

Advanced LED-Dimming Function: PSR Control Method by Using MD6721

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Abstract Primary side regulation (PSR) control has become more popular because of its advantages, such as lower BOM cost and longer lifetime. In addition, there are some known issues in LED lighting control field that need to be solved, such as lack of accuracy under light load condition or when using different LEDs. In this article, we use the MD6721 which is designed for high performance SMPS (Switched-Mode Power Supply) LED driver, and provides an advanced PSR control algorithm for precise output current control in wide load range.

1. Introduction

The market acceptance of smart lighting in high performance is gradually increasing. For example, people working in the office need sufficiently stable light without flicker and users in personal area need highly dimmable light source for different occasions.

The MD6721 is digital power control IC based on MD6603, which includes 8051 (8-bit), DSP (16-bit) and Event Process Unit (EPU) (16-bit)⁽¹⁾. This article describes high performance PSR control method that uses DSP and 8051 for high-precision full-range dimming.

2. PSR Control for LED Application

Comparing with secondary-side regulation (SSR), primary-side regulation (PSR) is mostly used for its better power efficiency and cost competitive design. Typical SSR Constant Current control requires direct feedback from the output current. For safety reason, isolated LED drivers require non-electrical conductive feedback; output LED must be electrically isolated from AC input. Traditionally, opto-coupler transistor is used for this isolation.

The PSR control method eliminates opto-coupler,

sensing and compensating components. The magnetic field in the transformer provides feedback information that can be used to replace the function of opto-coupler.

Reducing the use of opto-coupler, sensing resistors and capacitors does save material cost and reduce the design of printed circuit board (PCB) area. In addition, the less the components are used, the longer lifetime of the product.

Most product developments in PSR control use “knee point sampling” for parts of the feedback signal, and the controller operates in critical conduction mode (CRM) during full load. However, simple CRM mode operation will result in system operated in ultra-high frequency region with thermal increase and reducing efficiency under light load condition.

Some articles are discussing the solutions of this issue, but most of them do not discuss operating under ultra-light load condition (<1%). In this paper, we will begin with an introduction to the basic PSR control with QR (quasi-resonant) operations, and improve the control method for ultra-light load condition.

2.1 Basic PSR Control with QR

Fig.1 shows the basic information for understanding the PSR control. Fig.1(a) is a schematic diagram of flyback circuit with auxiliary winding and I_{LED} represents LED current which is the major control target of LED driver. Fig.1(b) shows the key waveforms of the flyback circuit, including the voltage driving waveform

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from primary side, the current waveform of both primary side and secondary side, and the secondary side voltage sampled from the auxiliary winding during the OFF time. The driving period time is defined as T_s and can also be separated into the ON time plus the OFF time as shown in Eq. 1a or other form as shown in Eq. 1b. $[t_{ON}]$ is defined as the primary side charging time, $[t_{demag}]$ is defined as secondary side discharging time, and the last part $[t_{skip}]$ is defined as resonant time.

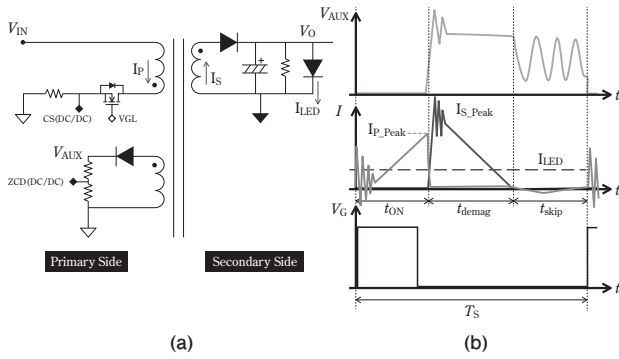


Figure 1

Fig.1.(a) Schematic of flyback converter with auxiliary winding: $[I_p]$ is primary side trans. current, $[I_s]$ is secondary side trans. current, $[I_{LED}]$ is LED current. $[VGL]$ is flyback driving pin. $[CS]$ is current sensing pin. $[ZCD]$ is auxiliary winding voltage sensing pin. **(b)** Waveform of flyback converter: $[V_G]$ shows circuit driving waveform. $[I]$ shows the waveform of I_p , I_s and I_{LED} , $[I_{p_Peak}]$ is the peak value of primary side current, $[I_{s_Peak}]$ is the peak value of secondary side current. $[V_{AUX}]$ shows the voltage waveform of auxiliary winding.

$$T_s = t_{ON} + t_{OFF} \quad \dots\dots\dots (1a)$$

$$T_s = t_{ON} + t_{demag} + t_{skip} \quad \dots\dots\dots (1b)$$

According to the law of charge conservation at secondary side when operated in stable situation, charge through LED should be equal to the charge passing secondary side transformer (Eq. 2)

$$I_{LED} \times T_s = \frac{1}{2} \times t_{demag} \times I_{s_Peak} \quad \dots\dots\dots (2)$$

By using the transformer characteristic of primary side and secondary side, Eq. 2 will become:

$$I_{LED} \times T_s = \frac{1}{2} \times t_{demag} \times I_{p_Peak} \times \frac{N_p}{N_s} \times K_{couple} \quad \dots\dots (3)$$

N_p represents the winding turns of primary side and N_s is the turns of secondary side, K_{couple} is coupling coefficient of transformer.

After formulating with Eq. 1b

$$I_{LED} = Cons \times I_{p_Peak} \times \frac{t_{demag}}{t_{ON} + t_{demag} + t_{skip}} \quad \dots\dots\dots (4a)$$

$$Cons = \frac{1}{2} \times \frac{N_p}{N_s} \times K_{couple} \quad \dots\dots\dots (4b)$$

Eq. 4a is the major formula of PSR control and shows that once we know all the right hand side information of formula from primary side circuit, the LED current can be calculated by the equation without direct sensing feedback.

2. 2 Using MD6721 in PSR control

Fig.2 shows open loop PSR control program architecture of MD6721. There are 4 cores inside the IC. Here we use one of DSP core for calculations, including the PSR control formula shown in Eq. 4a. The IIR (infinite impulse response) filter function is used for prevent some high frequency noise, the PI (Proportional Integral) controller function is used for PWM control, and finally uses a MMX function for maximum and minimum limitation.

$[I_{LED_Target}]$ is the LED output current target that can be set by the user and be updated to the DSP by the 8051. The final calculation result of DSP will be transferred to DPWM module, and then will be output through $[VGL]$ pin to directly control hardware circuit Fig.1 (a).

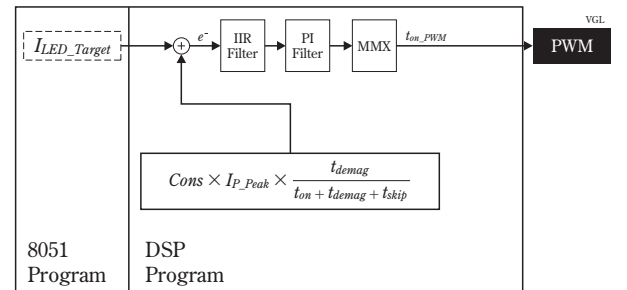


Figure 2

Fig.2. PSR control program architecture of MD6721, including PSR control formula (Eq. 4a), IIR filter, PI controller and MMX function. $[I_{LED_Target}]$ is the LED output target that can be set by the user. The final calculation result will be transferred to DPWM module, then be output through $[VGL]$ pin.

The following content will describe the control program step-by-step in the separated region I to III. Region I represents primary side charging, region II represents secondary side discharging and region III represents quasi-resonant.

(Fig.3) In region I, the control program will calculate the t_{on_PWM} for on time target of DPWM according to the initial settings (STEP 1a), but the peak current does not occur at the end of t_{on_PWM} , and it comes after propagation delay time due to the parasitic capacitance of the MOSFET. This phenomenon is usually ignored under heavy load condition, but has un-negligible impact under light load condition. Therefore, in the STEP 1b, $[t_{P_delay}]$ (Eq. 5) which needs to be considered with different MOSFET is set with digital counter control for the current sensing time delay (STEP 1c), and the last step is to detect the peak current at the end of t_{on} time (STEP 1d).

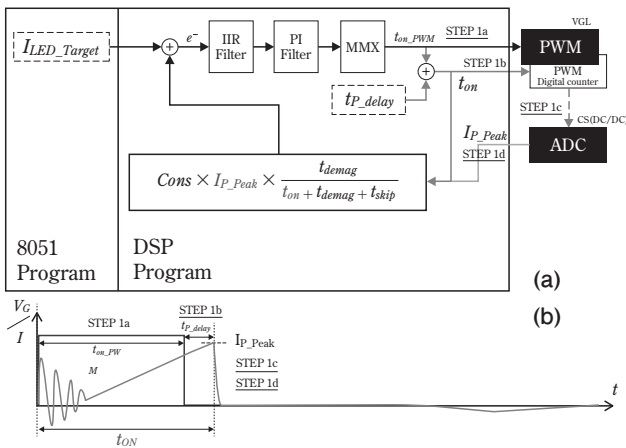


Figure 3

Fig.3(a), 3(b). Region I of PSR control: Primary side charging region. Main purpose of this region is checking t_{on} and I_{P_Peak} in PSR formula with relative circuit control. (a) shows PSR control operation, and (b) shows operation waveform.

$$t_{on} = t_{on_PWM} + t_{P_delay} \dots\dots\dots (5)$$

(Fig.4) During the end of region I (STEP 1c), the digital counter also sends a start signal to the TIMER (STEP 2a) for the start of region II duration measurement. After the secondary side current discharge is completed, the knee point can be sampled from the ZCD pin through the comparator (Fig.1.(a)), and a stop signal is sent to the TIMER (STEP 2b) to obtain the duration result of region II: t_{demag} (STEP 2c).

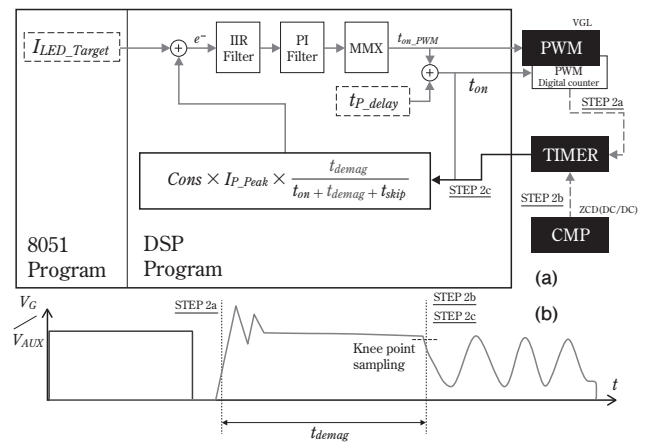


Figure 4

Fig.4(a), 4(b). Region II of PSR control: Secondary side discharging region. Main purpose of this region is to check t_{demag} in the PSR formula with the relative circuit control. (a) shows the PSR control operation, and (b) shows operation waveform.

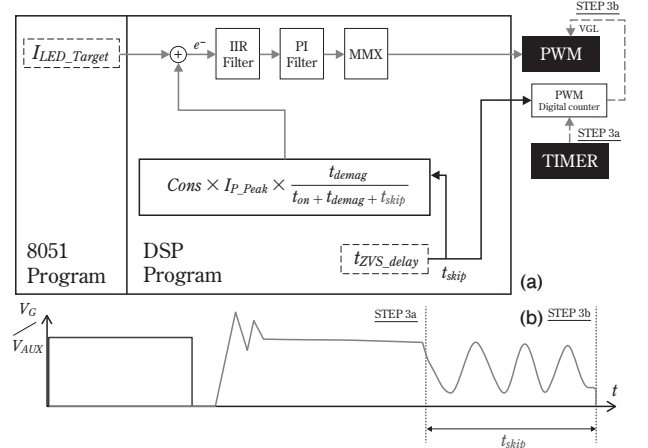


Figure 5

Fig.5(a), 5(b). Region III of PSR control: quasi-resonant region. The main purpose of this region is to check t_{skip} in PSR formula with relative circuit control. (a) shows the PSR control operation, and (b) shows the operation waveform.

(Fig.5) After current is discharged in the secondary side, the control program is operated into region III. Similar to region I, region III use a digital counter for PWM re-start time control to enter a new PWM cycle. (STEP 3a) The digital counter starts from the end of region II (STEP 2c), and the counting target $[t_{ZVS_delay}]$ of the digital counter is decided by the characteristics of snubber circuit design, or experimental result. From an efficiency point of view, $[t_{ZVS_delay}]$ controls the next

starting point in the voltage valley of resonant region in the current cycle to minimize switching loss when MOSFET is turned on.

After finished operation of region III of Fig.5, the control program will return to region I of Fig.3 and begin a new cycle of close loop control.

2.3 Advanced dimming function

The basic PSR control has some limitations on light load operation. Eq. 4(a) shows that when a light load operation is required, PSR formula will control t_{ON} as small as possible. Finally, it will be limited by the MMX function in the DSP program (Fig.2). In order to improve this, this section shows two types of control algorithms, (A) hybrid PSR control and (B) Feedforward control.

2.3.1 Hybrid PSR Control

Hybrid PSR control is a method of t_{skip} (Eq. 4a) control for switching operation between CRM and DCM (discontinuous conduction mode). As we have described (Fig.5), t_{skip} is set to the value of $[t_{ZVS_delay}]$, which is defined as restart of a new PWM cycle in the voltage valley of the resonant waveform to minimize switching losses.

We can also choose different number of voltage valley for t_{skip} switching to achieve a smaller minimum output target, but as the resonance time increases, the voltage valley selection will be more difficult.

Hybrid PSR control is a t_{skip} control algorithm based on t_{on} result. Fig.6(a) shows a t_{on} boundary diagram, the original basic PSR control, the design maximum and the design minimum is set in MMX function (Fig.2). In addition, we created two values for the hybrid PSR control, one is “DCM Boundary” and the other is “CRM Boundary”. Fig.6(b) shows the schematic diagram of the t_{skip} control algorithm based on t_{on} condition. When t_{on} is smaller than “DCM Boundary”, t_{skip} will be slightly reduced in the t_{slop} value. On the other hand, when the t_{on} become larger than the “CRM Boundary”, t_{skip} value will be slightly increased in t_{slop} value. This simple algorithm can be used for light load conditions. We only need to consider the t_{slop} value to avoid the LED blink caused by sudden t_{skip} changes, while DCM Boundary and CRM Boundary value are the hysteresis region design of DCM region and CRM region switching.

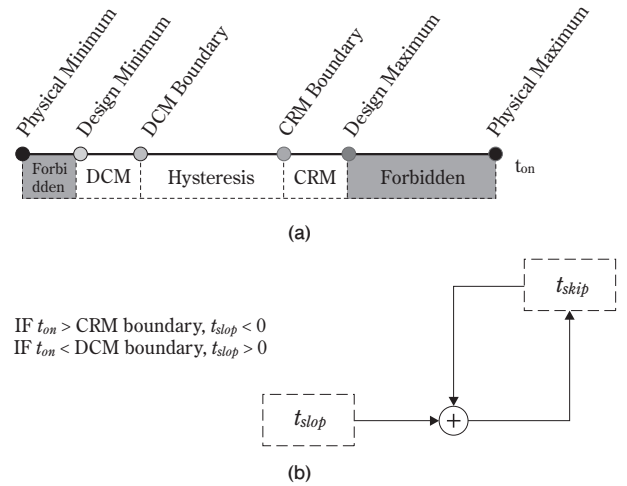


Figure 6

Fig.6(a) schematic diagram of t_{on} boundary: the physical maximum and minimum value are determined by the mosfet specification or physical operation. Design maximum and minimum value are designed by system operation limitations. In addition, DCM Boundary and CRM Boundary value are used for t_{skip} control in the hybrid PSR algorithm.

Fig.6(b) shows a schematic diagram of a t_{skip} control algorithm based on t_{on} condition.

2.3.2 Feedforward Control

As described in the previous section, Fig.6(a) shows the design maximum/ minimum boundaries and is used for the MMX function. The reason of designing the minimum limitation is shown in Fig.3(b). Oscillation noise near the start of the t_{on} region is produced due to parasitic capacitance of the inductor (marked circle in Fig.7). It is difficult to detect the correct peak current in STEP 1d of Fig.3, and minimum limitation will help to avoid sensing from this region.

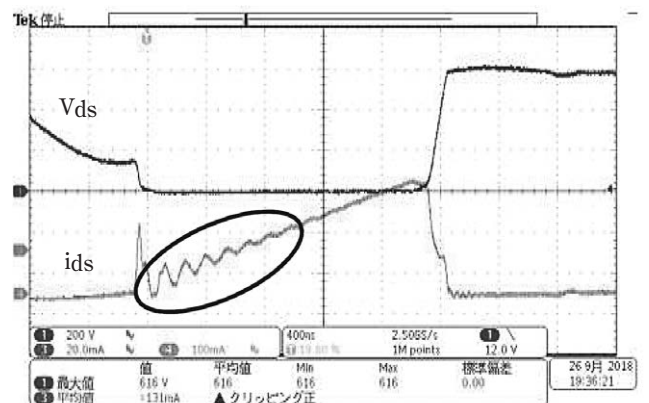


Figure 7

Fig.7 MOSFET related waveform: CH1 is Vds response and correlated with ZCD pin, CH4 is Idc response and correlated with CS pin. There are some oscillation noise near the start of the t_{on} region.

Of course, the inductor design used to minimize the parasitic capacitance will improve this. However, here we use software solution called feedforward algorithm to switch between feedback and feedforward for close loop control. Fig.8 shows the feedforward algorithm, that we use 8051 core for this part operations. (STEP A) The program is intermittently checks the PSR calculation result and once less than the target defined as $I_{Feedforward}$, the PSR control program will skip STEP 1d of Fig.3(a) and replace the peak current sensing result by calculation based on theoretical design at target t_{on} . (STEP B receiving t_{on} value from DSP, calculating peak current with Eq. 6 and STEP C sending the result to DSP). Moreover, in order to obtain a smaller t_{on} value, it temporarily reduces the design minimum value of MMX function.

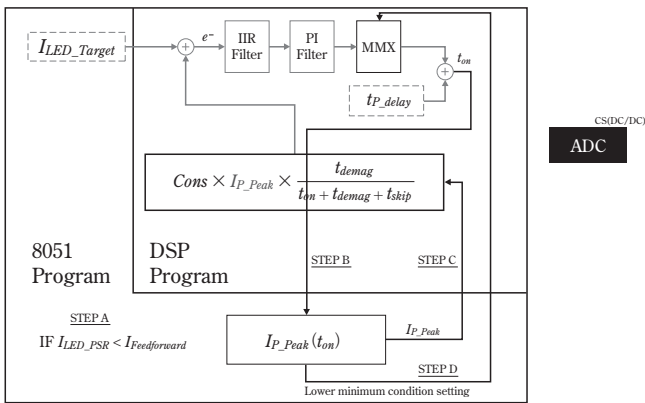


Figure 8

Fig.8 Feedforward control algorithm. Replace peak current sensing result by calculation based on theoretical design. Moreover, temporary lower the design minimum value of MMX function for getting smaller t_{on} value.

$$I_{P_Peak} = \frac{V_{IN}}{L} \times t_{on} \dots\dots\dots(6)$$

3. Experiment Result

We design a 60W PFC and QR flyback two-stage LED driver with self-power circuit and embedded DALI

interface for testing. Fig.9 shows the PSR operation waveform. Above medium load (>40%), the system operates in CRM mode with t_{on} only control. From light load to medium load (18%~40%), the hysteresis region design of hybrid PSR algorithm is shown; comparing (a) and (b), the results of CRM and DCM region switching are different, avoiding some unstable situation. In addition, below light load condition (<3%), PSR control is operated by feedforward algorithm.

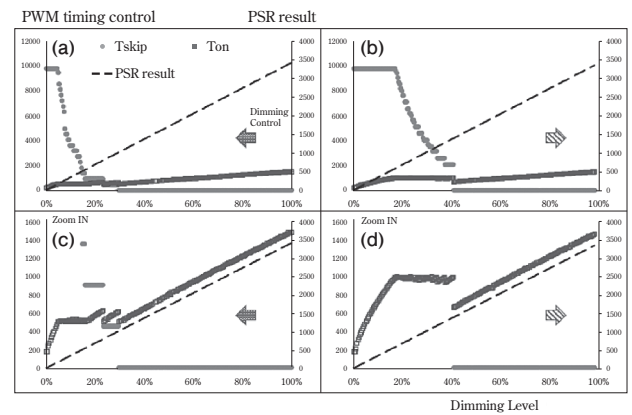


Figure 9

Fig.9 Advanced PSR Control Result: The X-axis is relative dimming level (%), the major Y-axis is the relative digital value of time, and minor Y-axis is the relative digital value of current. The filled-circle is the T_{skip} control by hybrid PSR method, the hollow-square is the T_{on} control by basic PSR method, and dash-line is the PSR calculation result. (a) is the PSR operation result, with dimming level from high to low. (b) is the PSR operation result, with dimming level from low to high. (c) is the ZOOM IN result of (a) in major Y-axis. (d) is the ZOOM IN result of (b) in major Y-axis.

(Fig.10) is the waveform result of PSR control. The operation condition of Fig.10a is at 95% load, and t_{skip} is controlled to the $[t_{ZVS_delay}]$ value for better efficiency. Fig.10b shows the system operation in 18% load conditions, both t_{on} and t_{skip} have been controlled by the hybrid mode algorithm. Fig.10c shows at 4% load condition, t_{on} is limited by the design minimum value, and only t_{skip} is used for output control. Fig.10d shows a 1.5% load condition, with a gradual increase in noise during peak current detection, and the feedforward close loop control.

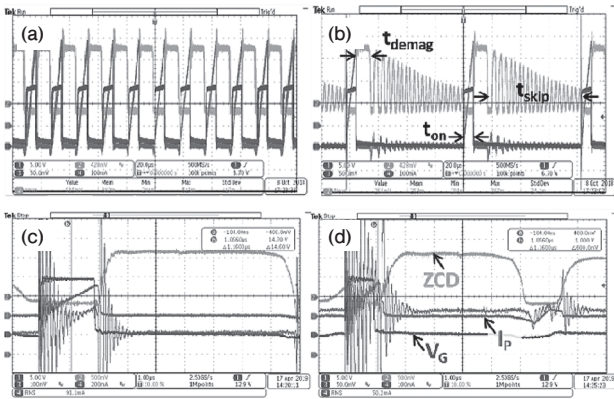
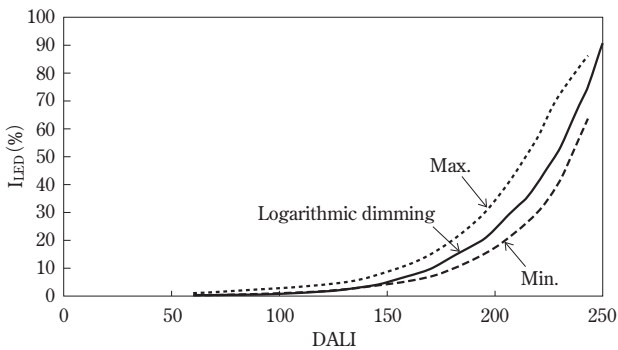


Figure 10

Fig.10 Waveform of PSR Control: CH1 is the drive signal output from “VGL” pin, CH2 is the Vaux relative signal detected from “ZCD” pin, and CH4 is the current of primary side correlated with “CS” pin. (a) is the 95% result of CRM operation output, (b) is the 18% result of hybrid PSR operation output, (c) is the 4% result with t_{skip} operation output, and (d) is the 1.5% result of feedforward operation output.



Arc Power level	60	85	126	145	170	195	216	229	243
Minimum value	0.25	0.5	2	3.93	7	15	27.28	40	63.53
Nominal value	0.5	0.99	3.04	5.1	10.09	19.97	35.43	50.53	74.05
Maximum value	1	2	4.5	7.5	15	30	52.09	71	86.14
Dimming curve	0.31	0.73	2.32	4.76	9.06	20.46	35.45	53.21	73.32

Figure 11

Fig.11 Digital Addressable Lighting Interface (DALI) interface dimming curve test: X-axis is DALI level, the range is “0”, “1~254”. Y-axis is the relative LED current (%).

(Fig.11) shows the overall test results as defined by IEC 62386-102⁽²⁾. The DALI level “0” indicates that the LED is off that there is no current, and the logarithmic relationship between DALI level “1~254” and the relative LED current is defined in IEC 62386-102 clause 9.3. The PSR algorithm allows precise control of LED current with a minimum output of 0.3%.

4. Conclusion

This article describes a high performance LED control system with the MD6721 IC. PSR with QR control in heavy load for high-efficiency operation; hybrid PSR control with feedforward algorithm for ultra-light load condition; in addition, BOM cost is reduced by eliminating the feedback components and system miniaturization is achieved through DALI interface integration, eliminating the need of discrete MCU communication.

We are thankful to our colleagues in TSDC and SKJ who provided expertise that greatly assisted the development.

Reference

- (1) Mima: Sanken Technical Report, Vol.48, pp.9-12 (2016.11)
- (2) IEC 62386-102 : Digital addressable lighting interface - Part 102