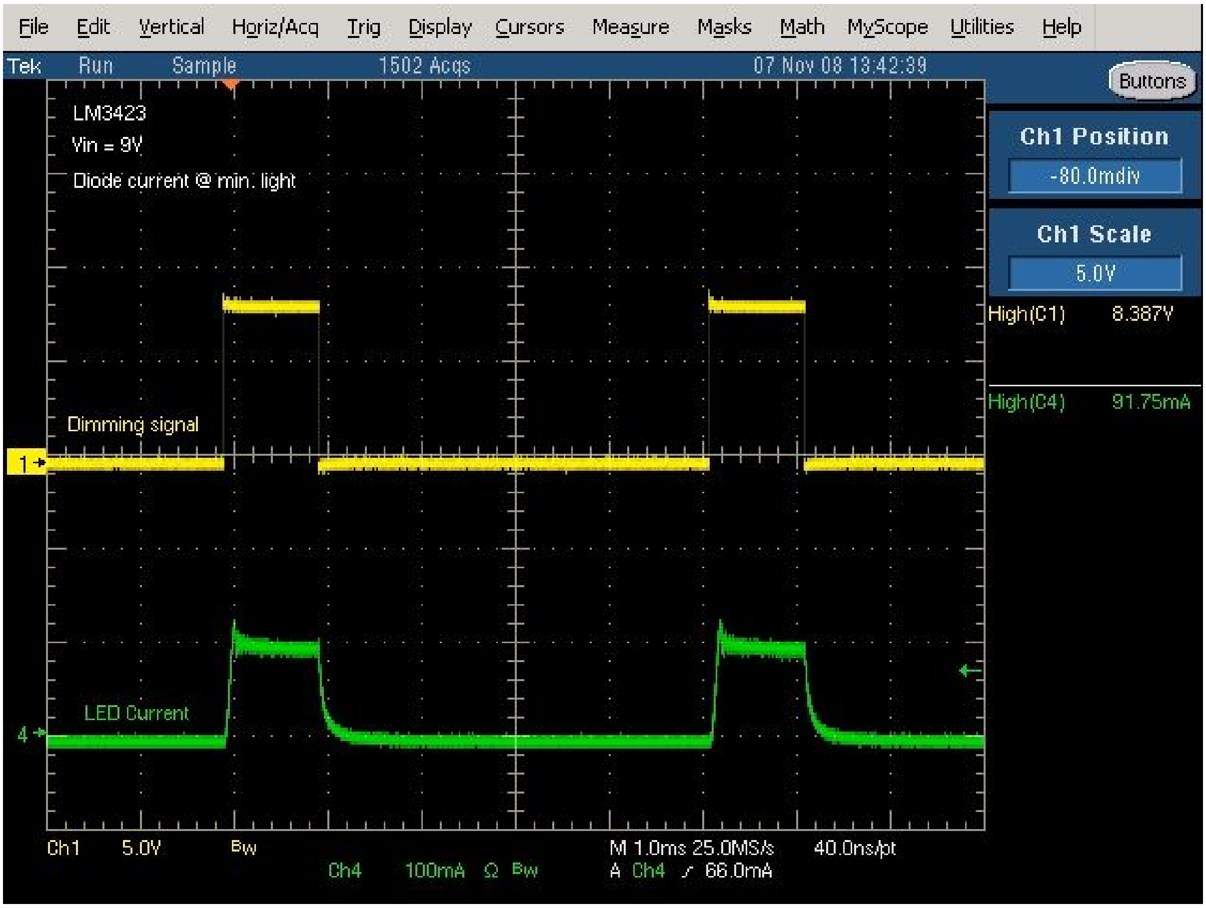
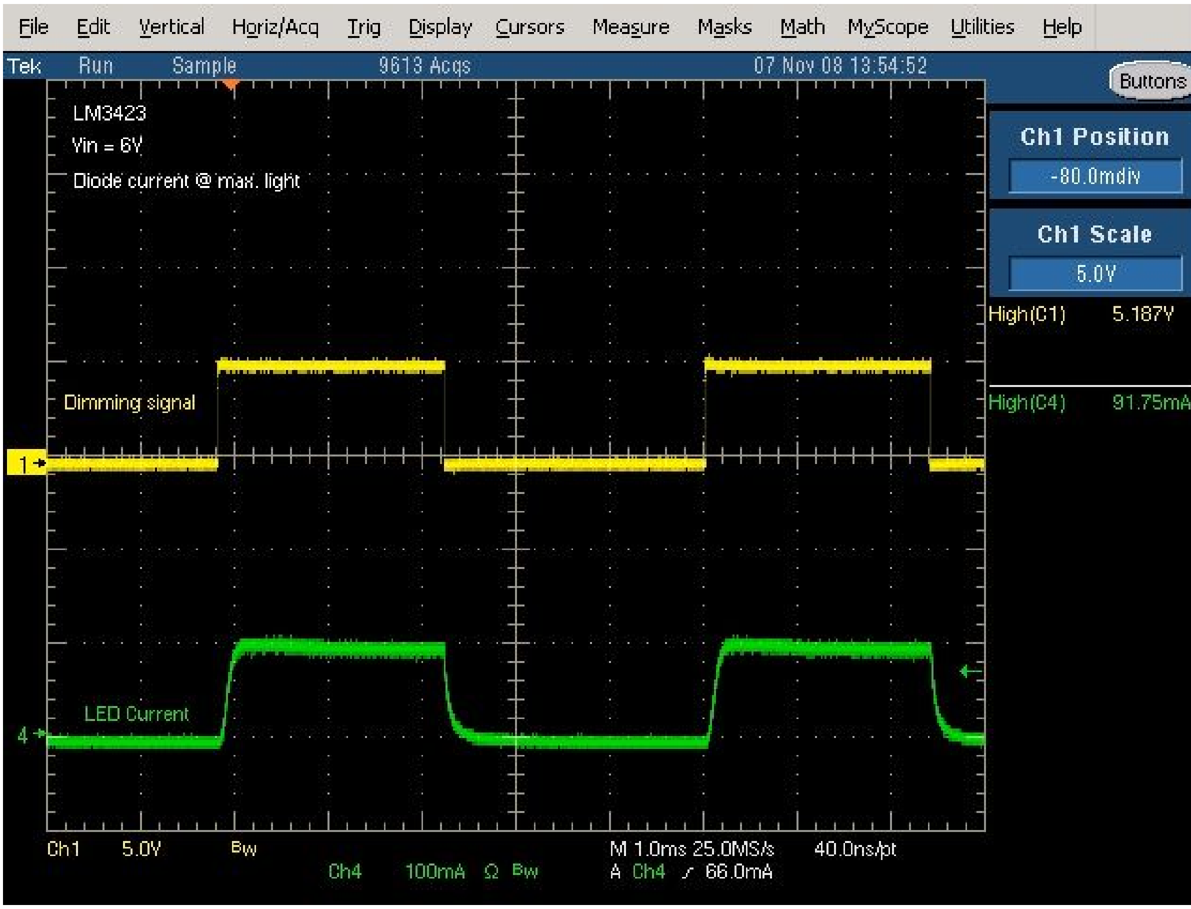
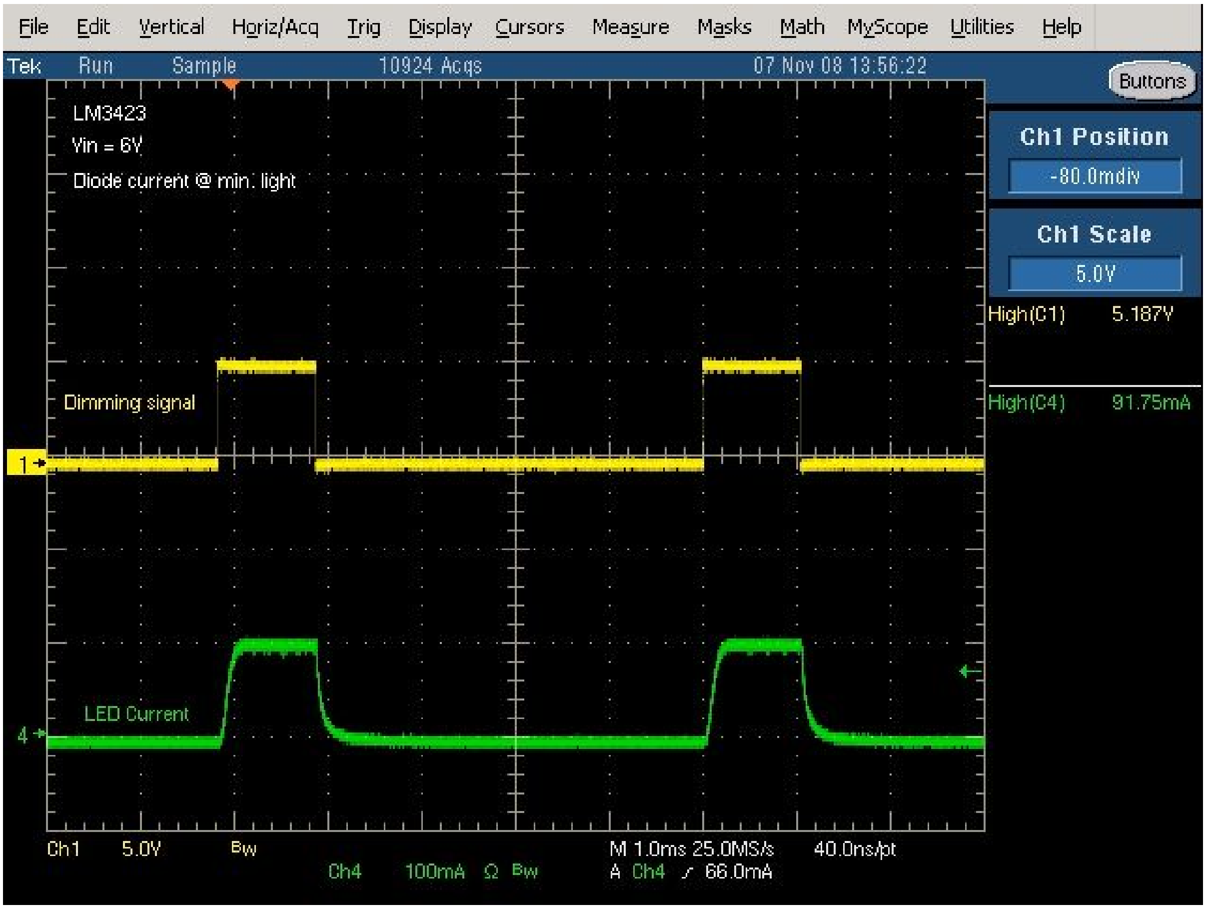


FIGURE 6. Vin = 9_diode current @min. light



waveform2

FIGURE 7. Vin = 6_diode current @max. light



waveform3

FIGURE 8. Vin = 6_diode current @min. light

12.0 Appendix

Equations

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

D is the duty ratio of Q1.

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

$$I_{LED} = \frac{V_{REF} R_{11}}{R_1 R_{20}}$$ Eq. 3

Where $V_{REF} = 1.235V$ is the reference voltage of the error amplifier of the LM3423.

$$f_{DIM} = \frac{1.44}{\left(R_{10} + 2R_{14}\right)C_{16}}$$ Eq. 4

$$C_{14}(t) = V_{OUT}\left(1 - e^{-\frac{t}{C_{14}R_7}}\right)$$ Eq. 5

$$V_P = I_P R_{25}$$ Eq. 6

where I_P is the photodiode current.

$$V_7 = V_{D4} + i_{D4}R_{23} = V_{D4} + R_{23}i_{D4} \approx V_{D4} + R_{23}I_o\left(\mathrm{e}^{\frac{V_{D4}}{0.026}} - 1\right)$$ Eq. 7

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

$$V_7 = V_{D4} + R_{23}I_o\,\mathrm{e}^{\frac{V_{D4}}{0.026}}$$ Eq. 8.

$$V_{10P} = \frac{V_7 R_{24}}{R_{24} + R_{26}}$$ Eq. 9

image

FIGURE 9. LM3423_Equations

Notes

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