# Atmel MSL3086 / MSL3088

8-String 60mA LED Drivers with Integrated Boost Controller and Phase Shifted Dimming

FULL DATASHEET

Features:

- Up to 8 parallel 60mA LED strings with up to 10 series white LEDs per string
- Integrated boost controller (MSL3086/88)
- Offers true 4095:1 (12-bit) LED dimming at 120Hz
- String open circuit and LED short circuit fault detection and automatic correction
- ±3% current accuracy and current balance
- Single resistor sets current for all LED strings
- Simple to use external PWM dimming
- Optional internal PWM dimming
- Automatic string phasing reduces EMI and supply ripple
- Synchronizes PWM dimming to LCD panel refresh rate
- Frequency multiplier allows PWM dimming at multiples of LCD panel refresh frequency (see Programming Guide)
- 1MHz I²C/SMBus interface; use optional
- Resistor programmable LED short circuit threshold
- Die over-temperature cut-off protection
- -40°C to +85°C operating temperature range
- Lead free, halogen free, RoHS compliant package
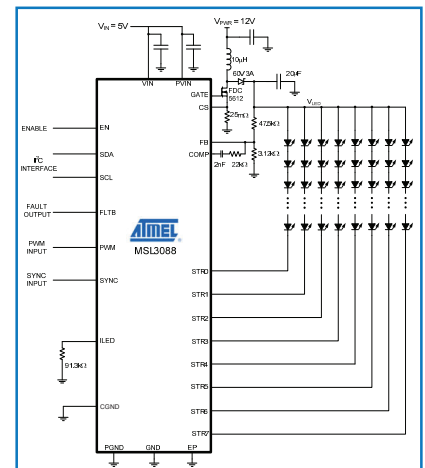
APPLICATION CIRCUIT

Description

The MSL3086/88 8-channel LED drivers with integrated boost regulator controller offer a complete solution to drive up to eight parallel LED strings at up to 40V. The LED current sinks control up to 60mA peak for up to 19W of LED power. A single resistor sets LED current with string matching and accuracy within ±3%.

The advanced integrated PWM circuitry allows up to 4095:1 dimming, and offers simple PWM dimming control. The MSL3086 uses a single PWM input to control the LED dimming signals. The MSL3088 has two inputs, one for frequency and the other for duty cycle. Additionally, internal registers, available through the I²C interface, optionally control PWM dimming frequency and/or duty cycle.

The MSL3086/88 feature phase-shifted PWM dimming to reduce the boost regulator transient response. The integrated fault detection circuitry detects and acts upon string open-circuit and LED short circuit faults, boost regulator over-voltage faults, and die over-temperature faults.

A proprietary Efficiency Optimizer maintains sufficient boost regulator output voltage for proper LED current while minimizing power use. A 1MHz I²C/SMBus serial interface allows optional dimming control, fault inspection and control of device parameters; for serial interface information see the MSL3040/50/60/80/86/87/88/89 Programming Guide.
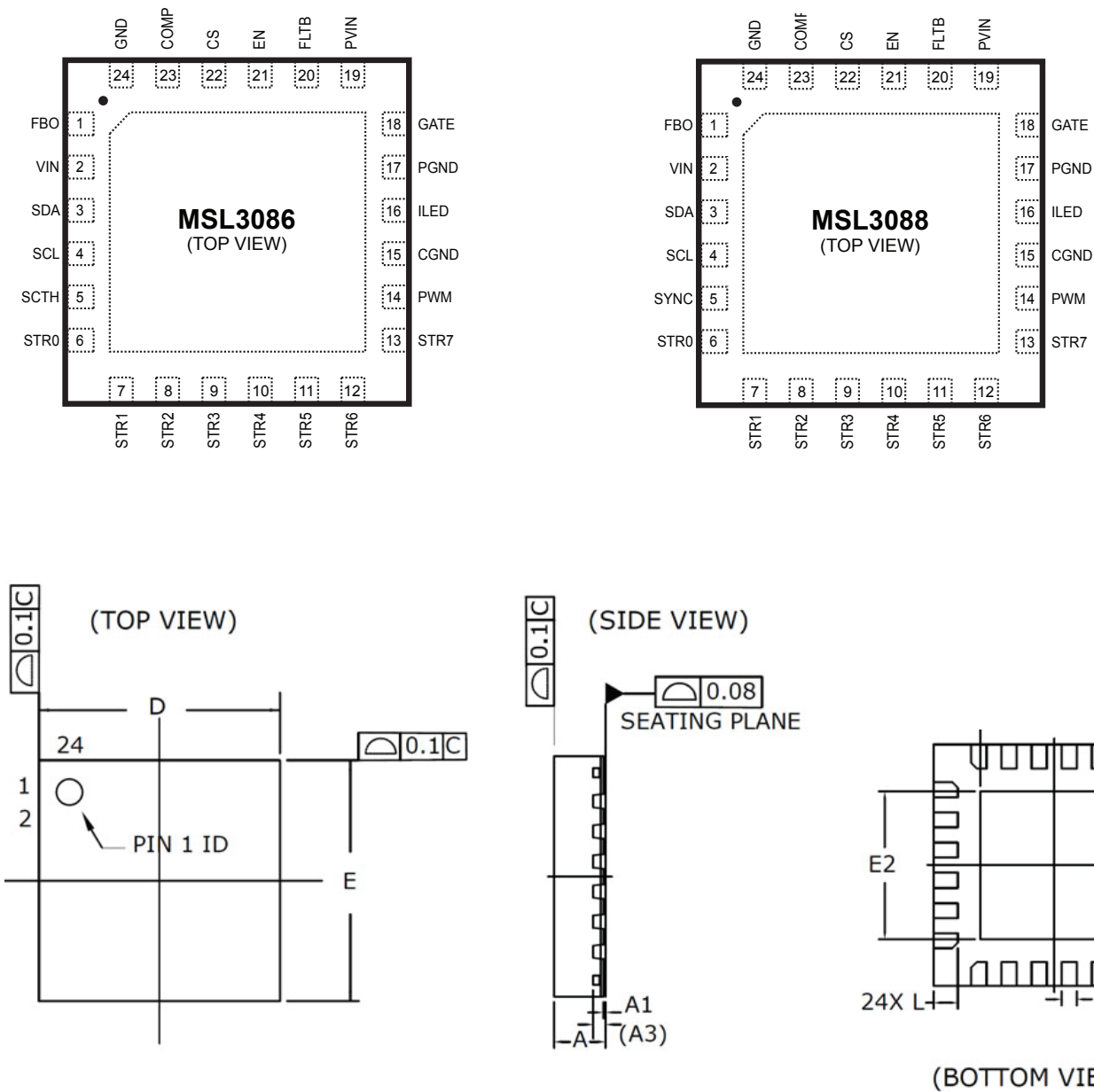
The MSL3086/88 are offered in the 24-pin VQFN lead-free, halogen-free, RoHS compliant package and operate over -40°C to +85°C.

Table of Contents

1.0 Packages and Pin Connections

Figure 1.1   24 pin 4 x 4 x 0.75mm VQFN Package

COMMON DIMENSIONS
(UNIT OF MEASURE=MM)

SYMBOL	MIN	NOM	MAX	NOTE
A	-	0.85	0.90	
A1	0.00	-	0.05	
A3		0.203 REF		
b	0.20	0.25	0.30	2
D		4.00 BSC		
D2	2.35	2.45	2.55	
E		4.00 BSC		
E2	2.35	2.45	2.55	
e		0.50 BSC		
L	0.35	0.40	0.45	
K	0.20	-	-	

NOTES:

1. Refer to JEDEC Drawing MO-220 (SAW SINGULATION)

2. Dimension "b" applies to metalized terminal and is measured between 0.15mm and 0.30mm from the terminal tip. If the terminal has the optional radius on the other end of the terminal, the dimension should not be measured in that radius area.

2.0 Pin Descriptions

Table 2.1 Pin Assignments

Name	MSL 3086	MSL 3088	Pin Description
FB	1	1	**V$_{LED}$ Voltage Regulator Feedback Input:** Connect a resistive voltage divider from the boost regulator output, V$_{LED}$, to FB to set the un-optimized boost regulator output voltage. The feedback regulation voltage is 2.5V.
VIN	2	2	**Power Supply Input:** Power supply input. Apply 4.5V to 5.5V to VIN. Decouple VIN to GND a 1uF or greater capacitor placed close to VIN.
SDA	3	3	**I²C Serial Data I/O:** SDA is the I²C serial interface data input/output. Connect SDA to VIN when unused. For interface information see the MSL3040/50/60/80/86/87/88/89 Programming Guide.
SCL	4	4	**I²C Serial Clock Input:** SCL is the I²C serial interface clock input. Connect SCL to VIN when unused. For interface information see the MSL3040/50/60/80/86/87/88/89 Programming Guide.
SYNC	-	5	**PWM Synchronization Input:** A signal of 20Hz to 50kHz applied to SYNC controls the LED PWM dimming frequency. The signal at PWM controls the LED PWM dimming duty cycle. For serial interface controlled PWM dimming, connect SYNC to GND and refer to the register definitions section for registers 0x10 through 0x14 in the MSL3040/50/60/80/86/87/88/89 Programming Guide.
SCTH	5	-	**String Short Circuit Threshold Level Setting Input:** SCTH programs the LED string short-circuit detection threshold. Connect a resistor from SCTH to GND to set the short-circuit threshold level to 4.9V (1kΩ), 5.8V (27kΩ), 6.8V (68kΩ) or 7.6V (330kΩ). A short circuit is detected when the STRn voltage is above the threshold while STRn is on.
STR0	6	6	**LED String 0 Current Sink:** Connect the cathode end of series LED String 0 to STR0. If not used, connect STR0 to GND.
STR1	7	7	**LED String 1 Current Sink:** Connect the cathode end of series LED String 1 to STR1. If not used, connect STR1 to GND.
STR2	8	8	**LED String 2 Current Sink:** Connect the cathode end of series LED String 2 to STR2. If not used, connect STR2 to GND.
STR3	9	9	**LED String 3 Current Sink:** Connect the cathode end of series LED String 3 to STR3. If not used, connect STR3 to GND.
STR4	10	10	**LED String 4 Current Sink:** Connect the cathode end of series LED String 4 to STR4. If not used, connect STR4 to GND.
STR5	11	11	**LED String 5 Current Sink:** Connect the cathode end of series LED String 5 to STR5. If not used, connect STR5 to GND.
STR6	12	12	**LED String 6 Current Sink:** Connect the cathode end of series LED String 6 to STR6. If not used, connect STR6 to GND.
STR7	13	13	**LED String 7 Current Sink:** Connect the cathode end of series LED String 7 to STR7. If not used, connect STR7 to GND.
PWM	14	-	**PWM Dimming and Synchronization Input:** Drive PWM with a pulse-width modulated signal with duty cycle of 0% to 100% and frequency of 20Hz to 50kHz to control the duty cycle and the frequency of all LED strings. For serial interface controlled PWM dimming connect PWM to GND and refer to the register definitions section for registers 0x10 through 0x14 in the MSL3040/50/60/80/86/87/88/89 Programming Guide.
PWM	-	14	**PWM Dimming Input:** Drive PWM with a pulse-width modulated signal with duty cycle of 0% to 100% and frequency of 20Hz to 50kHz to control the duty cycle of all LED strings. The frequency of the signal applied to SYNC controls the LED PWM frequency. For serial interface controlled PWM dimming, connect PWM to GND and refer to the register definitions section for registers 0x10 through 0x14 in the MSL3040/50/60/80/86/87/88/89 Programming Guide.
CGND	15	15	**Connect To Ground:** Connect to CGND to GND close to driver.
ILED	16	16	**Maximum LED Current Control Input:** Connect a resistor from ILED to GND to set the full-scale LED current. See the section "Setting the LED Current" beginning on page15 for more information.
PGND	17	17	**Power Ground:** Ground of the boost regulator gate driver. Connect PGND to CGND and EP as close to the MSL3086/88 as possible.
GATE	18	18	**Gate Drive Output:** Connect GATE to the gate of the boost regulator switching MOSFET
PVIN	19	19	**Boost Regulator Power Supply Input:** PVIN is the power supply input for the external MOSFET gate driver. Apply 4.5V to 5.5V to PVIN. Decouple PVIN with two 1uF capacitors placed close to PVIN.
FLTB	20	20	**Fault Output:** FLTB sinks current to GND when a fault is detected. The Boost Over-Voltage Fault does not latch; the fault goes away when the fault condition no longer exists, all other faults latch. Clear faults by toggling EN low and then high, or by cycling input power off and on. Additionally, fault control is available through the I²C compatible serial interface; see the MSL3040/50/60/80/86/87/88/89 Programming Guide for information.
EN	21	21	**Enable Input:** Drive EN high to turn on the device, drive it low to turn it off. For automatic startup connect EN to VIN. Toggle EN low then high to reset FLTB.
CS	22	22	**Boost Regulator Current Sense Input:** Connect the current sense resistor from CS and the MOSFET source to GND to set the boost regulator current limit. The current limit threshold is 100mV. See the section "Setting the Current Limit" beginning on page 20 for more information.
COMP	23	23	**Boost Regulator Compensation Node:** Connect the compensation network components from COMP to FB to compensate the boost regulator control loop, as shown in the Typical Applications Circuit on page 11. See the section "Loop Compensation" beginning on page 21 for more information.
GND	24	24	**Signal Ground:** Connect GND to EP as close to the device as possible.
EP	EP	EP	**Exposed Die-Attach Paddle :** Connect EP to CGND, PGND and to the system ground. EP is the return path for the LED current as well as the primary thermal path to remove heat generated in the MSL3086/88. Use a large circuit board trace to connect from EP to the boost supply output capacitor ground and to the input supply ground return. Connect EP to a large copper ground plane for best thermal and electrical performance.

3.0 Absolute Maximum Ratings

Voltage (with respect to GND)

VIN, PVIN, EN, SDA, SCL, PWM, FLTB.. -0.3V to +5.5V

SYNC, SCTH, CS, COMP, FB, GATE ....-0.3V to +5.5V

ADDR, ILED, SCTH.. -0.3V to +2.75V

STR0 to STR7 .... -0.3V to +40V

PVIN to VIN .... ±1V

PGND, CGND, EP ....-50mV to 50mV

Current (into pin)

VIN...50mA

GATE, PVIN...±1250mA

STR0 to STR7 ....75mA

EP, PGND, GND .... -1000mA

All other pins .... -20mA to 20mA

Continuous Power Dissipation

24-Pin 4mm x 4mm VQFN (derate 25mW/°C above TA = +70°C) 1850mW

Ambient Operating Temperature Range $T_A = T_{MIN}$ to T_{MAX}.................................. -40°C to +85°C

Junction to Ambient Thermal Resistance (θ_{JA}), 4-Layer (Note 8) .... 29°C/W

Junction to Ambient Thermal Resistance (θ_{JA}), 2-Layer (Note 8) .... 38°C/W

Junction to Case Thermal Resistance (θ_{JC}) .... 8.6°C/W

Junction Temperature .... +125°C

Storage Temperature Range .... -65°C to +125°C

Lead Soldering Temperature, 10s ....+300°C

4.0 Electrical Characteristics

V_{VIN} = 5V, V_{EN} = 5V, Default Register Settings of Table 1, TA = -40°C to 85°C, unless otherwise noted. Typical values are at TA = +25°C

Parameter	Conditions and Notes		Min	Typ	Max	Unit
DC Electrical Characteristics						
VIN Operating Supply Voltage			4.5		5.5	V
VIN Operating Supply Current	All STR*n* outputs 100% duty				18	mA
VIN Shutdown Supply Current	EN = GND				1	μA
SDA, SCL, PWM, SYNC Input High Voltage			1.82			V
SDA, SCL, PWM, SYNC Input Low Voltage					0.72	V
Minimum PWM On-Time				400		ns
PWM, SYNC Input Frequency Range			20	200	50,000	Hz
SDA, FLTB Output Low Voltage	Sinking 6mA				0.4	V
EN Threshold	V_{EN} rising		1.5			V
ILED Regulation Voltage	Minimum R_{ILED} = 60kΩ			1.25		V
STR0 to STR7 LED Regulation Current	R_{ILED} = 100kΩ, TA= 25°C V_{STRn} = 1V		58.2	60.0	61.8	mA
STR0 to STR7 LED Current Load Regulation	R_{ILED} = 100kΩ V_{STRn} = 1V to 5V			0.15		%/V
STR0 to STR7 LED Current Matching	String to average of all strings		-3		3	%
STR0 to STR7 Minimum Headroom	V_{STRn} = 60mA			0.5		V
STR0 to STR7 Short Circuit Fault Threshold	MSL3086, R_{SCTH} = 1.0kΩ		3.98	4.96		V
	MSL3088, scThrshLvl[1:0] = 00		3.98	4.96		V
FB Feedback Output Current	FBO DAC = 0xFF, V_{FB} = 0		224		350	μA
FB Feedback Output Current Step Size				1.1		μA
Thermal shutdown temperature	Temperature Rising, 10°C Hysteresis			135		°C
Boost Regulator Electrical Characteristics						
Switching Frequency			569	665	762	kHz
Gate Voltage Rise/Fall Time	C_{GATE} = 1nF			50		ns
CS Current Limit Threshold Voltage			75	111	147	mV
Maximum Duty Cycle	At factory set boost frequency			90.1		%
Minimum On Time	f_{BOOST} = 350kHz to 1MHz (contact factory for boost frequencies different from 625kHz)			241	300	ns
Boost Regulator Leading-Edge Blanking Period				130		ns
FB Regulation Voltage			2.4	2.5	2.6	V
I²C Switching Characteristics						
SCL Clock Frequency	1/t_{SCL}	Bus timeout disabled (Note 1)	0		1000	kHz
Bus Timeout Period	$t_{timeout}$	TA = 25°C (Note 7)	29	30		ms
STOP to START Condition Bus Free Time	t_{BUF}	(Note 7)	0.5			μs
Repeated START condition Hold Time	$t_{HD:STA}$	(Note 7)	0.26			μs
Repeated START condition Setup Time	$t_{SU:STA}$	(Note 7)	0.26			μs
STOP Condition Setup Time	$t_{SU:STOP}$	(Note 7)	0.26			μs
SDA Data Hold Time	$t_{HD:DAT}$	(Note 7)	0			ns
SDA Data Valid Acknowledge Time	$t_{VD:ACK}$	(Note 2) (Note 7)	0.05		0.55	μs
SDA Data Valid Time	$t_{VD:DAT}$	(Note 3) (Note 7)	0.05		0.55	μs
SDA Data Set-Up Time	$t_{SU:DAT}$	(Note 7)	100			ns
SCL Clock Low Period	t_{LOW}	(Note 7)	0.5			μs
SCL Clock High Period	t_{HIGH}	(Note 7)	0.26			μs
SDA, SCL Fall Time	t_f	(Note 4) (Note 5) (Note 7)			120	ns
SDA, SCL Rise Time	t_r	(Note 7)			120	ns
SDA, SCL Input Suppression Filter Period	t_{SP}	(Note 6) (Note 7)		50		ns

Note 1. Minimum SCL clock frequency is limited by the bus timeout feature, which resets the serial bus interface if either SDA or SCL is held low for timeout.
Note 2. tVD:ACK = SCL LOW to SDA (out) LOW acknowledge time.
Note 3. tVD:DAT = minimum SDA output data-valid time following SCL LOW transition.
Note 4. A master device must internally provide an SDA hold time of at least 300ns to ensure an SCL low state.
Note 5. The maximum SDA and SCL rise times is 300ns. The maximum SDA fall time is 250ns. This allows series protection resistors to be connected between SDA and SCL inputs and the SDA/SCL bus lines without exceeding the maximum allowable rise time.
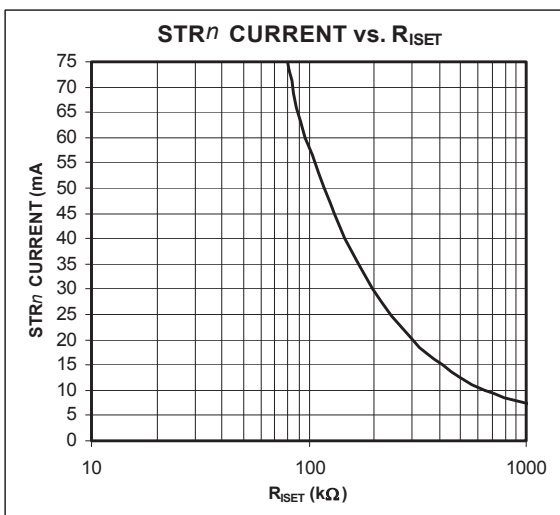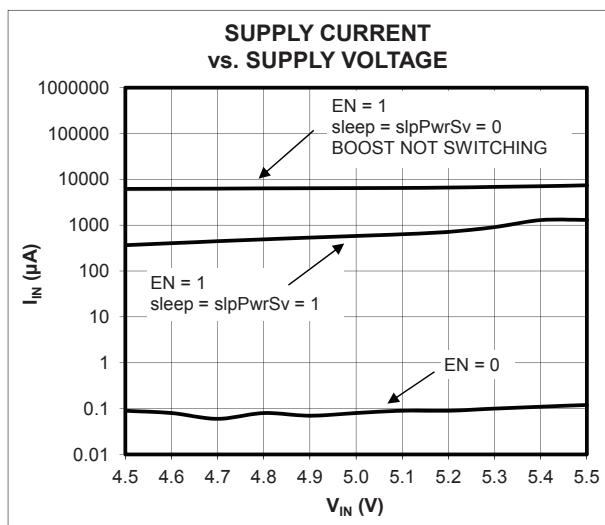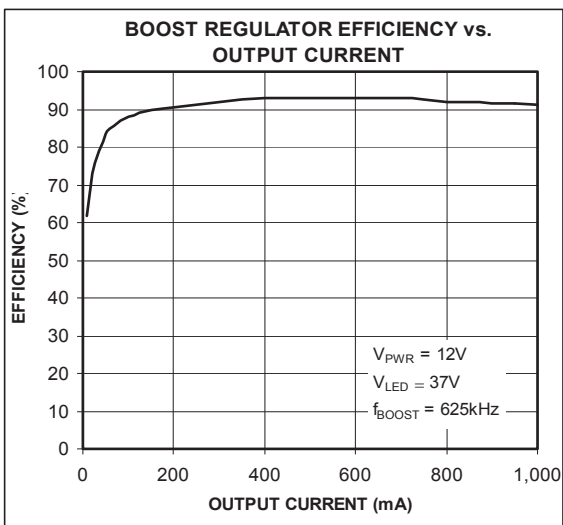Note 6. MSL3086/88 include input filters on SDA and SCL that suppress input noise less than 50ns
Note 7. Parameter is guaranteed by design and not production tested.
Note 8. Per JEDEC specification JESD51-5 and JESD51-12.
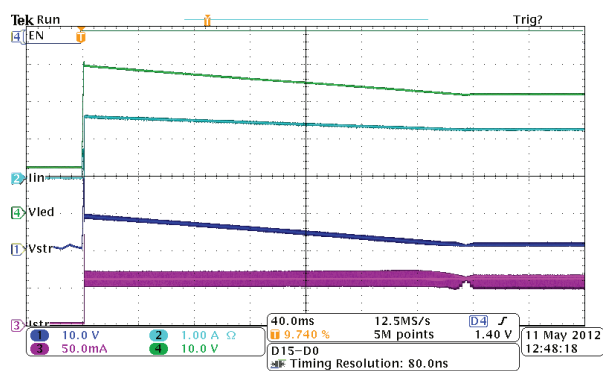Note 9. Tests performed at TA = 25°C, specifications over temperature guaranteed by design.
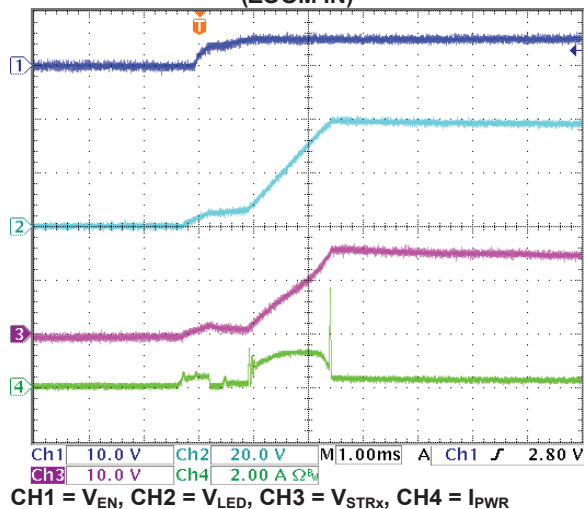
5.0 Typical Operating Characteristics

(Typical Operating Circuit, unless otherwise stated, TA = +25°C, unless otherwise noted)

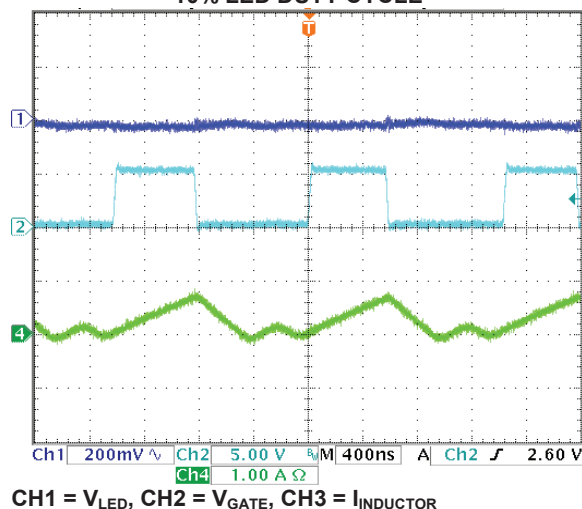BOOST REGULATOR EFFICIENCY vs. OUTPUT CURRENT

$V_{PWR} = 12V$
$V_{LED} = 37V$
$f_{BOOST} = 625kHz$

SUPPLY CURRENT vs. SUPPLY VOLTAGE

EN = 1
sleep = slpPwrSv = 0
BOOST NOT SWITCHING

EN = 1
sleep = slpPwrSv = 1

EN = 0

STRn CURRENT vs. R$_{ISET}$

POWER-UP WAVEFORMS INTO 100% DUTY CYCLE
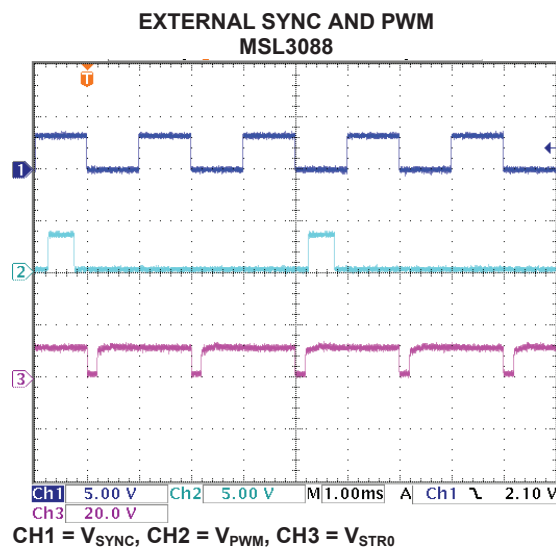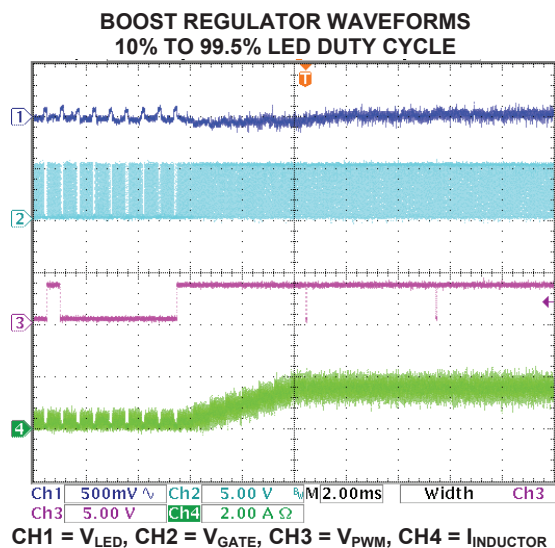

POWER-UP WAVEFORMS INTO 100% DUTY CYCLE (ZOOM IN)

CH1 = V_{EN}, CH2 = V_{LED}, CH3 = V_{STRx}, CH4 = I_{PWR}

BOOST WAVEFORMS 10% LED DUTY CYCLE

CH1 = V_{LED}, CH2 = V_{GATE}, CH3 = $I_{INDUCTOR}$
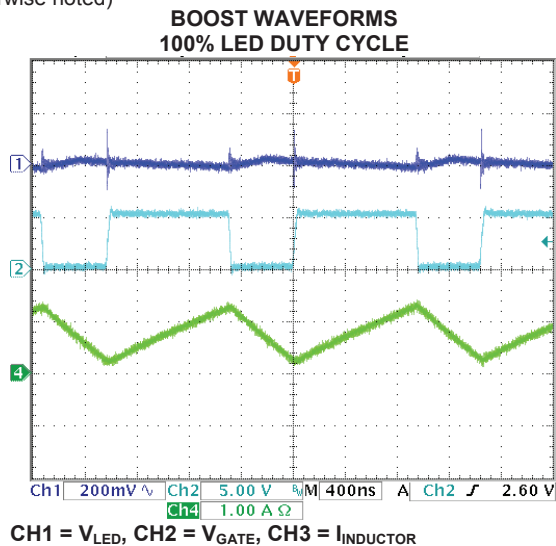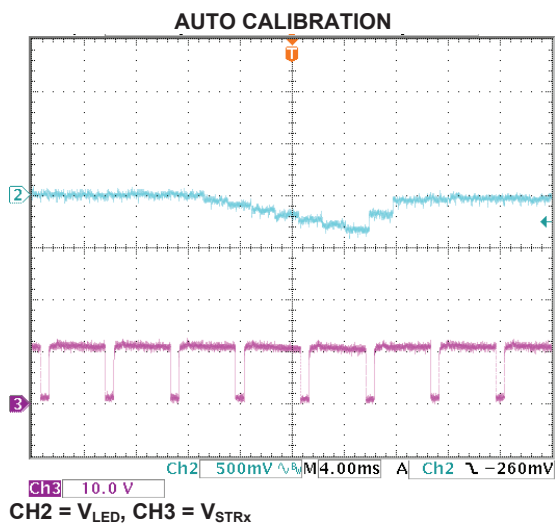
5.0 Typical Operating Characteristics *(continued)*

(Typical Operating Circuit, unless otherwise stated, TA = +25°C, unless otherwise noted)

AUTO CALIBRATION

CH2 = V$_{LED}$, CH3 = V$_{STRx}$

BOOST WAVEFORMS
100% LED DUTY CYCLE

CH1 = V$_{LED}$, CH2 = V$_{GATE}$, CH3 = I$_{INDUCTOR}$

BOOST REGULATOR WAVEFORMS
10% TO 99.5% LED DUTY CYCLE

CH1 = V$_{LED}$, CH2 = V$_{GATE}$, CH3 = V$_{PWM}$, CH4 = I$_{INDUCTOR}$

EXTERNAL SYNC AND PWM
MSL3088

CH1 = V$_{SYNC}$, CH2 = V$_{PWM}$, CH3 = V$_{STR0}$

AUTOMATIC PHASE SHIFTED PWM DIMMING

CH1 = V$_{STR0}$, CH2 = V$_{STR2}$, CH3 = V$_{STR4}$, CH4 = V$_{STR6}$

EXT SYNC AND PWM, FREQUENCY MULTIPLIED
MSL3088

CH1 = V$_{SYNC}$, CH2 = V$_{PWM}$, CH3 = V$_{STR0}$
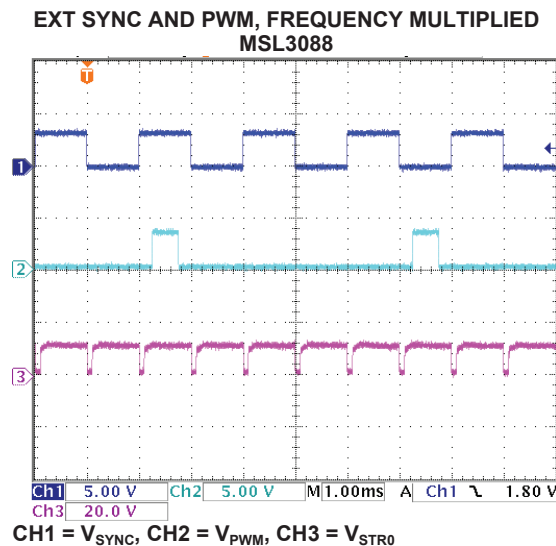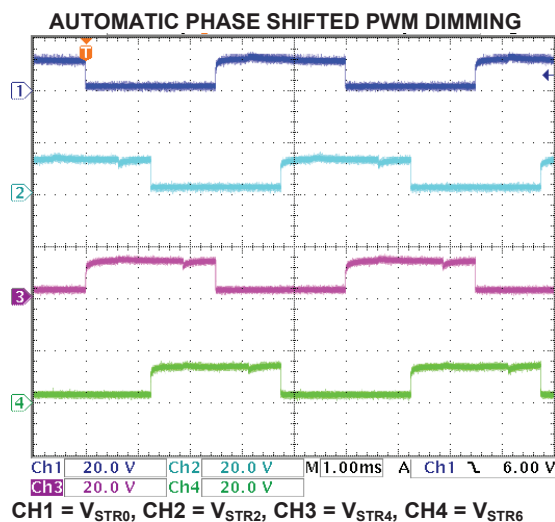
5.0 Typical Operating Characteristics *(continued)*

(Typical Operating Circuit, unless otherwise stated, TA = +25°C, unless otherwise noted)

BOOST REGULATOR GATE DRIVE RISE/FALL WITH 3nF CAPACITIVE LOAD
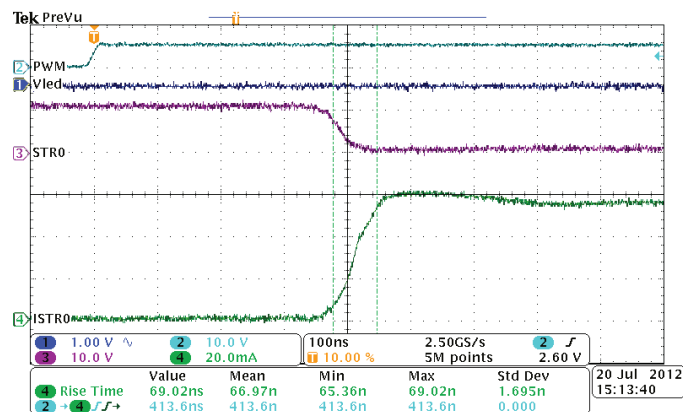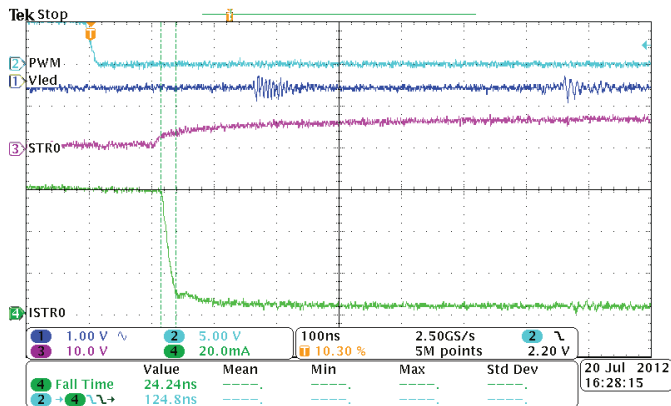

CH2 = V_{GATE}

DRIVER RISE TIME

This scope image shows the voltage (VSTR0) and current (ISTR0) waveforms for string zero, and their turn-on rise times and delay from PWM rising. Also shown is the string power supply output (VLED), which shows little disturbance. For this photo string 0 is enabled with all other strings disabled.

DRIVER FALL TIME

This scope image shows the voltage (VSTR0) and current (ISTR0) waveforms for string zero, and their turn-off fall times. Also shown is the string power supply output (VLED), which shows very little disturbance. For this photo string 0 is enabled with all other strings disabled, and a 220pF capacitor in series with a 11Ω resistor in series is placed from STR0 to GND at the device.

6.0 Block Diagram
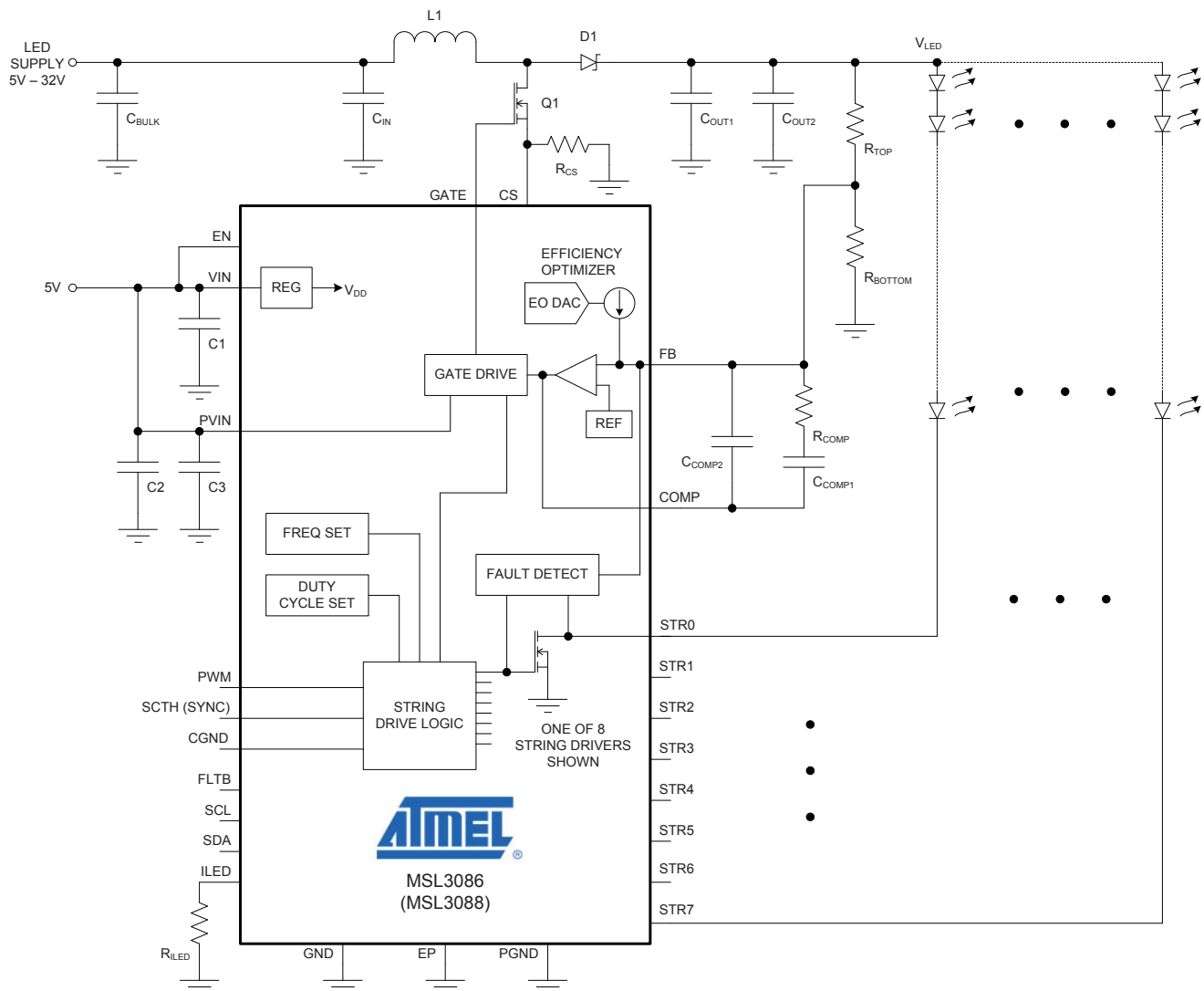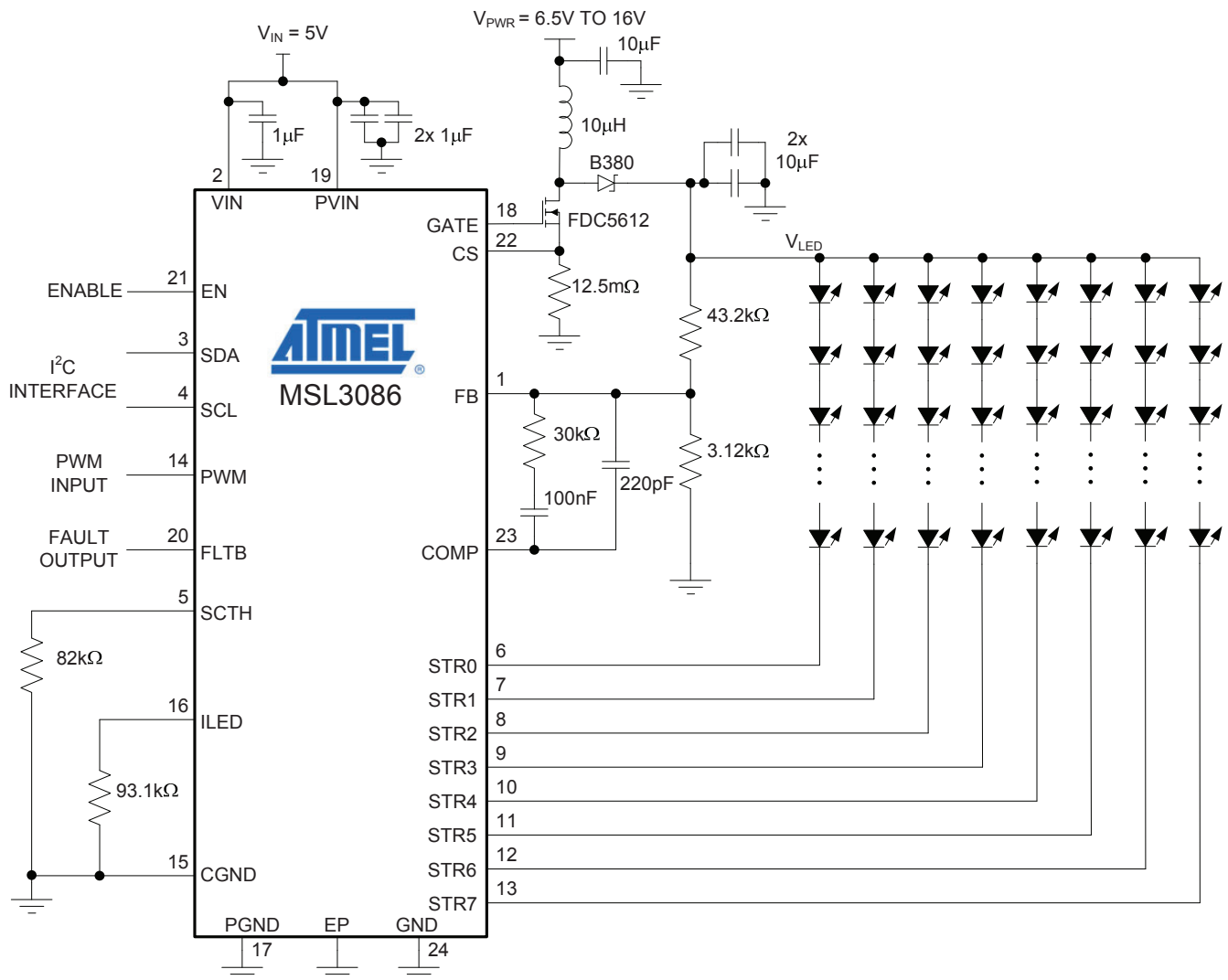
Figure 6.1. Block Diagram

Figure 1. MSL3086/MSL3088 Block Diagram

7.0 Typical Application Circuit

Figure 7.1. Typical Application Circuit

8.0 Detailed Description

The MSL3086/88 are LED drivers with eight internal current regulators capable of driving up to 60mA LED current each. The MSL3086/88 feature an integrated boost regulator controller to power the LED strings. They provide a complete LED driver solution for multi-LED string applications. A single resistor sets the LED current for all strings. The MSL3086/88 support PWM LED dimming up to 4095:1 and feature automatic phase shifted dimming, and dimming synchronized with external digital signals. The MSL3088 features independent frequency and duty cycle control inputs. All devices feature optional register-set PWM dimming, fault and other controls via the I²C serial interface; for interface information see the **"MSL3040/50/60/80/86/87/88/89 Programming Guide"**.

The MSL3086/88 include comprehensive fault monitoring and automatic fault handling. Automatic fault handling allows the MSL3086/88 to operate without any microcontroller or FPGA, while control via I²C allows customized fault handling and device control for more complex applications.

The small 4x4mm VQFN package allows a small overall LED driver solution, while the high package power dissipation offers high output power capability.

8.1 Differences between the MSL3086 and MSL3088

The MSL3086 requires only power and a single PWM input to set both the frequency and duty cycle of the LED drive signals, and includes a boost converter controller. The MSL3088 accepts an additional SYNC signal that sets the frequency of the LED dimming signals, while the PWM input sets the LED duty cycle. Similar devices are presented in Table 8.1 for comparison:

Table 8.1. LED Driver Comparison with Similar Parts

PART	NUMBER OF LED STRINGS	MAX CURRENT PER STRING	PHASE SHIFTED STRING DRIVERS	INTERNAL BOOST CONTROLLER	RESISTOR SET LED SHORT CIRCUIT THRESHOLD	SEPARATE SYNC INPUT***	BEST FOR
MSL3086	8	60mA	YES	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
MSL3087*	8	60mA	YES	NO	YES	NO	SMALL TV
MSL3088	8	60mA	YES	YES	NO	YES	SMALL TV
MSL3080	8	60mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	4**	120mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	2**	240mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	1**	480mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
MSL3040*	4	120mA	YES	YES	YES	NO	MONITOR, AUTOMOTIVE
MSL3041*	4	120mA	YES	YES	YES	YES	MONITOR, AUTOMOTIVE
MSL3050*	5	60mA	NO	YES	YES	NO	INDUSTRIAL PANEL
	1**	300mA	NO	YES	YES	NO	INDUSTRIAL PANEL
MSL3060*	6	60mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	3**	120mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	2**	180mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL
	1**	360mA	NO	YES	YES	NO	MONITOR, INDUSTRIAL PANEL

* Future product, contact factory for information.
** Drivers without phase shift allow parallel connection of string drive outputs for increased string current.
*** Drivers with separate SYNC input expect two control signals, one for dimming duty cycle and one for dimming frequency.

8.2 Operating the MSL3086/88

The MSL3086/88 are simple to operate; set up the boost regulator (see the section **"Boost Regulator"** beginning on page 17), set the string on-current (see the section **"Setting the LED Current"** beginning on page 16), supply a PWM control signal to the PWM input (MSL3088 requires a second control signal applied to the SYNC input), set the LED short circuit threshold voltage (see the section **"Setting the LED Short-Circuit Threshold"** beginning on page 16), connect the LED strings and apply power (decoupled as instructed in the section **"Bypassing VIN and PVIN"** beginning on page 16).

8.3 Boost Regulator Overview

The MSL3086/88 boost regulator boosts the input voltage up to the regulated output voltage. For design details see the section *"Boost Regulator"* beginning on page 17, the following text presents an overview of the boost regulator controller.

The boost regulator uses an external switching MOSFET, current sense resistor, inductor, rectifier, and input and output capacitors for this purpose (Figure 8.1). Because the MOSFET and current sense resistor are external, the boost regulator operates over a wide range of input and output voltage, and LED current configurations. It includes a 2.5V reference voltage, fixed slope compensation and external voltage regulator compensation to optimize the control loop for each configuration. Because the boost regulator components are external, it is useful for a number of topologies such as SEPIC, flyback, and single-switch forward converters. The boost regulator includes soft-start, adjustable cycle-by-cycle current limiting, and output over-voltage fault detection.

Figure 8.1. Power section of MSL3086/MSL3088
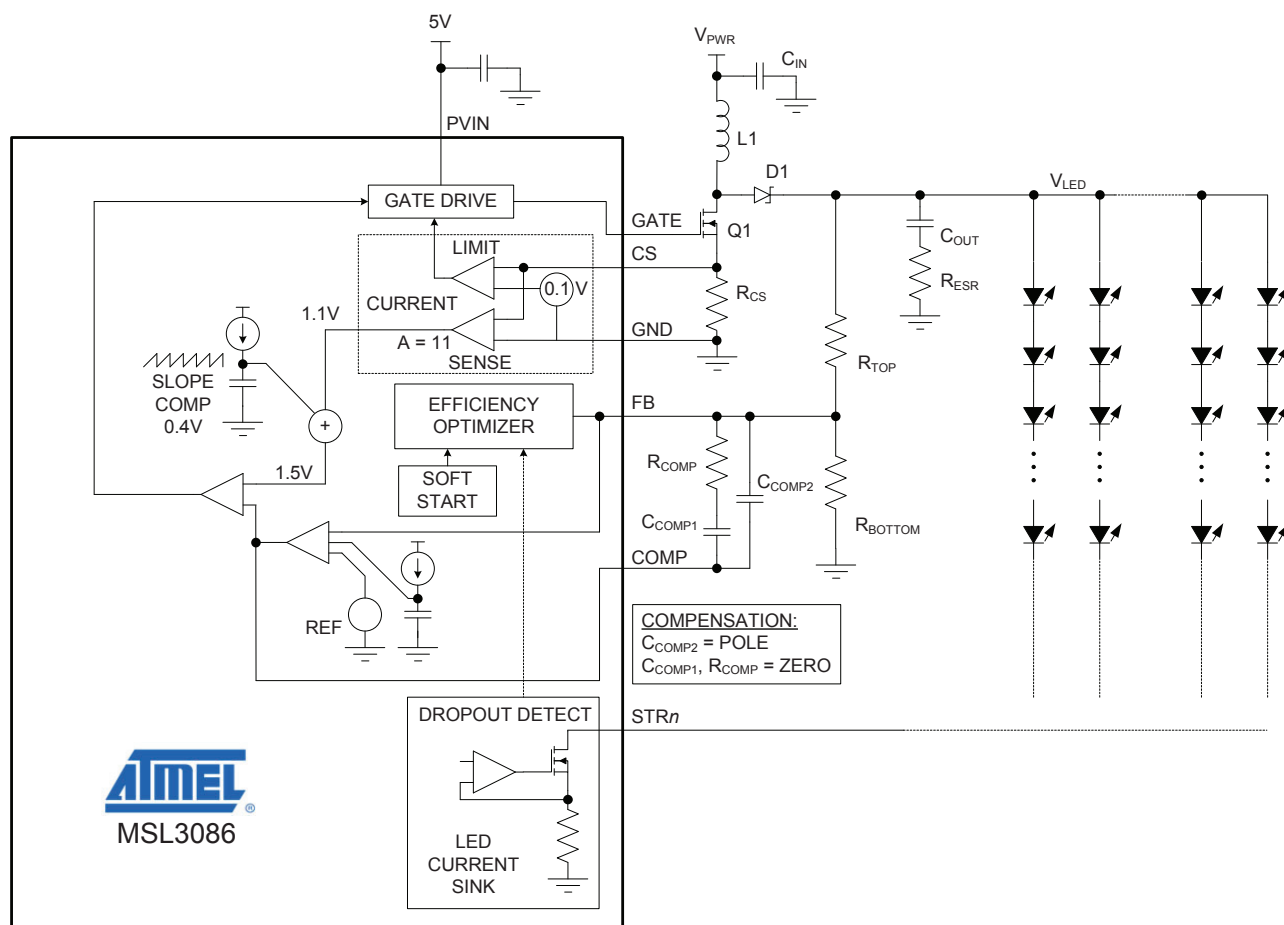
8.4 Error Amplifier

The internal error amplifier compares the external divided output voltage at FB to the internal 2.5V reference voltage to set the regulated output voltage. The error amplifier output voltage at COMP is externally accessible and is used in conjunction with an external RC network to compensate the voltage regulator. FB also drives the integrated boost over-voltage comparator that detects if the output voltage exceeds the regulation voltage, to generate a fault condition. The error amplifier internally controls the current mode PWM regulator.

8.5 Gate Driver

The gate driver drives the gate of the external boost regulator switching MOSFET. The drain of the switching MOSFET in turn drives the boost inductor and rectifier to boost the input voltage to the regulated output voltage. The gate driver sources and sinks up to 1A allowing fast switching speed and allows the use of MOSFETs with high gate capacitance. The gate driver power is separated from the internal circuitry power to reduce internal noise and to allow separate gate driver bypassing for optimal performance.

8.6 Soft-Start

The boost regulator includes a built in soft-start to prevent excessive input current overshoot at turn-on. The soft-start ramps the output regulation voltage from 0V at turn-on to the as-configured regulation output voltage over 1.6ms. Note that the boost regulator only controls output voltages greater than the input voltage; when the soft-start sets the regulation voltage below the input voltage, the actual output voltage remains at approximately the input voltage.

8.7 Boost Fault Monitoring and Protection

The boost regulator includes fault monitoring and protection circuits to indicate faults and prevent damage to the boost regulator or other circuitry. The boost regulator has cycle by cycle current limiting that prevents excessive current through the power MOSFET. The current limit is has a fixed threshold voltage across the current sense resistor, thus the current limit is set by choosing the proper value current sense resistor.

The boost regulator includes an output over-voltage fault monitor that indicates a fault when the voltage at FB exceeds the 2.8V over-voltage protection (OVP) threshold. When an over-voltage fault occurs FLTB sinks current to GND to indicate that a fault has occurred. OVP fault is non-latching, the fault clears when the over-voltage condition disappears.

8.8 LED Current Regulators and PWM Dimming Modes

The MSL3086/88 include eight open-drain LED current regulators that regulate LED current up to 60mA per channel and sustain up to 40V, allowing them to drive up to 10 white LEDs each. The current regulators control the Efficiency Optimizers which in turn controls the boost regulator output voltage to minimize LED voltage while maintaining sufficient headroom for LED current regulators.

The LED regulation current is set by a single resistor from ILED to GND. LED dimming is by PWM, and is controlled by default through an external signal(two signals in the case of the MSL3088), or optionally by internal registers accessed through the I^{2}C compatible serial interface (for interface information see the MSL3040/50/60/80/86/87/88/89 Programming Guide). LED drive dimming signals are phase shifted, where LED string on-times are successively delayed by 1/8th cycle from STR0 to STR7, reducing boost regulator transient response and increasing the transient frequency of the boost regulator. The MSL3088 features synchronized dimming mode where separate PWM and SYNC inputs control PWM dimming duty cycle and frequency.

8.9 Efficiency Optimizer (EO)

The efficiency optimizer monitors LED strings and controls the boost regulator output voltage to minimize LED current regulator overhead voltage while maintaining sufficient voltage for accurate current regulation. The efficiency optimizer injects a current into the boost regulator FB input node to reduce the boost regulator output voltage.

The efficiency optimizer has two modes of operation, initial calibration and auto calibration. Initial calibration happens at turn-on and optimizes boost regulator output voltage. Auto calibration happens once per second to re-optimize the boost output voltage in response to changing LED forward voltage due to aging or temperature effects. The efficiency optimizer requires that strings have a minimum on-time of 2μs for proper EO operations to maintain current regulation.

8.10 Fault Monitors

The MSL3086/88 include comprehensive fault monitoring and corrective action. They monitor the LED current regulators for LED string open circuit and LED short circuit faults. They also monitor the boost regulator for output over-voltage. Strings with LED Short Circuit or Open Circuit faults are turned off and ignored by the Efficiency Optimizer.

FLTB sinks current to GND when a fault is detected. The Boost Over-Voltage Fault does not latch, the fault goes away when the fault condition no longer exists and FLTB is released; all other faults latch. Clear faults by toggling EN low and then high, or by cycling input power off and on. Additionally, fault control is available through the I^{2}C compatible serial interface; see the MSL3040/50/60/80/86/87/88/89 Programming Guide for information. For more information about string faults and automatic fault handling see the section *"Fault Monitoring and Automatic Fault Handling"* beginning on page 15.

8.11 Internal Supervisory and LDO

The MSL3086/88 have a Power-On-Reset circuit that monitors VIN and allows operation when VIN exceeds 4.25V. The MSL3086/88 have built-in LDOs that generate 2.5V to power the logic and oscillator sections. An integrated supervisor ensures that the LDO and internal oscillator are stable before enabling the boost controller. The boost controller goes through a soft-start before the LED drivers are enabled.

8.12 Internal Oscillator

The MSL3086/88 include a 20MHz internal oscillator that is divided down to drive the boost controller, and the LED PWM engine. The oscillator is factory trimmed. Contact the factory if required to change the 20MHz default oscillator frequency, available frequencies fall between 16MHz and 24MHz

8.13 Over Temperature Shutdown

The MSL3086/88 include automatic over-temperature shutdown. When the die temperature exceeds 135°C, the device turns off, as if EN is pulled low, and is held off until the die temperature drops below 120°C, at which time it turns back on. While MSL3086/88 is in over-temperature shutdown the onboard regulators are off, register values reset and the serial interface is disabled.

8.14 Power Saving Modes

The MSL3086/88 have 3 primary power save modes available through the I^{2}C compatible serial interface. See the MSL3040/50/60/80/86/87/88/89 Programming Guide for information.

8.15 I^{2}C Serial Interface and Driver Control

The I^{2}C serial interface allows control of PWM dimming, fault monitoring, and various other control functions. For a detailed explanation of interface operation see the *"MSL3040/50/60/80/86/87/88/89 Programming Guide"*.

9.0 Application Information

9.1 Bypassing VIN and PVIN

Bypass VIN with a capacitor of at least 1µF. Bypass PVIN with at least 2µF. Place all bypass capacitors close to the device.

9.2 Setting the LED Current

Set the on-current for all LED strings with a resistor from ILED to GND. Choose the resistor using:

$$R_{ISET} = \frac{6050}{I_{LED}} \Omega$$

where I_{LED} is the LED on-current in Amps.

The maximum LED current per-string is 60mA. Driving all eight strings with 60mA at high duty cycles and elevated ambient temperatures requires proper thermal management to avoid over-temperature shutdown. Connect the exposed pad (EP) to a large copper ground plane for best thermal and electrical performance.

9.3 Fault Monitoring and Automatic Fault Handling

The MSL3086/88 monitor the LED strings to detect LED short-circuit, LED string open-circuit and Boost Over-voltage faults. String faults latch the open drain fault output FLTB low. A boost over-voltage fault pulls FLTB low but is not latching.

When shorted LEDs are detected in a string the string is disabled and no longer monitored by the Efficiency Optimizer. The MSL3086/88 pulls FLTB low and recalibrates the LED power supply voltage. Set the short circuit voltage threshold with a resistor between SCTH and GND, as explained in the section "Setting the LED Short-Circuit Threshold" beginning on page 16. Additionally, strings with shorted LEDs are flagged in registers 0x05 through 0x08. For information about the fault registers and the I^{2}C compatible serial interface see the MSL3040/41/50/60/80/86/87/88 Programming Guide.

When an open circuit occurs, the Efficiency Optimizer detects a loss of current regulation which must persist for greater than 2µs to be detected therefore the minimum on-time for the strings is 2µs. In this case the Efficiency Optimizer keeps increasing the LED voltage (boost regulator output voltage), in an attempt to bring the string back in to regulation. This continues until the voltage is at the maximum level. The MSL3086/88 then determine that any LED strings that are not regulating current are open circuit. It disables those strings, pulls FLTB low and recalibrates the LED power supply voltage. When the boost regulator is at its maximum value, fictitious LED short circuit faults can occur when the LED short circuit threshold is set to a low value and/or the string LEDs exhibit excessive voltage mismatch. Toggle EN low and then high to clear all faults and return the MSL3086/88 to controlling and monitoring all strings. Fault conditions that persist re-establish fault responses. Additionally, strings with open circuits faults are flagged in registers 0x05 through 0x08. For information about the fault registers and the I^{2}C compatible serial interface see the MSL3040/41/50/60/80/86/87/88 Programming Guide.

## 9.4 Setting the LED Short-Circuit Threshold on the MSL3086

When a given string, STRn, is sinking LED string current, the fault detection circuit monitors the STRn voltage. Typical optimized STRn on-voltage is 0.5V. When one or more LED's of a string are shorted out, the STRn voltage increases above the nominal. When the voltage is above the Short-Circuit Threshold the fault circuit generates an LED short circuit fault. In most cases, two LEDs in a string must be shorted to cause a short circuit fault, but because LED V$_F$ differs for different LEDs, the number of shorted LEDs required to generate a fault varies. Set the LED short-circuit threshold with a resistor from SCTH to GND using:

Table 9.1 Short Circuit Threshold Resistor

R$_{SCTH}$	Threshold Voltage
1.0kΩ (or GND)	4.9V
27kΩ	5.8V
68kΩ	6.8V
330kΩ (or open)	7.6V

R$_{SCTH}$ is queried at power up, and when EN is taken high, to set the threshold level. The MSL3088 does not have an SCTH input; the threshold is pre-set to 6.8V. Additionally, register 0x04 holds the Short Circuit Threshold level, changeable through the I^{2}C compatible serial interface. For information about the Short Circuit Threshold register and the serial interface see the *"MSL3040/50/60/80/86/87/88/89 Programming Guide"*.

Figure 9.1 Open-Circuit and Short-Circuit Detection Block Diagram
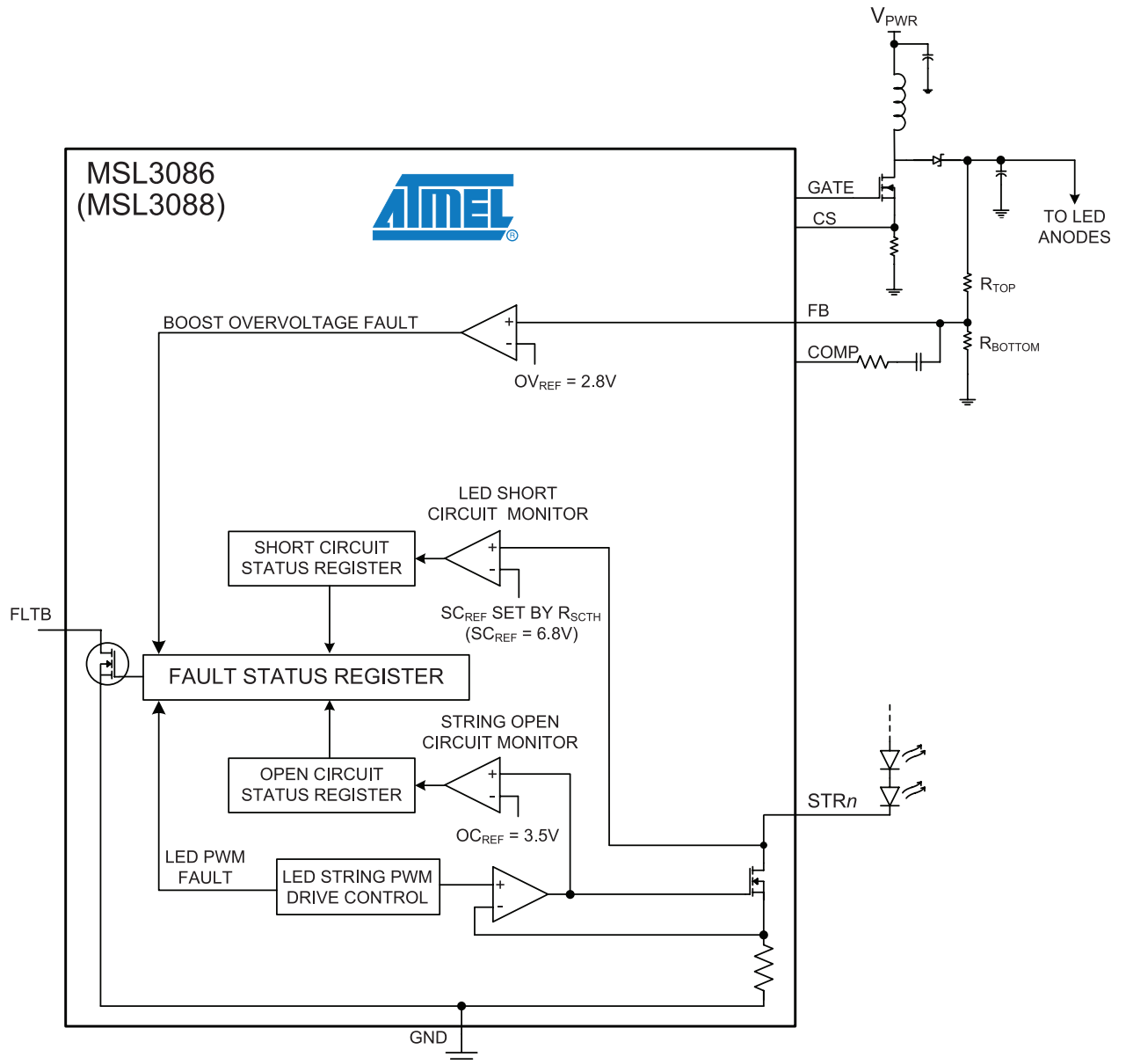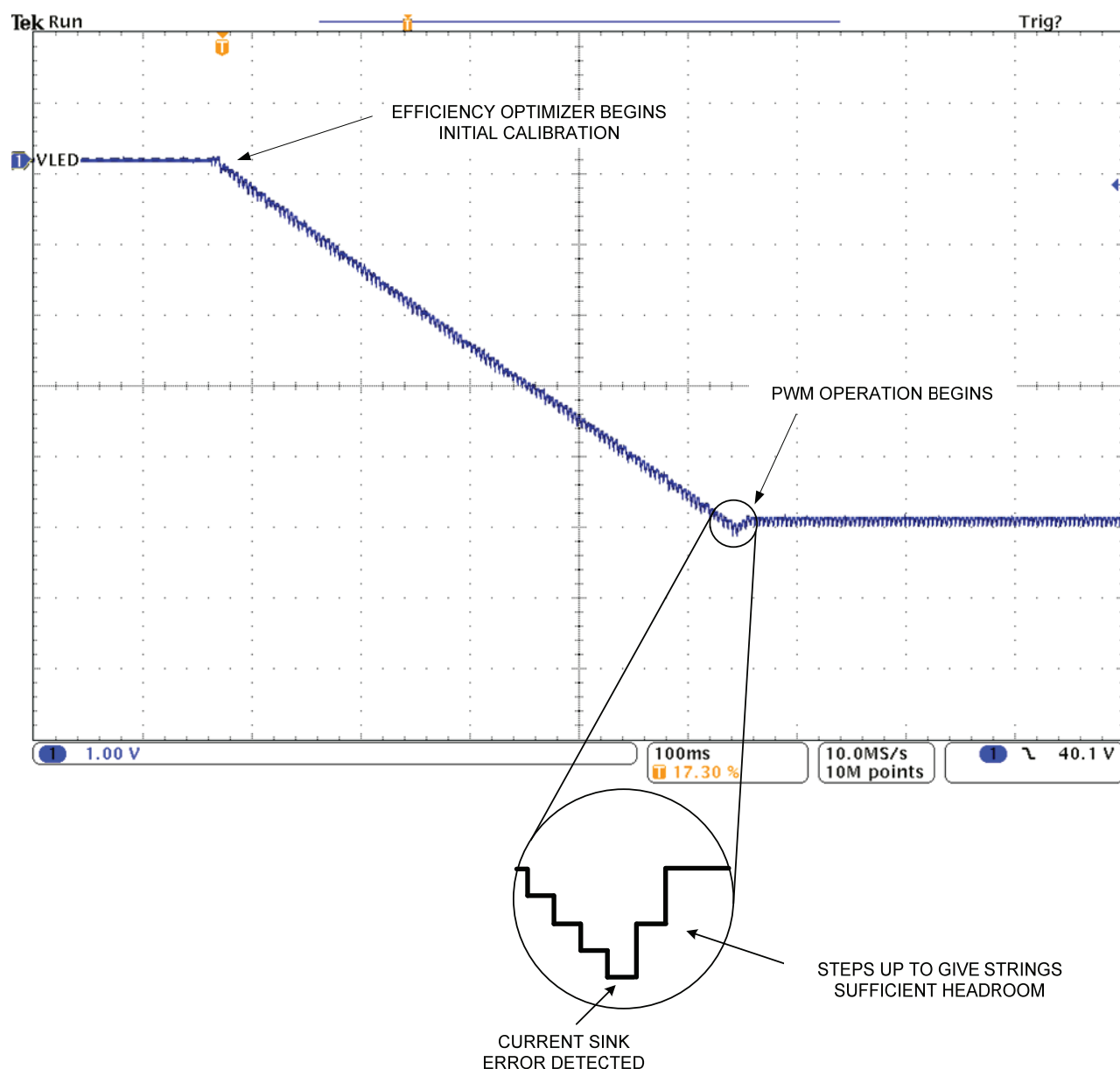

9.5 Boost Regulator

The boost regulator boosts the input voltage to the regulated output voltage that drives the LED anodes. The MSL3086/88 boost regulators use external MOSFET switches and current sense resistors, allowing a wide variety of input/output voltage combinations and load currents. The boost regulator switching frequency is 625kHz. Switching frequencies of 350kHz, 500kHz, 750kHz, 875kHz and 1Mhz are also available; contact the factory for information.

9.6 The Efficiency Optimizer (EO)

A voltage divider from the boost regulator output voltage to FB sets the regulation voltage (R_{TOP} and R_{BOTTOM} in Figure 8.1 on page 13). The EO improves power efficiency by dynamically adjusting the power supply output voltage to the minimum required to power the LEDs. This ensures that there is sufficient voltage available for LED current control, and good power supply noise rejection, while minimizing power dissipation. It does this by injecting a small current into the FB input over 256 steps (8-bit resolution).

When turned on, either by applying input voltage to VIN while EN is high, or by driving EN high with voltage applied to VIN, the EO begins an initial calibration cycle by monitoring the external LED current regulators. If all the current regulators maintain LED current regulation the EO output current is increased to reduce the boost output voltage. After the 4ms power supply settling time, it rechecks the regulators, and if they are maintaining regulation the process repeats until one or more current regulator looses regulation. This step requires that the strings are turned on for a minimum of 2µs to detect current regulation. The EO then decreases the output current to increase boost output voltage, giving the regulator enough headroom to maintain regulation with minimal power dissipation. The oscilloscope picture Figure 9.2 shows this procedure. The EO automatically re-calibrates VOUT every 1 second, and always increases the string voltage when a string is detected with insufficient current.

Figure 9.2 Efficiency Optimizer (EO)

9.7 Setting the Boost Regulator Output Voltage

Select the voltage divider resistors (R_{TOP} and R_{BOTTOM} in Figure 8.1 on page 13) by first determining $V_{OUT(MIN)}$ and $V_{OUT(MAX)}$, the minimum and maximum LED string anode power supply (boost regulator) voltage, using:

$$V_{OUT(MIN)} = \left(V_{f(MIN)} \times [\# \, of LEDs]\right) + 0.5 \qquad \text{and} \qquad V_{OUT(MAX)} = \left(V_{f(MAX)} \times [\# \, of LEDs]\right) + 0.5$$

where $V_{f(MIN)}$ and $V_{f(MAX)}$ are the LED's minimum and maximum forward voltage drops at the full-scale current set by R_{ILED} (page 16). For example, if the LED minimum forward voltage is $V_{f(MIN)}$ = 3.5V and maximum is $V_{f(MAX)}$ = 3.8V, using 10 LEDs in a string, the total minimum and maximum voltage drop across a string is 35V and 38V. Adding allowance of 0.5V for the current regulator headroom brings $V_{OUT(MIN)}$ to 35.5V and $V_{OUT(MAX)}$ to 38.5. Next determine R_{TOP} using:

$$R_{TOP} = \frac{V_{OUT\,(MAX)} - V_{OUT\,(MIN)}}{350 \times 10^{-6}} \; \Omega \qquad \begin{array}{c} \text{Then determine} \\ \text{R}_{BOTTOM}\text{ using:} \end{array} \qquad R_{BOTTOM} = R_{TOP} \times \frac{2.5}{V_{OUT(MAX)} - 2.5} \Omega$$

9.8 Choosing the Input and output Capacitors

The input and output capacitors carry the high frequency current due to the boost regulator switching. The input capacitor prevents this high frequency current from travelling back to the input voltage source, reducing conducted and radiated noise. The output capacitor prevents high frequency current to the load, in this case the LEDs, and also prevents conducted and radiated noise. The output capacitors also have a large effect on the boost regulator loop stability and transient response, and so are critical to optimal boost regulator operation.

Use ceramic input and output capacitors that keep their rated capacitance values at the expected operating voltages. The *"Typical Application Circuit"* on page 11 shows recommended values for and 10 LEDs and 60mA per string. Use a bulk electrolytic capacitor where power enters the circuit board.

9.9 Choosing the Inductor

The boost regulator inductor takes the current from the input source and directs that current to the load. Using the proper inductor is critical to proper boost regulator operation. Choose an inductor with sufficient inductance to keep the inductor ripple current within limits, and with sufficient current handling capability for steady-state and transient conditions.

The boost regulator switching causes ripple current through the inductor. The current rises during the on-time and falls during the off time. The slope of the inductor current is a function of the voltage across the inductor, and so the total change in current, Δ_{IL}, is the current slope multiplied by the time in that phase (on time, t_{ON}, or off time, t_{OFF}). In steady-state, where the load current, input voltage, and output voltage are all constant, the inductor current does not change over one cycle, and so the amount the current rises during the on time is the same as the amount the current drops during the off time. Calculate the duty cycle (equal to the on-time divided by the switching period) using:

$$D \approx \frac{V_{OUT} - V_{IN}}{V_{IN}}$$

where V_{OUT} is the output voltage and V_{IN} is the input voltage. Calculate the on-time in seconds using:

$$t_{ON} = \frac{D}{f_{SW}} = \frac{V_{OUT} - V_{IN}}{V_{OUT} \times f_{SW}},$$

where f_{SW} is the boost regulator switching frequency. Calculate the inductor ripple current using:

$$\Delta I_L = \frac{V_{IN} \times t_{ON}}{L} = \frac{V_{IN}[V_{OUT} - V_{IN}]}{V_{OUT} \times f_{SW} \times L}$$

where L is the inductance value in Henrys. Choose a value for L that produces a ripple current in the range of 25% to 50% of the steady state DC inductor current. The steady state DC inductor current is equal to the input current. Estimate the steady-state DC input current using:

$$I_{IN} \approx I_{LOAD} \times \left[\frac{V_{OUT}}{V_{IN}}\right],$$

where I_{LOAD} is the sum of all strings steady-state LED currents with all LEDs on simultaneously, V_{OUT} is the maximum (un-optimized) boost regulator output voltage, and VIN is the minimum boost regulator input voltage.

Inductors have two types of maximum current ratings, RMS current and saturation current. Make sure that the peak inductor current is less than the saturation current rating. Note that during load current transients, which occur whenever the LEDs are turned on or off (due to PWM dimming), the inductor current may overshoot its steady state value. How much it overshoots depends on the boost regulator loop dynamics. If unsure of the loop dynamics, a typical value to use for the overshoot is 50% of the steady-state current. Add half of the inductor ripple current to this value to determine the peak inductor current. With inductor ripple current in the 25% to 50% range, estimate the inductor RMS current as 115% of the DC steady state inductor current.

9.10 Setting the Current Limit

The current sense resistor, connected from the switching MOSFET source to GND, sets the boost regulator current limit. The cycle-by-cycle current limit turns-off the boost regulator switching MOSFET when the current sense input detects instantaneous current above the current limit threshold. This causes the current to drop until the end of the switching cycle. The current limit threshold is 100mV typical, and 75mV minimum. Choose the current sense resistor value to set the current limit using:

$$R_{CS} = \frac{0.111}{I_{L\,(MAX)}} \quad \Omega$$

where $I_{L(MAX)}$ is the maximum inductor current.

9.11 Choosing the Switching MOSFET

The MSL3086/88 use an external logic level MOSFET to implement the boost converter. Choose a MOSFET designed to pass twice at least the peak inductor current, and that has the lowest possible R_{DSon} while maintaining minimal gate charge for fast switching speed. Make sure that the MOSFET drain-source voltage rating is above the maximum un-optimized boost output voltage, with some extra margin for voltage overshoot due to excess circuit board stray inductance and output rectifier recovery artIfacts. Make sure that the MOSFET package can withstand the worst-case power dissipation while maintaining die temperature within the MOSFET ratings.

9.12 Choosing the Output Rectifier

The output rectifier passes the inductor current to the output capacitor and load during the switching off-time. Due to the high boost regulator switching frequency use a Schottky rectifier. Use a Schottky diode that has a current rating at least as high as that of the external MOSFET, and a voltage rating higher than the maximum boost regulator output voltage. Schottky rectifiers have very low on voltage and fast switching speed, however at high voltage and temperatures Schottky leakage current can be significant. Make sure that the rectifier power dissipation is within the rectifier specifications. Place the MOSFET and rectifier close together and as close to the output capacitor(s) as possible to reduce circuit board radiated emissions.

9.13 Loop Compensation

Use a series RC network from COMP to FB to compensate the MSL3086/88 regulation loop (Figure 8.1 on page 13). The regulation loop dynamics are sensitive to output capacitor and inductor values. To begin, determine the right-half-plane zero frequency:

$$f_{RHPZ} = \left[\frac{V_{IN}}{V_{OUT}}\right]^2 \times \left[\frac{R_{LOAD}}{2\pi L}\right]$$

where RLOAD is the minimum equivalent load resistor, or

$$R_{LOAD} = \frac{V_{OUT}}{I_{OUT(MAX)}}$$

The output capacitance and type of capacitor affect the regulation loop and method of compensation. In the case of ceramic capacitors the zero caused by the equivalent series resistance (ESR) is at such a high frequency that it is not of consequence. In the case of electrolytic or tantalum capacitors the ESR is significant, so must be considered when compensating the regulation loop. Determine the ESR zero frequency by the equation:

$$f_{ESRZ} = \frac{1}{2\pi \times ESR \times C_{OUT}}$$

where C_{OUT} is the value of the output capacitor, and ESR is the Equivalent Series Resistance of the output capacitor. Assure that the loop crossover frequency is at least 1/5th of the ESR zero frequency.

Next determine the desired crossover frequency as 1/5th of the lower of the ESR zero f_{ESRZ}, the right-half-plane zero f_{RHPZ} or the switching frequency fSW. The crossover frequency equation is:

$$f_C = \left[\frac{R_{COMP}}{R_{TOP}}\right] \times \left[\frac{R_{LOAD}}{11 \times R_{CS}}\right] \times \left[\frac{1}{2\pi \times R_{LOAD} \times C_{OUT}}\right]$$

where f_C is the crossover frequency, R_{TOP} is the top side voltage divider resistor (from the output voltage to FB), R_{COMP} is the resistor of the series RC compensation network. Rearranging the factors of this equation yields the solution for R_{COMP} as:

$$R_{COMP} = R_{TOP} \times 11 \times R_{CS} \times 2\pi \times f_C \times C_{OUT}$$

These equations are accurate if the compensation zero (formed by the compensation resistor R_{COMP} and the compensation capacitor C_{COMP}) happens at a lower frequency than crossover. Therefore the next step is to choose the compensation capacitor such that the compensation zero is 1/5th of the crossover frequency, or:

$$f_{COMPZ} = \frac{f_C}{5} = \frac{1}{2\pi \times R_{COMP} \times C_{COMP}}$$

Solving for C_{COMP}:

$$C_{COMP} = \frac{5}{2\pi \times R_{COMP} \times f_C}$$

Example:

As an example, set the maximum (un-optimized) output voltage to 39V, using voltage divider as follows:

R_{TOP} = 49.9k
R_{BOTTOM} = 3.40k

Let the load current be 800mA maximum, use 10µH inductor, a 20µF output capacitor, a 12V input voltage, a 0.25Ω R_{CS}, and the switching frequency is 625kHz.

$$R_{LOAD} = \frac{V_{OUT}}{I_{LOAD}} = \frac{39V}{0.8A} = 48.75\Omega$$

$$f_{RHPZ} = \left[\frac{V_{IN}}{V_{OUT}}\right]^2 \times \left[\frac{R_{LOAD}}{2\pi L}\right] = \left[\frac{12}{39}\right]^2 \times \left[\frac{48.75}{2\pi \times (10 \times 10^{-6})}\right] \approx 73kHz$$

Set the crossover frequency to 1/5th f_{RHPZ}:

$$f_C = \frac{f_{RHPZ}}{5} \approx 14.6kHz$$

Next calculate the compensation resistor value to achieve the 15kHz crossover frequency, or

$$R_{COMP} = R_{TOP} \times 11 \times R_{CS} \times 2\pi \times f_C \times C_{OUT} = 49.9k \times 11 \times .025 \times 2\pi \times 15k \times 20\mu F \approx 25.9k\Omega$$

Then calculate the compensation capacitor, C_{COMP}, to set the compensation zero to 1/5th of the crossover frequency, or 3kHz

$$C_{COMP} = \frac{1}{2\pi \times R_{COMP} \times f_{COMPZ}} = \frac{1}{2\pi \times 25k \times 3k} \approx 2.1nF$$

When laying out the circuit board, place the voltage divider resistors and compensation resistor/capacitors as close to the MSL3086/88 as possible and minimize trace lengths connected to COMP and FB.

10.0 LED Dimming Control

10.1 External and I²C Control of LED Brightness

Control MSL3086 LED brightness using Pulse Width Modulation (PWM) with a PWM signal applied to the external PWM input. The PWM dimming signals (outputs) take the frequency and duty cycle of the input signal but are staggered in time so that they start at evenly spaced intervals relative to the PWM input signal. When one or more strings are disabled by fault response, the stagger delays automatically re-calculate for the remaining enabled strings.

The MSL3088 accepts two input signals, SYNC and PWM. SYNC provides the frequency information for the PWM dimming, and PWM provides the duty cycle information. The LED PWM dimming signals are staggered based on the frequency at SYNC.
For all devices, use PWM and SYNC inputs frequency between 20Hz and 50kHz and duty cycle between 0% and 100% (avoid duty cycles above 99.97% and less than 100%).

Additionally, internal registers accessed using the I2C compatible serial interface allow control of the PWM dimming frequency and duty cycle. For programming details see the MSL3040/50/60/80/86/87/88/89 Programming Guide.

10.2 Phase Shifted LED Dimming Signals

By default, string PWM dimming is staggered in time to reduce the transient current demand on the boost regulator. The MSL3086/88 automatically determine the stagger times based on the number of enabled strings and the PWM dimming frequency.

11.0 Ordering Information

Table 11.1 Ordering Information

PART	DESCRIPTION	PKG
MSL3086-IU	8-CH LED driver with integrated boost controller and resistor based LED Short Circuit threshold setting.	24 pin 4 x 4 x 0.75mm VQFN
MSL3088-IU	8-CH LED driver with integrated boost and SYNC input.	

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