Don't Want to Hear It? Avoid the Audio Band with PWM LED Dimming at Frequencies Above 20kHz

by Eric Young

Introduction

The requirements of LED drivers become more demanding as application designers exploit the unique characteristics of LEDs. Linear Technology offers a complete portfolio of LED drivers with the performance levels required to meet even the most challenging design requirements. One area where these LED drivers especially excel is in the performance and flexibility of their PWM dimming capabilities. LEDs can be turned on and off rapidly—it takes only nanoseconds to illuminate or extinguish the source. PWM dimming exploits this characteristic to achieve orders of magnitude dimming, even while maintaining a constant output spectrum over the entire dynamic light intensity range.

The broad field of available LED drivers narrows quite a bit when one considers PWM dimming at frequencies above 20kHz. Why 20kHz? Although most LED light designers worry about perceptible flicker at PWM frequencies below about 100Hz, in some applications the human eye is not the limiting factor; it is the human ear. The human ear perceives vibrations up to about 20kHz, which in some applications can become the important factor in determining PWM frequency. The versatile LT3755 and LT3756 are members of an elite group of LED controllers that can support very high PWM dimming ratios, as much as 50:1, at 20kHz. These controllers support a variety of topologies, including buck mode, boost and buck-boost at various power levels.

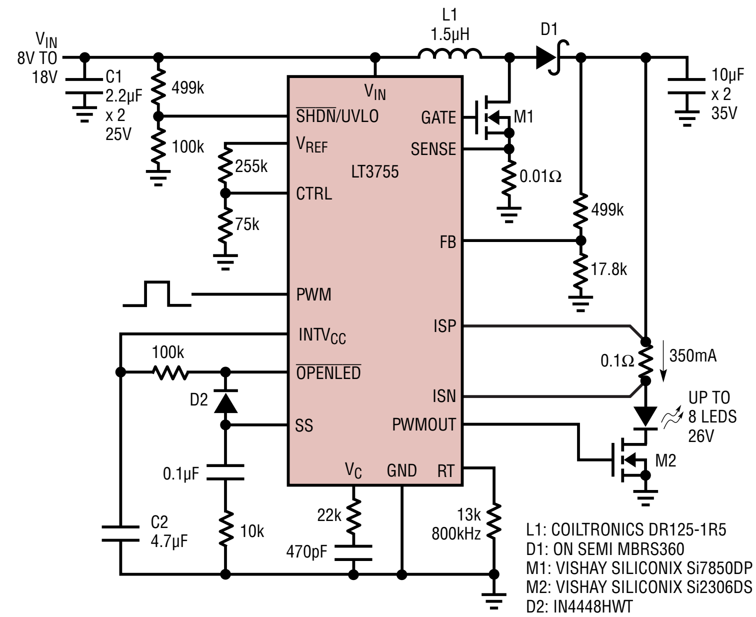

Figure 1. This 10W boost LED driver stays out of the audio band by achieving 50:1 PWM dimming at 20kHz. Lower PWM frequencies can result in an audible hum as ceramic capacitors vibrate.

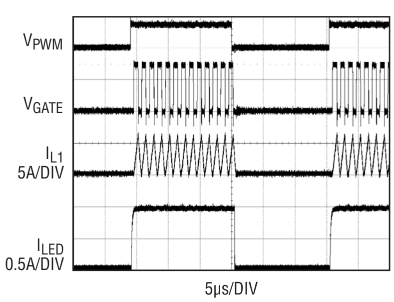

Figure 2. DCM operation of the boost LED driver in Figure 1

High Performance PWM Dimming

The PWM dimming method is straightforward; the LED is driven by a tightly regulated current for a fixed interval in every PWM period. During the off-phase, the current in the LED is zero. During the on-phase, the current is carefully regulated. It is important that the "on" current is consistent, since an LED's output spectrum is a function of forward current. The duty cycle of the PWM signal corresponds to the dimming value.

Although the concept is simple, designing a controller that can achieve this at a high PWM frequency is anything but simple. The rise and fall times of the pulsed current should be fast, less than 100ns. Generating a suitable PWM current pulse from an arbitrary input voltage can prove a challenge. This usually requires a high bandwidth DC/DC converter to regulate the current, a storage/filter capacitor across the LED to provide current during PWM on/off transitions, and a disconnect switch to ensure that the current waveform has sharp turn-on and off edges.

Hysteretic converters, while simple to use from the standpoint of closed loop stability, have problems. The slow LED current rise and fall times are one consequence of using a large value inductor to smooth the current through the LED because there is no output capacitor. And since the average current in the LED is related to the ripple current in the inductor, which is in turn sensitive to input voltage transients, the LED light output changes with input supply. In most cases, this method cannot provide acceptable PWM performance.

What determines PWM performance? The PWM interval or frequency is determined by the application, and there are several considerations to bear in mind. First, the human eye generally does not perceive flicker if the PWM frequency is greater than 120Hz, thus a lower bound on the interval is typically taken to be 8ms.

The achievable dimming ratio is a function of the minimum on- and off-times of the current pulse provided by the driver circuit. So an 8µs minimum pulse yields a 1000:1 dimming capability at 120Hz. The 20kHz audible requirement comes about because audible physical vibrations can be introduced to the PC board by the ceramic capacitors, and these caps are ubiquitous in high bandwidth converter circuits because of their low ESR, ruggedness, and long-term reliability. Ceramic capacitors physically change dimension (as well as value) with a change in applied voltage, and rapid voltage transients during the PWM transients cause rapid changes in dimensions that couple vibrations into the boards. If you ever noticed

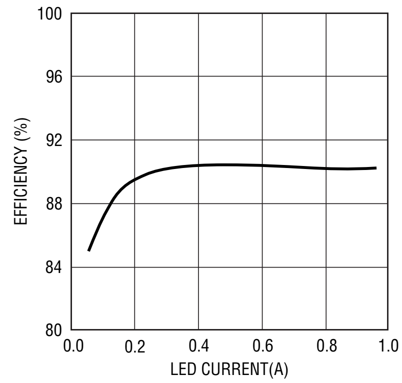

Figure 3. The efficiency of the boost LED driver in Figure 1 is greater than 90%.

an annoying buzz or hum next to a handheld device containing one of these circuits, then you have observed this effect.

The use of a disconnect switch in series with the LED greatly reduces the voltage transient and therefore the hum from the output capacitor. While good design techniques can greatly minimize audible noise for lower PWM frequencies, the elimination of audible emission is not assured so long as PWM frequency is below 20kHz. Many application designers don't want to tinker with acoustics, preferring instead quiet running circuits that do a reasonable job of PWM dimming. The LT3755 and LT3756 current-mode switching controllers can be configured into several different converter circuits to provide a high bandwidth, well regulated output current that can be pulsed at intervals as short as 1µs.

Discontinuous Conduction Mode Is the Secret to Maximizing PWM Performance

The key to short on/off times is for the switching regulator to operate in discontinuous conduction mode (DCM). In this mode, the inductor current always starts from zero at the beginning of each switching period and the peak inductor current is determined by the load and adjusted through the switch duty cycle. In contrast, continuous conduction mode (CCM) maintains a relatively constant switch duty cycle and adjusts the average inductor current to meet the demands of the load.

DCM is superior for high performance PWM dimming because it delivers the required energy to the output in a single switching period. This allows the controller to bypass the typical minimum PWM period of 3-4 switching cycles to reach steady state, a familiar requirement of CCM. Operation in DCM places greater demands

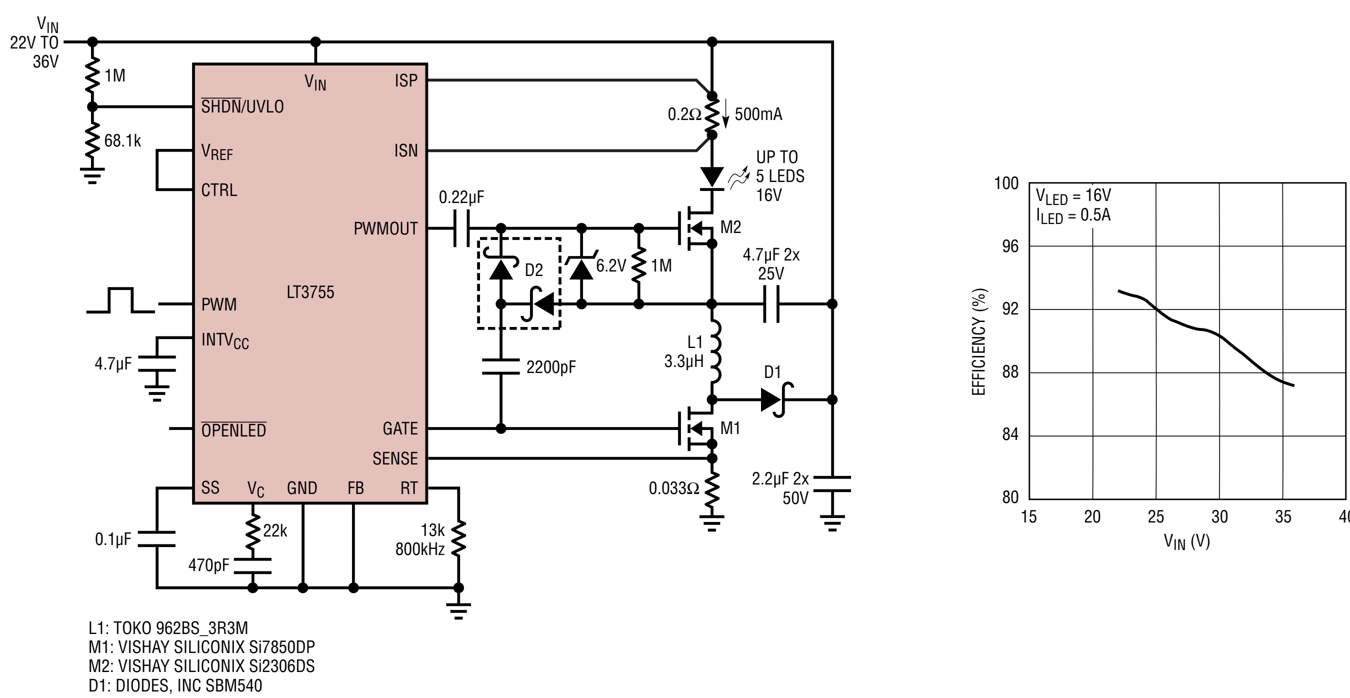

Figure 4. An 8W buck-mode LED driver with 50:1 PWM dimming at 20kHz and 90% efficiency

on switching components because the switching components see higher peak currents for a given load. Because of this, a controller is easier to use than a monolithic converter because its maximum switching current can be programmed to the needs of the application, without having to change the application's features.

Operating in DCM does come at a price when compared to CCM: efficiency, input supply range and analog dimming range all suffer some reduction. The ratio of maximum-to-minimum input supply range is slightly less than the ratio of the minimum PWM pulse width to the minimum switch on-time. Likewise, provided the input supply is fixed, the maximum analog dimming ratio is the same ratio of minimum PWM pulse to minimum switch on-time. Nevertheless, the benefit of this technique is that minimum PWM period is four to five times shorter compared with continuous conduction mode. If the application calls for high PWM dimming ratio, DCM mode provides a sure path to achieve that objective. Three application circuits built with LT3755 and shown here demonstrate this technique.

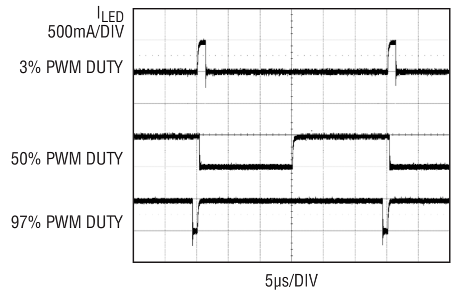

Figure 5. Three PWM dimming settings for the buck mode driver in Figure 4. Even at 33kHz there is no perceptible change in the LED current from minimum to maximum duty cycle.

Figure 1 shows a 9W boost converter that regulates 26V of LEDs at a steady 350mA from a supply ranging between 8V and 18V. If the supply is fixed at 12V, the regulator operates at constant switching frequency for LED currents programmed by the CTRL pin between 125mA and 1A (2.4W to 27W). The minimum on-time is 1µs, as is the minimum off-time. The switching waveforms in Figure 2 show the operation at 50% duty cycle, 27V/1A load and 12V supply. Notice the fast rise and fall times of the LED current signal, even at 1A. At maximum load, the GATE pin is 7V for almost 1µs (same as the minimum pulse width) and the inductor current reaches zero before the start of the each GATE pulse, a characteristic of DCM operation. Figure 3 shows the efficiency versus LED current at 12V input, which peaks at just over 90%.

Figure 4 shows a buck-mode converter that regulates a 16V LED string at 500mA from a 22V to 36V supply. This circuit has an external charge-pump and level shift to drive the gate of an LED disconnect NMOS. This level shift provides much faster rise and fall times than the familiar resistor level shift driving a PMOS, and uses much less current. The scope trace in Figure 5 shows PWM dimming at several duty cycles—it is clear that the output LED current has no perceptible variation as pulse width is smoothly adjusted between the minimum on-time and the minimum off-time. The efficiency of this 8W circuit exceeds 90%.

Figure 6 shows a SEPIC converter driving a 1A, 20V LED string from a 12V-to-36V supply. In addition to providing step-up and step-down capability, this circuit is handy because it provides input-output isolation and built in protection from a short to GND on the output. The efficiency of this circuit exceeds 87%. The minimum

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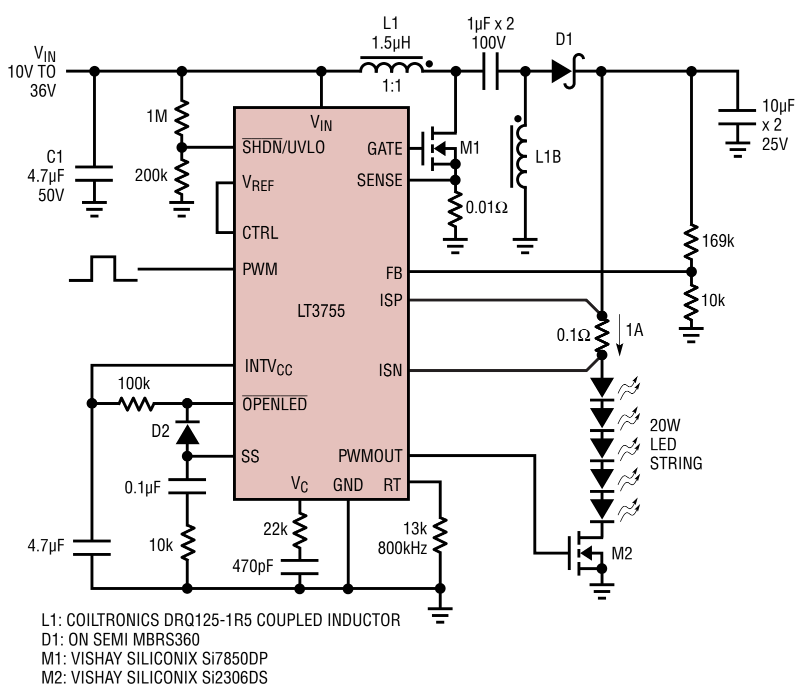


Figure 6. A 20W SEPIC LED Driver with 50:1 PWM dimming at 20kHz and output fault protection

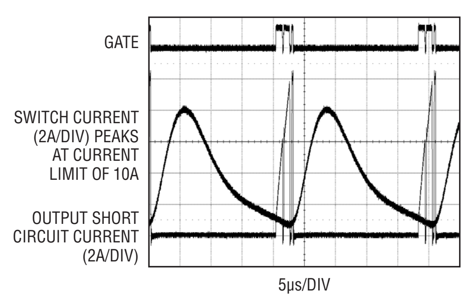


Figure 7. The SEPIC converter in Figure 6 maintains control during an output fault to GND.

efficiency combined with its excellent thermal management capability enables it to deliver up to 240W output power without a heat sink or forced airflow. Figure 3 shows the thermalgraphs taken with three different input voltages and loads at 25°C ambient temperature. With 240W output and 36V input, the maximum temperature rise of the LTM4609 is only 52.8°C.

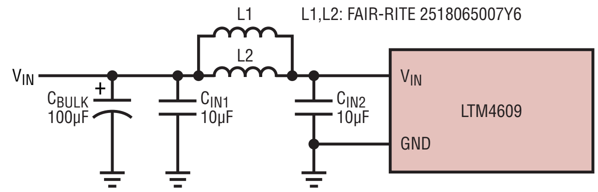
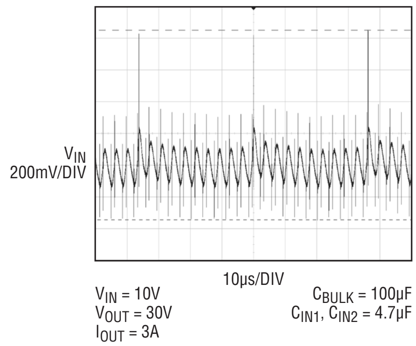
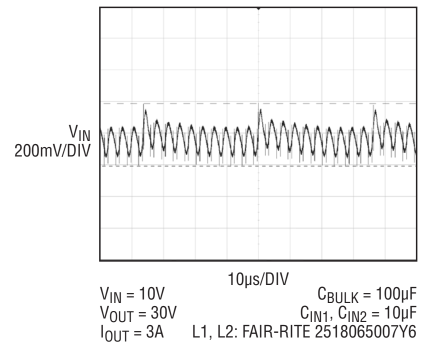


Figure 4. The LTM4609 µModule regulator with an input π filter.



5a. Input voltage waveform without the input π filter shown in Figure 4



5b. Input voltage waveform with input π filter as shown in Figure 4

Figure 5. The input π filter shown in Figure 4 effectively reduces the input voltage spike caused by switching action of the MOSFETs.

Input Ripple Reduction

One way to improve efficiency in a switching DC/DC converter is to minimize the turn-on and turn-off times of the MOSFET—shorter transitions correspond to lower switch losses. However, fast transitions also lead to high frequency switching noise, which can pollute the input power source. For the applications where the input voltage ripple must be limited, a simple LC π filter can be inserted at the input side to attenuate the high frequency input voltage noise. Figure 4 shows the LTM4609 with an input π filter. The filter includes two 10µF low ESR ceramic capacitors and two very small magnetic beads. For lower output power applications, only one magnetic bead is necessary.

Figure 5 shows the input ripple reduction with the π filter. Figure 5a shows the input ripple with 100µF aluminum electrolytic plus 2 × 4.7µF ceramic input capacitors. Figure 5b shows the input ripple with the filter shown in Figure 4. Both waveforms are measured across the 100µF aluminum capacitor. A 67% reduction in input ripple is obtained with the input π filter, which requires only two small additional magnetic beads.

Table 1. Specification comparison of the LTM4605, LTM4607 and LTM4609

	LTM4605	LTM4607	LTM4609
V_{IN}	4.5V ~ 20V	4.5V ~ 36V	4.5V ~ 36V
V_{OUT}	0.8V ~ 16V	0.8V ~ 24V	0.8V ~ 34V
I_{OUT}	5A (12A in buck mode)	5A (10A in buck mode)	4A (10A in buck mode)
Package	15mm × 15mm × 2.8mm LGA		

Conclusion

Buck-boost µModule regulators are easy-to-use, high performance solutions for applications where a regulated output voltage sits within the range of the input voltage. The 15mm × 15mm × 2.8mm LTM4609 widens the input/output voltage range of the pin compatible LTM4605 and LTM4607. The advanced package technology, as well as the high efficiency design of the LTM4609, allows it to deliver up to 240W of output power without heat sinks or forced airflow. For applications that require low input voltage ripple, a simple π filter can be added by inserting one or two small magnetic beads to significantly reduce the high frequency input noise.

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PWM on- and off-times are 1µs as with the other circuits. Figure 7 shows the waveforms during a short circuit fault on the output. The input current remains in control as the switch current ramps up to the set limit of 10A, then skips the next few cycles while the current sensed by the LED resistor ramps down to 1.5A. This faulted mode of circuit operation can continue indefinitely without damage to the components.

Conclusion

The LT3755 and LT3756 offer unparalleled performance for an LED controller generating PWM pulse widths as narrow as 1µs, which enables 50:1 PWM dimming at frequencies above the audible range. Other features include open LED protection, an open LED status indicator, and programmability of the LED current via an analog input.