Design of a Buck-Boost Converter without Output Capacitor for Driving Automotive LED

Dong Soo Lee[1], Seung Gyun Ha, Byeong Ik Kim, Chae Young Kang, and Jeong Jin Roh[a]
Department of Electrical Engineering, Hanyang University
E-mail : [1]dlehdtn1998@hanyang.ac.kr

Abstract – **LEDs are widely used in automotive lighting systems due to their long lifespan, low power consumption, and fast response characteristics. Consequently, significant research has been conducted on LED drivers. Automotive LED drivers must rapidly adjust their output voltage to accommodate the wide input voltage range of vehicle batteries (7-60V) and the operating conditions of LED matrices. While buck-boost converters are commonly used for this purpose, conventional converters face the risk of LED damage caused by input voltage fluctuations and LED switching, primarily due to the presence of an output capacitor. To overcome this limitation, this study designs a buck-boost converter without an output capacitor. The designed buck-boost converter utilizes a flying capacitor structure, ensuring that LED current is always supplied through the inductor. Additionally, by adopting LED current-based feedback, both the current regulator and reference voltage controller are eliminated. The designed converter maintains a stable output voltage and LED current across an input voltage range of 7-60V. The chip was fabricated using TSMC's 180nm BCD process.**

Keywords—**Automotive LED, Buck-Boost Converter, Output Capacitor**

I. INTRODUCTION

The Light-Emitting Diode (LED) is known for its long lifespan and lower power consumption compared to traditional light sources such as halogen lamps [1]. Additionally, LEDs have the characteristic of turning on and off instantly, making them well-suited for signal lighting applications such as brake lights and turn signals [2], [3]. Due to these advantages, LEDs are actively utilized in automotive lighting systems, and research on LED drivers is being actively conducted. Automotive batteries, influenced by various conditions such as engine startup and load dump, have a wide input voltage range of 7-60V [4]. In an LED matrix, individual LEDs are controlled independently, and the required output voltage varies depending on the number of LEDs lit and their brightness. Therefore, automotive LED drivers must quickly adjust the output voltage according to the input and output voltage requirements. For this reason, buck-boost converters, which can increase or decrease the input voltage, are commonly used in automotive LED drivers [5].

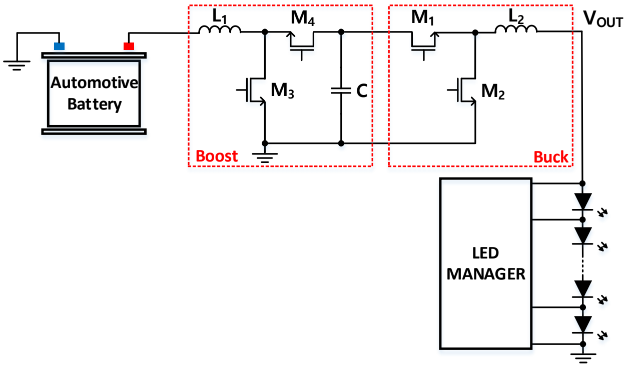
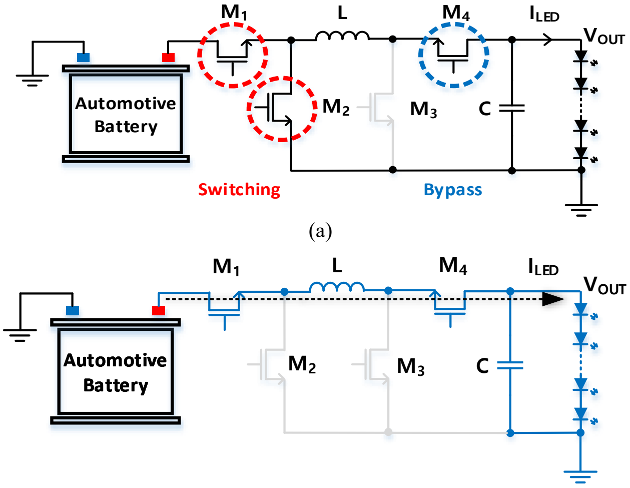


Fig. 1. Conventional automotive LED driver.

Typically, as shown in Fig. 1, a boost converter and a buck converter are used together to drive LEDs. The boost converter first steps up the voltage, and the buck converter supplies the required current for the LEDs. However, this configuration utilizes two inductors, leading to reduced efficiency and poorer Electromagnetic Interface (EMI) performance. Furthermore, larger inductors are required to minimize the ripple in the inductor current.



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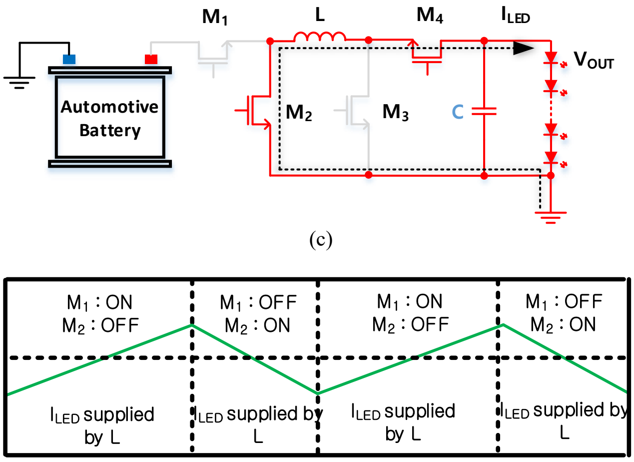
a. Corresponding author; jroh@hanyang.ac.kr

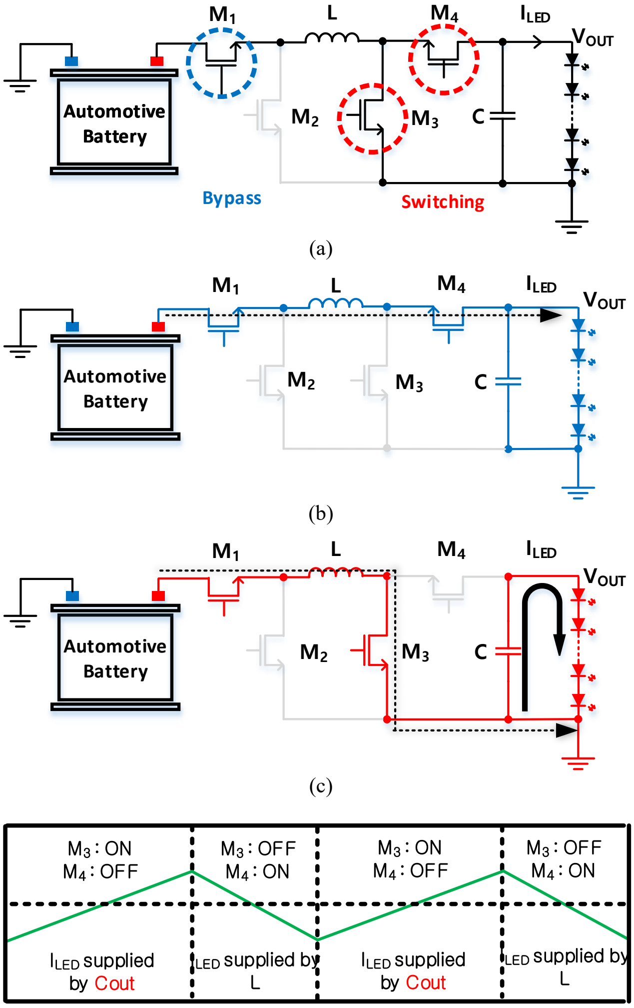
Manuscript Received Dec. 18, 2024, Revised Feb. 28, 2025, Accepted Mar. 17, 2025



(c)

(d)

Fig. 2. Non-inverting buck-boost converter (a) buck-mode, (b) on-time operation, (c) off-time operation, and (d) waveform of inductor current (adopted from [5]).



(a)

(b)

(c)

(d)

Fig. 3. Non-inverting buck-boost converter (a) boost-mode, (b) off-time operation, (c) on-time operation, and (d) waveform of inductor current (adopted from [5]).

In a non-inverting buck-boost converter, a single inductor is used, but an output capacitor is required for proper operation. Fig. 2 highlights the role of the output capacitor in both buck and boost modes. In the buck mode, as shown in Fig. 2(a), transistors M_1 and M_2 are switched, enabling the inductor to continuously supply the load current. This allows the converter to operate as a current regulator with little to no reliance on an output capacitor. Fig. 2 (b) and (c) illustrate the operating modes during the on-time and off-time phase in buck mode, respectively.

In contrast, during boost mode operation, depicted in Fig. 3(a), transistors M_3 and M_4 are switched. When M_4 is conducting, the inductor directly provides current to the load. However, when M_3 is conducting, the load current is supplied entirely by the output capacitor. Therefore, the inclusion of an output capacitor is crucial in boost mode to maintain a stable and continuous current supply. Fig. 3 (b) and (c) illustrate the operating modes during the on-time and off-time phases in boost mode, respectively.

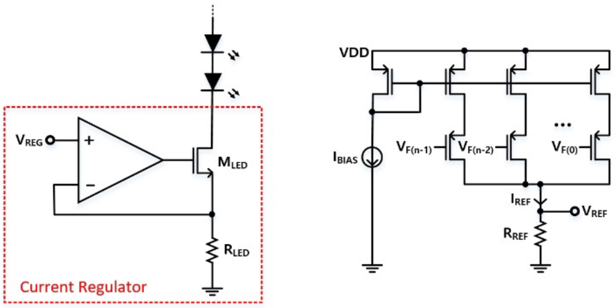


Fig. 4. Structure of the current regulator and reference voltage controller.

When driving an LED matrix with a non-inverting buck-boost converter, several challenges arise. Capacitors inherently resist instantaneous voltage changes, preventing the output voltage from responding quickly to the on/off switching of LEDs. This can lead to excessive current flow through the LEDs if the voltage exceeds the required level, potentially causing damage. To address this issue, as shown in Fig. 4, both a current regulator and a voltage regulator are required to ensure stable operation. The current regulator maintains a stable current to the LEDs, while the voltage regulator helps control the buck-boost converter under varying conditions, such as changes in input/output voltage and load current. This requires a feedback loop to dynamically adjust the converter's operation. In this system, the reference voltage for the error amplifier is determined based on the number of illuminated LEDs, necessitating the use of a reference voltage controller.

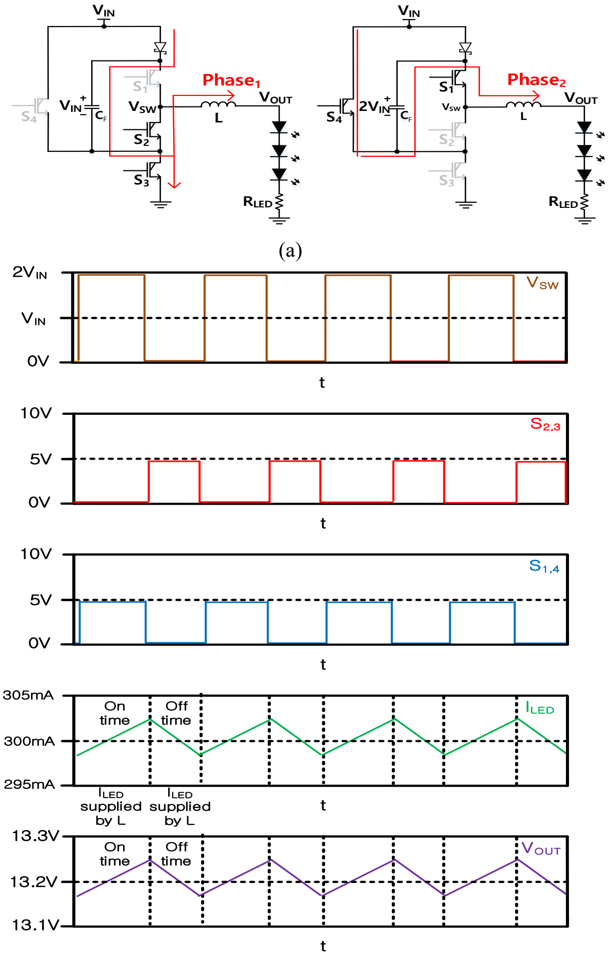
II. DESIGN METHODOLOGY

A. Power Stage

Fig. 5 (a) illustrates the power stage of the buck-boost converter implemented in this design. To eliminate the need for an output capacitor, a three-level buck-boost (TLBB) topology incorporating a flying capacitor is employed [6]. This topology is particularly effective for removing the output capacitor, as the inductor current is continuously directed toward the load current path. Since the output capacitor is eliminated, the ripple increases. However, by employing a large inductor of approximately 100 μH, both current ripple and voltage ripple are minimized, resulting in high current accuracy and fast transient response characteristics.

Previously, the operation of buck, boost, and buck-boost modes was determined by the combination of three distinct phases. However, in this design, only two phases are utilized.

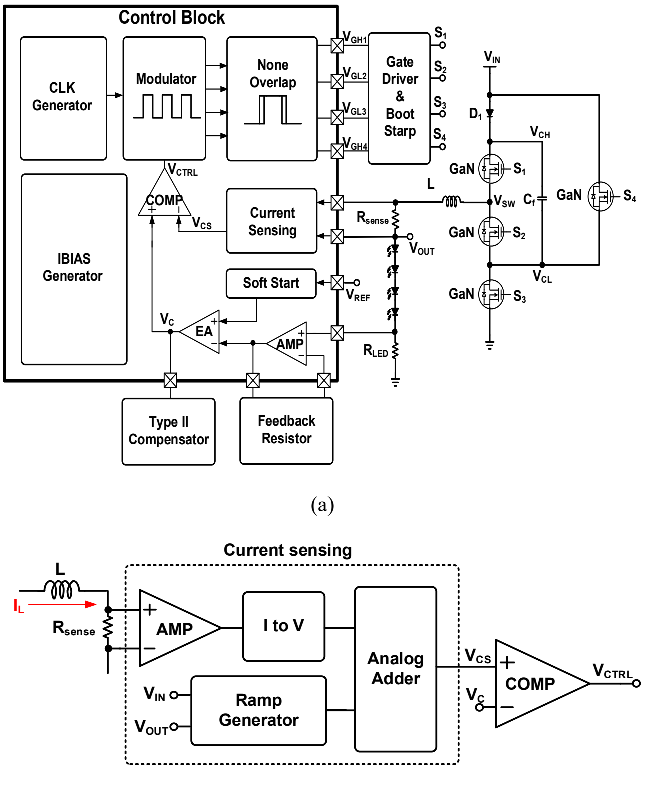
During Phase 1, switches S2, and S3 are activated, allowing the flying capacitor to charge with the input voltage. In phase 2, switches S1 and S4 are turned on, and the flying capacitor maintains the V_{IN} voltage, causing the capacitor voltage to double, becoming $2V_{IN}$. Based on the inductor volt-second balance, the conversion ratio is given by $V_{OUT}/V_{IN}=2D$, where D represents the duty cycle. As D varies between 0 and 1, this design achieves both step-up and step-down functionality within a single operational mode. Typically, mode selection in buck-boost converters relies on resistors, which are highly sensitive to process, voltage, and temperature variations. By eliminating the need for a mode selector, this design offers a significant advantage in terms of robustness and reliability. Fig. 5 (b) illustrates the switching operation of S1, S2, S3, and S4 in each phase during steady-state operation. It also presents the waveforms of the switching node voltage (VSW), the LED current (ILED), and the output voltage (VOUT).



(a)

(b)

Fig. 5. Designed buck-boost converter (a) operation phase, and (b) Waveform.



(a)

(b)

Fig. 6. Block diagram of (a) designed buck-boost converter, and (b) current sensing block.

B. Feedback Loop

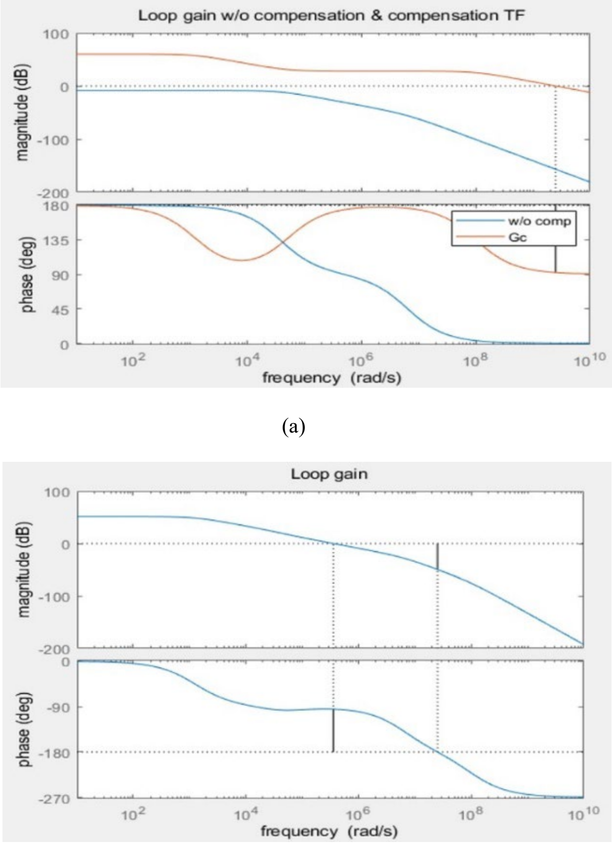
Fig. 6 presents the overall block diagram of the proposed buck-boost converter, including its feedback loop. The design incorporates four GaN switches, a Schottky diode, an inductor, sensing resistors, and a gate driver as off-chip components.

In contrast to conventional buck-boost converters, this design employs the LED current for feedback instead of the output voltage. The LED current is measured through the voltage across the resistor RLED. To minimize power losses, RLED is chosen to have a low resistance value, typically around 330 mΩ. The measured voltage is then amplified using an operational amplifier and compared with a reference voltage. If the LED current falls below the desired level, indicating insufficient output voltage, the feedback mechanism increases the duty cycle to compensate. This approach eliminates the need for a separate reference voltage controller, allowing the LED matrix to be effectively driven using a fixed reference voltage.

In Fig. 6(a), the system includes a clock generator that provides the necessary clock signal for a 5 MHz switching frequency. The current sensing block monitors the inductor current for current mode control. To prevent subharmonic oscillation, an artificial ramp generator is incorporated, ensuring stable operation. A soft start mechanism is implemented to gradually increase the duty cycle at startup, effectively preventing inrush current. The error amplifier (EA) and voltage regulator detect variations in the output voltage and regulate the system accordingly. Finally, a comparator and modulator process the information from the current sensing circuit and the error amplifier, generating an appropriate duty cycle to maintain stable and efficient operation.

The current sensing block, as illustrated in Fig. 6(b), consists of an amplifier (AMP), a voltage-to-current (V-to-I) converter, a ramp compensation circuit, and an analog adder. The inductor current is sensed through R_{sense} and then amplified by the AMP. The amplified inductor current is then converted into a voltage signal through the I-to-V block. To mitigate subharmonic oscillation, the voltage waveform from the ramp generator is added via an analog adder to implement slope compensation. The resulting Vcs output is then compared with the Vc output from the EA, and the comparator generates the PWM signal accordingly.

A type-2 compensator is used in this study. The buck-boost converter and compensator were modeled using MATLAB and Simulink. Since the operation of the circuit is fundamentally similar to that of a buck converter, a conventional converter model was modified for this purpose. In the absence of an output capacitor, approximate compensation values were initially determined using MATLAB and later fine-tuned through simulations. Fig. 7 displays the AC response obtained from the MATLAB simulation.



(a)

(b)

Fig. 7. AC simulation of (a) power loop and compensator, and (b) overall control to the output transfer function.

III. RESULTS AND DISCUSSION

The designed buck-boost converter was fabricated using TSMC's BCDMOS HV 180nm process. The overall implementation utilized 5V SVT (Standard Threshold Voltage) MOS devices, and LDMOS (Laterally Diffused MOS) devices. The final chip layout is presented in Fig. 8.

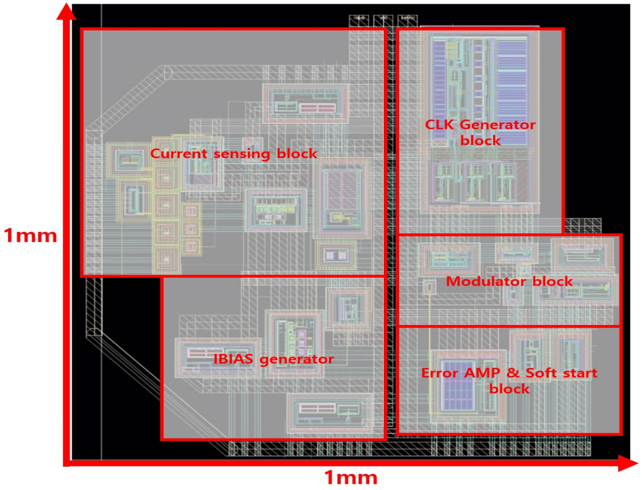


Fig. 8. Chip layout.

The buck-boost converter developed in this study is designed for high-frequency operation, targeting a switching frequency of 5 MHz. To achieve this, GaN (Gallium Nitride) power transistors are employed. The simulation result shown in Fig. 9 demonstrates that the output voltage is appropriately adjusted as LEDs are turned on and off individually, while the LED current remains constant.

Fig. 10 presents the power conversion efficiency as LEDs are switched on and off, confirming that the peak efficiency reaches 91.5%. Additionally, Fig. 11 illustrates the current accuracy of the LED current depending on the number of illuminated LEDs. When five LEDs are turned on, the current accuracy reaches 99.3%, demonstrating highly precise current regulation.

Table I presents a summary of the system and components used in the hardware prototype.

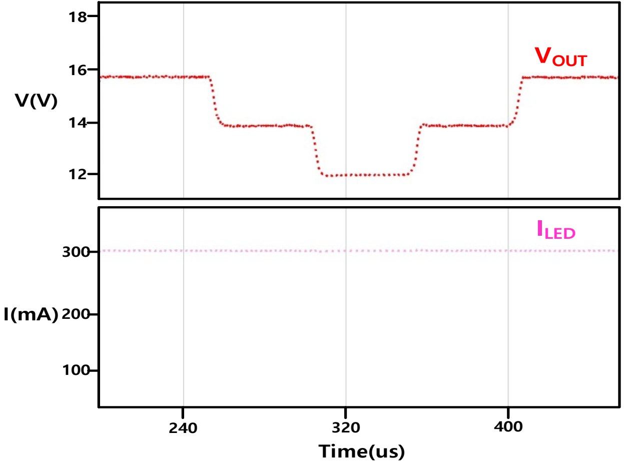


Fig. 9. Load regulation of the designed buck-boost converter.

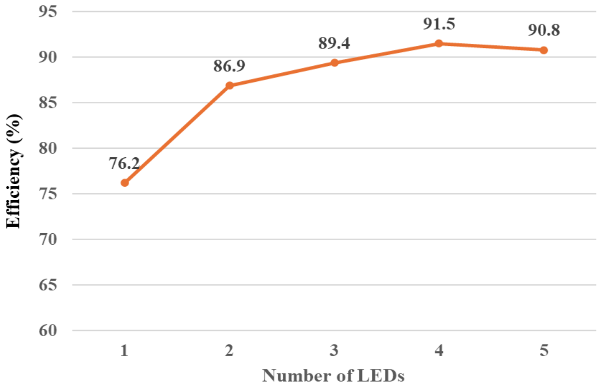


Fig. 10. Efficiency according to the number of LEDs.

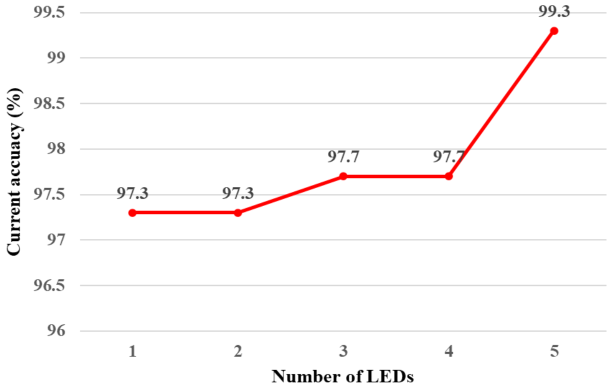


Fig. 11. Current accuracy according to the number of LEDs.

TABLE I. EXPERIMENTAL SPECIFICATIONS.

Symbol	Quantity
Input Voltage V_{IN}	7~60 V
Output Voltage V_{OUT}	7~60 V
LED Current I_{LED}	300 mA
Switching Frequency F_{SW}	5 MHz
Power Switches	EPC2214
Gate Drivers	1EDN7116UXTSA1
Power Inductor L	100 µH
Flying Capacitor C_F	10 µF

IV. CONCLUSION

In this study, to effectively drive an automotive LED matrix, a structure without an output capacitor was designed using LED current as feedback. The design employs GaN power switches operating at a high frequency of 5 MHz. By eliminating the output capacitor, the system achieves rapid output voltage adjustments, enabling quick responses to dynamic operating conditions. Furthermore, the removal of the current regulator and reference voltage controller was possible.

ACKNOWLEDGMENT

The chip fabrication and EDA Tools were supported by the IC Design Education Center (IDEC).

This work was supported in part by the Korea Evaluation Institute of Industrial Technology (KEIT) grant funded by the Korean government (MOTIE) (No.00154973, Development of Integrated Power System with Embedded GaN device for Intelligent Multi-LED Headlamp of Electric Vehicle); in part by the Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE) (The Competency Development Program for Industry Specialist under Grant P0012451;

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Dong Soo Lee received the B.S. degree in electronic engineering from Hanyang University, Ansan, Korea, in 2023. He is currently working toward the M.S. degree in electronic engineering at Hanyang University, Ansan, Korea. His current research interests include integrated power management ICs design and high-performance DC-DC Converter design.

Seung Gyun Ha received the B.S. degree in electronic engineering from Chungju University, Chungju, Korea, in 2023. He is currently working toward the M.S. degree in electronic engineering at Hanyang University, Ansan, Korea. His current research interests include integrated power management ICs design and high-performance DC-DC Converter design.

Byeong Ik Kim received the B.S. degree in electronic engineering from Hanyang University, Ansan, Korea, in 2023. He is currently working toward the M.S. degree in electronic engineering at Hanyang University, Ansan, Korea. His current research interests include integrated power management ICs design and high-performance DC-DC Converter design.

Chae Young Kang received the B.S. and M.S. degrees in electronic engineering from Hanyang University, Ansan, Korea, in 2022 and 2024, respectively. Her main interests are integrated power managements ICs design and high-performance DC-DC Converter design.

Jeong Jin Roh (Senior Member, IEEE) received the B.S. degree in electrical engineering from Hanyang University, Seoul, South Korea, in 1990, the M.S. degree in electrical engineering from Pennsylvania State University, in 1998, and the Ph.D. degree in computer engineering from The University of Texas at Austin, in 2001. From 1990 to 1996, he was a Senior Circuit Designer for mixed-signal products with Samsung Electronics, Giheung, South Korea. From 2000 to 2001, he was a Senior Analog Designer for delta-sigma data converters with Intel Corporation, Austin, TX, USA. He joined the Faculty of Hanyang University, Ansan, South Korea, in 2001. His research interests include power management circuits and oversampled delta-sigma converters.