



High Power LED Temperature and PWM Controller with LED-Sense™ In-Situ LED T_j Sensing

FEATURES

- High temperature LED current de-rating and thermal control using the LED-Sense™ algorithm that directly monitors LED T_{junction}
- No external thermal sensor is required
- Up to three temperature sensing and control channels on LDS9003 supports multi-point thermal monitoring or multi-color LED applications; LDS9001 is a single channel
- Programmable Temp vs. PWM Duty Cycle profiles (3 for LDS9003; 1 for LDS9001)
- Integrated PWM for dimming control of high brightness (HB) LED Drivers in logarithmic duty cycle steps from 0% to 100% (~ 0.17 dB / step)
- PWM Dimming Control range of 256:1
- I²C compatible serial programming interface
- Interfaces to available high side HB LED drivers and low cost microcontrollers
- LDS9003 is available in a small footprint 3 mm x 3 mm² 16-pin TQFN
- LDS9001 is in a 3 x 2 mm² 8-pin DFN

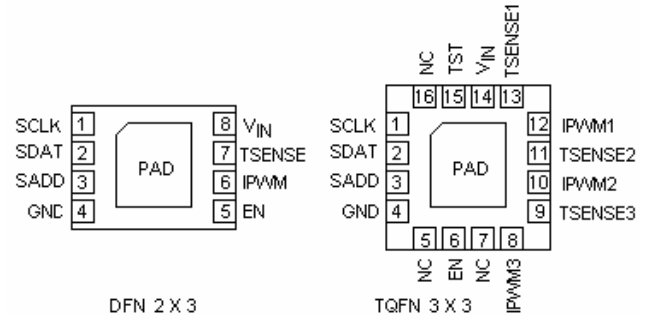
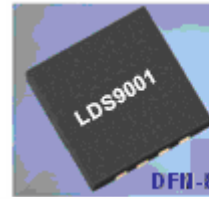
APPLICATIONS

- HB LED General Illumination Lighting
- Automotive LED Lighting
- Architectural LED Lighting

DESCRIPTION

The LDS9003 is a 3-channel and LDS9001 is a 1-channel LED junction temperature monitor and control device intended for use in high power LED solid state lighting applications. It connects directly to a LED anode and the PWM input of available high power HB drivers to real-time adjust LED current to meet maximum LED temperature. A two wire I²C interface allows communication to a local low cost microcontroller or other remote host processor device.

LDS9003 / 9001 can improve thermal management of high power LED systems by controlling reliable LED junction temperature levels to meet maximum operating lifetimes. In addition, it can reduce cost by allowing operation at optimal LED current/luminance levels minimizing the number HB LED lamps per fixture required to meet illumination targets.



The LDS9003/9001 utilizes the LED-Sense™ sensing and control algorithm that directly measures the LED junction and controls the temperature by closed loop adjustment of the LED Driver current via PWM duty cycle corrections.

The control loop real-time adjusts the LED current via PWM correction codes in user programmed Look up Tables (LUTs) assigned to each sensing channel. The user programs desired correction profiles for every 5°C increment from -35°C to 120°C. A single sensing channel and correction LUT is available in the LDS900, whereas three correction profiles are available in LDS9003 to support multi-point temperature sensing or multi-color LED applications.

Integrated PWM generators support dimming and LED temperature vs. current compensation. The PWM duty cycle is programmable via the I²C serial interface from 0% to 100%. User-programmed 8-bit codes are converted to 12-bit logarithmic steps of ~ 0.17 dB per step. The PWM frequency is ~280 Hz to minimize noise generation.

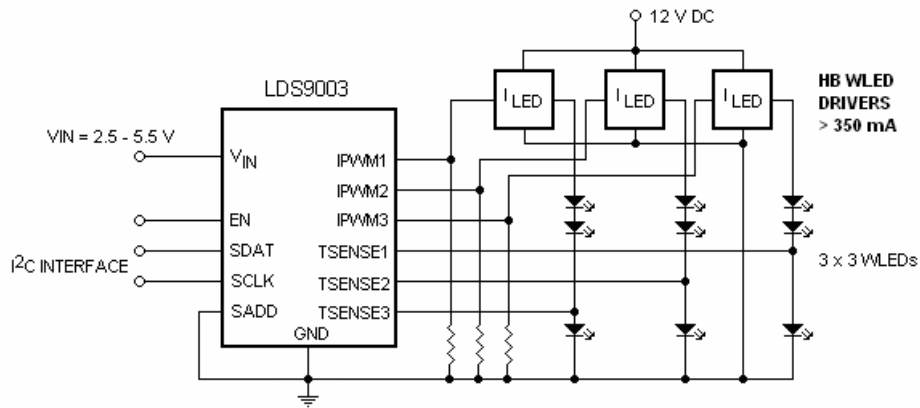
The EN logic input functions as a chip enable. A logic HIGH applied at the EN pin allows the LDS9003 / LDS9001 to respond to I²C communications. An optional external serial interface address pin is available for use in multi-target applications.

The device operates from 2.5 to 5.5V.

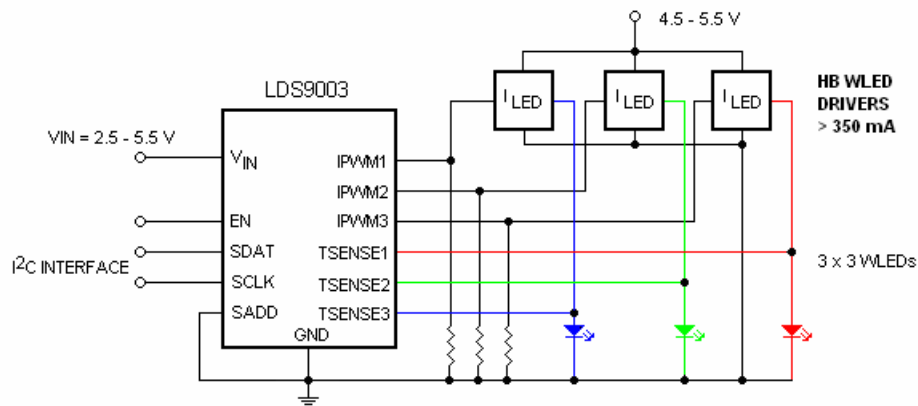
The LDS9001 is available in an 8-lead 3 x 2 mm² DFN package. The LDS9003 is in a 16-lead 3 x 3 mm² TQFN package.

TYPICAL APPLICATION CIRCUITS

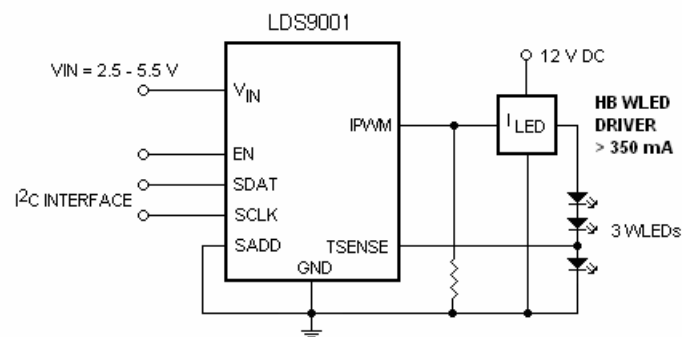
Using LDS9003 for 3 x 3 series WLEDs



Using LDS9003 for HB RGB for Projector



Using LDS9001 for series WLEDs



ABSOLUTE MAXIMUM RATINGS

Parameter		Rating	Unit
V _{IN} , IPWMX, TSENSE _x		6	V
EN, SDAT, SCLK, SADD voltage		V _{IN} + 0.7V	V
Storage Temperature Range		-65 to +160	°C
Junction Temperature Range		-40 to +125	°C
Soldering Temperature		300	°C
ESD Protection Level	HBM	2	kV
	MM	200	V

RECOMMENDED OPERATING CONDITIONS

Parameter	Rating	Unit
V _{IN}	2.5 to 5.5	V
IPWM _x	1	mA
Junction Temperature Range	-40 to +125	°C

Typical application circuit with external components is shown on page 1.

ELECTRICAL OPERATING CHARACTERISTICS

(Over recommended operating conditions unless specified otherwise) V_{in} = 3.6V, C_{in} = 0.1 μF, EN = High, T_{AMB} = 25°C

Name		Conditions	Min	Typ	Max	Units	
IPWM _x Channel DC Current Level			0.8	1	1.2	mA	
Quiescent Current	EN = V _{IN}	Standby (no I ² C clock)	60	100	140	μA	
Shutdown Current		V _{EN} = 0V		0.5	1	μA	
PWM Frequency			240	285	320	Hz	
# of PWM duty cycle steps		Log Mode steps		256			
Minimum PWM On Time			10	13.7	20	μs	
PWM resolution		Log Mode		12		bits	
PWM Step Size		Log Mode		0.17		dB/step	
# of ΔPWM Steps for current adjust		1-x Scale Mode	-7		0	PWM Steps/5°C	
		2-x Scale Mode	-14		0		
Temperature Compensation Adjust Steps				5		°C	
EN Pin	Input current		Active mode, EN = V _{IN}		-1	1	μA
	Logic Level	High	Active Mode or Normal		1.2		V
		Low	Standby Mode			0.4	
Thermal Shutdown				150		°C	
Thermal Hysteresis				20			
Wake-up/Shutdown Delay Time from EN		Soft ramp disabled		10		ms	
Raising/Falling Edge		Soft ramp enabled		250		ms	

I²C CHARACTERISTICS

Over recommended operating conditions unless otherwise specified for $2.5 \leq V_{IN} \leq 5.5V$, over full ambient temperature range -40 to $+85^{\circ}C$.

Symbol	Parameter	Min	Max	Unit
f_{SCL}	SCL Clock Frequency	0	400	kHz
$t_{HD:STA}$	Hold Time (repeated) START condition	0.6		μs
t_{LOW}	LOW period of the SCL clock	1.3		μs
t_{HIGH}	HIGH period of the SCL clock	0.6		μs
$t_{SU:STA}$	Set-up Time for a repeated START condition	0.6		μs
$t_{HD:DAT}$	Data In Hold Time	0	0.9	ns
$t_{SU:DAT}$	Data In Set-up Time	100		ns
t_R	Rise Time of both SDAT and SCLK signals		300	ns
t_F	Fall Time of both SDAT and SCLK signals		300	ns
$t_{SU:STO}$	Set-up Time for STOP condition	0.6		μs
t_{BUF}	Bus Free Time between a STOP and START condition	1.3		μs
t_{AA}	SCLK Low to SDAT Data Out and ACK Out		0.9	μs
t_{DH}	Data Out Hold Time	300		ns

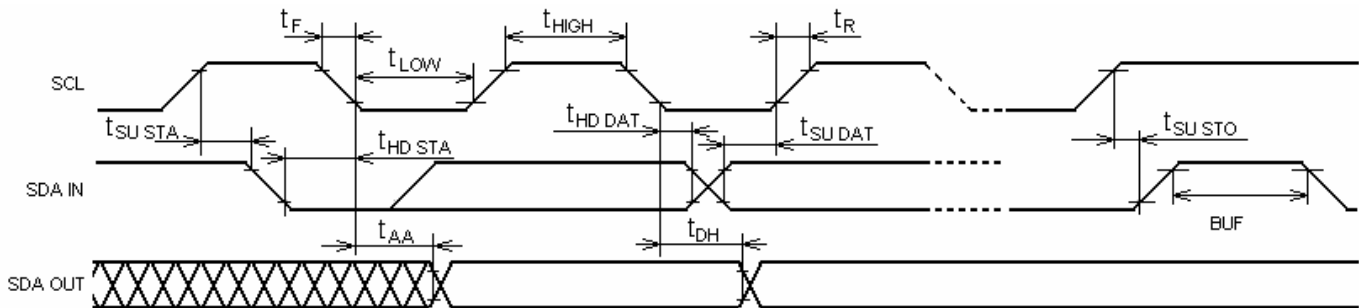
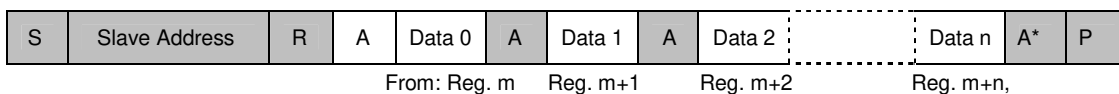


Figure 1: I²C Bus Timing Diagram

READ OPERATION:

Option 1: Standard protocol sequential read:



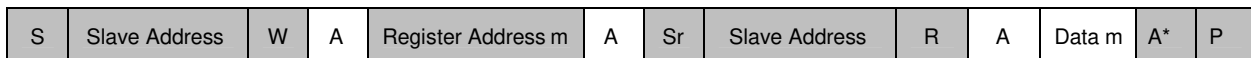
where Reg. m is the last addressed in the write operation register

Option 2: Random access:



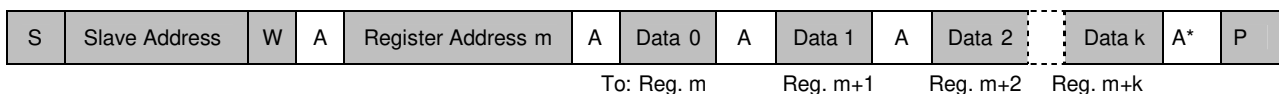
From reg. m, where Reg. m is the last addressed in the write operation register

Option 3: Random access with combined (extended) protocol:

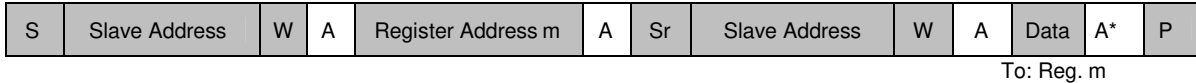


WRITE OPERATION:

Option 1: Standard protocol sequential write:



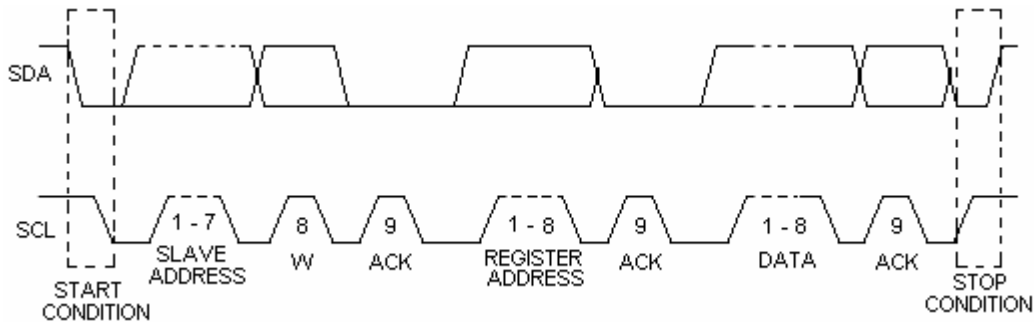
Option 2: Combined (extended) protocol:



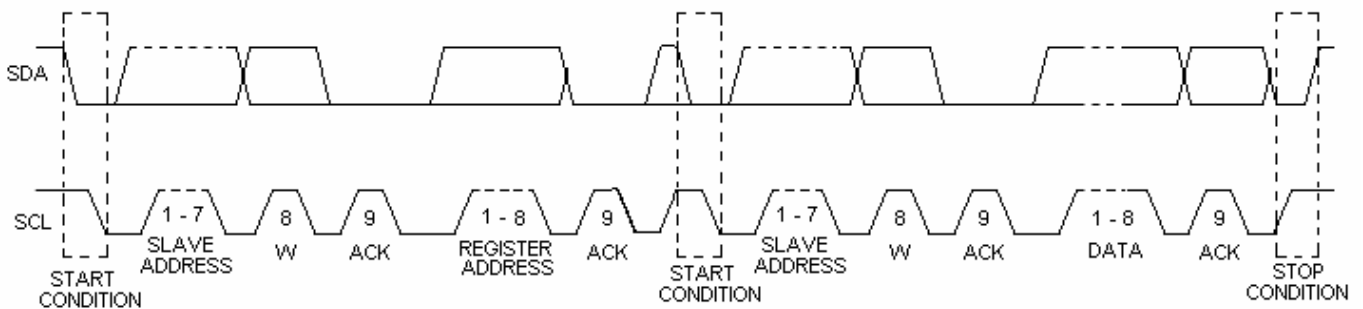
- S: Start Condition
- Sr Start Repeat Condition
- R, W: Read bit (1), Write bit (0)
- A: Acknowledge (SDAT high)
- A*: Not Acknowledge (SDAT low)
- P: Stop Condition
- Slave Address: Device address 7 bits (MSB first).
- Register Address: Device register address 8 bits
- Data: Data to read or write 8 bits
- send by master
- send by slave

I²C BUS PROTOCOL

Standard protocol



Combined protocol:

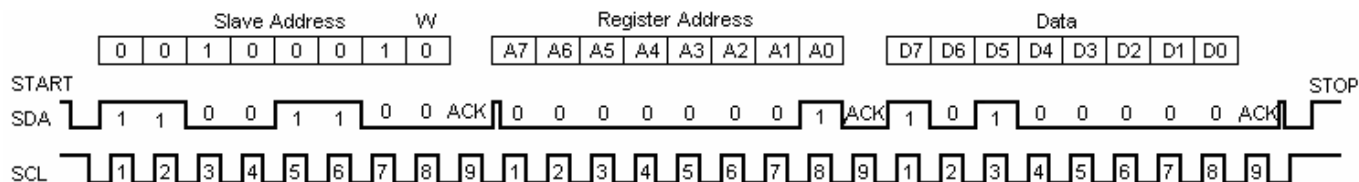


WRITE INSTRUCTION SEQUENCE

Standard protocol:



Write Instruction Example - Setting 20mA Current in LEDB1 and LEDB2



LDS9003 / 9001 REGISTERS DEFINITION AND PROGRAMMING

Note: Unlisted register addresses are for factory use only; For proper operation write only to registers defined.

ADDRESS	DESCRIPTION	BITS	NOTES
00h	IPWM1 Current setting IPWM (9001)	8	User Loads code 08h (8 decimal) for 1 mA peak current For PWM control current output. This is only valid user code.
01h	IPWM2 Current setting (Not used for 9001)	8	
02h	IPWM3 Current setting (Not used for 9001)	8	
03h	IPWMx and TSENSEx Channel Enable	6	User loads 2Ah for 9003. User loads 02h for 9001.
04h	Global PWM Dimming	8	Log mode: (default) Simultaneously decreases PWM duty cycle for IPWMx Data Code 00h = 0 dB dimming, FEh = - 72 dB FFh = OFF Example: 50% brightness reduction (- 6dB) requires: - 6dB / - 0.17dB = 35 (decimal) = 23h steps Linear Mode: Simultaneously decreases I _{LED} in banks A – C by subtracting Global Dimming Code (Reg04h data) from PWM Duty Cycle Code (Reg05h – Reg07h data) Data Code 00h = 0 dimming, If Global Dimming Code is equal or exceeds PWM Duty Cycle Code, I _{LED} = 0 mA.
05h	IPWM1 User Duty Cycle IPWM (9001)	8	Log Mode: ~ - 0.17dB dimming per LSB for currents > 300 μA; Refer to 8 to 12 bit conversion curve (Figure 3 and Table 10) for resolution in range 0 – 300 μA Data Code 00h = 0% Duty Cycle, FFh = 100% Duty Cycle Example: 50% brightness reduction (- 6dB) requires: 255 – (- 6 dB / - 0.17 dB) = 255 – 35 = 220 (decimal) = DCh steps
06h	IPWM2 User Duty Cycle IPWM (9001)	8	Same as above for reg 05h
07h	IPWM3 User Duty Cycle IPWM (9001)	8	Same as above for reg 05h
19h	LED Diagnostics Test	8	See Table 2; Bit 5 = 1 sets user-initiated LED short/open diagnostic
1Ch	LED Faults Status (shorted to GND)	5	Bits from bit 5 to bit 0 represent LED status for sensed LEDs Bit =1 LED short to GND
1Dh	LED Faults Status (shorted to V _{IN} /open)	5	Bits from bit 5 to bit 0 represent LED status for sensed LEDs respectively. Bit = 1 represents LED shorted to V _{IN} /open
1Eh	Configuration register	8	See Table 3
1Fh	Software reset, Standby	8	See Table 4
49h	Ta-Tj Temperature Offset	8	Since LED junction temperature is measured, the values loaded here allow an offset to account for Tj – Ta gradient. This allows correction tables to be referenced to ~ Ta levels. Two 4 bit offsets value for the LED and the Si Diode; Bit [7:4] = Tj-Ta offset for the LEDs

ADDRESS	DESCRIPTION	BITS	NOTES
			Bit [3:0] = T _j -T _a offset for the Si diode. Typically should set both offsets to be equal. See Table 5 & 6
4Ah	LED Shutdown Temperature	5	Defines T-code, at which IPWMs channels are shut down (i.e. 0% duty cycle) per LED vendor reliability and de-rating specification (see Table 5); Factory default value = 11100 (bin) = 1Ch represents 105°C T _j
4Bh	2-x Table enable and breakpoint (T-code)	6	Bit 5 = 1 enables 2-x scale LUT ΔPWM code correction (de-rating) starting at the breakpoint set by T-code (bits 4:0) Bit 5 = 0 ; 1x scale (default) for entire temperature range Bit [4:0] defines T-code, where temperature de-rating starts, or where 2x scaling begins (see Table 6)
50h – 5Fh	Temp vs IPWM1 DC LUT -35C to 120C (one 5C step every nibble) (IPWM LUT for 9001) ΔPWM code1[7:4], ΔPWM code0[3:0] – ΔPWM code 31[7:4], ΔPWM code 30[3:0]	8	Two LUT words per 1°C address. Each word contains two 4-bit numbers representing of ΔPWM codes. See Table 6 and Appendix 1 for LUT programming.
60h – 6Fh	Temp vs IPWM2 DC LUT -35C to 120C (one 5C step every nibble) ΔPWM code1[7:4], ΔPWM code0[3:0] – ΔPWM code 31[7:4], ΔPWM code 30[3:0]	8	Same as above for regs 50h-5Fh Not used for 9001
70h – 7Fh	Temp vs IPWM3 DC LUT -35C to 120C (one 5C step every nibble) ΔPWM code1[7:4], ΔPWM code0[3:0] – ΔPWM code 31[7:4], ΔPWM code 30[3:0]	8	Same as above for regs 50h -5Fh Not used for 9001
A0h	Silicon diode dV _F /dT [7:0]	8	Silicon diode V_F temperature coefficient (K factor) : Factory recommended loaded value is 36h = -1.71 mV/°C = 001 10110 (bin), where bits from bit 7 to bit 5 represent integer part [1 (decimal) = 001 (bin)], and bits from bit 4 to bit 0 – fractional part [0.710 / 0.03125 = 22 (decimal) = 10110 (bin)]
A2h	LED1 dV _F /dT [7:0] (connected to TSENSE1; TSENSE for 9001)	8	User-loaded V _F temperature coefficient @ 1mA for LEDs used at TSENSE1 (TSENSE for 9001) Negative tracking is assumed with temperature; Bits from bit 7 to bit 5 represent integer part and bits from bit 4 to bit 0 - fractional part of the coefficient Example: Temperature coefficient = -2.26 mV/°C; Bit 7 – bit 6 = 2 (decimal) = 010 (bin), and Bit 4 – bit 0 = INT{0.26 / 0.03125} = 8 (decimal) = 01000 (bin) User loads 010 01000 (bin) = 48h = -2.25 (closest setting)
A4h	LED2 dV _F /dT [7:0] (connected to TSENSE2)	8	Same as above reg A2h Not used for 9001 \\

ADDRESS	DESCRIPTION	BITS	NOTES
A6h	LED3 dV_F/dT [7:0] (connected to TSENSE3)	8	Same as above for reg A2h Not used for 9001
C0h	Silicon diode η [7:0]	8	Silicon diode η (eta, or non-ideality factor): Factory recommended loaded value is default is 1.00 = 01000000(bin) = 40h Bits from bit 7 to bit 5 represent integer part and bits from bit 4 to bit 0 - fractional part (resolution = 0.015625 per LSB) Example: $\eta = 1.00$; Bit 7 – bit 6 = 1 (decimal) = 01 (bin), and Bit 5 – bit 0 = INT{0.00 / 0.015625} = 0 (dec) = 000000 (bin) User loads 01 000000 = 40h = 1.00
D4h	Silicon diode R_s offset [7:0]	8	Silicon diode series resistance offset Factory recommended loaded value = 04h = ~ 68 ohms Formula (decimal) = $8192 \times [(68 \text{ ohms} \times 8 \times 10^{-6} \text{ A}) / 1.14 \text{ V}]$
D6h	LED1 R_s offset [7:0]	8	LED R_s offset (user-loaded) for LED sensing channels 1, 2, and 3 for specific LEDs used User loads per LED used. (1/slope of high current region of LED I-V characteristic). Formula (decimal) = $8192 \times [(R_s \Omega \times 8 \times 10^{-4} \text{ A}) / 1.14 \text{ V}]$
D8h	LED2 R_s offset [7:0] (not used for 9001)	8	Same as above for reg D6h. Not use for 9001
DAh	LED2 R_s offset [7:0] (not used for 9001)	8	Same as above for reg D6h. Not used for 9001

Table 1

Register Address	Channel Enable Register							
	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
03h (9003)	LED OT Flag	N/A	1	0	1	0	1	0
(9001)	Same	N/A	0	0	0	0	1	0

Note: User must load shown values upon “boot” or after reset; all POR bit values are 0

Table 2

Register Address	Digital Test Modes Register							
	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
19h	Factory Only	Factory Only	Diagnostics Request	Slow Ramp Bypass = 1	Fast PWM adjust = 1	Factory Only	Post ADC Filter Enable = 1	Factory Only
	0*	0*	0*	0*	Normal = 0*	0*	Filter Off=0*	0*

Note: *) Value by default

Table 3

Register Address	Configuration Register							
	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
1Eh (9003)	1	0	0	0	1	0	0	0
1Eh (9001)	0	0	0	0	0	0	0	0

Note: User must load shown values upon “boot” or after reset; all POR bit values are 0

Table 4

Register Address	Control Register							
	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
1Fh	Software reset = 1	Standby mode = 1	Temperature request = 1	Calibration request = 1	Custom OSC trim = 1	Osc trim 2 **	Osc trim 1 **	Osc trim 0 **
	Normal operation = 0*	Normal operation = 0*	Normal operation = 0*	Normal operation = 0*	Factory preset value = 0*			

Note: *) Value by default
 **) Trim code defined by customer
 Bit 7 = 1 — Software reset: resets device, all registers reset/cleared.
 Bit 6 = 1 — Standby (oscillator disabled, all registers retain programmed values.)

Table 5: Ta-Tj Temperature Gradient Offset

(set offset code to match reference De-rate point in LUT from LED Tj to Ta. Typically LED and Si are equal)

Register Address	Control Register							
	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
49h	LED Offset 3	LED Offset 2	LED Offset 1	LED Offset 0	Si Diode Offset 3	Si Diode Offset 2	Si Diode Offset 1	Si Diode Offset 0
	0*	0*	0*	0*	0*	0*	0*	0*

Note: *) Value by default

Table 6: Offset Codes for Tj-Ta Temperature Gradient Offset (both LED and Si per Table 5).

Temperature Offset °C (Ta-Tj)	Bit3– Bit 0	Temperature Offset °C (Ta-Tj)	Bit3– Bit 0	Temperature Offset °C (Ta-Tj)	Bit3– Bit 0	Temperature Offset °C (Ta-Tj)	Bit3– Bit 0
-40	1000	-20	1100	0	0000	20	0100
-35	1001	-15	1101	5	0001	25	0101
-30	1010	-10	1110	10	0010	30	0110
-25	1011	-5	1111	15	0011	35	0111

Table 7: T-code values vs. Temperature (for registers 4Ah and 4Bh)

Temperature, °C	Bit4 – Bit 0	Temperature, °C	Bit4 – Bit 0	Temperature, °C	Bit4 – Bit 0	Temperature, °C	Bit4 – Bit 0
-35	00000	5	01000	45	10000	85	11000
-30	00001	10	01001	50	10001	90	11001
-25	00010	15	01010	55	10010	95	11010
-20	00011	20	01011	60	10011	100	11011
-15	00101	25	01100	65	10100	105	11100
-10	00101	30	01101	70	10101	110	11101
-5	00110	35	01110	75	10110	115	11110
0	00111	40	01111	80	10111	120	11111

Table 8: ΔPWM CorrectionCode Allocation

Register Address	Data bits		Register Address	Data bits	
	7 – 4	3 – 0		7 – 4	3 – 0
	ΔPWM code for temperature, °C			ΔPWM code for temperature, °C	
50h, 60h, 70h	-30	-35	58h, 68h, 78h	50	45
51h, 61h, 71h	-20	-25	59h, 69h, 79h	60	55
52h, 62h, 72h	-10	-15	5Ah, 6Ah, 7Ah	70	65
53h, 63h, 73h	0	-5	5Bh, 6Bh, 7Bh	80	75
54h, 64h, 74h	10	5	5Ch, 6Ch, 7Ch	90	85
55h, 65h, 75h	20	15	5Dh, 6Dh, 7Dh	100	95
56h, 66h, 76h	30	25	5Eh, 6Eh, 7Eh	110	105
57h, 67h, 77h	40	35	5Fh, 6Fh, 7Fh	120	115

Table 9: ΔPWM Codes Codes vs. Number of Adjustment Steps

Number of steps	Binary Code	Number of steps	Binary Code	Number of steps	Binary Code	Number of steps	Binary Code
Not Valid	1000	-4	1100	0	0000	4	0100
-7	1001	-3	1101	1	0001	5	0101
-6	1010	-2	1110	2	0010	6	0110
-5	1011	-1	1111	3	0011	7	0111

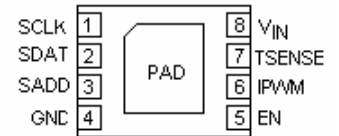
PROGRAMMING EXAMPLES

Operation	Register Address	Register Data	Command (hex)
Disable Temperature De-rating (DT Adjust disable)	1Eh	04h	XX 1E 04
Re-Enable Temperature De-rating	1Eh	00h	XX 1E 00
Short/open LED diagnostic request	19h	20h	XX 19 20
Read out LED short to GND status	1Ch		XX 1C YY
Read out LED short to V _{IN} /open status	1Dh		XX 1D YY
Set Standby Mode	1Fh	40h	XX 1F 40
Resume normal operation from standby mode	1Fh	00h	XX 1F 00
Calibration request (conduct temperature calibration)	1Fh	10h	XX 1F 10
Set LEDs in shutdown mode at junction temperature above 100°C	4Ah	1Bh	XX 4A 1B
Set Ta-Tj offset for LED and Si Diode to -20°C	49h	CCh	XX 49 CC
Software Reset (to default values) and/or clear of all registers	1Fh	80h	XX 1F 80

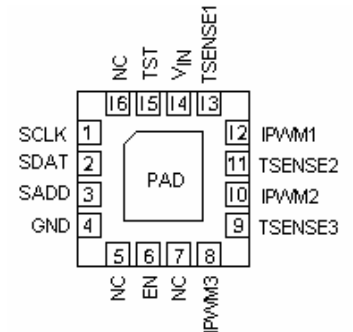
Note: XX – The LD9003/9001 I²C customer-selected slave address followed by binary 1 for write command, i.e. if I²C slave address is 001 0001 (see Table 8), XX = 0010 0011 (bin) = 23h
 YY – The 90003/9001 I²C customer-selected slave address followed by binary 0 for read command, i.e. if I²C slave address is 001 0001 (see Table 8), YY = 0010 0010 (bin) = 22h

PIN DESCRIPTION

Pin #	Name LDS9001	Name LDS9003	Function
1	SCLK	SCLK	I ² C Serial clock input
2	SDAT	SDAT	I ² C Serial data input/output
3	SADD	SADD	I ² C Serial interface Address Programming
4	GND	GND	Ground Reference
5	EN	NC	Not connect (no internal connect to the device)
6	TSENSE	EN	9001: LED Led-Sense for LED anode 9003: Device enable (active high)
7	IPWM	NC	9001: PWM current source output 1mA 9003: NC
8	VIN	IPWM3	9001: Power Source Input; connect to 2.5V-5.5Vdc 9003: PWM3 current source output 1mA
9		TSENSE3	LED-Sense input for LED3 anode
10		IPWM2	PWM3 current source output 1mA
11		TSENSE2	LED-Sense input for LED2 anode
12		IPWM1	PWM1 current source output 1mA
13		TSENSE1	LED-Sense input for LED1 anode
14		V _{IN}	Power Source Input; connect to 2.5-5.5Vdc
15		TST	Not connected by user; leave floating Factory Test pin
16		NC	Not connect (no internal connect to the device)
PAD		PAD	Connect to GND on the PCB



Top View :
DFN 8-Lead 3 x 2 mm²



Top View :
TQFN 16-Lead 3 x 3 mm²

PIN FUNCTION

V_{IN} is the supply pin. The operating input voltage range is from 2.5 V to 5.5 V.

EN is the enable input for the entire device. Guaranteed levels of logic high and logic low are set at 1.3 V and 0.4V respectively. When EN is initially taken high, the device becomes enabled and may communicate through I²C interface

SDAT is the I²C serial data line. This is a bidirectional line allowing data to be written into and read from internal registers.

SCLK is the I²C serial clock input.

SADD is I²C Serial interface Addresses tie to either GND or VIN pin to allow choice of two slave addresses. Allows two 9003 or 9001 on same control bus for optional increased LED-Sense™ point monitoring control

GND is the ground reference for internal circuitry. The pin must be connected to the ground plane on the PCB.

TSENSE1, TSENSE2, TSENSE3 (LDS9003) and **TSENSE** (LDS9001) are the LED-Sense™ temperature sensing pins for the LEDs. These connect to the LED anodes. These pins force currents of 1mA and 200ua and measure voltages for calculation of LED junction temperature. These pins enter high-impedance zero current state whenever the device is in shutdown mode.

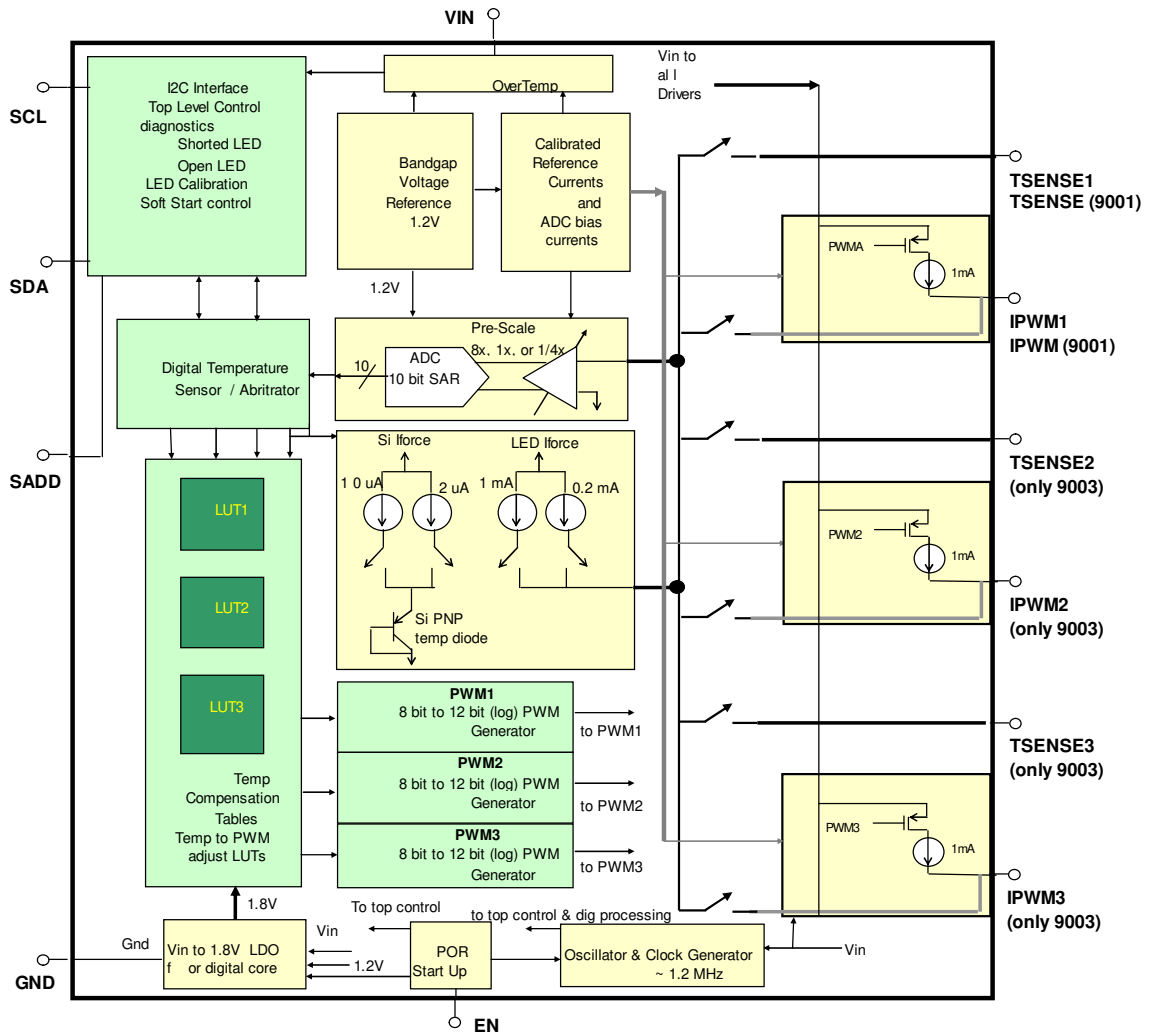
IPWM1, IPWM2, IPWM3 (LDS9003) and **IPWM** (LDS9001) are the PWM 1mA peak to GND current sources outputs for controlling PWM of external HB LED driver. User adds resistor to GND to generate desired PWM voltage range levels. These pins enter high-impedance zero current state whenever the device is in shutdown mode.

TST is a test pin used by factory only. Leave it floating (no external connection)

PAD is the exposed pad underneath the package. For best thermal performance, the tab should be soldered to the PCB and connected to the ground plane

BLOCK DIAGRAM

Figure 2: LDS9003 / 9001 Functional Block Diagram



BASIC OPERATION

The LDS9003/9001 may operate in the following modes:

- Normal Operation Mode
- Normal Standby Mode
- Programming Modes
- Shutdown Mode

NORMAL OPERATION MODE

At power-up, V_{IN} should be in the range from 2.5 V to 5.5 V (max). If V_{IN} is slow rising, EN pin should be logic LOW at least until V_{IN} reaches a 2.5 V level.

When EN is taken HIGH, a soft-start power-up sequence begins and performs an internal circuits reset that requires less than 100 μ s.

An initialization sequence then begins, taking less than 10 ms. This sequence determines the user-selected I²C slave address and loads factory programmed settings

At this point, the I²C interface is ready for communication and the LDS9003 / 9001 may be user-programmed. Upon programming completion for all required initial "boot" parameters a calibration command is given by setting bit 4 of the Control Register (1Fh) HIGH. This starts the calibration sequence of the LDS9003 / 9001 LED-Sense™ temperature sensing and measurement circuits and occurs simultaneous with a gradual ramp-up of the PWMs and current levels to the user programmed values. This initialization is completed in less than 250 ms in the default soft-start ramp mode, or less than

10 ms with the soft-start ramp mode disabled by setting bit 1 of the Configuration Register (1Eh) HIGH.

The calibration parameters for the temperature measurement engine and all customer-set parameters remain intact until the part is reset or powered-down. Additionally, the user can recalibrate LDS9003 / 9001 during times when LED currents are brought to zero and the system is thermally stabilized by programming the calibration command bit as discussed.

Temperature vs PWM Duty Cycle Profiles

The user must load the PWM correction look up tables (LUTs) prior to operation. For the LDS9003 all three tables, LUT1, LUT2 and LUT3 require loading (even if using same data) with the user correction profiles prior to operation. The LDS9001 just requires loading of LUT1.

The correction tables are based upon LED vendor characteristics for illumination vs temperature and current, LED current de-rating specifications, and user system thermal design parameters. The following figures show examples for Luxeon Rebel WLEDs,

Figure 3: Typical Light Output vs Temperature for Luxeon Rebel 3W WLED

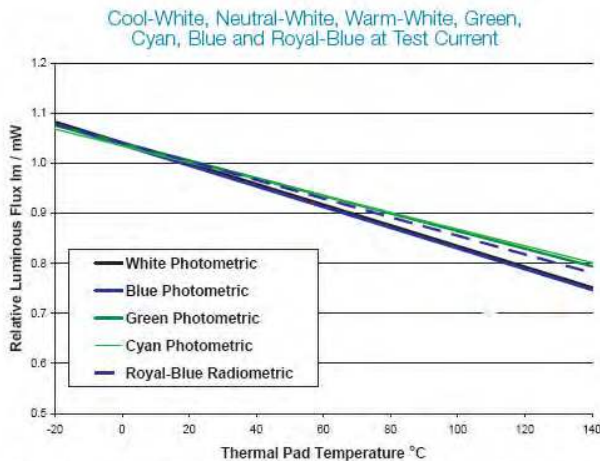


Figure 3. Relative light output vs. Thermal Pad temperature for White, Green, Cyan, Blue and Royal-Blue.

Figure 3 shows the typical characteristic of decreasing illumination over temperature by approximately 30% from -20°C to 100°C.

Figure 4 shows that illumination is approximately linearly dependent with LED forward current. Therefore loss of illumination over temperature can be compensated by associated increases in LED current.

Figure 4: Typical Light Output vs LED Current for Luxeon Rebel WLED

Typical Relative Luminous Flux vs. Forward Current for Cool-White, Neutral-White, Warm-White, Green, Cyan, Blue and Royal-Blue, Thermal Pad Temperature = 25°C

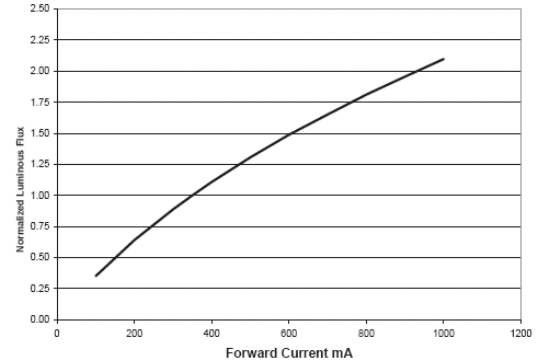
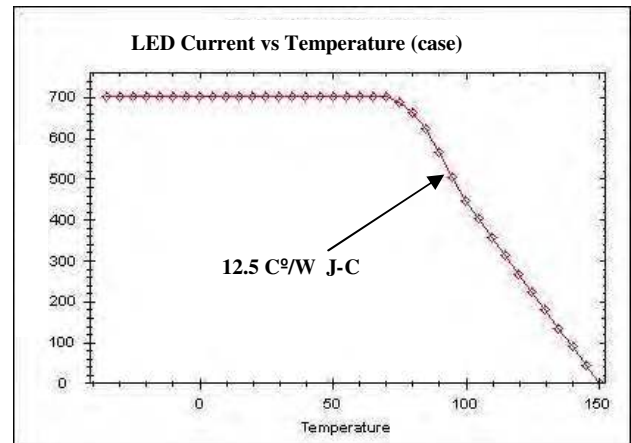


Figure 5 gives the LED current de-rating specification for a Luxeon Rebel WLED for 700mA LED current that insures not exceeding the maximum specified LED junction temperature of 150°C. This specific curve is for thermal resistance, Θ_{JC} , from LED junction to case designed for 12.5°C/W.

Figure 5: Typical LED Current De-rating vs Case Temperature for Luxeon Rebel WLED



It is customary for LED lighting systems to be designed with guard-bands to the operating level to account for design variations in the actual thermal profile and to maximize operating lifetimes. A user may target a lower maximum junction temperature than the absolute maximum rating specified by the LED vendor, such as 125°C, for example, as well as reducing the LED operating current=

The lower T_j guard-band will shift the curve to the right, extending maximum lifetime, but the lower operating current guard-banding results in more LEDs lamps per fixture to meet the desired lumen output level.

LED-Sense™ can eliminate the amount of operating current guard-banding as the direct measurement of the LED T_j reduces min to max thermal uncertainty.

Figure 6 shows a typical LDS9003 / 9001 PWM LUT correction profile that could be programmed by the user.

Given the 5°C increments of the temperature adjustment intervals for the LDS9003 / 9001, the currents are slowly ramped to equalize loss of light output before the de-rating profile begins. Once de-rating begins, the PWM duty cycle is reduced, lowering LED driver current, to insure meeting and regulating to the desired LED T_j.

Table 10 shows a simple text format of the correction table for the graph shown in Figure 6. Table 11 shows the exact data loaded to the LUTs' °C address locations as defined in Table 8.

Figure 6: Example LDS9003 / 9001 Accumulated PWM Correction Curve

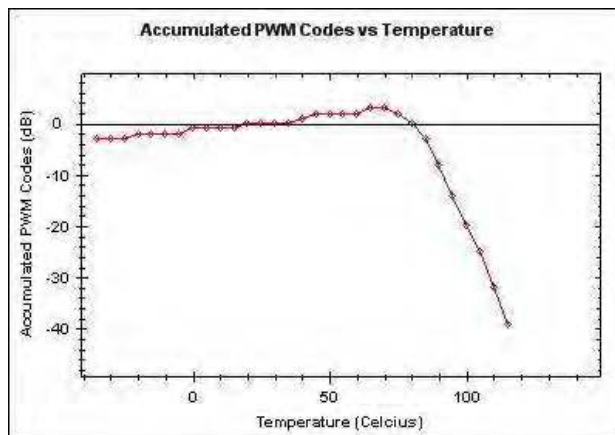


Table 10: PWM Correction Look Up Table Example (per graph)

Temp.	LUT1	LUT2	LUT3	Scale	Temp.	LUT1	LUT2	LUT3	Scale
-35	0	0	0	1	45	1	1	1	1
-30	0	0	0	1	50	0	0	0	1
-25	-1	-1	-1	1	55	0	0	0	1
-20	0	0	0	1	60	0	0	0	1
-15	0	0	0	1	65	1	1	1	1
-10	0	0	0	1	70	0	0	0	1
-5	-1	-1	-1	1	75	-1	-1	-1	1
0	0	0	0	1	80	-2	-2	-2	1
5	0	0	0	1	85	-3	-3	-3	1
10	0	0	0	1	90	-5	-5	-5	1
15	0	0	0	1	95	-6	-6	-6	1
20	-1	-1	-1	1	100	-6	-6	-6	1
25	0	0	0	1	105	-7	-7	-7	1
30	0	0	0	1	110	-7	-7	-7	1
35	0	0	0	1	115	-7	-7	-7	1
40	1	1	1	1	120	0	0	0	0

Note:

3 LUTs required for LDS9003 (can be same or different).

1 LUT only needed for LDS9001.

Table entries represent PWM correction steps change from the last temperature step point

Table is based on 25 °C reference point.

Steps are accumulated per this table as temperature increases or decreases.

If Scale = 1, each step is ~ 0.17 dB change in PWM duty cycle,

If Scale = 2, each step is ~ 0.34 dB change in PWM duty cycle,

The correction table stored in the correction LUT is referenced to the LED T_j. Register 49h can be used to apply the T_a-T_j temperature offset between the ambient (or case) and the LED junction temperature. This can effect a +/- shift of the correction curve in the Temperature axis to reference the profile to ambient or case temperature points.

Register 4Ah sets the LEDs' shutdown junction temperature per the T-codes provided in Table 7.

When this temperature is exceeded, all of the IPWM channels are disabled (i.e. 0% duty cycle) to insure no damage to the LEDs. Additionally, an LED OT (over temperature) status flag is set HIGH in Bit 7 of the enable channel register 03h. If the flag is set the user

can re-enable the channels by re-writing to the channel enable bits in register 03h, however the OT flag will still remain HIGH, until the device is power sequenced, reset, or placed in the shutdown mode.

If a Ta-Tj offset is used other than 00h (i.e. 0°C) in register, 49h, than the shutdown junction temperature loaded in 4Ah should also include this

offset. This insures the LED shutdown is also properly referenced to the same reference temperature level

IXYS can provide customers with software support to generate the LUT data tables. In addition, a separate applications report can be obtained. Please consult a sales representative or the factory to obtain.

Table 11: PWM LUT Register Load Example

LUT1		LUT2		LUT3	
Address (hex)	Data (hex)	Address (hex)	Data (hex)	Address (hex)	Data (hex)
50	00	60	00	70	00
51	0F	61	0F	71	0F
52	00	62	00	72	00
53	0F	63	0F	73	0F
54	00	64	00	74	00
55	0F	65	0F	75	0F
56	00	66	00	76	00
57	10	67	10	77	10
58	01	68	01	78	01
59	00	69	00	79	00
5A	01	6A	01	7A	01
5B	EF	6B	EF	7B	EF
5C	BD	6C	BD	7C	BD
5D	AA	6D	AA	7D	AA
5E	9B	6E	9B	7E	9B
5F	09	6F	09	7F	09

Recommended User Register Initialization

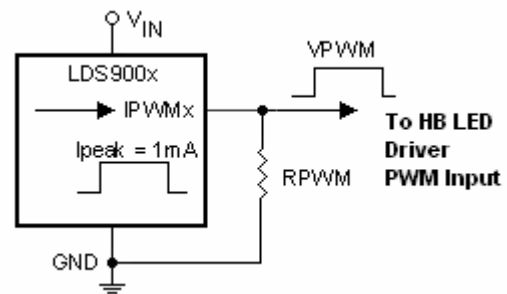
Table 12 is provided as a recommended user I²C register initialization and calibration sequence for the LDS9003 and LDS9001 respectively. Register load (i.e. write) steps marked with “*” mean LDS9001 steps, as well as LDS9003. Data value entries in **RED** indicate the data value is user / system dependent. Values shown for these registers are for example only.

IPWM Current Setting & Interface

IPWMx Current setting registers 00h – 02h should be programmed to 08h using the I²C interface to set the peak DC level current for the IPWM current source(s). This sets for 1mA ±5% DC current, and the LDS9003 LED-Sense™ configuration code 2Ah, or 02h for LDS9001, should be programmed using register 03h during initialization.

IPWMx are current source outputs. Users must connect an external resistor to GND from each output to establish the peak to peak PWM voltage level required by the HB LED driver. This is depicted in Figure 7.

Figure 7: Setting up PWM Voltage Level to HB LED Driver



Digital dimming using the internal PWM generator changes the duty cycle per the value set in registers 05h, 06h, and 07h and therefore adjusts the average LED current. This is referred to as dynamic mode.

For dynamic mode, the LDS9003/9001 integrates a digital PWM generator(s) that operates at a frequency of ~ 285 Hz. It operates in Logarithmic Mode. The PWM generator has 12-bit resolution and can be programmed with an 8-bit code to provide 256 internally mapped 12-bit logarithmic duty cycle steps to adjust the dimming level

Table 12: Recommended Register Load Sequence for LDS9003/9001

Reg Load Sequence #	Reg (hex)	Value (hex)	Comments
1*	1Eh	88h (9003) or 00h (9001)	Initialize Configuration Register
2*	00h	08h	IPWM1 current @ 1mA
3	01h	08h	IPWM2 current @ 1mA
4	02h	08h	IPWM3 current @ 1mA
5*	03h	A2h (9003) or 02h (9001)	Set up Led-sense configuration for 9003 & 9001
6*	04h	00h	Global PWM Dimming 00h is full ON = 100% DC
7*	05h	FBh	Duty Cycle code for IPWM1. Use set FBh=95% DC
8	06h	FBh	Same as reg 05h
9	07h	FBh	Same as reg 05h
10*	49h	00h	Ta-Tj Offset
11*	4Ah	1Eh	Set LED Shutdown temperature 1Eh = 120C
12*	4Bh	1Fh	Set optional 2x PWM adjust step start point; 1x scale below this point
13*	A0h	36h	Load Si Diode K factor for - 1.71mV/C
14*	A2h	User Loads Per LED Used	User loads LED K factor @ 1mA I _F . 4Bh = -2.3mV/C for Luxeon Rebel WLED
15	A4h	User Loads Per LED Used	User loads LED K factor @ 1mA I _F for LED1 4Bh = -2.3mV/C for Luxeon Rebel WLED
16	A6h	User Loads Per LED Used	User loads LED K factor @ 1mA I _F for LED2
17*	C0h	40h	Load Si Diode α factor = 1.0
18*	D4h	04h	Load Si Diode R _s = 68 ohms
19*	D6h	User Loads Per LED Used	User loads LED R _s for LED1 0Ah = 1.4 ohms for Luxeon Rebel WLED
20	D8h	User Loads Per LED Used	User loads LED R _s for LED2
21	DAh	User Loads Per LED Used	User loads LED R _s for LED3
22-47*	50h – 5Fh	User Loads Per LED Used	LUT1 correction Table
48-64	60h – 7Fh	User Loads Per LED Used	LUT2 correction Table
65-80	70h – 7Fh	User Loads Per LED Used	LUT3 correction Table
81*	1Fh	10h	User issues temp calibration command

The advantage of PWM dimming is stable LED color temperature / wavelength that is determined by the maximum static mode LED current value set by the external HB LED driver. The integrated PWM generator reduces the system requirement to provide a continuous pulsed waveform, and is automatically adjusted by the LED-Sense™ algorithm to maintain the programmed Temperature vs PWM DC thermal control profile.

To use the dynamic PWM mode for LED current setting, the maximum I_{LED} value should first be set by the HB LED Driver current setting resistor (per vendor specifications) and the desired dimming / user duty cycle can be set by registers 05h, 06h, and 07h.

The logarithmic operating mode provides a dimming resolution of approximately -0.17 dB per step with 0dB dimming (i.e. 100% duty cycle) at the 256th step

(i.e. FFh), and 0% duty cycle (~ -80 dB dimming) at 00h.

Figure 8 shows the dimming transfer function for dimming level in dB (from maximum level) vs programmed data code (decimal).

Figure 9 shows the dimming transfer function for dimming level in percent (%) vs programmed data code (decimal). 0% dimming is full ON brightness (i.e. PWM duty cycle = 100%).

Register 04h is available as a global dimming control register. It will simultaneously control all IPWM generators so is especially helpful in applications using the LDS9003. It is recommended that the user use registers 05h, 06h, and 07h to establish the desired duty cycle at ambient room temperature (i.e 25°C) conditions that account for further LED-Sense™ adjustment over temperature per the

programmed Temperature vs PWM thermal control profile. For example if the thermal control profile requires increasing the PWM duty cycle by 5% prior to de-rating to account for light output loss with temperature, then the User PWM registers 05h, 06h, and 07h should be programmed with maximum of code FBh for 95% duty cycle at room temperature.

Figure 8: Dynamic Mode Dimming in Logarithmic Mode in dB vs. register 05h, 06h and 07h data (0dB dimming = full LED brightness)

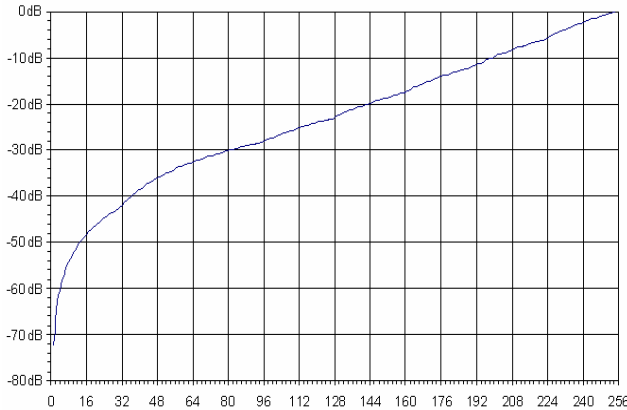
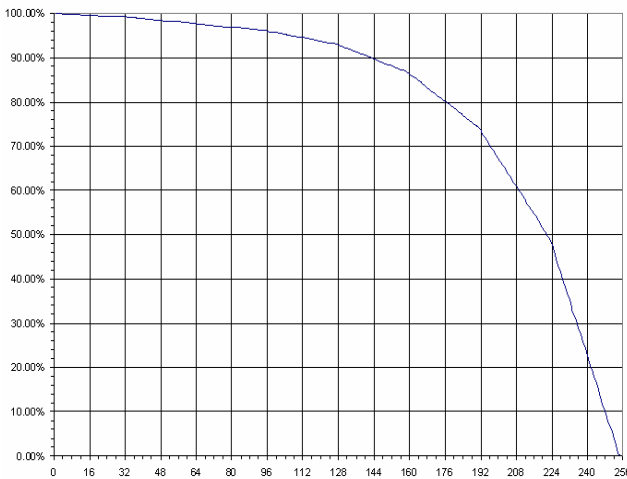


Figure 9: Dynamic Mode Dimming in Logarithmic Mode in percent vs. register 05h, 06h and 07h (0% dimming = full LED brightness)



Global PWM Dimming Control

Further dimming by the user to control real-time brightness, if desired, should then be done using the Global Dimming option by writing register 04h. Code 00h in this register represents no further dimming from the current level set by the user in the IPWM duty cycle registers 05h, 06h, and 07h.

The final dimming code value is the algebraic sum of three codes: the user Dynamic Dimming code, Global

Dimming Code, and the Temperature Compensation Code. If this sum is equal or below zero, LED in particular channel is limited to 0% duty cycle (i.e. the channel is OFF). It means that Global Dimming dynamic range is limited by Dynamic Dimming and Temperature Correction Table used.

As an example:

If Dynamic Dimming in the particular channel is set by -20 dB (registers 05h – 07h data code 143 (dec)) and Temperature Correction requires 8 steps dimming (data code 8 (dec)), the maximum allowable Global Dimming range = 143 – 8 = 135 (dec) steps or ~21.4 dB.

Figure 10 shows the dimming transfer function for dimming level in dB (from maximum level) vs programmed data code (decimal).

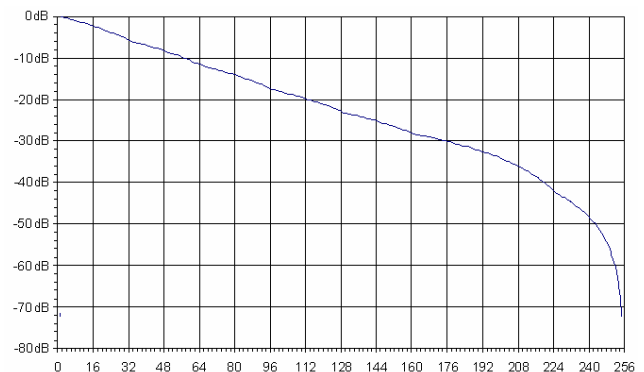
Figure 11 shows the dimming transfer function for dimming level in percent (%) vs programmed data code (decimal). 0% dimming is full ON brightness (i.e. PWM duty cycle = 100%).

LED-Sense™ High Temperature Current De-rating

The LDS9003/9001 integrates the IXYS LED-Sense™ temperature measurement and PWM current/duty cycle control algorithm to insure LED reliability and operating life-times.

LED current is controlled and de-rated via automatic adjustments in the PWM duty cycle to meet LED vendor power dissipation vs LED junction temperature specifications and system thermal constraints

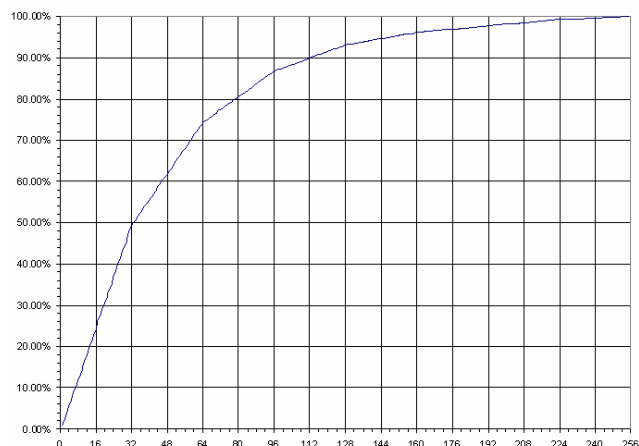
Figure 10: Global Dimming in Logarithmic Mode in dB vs. register 04h data (0dB dimming = full LED brightness)



User programmable de-rating adjustments are stored in a correction LUT(s) comprised of sixteen 8-bit registers each for up to three sensing and control channels (LDS9001 is only one channel). Registers

50h to 5Fh, 60h to 6Fh, and 70h to 7Fh store the correction profiles for LUT1, LUT2, and LUT3 respectively.

Figure 11: Global Dimming in Logarithmic Mode in percent vs. register 04h data (0% dimming = full LED brightness)



Each register stores a 4 bit adjustment code for two 5°C temperature steps in its lower (bits 3:0) and higher (bits 7:4) nibble. User loadable PWM correction codes in the 1x scale mode represent 0 to -7 PWM de-rating steps. In the 2 x scale mode the correction codes represent 0 to -14 PWM steps.

Additionally, the IPWM current sources are disabled (i.e. 0 DC current = 0% PWM duty cycle) if the measured LED junction temperature exceeds a preset value that is loaded in register 4Ah

The LED-Sense™ engine periodically measures the LED junction temperature on three TSENSEx channels (just TSENSE for LDS9001) and encodes the value into 5-bit T-codes representing 5°C temperature intervals from -35 to +120°C.

The measured T-code value addresses the stored ΔPWM correction codes stored in the LUT registers to adjust the PWM duty cycle. Therefore this reduces the average current through the LEDs as defined by the LUT table.

The user loads specific ΔPWM correction codes into the LUT(s) for every 5°C temperature step from -35°C to 120°C, as prior discussed, to meet desired current and power vs LED junction temperature.

LUT correction codes are subtracted from the user-set duty cycle/dimming code (dynamic mode) loaded in registers 05h, 06h, and 07h and the global dimming level code, if used, to maintain reliable LED current levels.

The LDS9003/9001 includes a 10-bit ADC and digital processing engine to determine LED temperatures

approximately every 2.5 seconds. The proprietary LED-Sense™ algorithm allows direct measurement of LED junction temperatures on the TSENSEx sensing channels, without the need for an external temperature sensor. Additionally an on-chip silicon temperature sensing diode is also measured to enhance temperature estimation accuracy.

I²C Interface

The LDS9003/9001 uses a 2-wire serial I²C-bus interface. The SDAT and SCLK lines comply with the I²C electrical specification and should be terminated with pull-up resistors to the logic voltage supply. When the bus is not used, both lines are high. The device supports a maximum bus speed of 400kbit/s. The serial bit sequence is shown at REGISTER DEFINITION AND PROGRAMMING section for read and write operations into the registers. Read and write instructions are initiated by the master controller/CPU and acknowledged by the slave LED driver.

The LDS9003/9001 allows user to choose between two I²C addresses by connecting SADD pin (#3) either to ground, or V_{IN} pin (see Table).

Table 13: LDS9003/9001 I²C Slave Addresses

SADD pin connected to	I ² C Address	
	Binary code	Hex
Ground	001 0001	11h
V _{IN}	101 0101	55h

For further details on the I²C protocol, please refer to the I²C-Bus Specification, document number 9398-393-40011, from Philips Semiconductors.

Over-Temperature Protection

If the die temperature exceeds +150°C, the driver will enter shutdown mode. The LDS9003/9001 requires restart after die temperature falls below 130°C.

OPTIONAL USE of EXTERNAL TEMPERATURE DIODE

The LDS9003/9001 also provides the option for using an external remote temperature-sensing diode device such as a 2N3904. To use this option the diode anode should be connected to the corresponding TSENSEx channel. The cathode should be connected to GND.

STANDBY MODE

The LDS9003/9001 has a “soft” standby or sleep mode, which the customer may set by I²C interface by addressing register 1Fh with bit 6 = 1 (see Table 4).

In Standby Mode, the I²C interface remains active and all registers retain their programmed information.

Further in Standby Mode the IPWMx current drivers and internal clock are powered off; however, internal regulators and reference circuits remain active to insure power to the digital sections to hold register values and maintain I²C interface communications.

This results in standby current ~ 100 μ A typical. For this mode, the EN pin should be logic HIGH with signal level from 1.3 to V_{IN} voltage.

SHUTDOWN MODE

To set LDS9003/9001 into the shutdown mode, the EN pin should be logic low more than 10 ms. The LDS9003/9001 shutdown current is less than 1 μ A.

The LDS9003/9001 wakes up from shutdown mode with factory-preset default data. To preserve customer-programmed data, use the standby mode.

PROGRAMMING MODES

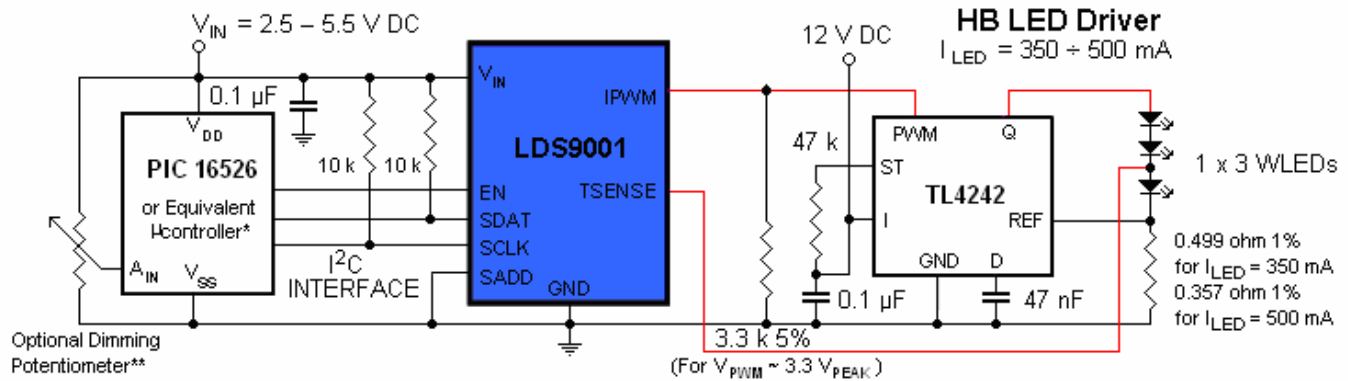
The LDS9003/9001 is factory pre-programmed with certain default POR levels to facilitate both factory testing and user operation. However, specific LEDs and other user system conditions require user programming of the temperature compensation LUTs and other LED specific parameters.

The loading of these registers can easily be conducted with a low cost "boot" type microcontroller having non-volatile memory to hold system and user parameters. 1K bits of non-volatile data storage is sufficient for the LDS9003. 256 bits is required for the LDS9001.

After initialization and user programming the user should conduct an I²C calibration sequence command by writing Bit 4 = 1 in the Control register 1Fh. This conducts a real time calibration of the initial starting temperature and actual LED parameters. Upon completion, Bit 4 will be internally reset to 0, and the LDS9003/9001 is ready for use.

DETAILED WLED LIGHTING SYSTEM APPLICATION

LDS9001 Monitoring / Controlling 3 Series WLEDs



μ Controller Requirements:

* Non-Volatile Memory for Program and Data Storage

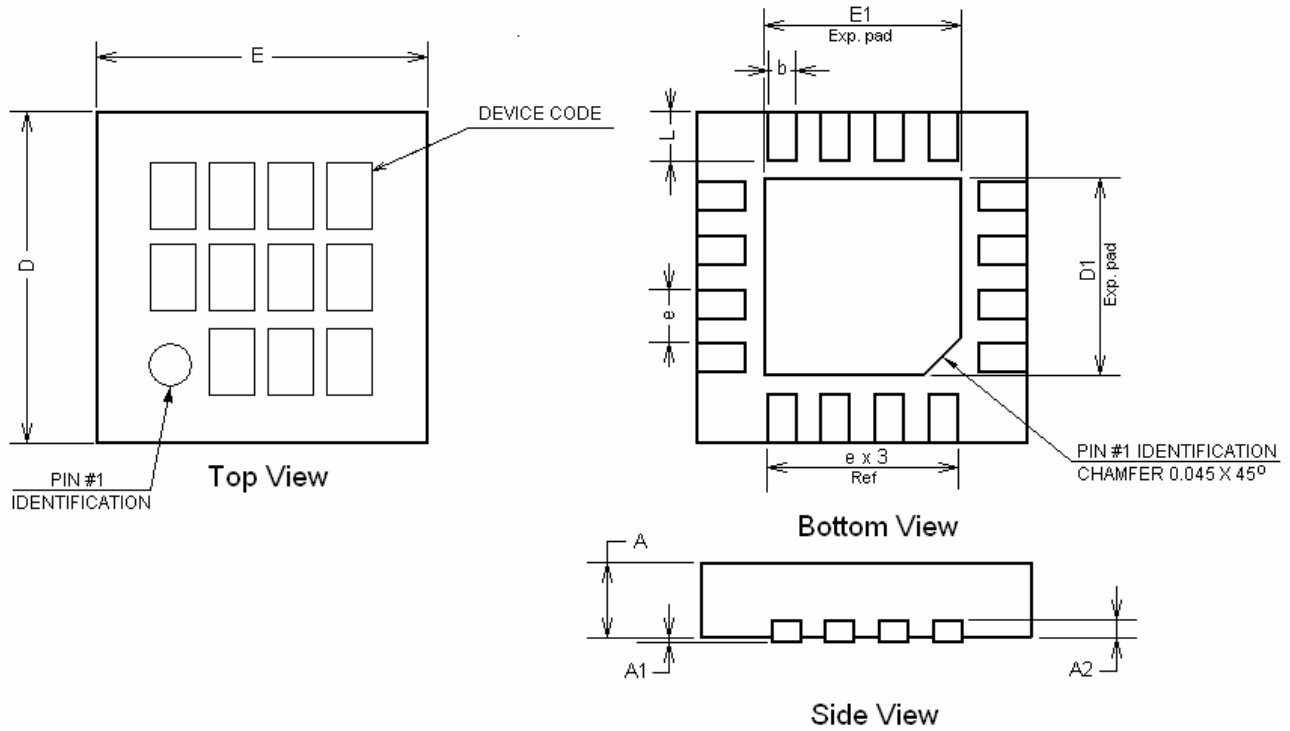
- 1K Bytes Program Memory Downloads Stored Calibration Parameters & Temperature Correction Curves Via I^2C to LDS9001
- 64 Bytes Data Memory Stores Calibration Parameters and Temp Correction Curves

** Eight Bit Integrated ADC (If Optional External Dimming Used)

- Polls Dimming Pot, Converts to Digital PWM Code & Transmit to LDS9001 via I^2C

PACKAGE DRAWING AND DIMENSIONS

16-PIN TQFN (HV3), 3mm x 3mm, 0.5mm PITCH



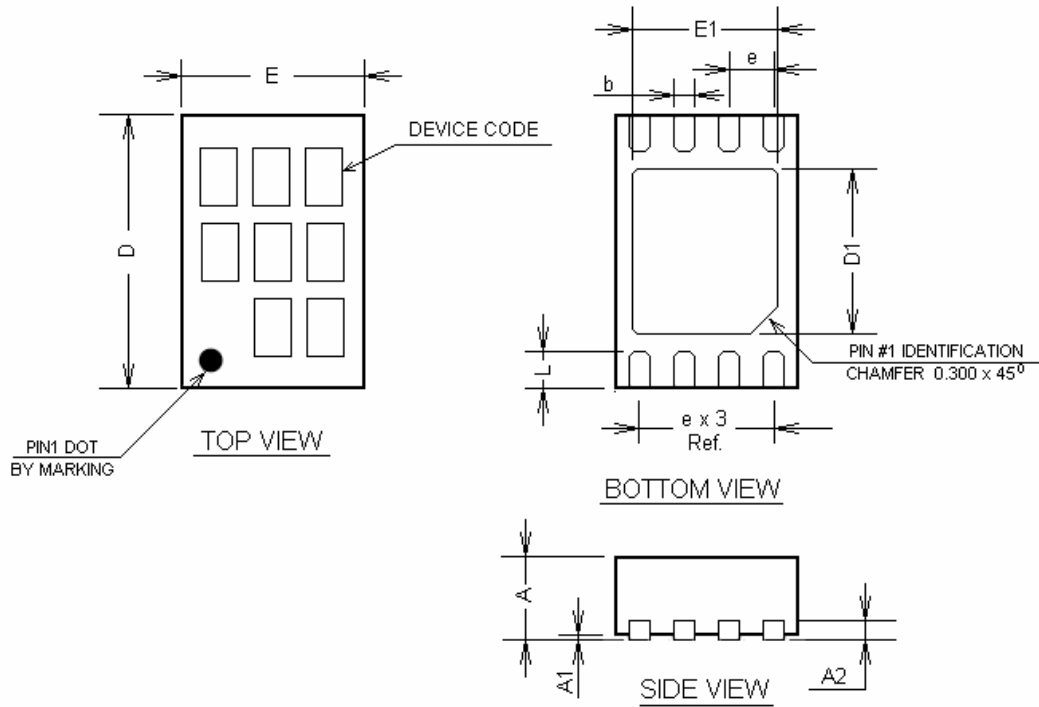
SYMBOL	MIN	NOM	MAX
A	0.70	0.75	0.80
A1	0.00	0.02	0.05
A2	0.178	0.203	0.228
b	0.20	0.25	0.30
D	2.95	3.00	3.05
D1	1.65	1.70	1.75
E	2.95	3.00	3.05
E1	1.65	1.70	1.75
e		0.50 typ	
L	0.325	0.375	0.425
m		0.150 typ	
n		0.225 typ	

Note:

1. All dimensions are in millimeters
2. Complies with JEDEC Standard MO-220

PACKAGE DRAWING AND DIMENSIONS

8-PIN TDFN, 2mm x 3mm, 0.5mm PITCH



SYMBOL	MIN	NOM	MAX
A	0.700	0.750	0.800
A1	-	0.000	0.050
A2		0.203 Ref.	
b	0.180	0.230	0.280
D	2.950	3.000	3.050
D1	1.750	1.800	1.850
E	1.950	2.000	2.050
E1	1.550	1.600	1.650
e		0.500 Bsc	
L	0.350	0.400	0.450

Note:

- All dimensions are in millimeters
- Complies with JEDEC Standard MO-220

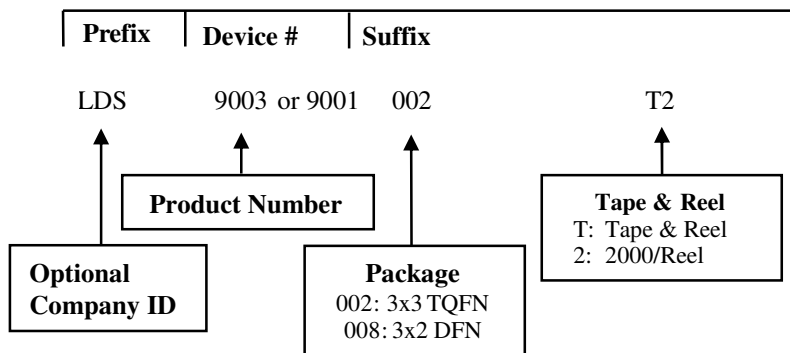
ORDERING INFORMATION

Part Number	Package	Package Marking
LDS9003 002-T2	TQFN-16 3 x 3 mm ⁽¹⁾	9003
LDS89001 008-T2	DFN-8 3 x 2 mm ⁽¹⁾	9001

Notes:

1. Matte-Tin Plated Finish (RoHS-compliant)
2. Quantity per reel is 2000

EXAMPLE OF ORDERING INFORMATION



Notes:

- 1) All packages are RoHS-compliant (Lead-free, Halogen-free).
- 2) The standard lead finish is Matte-Tin.
- 3) The device used in the above example is a LDS9003A 002-T2 (3x3 TQFN, Tape & Reel).
- 4) For additional package and temperature options, please contact your nearest IXYS Corp. Sales office.

Appendix 1

Table 14 Dynamic Mode Dimming in Logarithmic Mode vs. register 05h - 07h data

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
0	00		100	32	20	-41.9	99.19	64	40	-32.6	97.63
1	01	-72.3	99.98	33	21	-41.4	99.15	65	41	-32.4	97.58
2	02	-66.3	99.95	34	22	-40.9	99.10	66	42	-32.2	97.53
3	03	-62.8	99.93	35	23	-40.5	99.05	67	43	-32.1	97.49
4	04	-60.3	99.90	36	24	-40.1	99.00	68	44	-31.9	97.44
5	05	-58.3	99.88	37	25	-39.6	98.95	69	45	-31.7	97.39
6	06	-56.7	99.85	38	26	-39.2	98.90	70	46	-31.6	97.34
7	07	-55.4	99.83	39	27	-38.9	98.85	71	47	-31.4	97.29
8	08	-54.3	99.80	40	28	-38.5	98.80	72	48	-31.3	97.24
9	09	-53.2	99.78	41	29	-38.2	98.75	73	49	-31.1	97.19
10	0A	-52.3	99.76	42	2A	-37.8	98.71	74	4A	-30.9	97.14
11	0B	-51.5	99.73	43	2B	-37.5	98.66	75	4B	-30.8	97.09
12	0C	-50.7	99.71	44	2C	-37.2	98.61	76	4C	-30.7	97.05
13	0D	-50	99.68	45	2D	-36.9	98.56	77	4D	-30.5	97.00
14	0E	-49.4	99.66	46	2E	-36.6	98.51	78	4E	-30.4	96.95
15	0F	-48.8	99.63	47	2F	-36.3	98.46	79	4F	-30.2	96.90
16	10	-48.2	99.61	48	30	-36.1	98.41	80	50	-30.1	96.85
17	11	-47.7	99.58	49	31	-35.8	98.36	81	51	-30	96.80
18	12	-47.2	99.56	50	32	-35.5	98.32	82	52	-29.8	96.75
19	13	-46.7	99.54	51	33	-35.3	98.27	83	53	-29.7	96.70
20	14	-46.3	99.51	52	34	-35	98.22	84	54	-29.6	96.66
21	15	-45.9	99.49	53	35	-34.8	98.17	85	55	-29.5	96.61
22	16	-45.5	99.46	54	36	-34.6	98.12	86	56	-29.3	96.56
23	17	-45.1	99.44	55	37	-34.4	98.07	87	57	-29.2	96.51
24	18	-44.7	99.41	56	38	-34.1	98.02	88	58	-29.1	96.46
25	19	-44.4	99.39	57	39	-33.9	97.97	89	59	-29	96.41
26	1A	-44	99.37	58	3A	-33.7	97.92	90	5A	-28.8	96.36
27	1B	-43.7	99.34	59	3B	-33.5	97.88	91	5B	-28.7	96.31
28	1C	-43.4	99.32	60	3C	-33.3	97.83	92	5C	-28.6	96.26
29	1D	-43.1	99.29	61	3D	-33.1	97.78	93	5D	-28.5	96.22
30	1E	-42.8	99.27	62	3E	-32.9	97.73	94	5E	-28.4	96.17
31	1F	-42.5	99.24	63	3F	-32.8	97.68	95	5F	-28.3	96.12

Continued

Table 14 Dynamic Mode Dimming in Logarithmic Mode vs. register 05h – 07h data

Continue

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
96	60	-28.1	96.02	128	80	-22.9	92.80	160	A0	-17.4	86.35
97	61	-27.9	95.92	129	81	-22.7	92.60	161	A1	-17.1	85.96
98	62	-27.7	95.83	130	82	-22.5	92.41	162	A2	-16.9	85.57
99	63	-27.5	95.73	131	83	-22.2	92.21	163	A3	-16.6	85.18
100	64	-27.3	95.63	132	84	-22	92.02	164	A4	-16.4	84.79
101	65	-27.1	95.53	133	85	-21.8	91.82	165	A5	-16.2	84.40
102	66	-26.9	95.43	134	86	-21.6	91.63	166	A6	-16	84.01
103	67	-26.7	95.34	135	87	-21.4	91.43	167	A7	-15.8	83.62
104	68	-26.5	95.24	136	88	-21.2	91.24	168	A8	-15.6	83.23
105	69	-26.3	95.14	137	89	-21	91.04	169	A9	-15.4	82.84
106	6A	-26.2	95.04	138	8A	-20.8	90.84	170	AA	-15.2	82.45
107	6B	-26	94.95	139	8B	-20.6	90.65	171	AB	-15	82.06
108	6C	-25.8	94.85	140	8C	-20.5	90.45	172	AC	-14.8	81.67
109	6D	-25.7	94.75	141	8D	-20.3	90.26	173	AD	-14.6	81.27
110	6E	-25.5	94.65	142	8E	-20.1	90.06	174	AE	-14.4	80.88
111	6F	-25.3	94.56	143	8F	-20	89.87	175	AF	-14.3	80.49
112	70	-25.2	94.46	144	90	-19.8	89.67	176	B0	-14.1	80.10
113	71	-25	94.36	145	91	-19.6	89.48	177	B1	-13.9	79.71
114	72	-24.9	94.26	146	92	-19.5	89.28	178	B2	-13.8	79.32
115	73	-24.7	94.17	147	93	-19.3	89.09	179	B3	-13.6	78.93
116	74	-24.6	94.07	148	94	-19.2	88.89	180	B4	-13.4	78.54
117	75	-24.5	93.97	149	95	-19	88.70	181	B5	-13.3	78.15
118	76	-24.3	93.87	150	96	-18.9	88.50	182	B6	-13.1	77.76
119	77	-24.2	93.77	151	97	-18.7	88.31	183	B7	-13	77.37
120	78	-24	93.68	152	98	-18.6	88.11	184	B8	-12.8	76.98
121	79	-23.9	93.58	153	99	-18.4	87.92	185	B9	-12.7	76.59
122	7A	-23.8	93.48	154	9A	-18.3	87.72	186	BA	-12.5	76.20
123	7B	-23.7	93.38	155	9B	-18.1	87.52	187	BB	-12.4	75.81
124	7C	-23.5	93.29	156	9C	-18	87.33	188	BC	-12.3	75.42
125	7D	-23.4	93.19	157	9D	-17.9	87.13	189	BD	-12.1	75.02
126	7E	-23.3	93.09	158	9E	-17.7	86.94	190	BE	-12	74.63
127	7F	-23.2	92.99	159	9F	-17.6	86.74	191	BF	-11.8	74.24

Continued

Table 14 Dynamic Mode Dimming in Logarithmic Mode vs. register 05h – 07h data

Continue

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
192	C0	-11.6	73.46	224	E0	-5.7	47.68
193	C1	-11.3	72.68	225	E1	-5.4	46.12
194	C2	-11.1	71.90	226	E2	-5.2	44.56
195	C3	-10.9	71.12	227	E3	-4.9	42.99
196	C4	-10.6	70.34	228	E4	-4.7	41.43
197	C5	-10.4	69.56	229	E5	-4.5	39.87
198	C6	-10.2	68.77	230	E6	-4.3	38.31
199	C7	-10	67.99	231	E7	-4	36.74
200	C8	-9.8	67.21	232	E8	-3.8	35.18
201	C9	-9.5	66.43	233	E9	-3.6	33.62
202	CA	-9.3	65.65	234	EA	-3.4	32.06
203	CB	-9.2	64.87	235	EB	-3.2	30.49
204	CC	-9	64.09	236	EC	-3	28.93
205	CD	-8.8	63.31	237	ED	-2.8	27.37
206	CE	-8.6	62.52	238	EE	-2.7	25.81
207	CF	-8.4	61.74	239	EF	-2.5	24.24
208	D0	-8.2	60.96	240	F0	-2.3	22.68
209	D1	-8.1	60.18	241	F1	-2.1	21.12
210	D2	-7.9	59.40	242	F2	-2	19.56
211	D3	-7.7	58.62	243	F3	-1.8	17.99
212	D4	-7.6	57.84	244	F4	-1.6	16.43
213	D5	-7.4	57.06	245	F5	-1.5	14.87
214	D6	-7.3	56.27	246	F6	-1.3	13.31
215	D7	-7.1	55.49	247	F7	-1.2	11.74
216	D8	-6.9	54.71	248	F8	-1	10.18
217	D9	-6.8	53.93	249	F9	-0.8	8.62
218	DA	-6.7	53.15	250	FA	-0.7	7.06
219	DB	-6.5	52.37	251	FB	-0.6	5.49
220	DC	-6.4	51.59	252	FC	-0.4	3.93
221	DD	-6.2	50.81	253	FD	-0.3	2.37
222	DE	-6.1	50.02	254	FE	-0.1	0.81
223	DF	-6	49.24	255	FF	0	0.00

Appendix 2

Table 15 Global Dimming in Logarithmic Mode vs. register 04h data

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
0	0	0	0.00	32	20	-6	49.24	64	40	-11.8	74.24
1	01	-0.1	0.81	33	21	-6.1	50.02	65	41	-12	74.63
2	02	-0.3	2.37	34	22	-6.2	50.81	66	42	-12.1	75.02
3	03	-0.4	3.93	35	23	-6.4	51.59	67	43	-12.3	75.42
4	04	-0.6	5.49	36	24	-6.5	52.37	68	44	-12.4	75.81
5	05	-0.7	7.06	37	25	-6.7	53.15	69	45	-12.5	76.20
6	06	-0.8	8.62	38	26	-6.8	53.93	70	46	-12.7	76.59
7	07	-1	10.18	39	27	-6.9	54.71	71	47	-12.8	76.98
8	08	-1.2	11.74	40	28	-7.1	55.49	72	48	-13	77.37
9	09	-1.3	13.31	41	29	-7.3	56.27	73	49	-13.1	77.76
10	0A	-1.5	14.87	42	2A	-7.4	57.06	74	4A	-13.3	78.15
11	0B	-1.6	16.43	43	2B	-7.6	57.84	75	4B	-13.4	78.54
12	0C	-1.8	17.99	44	2C	-7.7	58.62	76	4C	-13.6	78.93
13	0D	-2	19.56	45	2D	-7.9	59.40	77	4D	-13.8	79.32
14	0E	-2.1	21.12	46	2E	-8.1	60.18	78	4E	-13.9	79.71
15	0F	-2.3	22.68	47	2F	-8.2	60.96	79	4F	-14.1	80.10
16	10	-2.5	24.24	48	30	-8.4	61.74	80	50	-14.3	80.49
17	11	-2.7	25.81	49	31	-8.6	62.52	81	51	-14.4	80.88
18	12	-2.8	27.37	50	32	-8.8	63.31	82	52	-14.6	81.27
19	13	-3	28.93	51	33	-9	64.09	83	53	-14.8	81.67
20	14	-3.2	30.49	52	34	-9.2	64.87	84	54	-15	82.06
21	15	-3.4	32.06	53	35	-9.3	65.65	85	55	-15.2	82.45
22	16	-3.6	33.62	54	36	-9.5	66.43	86	56	-15.4	82.84
23	17	-3.8	35.18	55	37	-9.8	67.21	87	57	-15.6	83.23
24	18	-4	36.74	56	38	-10	67.99	88	58	-15.8	83.62
25	19	-4.3	38.31	57	39	-10.2	68.77	89	59	-16	84.01
26	1A	-4.5	39.87	58	3A	-10.4	69.56	90	5A	-16.2	84.40
27	1B	-4.7	41.43	59	3B	-10.6	70.34	91	5B	-16.4	84.79
28	1C	-4.9	42.99	60	3C	-10.9	71.12	92	5C	-16.6	85.18
29	1D	-5.2	44.56	61	3D	-11.1	71.90	93	5D	-16.9	85.57
30	1E	-5.4	46.12	62	3E	-11.3	72.68	94	5E	-17.1	85.96
31	1F	-5.7	47.68	63	3F	-11.6	73.46	95	5F	-17.4	86.35

Continued

Table 15 Global Dimming in Logarithmic Mode vs. register 04h data

Continue

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
96	60	-17.6	86.74	128	80	-23.2	92.99	160	A0	-28.3	96.12
97	61	-17.7	86.94	129	81	-23.3	93.09	161	A1	-28.4	96.17
98	62	-17.9	87.13	130	82	-23.4	93.19	162	A2	-28.5	96.22
99	63	-18	87.33	131	83	-23.5	93.29	163	A3	-28.6	96.26
100	64	-18.1	87.52	132	84	-23.7	93.38	164	A4	-28.7	96.31
101	65	-18.3	87.72	133	85	-23.8	93.48	165	A5	-28.8	96.36
102	66	-18.4	87.92	134	86	-23.9	93.58	166	A6	-29	96.41
103	67	-18.6	88.11	135	87	-24	93.68	167	A7	-29.1	96.46
104	68	-18.7	88.31	136	88	-24.2	93.77	168	A8	-29.2	96.51
105	69	-18.9	88.50	137	89	-24.3	93.87	169	A9	-29.3	96.56
106	6A	-19	88.70	138	8A	-24.5	93.97	170	AA	-29.5	96.61
107	6B	-19.2	88.89	139	8B	-24.6	94.07	171	AB	-29.6	96.66
108	6C	-19.3	89.09	140	8C	-24.7	94.17	172	AC	-29.7	96.70
109	6D	-19.5	89.28	141	8D	-24.9	94.26	173	AD	-29.8	96.75
110	6E	-19.6	89.48	142	8E	-25	94.36	174	AE	-30	96.80
111	6F	-19.8	89.67	143	8F	-25.2	94.46	175	AF	-30.1	96.85
112	70	-20	89.87	144	90	-25.3	94.56	176	B0	-30.2	96.90
113	71	-20.1	90.06	145	91	-25.5	94.65	177	B1	-30.4	96.95
114	72	-20.3	90.26	146	92	-25.7	94.75	178	B2	-30.5	97.00
115	73	-20.5	90.45	147	93	-25.8	94.85	179	B3	-30.7	97.05
116	74	-20.6	90.65	148	94	-26	94.95	180	B4	-30.8	97.09
117	75	-20.8	90.84	149	95	-26.2	95.04	181	B5	-30.9	97.14
118	76	-21	91.04	150	96	-26.3	95.14	182	B6	-31.1	97.19
119	77	-21.2	91.24	151	97	-26.5	95.24	183	B7	-31.3	97.24
120	78	-21.4	91.43	152	98	-26.7	95.34	184	B8	-31.4	97.29
121	79	-21.6	91.63	153	99	-26.9	95.43	185	B9	-31.6	97.34
122	7A	-21.8	91.82	154	9A	-27.1	95.53	186	BA	-31.7	97.39
123	7B	-22	92.02	155	9B	-27.3	95.63	187	BB	-31.9	97.44
124	7C	-22.2	92.21	156	9C	-27.5	95.73	188	BC	-32.1	97.49
125	7D	-22.5	92.41	157	9D	-27.7	95.83	189	BD	-32.2	97.53
126	7E	-22.7	92.60	158	9E	-27.9	95.92	190	BE	-32.4	97.58
127	7F	-22.9	92.80	159	9F	-28.1	96.02	191	BF	-32.6	97.63

Continued

Table 15 Global Dimming in Logarithmic Mode vs. register 04h data

Continue

# of steps	Hex code	Dimming, dB	Dimming, %	# of steps	Hex code	Dimming, dB	Dimming, %
192	C0	-32.8	97.68	224	E0	-42.5	99.24
193	C1	-32.9	97.73	225	E1	-42.8	99.27
194	C2	-33.1	97.78	226	E2	-43.1	99.29
195	C3	-33.3	97.83	227	E3	-43.4	99.32
196	C4	-33.5	97.88	228	E4	-43.7	99.34
197	C5	-33.7	97.92	229	E5	-44	99.37
198	C6	-33.9	97.97	230	E6	-44.4	99.39
199	C7	-34.1	98.02	231	E7	-44.7	99.41
200	C8	-34.4	98.07	232	E8	-45.1	99.44
201	C9	-34.6	98.12	233	E9	-45.5	99.46
202	CA	-34.8	98.17	234	EA	-45.9	99.49
203	CB	-35	98.22	235	EB	-46.3	99.51
204	CC	-35.3	98.27	236	EC	-46.7	99.54
205	CD	-35.5	98.32	237	ED	-47.2	99.56
206	CE	-35.8	98.36	238	EE	-47.7	99.58
207	CF	-36.1	98.41	239	EF	-48.2	99.61
208	D0	-36.3	98.46	240	F0	-48.8	99.63
209	D1	-36.6	98.51	241	F1	-49.4	99.66
210	D2	-36.9	98.56	242	F2	-50	99.68
211	D3	-37.2	98.61	243	F3	-50.7	99.71
212	D4	-37.5	98.66	244	F4	-51.5	99.73
213	D5	-37.8	98.71	245	F5	-52.3	99.76
214	D6	-38.2	98.75	246	F6	-53.2	99.78
215	D7	-38.5	98.80	247	F7	-54.3	99.80
216	D8	-38.9	98.85	248	F8	-55.4	99.83
217	D9	-39.2	98.90	249	F9	-56.7	99.85
218	DA	-39.6	98.95	250	FA	-58.3	99.88
219	DB	-40.1	99.00	251	FB	-60.3	99.90
220	DC	-40.5	99.05	252	FC	-62.8	99.93
221	DD	-40.9	99.10	253	FD	-66.3	99.95
222	DE	-41.4	99.15	254	FE	-72.3	99.98
223	DF	-41.9	99.19	255	FF		100

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IXYS Corp.
1590 Buckeye Dr.,
Milpitas, CA 95035-7418
Phone: 408.457.9000
Fax: 408.496.0222
<http://www.ixys.com>

Document N: 9003/01_DS
Revision: N1.0
Issue date: 10/20/2009