An Energy Efficient OLED Lamp Driver for Wearable Light Therapy Device

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***Abstract* - In this study, we propose a power conversion circuit capable of self-compensation for the organic light emitting diode (OLED) based light therapy and optical platform. In order to compensate for degradation caused by a long time operation of the OLED, a constant-current driving of the OLED should be used instead of constant-voltage driving of the OLED. To increase the efficiency of the OLED lamp driver, a single-stage structure which is combined power stage and OLED current driving stage, is suggested. Also, the SenseFET-based current sensor is used for accurate, continuous, and lossless current sensing. This study was conducted based on the TSMC 180-nm BCD process and implemented a high-efficiency OLED driving system with 2V supply voltage, an efficiency of 90.9% at 1MHz.**

Keywords—Lossless-current sensor, OLED lamp driver, Wearable light therapy device

I. INTRODUCTION

Human attachment therapy device is in the spotlight as the next-generation medical treatment method. Among them, light therapy is a promising treatment with advantages of non-invasive, patient safety, and no side effects. Therefore, researches for light therapy have been conducted for a long time. In particular, there have been many research results in the field of skin wound promotion, and in practice, the medical field uses light therapy as a treatment. In recent years, beyond wound treatment, the effectiveness of light therapy in various areas, such as insomnia and dementia prevention, has been revealed. [1] As a result, the benefits of light therapy have become prominent, and research on making light platforms related to it has also been in the spotlight. [2]

In the past, light therapy treatments have been conducted using light-emitting diode (LED) as a light source. However, in the case of point light sources such as LEDs, it is difficult to irradiate uniform light over a large area and has a local heating problem which is hazardous to the human body. Therefore, in order to obtain the uniform light in a large area, the size of the light source becomes large. In addition, since

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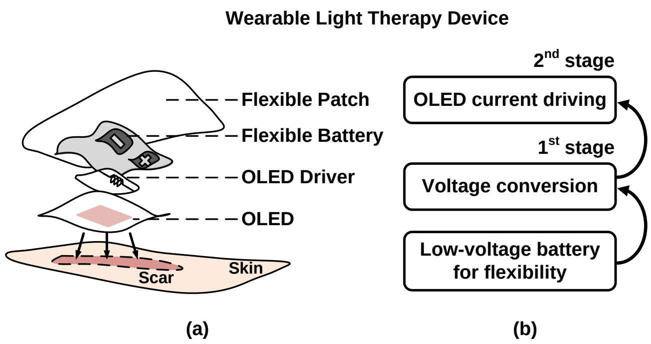


Fig. 1. (a) Concept and (b) requirements of wearable light therapy devices.

the material is hard, it is difficult to make a flexible form, which is difficult to attach to the human body. Until now, because of these characteristics, light therapy devices are large equipment which is installed in hospitals. However, as the effect of light therapy is remarkable, the demand for small-sized homecare devices or wearable devices increases.

An OLED, which is being commercialized in recent years, is a new light source of wearable light therapy devices. As an OLED can be manufactured in a thin film, it has a form of a surface light source and flexibility. In addition, OLED light sources can operate at lower power than conventional LED light sources, so they can be used in portable devices using batteries. The OLED basically has similar current-voltage characteristics with diodes, and the luminance of the OLED is proportional to the density of the OLED current. However, OLEDs are vulnerable to the heat generated by Joule heating due to their physical properties of using organic materials to emit light. In the end, a threshold voltage of the OLED increases by joule heating. If the OLED drives at the constant voltage, the current density of the OLED decreases, and the luminance decrease. Therefore, to use the OLED as a light source of the wearable light therapy device, it is important to control the current of the OLED accurately.

A small-sized and flexible battery is suitable in the wearable light therapy device [3]. However, the flexible battery has limited voltage levels and capacities. Fig. 1. (a) shows the wearable light therapy device consisting of a flexible battery and the OLED as a light source. Because the flexible battery has a low voltage level, to drive the OLED, which has a large threshold voltage, a voltage conversion stage is needed before the OLED-current driving. This cascaded structure consumes large power and limits the battery life. So, the energy-efficient OLED-current driving technique is required for the wearable light therapy device. In this paper, we propose a high-efficient OLED-current driving circuit that can control the OLED current accurately and efficiently.

II. SYSTEM ARCHITECURE

A. Voltage-conversion stage of the OLED lamp driver

As shown in Fig. 1., an OLED lamp driver for wearable light therapy devices consists of a voltage-conversion stage and an OLED-driving stage. Fig. 2. (a) shows a conventional boost converter-based OLED lamp driver. The OLED has a large threshold voltage which is typically larger than 5V. Due to this large threshold voltage, the voltage level of the flexible battery, which is usually lower than 2V, should be converted by a boost converter. The boost converter steps up the output voltage V_{OUT} by turning on the S_1 and S_2 alternatively. In the D phase, S_1 is on, and the inductor builds up the energy at the rate of V_{IN}/L. Next, in the D′ phase, the energy is used to drive the output voltage, V_{OUT}, and the inductor current decreases at the rate of $(V_{IN}-V_{OUT})/L$. The bottom of Fig. 2. (a) shows timing diagrams of the boost converter. The voltage stress of power switches is V_{OUT} at the boost converter. If more current of the OLED is needed, the

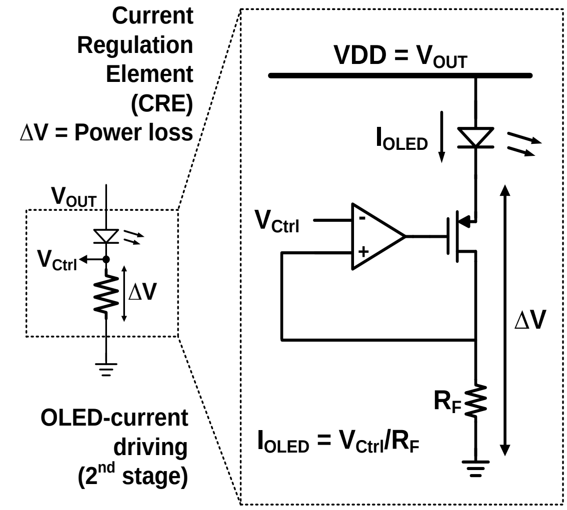


Fig. 3. Circuit schematic of the OLED-current driving stage

larger V_{OUT} is required at the voltage conversion stage, and this large V_{OUT} incurs the large voltage stress at power switches.

The single-inductor bipolar-output (SIBO) converter mitigates this voltage stress at the voltage-conversion stage. The SIBO converter drives the output voltage with a positive voltage, VOP, and negative voltage, VON. By using this separated output voltage, the voltage stress of the SIBO converter is lower than that of the conventional boost

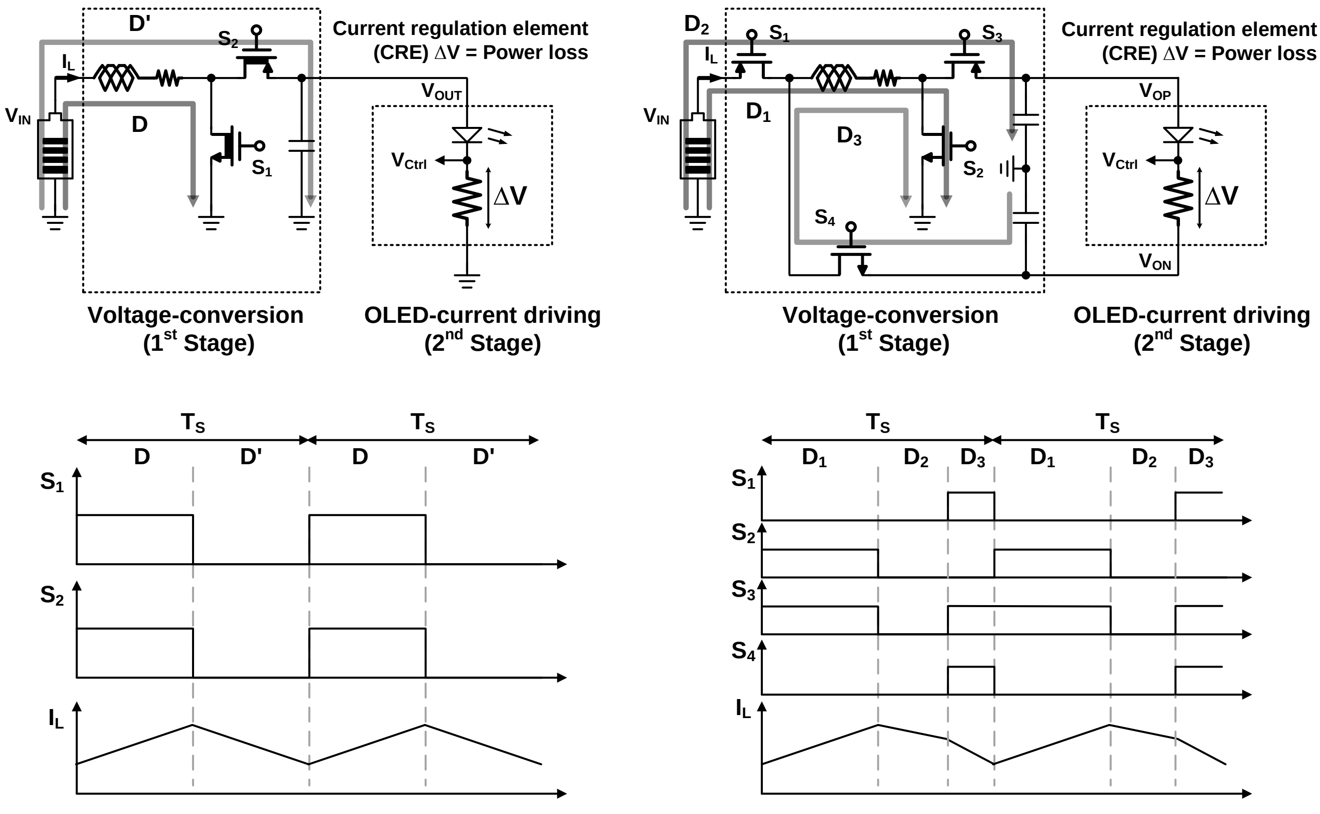
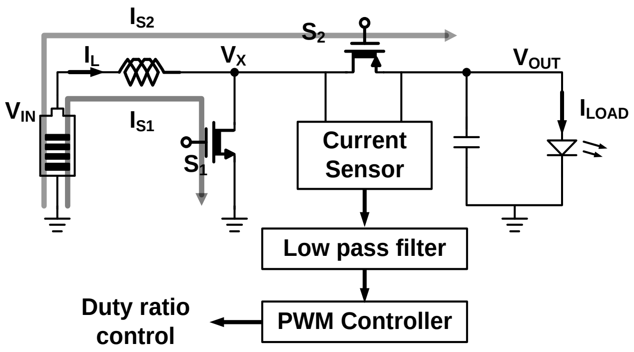


Fig. 2. (a) Conventional boost converter based OLED lamp driver [4] and (b) single inductor bipolar output (SIBO) based OLED lamp driver [5].

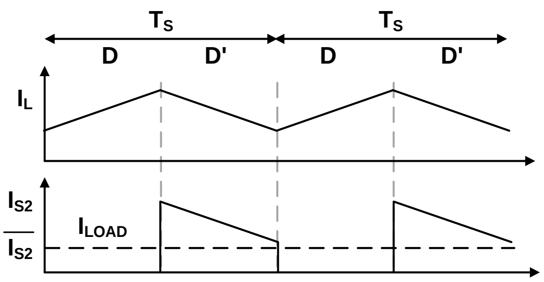
converter. The SIBO converter operates in three phases which are D_1, D_2, and D_3. The bottom of Fig. 2. (b) shows timing diagrams of the SIBO converter. In the D_1 phase, S1 and S2 switches are on, and the inductor builds up the energy at the rate of V_{IN}/L. In the D_2 phase, the V_{OP} is derived by the energy of the inductor, and the inductor current decreases at the rate of $(V_{IN}-V_{OP})/L$. Finally, at the D_3 phase, V_{ON} is derived through the rest energy of the inductor, which remains after driving the V_{OP}, and the inductor current decreases at the rate of V_{ON}/L.

B. OLED-current driving stage of the OLED lamp driver

For maintaining the constant and uniform luminance of the light therapy device, the current of the OLED should be regulated, as explained in the introduction. However, the voltage conversion stage of the OLED lamp driver regulates the output voltage, not the current of the OLED. Therefore, the OLED-current driving stage is needed to regulate the current of the OLED. In the OLED-current driving stage, a current regulation element (CRE) such as a resistor is used, and the voltage drop at the CRE incurs the additional power loss. This power loss becomes significant when a large OLED current is needed. Fig. 3. shows the detailed OLED-current driving circuit consisting of a PMOS feedback loop and a resistor, R_F. The VDD of the OLED-current driving stage is the regulated output voltage of the voltage-conversion stage. The PMOS feedback loop makes the voltage of R_F as V_{Ctrl} and regulates the current flows through the R_F as V_{Ctrl}/R_F. At the same time, the same amount of current flows through the OLED. Therefore, the current of the OLED is regulated as V_{Ctrl}/R_F. However, this topology makes the voltage drop at the load because the CRE is connected in series. To regulate the OLED current exactly, the loop gain of the PMOS feedback look should be large, and typically 250mV of the voltage drop is needed. This voltage drop makes additional power loss at the OLED-current-driving stage.



(a)



(b)

Fig. 4. (a) Block diagrams of the proposed OLED lamp driver using boost converter (b) relation between the inductor current and the load current at the boost converter

C. Proposed OLED lamp driving circuit

In this study, a boost converter structure is used to drive the OLED with a high threshold voltage over 5V using a low input voltage lower than 2V. Fig. 4. (a) shows block diagrams of the proposed OLED lamp driver. The proposed OLED lamp driver removes the additional power loss which is consumed while regulating the OLED current by directly controlling the load current at the voltage-conversion stage without the need for any additional current-regulation element (CRE). Fig. 4. (b) shows the relation between the inductor current and the load current at the boost converter. In the boost converter, the inductor current is transferred to the load only at D' phase through the S_2 switch. So the transferred current through the S_2 switch, which is I_{S2}, is the same as the inductor current at the D' phase, and no current flows at the D phase. Therefore, the load current is the same as the average value of the I_{S2} during a period. As Fig. 4. (a), we can regulate the load current, which is the same as the OLED current using the current sensor at the S_2 switch and the low-pass filter.

An accurate and lossless current sensor is required at the S2 switch to regulate the load current without the current regulation element. Fig. 5. shows the SenseFET [4] based current sensor. A PMOS feedback loop makes the source voltage of the SenseFET as V_{OUT}. Because the drain of the S2 switch and SenseFET are tied together, the SenseFET senses the the current which flows through the S_2 switch as the size ratio between S_2 and SenseFET. For minimizing the

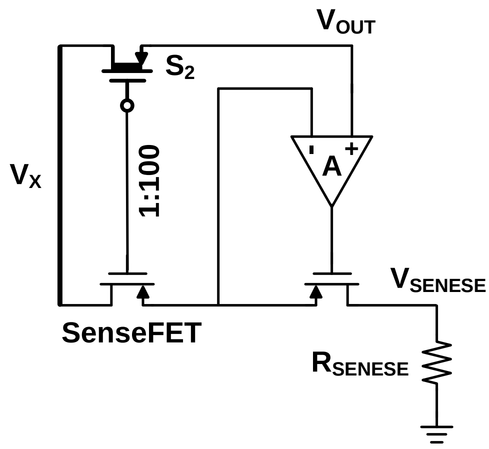


Fig. 5. SenseFET based current sensor [7]

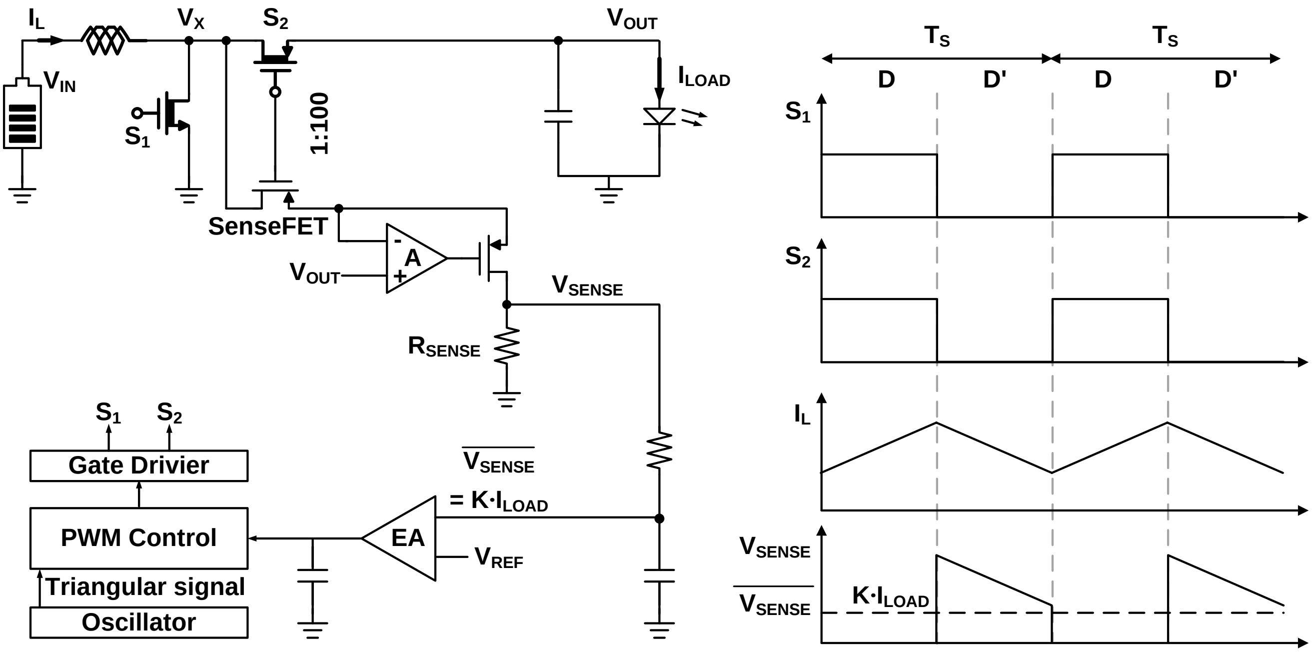


Fig. 6. The overall circuit schematic of the proposed OLED lamp driver and its timing diagrams

wasted energy at the current sensor, the size ratio between the SenseFET and the S_2 switch is set to one over one hundred. For accurate-current sensing, the amplifier of the current sensor should have large bandwidth and enough gain. The folded-cascode amplifier with a source follower buffer is used to obtain high gain and large bandwidth.

Fig. 6. shows the overall circuit schematic of the proposed OLED lamp driver. The LDMOS power switches are used due to large voltage stress to drive the OLED, which has a large threshold voltage. The current which flows through the S_2 is sensed and converted to V_{SENSE} by R_{SENSE}, and then, the V_{SENSE} is averaged by passive low pass filter. Finally, we can achieve the load current data through the average value of V_{SENSE}, which is $K \cdot I_{LOAD}$, where the K is $R_{SENSE}/100$. By using this sensed I_{LOAD} value as an input of the error amplifier EA, the duty ratio of the boost converter operation is determined, and the load current is regulated to reference value.

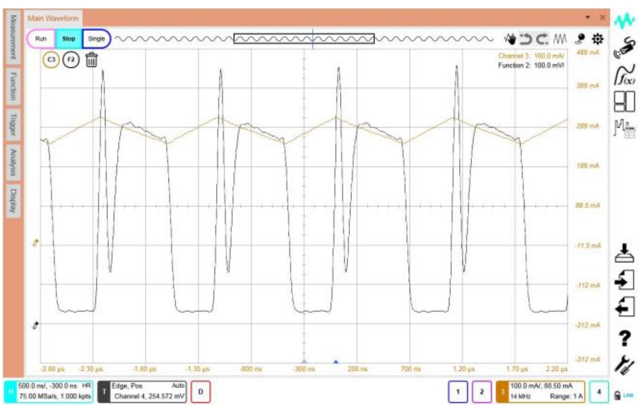
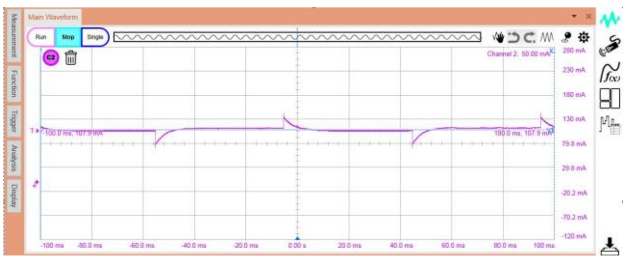
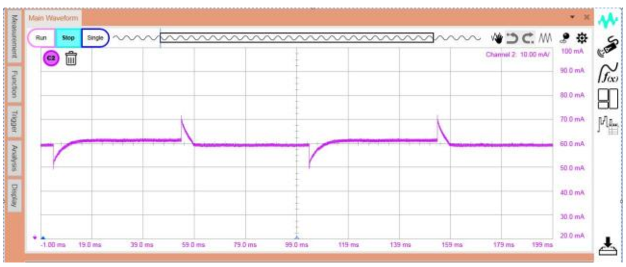


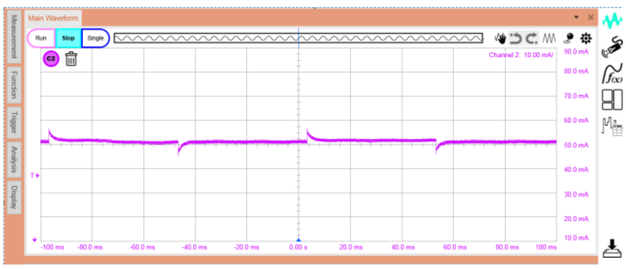
Fig. 7. Waveform of inductor current and V_{SENSE} value



(a) I_{LOAD} = 108mA



(b) I_{LOAD} = 60mA



(c) I_{LOAD} = 50mA

Fig. 8. Waveforms of the load current regulation at V_{IN} changes from 1.8V to 2.0V at R_{LOAD} is 100Ω.

III. RESULTS AND DISCUSSIONS

Fig. 7. shows measured waveforms of the current sensor and the inductor current. The yellow line is the inductor-current waveform of the proposed OLED lamp driver, and the black line is the V_{SENSE} waveform of the current sensor. Because the current flows through the S_2 switch only at the D' phase, the Fig. 7. shows that the black line follows the yellow line closely at the D' phase at 1MHz switching frequency. Fig. 8. shows the measured waveforms of regulated load current changing the V_{IN} between 1.8V and 2V. It presents that the proposed OLED lamp driver operates successfully at the load current of 50mA, 60mA, and 108mA when the R_{LOAD} is 100Ω. The chip which is fabricated in a TSMC 180-nm BCD process is shown in Fig. 9., and it occupies an area of 1.5mm×2.5mm. The Fig. 10. shows the measured efficiency of the proposed OLED lamp driver at R_{LOAD} is 100Ω. The measured peak efficiency is 90.9% at I_{LOAD} is 90mA.

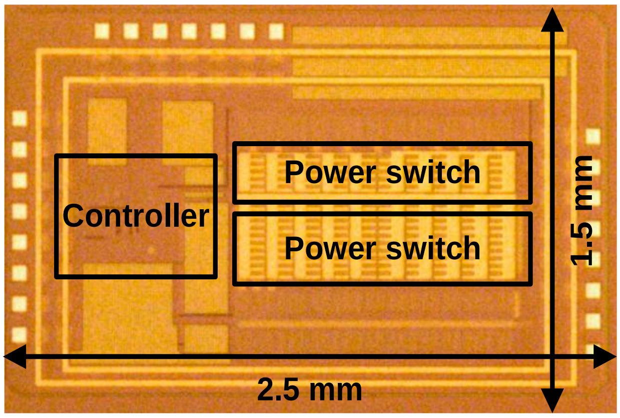


Fig. 9. Chip micrograph

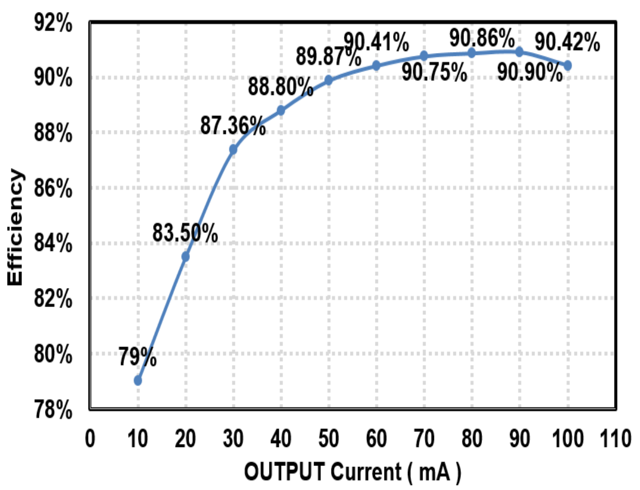


Fig. 10. Measured efficiency of the proposed OLED lamp driver at R_{LOAD} is 100Ω.

IV. CONCLUSIONS

In this paper, we present an energy-efficient OLED lamp driver for a light therapy device. The additional current regulation element, which is used for regulating the OLED current, is removed by combining the voltage conversion stage and the OLED-current regulation stage into a single stage. An accurate and lossless SenseFET based current sensor regulates the OLED current at the voltage conversion stage. Therefore, the additional power loss which occurs at the load is removed, and 90.9% of the peak efficiency is achieved at the I_{LOAD} of 90mA when R_{LOAD} is 100Ω.

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REFERENCES

[1] Barolet, Daniel, et al. "Regulation of skin collagen metabolism in vitro using a pulsed 660 nm LED light source: clinical correlation with a single-blinded study." Journal of Investigative Dermatology129.12 (2009): 2751-2759.

[2] Jablonski, Michal, et al. "Conformable, low level light therapy platform." Biophotonics: Photonic Solutions for Better Health Care IV. Vol. 9129. International Society for Optics and Photonics, 2014.

[3] Y. Jeon, H.-R. Choi, J. H. Kwon, S. Choi, K.-C. Park, and K. C. Choi, "Wearable photobiomodulation patch using attachable flexible organic light-emitting diodes for human keratinocyte cells," in *SID Symposium Digest of Technical Papers*, May 2018, pp. 279–282.

[4] T.-H. Kong, S.-W. Hong, and G.-H. Cho, "A 0.791 mm^2 on-chip self-aligned comparator controller for boost DC-DC converter using switching noise robust charge-pump," *IEEE Journal of Solid-State Circuits*, vol. 49, pp. 502–512, Feb. 2014.

[5] K.-L. Lin, S. S. Ng, T.-C. Huang, K.-H. Chen, S.-F. Liu, P.-H. Chiu, S. Chen, C.-Y. Shen, M.-T. Hsieh, and H.-A. Li, "A single-inductor bipolar-output DC/DC converter with high efficiency over wide load range for active matrix OLED," in *SID Symposium Digest of Technical Papers*, June 2014, pp. 1183–1186.

[6] C. F. Lee and P. K. T. Mok, "A monolithic current-mode CMOS DC-DC converter with on-chip current-sensing technique," *IEEE Journal of Solid-State Circuits*, vol. 39, pp. 3–14, Jan. 2004.

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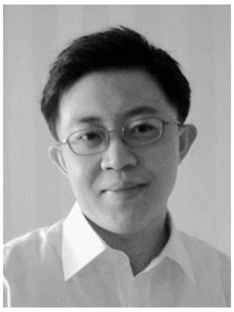

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