TI Information — Selective Disclosure

LED Driver for DLP3030-Q1 Displays

Application Report

TEXAS INSTRUMENTS

Literature Number: DLPA084
April 2018

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Purpose and Scope

Purpose and Scope

This document provides a description of TI's reference RGB LED driver and color control system to meet the application needs of automotive head-up display (HUD) and other interior displays, based on the DLP3030-Q1 chipset. The approaches introduced in this document are not final, are under development, and are subject to revision as new information warrants.

A word on software development for the Piccolo device:

TI provides access to reference software running on a TI Piccolo family MCU for the LED controller, that implements a dimming and color control scheme as outlined in this document. The resulting software code can be licensed to TI customers, in addition to the hardware design files. This reference design serves as a starting point for customers to help them develop their own production solution more quickly.

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Chapter 1

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Terms and Abbreviations

1.1 Terms and Abbreviations

Abbreviations	Description
SPI	Serial Peripheral Interface
I2C	Inter-Integrated Circuit
HUD	Head-Up Display
LED	Light Emitting Diode
MCU	Microprocessor Control Unit
PWM	Pulse Width Modulation
RGB	Red, Green, and Blue
ADC	Analog to Digital Converter
FET	Field Effect Transistor
NFET	N-channel Field Effect Transistor
PFET	P-channel Field Effect Transistor
LSB	Least Significant Bit
PCB	Printed Circuit Board

Chapter 2

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References

2.1 References

1.	2514132	DLPC120 Controller and LED Driver Schematic
2.	2514134	DLPC120 Controller and LED Driver BOM
3.	DLPA082	Photodiode Selection Guide
4.	DLPU066	DLP3030-Q1 RGB LED Calibration for Automotive Display User's Guide
5.	DLPU056	DLPC120-Q1 I2C User Interface Programmer's Guide

Chapter 3

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Application

3.1 Application

The DLP3030-Q1 LED driver is designed to cost effectively support automotive DLP® applications requiring precise control of color and brightness over a wide dimming range. The driver is a sub-system level reference design that leverages many unique features of the Piccolo TMS320F28023 MCU and specific functions designed into the automotive DLPC120-Q1 DMD controller ASIC.

The driver utilizes two operating modes to support a brightness (dimming) range of over 5000:1. These modes are referred to as continuous mode (CM) and discontinuous mode (DM).

Continuous mode features:

- High to mid brightness levels
- Rectangular light pulses are created for each color
- Pulse amplitude and width are varied to adjust brightness level

Discontinuous mode features:

- Mid to low brightness levels
- A series of small triangular light pulse are created for each color
- Number of pulses, pulse height and current are varied to adjust brightness level

Chapter 4

Functional Description

4.1 Functional Block Diagrams

Figure 4-1 shows a typical DLPC120-Q1 system block diagram highlighting the LED driver sub-system. Figure 4-2 is a detailed diagram of the LED driver and control loops implemented with the Piccolo MCU.

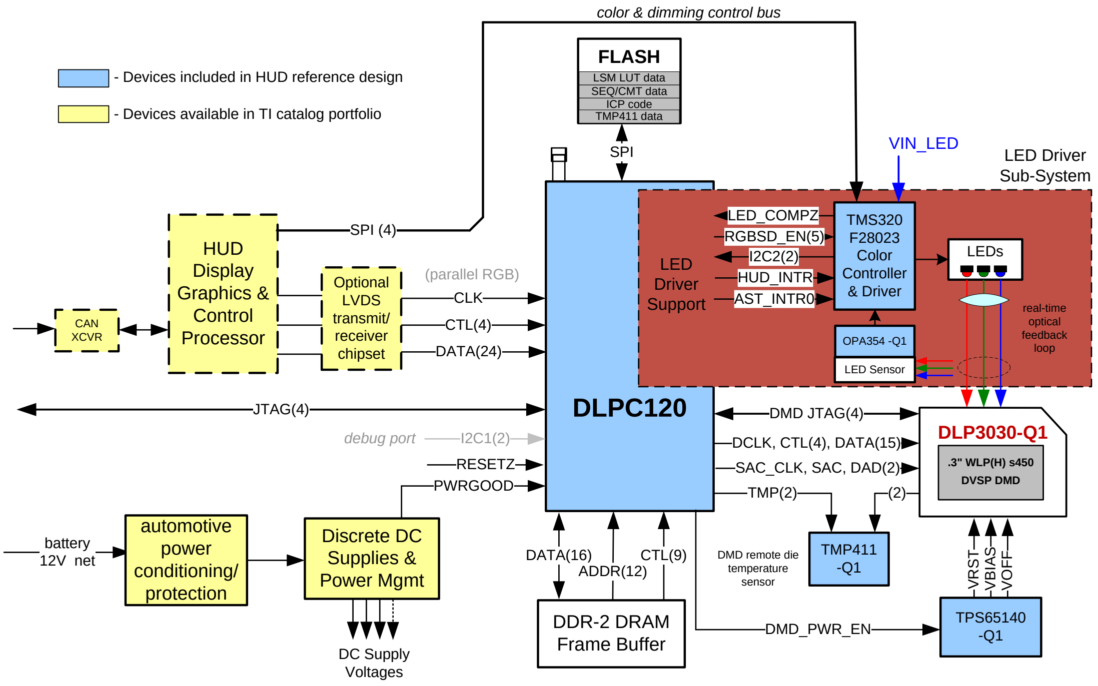


Figure 4-1. Typical Application

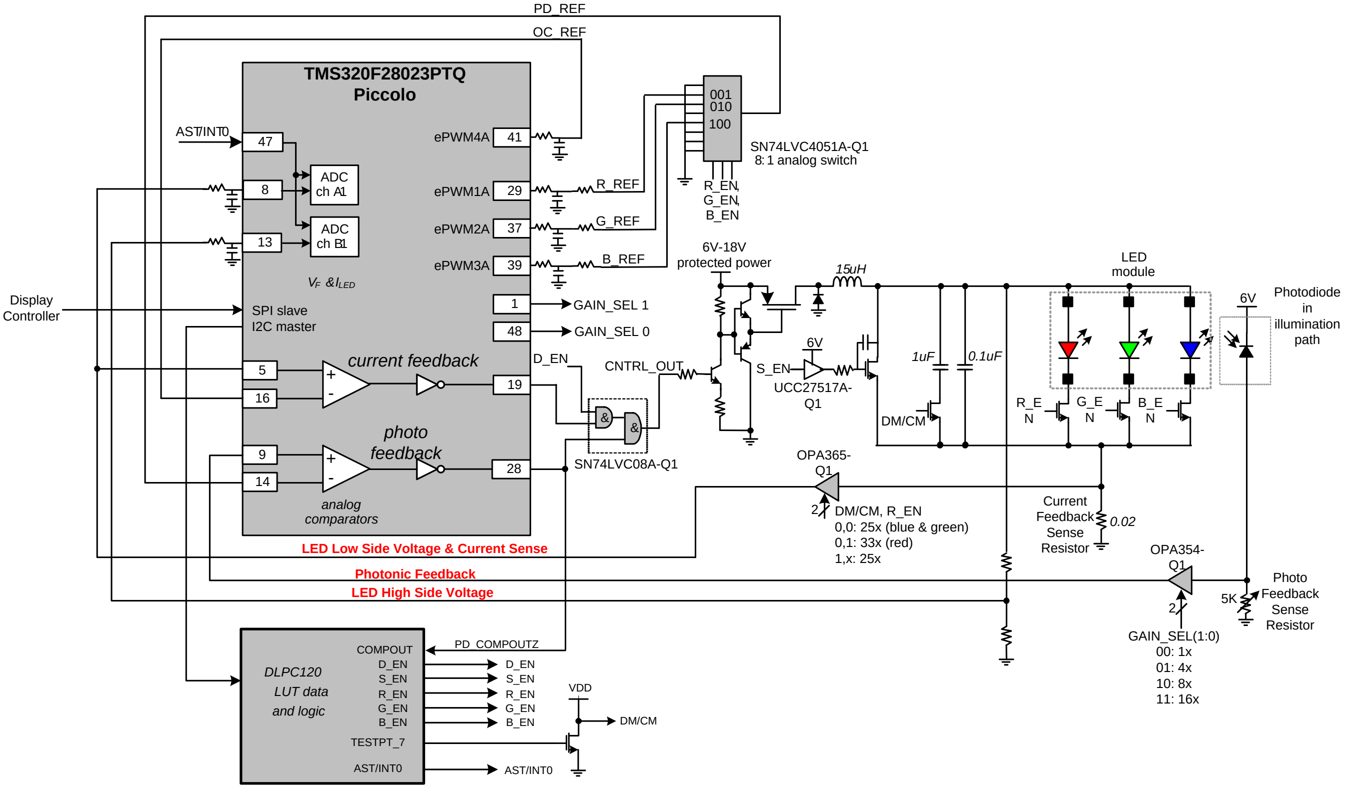


Figure 4-2. DLP3030-Q1 LED Driver Block Diagram

4.2 Piccolo Command and Control Flow/Interfaces

4.2.1 Piccolo Command Interface

As shown in Figure 4-1 and Figure 4-2, the LED driver's Piccolo MCU provides a SPI slave interface that serves as the communication port to the HUD display control processor. The display processor is typically a MCU with graphics capability that serves as the HUD display system master. This display processor will make decisions regarding desired display brightness (based on screen content, user settings and ambient light measurements) and then send brightness/dimming commands to the Piccolo via the SPI bus at a rate of up to 60 Hz (one new brightness command per frame). Piccolo SW interprets these commands and coordinates all adjustments within the sub-system.

4.2.2 Piccolo Control Interface to DLPC120-Q1

The Piccolo configures the DLPC120-Q1 over a dedicated I^{2}C bus (I2C2 in Figure 4-1). Registers and look up table (LUT) data content in the DLPC120-Q1 determine the LED sequence selection, bit slice pulse widths, continuous or discontinuous mode, and pulse counts per bit slice (in the case of discontinuous mode). Registers and LUTs in the DLPC120-Q1 that are adjustable by the Piccolo are double-buffered and pipelined, to support seamless updates on a per-frame basis. One exception to this is the VAC function (see the DLPC120-Q1 Programmer's Guide for further information). When the Piccolo receives a brightness command, it will send I2C commands to the DLPC120-Q1 to update the LUT data. The DLPC120-Q1 will perform this update synchronously with a frame sync. When the DLPC120-Q1 updates the tables, it will inform the Piccolo using the HUD_INTR signal. This will prompt the Piccolo to update the LED amplitudes. See the DLPC120-Q1 Programmer's Guide for further information.

4.2.3 Piccolo ePWM Control Outputs

As highlighted in Figure 4-3, the Piccolo MCU is configured to output three enhanced PWMs (ePWMs) to set the light levels for the red, green, blue LEDs and one ePWM output for setting the LED current level or limit. The ePWM outputs are low pass filtered to produce high resolution analog levels. The DLP3030-Q1 hardware reference design uses a 330-µs RC filter time constant with an ePWM frequency of 41.67KHz. Lowering the filter time constant or ePWM frequency will result in higher ripple and could result in flicker at low discontinuous mode brightness settings. Increasing the filter time constant increases the time for the filter to settle to a new value which could create artifacts as the brightness is changed. Increasing the ePWM frequency lowers the effective resolution available.

An analog switch (SN74LV4051A-Q1) is used to select between the filtered RGB ePWM settings. The output of the switch is an input to one of the Piccolo's comparators (Section 4.2.4).

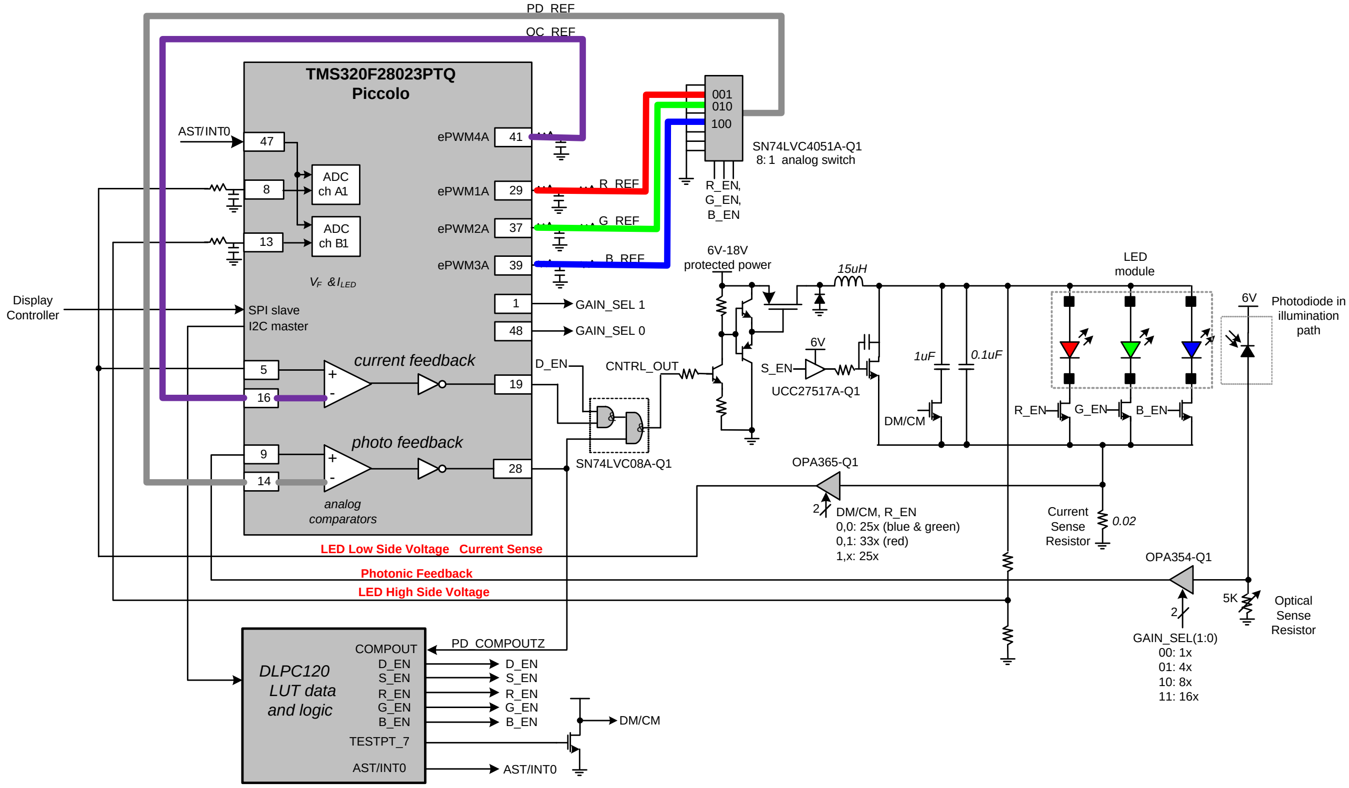


Figure 4-3. Piccolo ePWM Outputs to Comparators

4.2.4 Piccolo Comparators

As seen in Figure 4-2, two internal Piccolo comparators are used for LED control. One comparator is used for regulating LED driver current (current feedback), and one is used to regulate LED light (photo feedback).

The photo feedback comparator uses Pin 9 and Pin 14 of the Piccolo as the input. Pin 14 is the target light level generated from the selected ePWM. Pin 14 is the amplified response of the photodiode. Notice, the gain of the photodiode amplifier (OPA354-Q1) can be adjusted by the Piccolo. A higher gain allows smaller LED light amplitudes. This helps the system achieve lower brightness targets.

The current feedback amplifier uses Pin 5 and Pin 16 on the Piccolo as inputs. Pin 16 is the output of ePWM4A, the current level or limit target. Pin 5 is the amplified response measured from the current sense resistor. The current through the LEDs or through the parallel S_EN FET generates a voltage when it passes through the current sense resistor. This voltage is amplified and used an input to the current feedback amplifier.

4.2.5 Piccolo ADCs

The two ADCs in the Piccolo are configured to make simultaneous samples of the LED current and voltage. See Section 5.7 for further information.

4.3 Continuous Mode Operation

When operating in continuous mode (continuous *light output* mode) a hysteretic control scheme is utilized. Real-time analog light amplitude measurements are used in the photo feedback loop to achieve and maintain a target light level. Figure 4-4 highlights the photo feedback paths in the driver for continuous mode driving the red LED. The on-board analog comparator in the Piccolo MCU is used to compare desired target LED light amplitude (PD_REF) to actual LED light output amplitude measured with the photodiode circuit. When the light output is below the threshold (set by the filtered ePWM outputs of the Piccolo), the comparator will output a high level on PD_COMPOUTZ, causing a connection from the power rail to the LED drive inductor to be made through a PFET. This will cause current flow to the LED to increase. When the light value goes above the threshold, PD_COMPOUTZ goes low and the PFET is turned off, breaking the connection to the power rail. Once the light level drops below the threshold (minus a 35-mV hysteresis inherent in the Piccolo comparator), the PFET is turned back on, delivering more power to the LED. This process repeats as long as the LED circuit is enabled. The hysteretic control will result in ripple in the LED current. The amplitude and frequency of this ripple is a function of the inductance, input voltage, comparator hysteresis and loop latency. An advantage of this hysteretic control approach is unconditional stability of the control loop. Figure 4-5 shows the continuous mode signals and light output for a red, green, and blue bit slice.

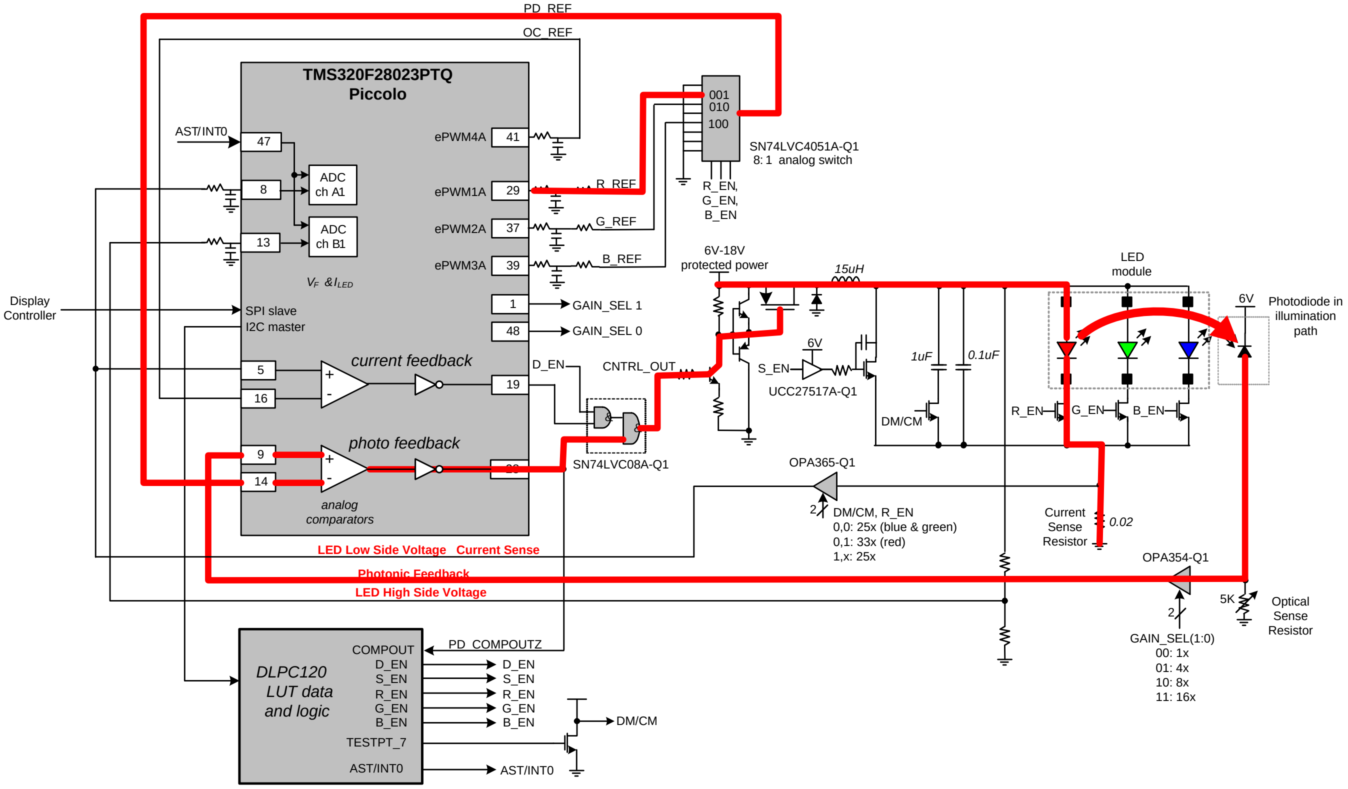


Figure 4-4. Continuous Mode Photo Feedback Path

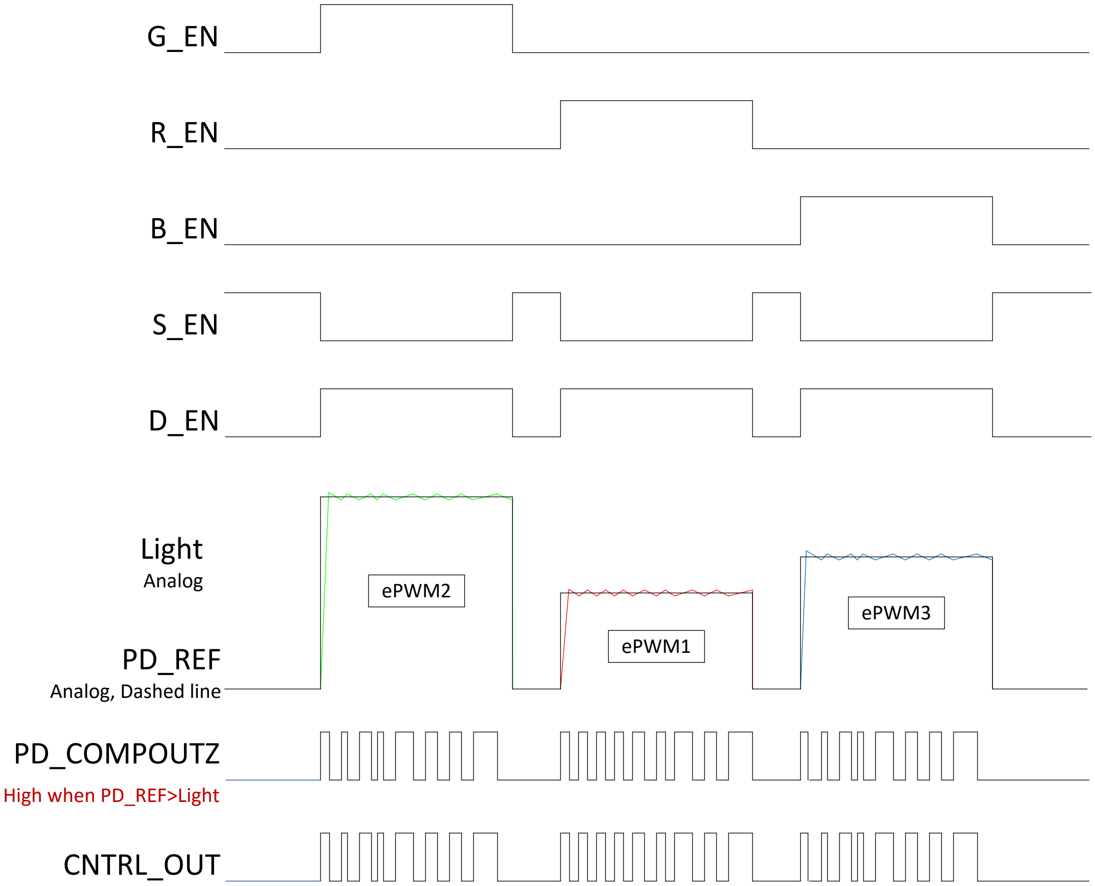


Figure 4-5. Continuous Mode Signals

In continuous mode, LED light output is displayed for the entire length of each bit slice, unless the display is being dimmed. Dimming is accomplished through a combination of amplitude/flux dimming and pulse time attenuation. Amplitude dimming is done by adjusting the Piccolo ePWM outputs. Time attenuation is accomplished by adjusting the length of shunt enable (S_EN) and drive enable (D_EN) (see Figure 4-21). Figure 4-6 shows an example with a 100% bit and a bit with time and amplitude attenuation to achieve 32:1 dimming. Figure 4-7 is a more generic example showing how many different dimming levels can be achieved with combinations of time and amplitude dimming.

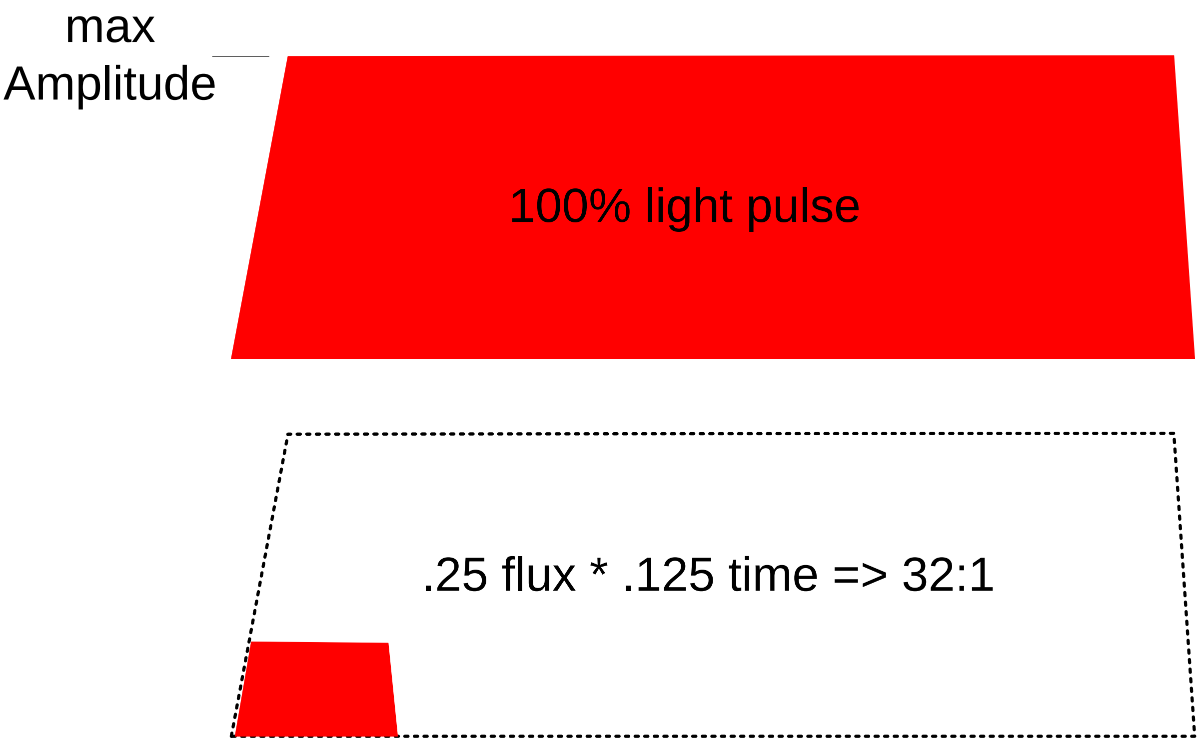


Figure 4-6. Continuous Mode Dimming Example 1

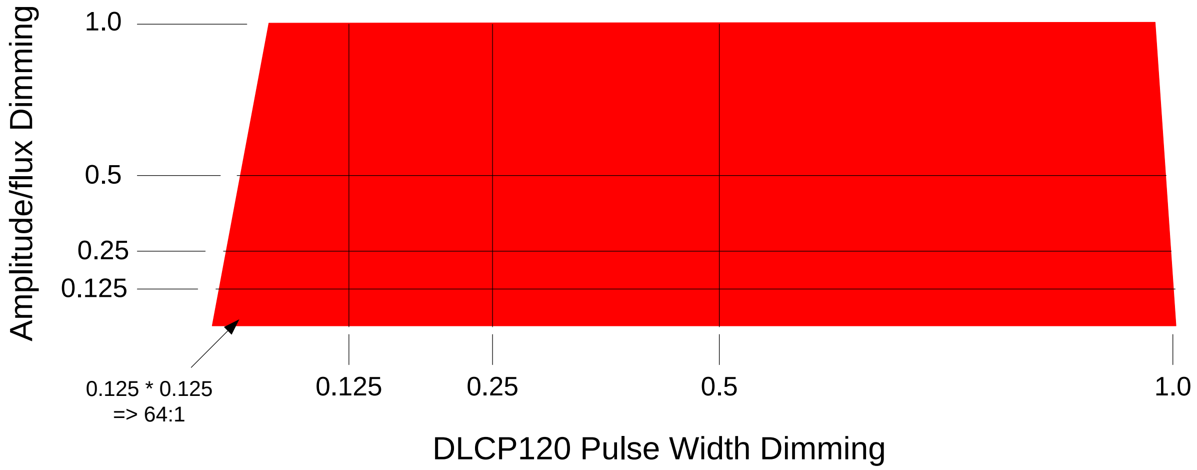


Figure 4-7. Continuous Mode Dimming Example 2

In continuous mode the DM/CM signal is set low so the FET controlling the 1-µF capacitor is turned off leaving only the 0.1-µF capacitor in parallel with the LEDs and shunt FET (Figure 4-4). This allows the voltage across the capacitor and LED to charge up faster than the current in the inductor increases which prevents the current/light from overshooting at the beginning of bit slices.

4.3.1 Continuous Mode Driver Distortion

Figure 4-8 shows the control signals and bit slice timing for a time attenuated green bit. The non-attenuated full bit slice time is defined by the G_EN high time. The system attenuates the bit time by de-asserting D_EN and asserting S_EN before the end of the bit slice. As shown in Figure 4-8, the actual LED current pulse can be distorted from the desired D_EN/S_EN time if the rising (Tr) and falling (Tf) edge rates are not equal and/or the turn-on (Tp1) and turn-off (Tp2) propagation delays are not equal. The rising edge rate of the current pulse is primarily a function of the voltage across the inductor and the desired current. Supplying the driver with a regulated input voltage instead of the battery voltage is desirable to eliminate variation in the pulse width. Note also that the pulse width distortion will vary for different amplitude attenuations. For example a 4-A current pulse will have a longer rising edge than the 2-A current pulse. The falling edge rate of the pulse is controlled by the shunt FET turn-on time. Since a regulated 6 V is used for the shunt FET driver the falling edge does not vary due to input voltage.

Pulse width distortion can cause non-linearities in the light output for different input gray shades. These non-linearities are most noticeable in a gray ramp. The pulse width distortion will have the biggest impact on the most time-attenuated bits. Driver pulse width distortion can be compensated for by adjusting the bit timing for time attenuated bits as shown in Figure 4-9. Note it is not possible to completely compensate for all driver distortion since the distortion varies with amplitude attenuation (current).

It is also possible to adjust the timing of the D_EN and S_EN signals relative to each other and relative to the red, green and blue LED enables (G_EN, B_EN, R_EN) to compensate for different delays in the driver hardware for these signals to take effect. Please contact a TI application engineer for further information.

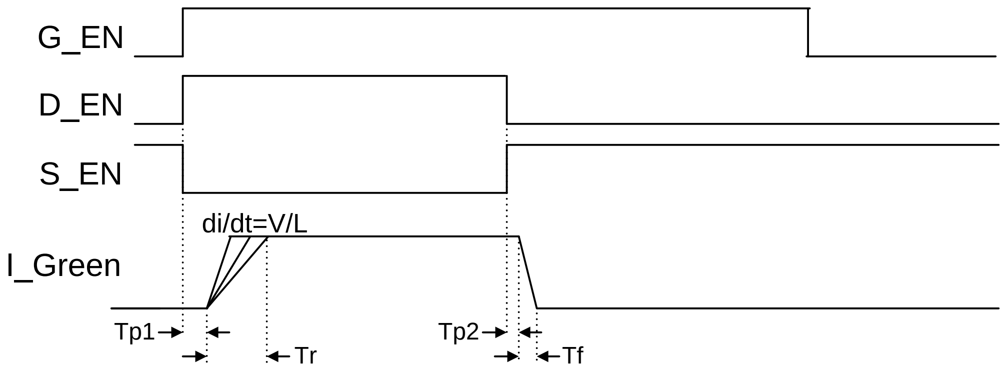


Figure 4-8. Continuous Mode Driver Distortion

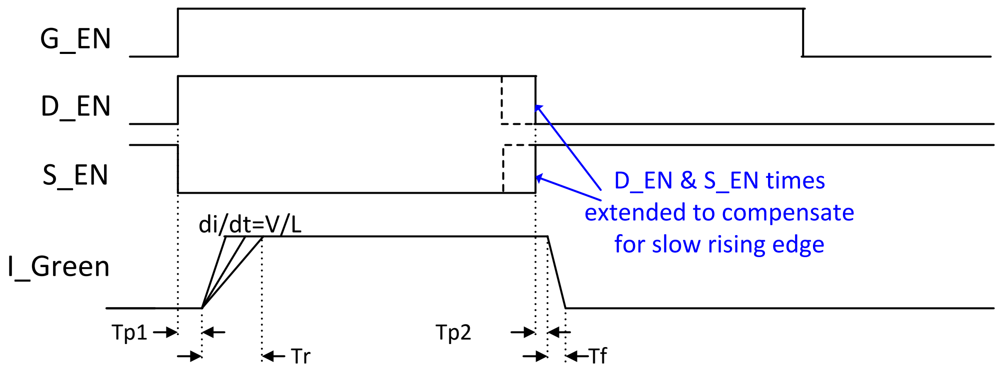


Figure 4-9. Continuous Mode Driver Distortion Correction

4.3.2 Continuous Mode Current Limit

In continuous mode, the control scheme also includes a current feedback path, utilizing the second comparator block in the Piccolo TMS320F28023 device. This loop serves as an alternate control path to limit the current for the LEDs to their maximum value. This might occur at high temperature or when an LED ages and requires more current to achieve the same brightness. Ideally this would not happen, but if it does the brightness can be lowered until the current limited condition is eliminated.

4.4 Discontinuous Mode Operation

A discontinuous mode of operation is included in the LED driver to support highly dimmed displays, necessary for nighttime use in automotive applications. In discontinuous mode, the controller produces discrete pulses of light with fixed "off times" between pulses. Two hysteretic control loops are employed. The first loop is shown in Figure 4-10 and is used to create a fixed current in the inductor. The second loop shown in Figure 4-11 uses photo feedback and the shunt FET to pulse the LED on and off.

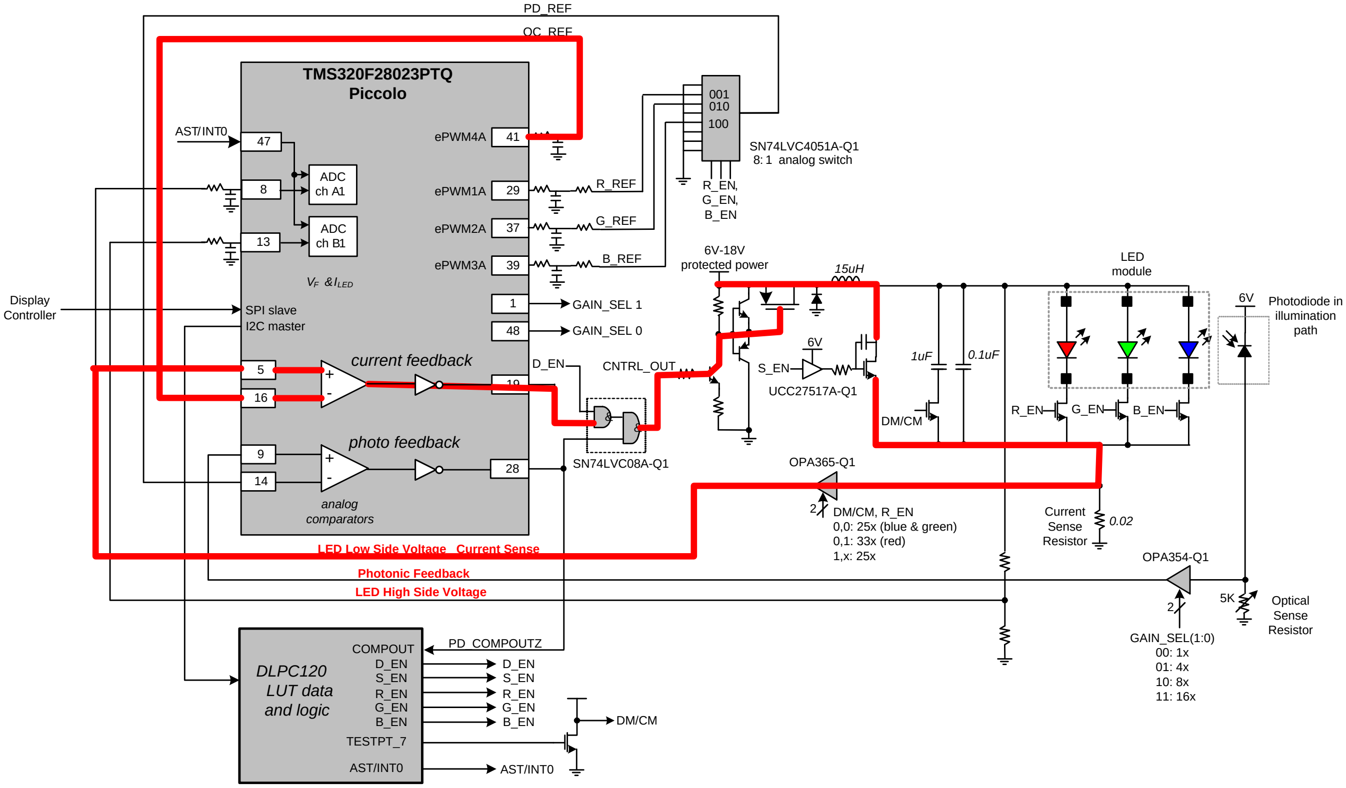


Figure 4-10. Discontinuous Mode Current Control Loop

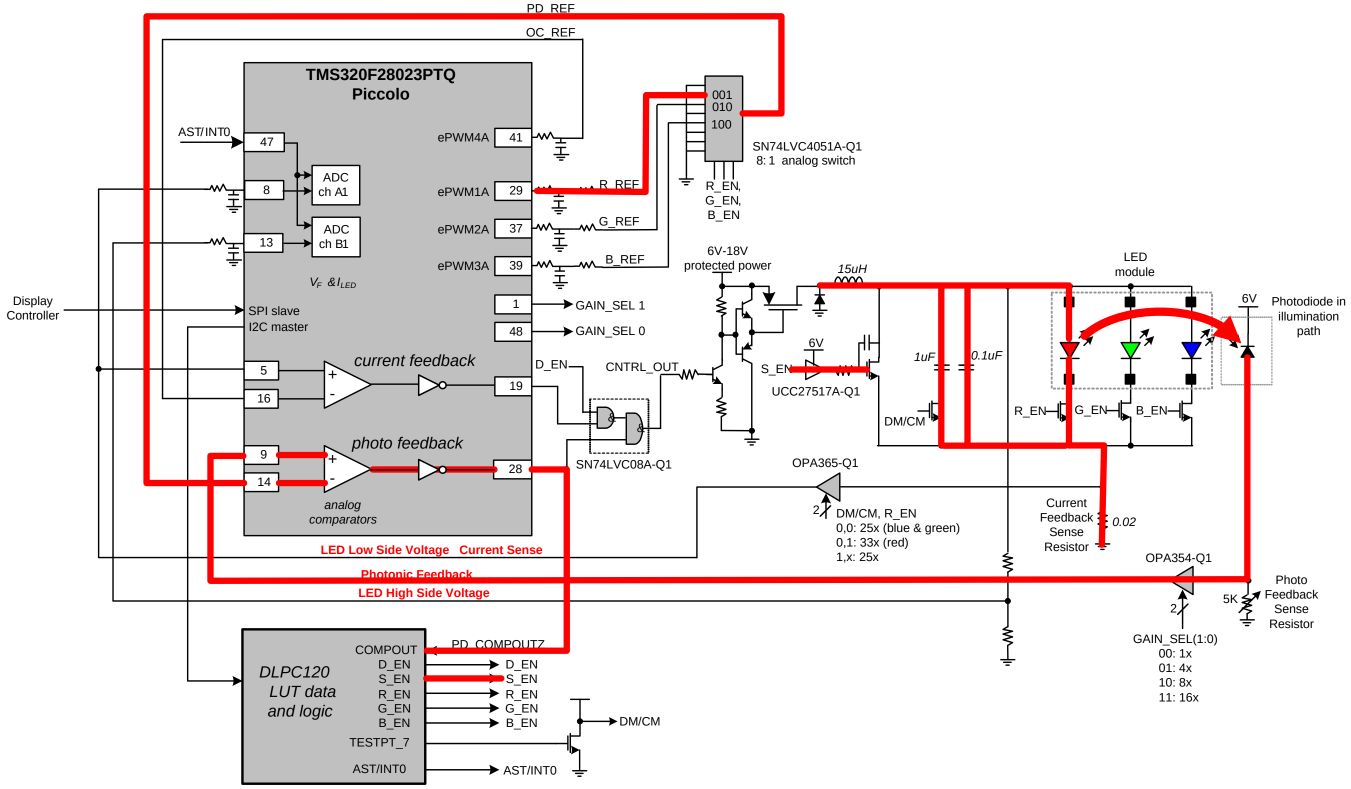


Figure 4-11. Discontinuous Mode Photo Control Loop

The hysteretic current control loop shown in Figure 4-10 establishes a DC current in the inductor that is either shunted to ground or allowed to charge up the parallel capacitors and flow through one of the LEDs, depending on the state of the S_EN and the R_EN, G_EN, B_EN signals from DLPC120-Q1. The current feedback gain is set to 25x for all colors in discontinuous mode to provide better balance between the color amplitudes. The DM/CM signal is high in discontinuous mode enabling the FET in series with the 1-µF capacitor. This results in 1.1µF of total capacitance in parallel with the LEDs which produces a slower voltage ramp allowing smaller light pulses to be generated.

The general idea with discontinuous mode is to replace the constant block of light during a bit slice with a predetermined series of light pulses of controlled amplitude, as illustrated in Figure 4-12. The number of pulses is controlled by the Piccolo controller by selecting among a predetermined set of look up tables held in application flash.

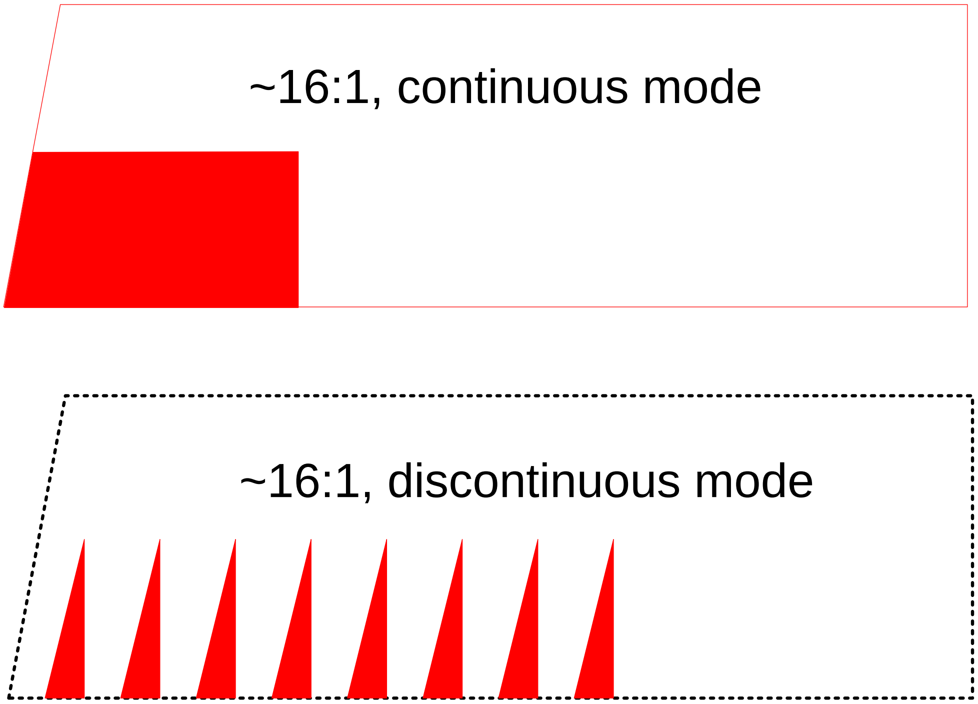


Figure 4-12. Continuous vs Discontinuous Modes

Figure 4-13 is an example diagram showing the Discontinuous Mode signals generating 4 pulses for each color. Each pulse is generated by the following steps:

1. The DLPC120-Q1 drives the S_EN low to disable the Shunt FET.
2. Current in the inductor starts to charge the parallel capacitors, ramping up the voltage across the selected LED.
3. When the voltage across the LED ramps high enough, light from the LED will start to ramp up.
4. Once the light level detected by the photodiode feedback circuit exceeds the desired light level defined by filtered the ePWM, the comparator output (PD_COMPOUTZ) will go low.
5. The falling edge on PD_COMPOUTZ triggers the DLPC120-Q1 to count the pulse and assert S_EN high to enable the Shunt FET and end the pulse.
6. The DLPC120-Q1 will keep S_EN high until PD_COMPOUTZ goes back high and an internal delay time has expired.
7. This process will repeat until the desired number of pulses has been generated.
8. When the desired number of pulses is counted by the DLPC120-Q1, it will hold S_EN high for the remainder of the bit slice.

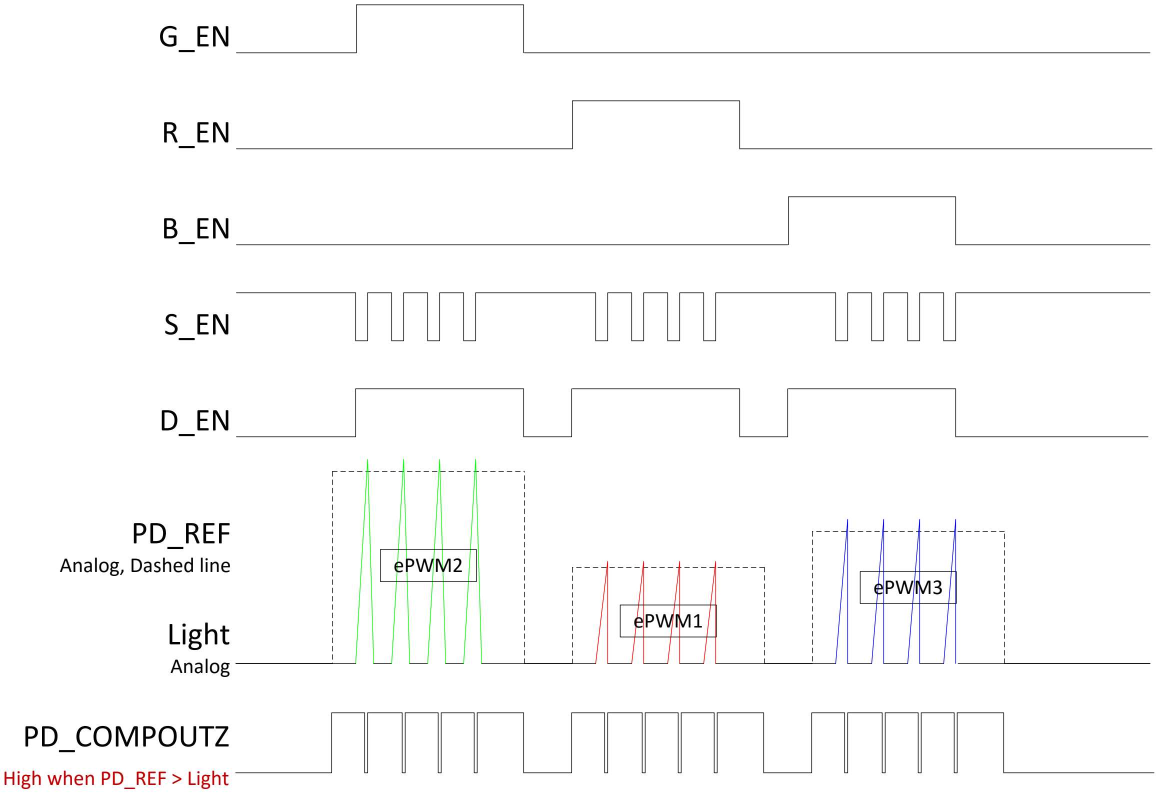


Figure 4-13. Discontinuous Mode Signals

Figure 4-14 is a more detailed figure showing the timing for two green pulses. The time that S_EN is held high after PD_COMPOUTZ goes low can be configured to keep the pulse frequency below the AM band (535 kHz) and to prevent switching transients and noise from falsely triggering the pulse counting logic in the DLPC120-Q1. Note that the delay will be reset for each falling edge of PD_COMPOUTZ, so noise that creates multiple PD_COMPOUTZ falling edges will extend the time.

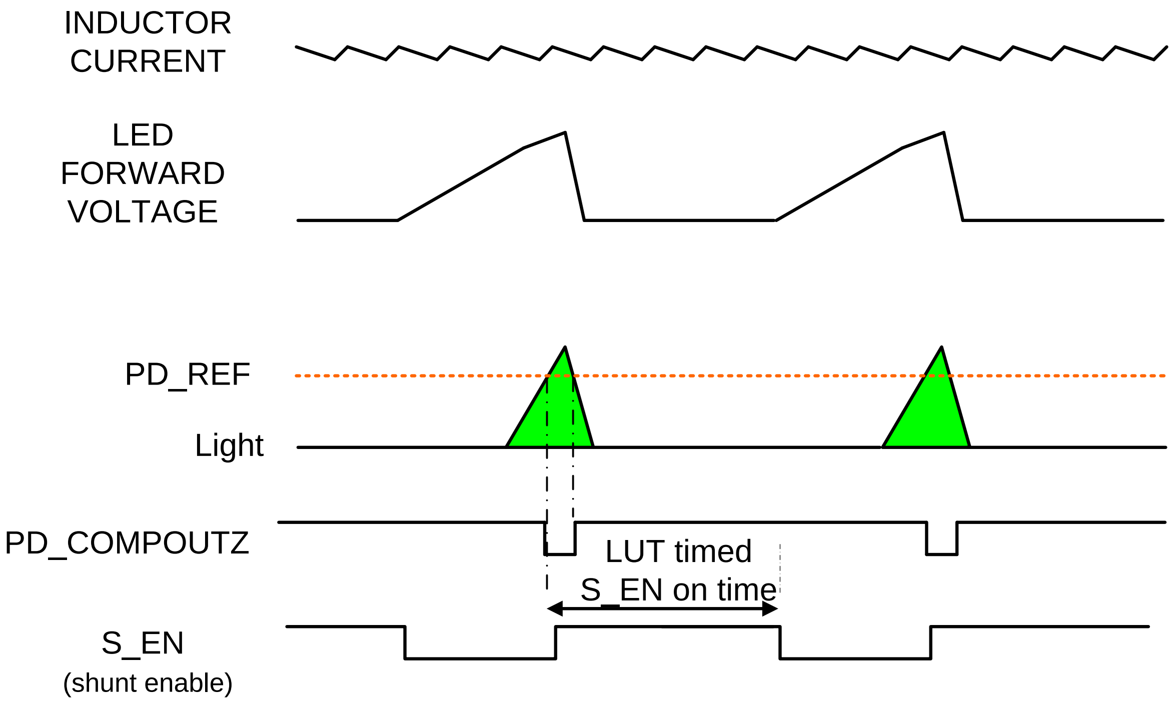


Figure 4-14. Discontinuous Mode Pulses

When operating in discontinuous mode, two methods of dimming are used concurrently to reduce brightness of the display:

1. Amplitude dimming using the ePWM RGB output settings.
2. Controlling the number of pulses per bit slice (via commands to DLPC120-Q1, selecting specific look up table data).

Figure 4-15 is an example of the brightest LUT data table having 8 pulses per LSB (smallest bit slice). The LED pulse height is modulated to achieve a 2:1 dimming ratio while still maintaining 8 pulses per LSB. To allow for a seamless transition to lower dimming levels, a change to 4 pulses per LSB plus higher LED amplitude is made as illustrated in Figure 4-16. The total light generated in both cases in Figure 4-16 is approximately equal. A system calibration is used to determine this ½ LED amplitude ePWM setting.

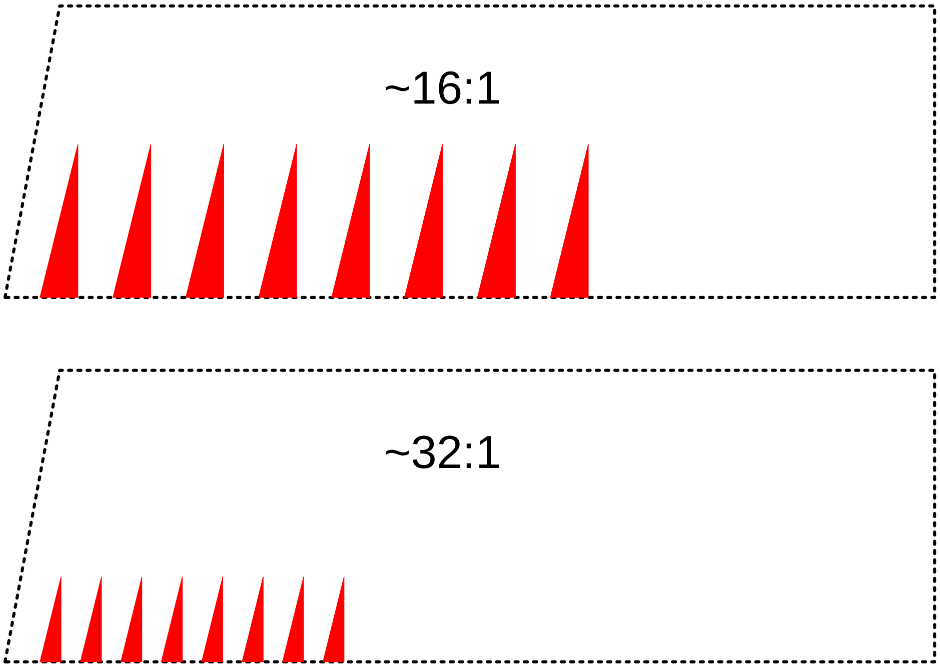


Figure 4-15. Discontinuous Mode Amplitude Dimming

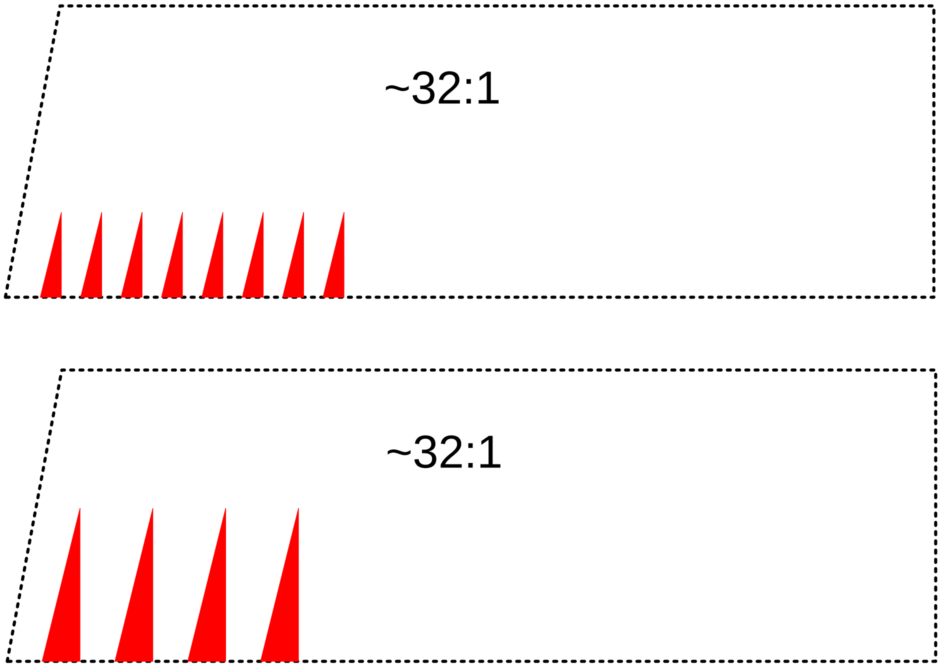


Figure 4-16. Discontinuous Mode Pulse Count Change

As a smooth dimming (brightness going down) sequence continues, the process above eventually results in using a 1 pulse per LSB. Amplitude dimming is used to dim to the absolute minimum display brightness level as illustrated in Figure 4-17.

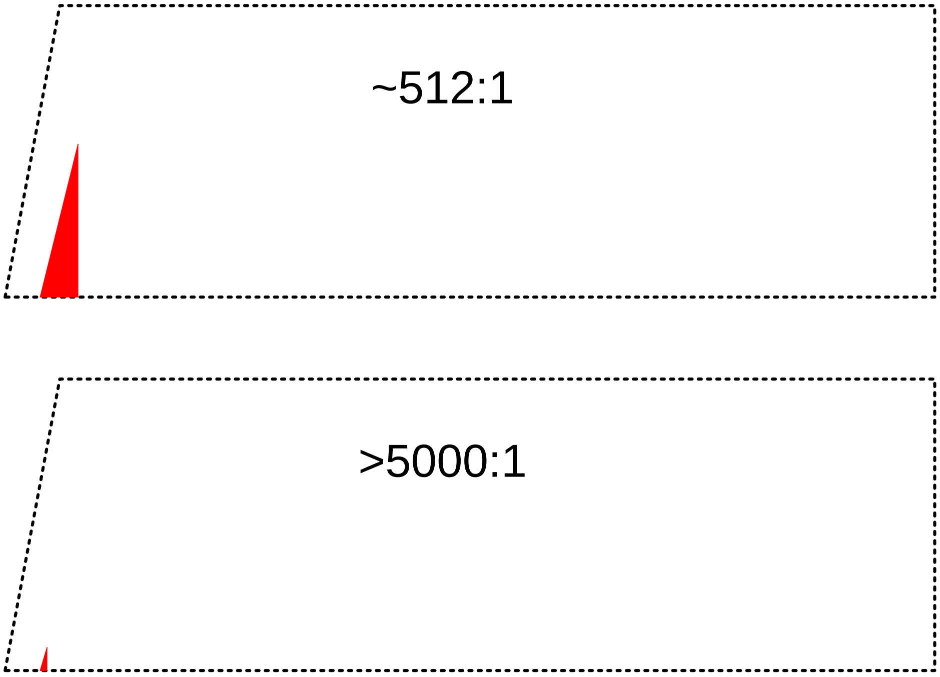


Figure 4-17. Discontinuous Mode Amplitude Dimming, 1 Pulse per LSB

4.4.1 Low Level Discontinuous Mode Flicker Reduction

At the very low end of discontinuous mode the brightness can be low enough that variation in the amplitude of the light pulses due to inductor current ripple can cause observable flicker in some displayed images. To mitigate this affect the circuit shown in Figure 4-18 can be added to the driver. This circuit synchronizes the start of the DM pulses to when the inductor current drops below the regulated current level (OC_REF). This results in a more consistent current at the start of each pulse and a more consistent pulse amplitude. One impact of this circuit is to increase the spacing between pulses. As a result the circuit is only enabled when AUXBIT0 equals 1 at the very lowest DM levels when the number of pulses required for each bit is small. It is important that the RS latch be set dominate. In other words, if the S input to the latch is asserted than the output of the latch is high regardless of the R input. Figure 4-19 shows an implementation of the flicker reduction circuit. Note the RS latch in this circuit has active low S and R inputs. Figure 4-20 shows how the shunt enable falling edge is delayed until the inductor current falls below the reference ePWM current level.

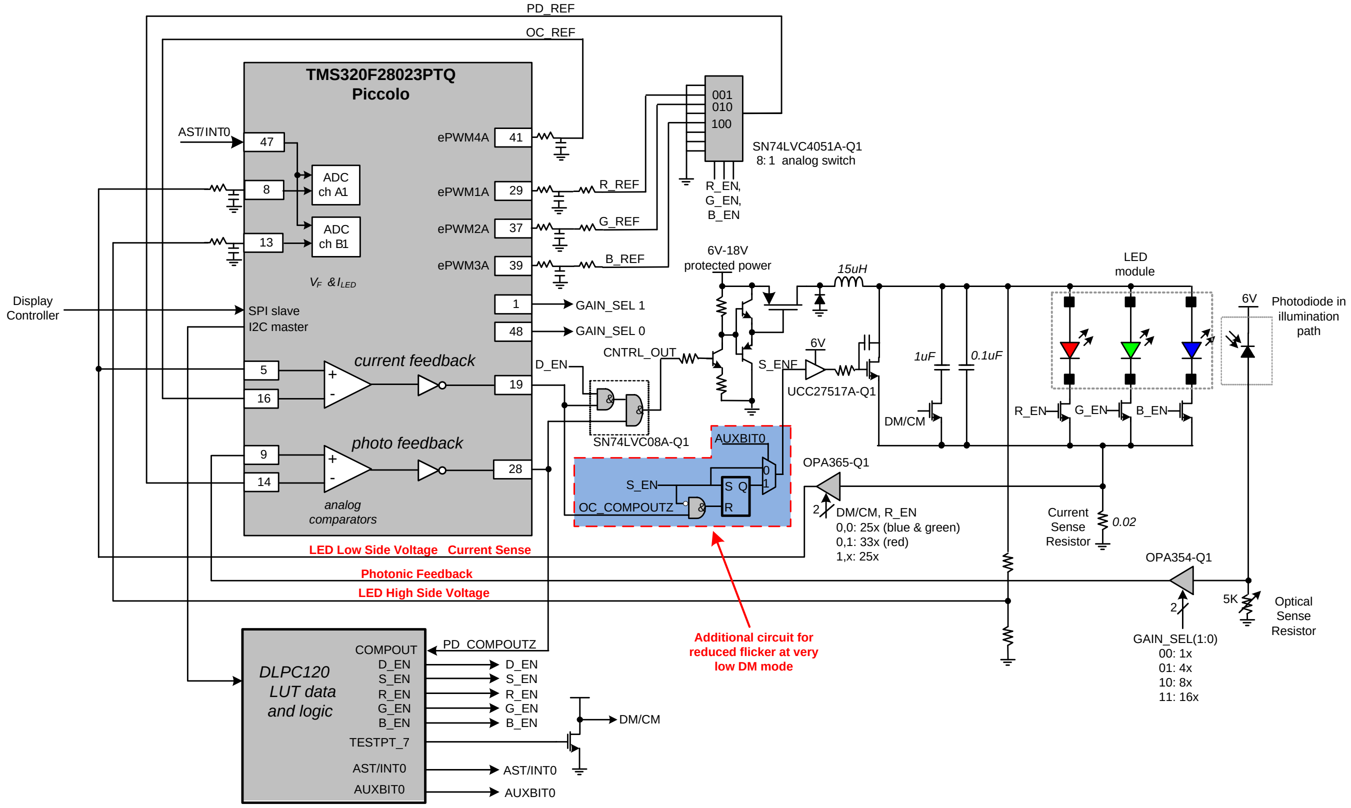


Figure 4-18. Driver With Low Level Discontinuous Mode Flicker Reduction Circuit

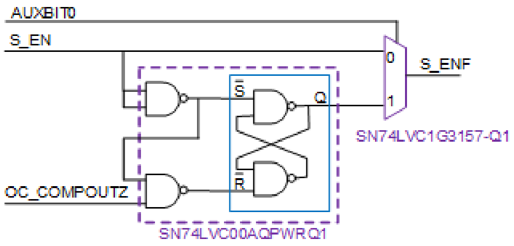


Figure 4-19. Low Level Discontinuous Mode Flicker Reduction Circuit

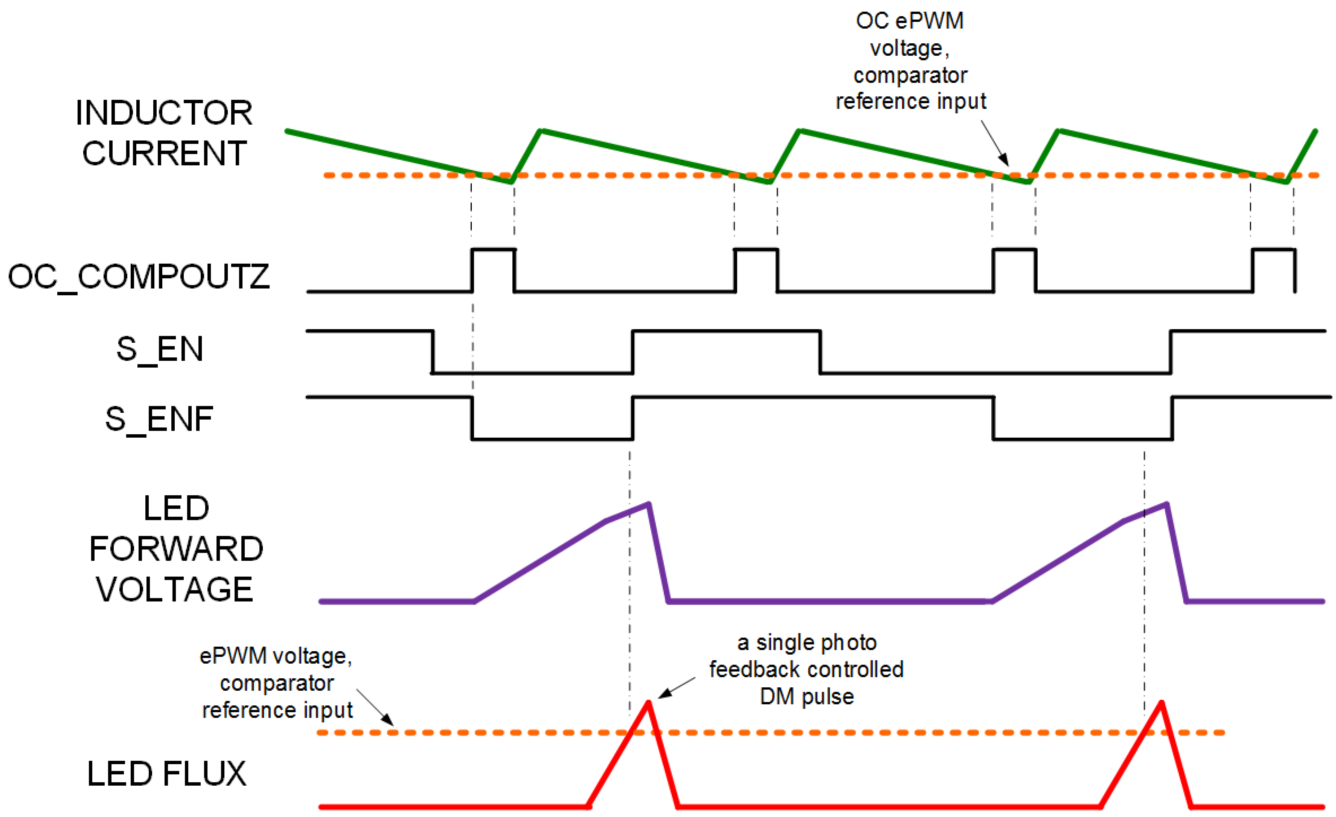


Figure 4-20. Low Level Discontinuous Mode Flicker Reduction Signals

4.4.2 Discontinuous Mode Gain and Current Setting

In addition to adjusting the ePWM setting to control the pulse amplitude, the photo feedback gain can also be adjusted. Setting the photo feedback gain higher than 1x has the effect of reducing the pulse amplitude threshold by that gain factor. The driver supports gain settings of 1x, 4x, 8x, and 16x. The gain can be used to keep the ePWM values in the working range of the hardware. The ePWM minimum value is limited primarily by the photo feedback gain amplifier's (Section 5.6) minimum output voltage of about 100 mV. For TI's system, this corresponds to an ePWM value of 1800 to 2000. Setting the ePWM below this will result in the LED not turning on.

At very low Discontinuous Mode brightness levels the current can be lowered to further reduce the amount of light in a pulse. A lower current results in a slower voltage ramp time. Until the LED starts to conduct, the voltage ramp will be a function the current setting divided by the parallel capacitance. This slower voltage ramp and lower current setting results in a smaller light pulse. For the TI reference design, the current is typically set to ≈3 A for most of the discontinuous mode and down as low as 0.8 A at low discontinuous mode brightness settings.

4.5 Drive and Shunt Enable Inputs

The LED driver uses R_EN, G_EN and B_EN input signals to allow the DLPC120-Q1 ASIC to control which LED is producing light during a display time period (bit slice). In addition to these signals, the controller design includes two signals: S_EN and D_EN to implement continuous and discontinuous modes.

The drive enable signal (D_EN) is AND'ed with the photo feedback (PD_COMPOUTZ) and the current feedback (OC_COMPOUTZ) to create the high true enable for the PFET driver (CNTRL_OUT). A low on this signal disables current switching, and a high enables current switching, independent of RGB enable states.

The S_EN input is a LED "shunt" enable. A high on this signal will cause any current established in the inductor to pass through an NFET (shunt) instead of going through the selected LED (LED circuit is "shunted", or shorted out). When a low is subsequently placed on S_EN, the shunt FET is turned off, and current established in the inductor charges the parallel capacitance and then flows through the selected LED.

In continuous mode, the combination of these two signals (D_EN, S_EN) allows the LED to be turned off quickly without causing large voltage spikes on the output terminal of the inductor. Different analog delays in the driver for the S_EN and D_EN can be compensated for in the timing. For further information contact a TI application engineer.

D_EN and S_EN also allow the bit slices to be time attenuated to achieve lower brightness. Figure 4-21 shows examples of bit slices with and without time attenuation.

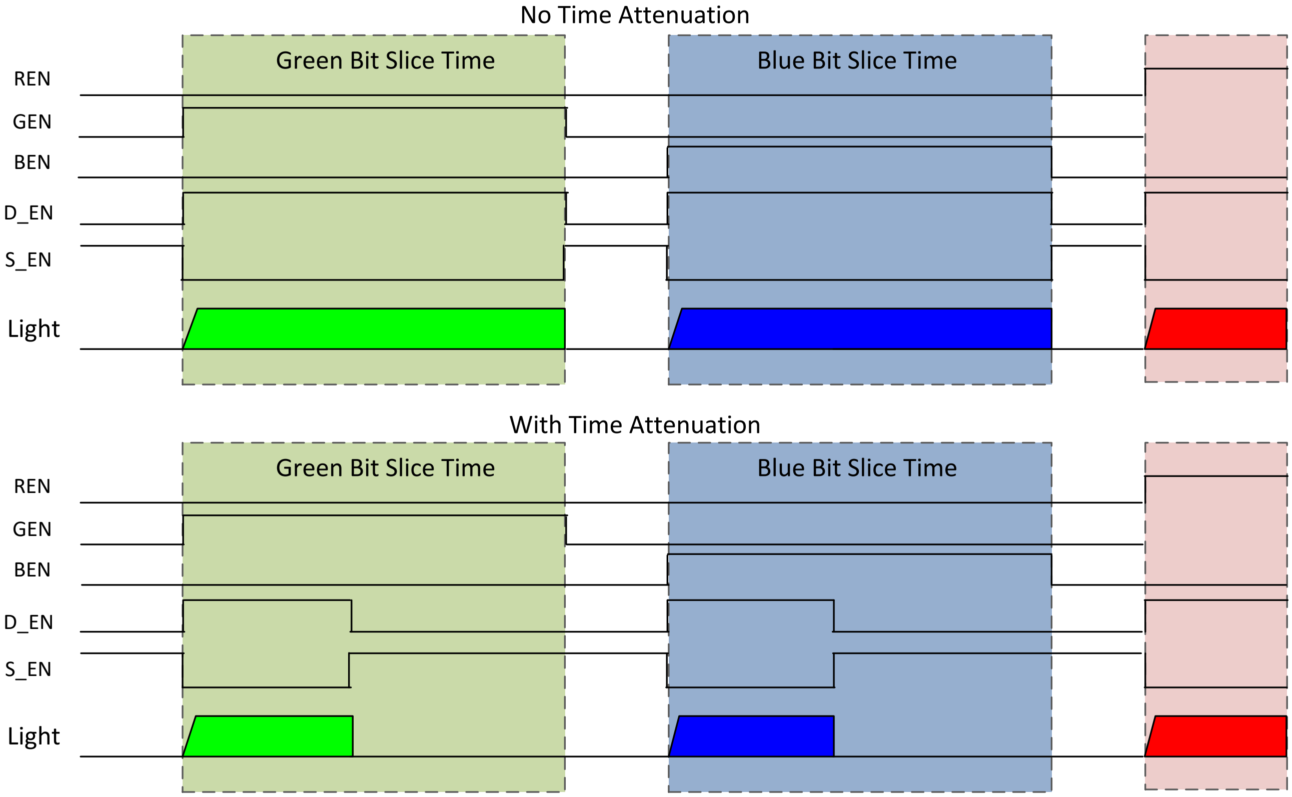


Figure 4-21. Bit Slice With and Without Time Attenuation

In discontinuous mode, very narrow pulses are possible while maintaining photo feedback control of the peak light amplitude. To make very narrow pulses of light in discontinuous mode the Shunt FET must turn on and off quickly. The TI reference design utilizes a UCC27517A to drive the Shunt FET. The driver is connected to the shunt FET through an 82-Ω resistor with a 1000-pF capacitor from the FET's gate to drain (Figure 4-22). The resistor capacitor (RC) circuit provides some adjustment to the discontinuous pulse wave shape and can be used to balance the turn-on or turn-off time of the FET with the peak current discharging the parallel capacitance. The RC values might need adjustment for a different FET, FET driver or supply voltage to the driver. Note also that the peak current while discharging the capacitor is quite high and limited only by the on-resistance of the shunt FET, the capacitor ESR, the DM/CM FET on-resistance and the resistance of the PCB traces. Figure 4-23 shows the current paths through the shunt FET when it is enabled and Figure 4-24 shows the current paths when the shunt FET is disabled.

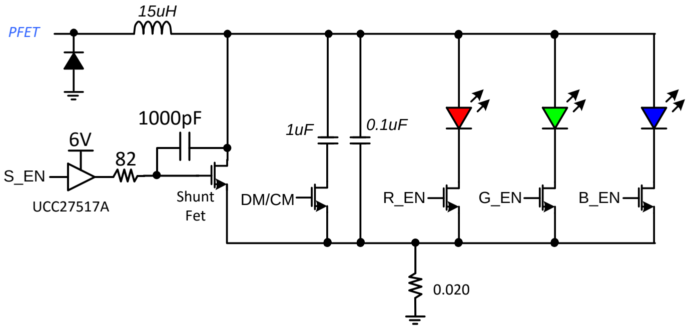


Figure 4-22. Shunt FET Drive

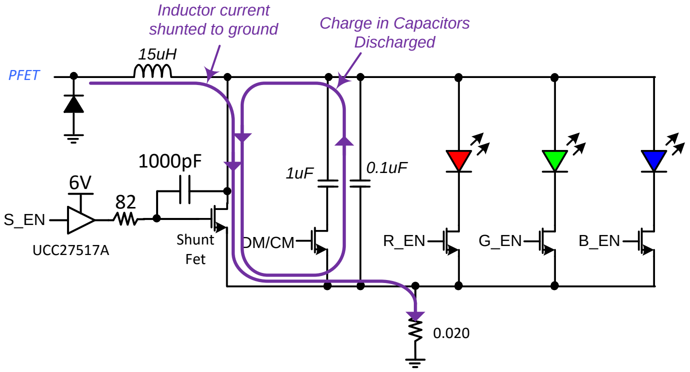


Figure 4-23. Discontinuous Mode Current Paths With Shunt Enabled

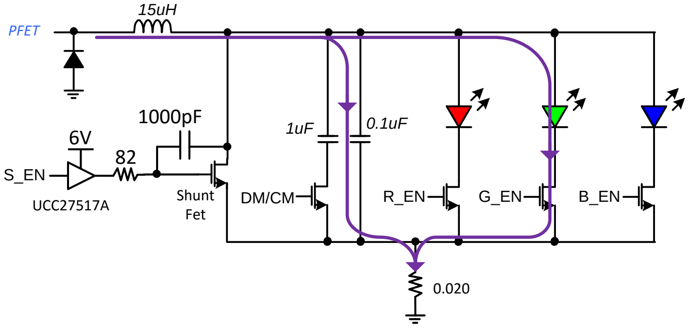


Figure 4-24. Discontinuous Mode Current Paths With Shunt Disabled

4.6 Photo Feedback Buffer

The photo feedback control scheme relies on fast, accurate *instantaneous and continuous* measurements of LED flux in the DMD illumination path as part of the feedback to the analog comparator block. Phase delay, slow slew rates, and noise cause degradation of the control loop, resulting in greater ripple and less accurate control of amplitude.

The photo feedback buffer from TI reference design is shown in Figure 4-25. The photo feedback buffer provides gain settings of 1x, 4x, 8x and 16x controlled by Gain SEL (1:0) signals from the Piccolo. The higher gain settings are used in discontinuous mode to achieve low light level pulses. A gain setting of 1x is normally used in continuous mode. The analog multiplexer (SN74LV4051) is used as a 2 to 4 logic decoder to enable the appropriate gain setting resistor. To achieve accurate gain settings, 2N7002 NFETs (on-resistance of about 1 to 3 Ω) are used to select gain setting resistors. It is also important to use a FET with a low-output capacitance to minimize peaking at the 1x gain setting. Replacing the discrete FETs with an analog multiplexer is not recommended because analog multiplexers typically have much higher on-resistance and/or higher output capacitance.

During circuit layout, please note that care must be taken to isolate high-impedance nodes in sensor gain circuit from high power switching elements in LED driver to avoid noise coupling from LED drive circuits to sensor inputs.

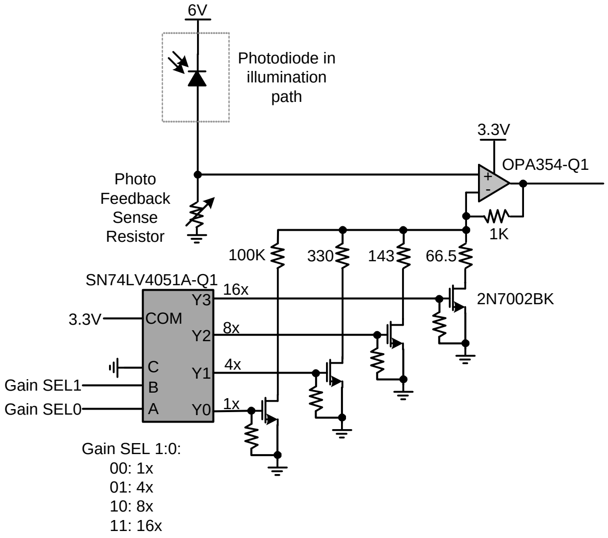


Figure 4-25. Photo Feedback Buffer

4.6.1 Photodiode

In addition to the photo feedback buffer performance, placement of the photodiode within the optical path is critical to system performance (see Photodiode Selection Guide for more detailed information). Several factors for the photodiode should be considered:

- **Position:** Ideally, a position in the illumination path (Figure 4-26) should be located that produces strong, but also relatively balanced photodiode amplitude from each of the three LEDs at the systems target white point. Imbalance between the three channels due to non-ideal placement of the detector will limit dynamic range of the dimming system. Note that relative signal responses for the three LEDs can vary for continuous mode versus discontinuous mode so both modes should be considered.
- **Irradiance on the Photodiode:** It is also important that the irradiance on the photodiode is not too high or too low. A high magnitude of irradiance can cause saturation and slower response from the photodiode. The TI reference design biases the photodiode at 6 V to increase the amount of irradiance the photodiode can accept without saturating. A low magnitude of irradiance can make the system more susceptible to noise, photodiode dark current and can degrade the light pulse tracking due to the time constant of the photo feedback sense resistor in parallel with the capacitance of the photodiode and interconnect. TI recommends keeping the RC time constant below 30 ns.
- **Cable to remote PD placement:** If the photodiode is located remotely, it is recommended to use a low-capacitance cable and minimize the cable length. For noise rejection, the TI reference design uses a one conductor shielded cable with the photodiode bias (cathode) connected to the cable shield and the photodiode output (anode) connected to the inner conductor. Better noise rejection could possibly be achieved by using a shielded two conductor cable with the shield tied to a low-noise ground. Experiments may be necessary to determine an optimal photodiode position to achieve adequate response balance between the colors and an acceptable irradiance level. See the Photodiode

Selection Guide for more information.

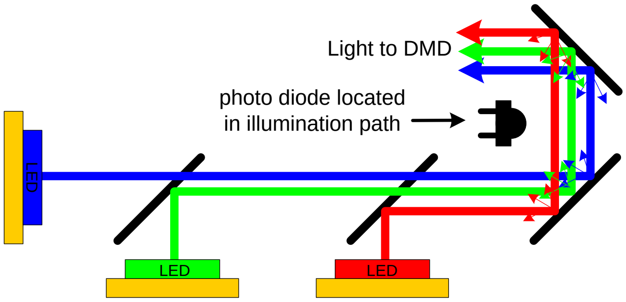


Figure 4-26. Illumination Path Photodiode

4.6.2 Photo Feedback Sense Resistor

The photo feedback sense resistor should be adjusted to optimize the driver's dynamic range. Generally, a value should be chosen so that maximum continuous mode brightness is limited by one or more LEDs hitting the current limit and not by the driver hitting the maximum ePWM. Variations over temperature should also be considered in this selection. For example, the current required for the red LED to achieve a specific brightness level increases significantly at high temperature.

4.7 Forward Voltage and LED Current Measurements

The TI reference design utilizes the Piccolo MCU's analog to digital conversion block for simultaneous samples of LED forward voltage and current. As highlighted in Figure 4-27, the reference design connects the LED high side voltage (LED anodes) to the Piccolo's B1 ADC through a resistor divider (2.2k / (10k + 2.2k)) to ensure the voltage is within the ADC's working range. The low side (cathode) of the three LEDs after the RGB FETs is connected to the current sense resistor. This voltage is gained and connected to ADC A1 of the Piccolo. This measurement point provides both the LED current and the low side LED voltage. Equation 1 and Equation 2 can be used to calculate the LED current and forward voltage where FET_RDSon is the on-resistance of the red, green or blue FET enabling the LED and Gain (33x for red and 25x for blue and green). The different gain for red allows the current limit to be set to 4.5 A for red and 6 A for blue and green. These current limits apply to the OSRAM™ Q8 LEDs and might need to be adjusted if different LEDs are used.

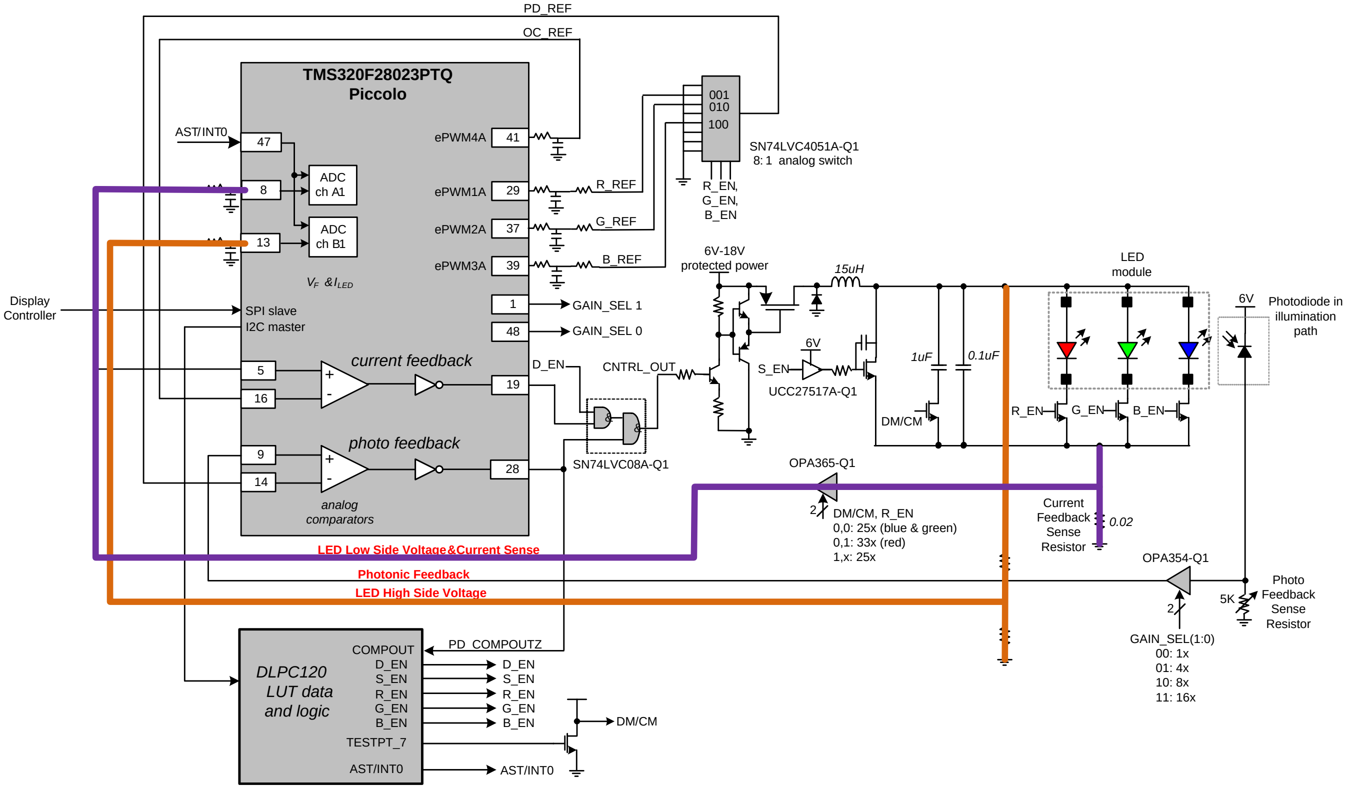


Figure 4-27. LED Forward Voltage and Current Measurements

$$I_{LED} = \frac{V\_ADC_{a1}}{(Gain*0.02)} \tag{1}$$

$$V_{LED} = V\_ADC_{b1} * \frac{(10K+2.2K)}{2.2K} - \frac{V\_ADC_{a1}}{Gain} - I_{LED} * FET\_RDS_{on} \tag{2}$$

The DLPC120-Q1 block contains logic that can be configured to provide ADC sample strobe pulses at predetermined times in each display frame. The Flash “.cfg” file provides sample times for each LED. Note that the inputs to the ADCs are filtered to reduce some of the ripple on the measurement. The time constant for the filters is ≈3.3 µs and should be taken into account when setting the sample timing.

The LED current and voltage measurements are available to the MCU color control code and can be used to monitor “aging” effects of LEDs. When an LED ages and cannot output the required brightness due to the current limit the MCU can lower the overall brightness (backlight) level until the over current condition is eliminated. These ADC measurements are also available for general purpose uses for customer specific algorithms (that is, detailed condition monitoring of LEDs, LED die temperature estimation, and so forth).

Dimming Scheme

5.1 Overview

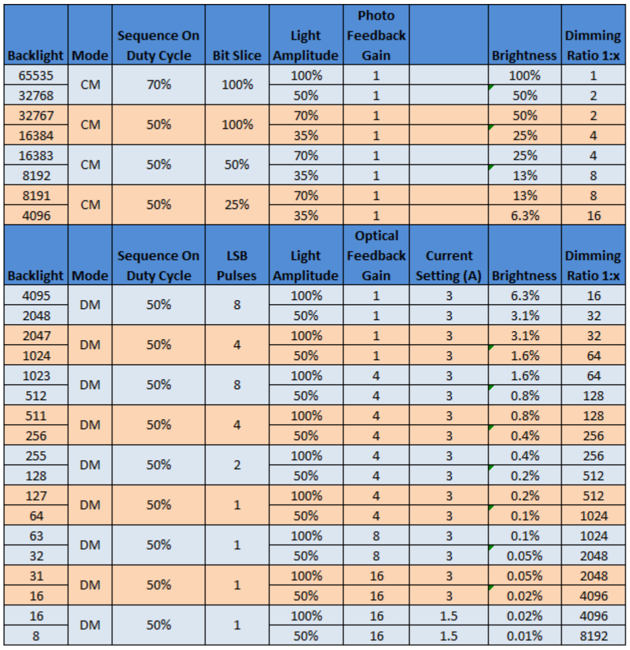
A HUD system must typically meet a target white point requirement over a wide range of brightness backlights. To cover a wide brightness (dimming) range like 5000:1 requires a combination of continuous and discontinuous modes. Continuous mode will utilize different combinations of sequence duty cycles, time attenuation and amplitude attenuation and discontinuous mode will utilize different combinations of the number of pulses, photo feedback gain, current setting and light amplitude. TI's calibration approach breaks these parameters up as shown in Table 5-1.

Table 5-1. Calibration Parameters

Parameter Type	Parameter	Description
Coarse Adjustment	LDC Index	Total time the LEDs are on, calculated according to the following variables: **Continuous Mode:** LED sequence duty cycle multiplied by time attenuation percentage. **Discontinuous Mode:** LED sequence duty cycle and the number of pulses in each bit of the sequence.
	LED Driver Current Limit/Level	**Continuous Mode:**The maximum current allowed through the LEDs. **Discontinuous Mode:** The regulated current level driving the LED pulse generation.
	Photo Feedback Amplifier Gain	Amount of gain applied to the output of the photodiode used to sense LED light. Higher gain results in lower brightness. **Continuous Mode:** Normally set to 1x. **Discontinuous Mode:** Gain increased to achieve very low brightness settings.
Fine Adjustment	R/G/B ePWM	The target photo feedback amplitude threshold for each LED.

Figure 5-1 shows the basic concept of how different combinations of continuous mode and discontinuous mode course adjustment settings can cover a wide dimming range. The “sequence on duty cycle” refers to the amount of time during each video frame (1/60s) that the LED is on and the image is displayed on the DMD. Note that high temperature and "sequence on duty cycle" are factors for DMD lifetime. If each of these course adjustment groups is properly calibrated there should not be any noticeable difference in brightness and color point at the transitions between groups.

The approach shown in Figure 5-1 operates the LEDs at reduced current whenever possible. As such, the full LED current (amplitude 100%) is only used in the top brightness course adjustment group. Continuous mode course adjustment groups below the top group operate at amplitudes from 35% to 70%. The continuous mode in this example provides a dimming range of 16:1.



Backlight	Mode	Sequence On Duty Cycle	Bit Slice	Light Amplitude	Photo Feedback Gain		Brightness	Dimming Ratio 1:x
65535	CM	70%	100%	100%	1		100%	1
32768				50%	1		50%	2
32767	CM	50%	100%	70%	1		50%	2
16384				35%	1		25%	4
16383	CM	50%	50%	70%	1		25%	4
8192				35%	1		13%	8
8191	CM	50%	25%	70%	1		13%	8
4096				35%	1		6.3%	16
Backlight	**Mode**	**Sequence On Duty Cycle**	**LSB Pulses**	**Light Amplitude**	**Optical Feedback Gain**	**Current Setting (A)**	**Brightness**	**Dimming Ratio 1:x**
4095	DM	50%	8	100%	1	3	6.3%	16
2048				50%	1	3	3.1%	32
2047	DM	50%	4	100%	1	3	3.1%	32
1024				50%	1	3	1.6%	64
1023	DM	50%	8	100%	4	3	1.6%	64
512				50%	4	3	0.8%	128
511	DM	50%	4	100%	4	3	0.8%	128
256				50%	4	3	0.4%	256
255	DM	50%	2	100%	4	3	0.4%	256
128				50%	4	3	0.2%	512
127	DM	50%	1	100%	4	3	0.2%	512
64				50%	4	3	0.1%	1024
63	DM	50%	1	100%	8	3	0.1%	1024
32				50%	8	3	0.05%	2048
31	DM	50%	1	100%	16	3	0.05%	2048
16				50%	16	3	0.02%	4096
16	DM	50%	1	100%	16	1.5	0.02%	4096
8				50%	16	1.5	0.01%	8192

Figure 5-1. Simplified Calibration Table Example

The column in Figure 5-1 labeled light amplitude is a simplified representation of the combination of red, green, and blue LED brightness magnitude. To achieve a brightness level at a certain white point the driver must output the correct amount of light for each of the red, green and blue LEDs. The light amplitude for each color is set with filtered ePWMs from the Piccolo.

Figure 5-2 shows an actual calibration table for the TI reference design system taken at 25°C. During calibration, software will find ePWM values for red, green and blue to meet the target brightness (Y) and color point (x,y) at the top and bottom of each course adjustment group. Then during operation, software will interpolate ePWM setting for backlights between the top and bottom of a course adjustment group. The system response is not completely linear so there is some variation in brightness and color point for interpolated backlights, but generally the variation is below human perception.

Backlight	LDC	Mode	Sequence On Duty Cycle	Bit Slice	LSB Pulses	Photo Feedback Gain	Current PWM	R_PWM	G_PWM	B_PWM	Y
65535	0	CM	70%	100%		1x		29623	51746	31311	84024
25000								9298	17979	10938	32067
24999	2	CM	50%	100%		1x		17186	30112	18724	31860
18000								11421	21133	12977	22942
17999	4	CM	50%	50%		1x		26400	44439	27747	22943
8000								9721	18306	11216	10190
7999	6	CM	50%	22%		1x		26695	46321	28726	10143
4000								11519	21177	13123	5119
3999	14	DM	50%		8	1x	40000	27588	26440	29646	5078
2000								16014	15246	19202	2547
1999	15	DM	50%		6	1x	40000	20262	19399	23203	2546
970								10614	10101	14079	1238
969	15	DM	50%		6	4x	30000	30172	31240	43889	1182
600								16263	16967	27395	736
599	16	DM	50%		4	4x	30000	27497	28600	40926	732
300								10239	10990	19689	367
299	17	DM	50%		2	4x	30000	27457	28620	40963	368
180								13699	14471	24277	221
179	17	DM	50%		2	8x	30000	23300	25327	43505	220
91								6310	7379	17141	112
90	18	DM	50%		1	8x	30000	23590	25716	43890	111
45								6078	7152	16765	55.2
44	18	DM	50%		1	16x	15000	25507	27362	45053	54.2
33								16184	17537	31638	40.7
32	18	DM	50%		1	16x	8000	23687	24939	36851	39.5
20								12444	13107	21779	24.7
13								6427	6549	12506	16.1
11								4822	4914	9859	13.5
9								3390	3411	7371	11.1
7								2219	2170	5104	8.6

Figure 5-2. Room Temperature Calibration

Figure 5-3 shows the measured color point (x,y) for the TI reference design system over backlights from 9-65535 at 25°C with a 12-V input voltage. If the non-linear behavior is enough to be a concern, additional calibration points can be added within a course adjustment group. This was done at the very low end of the calibration shown in Figure 5-2. See the DLP3030-Q1 HUD Calibration Guide for more information on building a calibration table.

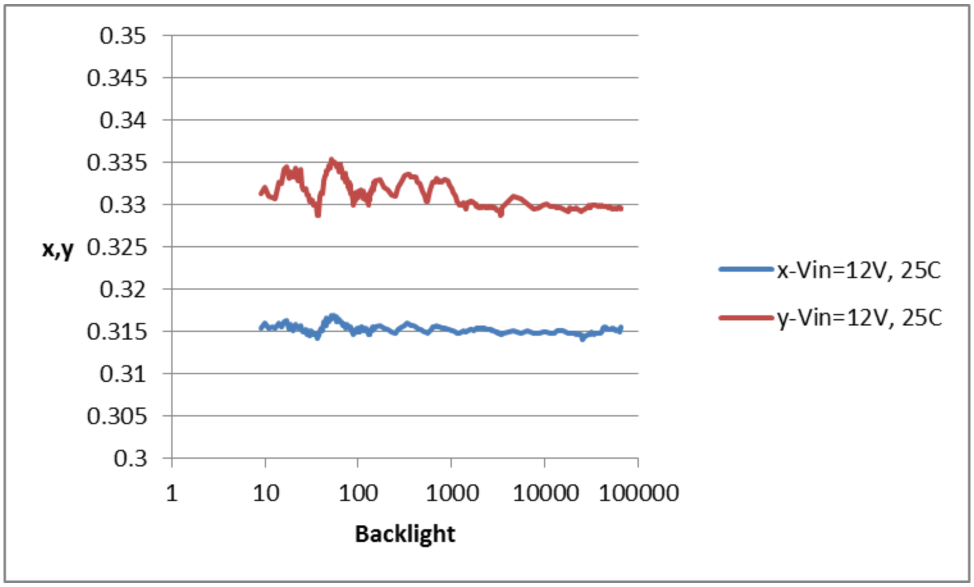


Figure 5-3. Typical Color Point Performance vs Backlight @ 25°C and 12-V Input

5.2 Input Voltage Impact

As discussed in Section 5.3, variation in the input voltage to the driver will affect the continuous mode waveform distortion. This is primarily due to the current ramp time of the inductor at the start of each bit slice. Figure 5-4 and Figure 5-5 show the typical color point variation (x,y) over the backlight range of 9 to 65535 for 6.5-V, 12-V and 18-V input voltage to a system calibrated at 12 V. Note that the most significant variation is to y in continuous mode at course adjustment group transitions. Using a regulated voltage input to the driver eliminates this variation.

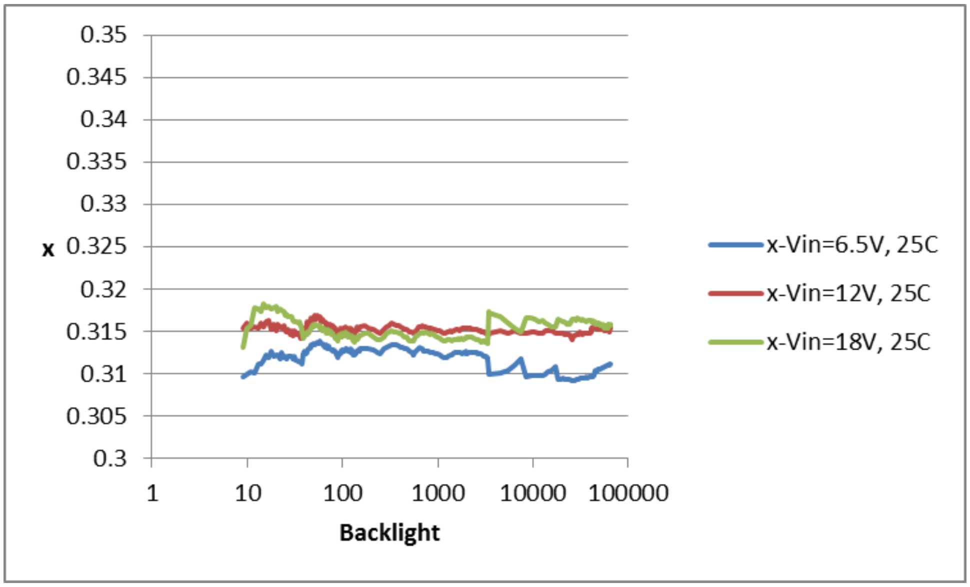


Figure 5-4. Color Point x Variation Due to Input Voltage

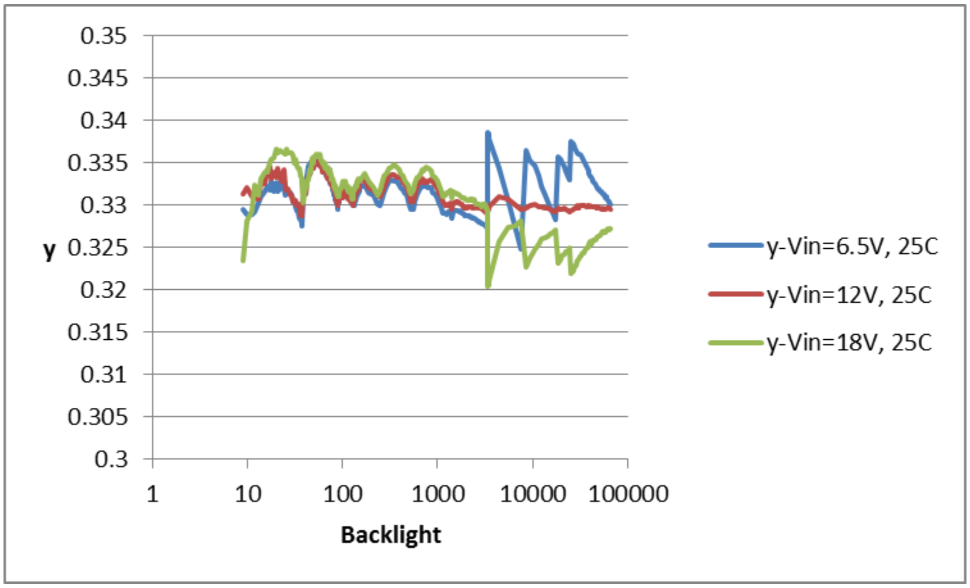


Figure 5-5. Color Point y Variation Due to Input Voltage

5.3 Continuous/Discontinuous Mode Transition Brightness

There are some tradeoffs in selecting the transition point from continuous mode to discontinuous mode. In general, gray ramp linearity is most challenging at the low end of continuous mode due to driver distortion (see Section 5.3) affecting bit weights. This can be compensated for to a large degree but not completely due to variation in distortion (due to variation in current) within a course adjustment group. Gray ramp linearity is typically very good at the high end of discontinuous mode so it is desirable to have the transition between modes at the highest brightness level possible. The highest brightness level discontinuous mode can support will be limited by the maximum light per pulse and the maximum number of pulses that will fit in the available bit slice time. The DLPC120-Q1 provides error bits to indicate conditions where the pulses do not fit. Margin should be included in the transition point to account for LEDs temperature and aging affects. The number of pulses and timing are controlled in the ".cfg" file. Consult a TI application engineer to get more information.

5.4 Sequence Bit Depth Performance Impact

It is desirable to have a high sequence bit depth to minimize low level dithering visibility in the display. Figure 5-6 is a very simplified sequence example showing how increasing the bit depth from 3 bits to 4 bits reduces the times for all the bits.

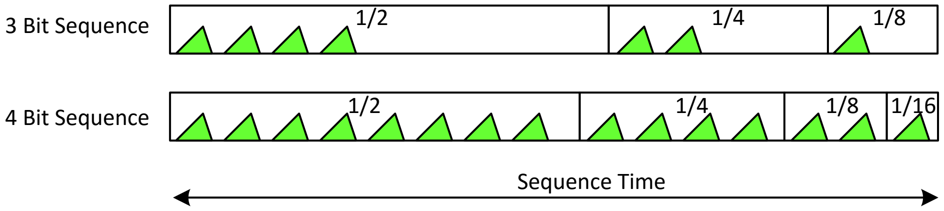


Figure 5-6. Simplified Bit Depth Sequence Example

Some performance tradeoffs of having a higher bit depth to minimize low level dithering visibility include:

- **Continuous mode**
  - Negative impact on gray ramp linearity because driver pulse width distortion (see Section 5.3) will have a bigger impact on the smaller LSB bit time.
- **Discontinuous mode**
  - Since the LSB will always have one pulse, the number of pulses in the other bits must increase (2x in the example in Figure 5-6).
    - More pulses combined with the smaller bit times, makes fitting the required number pulses more difficult. This can result in:
      - Reduction in the highest brightness that discontinuous mode can achieve.
      - Require continuous mode to operate at a lower brightness level which can increase the gray ramp linearity impact.
  - The smallest amount of light the driver can generate with one pulse is fixed and limited by the driver (photo feedback max gain, minimum useable current setting, photo feedback loop latency, etc).
    - This limits the lowest brightness level discontinuous mode can support.
    - In Figure 5-6, at the lowest brightness level, the amount of light in the 1/8 bit in the 3-bit sequence would be the same as the 1/16 bit in the 4-bit sequence. Thus, the lowest brightness for the 4-bit sequence would be about 2x brighter than the 3-bit sequence.

5.5 Continuous Mode ePWM Considerations

In continuous mode the ePWM sets the amplitude of the light for the bit slice. If the light pulses were perfect rectangles of light (no driver distortion) then reducing the ePWM by half as shown in Figure 5-7 would reduce the amount of light (area = L × W) by 2.

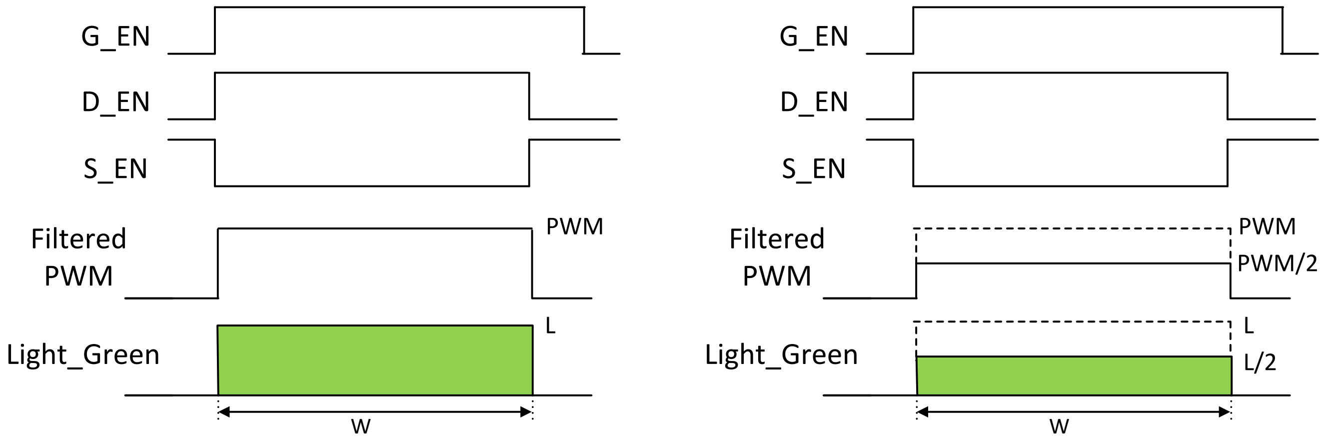


Figure 5-7. Ideal Continuous Mode Amplitude Attenuation

Since there is driver distortion as shown in Figure 5-8, an ePWM reduction by half results in more than half the prior amount of light (area). The smaller the bit time (W), the bigger the impact driver distortion will have on the ePWM setting. For time attenuated bits, the LED current (I) can be measured and used to calculate the rising edge time of the pulse (tr ≈ I × L / Vin), where L is the driver's inductance and Vin is the input voltage to the driver. The falling edge time is a function of the capacitance in parallel with the LEDs, the resistance in the discharge path through the shunt FET and the turn on speed of the FET. This is generally much faster than the turn on time.

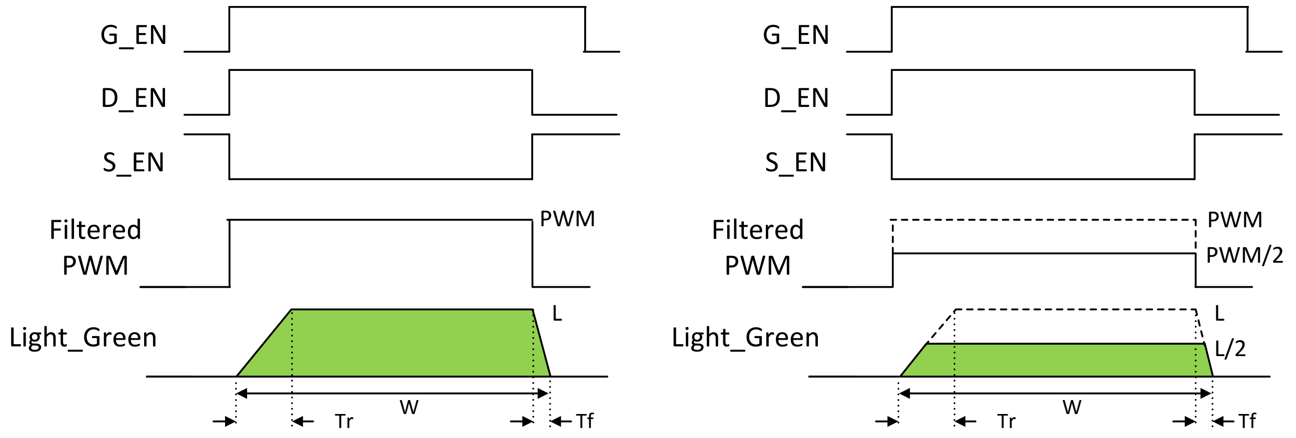


Figure 5-8. Non-ideal Continuous Mode Amplitude Attenuation

5.6 Discontinuous Mode ePWM Considerations

As shown in Figure 4-14, the leading edge of the light pulse in discontinuous mode is controlled by the charging rate of the capacitance in parallel with the LED. The filtered LED color ePWM from the Piccolo sets the threshold to turn on the shunt FET on which shunts the current away from the LED. Latency in the photo feedback loop will result in the light climbing higher than the threshold as shown in Figure 5-9. The amount of light that occurs after the threshold is reached (shown as hashed green area) can be the majority of the light at low discontinuous mode backlights. Figure 5-9 also shows that a reduction in ePWM by 2 does not reduce the total light (area) by a factor of two because of the light that occurs after the threshold. The amount of light after the threshold is a function of the photo feedback latency, inductor current, capacitance in parallel with the LED, LED voltage to current characteristics and Shunt FET timing. This excess light must be taken into account in any predictive calibration algorithm.

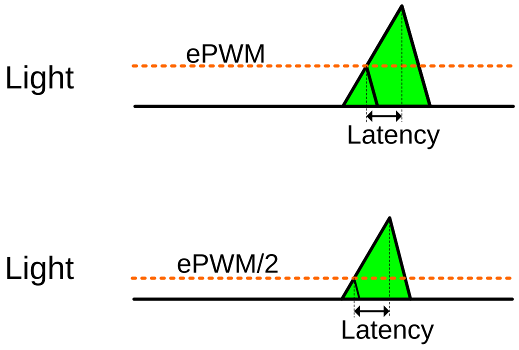


Figure 5-9. Discontinuous Mode Amplitude Attenuation

5.7 ePWM Range Considerations

To build a calibration file as shown in Figure 5-2 the useable ranges of the ePWMs and the effects of temperature must be taken into account for each course adjustment group. The driver hardware and software limits the usable range of the ePWM to about 1800-59000. The lower limit is a function of the minimum input voltage requirements of the photo feedback amplifier and the Piccolo's comparator. Each course adjustment group's backlight range must stay within the working range of the ePWM for each color LED. To allow for variation over temperature, a good guideline is to limit the backlight range for course adjustment groups at room temperature so the maximum can increase by a factor of 1.5 and the minimum can decrease by a factor of 2. See the DLP3030-Q1 HUD Calibration Guide for further information.

5.8 Temperature Compensation

An automotive HUD system must typically operate over a wide operating temperature range. Temperature changes will cause variation in:

- LED brightness and wavelength
- LED maximum current allowed
- Photodiode changes in
  - Response due to temperature
  - Response due to LED wavelength shift
- LED driver waveforms

To maintain the brightness and white point accuracy over temperature TI's current software supports calibrating at multiple temperatures and interpolating ePWM values at temperatures between calibrated temperatures. This approach works well however, a multiple temperature calibration for each unit may not be a practical production solution. Further investigation to minimize the required temperature calibration is in progress. Please see a TI application engineer for progress on this investigation.

Chapter 6

DLPA084–April 2018

Piccolo Pin Allocation

6.1 Piccolo Pin Allocation

The following Figure 6-1 shows the specific pin allocation on the Piccolo device.

NAME	REFERENCE USAGE	PIN #
LED Control PWM Outputs		
GPIO0/EPWM1A	red LED PWM output	29
GPIO2/EPWM2A	green LED PWM output	37
GPIO4/EPWM3A	blue LED PWM output	39
GPIO6/EPWM4A/EPWMSYNCI/EPWMSYNCO	LED current limit PWM output	41
GPIO7/EPWM4B/SCIRXDA	HUD INTR input, used to frame synchronize ePWM updates	42
LED Enable IN/OUT		
GPIO3/EPWM2B/COMP2OUT	input, master LED ON/OFF (spare GPIO if not used)	38
GPIO12/TZ1/SCITXDA	DLPC120 AST INTx input, used as a SOC for ADC blocks	47
Photonic Feedback Comparator		
GPIO1/EPWM1B/COMP1OUT	CMP1 output, LED photo switch	28
ADCINB2/COMP1B/AIO10	CMP1 B input, LED photo reference	14
ADCINA2/COMP1A/AIO2	CMP1 A input, LED photo feedback	9
Current Limit Feedback Comparator		
ADCINB4/COMP2B/AIO12	CMP2 B input, LED current reference	16
ADCINA4/COMP2A/AIO4	CMP2 A input, LED current feedback	5
Switching Frequency Monitor		
GPIO5/EPWM3B/ECAP1	Reset Monitor Function	40
Communication Buses		
GPIO19/XCLKIN//SCIRXDA~/ECAP1/SPISTEA~	SPI bus slave select, low true	25
GPIO17/SPISOMIA/TZ3	SPI bus MOSI	26
GPIO16/SPISIMOA/TZ2	SPI bus MISO	27
GPIO18/SPICLKA/SCITXDA/XCLKOUT	SPI bus clock	24
GPIO34/COMP2OUT	SPI SEL output, controls SPI bus multiplexer	19
GPIO32/SDAA/EPWMSYNCI/ADCSOCAO	I2C master SDA pin	31
GPIO33/SCLA/EPWMSYNCO/ADCSOCBO	I2C master SCL pin	36
Clocks and Resets		
XRS~	master reset in, watchdog reset out (open drain)	3
X1	crystal oscillator input, ground	45
X2	crystal oscillator input, no connect	46
Test / Programming Interface		
TEST	<reserved, leave unconnected>	30
TRST~	JTAG interface, pulled low	2
GPIO35 (TDI)	JTAG interface	20
GPIO36 (TMS)	JTAG interface	21
GPIO37 (TDO)	JTAG interface	22
GPIO38/XCLKIN (TCK)	JTAG interface	23
Power and Grounds		
VREGENZ	tie low to enable internal VDD regulator	34
VDDIO	IO and internal regulator power input (tie to 3.3V)	35
VDDA	analog VDD, tie to 3.3V	11
VDD	digital VDD bus, internal regulator, open except for cap	32
VDD	digital VDD bus, internal regulator, open except for cap	43
VSS	ground	33
VSS	ground	44
VSSA REFLO	ground	12
ADC Inputs		
ADCINB1	LED high side voltage	10
ADCINA1	Current measurement & LED low side voltage (VL)	8
ADCINA3	Reserved for LED Thermister	7
ADCINA7	Reserved for LED Thermister	6
ADCINA6/AIO6	Reserved for LED Thermister	13
ADCINA0/VREFHI	1.2V Supply For Monitoring	15
ADCINB3	1.8V Supply For Monitoring	18
ADCINB7	3.3V Supply For Monitoring	4
ADCINB6/AIO14	2.5V Supply For Monitoring	17
Optical Sensor Gain		
GPIO28/SCIRXDA/SDAA/TZ2	LSB	48
GPIO29/SCITXDA/SCLA/TZ3	MSB	1

Figure 6-1. Piccolo TMS320F28023PTQ Pin Allocation

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