12.4 A 7.5W-Output-Power 96%-Efficiency Capacitor-Free Single-Inductor 4-Channel All-Digital Integrated DC-DC LED Driver in a 0.18µm Technology

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Today's general lighting development is driven by improvements in semiconductor-based systems. It is expected that solid-state lighting (SSL) will dominate general lighting in the near future. Two main challenges that must be met in SSL are the reduction of the bill of materials (BOM), and an increase in functionality. In [1], a floating DC-DC buck controller is presented. This controller adds to the BOM, as every device of the power path is discrete and the ASIC can only drive a single LED string. In contrast to that, [2] offers a high-current fully integrated power stage. However, several external passives are introduced and the technology inhibits stacking multiple LEDs for high luminous efficacy. To overcome this, [3] presents an integrated HV power path with only the inductor as an external component. In a parallel development, [4] reports an LED driver similar to [3], but that uses a discrete Schottky diode for asynchronous rectification. In fact, [1-4] demonstrate single output LED drivers without additional functionality or full color spectrum. To overcome these drawbacks in light spectrum and control, [5] presents a 3-channel LED driver. However, the external passives are numerous, which significantly impairs the overall BOM.

This work presents a capacitor-free 4-channel LED driver shown in Fig. 12.4.1. The single-inductor multiple-output (SIMO) approach is widely used in portable electronics PMUs. The reason is the significant reduction of the external components count. This characteristic has been adapted to this work, where integrated parts are indicated by the gray background. To exploit the full SIMO potential, integrated double-diffused DMOS transistors are used. They offer high voltage capability between source and substrate compared to their LDMOS counterparts, where the source-substrate potential is typically low. A tunable high side current sense (HSCS) measures the equivalent voltage drop of the inductor current I_L across a 50mΩ sense resistor R and digitizes it with a 9b, 3.5MS/s SAR ADC. The integrated power stage is turned on anti-phased with S_{HS} and S_{LS}, so that the high side (HS) PMOS M0 charges L, while the switch-pin voltage V_{sw} is equal to the input voltage V_{in}. A single low side (LS) transistor is turned on and a freewheeling current makes the selected string emit light. The switch-pin becomes negative compared to the reference potential V_{ref} and L is discharged. Due to the inverting V_{sw} voltage, the SIMO LED driver is distinguished by the disregard of capacitors. As soon as the switch-pin is negative, the body diode of LDMOS transistors starts to conduct and other colors parasitically emit light. To avoid this, the substrate pre-biased DMOS transistors provide channel isolation without any external components. String cross-coupling is eliminated, as the pre-bias voltage is lower than the absolute minimum V_{sw}. In this work V_{ref} is chosen >0V and negative DMOS substrate generation is not provided.

To protect the LEDs from reverse polarity, integrated diodes are forward biased during PMOS charge to shorten the respective LED string. This yields a single inductor and a minimum number of integrated power switches, which is the lowest BOM and smallest possible form factor. The all-digital hysteretic converter control is capable of automatic CCM/DCM switching in the range of 2mA to 1A. Besides the wide output current range, several protection characteristics are included, such as overcurrent, min and max transistor on-times, and hysteretic boundaries between CCM and DCM to avoid shattering.

An appropriate color-mixing algorithm distributes the user-defined RGBW color information into minimum-length color sequences. The sequence's rate is based on the lowest color value in a 1kHz frequency, achieving roughly 9b color resolution with a switching frequency of 500kHz without color flickering. Together with the 9b current accuracy, a total 18b color resolution is achieved with the hybrid AM/PWM technique. The corresponding waveforms during CCM are illustrated in Fig. 12.4.2. An arbitrary white-white-red-white-blue (WWRWB) sequence is explained and transient measurements are given. During HS on, L is charged and the protection diodes short the LED strings. The diodes' forward voltages result in the respective voltage overshoot of the $V_{D,X}$ compared to V_{sw}. While a selected string is turned on, its $V_{D,X}$ is close to V_{ref} and the LED number m and voltage V_F dependent inductor discharge slopes indicate light emission. The drain potentials of the turn-off strings are mV_F above V_{sw}. Since no $V_{D,X}$ is below the bulk potential, no body diode conduction with parasitic light emission takes place.

To minimize the package size, all drivers are powered from the 24V input. Since this voltage is significantly higher than the maximum V_{GS} of the HS and LS devices, a digital centric V_{GS} control loop driver shown in Fig. 12.4.3 is used. A delay-line-based adjustable pulse-width generator (APWG) creates pulses of defined width. These pulses turn on M2 for a specific amount of time. Hence a certain charge flows into the gate of M0 turning it on. Once the APWG pulse is finished, M2 turns off and the gate of M0 is highly ohmic. To close the control loop, V_{GS} is sampled with a flying capacitor and digitized in the low-voltage domain with a 6b, 6.5MS/s SAR A/D employing MSB capacitor splitting. The digital control calculates a new APWG control word and after several switching cycles the targeted V_{GS} is achieved. This driver offers closed-loop V_{GS} control without quiescent current. At the system level this digital-centric approach enables operation-point-dependent V_{GS} tuning for efficiency enhancements and robust operation over a wide temperature and supply voltage range.

The circuit shown in Fig. 12.4.4 solves the challenging voltage feedback problem by sensing the 24V-referred V_{GS} voltage and digitizing it in the 1.8V supply domain. DMOS transistors are used to connect a flying capacitor C_{sense} to the gate (V_G) and source (V_S) nodes of the driven transistor. Once the voltage is sampled, M1 and M2 are turned off and the capacitors C_1 and C_2 compensate the charge injection of the turn off event. M3 and M4 establish connection to the LV part and Q_{sense} is redistributed on the capacitor array (C_{array}) of the SAR ADC until their voltages equal. Hence, the capacitance ratio of C_{sense} to C_{array} is utilized to scale the 5.5V V_{GSmax} to 1.8V. Once the V_{GS} voltage is sampled onto C_{array} a normal A/D conversion starts. M5 and M6 compensate the charge injection of M3 and M4 while the transmission gates at the nodes V_{SAR} are used to discharge C_{array} in advance of every conversion.

The system efficiency of different inductor and input voltage setups are shown in Fig. 12.4.5. The measurements with logarithmically scaled load current between 10mA and 1A were performed with 3 white LEDs in series. The peak efficiency of about 96% is achieved around 60mA with a 68µH inductor for 20V V_{in}, as well as about 96% around 110mA at 22V input voltage and around 300mA with 23V. The CCM/DCM boundary is located between 60 and 80mA for the different setups. Even in light load between 20mA to high currents up to 500mA the efficiency is above 90%, maintaining high efficiency within high dimming levels in comparison to [2-5], where dimming efficiency is not shown. Typical operating conditions for the Philips LUXEON Rebel with a luminous flux of 130lm per LED at 350mA, which is comparable to a 40W light bulb, achieve 92.5% efficiency.

A comparison with available general-lighting LED driver products is given in Fig. 12.4.6. The setup uses a 33-to-68µH inductor parallel to 4 LED strings with a single LED for each RGB color and 3 white LEDs in series to generate tunable white colors. At similar V_{in} levels the SIMOs' LED current I_{LED} and efficiency are nearly equal to the single-channel LED driver [4]. However, the presented driver offers higher color resolution than the 3-channel LED driver in [5], requiring only a single inductor instead of multiple external components. Furthermore, the I_{LED} and system efficiency are significantly higher than in [5].

A micrograph of the capacitor-free SIMO LED driver, which is fabricated in a 0.18µm 50V HVCMOS technology and packaged in QFN48, is given in Fig. 12.4.7.

References:

[1] V. Anghel, *et al.*, "Variable Off-Time Control Loop for Current-Mode Floating Buck Converters in LED Driving Applications," *IEEE J. Solid-State Circuits*, vol. 49, no. 7, pp. 1571-1579, July 2014.

[2] P. Malcovati, *et al.*, "A 0.18µm CMOS 91%-Efficiency 0.1-to-2A Scalable Buck-Boost DC-DC Converter for LED Drivers," *ISSCC Dig. Tech. Papers*, pp. 280-281, Feb. 2012.

[3] D. Park, Z. Liu, and H. Lee, "A 40V 10W 93%-Efficiency Current-Accuracy-Enhanced Dimmable LED Driver With Adaptive Timing Difference Compensation for Solid-State Lighting Applications," *IEEE J. Solid-State Circuits*, vol. 49, no. 8, pp. 1848-1860, Aug. 2014.

[4] Infineon Technologies AG, ILD6070, "60V / 0.7A High Efficiency Step-Down LED Driver," Datasheet, Dec. 2013.

[5] NXP Semiconductors, UBA3077HN, "Three-Channel Switched-Mode LED Driver," Datasheet, Feb. 2011.

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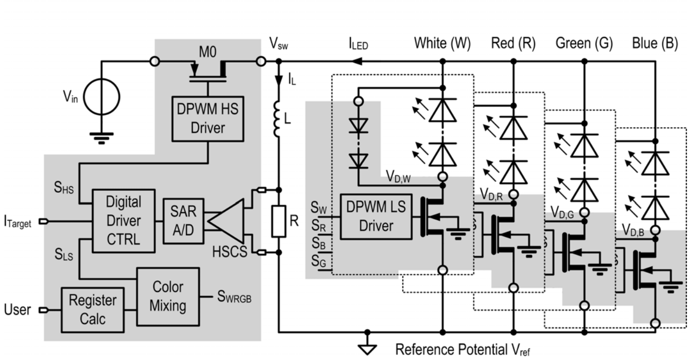

Figure 12.4.1: Single-inductor LED-driver top level.

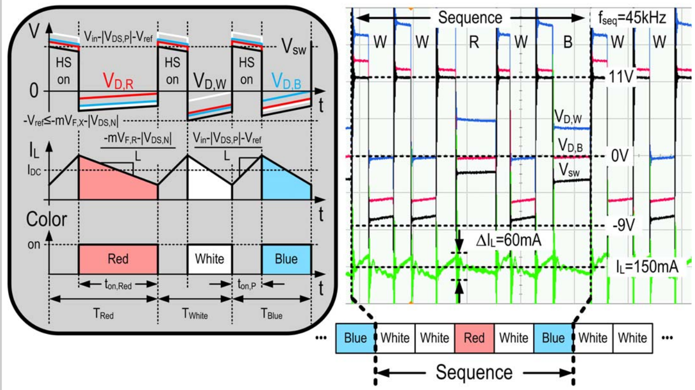

Figure 12.4.2: Transient CCM relative to V_{ref}.

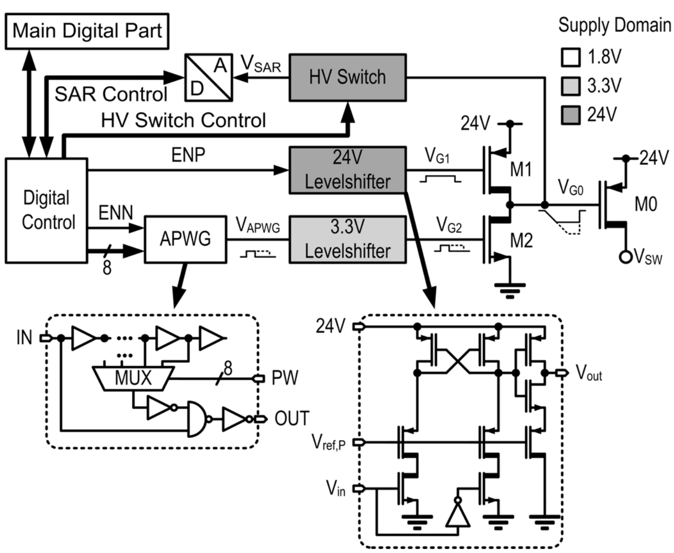

Figure 12.4.3: Digital PWM high-side driver.

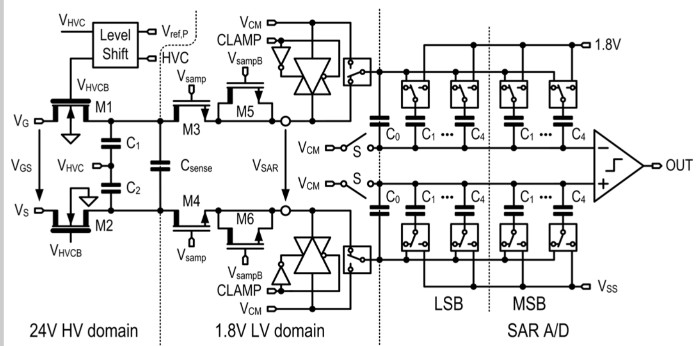

Figure 12.4.4: HV switch and ADC for the DPWM driver.

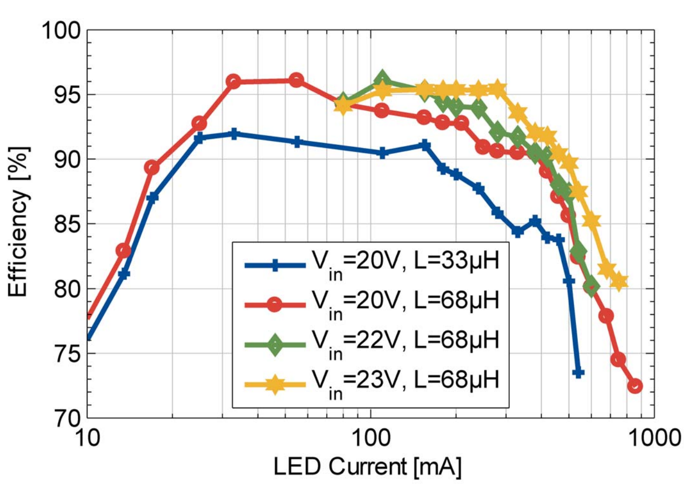

Figure 12.4.5: System efficiency over load current.

Parameter	Infineon ILD6070 [4]	NXP UBA3077HN [5]	This work
LED Application	Single-Channel	3-Channel	4-Channel
V_{in}	4.5V to 60V	10V to 42V	12V to 24V
I_{LED}	≤ 700mA	147mA to 153mA	2mA to 1A
External Components	1x 15μH to 220μH	3x 22μH	1x 33μH to 68μH
	None	3x 2μF	None
	1x Diode	3x Diode	None
PWM Frequency	≤ 25kHz	2kHz to 24kHz	1kHz to 500kHz
Efficiency	98%	90%	96%
Dimming / Color Resolution	PWM	14bit PWM	9bit+9bit AM/PWM

Figure 12.4.6: Comparison to LED driver products.

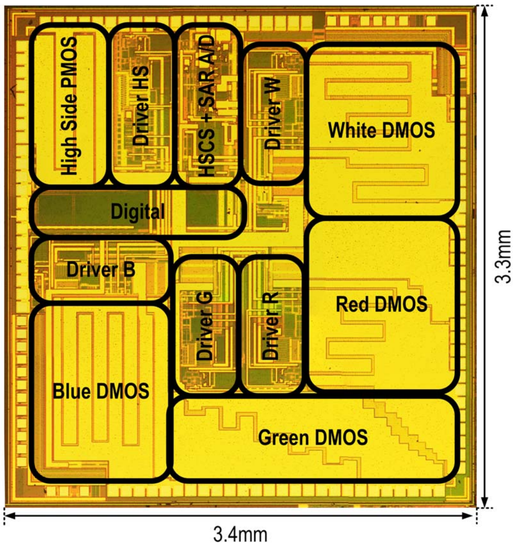

Figure 12.4.7: Micrograph of the 4-channel LED driver.