Design of a CMOS Led Print Head Driver With Compensation Circuits

Cheng-Ta Chiang, *Member, IEEE*, Chun-Ting Kuo, and Yu-Chung Huang

***Abstract*—In this paper, a CMOS LED print head driver with compensation circuits is newly proposed. Due to the process and fabrication variations, two compensation circuits are proposed. One is to perform the chip compensation, and the other is to do the pixel compensation. Besides, a method of a single-chip segment exposure is also proposed to make the power consumption more efficient. Based upon the device parameters of 0.5 μm 1P2M CMOS technology with 3.3 V power supply, all the functions and performance of the proposed CMOS LED print head driver with compensation circuits are successfully tested and proven through measurements. The area including ESD I/O pads is $2000 \times 2000\ \mu m^2$. The proposed chip is suitable for LED printers.**

***Index Terms*—Compensation circuits, LED printer, LED print head driver.**

I. Introduction

NOWADAYS, electrophotographic printers play a main role in the office and family. In the commercial printer market, both laser and ink printers are the most common printers. Although a laser printer has better printing quality than an ink printer, the cost of a laser printer is higher than an ink printer [1], [2]. To reduce the high cost and simplify the system complication, a technique of light emitting diode (LED) [3] applied on the printers is proposed. Although LED printers are still under researched, some achievements [4]–[10] are openly discussed. However, some achievements [4]–[7] mainly focus on bonding techniques of LED printers. For example, the bonding design of the chip-matrix LED print head and characteristics of the chip matrix LED are introduced in [4]. Three-dimensional epitaxial thin-film bonding is discussed in [7]. In this work, different to previous issues [4]–[7], circuit discussions of a CMOS LED print head driver with compensation circuits are firstly described. We not only propose a method of a single-chip segment exposure to improve power consumption of an LED array, but also compensation circuits to perform the chip and pixel compensation. Readers can understand the whole design techniques from this work, and this is the main contribution of this work.

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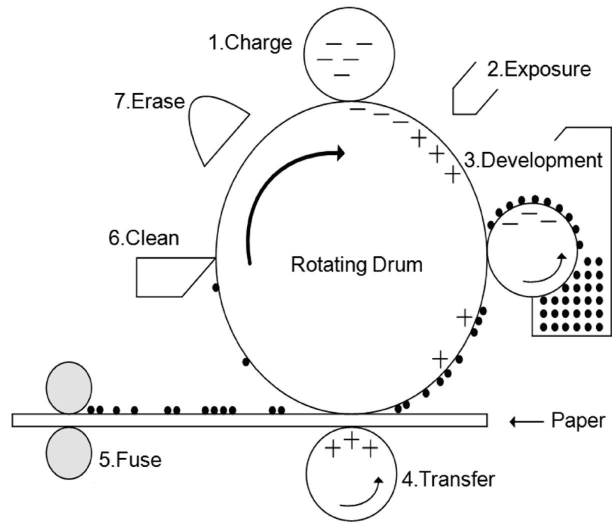


Fig. 1. The printer procedures of electrophotographic printers.

In this paper, a CMOS LED print head driver with compensation circuits is newly proposed. Compared with traditional pulsewidth modulation (PWM) [9], [10], this work improves the traditional PWM into dynamic pulsewidth modulation (DPWM). The improved circuit is easily implemented, and can make pulsewidth more adjustable for applying on the LED printer head drivers. With the design of DPWM, a proposed method of a single-chip segment exposure can make the power consumption more efficient. Another issue is the compensation techniques. Due to the process and fabrication variations, the characteristics of each driver IC or an LED pixel are different. To solve this problem, two compensation circuits are designed in the proposed chip. One is to perform the chip compensation, and the other is to do the pixel compensation. In Section III, these two compensations will be discussed in more detail. All the functions and performance of the proposed CMOS LED print head driver with compensation circuits are successfully tested through measurements. The chip area including ESD I/O pads is $2000 \times 2000\ \mu m^2$. The proposed chip is suitable for LED printers.

In the Section II, the operations of electrophotography printers are addressed. Section III discusses system architecture and simulation results. Section IV demonstrates the measurements. Finally, conclusions and future works are described.

II. The Operations of Electrophotography Printers

The printing procedures of electrophotography printers need seven steps as shown in Fig. 1. These steps are charge, exposure, development, transfer, fuse, clean, and erase. Among these

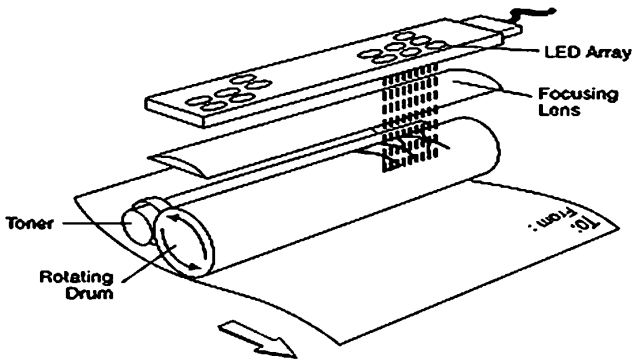


Fig. 2. Structure of the LED printer [8].

TABLE I
COMPARISONS OF LASER PRINTER HEAD AND LED PRINT HEAD

	Stability	Volume	Speed	Resolution	Cost
Laser Print Head	X	X	X	O	X
LED Print Head	O	O	O	X	O

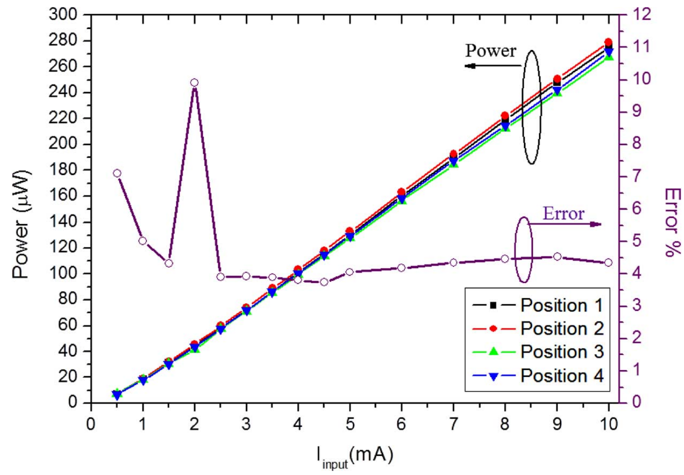


Fig. 3. Measured results of power versus inputting current of LED and error between 4 LEDs that were fabricated in the same material.

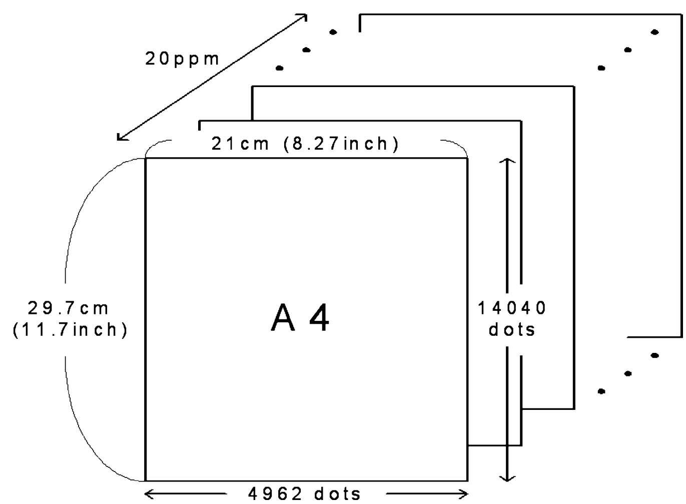


Fig. 4. Paper format used in the specification.

steps, the exposure is the most important step. It can largely decide the printing quality. In electrophotography printers, the lighting source can be generated by a laser diode or an LED array.

A laser printer includes a laser diode, complicated lens machinery, and a set of rotating multi-mirrors. This complicated system uses the principle of light refraction to perform the scanning operation and then to expose a column of printed data. The benefit is that laser does not have the scattering problem as general white light has. However, the disadvantage is that the cost of the whole system is higher, and the complicated systems designed to control the rotating multi-mirrors make the volume of printers larger. Sometimes, the stability of mechanical structure of laser printers is not good. The printing quality is thus affected.

To solve the problems of larger volume, worse stability, and high cost, LED printers [8] are proposed as shown in Fig. 2. The complicated systems, such as lens machinery and rotating multi-mirrors, can be totally removed. The stability is raised and the volume is reduced. Besides, the printing speed can be faster than a laser printer due to its simple machinery of LED printers. However, the resolution is still limited by LED technology and its package. The problem of resolution can be improved by following the industrial progress. The comparisons of these two kinds of printers are summarized in Table I.

LED print head consists of LED pixels and drivers. Both of them are connected by wire bonding [4]–[6]. The lighting performance is both controlled by LED and its driver. The characteristics of LED pixels are measured as shown in Fig. 3. Four LED pixels are measured. The relationship between power and inputting current of LED is linear. The error between LED pixels is derived as

$$\text{Error\%} = \frac{Y_{\max} - Y_{\min}}{\frac{1}{2}(Y_{\max} + Y_{\min})} \times 100 \tag{1}$$

where $Y_{\max}$ and $Y_{\min}$ are the maximum and minimum power of LED pixels under the same inputting current. Below the inputting current of 2 mA, the error is not uniform within 6%. It is not uniform until the inputting current is larger than 2.5 mA. This result is used to specify the driving current of each LED pixel. On the other hand, LED print head drivers can largely decide the main performance of LED printers. In Section III, the proposed CMOS LED print head driver with compensation circuits will be discussed. In the specification of this work, the paper format is an A4 type as shown in Fig. 4. The resolution is 1200 dots per inch (DPI). The printing speed is 20 pages per minute (PPM). The driving current of each LED pixel is 2.5 mA.

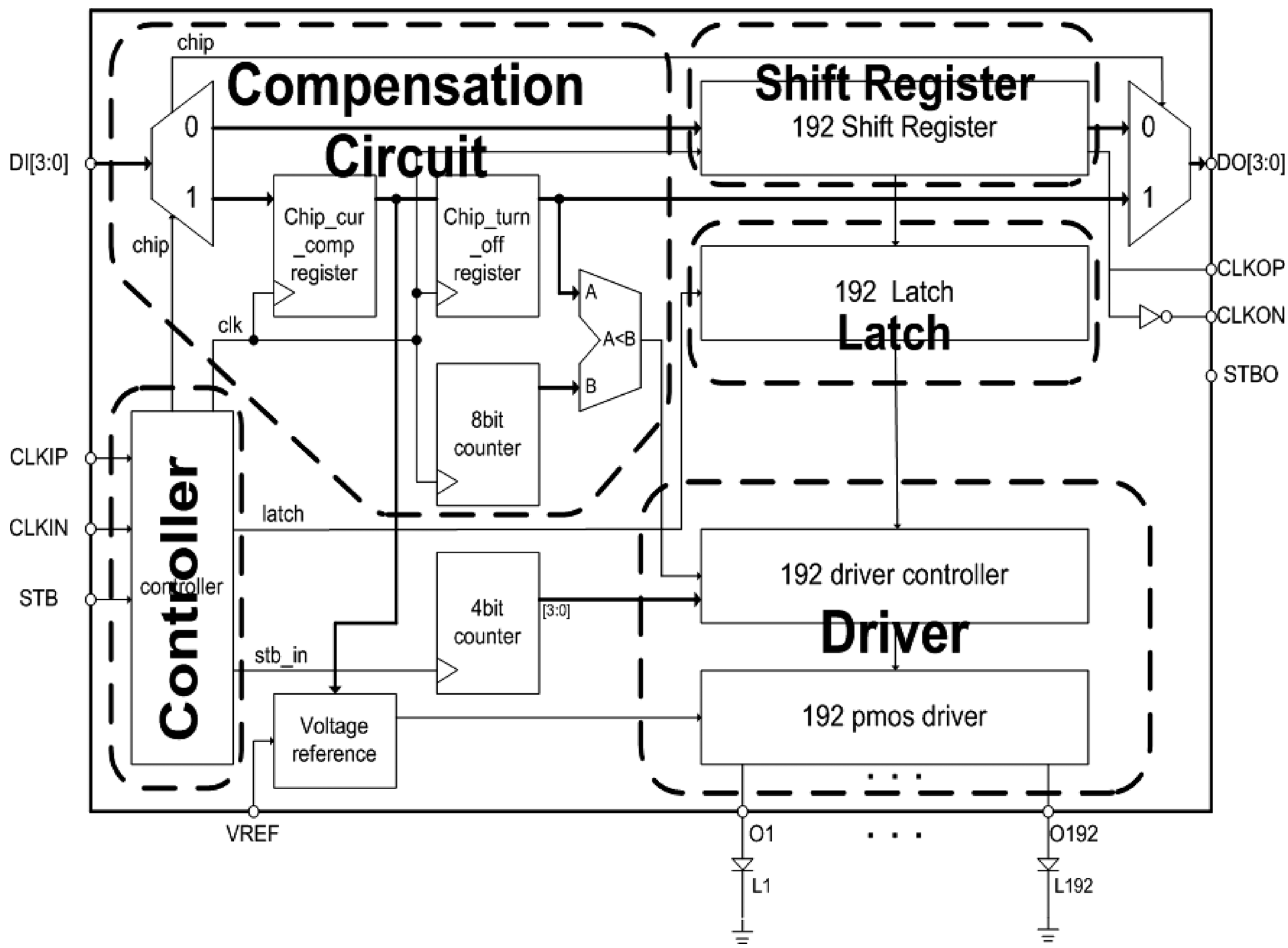


Fig. 5. Circuit diagram of the proposed LED printer driver with compensation circuits.

III. System Architecture and Simulation Results

The proposed CMOS LED print head driver with compensation circuits is shown in Fig. 5. The proposed circuits include control circuits that control three state transitions, shift registers and latches, compensation circuits, and output LED drivers.

A. Control Circuits of State Transitions

Fig. 6 shows the state transition graph. Three states are *CHIP_DATA* state which is to reset the chip and store the compensation data, *PIXEL_DATA* state which is to transfer and store the printed data, and *EXPOSURE* state. In the *CHIP_DATA* state, all counters and registers are reset to zero. Some compensation data are stored into the compensation circuits. In the *PIXEL_DATA* state, control circuits transfer printed data into shift registers and latches. Then, it waits for a permission signal which is defined as *next* to go into the next state. In the *EXPOSURE* state, LED drivers will trigger an LED array to perform the exposure procedure. Finally, the words or pictures are printed on the papers.

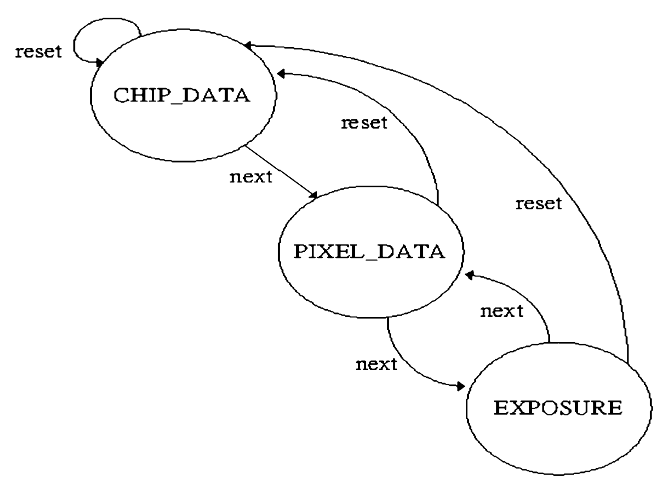


Fig. 6. State transition graph.

The timing diagram of control circuits is shown in Fig. 7. Control circuits generate signals to control state transition. Firstly, the *reset* and *next* signals are both generated by the *CLKI* and *STB* signals. The *STB* signal stands for a next state transition. Both of the *CLKI* and *STB* signals are generated by a field-programmable gate array (FPGA) or a microprocessor. By performing logic operations on the *reset* and *next* signals, controlling signals of three state transitions are thus obtained. When the *reset* signal is enabled, the proposed chip is in the *CHIP_DATA* state. The *chip* signal will be maintained in the

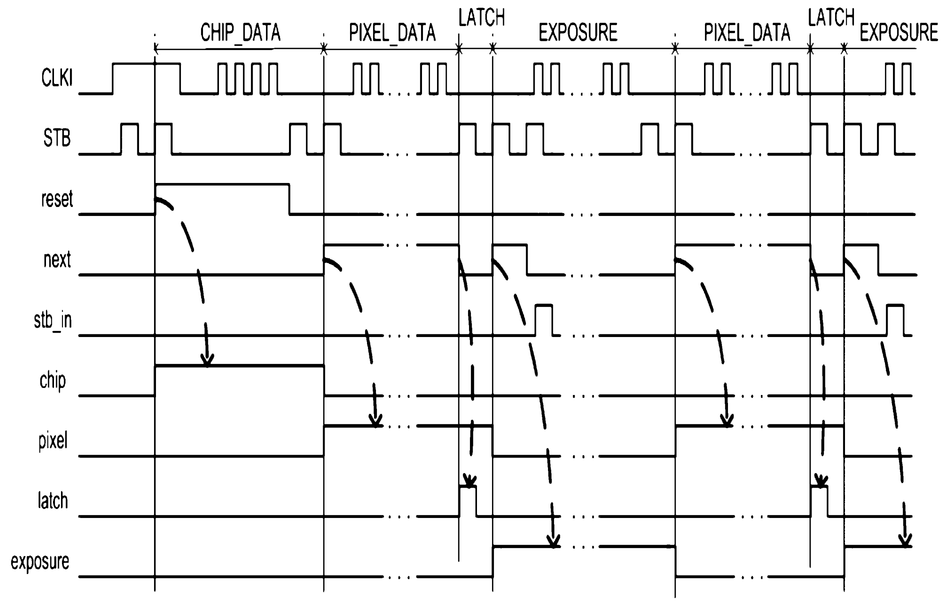


Fig. 7. The timing diagram of control circuits.

logic high until the *rest* signal is asserted into logic low. At the same time, the first *next* signal is enabled. The present state of the proposed chip is changed from *CHIP_DATA* state into *PIXEL_DATA* state. Similarly, the *pixel* signal will be maintained in the logic high until the procedure of data transfer is finished. Then, the second *next* signal is enabled. The present state is changed from *PIXEL_DATA* state into a short *latch* state. The *latch* state is to store the printed data in the latch. After latching these data, the *EXPOSURE* state begins its procedure. The *exposure* signal will be asserted into logic high until the exposure procedure is finished. Finally, all the procedures will be continuously performed until the words or pictures are totally printed.

B. Dynamic Pulse Width Modulation

Circuits and timing diagram demonstrated in Fig. 8 is to display the operation of traditional pulsewidth modulation. It compares the n-bit data with n-bit counter. For example, if n is 4 and *DATA* is 1100, the counter counts the number from 0 to 12. The *out* signal is always maintained in the logic high until it counts to the number of 13. That means an LED pixel will light on the duration of the number 0 to 12. That implies that the power is always consumed during this counting time. The power efficiency is not good. In order to make pulsewidth more adjustable, the pulsewidth modulation shown in Fig. 8 is improved into DPWM as demonstrated in Fig. 9. By performing the logic operations, the *stb_in* signal is generated from the *STB and CLKI* signals. Now, the trigger signal of counter is changed into the *stb_in* signal. The *stb_in* signal is triggered high at the rising edge of the *CLKI* signal when the *STB* signal is high. Then the counter counts at the rising edge of the *stb_in* signal. It counts upward one and holds until the next pulse of the *stb_in* signal appears. For example, the time duration of the number 1 is two times than others numbers in Fig. 9. By changing the *stb_in* signal, the pulsewidth can be more variable. Although the improved circuit is simple, the adjustable time duration can make power consumption more efficient. The proposed method of a single-chip segment exposure will also use the technique of DPWM to improve the power consumption.

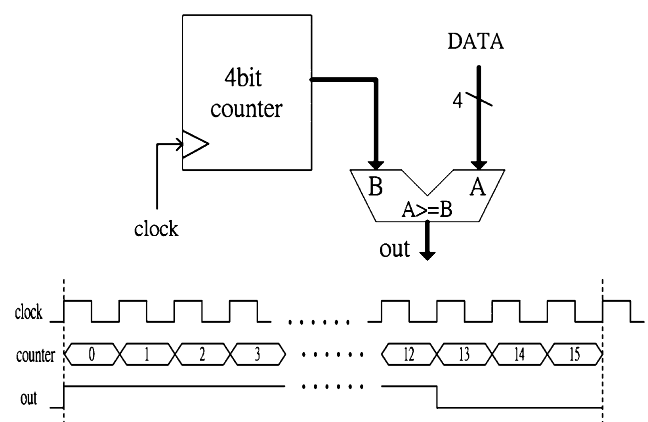


Fig. 8. Circuit and timing diagram of traditional pulsewidth modulation.

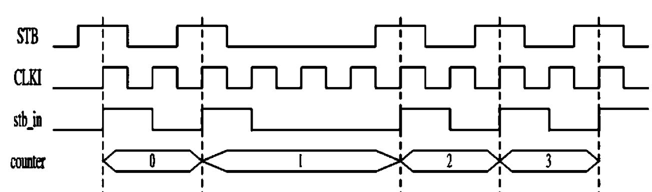


Fig. 9. Timing diagram of dynamic pulsewidth modulation.

C. Chip Compensation and Pixel Compensation

After the chip fabrication is finished, the characteristic of each driver IC could not be absolutely unity. The pulse start-limited circuit is thus proposed to perform the chip compensation as demonstrated in Fig. 10. The pulse start-limited circuit uses an

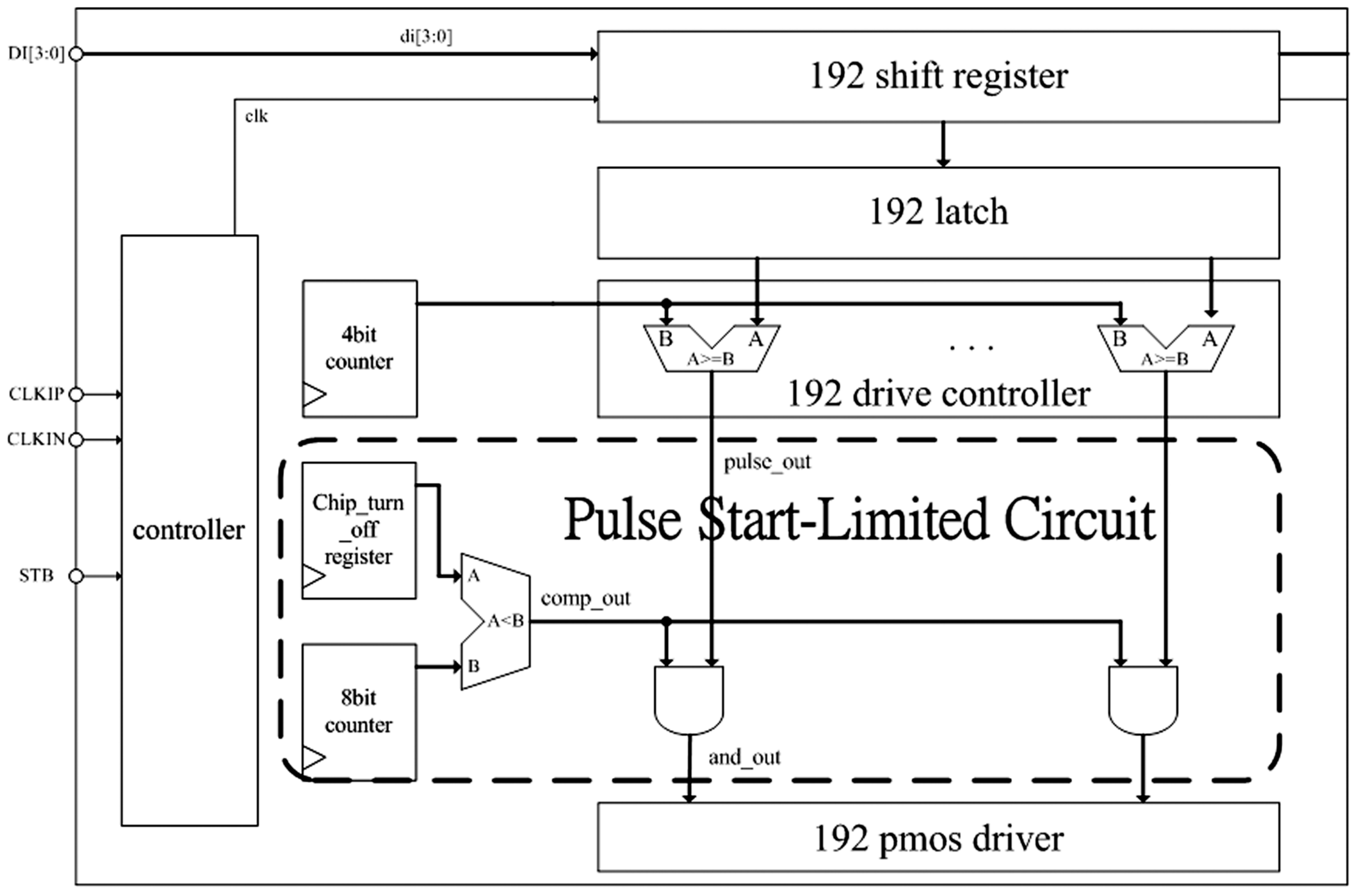


Fig. 10. Circuit diagram of the chip compensation.

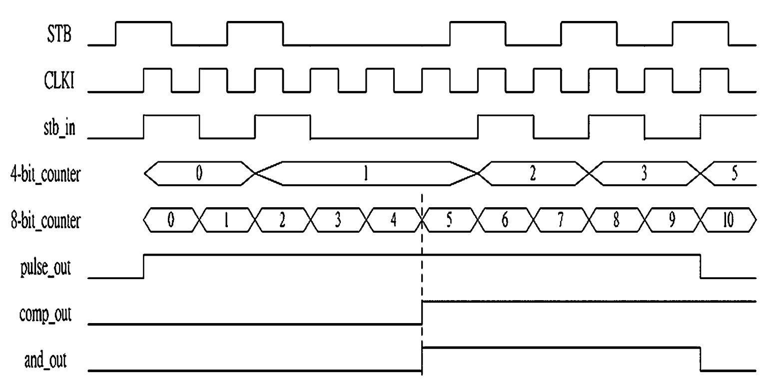


Fig. 11. Timing diagram of the chip compensation.

8-bit counter to compare with the compensation data. When the counting value is larger than the compensation data, the starting time of LED light is decided. For example, in Fig. 11, the compensation data is stored in the number of 4. After the operations of pulse start-limited circuit are finished, the pulsewidth of the signal *and_out* is also generated. This signal will be used to control the lighting time of an LED array.

By following the LED fabrication process, each LED has its individual difference. Thus, in the proposed pixel compensation, an output-current adjuster implemented by a 4-bit current-mode digital to analog converter is adopted. It can adjust the driving current of each LED according to the measured characteristic. The compensation data C_0 to C_3 shown in Fig. 12 are stored in the *CHIP_DATA* state, and used in the *EXPOSURE* state. The driving current is expressed as

$$I_d = I_{\rm pd} + C_0 * I_{p0} + C_1 * I_{p1} + C_2 * I_{p2} + C_3 * I_{p3} \quad (2)$$

$$I_{p0} = \frac{1}{2} I_{p1} = \frac{1}{4} I_{p2} = \frac{1}{8} I_{p3} \quad (3)$$

where $I_{\rm pd}, I_{p0}, I_{p1}, I_{p2}$, and I_{p3} are the current of MOS P_d, P_0, P_1, P_2, and P_3, respectively. V_R is the controllable bias voltage and $V_{\rm Td}$ is timing signal to turn on or off MOS P_S and

TABLE II
MEASURED RESULTS OF DELAY TIME OF CONTROLLING SIGNALS OF *STB* AND *CLK*

	STB→STBO (+)	CLKI→CLKO (+)
#01 Time (ns)	14	2.7
#02 Time (ns)	14.9	2.8
#03 Time (ns)	12.7	2.6
	STB→STBO (-)	CLKI→CLKO (-)
#01 Time (ns)	9.2	13.6
#02 Time (ns)	9.4	13.5
#03 Time (ns)	9.1	12.1

TABLE III
MEASURED RESULTS OF INTERVAL TIME OF OUTPUT SIGNALS OF *DATAO* AND *CLKO*

	DATAO(-)→ CLKO(+)	DATAO(+)→ CLKO(-)	DATAO(+)→ CLKO(+)	DATAO(-)→ CLKO(-)
#01 Time (ns)	0.127	0.950	0.430	0.036
#02 Time (ns)	0.764	0.400	0.210	0.220
#03 Time (ns)	0.620	0.350	0.320	0.870

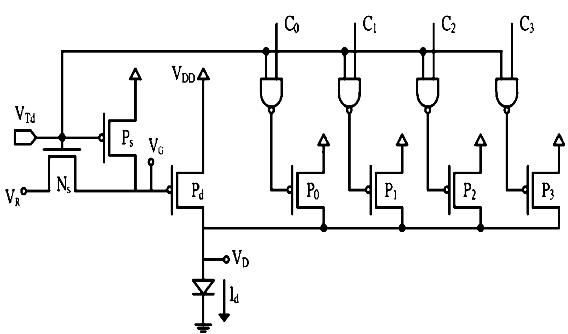


Fig. 12. Circuit diagram of the pixel compensation.

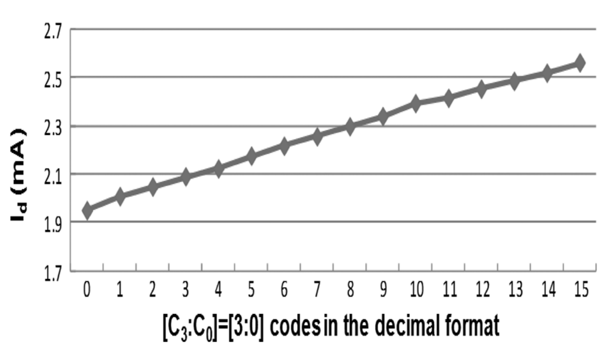


Fig. 13. SPICE simulations of the pixel compensation.

N_S. The SPICE simulations are demonstrated in the Fig. 13. The current of each LED pixel can thus be compensated by adaptively adjusting the codes of C_0 to C_3.

D. A Single-Chip Segment Exposure

To solve the problem of large power consumption, a method of a single-chip segment exposure shown in Fig. 14 is also proposed. In the *EXPOSURE* state, if the current of each LED pixel is 2.5 mA and the effective resistance is 1 kΩ, the resulting power consumption is equal to 6.25 mW. If there are 4962 LEDs within an LED array and are lighting together, the total power consumption will be 32 W. Such large power consumption will be a serious problem. The method of a single-chip segment exposure is to separate an LED array into two groups. Diodes within an array are numbered as odd and even diodes. The exposure time can be divided into two parts as shown in Fig. 15. The *L1* and *L2* LED diodes use a common output node together, which is *O1*. When the signal *SEL0* is in the logic high, odd LED diodes such as *L1* are turned on and even LED diodes such as *L2* are turned off. Similarly, if the signal *SEL1* is in the logic high, even LED diodes are turned on and odd LED diodes are turned off. The power consumption is thus reduced by 50%. This proposed method also can be made by dividing an LED array into more groups. However, the controlling signals are more complicated. The printing speed is affected due to the segment exposure. However, the printing speed is not a problem due to the fact that it can be easily compensated and adjusted by a faster clock frequency. In the next section, all the functions and performance of the proposed chip are proven through measurements.

IV. MEASUREMENT RESULTS

Fig. 16 demonstrates physical layout of the proposed CMOS LED print head driver with compensation circuits is

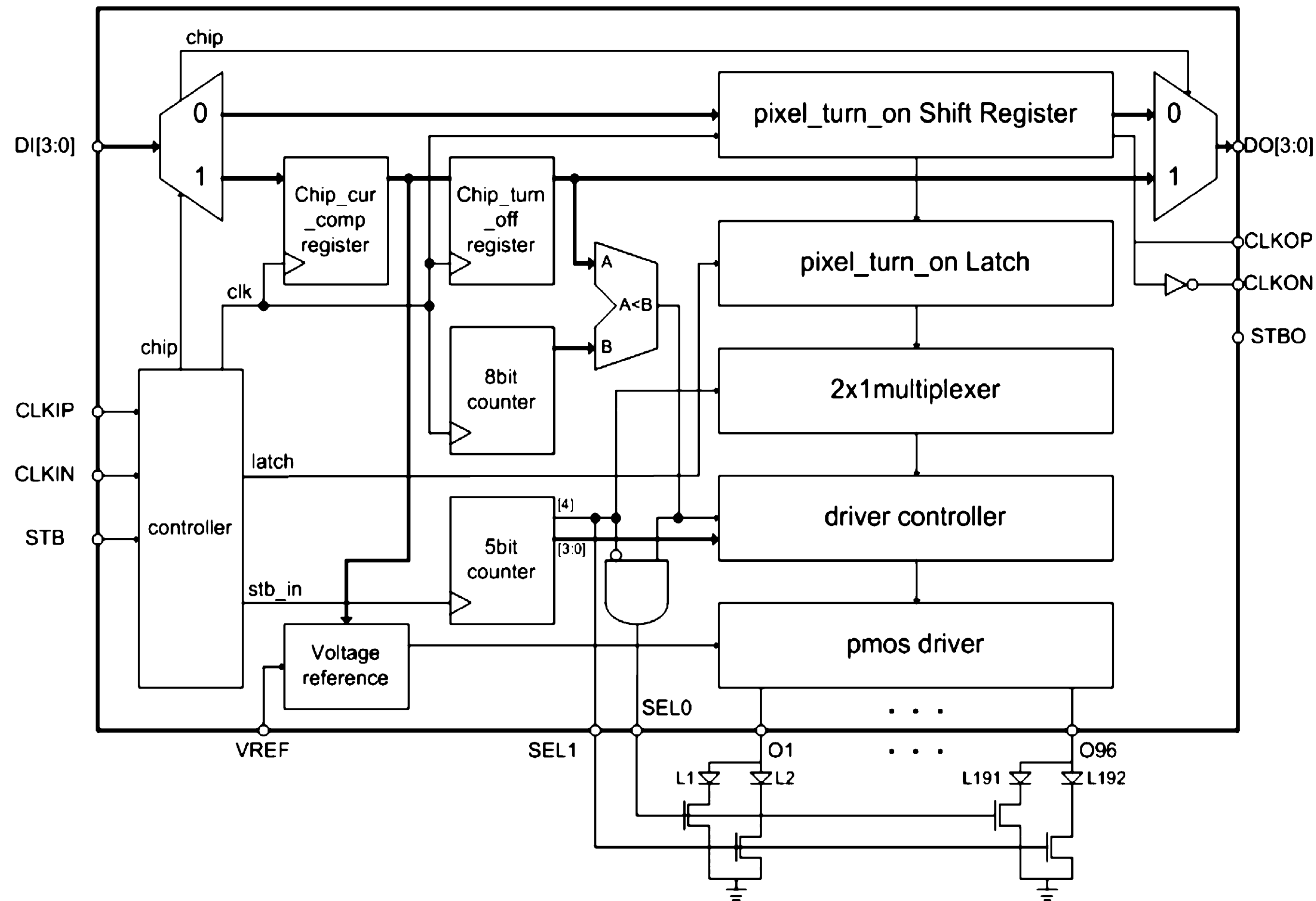


Fig. 14. Circuit diagram of the single-chip segment exposure.

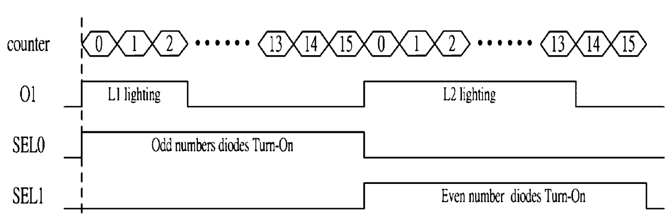


Fig. 15. Timing diagram of the single-chip segment exposure.

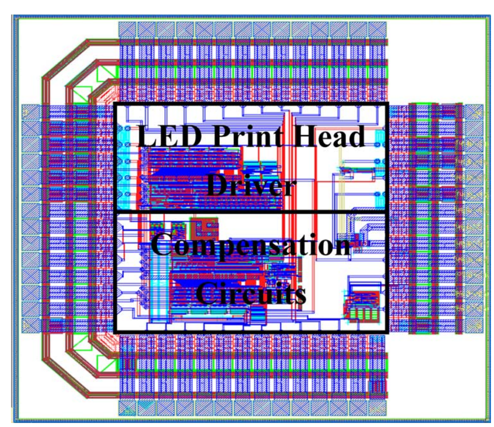
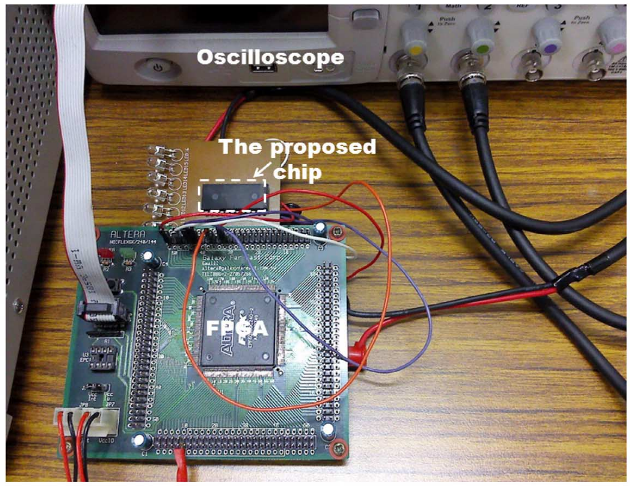


Fig. 16. Physical layout of the proposed CMOS LED print head driver with compensation circuits is $2000 \times 2000\ \mu m^2$ including ESD I/O pads.

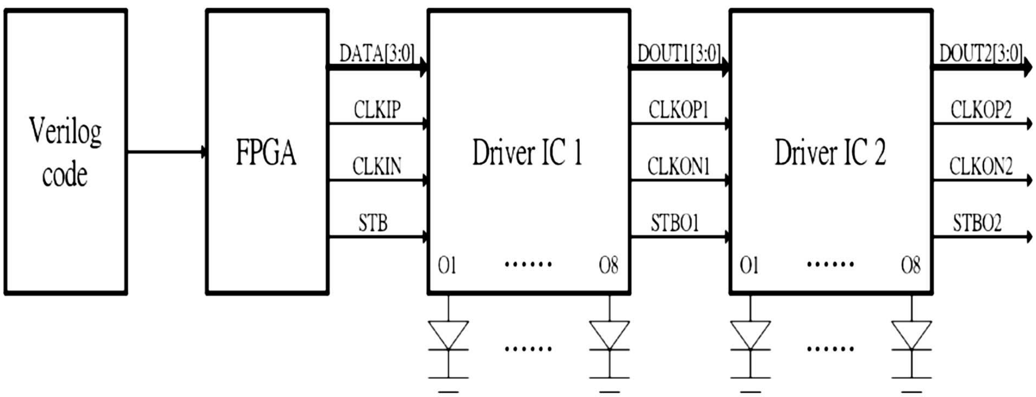
$2000 \times 2000\ \mu m^2$ including ESD I/O pads. The CMOS 0.5 μm 1P2M process with 3.3 V power supply is chosen due to its lower cost to fabricate this chip. The driving current of each LED pixel is 2.5 mA. The clock frequency *fc* is 20 MHz. Fig. 17(a) and (b) show the testing board and measurement setup, respectively. The data signals *DATA [3:0]* and controlling signals of CLKIP, *CLKIN* and *STB* are generated by FPGA. The FPGA is programmed by Verilog codes. In order to avoid error sampling, the signals of *DATA [3:0], CLKIP*, *CLKIN*, and STB are passing through stage by stage. These signals can be correctly captured and processed within each stage.

Firstly, the transmitting function is tested. This test is separated into two parts. One is to test the chip in the *CHIP_DATA* state. Fig. 18 shows the transmitting condition of the compensation data stored in the compensation circuits. The other test is to verify the chip in the *PIXEL_DATA* state. The measurement results are demonstrated in Fig. 19. As shown, the functions are correctly proven by the *DOUT* signals. The data can be captured in the rising and falling edges of the *CLKIP* signal. The *DOUT* signals are correctly delayed 2 and 4 clock cycles, respectively.

Although the transmitting function is tested successfully, the delay and interval time should also be verified. The delay time is to check if it interferences the sampling functions of the chip or



(a)



(b)

Fig. 17. (a) Testing board. (b) Measurement setup.

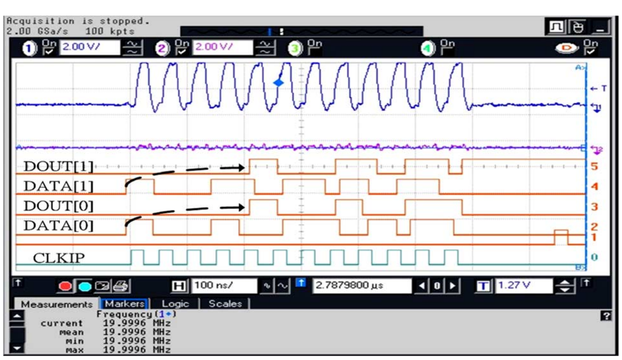


Fig. 18. Measurement results of state transition in the *CHIP_DATA* state.

Fig. 19. Measurement results of state transition in the *PIXEL_DATA* state.

not. The interval time is to judge if the following chip can successfully receive the data from the preceding chip or not. Table II demonstrates the measured results of delay time of controlling signals of *STB* and *CLK*. Three chips are measured and the delay time is almost the same. Table III displays the measured results of interval time of output signals of *DATAO* and *CLKO*. By measuring the interval time of three chips, the time is all less than 1 ns. Measurements can prove that these signals can correctly be captured and processed within each stage.

The measured I_d currents in the pixel compensation are plotted in Fig. 20. Three chips are tested again. The difference of each step is about 0.03 to 0.04 mA. This implied that good linearity of the compensated current is obtained. Finally, Fig. 21 demonstrates the measured total current through LED pixels based on two methods. One is based on the traditional PWM method in Fig. 21(a). The other is followed by the proposed method of a single-chip segment exposure with DPWM in Fig. 21(b). Firstly, sixteen LED pixels are grouped into a set.

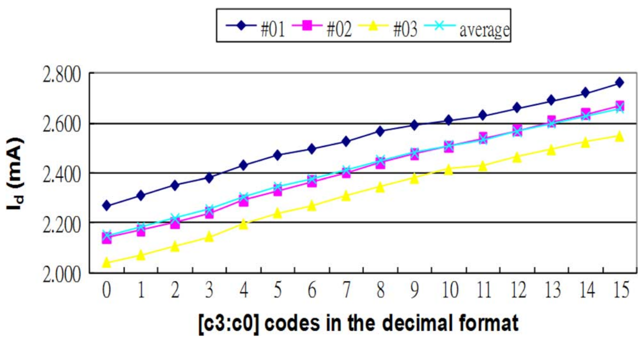


Fig. 20. The measured I_d currents in the pixel compensation.

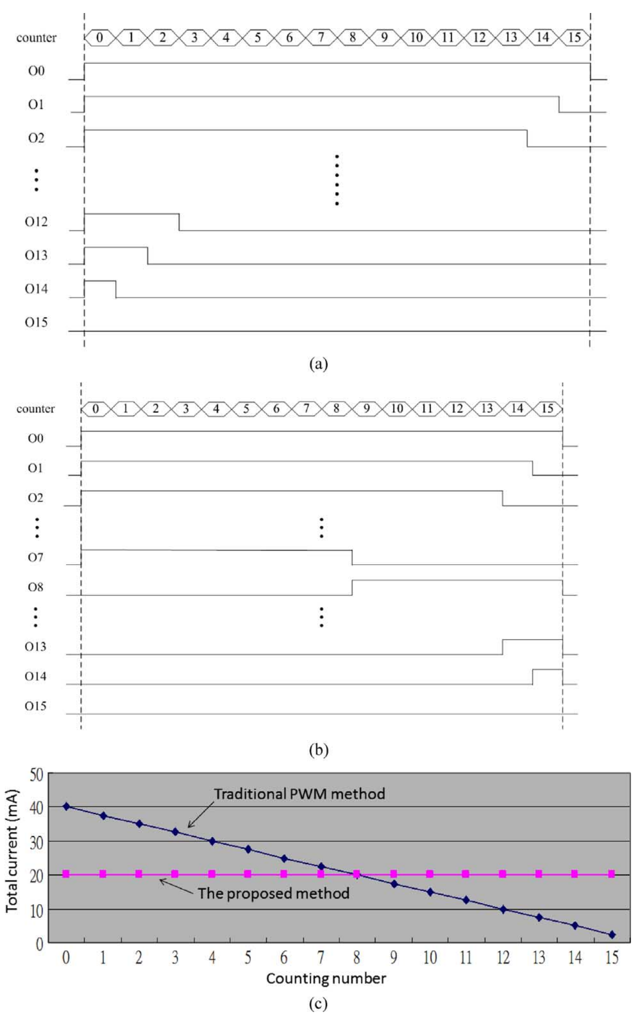


Fig. 21. (a) Timing diagram of the traditional PWM method. (b) Timing diagram of the proposed method of a single-chip segment exposure with DPWM. (c) Measured total current based on two methods.

The timing of the traditional PWM method is inputted to the proposed chip, and then the total current is measured. The maximum current is about 40 mA. The total current is different on the time variation. On the other hand, the total current based on the proposed method of a single-chip segment exposure with DPWM is measured. The total current is half of the maximum current of the traditional PWM method. Different to the traditional PWM method, the current is uniformly averaged. The power consumption is saved. In Fig. 22, another measurement is to prove that better power efficiency can also be obtained under different condition of the proposed DPWM. The pulsewidth is smaller and within counting number 7. In Fig. 22(b), although the total current is different on the time variation, the maximum total current is 20 mA and also half of the maximum current of the traditional PWM method. That implies the proposed method of a single-chip segment exposure with DPWM has efficient power consumption compared with traditional PWM method. The characteristics of the proposed CMOS LED print head driver with compensation circuits are summarized in Table IV.

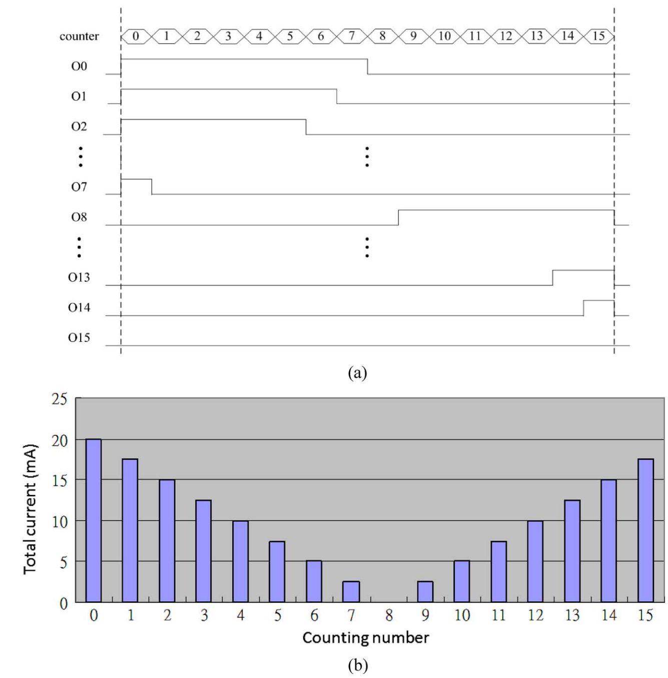


Fig. 22. (a) Timing diagram of the proposed method of a single-chip segment exposure with DPWM. (b) Measured total current.

TABLE IV
SUMMARY ON THE CHARACTERISTICS OF THE PROPOSED CMOS LED PRINT HEAD DRIVER WITH COMPENSATION CIRCUITS

Technology	0.5 μm CMOS 1P2M
Power supply	3.3 V
Maximum driving current	2.5 mA
Resolution (DPI)	1200
The diode number within a LED array	4962
Printed speed (PPM)	20
Sampling frequency	20 MHz
Physical layout area including ESDI/O pads	2000 × 2000 μm^2
Application field	LED Printers

V. CONCLUSION

A CMOS LED print head driver with compensation circuits is newly proposed. Two compensation methods are designed to overcome the process and fabrication variation of each driver

IC or an LED pixel. A method of single-chip segment exposure is also proposed to make the power consumption more efficient. The power consumption is reduced by 50%. Turning on all LED diodes, the measured power consumption of a single chip is 89 mW. Based upon the device parameters of 0.5 μm 1P2M CMOS technology with 3.3 V power supply, all the functions and performance of the proposed CMOS LED print head driver with compensation circuits are successfully tested and proven through measurements. The area including ESD I/O pads is $2000 \times 2000\ \mu\text{m}^2$. In the future research, the proposed chip will be adaptively tested on the LED printers.

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