A Current-Mode Digital Controlled Buck-Boost DC-DC Converter for LED Driver

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Abstract **- This paper presents a digital LED Driver that provides a high quality of the back light for display modules. The proposed LED driver is implemented in 0.18um CMOS process. Proposed LED driver consists of three types of circuits, a buck-boost converter, circuit for power efficiency and color reproducibility improvement and a circuit for constant current driving. The digital designed buck-boost converter improves power efficiency. To compensate for forward biased voltage of LED according to temperature, the regulator block generates a self-controlled variable reference voltage, in addition to that it also provides an optimal power efficiency of power converter. The regulator that gives a constant current to LED automatically controls the gate voltage that is needed to determine the minimum voltage headroom to prevent power deficiency. The supplying voltage of this circuit is 4.2V, 0V. Maximum operating frequency is 1MHz. Proposed LED driver can be applied to a low power chip-set projector for HD quality micro-display and in HMD also.**

I. INTRODUCTION

Information technology (IT) and the next generation-products provide a variety of functions in various fields of communication and electronics. Smart glasses is one of the contemporary products of IT that provides multiple smart features like-mail, map information and augmented reality (AR) information (such as positional information, velocity) along with its usage as an eyesight glasses. In April-2012, Google introduced a new type of smart glasses with implementing AR feature that makes it the center of attraction in wearable devices. Smart glasses are used in multiple applications including Display Chip-set and SoC such as Digital Micro-mirror Device (DMD), Micro-electromechanical systems (MEMS) Mirror and Liquid Crystal on Silicon (LCoS). They are used in core parts of Head-Mounted Display (HMD) and pico-projector. These display modules require a control circuit to drive a PWM-dimming and a constant current for LED that is used as a light source in projector.

To get a HD-color representation, it is important to ensure the spectral characteristics of the display for the compensation of colors reproducibility, by using the color mixing ratio of the RGB-type LED (Red, Green, Blue) instead of white type LED.

With this understanding, we propose a LED Driver Circuit that provides a high quality of the back light for display modules by driving RGB type LED with time division.

Because of battery driving, a circuit for driving RGB-type LED has buck-boost converter for providing a constant voltage, circuit that protects a lowering color reproducibility and power efficiency with temperature and circuit for protect lowering a power efficiency according to driving a PWM constant current.

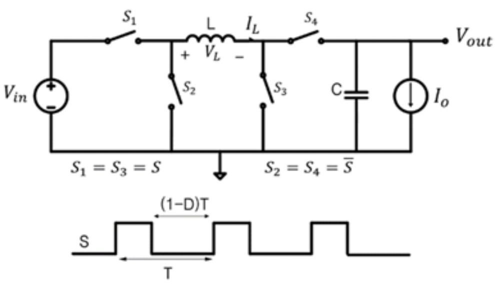

Fig. 1. Conventional buck-boost converter

A LED driver consists of three types of circuits, a buck-boost converter, circuit for power efficiency and color reproducibility improvement and a circuit for constant current driving. Buck-Boost converter provides a constant voltage to drive RGB-type LED. The complete circuit enhances the color reproducibility and power efficiency with temperature variations as well as it maintains that power efficiency by driving a PWM constant current. Buck-boost converter improves the transient characteristic with PWM current control. Regulator that gives a constant current to LED automatically controls the gate voltage that is needed to determine the minimum voltage headroom to prevent power deficiency. In addition, including a pulse control function to control the optimal light characteristics using PWM duty and pulse. Finally, to compensate a forward biased voltage of LED according to temperature, the regulator block generates a self-controlled variable reference voltage that also provides an optimal power efficiency of power converter.

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II. EXPERIMENTS

A. Proposed buck-boost converter

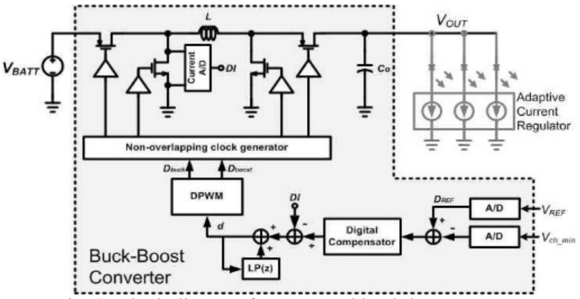

Fig. 2. Block diagram for proposed buck-boost converter

A conventional buck-boost converter is shown in Fig 1. The basic configuration consists of a total of four switches, an inductor and a capacitor. A synchronous converter is used to reduce the conduction loss of conventional asynchronous converters. The basic operation principle is that four switches are switched, S1 and S3 are turned on and off simultaneously, and S2 and S4 are turned on and off simultaneously. The buck-boost converter can both step-up and step-down to achieve the desired target output voltage. The relation between input voltage and output voltage is as follows.

$$V_{out} = \frac{D}{(1-D)} \times V_{in}$$

A desired output voltage can be obtained in accordance with the duty ratio of the switching pulse. The duty of this switching pulse is adjusted by the PWM generator.

Conventional buck-boost converter needs a control loop to achieve a target voltage what we want. There are two types of control block that is analog control and digital control loop respectably. Analog type controller uses an op-amp, capacitor and resistor whereas digital type controller uses a digital frequency compensation loop without any op-amp, capacitor and resistor.

Recently digital DC-DC converters are used because large capacitor of analog DC-DC converter for frequency compensation can be replaced with digital filter that can be integrated in a small area. Moreover, digital buck-boost converter can reduce price and has advantages in power efficiency aspects. The block diagram of proposed LED driver is shown Fig 2. It is based on the structure of the buck-boost converter to maintain a constant output voltage in a wide range (2.7V~4.2V). The digital control is implemented in proposed structure which is controlled by sensing the current in the inductor current-programmed mode.

Voltage selector sends a minimum voltage signal V_{CH_MIN} in 3chanel voltage at current regulator to ADC and then converts to digital value. The converted digital value sends an error signal to digital compensator that is further compared with D_{REF} after that digital value is passed through the digital filter and then compared with inductor current digital value (DI). The DI is passed through the low pass filter LP (z) called as current-loop compensator and then that value is converted to duty-cycle command (d). To cover a wide operation range, the converter divides a control the optimal non-overlapping clock and changes the reference clock to detect variation of the help of these additional circuits. An adaptive current regulator (ACR) is used to match driving through LED columns using a sense-FET. In addition, with PWM control and temperature compensation circuits, proposed LED driver can actively respond to variations of temperature. And achieves remarkable color reproducibility.

B. Determined specification of circuits

The proposed DC-DC converter targets its usage in small portable devices. The design specifications of this DC-DC converter are, input voltage range 2.7V~4.2V, the target output voltage 3V and maximum output current 120mA.

Fig. 3 shows a design flow diagram for proposed LED driver. First, define of the design and then verify a proposed circuit through a Matlab Simulink. Second, when circuit verified by Matlab then implement in Cadence tool for physical definition and physical verification. In this step, the prototype of proposed circuit will be completed. After Physical step then parasitic extraction will be implemented.

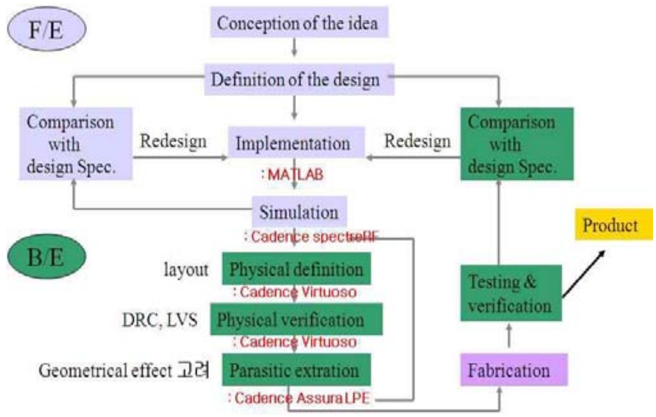

Fig. 3. Design flow diagram

TABLE I.
A performance parameters of the circuit

Parameter	Symbol	Condition	Min.	Typ.	Max.	Units
System Frequency	F_system			1M		Hz
Input Voltage	V_{in}	Constant	2.7	3.7	4.2	V
Output Voltage	V_{out}	Programmable	2.5	3	3.5	V
Output Current	I_{LED}	Constant	60	90	120	mA

Table I shows the performance parameters of the proposed circuit. The system frequency operates at 1MHz and the input voltage varies from a maximum of 4.2V to a minimum of 2.7V because of the battery voltage. At this time, the output voltage can be adjusted to 2.5V, 3V and 3.5V depending on the forward voltage of the LED, and the output current can also be adjusted to 60mA, 90mA and 120mA depending on the forward current of the RGB LED.

C. MATLAB simulation

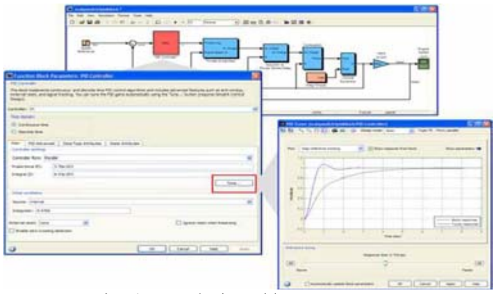

Fig. 4. PID designed by MATLAB

MATLAB-Simulink is used for circuit simulation. In this step, the most important thing is a design of digital compensator. The stability of digital compensator is same as whole system's stability. The closed loop stability predicts the probability of oscillation. A Verilog-code is used in compensator design. After coding, Verilog code was digital synthesized and then simulated with other blocks designed by AMS. Finally, the whole layout is completed by auto PNR.

Fig. 4 shows the PID controller designed with MATLAB. The PID controller consists of proportional (P), integral (I), and derivative (D) terms. The PID is basically a feedback controller that measures the output of the controlling circuit and compares it with a reference to produce an error value. The error value generated at this time is adjusted to reach the desired output. The proportional term compares the error value with the current value and outputs the control value. The integral term integrates the error value over time and outputs the control value. Finally, the derivative term is a method of determining the control value by the non-division value of the error value with respect to time. The PID controller adds the control values of P, I, and D to produce the final control value. There are three main indicators for determining the characteristics of the PID controller: overshoot, target value arrival time, and steady state error. In this case, increasing the gain of P can shorten the time to reach the target value and increasing the gain of I can reduce the error in the steady state. Finally, D can reduce the effect of overshoot or undershoot, because the manipulated variables of the PID can affect each other, and therefore all performance indicators cannot improve at the same time. Therefore, we used Matlab simulink to predict the operation of the controller to find the optimal gain. The reason why we design the PID controller using Matlab is that MATLAB Simulink has advantages in terms of speed and flexibility compared to device simulator, circuit simulator or Verilog AMS simulation.

D. Circuit design and simulation

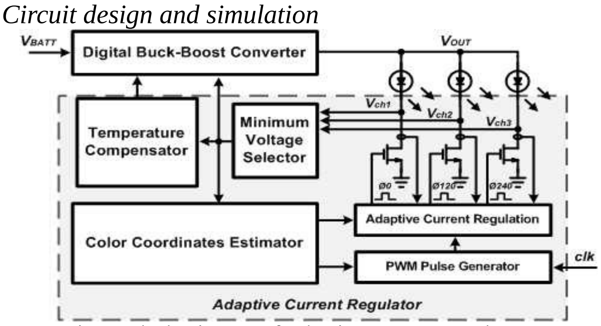

Fig. 5. Block Diagram of Adaptive Current Regulator

Buck-boost converter circuit is verified by simulation. Cadence IC 615 is used for this step.

Fig. 5 is shown the ACR block. The ACR block determines current regulator's minimum voltage headroom for constant current supplying and controls the gate voltage automatically. This constant current driving prevents the drop in power efficiency due to PWM. PWM pulse generator includes a pulse shaping function for optimal efficiency and optical characteristics control. The temperature compensator generates a variable reference voltage to compensate variability of forward bias voltage of LEDs according to temperature. Through this compensation, the output of buck-boost converter exhibits self-tuning control signal to ACR and PWM pulse generator to compensate variability of color reproducibility. Color-coordinates estimation sends control signals to ACR and PWM pulse generators to compensate for color reproducibility variations.

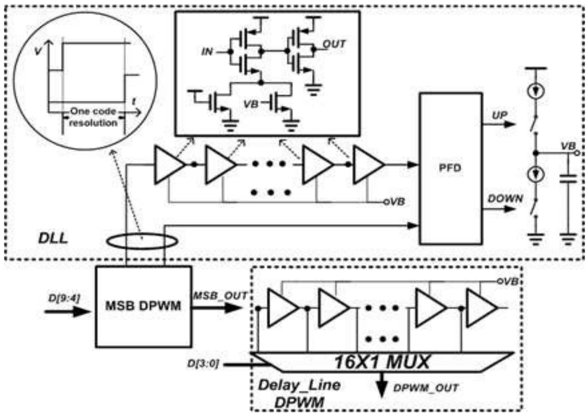

Fig. 6. Hybrid DPWM

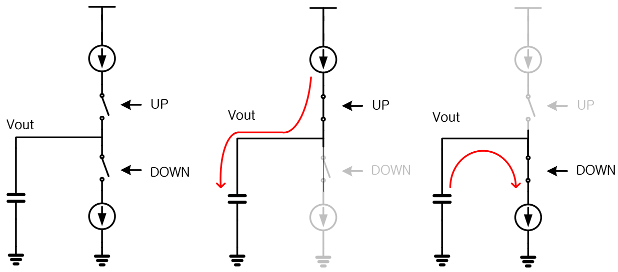

Fig. 7. Ideal charge pump model

Fig. 6 is Hybrid DPWM block diagram. DPWM uses delay line in many cases that has a disadvantage of lager area due to delay cells. We are proposing a new technique of DPWM in which high order bit as generated from delay line. And lower order bit is generated from Delay Locked Loop (DLL) which is used to control the duty. The DLL structure makes it able for calibration. The proposed DPWM architecture is resistant to PVT variations than other DPWM structures. Furthermore, delay line can be varied and compensated it helps in more precision of results.

Phase Frequency Detector is a basic block that compares the phase difference of two incoming pulses and outputs the output in the form of pulses. One of the MSB (Most Significant Bit) of the DPWM goes through the delay line and the other enters the input of the Phase Frequency Detector as it is. In this case, the two pulses have a phase difference due to the delay line. If the compared pulses are faster than the compared pulses, the UP signal is generated. In the opposite case, the DOWN signal is generated.

Fig. 7 is the ideal model of the charge pump. As shown Figure, charge pump consists of two current sources and two switches. The basic operation principle of the charge pump is that when the UP switch is turned on, the charge pump output capacitor begins to charge and the voltage increases. When the DOWN switch is turned on, the charge pump starts discharging and the voltage decreases. When this principle is applied to the DLL circuit, two UP and DOWN output signals of the phase frequency detector are inputted to the switch of the charge pump.

If the reference signal is faster and the UP signal is raised, the charge pump will charge the capacitor and VB will go up. As the charge pump output voltage (VB) increases, the control voltage of the delay line increases. As a result, the delay of the reference signal becomes longer.

As a result, the frequency decreases and the phase difference decreases. Then, the DOWN signal is generated, and the capacitor is discharged and VB is reduced. Finally, when the steady-state is entered due to the above operation, the duty and frequency of the PWM are fixed and stable operation can be performed.

E. Layout design & post layout simulation

After the circuit simulation and result, the layout of circuit was completed. Post layout simulation must be performed to improve the reliability and performance of the layout circuit. Post layout simulation including Design Rule Check (DRC), Layout Versus Schematic (LVS), Electrical Rule Check (ERC) and Layout Parasitic Extraction (LPE) were also competed. DRC, LVS, and ERC are performed to ensure the reliability of the laid-out circuit and are all performed in this design. After securing the reliability, LPE simulation was performed to analyze the parasitic components extracted from the actual layout circuit, and the layout was re-adjusted to the desired performance to secure the circuit performance. In this step Calibre of Mentor Graphics and IC 615 Layout-editor of Cadence was used.

III. RESULTS AND DISCUSSION

A. Simulation results

Fig. 8. Designed MATLAB PID result

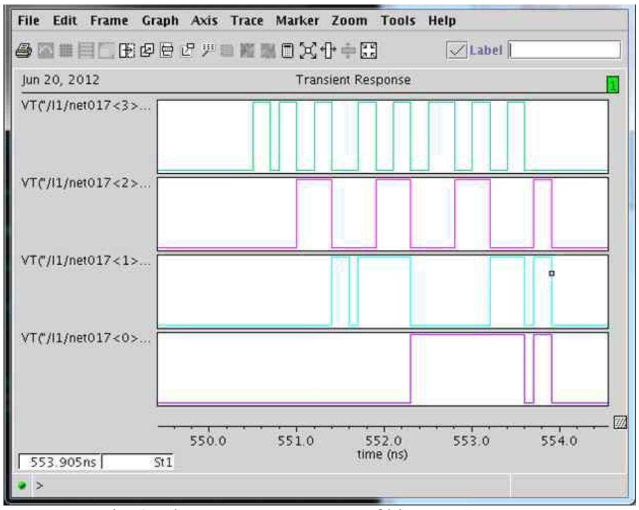

Fig. 9. Thermometer to output of binary converter

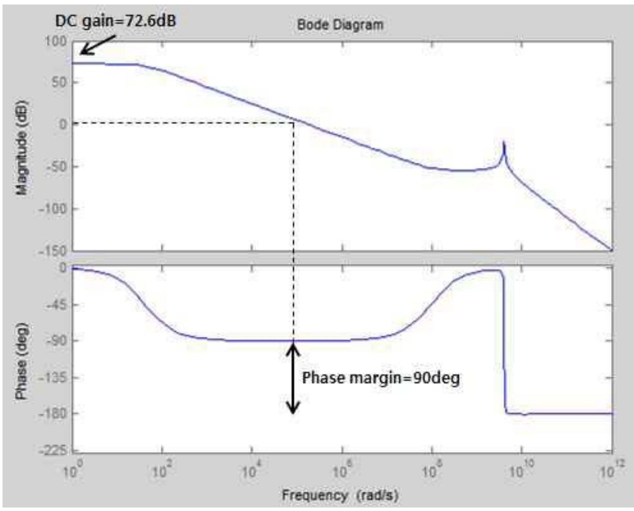

Fig 10. Bode plot for designed ACR

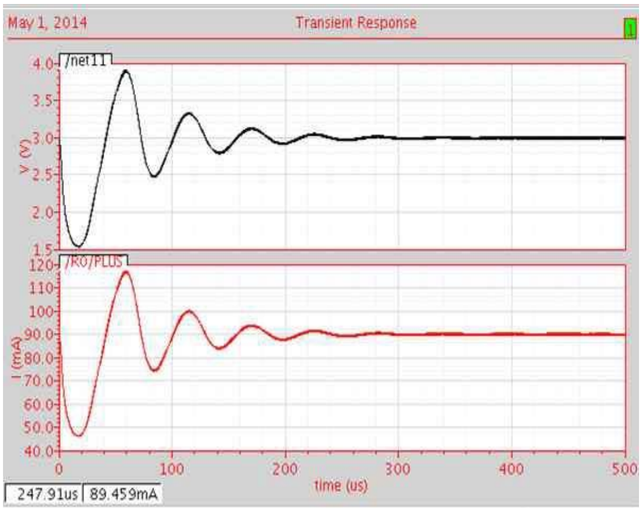

Fig. 11. Output of designed buck-boost converter

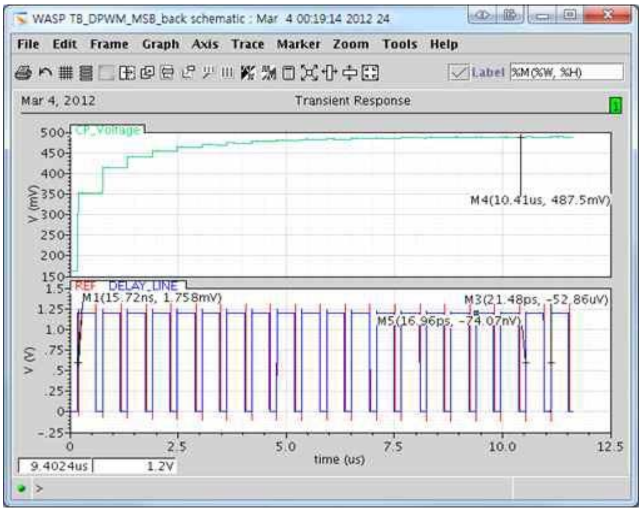

Fig. 12. DPWM DLL lock voltage and duty

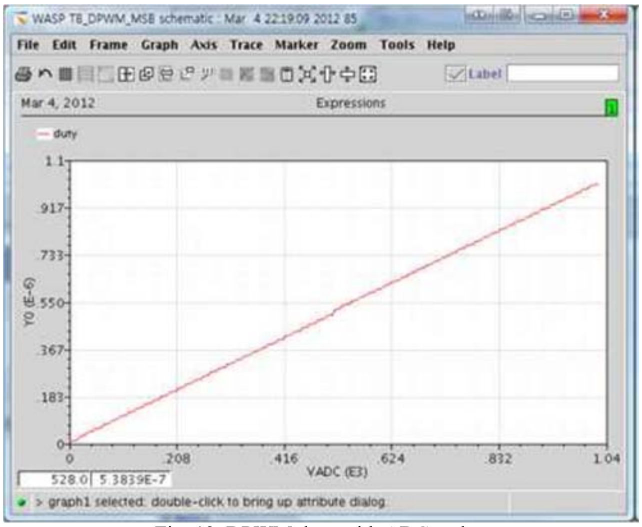

Fig. 13. DPWM duty with ADC code

Above figures are simulation result of proposed digital controlled buck-boost converter using Matlab and Cadence tool. Fig. 8 is Matlab Simulink result for Proposed PID controller. As shown that simulation result, proposed PID controller reduce an overshoot, undershoot and transient response time also when load current change in same condition. Fig. 9 is thermometer to output of binary converter. Fig. 10 is bode plot for designed ACR which has a 72.6dB DC gain. ACR has a 90 degree phase margin at unit gain frequency and ACR block will be stable because of phase margin. Fig. 11 is shown that output voltage and output current of buck-boost converter. In a simulation result, output voltage is 3V and output current is 90mA respectably. Fig. 12 is DPWM DLL lock voltage and duty cycle, as shown that simulation charge pump output voltage locked at 487.5mV and delay also locked by DLL at that point. Fig. 12 shows that DPWM duty with ADC code. As show in Fig. 12, DPWM step increases with same value when ADC code sweep with same value. In other words, DPWM will be controlled by code appropriately.

B. Chip verification plan

Measurement is now on going. First we will make the evaluation board after receiving the chip. After the board preparation, the measurements can be started. The bandgap voltage and operating frequency can be measured using Multi-meter and Oscilloscope respectively. After determining normal operation of bandgap voltage and operating frequency according to the control board values the normal operating point of the circuit can be determined. Output voltage and current can be measured by Multi-meter and Oscilloscope respectively. The output voltage will be checked with feedback duty signal in the circuit. The output current will be verified by checking the load current which is sinking enough. ACR output will be verified by Multi-meter and Oscilloscope. The increment and decrement in PWM duty of LED can be checked with the current probe and at the same time LED channel voltage can be measured. The DPWM can be measured with oscilloscope. Duty can be checked by applying SPI digital control. The system stability will be verified by Spectrum Analyzer and Oscilloscope.

C. Design information

TABLE II.
Design Information of circuit

Core Size	Number of Transistor	Number of Gate	Supplying Voltage	Maximum Operating Frequency	Circuit Type
1mm×1.2mm	15,000	1000	+3.3V -0V	1MHz	Mixed(Digital)

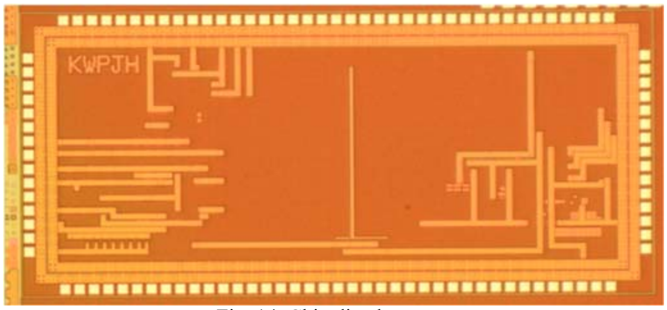

Fig. 14. Chip die photo

Table II is design information for designed circuit. A core size is 1mm×1.2mm except pad. Total Transistors is 15,000 and number of gate is 1,000 including a switch array. The maximum operating frequency is 1MHz at normal operating with PWM pulse. Fig. 14 shows a die photo of designed circuit. This circuit is implemented in 0.18um CMOS process.

IV. CONCLUSIONS

A digital controlled buck-boost converter for LED driver was proposed. By driving RGB type LED with time division, proposed LED driver provides a high quality of backlight for display module. Buck-boost converter designed with digital controller that is power efficiency and compensate a transient time. ACR block control a gate voltage for determination of minimum headroom voltage for prevent to degradation of power efficiency. Proposed LED driver including a pulse control function to control the optimal light characteristics using PWM duty and pulse. In addition, to compensate a forward biased voltage of LED according to temperature, the regulator block generates a self-controlled variable reference voltage that also provides an optimal power efficiency of power converter. Proposed Hybrid DPWM generator using DLL, it can be more robust to PVT than other DPWMs, and can compensate for variations in the delay line to produce more accurate output.

LED driver IC makes a low power chip-set projector for HD quality micro-display. It can adapt HMD that is fully capable of reproducing the 3D images also just not only smart glasses. Furthermore, LED driver IC is core part of pico-projector that has spot light recently in outdoor market.

Currently to overcome the situation that relies entirely on imports of HMD and pico-projectors it can be the part of these applications. In presenting the future direction it can change the digital lifestyle and it will be able to lead the new market.

The proposed LED driver actively controls the situation of changes in battery voltage. Thus it can reduce the power consumption by the digital design can be implemented in a small area without any discrete elements. Therefore, it is suitable for mobile applications as well.

ACKNOWLEDGEMENT

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