Energy-Recycling (ER) Technique for a Direct-Lit Intelligent Power Management Backlight Unit (BLU)

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***Abstract*—A field-sequential-color (FSC) liquid crystal display (LCD) technique with a direct-lit red, green, and blue LED backlight driver is proposed to achieve low weight, thin, perfect image quality, and low-power consumption of LCD television. The FSC technique performs a pseudorandom color sequence in the spatial and temporal domains to reduce color-breakup and motion-blur effects. The direct-lit RGB-LED backlight driver increases brightness, contrast, and uniformity due to the removal of a color filter. In this paper, the proposed FCS-LCD controller uses a single LED driver to switch the driving voltage alternatively between 36 V for driving 12-series G- or B-LEDs and 24 V for 12-series R-LEDs. The proposed energy-recycling technique can harvest the extra energy when the driving voltage switches from 36 to 24 V. Experimental results show that energy saving is higher than 17% of the conventional driving method.**

***Index Terms*—Direct-lit LED backlight, energy-recycling technique, field-sequential color (FSC), liquid crystal display (LCD) technique.**

I. Introduction

The COLOR gamut of liquid crystal displays (LCDs) with backlight units (BLUs) that employ cold cathode fluorescent lamps (CCFL), white-LEDs, and red, green, and blue (RGB)-LEDs is different. For the display demand of image quality, direct-lit RGB-LEDs backlight presents the best color gamut of 110% National Television System Committee and generally has a good color spectrum and saturation compared with other backlights. However, direct-lit RGB-LEDs backlight sources have high-power consumption with no proper power management. Therefore, the field-sequential-color (FSC) technique is proposed to improve the power efficiency of the display with RGB-LED backlight modules.

As shown in Fig. 1, removing the color filter can enhance brightness because the color filter passes only 33% of the light. Combining the FSC technique and the direct-lit RGB-LEDs backlight source reduces fabrication cost, whereas power consumption is greatly reduced in the FSC technique. Generally, the FSC technique can provide high-image quality to the consumers. RGB colors are alternately and sequentially displayed for the viewer's eyes to combine them into a full color image. Thus, the FSC technique can further reduce the power loss of RGB-LED backlight modules and maintain great color gamut because the sequential emission of the LEDs will not raise the environmental temperature. Heat is a major problem caused by white-LEDs [1].

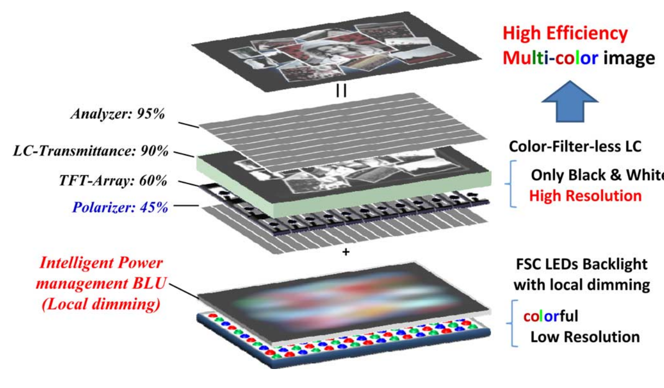

Fig. 1. High-efficiency FSC display due to the removal of the color filter and the smart LED driving techniques.

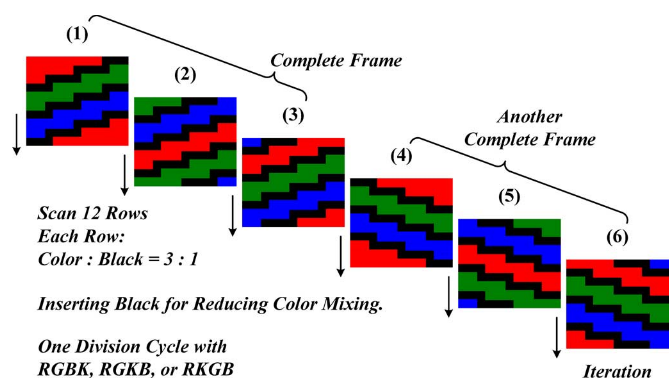

Fig. 2. Pseudorandom color sequences in the spatial and temporal domains for reducing CBU and motion-blur effects in the FSC-LCD technique.

The disadvantages of the FSC technique are color-breakup (CBU) and the motion-blur effects. Fortunately, the FSC-LCD technique in Fig. 2 serves pseudorandom color sequences in the spatial domain and the temporal domain to reduce CBU and motion-blur effects [1]. The FSC-LCD technique divides an LCD panel into many blocks and sequentially displays different colors. The FSC-LCD technique inserts one additional black (K) subframe to reduce CBU effect. Minimizing CBU and motion-blur effects improve the performance of the FSC-LCD

Manuscript received January 11, 2010; revised February 18, 2010 and March 24, 2010; accepted May 13, 2010. Date of current version September 17, 2010. This work was supported by the National Science Council, Taiwan, under Grant NSC 97-2221-E-009-172 and Grant NSC 97-2220-E-009-027. Recommended for publication by Associate Editor M. Ponce-Silva.

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Digital Object Identifier 10.1109/TPEL.2010.2050909

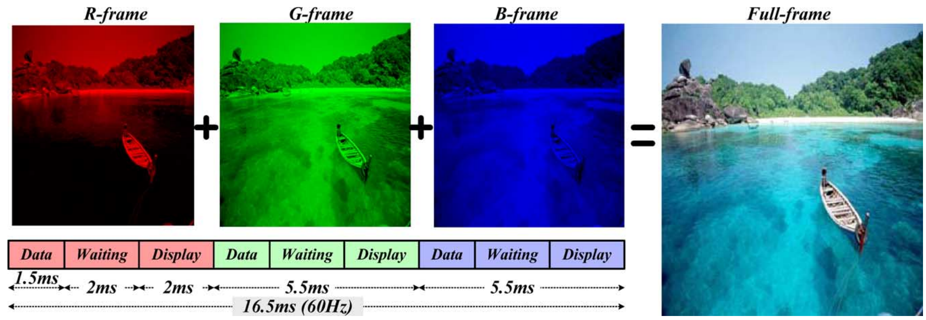


Fig. 3. Scanning subframe and related timing of the FSC-LCD technique.

technique. To reduce the power consumption of LED BLUs, an intelligent power management, such as local dimming techniques, is utilized to achieve a high efficiency FSC-display, as illustrated in Fig. 1. The local dimming technique can generate a low resolution of an image to reduce power consumption and to enhance contrast [2].

The forward voltage of G- or B-LED is about 3.3 V, whereas that of R-LED is 2.2 V. Two distinct driving voltages generated from two LED drivers are usually required; thus, the driver's volume and power increase. The FSC-LCD technique can reduce power loss because R-, G-, and B-LEDs are alternately turned on. High-power loss is still a serious problem because LEDs require different driving voltages generated by multiple backlight drivers. A single driver of a direct-lit RGB-LEDs backlight is presented in a conventional design, which can use the driving voltage for G- or B-LEDs to drive R-LEDs at the same time. This design can effectively reduce the volume of the LED driver, but greatly increase the power loss due to large power loss consumed by R-LEDs.

Therefore, the LED backlight driver must contain a fast transient response for FSC operation, high stability, high-power efficiency, and space-minimizing characteristics to handle large instant load variation without sacrificing image quality and increasing the motion-blur effects [1]. In the FSC-LCD technique, image quality highly depends on the switching time and the lumen of LEDs as sequential primary colors R, G, B, and K are alternately turned on. In Fig. 3, one frame per second (f/s) image data are divided into three subimage frames R-, G-, and B-subframe, in a 60 Hz frame scanning frequency [3]–[5].

Operating each subframe includes three steps during a 5.5 ms time interval. First, the "image processing" block decodes color data from one image frame to three primary colors. The timing control block then orients the column drivers and row drivers to the related LCD pixels of decoded image data at 1.5 ms. The selected LC pixels rotate to a corresponding angular position within 2 ms to display the subimage frame. Finally, the BLUs turn on the LED arrays to emit the corresponding color of subimage frame through the LCD panel and display the related color of the image at 2 ms [6], [7].

To consider space-efficiency and power-consumption compatibly in LCD television (TV), a single RGB-LED driver is proposed to switch the driving voltage between 36 and 24 V for 12 different color LEDs in series according to the FSC-LCD technique. Reference tracking and fast transient technologies demonstrate that a single LED driver can switch the driving voltage between 36 and 24 V for the dynamic driving voltage scaling requirement. As the LED driver frequently switches the driving voltage from 36 to 24 V, the extra charge on the conventional output capacitor is consumed by the feedback resistors and LEDs. Long settling time of the driving voltage occurs and affects the illumination and lifetime of LEDs when the driving voltage switches from 36 to 24 V. A dummy load can be used to accelerate the settling time of the driving output voltage, but it dissipates much power and heats up the LCD TV. A sub-converter can reserve extra energy and provide fast response to decrease the volume of the driving module, but a complex controller and extra components are required [8]–[12]. Therefore, to simplify the LED driver and to achieve power-efficient and space-minimized BLUs, an energy-recycling (ER) technique is proposed to provide a suitable solution for the FSC-LCD technique.

In the proposed ER technique, only one recycling capacitor C_R and one active diode M_R, instead of a Schottky diode D_R, are embedded in a synchronous boost converter as an energy tank for composing the system structure. When the FSC-LCD technique displays the subframe repeatedly, the driving voltage frequently switches between 36 and 24 V. The synchronous boost converter provides the driving voltage of the G- and B-LED series. Simultaneously, the ER technology acts as a normal power filter without affecting the synchronous boost converter. The proposed ER technique recycles extra energy from the output terminal of LED driver to the ER energy tank. In other words, a bidirectional energy delivering control circuit with minimum power consumption is the most important contribution in the proposed ER technique. A boundary current mode (BCM) is selected to simplify the complexity of a bidirectional energy control circuit [13]. Therefore, the proposed ER technique not only recycles extra energy when the output voltage switches from 36 to 24 V, but also increases power efficiency and reduces the volume of RGB-LEDs driver.

This paper is organized as follows. Section II describes the structure and behavior of the proposed ER technique. The implementation of the ER technique is presented in Section III. Experimental results prove the performance and correctness of the ER technique in Section IV. Finally, a conclusion is made in Section V.

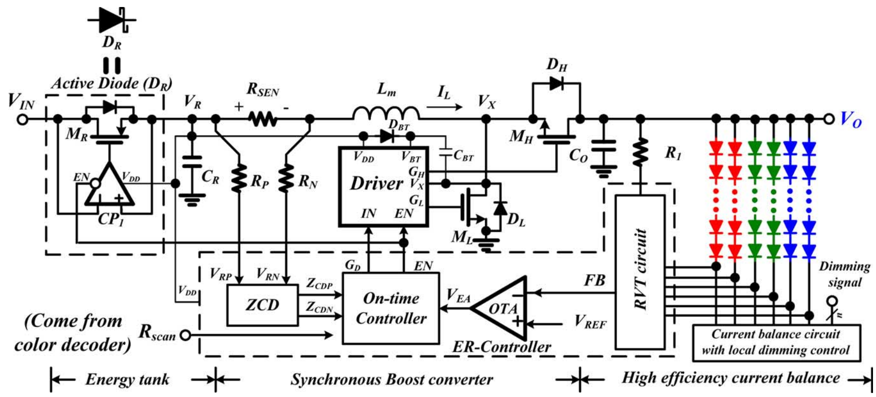


Fig. 4. Proposed structure of ER technology.

II. Structure and Behavior of the Proposed ER Technique

The structure of the proposed ER technology as depicted in Fig. 4 contains three function blocks. The first is the ER controller, the second is the energy tank, and the third is the high-efficiency current balance (CB).

The ER controller is based on the BCM synchronous boost converter with an external high/low-side driver to turn on/off power MOSFETs M_L and M_H, which contain parasitic diodes D_L and D_H. An energy-storage inductor L_m, an output capacitor C_o, and feedback resistors are used to constitute the synchronous boost converter. As the gate driver needs a high-driving voltage to turn ON the high-side MOSFET M_H, a boost-trap circuit, which is composed of the diode D_{BT} and the capacitor C_{BT}, can provide a boost voltage $V_{\mathrm{BT}} = V_R + V_X$, to ensure that the driving voltage is high enough to reduce on-resistance. The essential part of the proposed ER technology is the energy tank that stores the recycling charge from V_O. To simplify the cost in the energy tank structure to improve power conversion efficiency, the active diode, which is composed of the power p-type MOSFET M_R, and the comparator CP_1 are added between V_{IN} and the synchronous boost converter. The original input capacitor, which is used to filter input ripple and switching noise, becomes the recycling capacitor C_R and constitutes the energy tank with the active diode. Moreover, the active diode can be simplistically implemented by the Schottky diode D_R to simplify the control circuit of the ER technology. However, it sacrifices the conversion efficiency due to large conduction loss. To turn off the power p-type MOSFET M_R, the comparator CP_1 is connected to the highest voltage between the supply voltage V_{IN} and the recycling voltage V_R.

The output voltage of the boost converter is determined by the reference-voltage tracking (RVT) technique to minimize the voltage stress on the CB circuit. As a result, the high-efficiency CB circuit can reduce the power loss of the CB circuit. The local dimming technique can reduce LED power consumption by expanding the grayscale level for high contrast, as shown in Fig. 5(a). A serious problem in the dimming control is the output driving voltage switches between two regulated voltages when the dimming signal turns off all LEDs. Thus, the RVT technique uses the minimum voltage tracking method to stabilize the output driving voltage without being affected by the local dimming technique. That is, the local dimming technique can be effectively implemented in the ER technology to reduce the LED power consumption, as shown in Fig. 5(b).

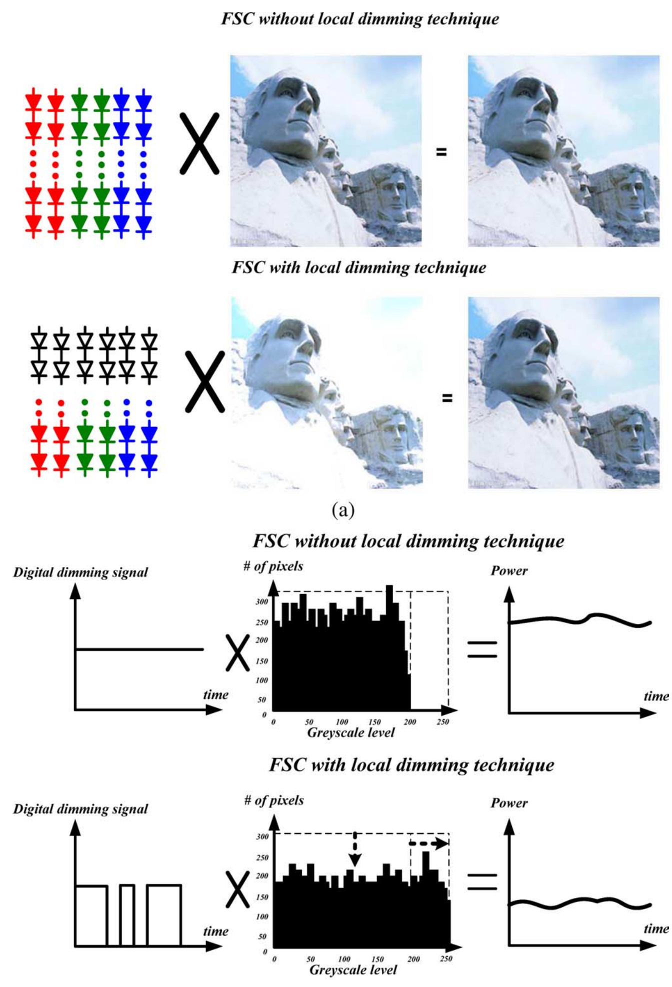


Fig. 5. Local dimming technique can reduce the power consumption of LEDs. (a) Comparison of the power consumption with and without local dimming technique. (b) Extended grayscale level to reduce the power consumption of LEDs.

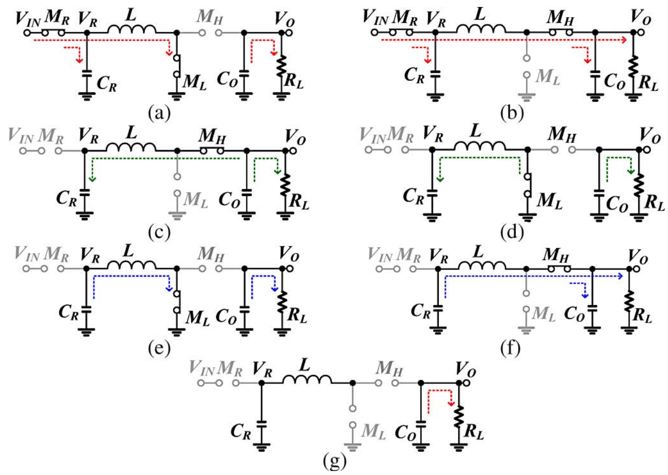


Fig. 6. Four operation phases in the proposed ER technology. (a) and (b) constitute the BCM operation. (c) and (d) form the ERM operation. (e) and (f) constitute the ETM operation. (g) SLM operation is presented.

The operation behavior of the ER technique can be classified under four operation phases. The switching status of the ER technique, as depicted in Fig. 6, illustrates the behavior of the inserted energy tank in the synchronous boost converter. The first phase is the boost BCM operation, as depicted in Fig. 6(a) and (b). This phase is similar to the discontinuous conduction mode (DCM) operation. The right-half plane (RHP) zero can be moved to high frequencies, and compensation can be simplified [14], [15]. The BCM operation has the advantage of high-driving capability compared with the DCM operation because the period of zero current is minimized to zero. The switching period of the BCM operation depends on the load current condition without the need for a constant frequency control. Thus, the power loss in the BCM operation can be reduced. The on-time period in Fig. 6(a) is determined by the closed-loop control. The feedback signal FB compares with the reference voltage $V_{\rm ref}$ to generate an error signal $V_{\rm EA}$, which is used to compare with a sawtooth signal to adjust the on-time value.

On the other hand, the off-time period in Fig. 6(b) is decided by the zero current detection (ZCD). Thus, a current sensing resistor $R_{\rm SEN}$ connected in series with the inductor L_m is used to detect the bidirectional current signal with a slight increase in conduction loss. A current transformer can replace the current sensor $R_{\rm SEN}$ to improve power efficiency in today's commercial products. In this paper, a simple sensing resistor is used to detect the bidirectional inductor current information. As a result, the inductor, which decreases to zero, can be detected by the sensing resistor during the off-time period. The voltage across $R_{\rm SEN}$ decreases to zero, and the ZCD circuit can decide the end of the off-time period, triggering the next switching cycle. A voltage clamper, composed of resistors R_P and R_N, is used to avoid breakdown and latch-up issues if a high-voltage stress exists across $R_{\rm SEN}$. The output signal G_D is a pulsewidth modulation (PWM) signal used to turn on/off the power MOSFETs. If overvoltage protection (OVP) occurs, the G_D signal will be shut down to avoid damaging the system.

Different from a conventional boost converter, the proposed ER technique provides one energy-delivering path from $V_{\rm IN}$ to V_O. This energy-delivering path is used to recycle extra energy from the output capacitor C_O to the recycling capacitor C_R when the output voltage switches from high- to low-driving voltage. The switch between high- and low-driving voltages is determined by $R_{\rm scan}$. A bidirectional energy control has to be created in the proposed ER technique structure. Therefore, the bidirectional energy control becomes the major challenge in achieving the minimum power loss and smoothly switching operation modes. The second phase is the ER mode (ERM), as depicted in Fig. 6(c) and (d). The inductor current I_L is a clear indicator of the direction used to decide the delivering and recycling operation modes. Thus, the inductor current needs to be monitored during the entire operation phases. The ZCD circuit not only decides the end of the off-time period, but is also used as a mode decision circuit. The third phase is the energy transmission mode (ETM), as shown in Fig. 6(e) and (f). The last phase is the silence mode (SLM), as illustrated in Fig. 6(g).

The proposed ER controller in the FSC algorithm is illustrated in Fig. 7. The four operation phases are described as follows to show how extra energy is stored and recycled.

A. BCM Operation

The BCM operation can boost the driving voltage to a specific voltage level for the requirement of different color LEDs. Thus, the driving output voltage is raised to a higher level, which is approximately equal to 36 V in this paper, to drive 12 G- or B-LEDs in series. According to the FSC algorithm, the BCM operation is required during the displaying period. On the other hand, the driving output voltage is raised to a lower level, which is approximately equal to 24 V in this paper, to drive 12 R-LEDs in series. At the beginning of the displaying period, the ETM operation starts first, followed by the BCM operation, as the recycling energy can be used to drive the LEDs at the beginning. Thus, the period of the BCM operation can be shortened to save much power.

Active diode M_R (or Schottky diode D_R) and recycling capacitor C_R work as a ripple filter, and V_R is the voltage across C_R. Transistor M_L is turned on by the output ZCD_P from the ZCD circuit to continue the inductor current waveform. The on-time value $T_{\rm ON}$ is decided by the on-time controller using a simple constant on-time control. Thus, the peak inductor current level $I_{\rm LPEAK}$ can be calculated as follows:

$$I_{\rm LPEAK} = \frac{V_R}{L_m} T_{\rm ON} \approx \frac{V_{\rm IN}}{L_m} T_{\rm ON}. \qquad (1)$$

After the on-time period, the ZCD circuit starts to detect the end of the off-time period. Once the inductor current is equal to zero when the output $Z_{\rm CDP}$ is set to high, transistor M_L is turned on again for the next switching cycle. Moreover, $T_{\rm ON}$ is limited by a maximum on-time $T_{\rm ON\_MAX}$ to clamp $I_{\rm LPEAK\_MAX}$ to protect the system. For a given maximum driving power P_O and a conversion efficiency η, $T_{\rm ON\_MAX}$ can be derived as (2) if V_R

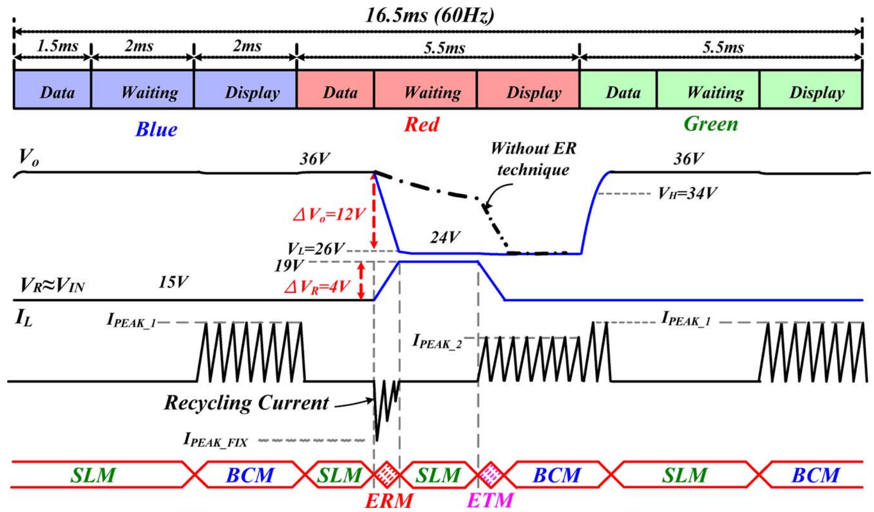


Fig. 7. Behavior of ER technology in the FSC algorithm.

is approximately equal to $V_{\rm IN}$ during the BCM operation

$$T_{\rm ON\_MAX} = \frac{L_m I_{\rm LPEAK\_MAX}}{V_{\rm IN}} = \frac{2P_{o\_\rm MAX} L_m}{\eta V_R^2}. \quad (2)$$

B. ERM Operation

Once the color decoder subsequently detects that the *subframe* is the red color, the $R_{\rm scan}$ is set from low to high to trigger the ERM operation, and the output driving voltage drops from 36 to 24 V. The ER controller starts to recycle energy from C_O to the recycling capacitor C_R. As a result, the ER controller forces the transistor M_H ON until the inductor current I_L becomes negative. The current flows from C_O to the re-cycling capacitor C_R. Not only the driving output voltage can be rapidly decreased to a lower voltage level, but the energy can also be fully stored in the recycling capacitor C_R. However, the dropping output voltage causing the output signal $V_{\rm EA}$ from the error amplifier is set to zero, and the on-time controller cannot properly control the switching time $T_{\rm ON}$ of the transistors M_H and M_L. To solve the unregulation issue properly and to simplify the design complexity of the ER controller, a fixed on-time $T_{\rm ON\_FIX}$ controller is used instead of the on-time controller during the ERM operation. When the ERM operation is triggered, and the signals ZCD_P and $R_{\rm scan}$ are used as synchronous and trigger signals, the ER controller turns on the transistor M_H for a period of $T_{\rm ON\_FIX}$, and the inductor current $I_{\rm LM}$ becomes negative. The negative inductor current increases the value of V_R; thus its value will be larger than $V_{\rm IN}$ because the negative current and the increased voltage V_R, the active diode M_R, or the Schottky diode D_R can automatically disconnect the current path to the supply voltage. After the $T_{\rm ON\_FIX}$ period, the transistors M_H and M_L are turned off and on, respectively, to release the energy in the inductor to C_R. Thus, the inductor current is increased to zero again. The output $Z_{\rm CDN}$ from the ZCD circuit, which is the inverse signal of $Z_{\rm CDP}$, is used to decide the next switching cycle, i.e., the ZCD circuit can be used in the BCM and ERM operations to achieve low-cost implementation.

The reverse current is stored on C_R, and thus, V_R may be increased to be higher than $V_{\rm IN}$. A limitation voltage of V_R must be set to be not higher than V_O. Therefore, the relationship between the difference output voltage and difference recycling voltage, ΔV_O and ΔV_R, respectively, is expressed as following according to the voltage second balance principle:

$$\Delta V_o C_o = \Delta V_R C_R. \quad (3)$$

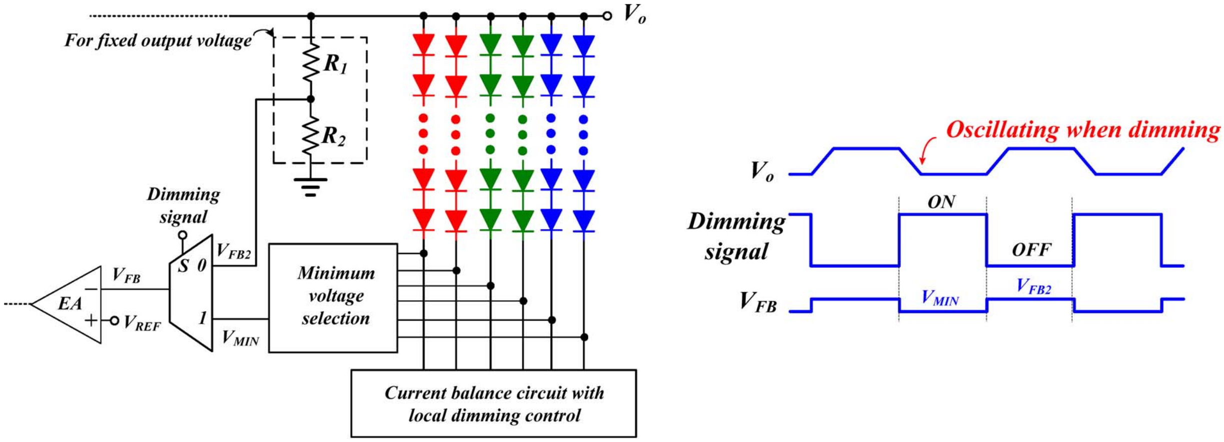
As a result, the limitation of V_R in the ERM operation can be expressed as follows:

$$V_R + \Delta V_o \left(1 + \frac{C_o}{C_R}\right) < V_o. \quad (4)$$

The decreasing rate of V_R depends on the load condition. Thus, the stored energy on C_R can be utilized for a long time for a light-load condition when the local dimming technique is used. The power consumption of LEDs can then be effectively reduced. High efficiency can be achieved in the proposed ER technology.

C. SLM Operation

In the FSC algorithm, data reading and LC rotation require 3.5 ms. Thus, the converter should be kept in the SLM operation. In the SLM operation, V_O slightly decreases due to leakage current and operation current in the ER controller. However, the ERM operation needs to be inserted in the SLM operation for string extra energy when the color changes from green or blue to red. The ERM operation is inserted when data reading ends. When V_O decreases from the higher driving voltage to less than 110% of the lower driving voltage, the ERM operation ends. The SLM operation takes over the system again. The SLM operation is used to turn off the switches fully until the driving voltage drops to the lower driving voltage. Before V_O reaches the lower driving voltage, an OVP circuit is required to ensure system reliability. An overvoltage comparator controls the enable signal EN for the external high-side driver. When the overvoltage condition occurs, the delivering energy becomes too high, and the gate driving signals need to be fully turned off



(a) (b)

Fig. 8. (a) Conventional feedback circuit design for the local dimming technique. (b) Output driving voltage oscillating between two voltages consumes more power.

until V_O reaches the lower driving voltage. The SLM operation is also applied to the BCM operation at ultralight loads for power saving. The BCM operation contains a skipping operation.

D. ETM Operation

In the FSC algorithm, the output driving voltage decreases to a lower voltage level, and the extra energy is also stored in the recycling capacitor when the color is changed from green or blue to red. The system needs to wait for the LC reaction, and the SLM operation is required, as illustrated in Fig. 7 before the ETM operation. The ETM operation aims to release the reserved energy to drive the LEDs. The release time of the recycling energy depends on the load condition because of the local dimming technique used in the ER technique. Thus, the power consumption of the LED is reduced. The recycling energy can be used for a long time if the load condition is light. Once the energy is empty, the BCM operation takes over the system to deliver energy from the input power source to the LEDs. Fortunately, the local dimming technique extends the period of the ETM operation; thus, the period of the BCM operation can be minimized without sacrificing the image quality, as shown in Fig. 5(a).

The local dimming technique can improve the power conversion of the ER technique. However, the output driving voltage may have small oscillation when the dimming signal changes between high and low in conventional design, as depicted in Fig. 8(a). When the dimming signal is high, the feedback voltage is decided by the minimum voltage V_{MIN}, which is selected from the parallel LEDs. On the other hand, the closed loop is broken, and a fixed output voltage V_{FB2} is set when the dimming signal is low. Unfortunately, the output driving voltage oscillates between the minimum voltage decided by the LEDs and the fixed voltage, as illustrated in Fig. 8(b). The oscillation causes much power dissipation. Thus, the RVT technique in Fig. 4 is proposed to minimize the difference between the two voltages to improve the power conversion efficiency. Therefore, the output driving voltage will not oscillate between the two voltages again.

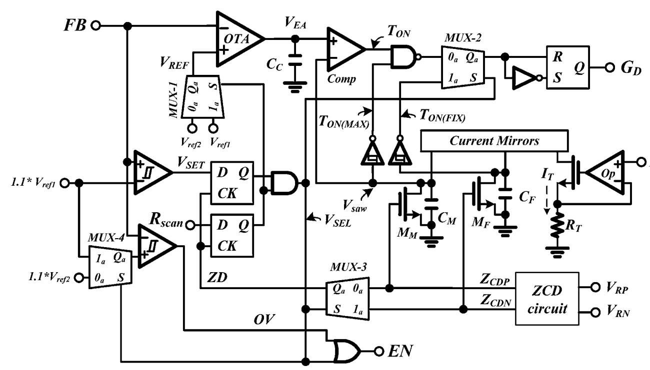


Fig. 9. ER controller.

III. Implementation of the ER Controller

A. ER Controller

The block diagram of the ER controller is shown in Fig. 9. The transconductance amplifier compares the feedback voltage FB with the reference voltage V_{ref1} or V_{ref2} to generate the error signal V_{EA}. V_{ref2} can regulate a higher driving output voltage for G- or B-LEDs, whereas V_{ref1} can define a lower driving output voltage for R-LEDs. The selection of V_{ref1} or V_{ref2} depends on R_{scan} if the ZD is equal to one. ZD is used to synchronize R_{scan} and disable V_{SET}. In the BCM operation, ZD is equal to Z_{CDP}, whereas ZD is equal to Z_{CDN} in the ERM operation.

In the BCM operation, the on-time value T_{ON} is simply decided by comparing V_{EA} and the sawtooth signal V_{saw}. A constant current I_T is used to charge the timing capacitor C_M to generate V_{saw}. I_T also defines the maximum on-time value $T_{\mathrm{ON(MAX)}}$, as shown in (5) to clamp the on-time value of the transistor M_L. V_{Schmitt} is the trigger voltage of the Schmitt trigger circuit

$$T_{\mathrm{ON(MAX)}} = C_M R_T V_{\mathrm{Schmitt}}. \quad (5)$$

During G- or B-LEDs emission, R_{scan} stays at low, V_{SEL} is set to low, V_{SET} is set to high, and V_{REF} is set to V_{ref2}. The ER controller can operate in the BCM or SLM operation. In

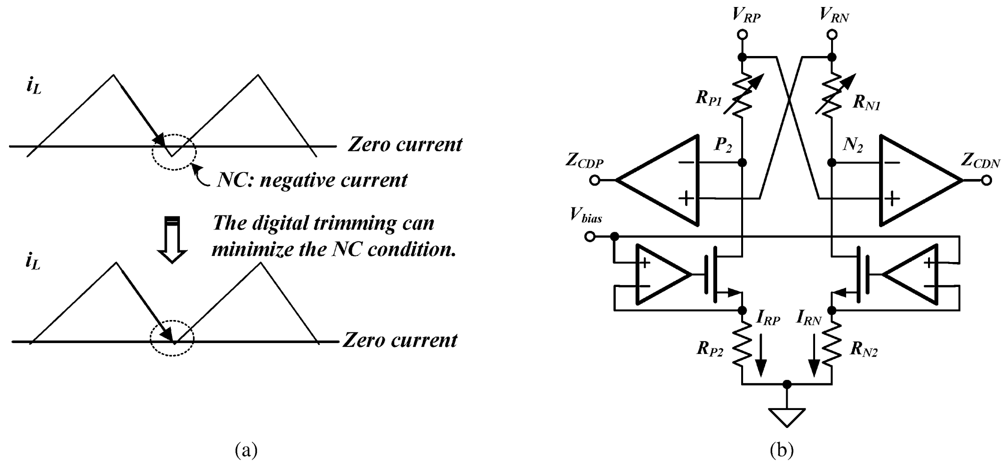


Fig. 10. (a) Inaccurate detection of the zero inductor current causes a large negative inductor current. (b) Proposed ZCD circuit.

the BCM operation, the zero-inductor current can be detected by the voltage across the sensing resistor $R_{\rm SEN}$. ZD is equal to $Z_{\rm CDP}$ in the ZCD circuit. The PWM signal G_D is controlled by $T_{\rm ON}$, which is clamped to $T_{\rm ONMAX}$. V_o is regulated to a higher driving voltage for G- or B-LEDs.

Thus, a ZCD circuit is required. In conventional design, the offset voltage of the comparator and the propagation delay in the ZCD circuit will cause an undesired reverse inductor current, as shown in Fig. 10(a). The zero current point is not accurate. Thus, the proposed ZCD circuit, as illustrated in Fig. 10(b), contains two resistors R_{P1} and R_{N1} to compensate for these nonideal conditions. The digital trimming of the values of two resistors can improve the accuracy of the ZCD circuit. The input pins $V_{\rm RP}$ and $V_{\rm RN}$ will have a high-voltage stress on them due to the high-input voltage and the recycling mechanism. To prevent the use of high-voltage devices in the chip for low cost, the ZCD circuit should be able to handle the high-voltage condition. Therefore, the pull-down constant currents $I_{\rm RP}$ and $I_{\rm RN}$ are generated by a voltage-to-current converter with a biasing voltage $V_{\rm bias}$ to generate accurately a voltage drop across the clamping resistors R_P and R_N, which are connected to the sensing resistor $R_{\rm SEN}$, as shown in Fig. 4. As a result, the zero current can be accurately detected without consuming a large power.

The voltage across the sensing resistor $R_{\rm SEN}$ can indicate the direction of the inductor current. Comparing $V_{\rm RP}$ and $V_{\rm RN}$ can detect the zero inductor current. If $V_{\rm RP}$ is larger than $V_{\rm RN}$, the inductor current is higher than the zero current. $Z_{\rm CDP}$ in the ZCD circuit is set to low. Once the zero current occurs, $Z_{\rm CDP}$ will be changed to high to reset the timing capacitor C_M for triggering the next switching cycle.

Furthermore, in the ERM operation, $R_{\rm scan}$ changes to high, and the charges on C_o will be transferred to C_R. $V_{\rm REF}$ is set to $V_{\rm ref1}$ at this time. During this period, $V_{\rm RN}$ is larger than $V_{\rm RP}$; thus, the inductor current is a reverse current. ZD is equal to $Z_{\rm CDN}$, which is set to low in the ZCD circuit. Once the zero current occurs, $V_{\rm RP}$ will be larger than $V_{\rm RN}$. $Z_{\rm CDN}$ will change to high to reset the timing capacitor C_F to trigger the next switching cycle. G_D is controlled by the on-time value $T_{\rm ON(FIX)}$ in the ERM operation. $T_{\rm ON(FIX)}$ is defined in (6) and is clamped by the trigger voltage $V_{\rm Schmitt}$ of the Schmitt trigger circuit

$$T_{\rm ON(FIX)} = C_F R_T V_{\rm Schmitt}. \quad (6)$$

B. RVT Circuit

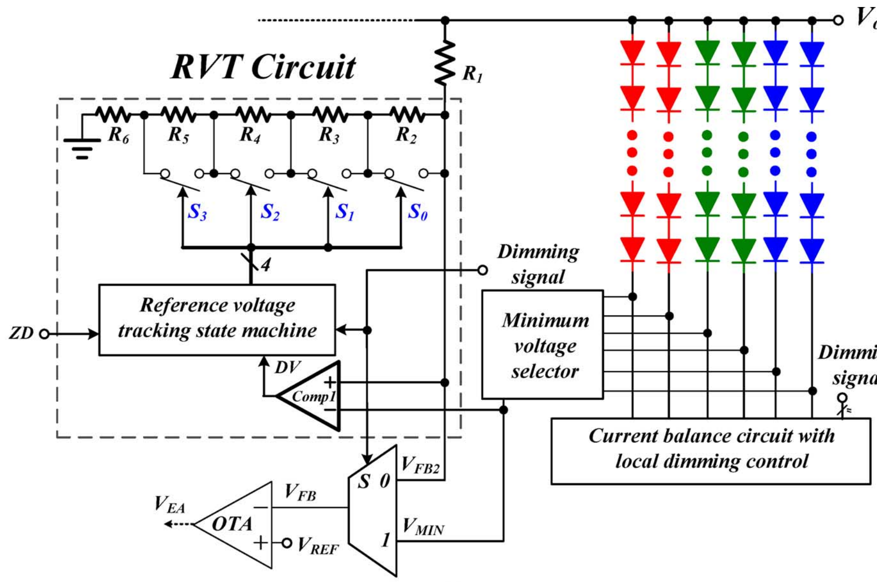
The RVT circuit maintains a constant output driving voltage V_o, whether the parallel LED strings are turned on or not. V_o can be regulated by two closed loops. One loop is defined by the minimum voltage selector [16]–[18] to keep a driving voltage high enough to turn ON all LEDs in series. However, the closed loop is broken when the dimming signal is low. Thus, the second loop is defined by the RVT circuit when the LEDs in series are turned off if the dimming signal is low. The RVT loop is decided by the voltage divider, which is composed of resistors R_1–R_6. The RVT state machine decides the value of the feedback voltage $V_{\rm FB2}$ by adjusting the switches S_0–S_3. As a result, V_o can be determined as follows:

$$V_{\rm OUT} = V_{\rm REF} \times \frac{R_1 + R_{DY}}{R_{DY}}, \text{ where}$$
$$R_{DY} = R_2 S_0 + R_3 S_1 + R_4 S_2 + R_5 S_3 + R_6. \quad (7)$$

The minimum voltage selector can find the $V_{\rm MIN}$ when the dimming signal is high. By comparing $V_{\rm FB2}$ and $V_{\rm MIN}$, $V_{\rm FB2}$ can track this value once the dimming signal is high. In the RVT operation, ZD can be used as the clock signal. The uptracking, downtracking, and idle mode can be determined by the RVT state machine. The truth table and the timing diagram are shown in Fig. 11(b) and (c), respectively. If $V_{\rm FB2}$ can track $V_{\rm MIN}$, the oscillation of V_o can be minimized. The power dissipation due to V_o oscillation can then be reduced.

IV. Experimental Results

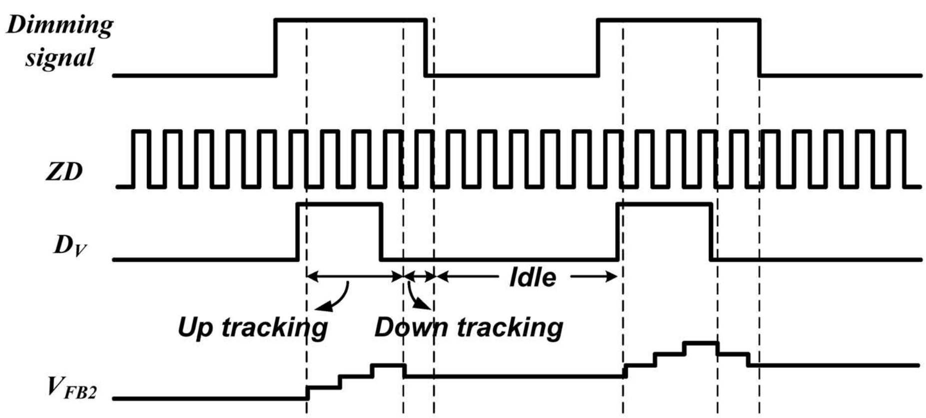
The proposed ER technology for the FCS-LCD backlight module was fabricated by Taiwan Semiconductor Manufacturing Company 0.25 μm 2.5/5 V bipolar–CMOS–DMOS (BCD) process. The threshold voltages of nMOSFET and pMOSFET are 0.477 and -0.596 V, respectively. The chip micrograph is shown in Fig. 12(a) with a die size of 800 $\times$ 1100 μm^2. The



(a)

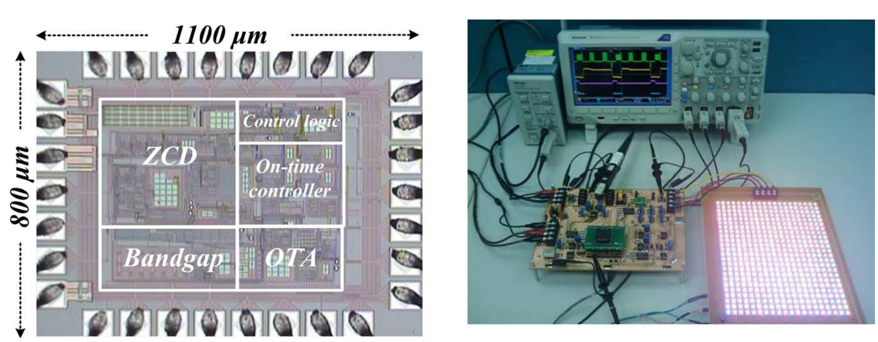
DV	*Dimming Signal*	V_{FB2}
0	1	Up tracking
1	1	Down tracking
X	0	Idle

(b)



(c)

Fig. 11. Proposed RVT technique. (a) Structure of the RVT technique. (b) Truth table of the RVT state machine. (c) Timing diagram of the controlling signals.



(a) (b)

Fig. 12. (a) Chip micrograph. (b) Prototype of the LED BLU with the ER technique.

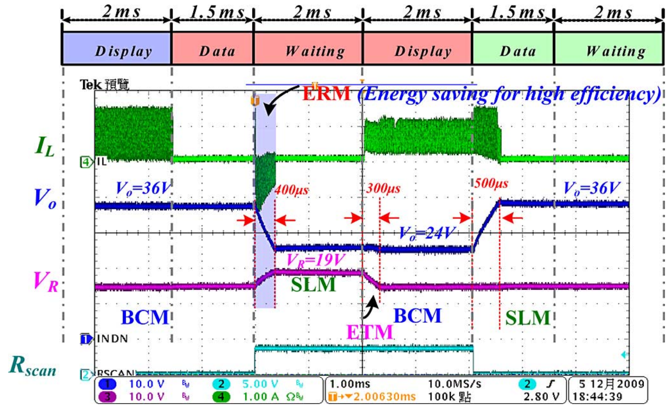


Fig. 13. $R_{\rm scan}$ area of the operating waveform in the FSC LCD technology.

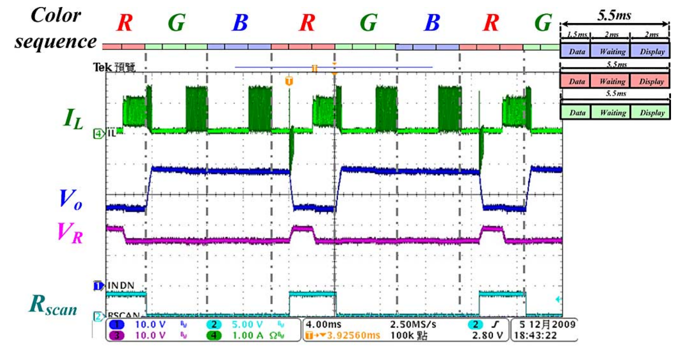


Fig. 14. Continuous operating waveforms of the FSC LCD technology.

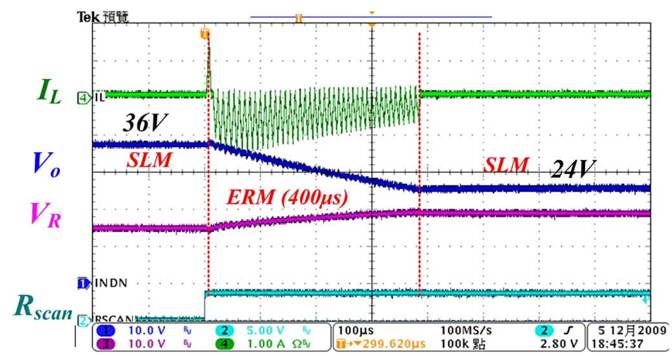


Fig. 15. Zoom-in operation waveforms during the ERM operation when the driving voltage decreases from 36 to 24 V for ER.

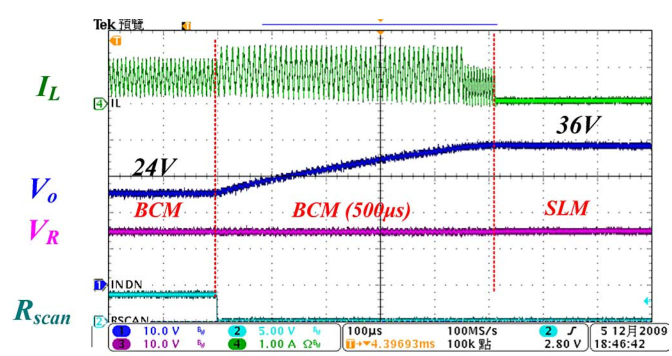


Fig. 16. Operating zoom-in waveforms when the driving voltage is raised from 24 to 36 V. The ER system enters the SLM operation for power saving.

specification of the prototype is shown in Fig. 12(b). The voltage V_R on the recycling capacitor C_R is limited and is smaller than 20 V according to (3) and (4). The driving current I_o is 380 mA for driving 12 R-LEDs in series. The 12 G-/B-LEDs in series require 290 mA driving current.

The ER controller boosts the low voltage $V_{\rm IN}$, which ranges from 14 to 16 V, to the high-driving voltage of about 36 V to drive 12 G-/B-LEDs in series or 24 V for 12 R-LEDs in series. After receiving the color sequence, the ER system can effectively change the driving output voltage and reuse the restored energy on the recycling capacitor. The voltage in the recycling capacitor is usually lower than 20 V without the overvoltage issue. The operation status of the ER system is shown in Fig. 13 when the color sequence changes from blue to red, and then, to green. The driving voltage should be changed from 36 to 24 V, and then, back to 36 V. Thus, the energy can be recycled when the color changes from blue to red. The signal $R_{\rm scan}$ indicates the ER status. At the beginning, the operation mode is BCM operation. Once the color changes to red, the energy is stored in the recycling capacitor, i.e., the operation changes from the BCM to the ERM operation. After the ERM operation, the red image data should be written on each pixel. The whole system is kept in the SLM operation to save energy because the quiescent current in this operation is quite small. When the LC is rotated to its correct position, the emitting time of the R-LEDs starts and consumes energy in the recycling capacitor first, i.e., the ETM operation releases the stored energy to drive the LEDs. The BCM operation takes over the whole system when the recycling energy is exhausted.

Continuous operating waveforms of the FSC LCD technology are shown in Fig. 14. Once $R_{\rm scan}$ changes from low to high, the ER mechanism is triggered to improve the efficiency. Each color display needs 5.5 ms to handle the procedure of data writing, waiting for LC rotation, and LED emitting. Thus, the response time of ERM operation is 400 μs. The enlarged waveforms are shown in Fig. 15. Similarly, as shown in Fig. 16, the response time of the driving voltage, which is raised to 36 V, needs 500 μs without affecting by the color brightness. Once the driving voltage reaches 36 V, the ER system enters the SLM operation again for power saving. On the other hand, the response time of the ETM operation depends on the brightness of the color. For example, the response time is 300 μs, as shown in Fig. 13.

In Fig. 14, there is deviation in the ETM operation due to the variation in brightness. The energy stored in C_R is released to drive LEDs in series when the procedure enters the display. In this paper, local dimming is utilized to reduce the LED backlight power. Thus, the period of the ETM operation depends on the brightness. In Figs. 17–19, the ETM operation period can be extended from 300 to 1100 μs when the brightness is tuned from a full load to 20% of the load. Thus, the efficiency can be further improved after implementing the local dimming technique.

The FSC display with RGB-LED backlight modules can dynamically switch the output voltage to 36 V for 12 G-/B-LEDs in series or 24 V for 12 R-LEDs in series according to each

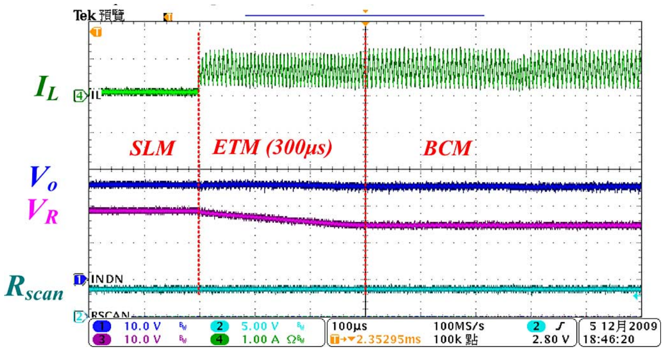


Fig. 17. Operating zoom-in waveform in the ETM operation when the dimming signal is always kept high (100% duty cycle).

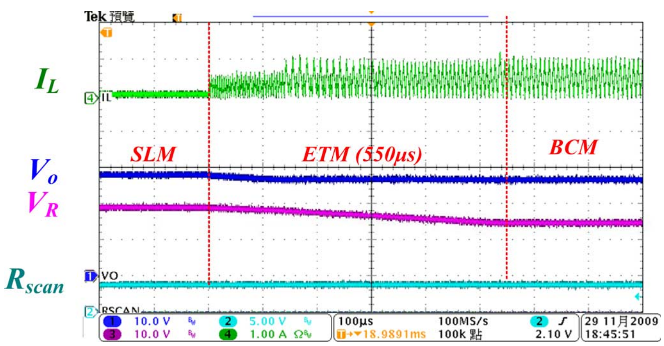


Fig. 18. Operating zoom-in waveform in the ETM operation when the dimming signal has a 50% duty cycle.

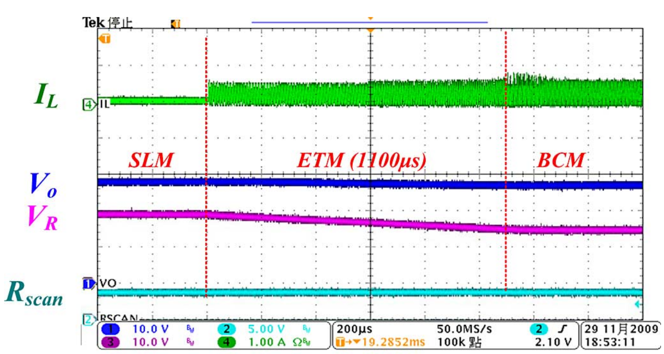


Fig. 19. Operating zoom-in waveform in the ETM operation when the dimming signal has a 20% duty cycle.

color sequence in the FSC technique. Therefore, it can reduce 13% of the total energy during the red color display period. The proposed ER technology can accelerate the settling time of the output voltage because the energy, which needs to be dissipated by load or leakage in conventional design, is stored in an ER capacitor from the output capacitor when the driving voltage is switched from 36 to 24 V. It can further reduce 17% of the dissipation energy. Fig. 20 shows the energy reduction curves, and Table I summarizes the design parameters and measurement results.

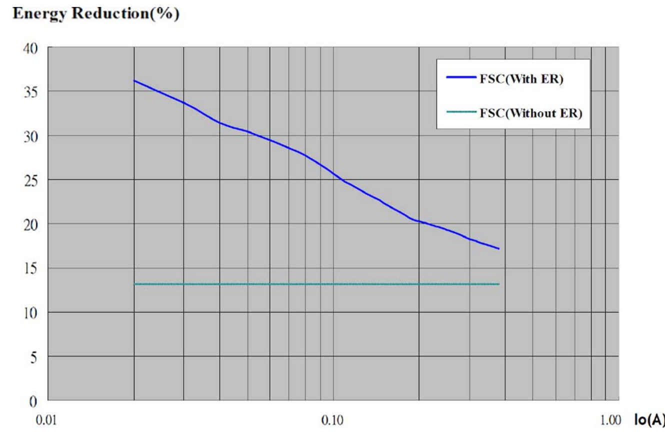


Fig. 20. Energy reduction curves.

TABLE I
MEASUREMENT PERFORMANCE OF THE ER SYSTEM

Inductor (μH)/ sensing resistor	33 μH/0.1 Ω
Co/C_R (μF)	10 μF/47 μF
V_{ref1}, V_{ref2}	2.2V/3.3V
Driving current of R-G-B LEDs (mA)	380-290-290 mA
Input voltage (V_{IN})	14~16 V
Output voltage (Vo)	36 V for G- and B-LEDs 24 V for R-LEDs
Output settling time (Tset)	500 μs (Rising)/400 μs (Falling)
Switching frequency (Hz)	100 kHz for 36 V output 120 kHz for 24 V output
Output ripple	< ± 5 %
Reduction in power consumption (%)	17 %

V. CONCLUSION

The FCS-LCD backlight module with the ER technology has been proposed to provide high-power conversion efficiency and to reduce fabrication cost. The proposed ER structure and controller rapidly switch the driving voltage between 36 and 24 V for 12-series different color LEDs. The recycling capacitor C_R properly acts as an energy tank to recycle the pressed charge when the driving voltage scales down to 24 V. The local dimming technique can save power using the RVT technique when a stabilized driving output voltage is ensured. Without large energy waste, the recycling charge is transferred to the output terminal again to drive the backlight module. Experimental results show that the maximum energy reduction of the proposed ER technology can be raised to about 17%.

ACKNOWLEDGMENT

The authors would like to thank RichTek Technology Corporation and Chunghwa Picture Tubes, Ltd. for their assistance.

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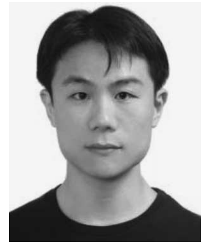

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