The PWM and Analog Dimming Solution to Implement 0.05% to 100% Dimming Range Based on UCC28810/11 Constant Current Buck

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ABSTRACT

In this paper, the combined dimming solution (PWM and 1- to 10-V analog) based on the UCC28810/11 device is provided to meet today's wider dimming range specification for the LED ceiling lamp application. This solution is different from the traditional 10% to 100% PWM dimming, and it divides the dimming range into two parts: for the first part, 5% to 100% LED current dimming will be implemented by 1- to 10-V analog dimming signal; for the second part, 0.05% to 5% LED current dimming will be implemented by 1% to 100% PWM dimming signal.

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1 Introduction

With the increasing stringent dimming control tendency for the ceiling lamp, the single traditional analog dimming or PWM dimming cannot meet the current market requirement. Instead, the combined mode of PWM and analog dimming is a good choice. However, deeper and wider dimming remains the challenge due to the influences of parasitic effect on the junction capacitor for the MOS and output diode. An additional challenge is meeting the good linearity specification between the LED output current and dimming signal.

In this paper, the combined analog dimming and PWM dimming solution based on the UCC28810/11 device is provided to meet this specification. Due to a contribution of power-factor correction (PFC) output or Flyback output in the front of AC input, in this paper the UCC28810/11 device will be provided by the DC input voltage. For a better understanding of this solution, this paper provides the detail theoretical analysis and practical design with extensive experiment data. This paper proves that the design calculation matches with the experiment very well.

2 Principle Analysis Based on UCC28810/11 Buck Constant Current Solution

2.1 The Origin of UCC28810/11 Constant Current Buck

To implement constant current, the logic circuit inside the UCC28810/11 device must be changed due to the influence of the internal multiplier (see Figure 1). Because the output-clamped voltage of this multiplier is 1.7 V, we can create a simple external circuit to let the multiplier stabilize at 1.7 V; that is, the internal reference voltage of 1.7 V can be created in this way.

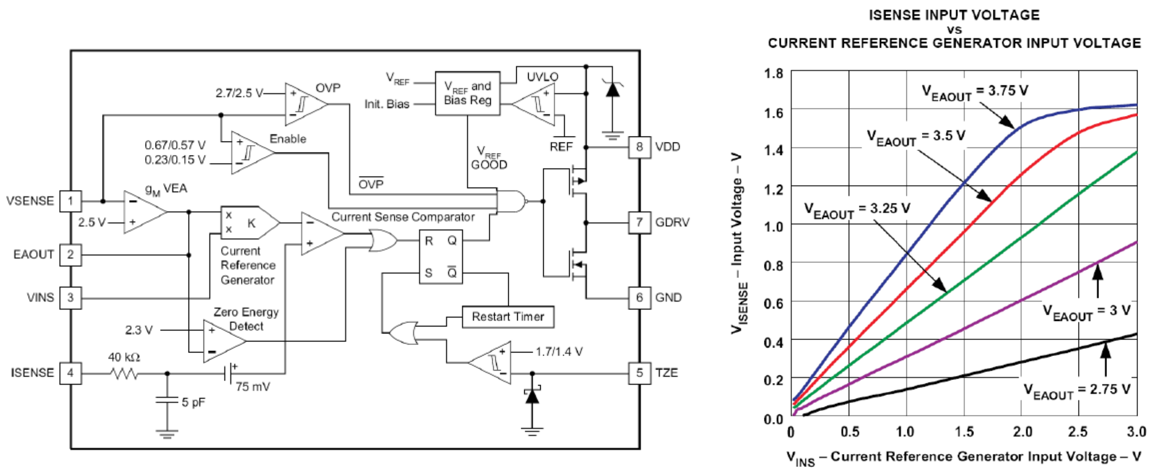


Figure 1. Internal Block Diagram of the UCC28810/11 Device and Its Multiplier Function

The internal reference voltage of 1.7 V can be created as shown in Figure 2.

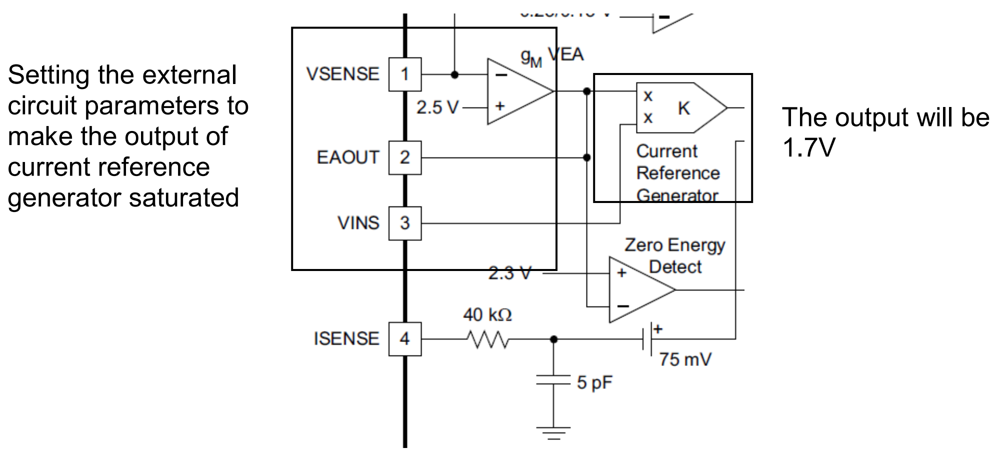


Figure 2. Internal 1.7-V Creating Function for the UCC28810/11 Device

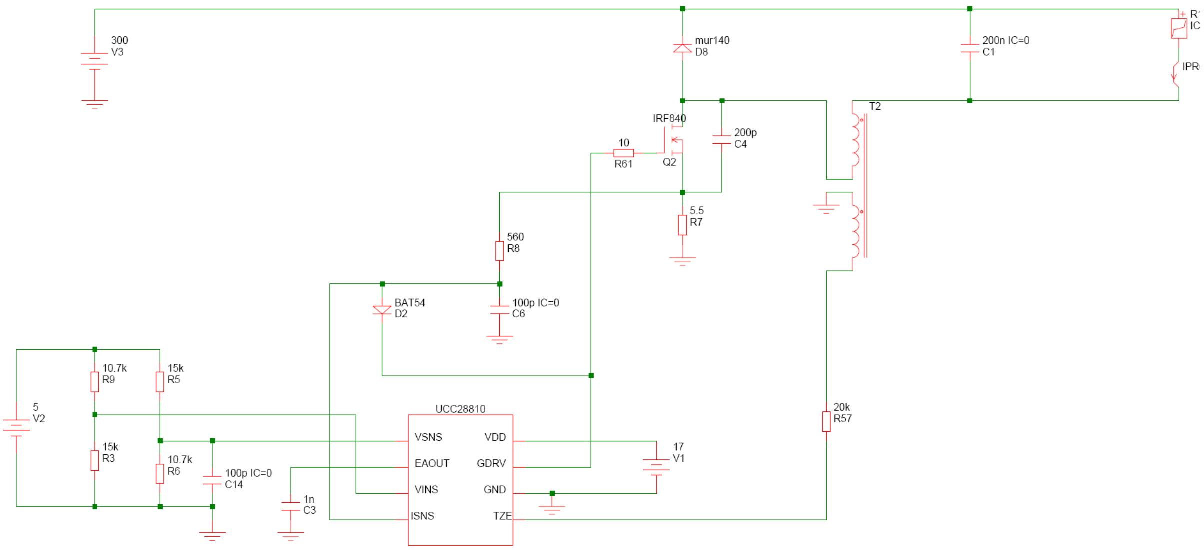


Figure 3. Basic Buck Constant Current Solution with the Internal 1.7-V Reference

2.2 Ideal Operation Analysis of UCC28810/11 Device Constant Current Buck

The LED output current will be 0.5 times the peak current going through the BUCK MOS due to the critical operation mode for the UCC28810/11. As mentioned in Section 2.1, the internal reference voltage will be 1.7 V, and then the current through MOS will be:

$$I_{PP} = \frac{1.7}{Rs}\cdot \quad (1)$$

Then the output current will be:

$$I_o = \frac{0.85}{Rs}\cdot \quad (2)$$

The turn-on time and turn-off time will be

$$T_{on} = \frac{2\cdot I_o \cdot L}{V_{in} - V_o}\cdot \qquad T_{off} = \frac{2\cdot I_o \cdot L}{V_o}\cdot \quad (3)$$

The switching frequency will be:

$$F_{sw} = \frac{(V_{in} - V_o)\cdot V_o}{2I_o \cdot L \cdot V_{in}}\cdot \quad (4)$$

3 Practical UCC28810/11 Device Constant Current Principle Analysis

3.1 Constant Current Analysis for the Traditional Operation

In practical operation, the resonance between the junction capacitor of the MOS and Diode and the inductance of the BUCK inductor occurred when the current of BUCK inductor decreased to zero. During this process, the V_{DS} of MOS decreases gradually. However, this voltage may come to zero at some certain input condition showing that the ZVS condition is realized completely. However, it must be pointed out that the negative current of inductor current will be discovered due to this resonance mechanism. This causes the total average current through the BUCK inductor to vary slightly from the ideal operation BUCK current. This variance means the practical LED current formula must be recalculated based on this resonance consideration.

Due to the complicated formula of junction capacitance of the MOS and Diode, it can be defined as C_{oss} for simplification but not affecting our analysis result. So the inductance of the BUCK inductor can be defined as L. We can obtain Equation 5, as referenced in Figure 4:

During the stage of $T_{d\_off:}$

The junction capacitor of the MOS and Diode will be discharged gradually, which makes the current through inductor go reverse when the BUCK inductor current decreases to zero. The voltage of MOS will be:

$$V_{DS}\_MOS = V_{in} - V_o + V_o \cdot \cos(\omega \cdot t) \qquad \omega = \frac{1}{\sqrt{L \cdot C_{oss}}} \tag{5}$$

The T_{d_off} stage will come to the end when the voltage of MOS decreases to $V_{in} - V_o$, (see Figure 4), then we have:

$$T_{d\_off} = \frac{\pi}{2\omega} \tag{6}$$

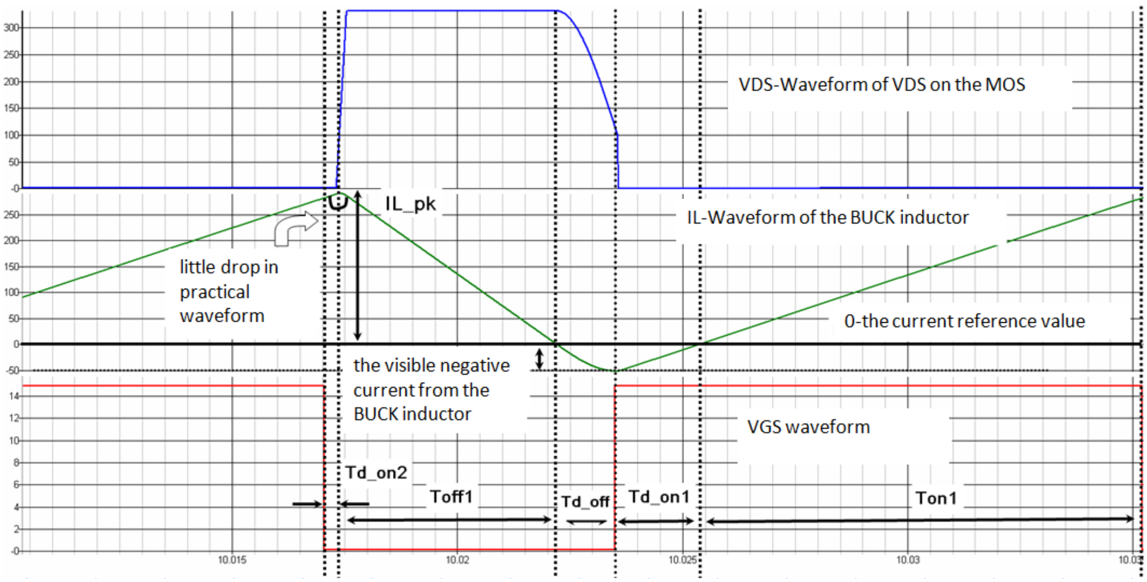


Figure 4. Waveform Analysis for the Steady Operation

According to the similar analysis, the following formulae can be obtained as:

$$T_{d\_on1} = \frac{V_o}{(V_{in} - V_o) \cdot \omega} \tag{7}$$

$$T_{on1} = \frac{1.7}{Rs} \cdot \frac{L}{V_{in} - V_o} \tag{8}$$

$$T_{off1} = \frac{1.7}{Rs} \cdot \frac{L}{V_o} \tag{9}$$

So the entire periodic can be obtained as:

$$Ts = T_{d\_on1} + T_{d\_off} + T_{d\_on1} + T_{d\_off1} \tag{10}$$

The switching frequency can be obtained as:

$$F_{sw} = \frac{1}{\frac{\pi}{2\omega} + \frac{V_o}{(V_{in} - V_o) \cdot \omega} + \frac{1.7}{Rs} \cdot \frac{L}{V_{in} - V_o} + \frac{1.7}{Rs} \cdot \frac{L}{V_o}} . \tag{11}$$

The ultimate LED output current can be obtained as:

$$Io = \frac{0.85}{Rs} - 0.5 \cdot \left(\frac{1.7}{Rs} + Vo \cdot \omega \cdot C_{oss} \right) \cdot \frac{\frac{\pi}{2} + \frac{V_o}{V_{in} - V_o}}{\left(\frac{\pi}{2\omega} + \frac{V_o}{(V_{in} - V_o) \cdot \omega} + \frac{1.7}{Rs} \cdot \frac{L}{V_{in} - V_o} + \frac{1.7}{Rs} \cdot \frac{L}{V_o} \right) \cdot \omega} \tag{12}$$

From Equation 12, it can be seen that LED current is not dependent on the single parameter; instead, it is influenced by several parameters such as Rs, V_{in}, V_o, L, and C_{oss}. In practical design, we can know the parameters of Rs, L, and C_{oss}, but V_{in} and V_o must be evaluated.

From Equation 12, we can see LED output current is minimally affected with some certain input voltage variation. However, the LED current will be affected when output voltage is varied. So, the compensation circuit must be determined to tightly stabilize the output current when the LED voltage changed.

3.2 The Improved UCC28811 Constant Output Current Solution

Because a variation in output voltage affects LED current, the simple compensation solution is proposed by connecting a large-value resistor, R_L, from the ISNS pin of the UCC28811 device to the negative terminal of the LED.

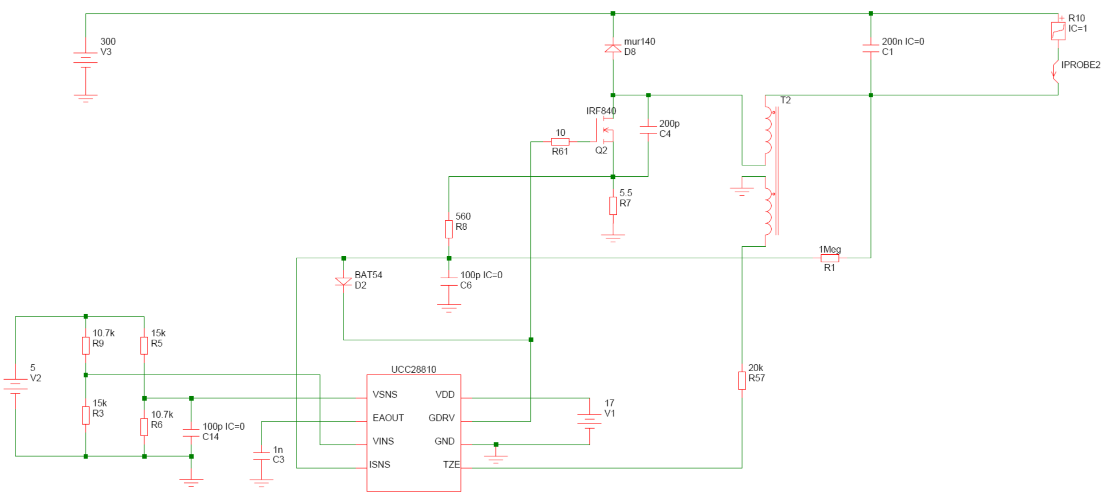


Figure 5. Solution for the Tight Output Current Control When Output Voltage Varies

Shown as Figure 5, the total output current can be calculated by Equations 13 and 14:

The voltage of the ISNS pin of the UCC28810/11 device will be:

$$Visns = Ipp \cdot Rs + \frac{(V_{in} - V_o) \cdot R_m}{R_m + R_L} \tag{13}$$

Then the LED output current can be obtained as:

$$Io = 0.5 \cdot Ipp - 0.5 \cdot \left(Ipp + V_o \cdot \omega \cdot C_{oss}\right) \cdot \frac{\dfrac{\pi}{2} + \dfrac{V_o}{V_{in} - V_o}}{\left(\dfrac{\pi}{2\omega} + \dfrac{V_o}{\left(V_{in} - V_o\right) \cdot \omega} + Ipp \cdot \dfrac{L \cdot V_{in}}{\left(V_{in} - V_o\right) \cdot V_o}\right) \cdot \omega}$$

$$Ipp = \frac{1.7 - \dfrac{\left(V_{in} - V_o\right) \cdot R_m}{R_m + R_L}}{Rs} \tag{14}$$

The switching frequency will be:

$$Fsw = \frac{1}{\left(\dfrac{\pi}{2\omega} + \dfrac{V_o}{\left(V_{in} - V_o\right) \cdot \omega} + Ipp \cdot \dfrac{L \cdot V_{in}}{\left(V_{in} - V_o\right) \cdot V_o}\right)} \tag{15}$$

4 The PWM and Analog Dimming Design Analysis

4.1 The 5% to 100% Analog Dimming Solution

Per the normal requirement, a wide range of analog dimming from 5% to 100% must be met. Figure 6 is shown to achieve this. D1 and R2 are added to compensate the ISNS pin of the UCC28810/11 device, and the external varied analog signal is provided to change the LED output current.

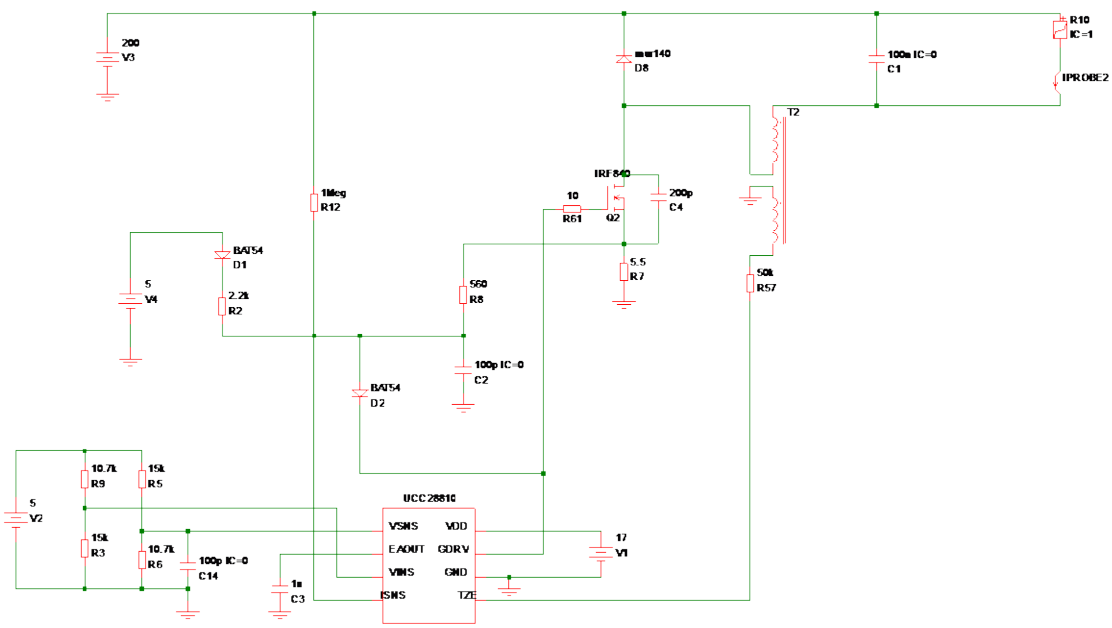


Figure 6. UCC28810/11 Analog Dimming Solution

Referring to Figure 6, if we designate resistor R8 as R_L, resistor R2 as R_{dim}, resistor R7 as Rs, and the external 5-V supply as V_{anog}, we can have the following formulae:

The LED output current when conducting analog dimming can be obtained as:

$$Io(V_{anog}) = 0.5 \cdot Ipp(V_{anog}) - 0.5 \cdot (Ipp(anog) + V_o \cdot \omega \cdot C_{oss}) \cdot \frac{\frac{\pi}{2} + \frac{V_o}{V_{in} - V_o}}{\left(\frac{\pi}{2\omega} + \frac{V_o}{(V_{in} - V_o)\cdot \omega} + Ipp(V_{anog}) \cdot \frac{L \cdot V_{in}}{(V_{in} - V_o) \cdot V_o}\right) \cdot \omega}$$

$$Ipp(V_{anog}) = \frac{1.7 - \frac{(V_{anog} - V_f - 1.7)\cdot R_L}{R_{\dim}}}{Rs} \qquad (V_{anog} \geq 1.7 + V_f) \qquad (16)$$

The switching frequency can be obtained as follows:

$$Fs(V_{anog}) = \frac{\omega}{\frac{\pi}{2} + \frac{V_o}{(V_{in} - V_o)} + Ipp(V_{anog}) \cdot \frac{L \cdot V_{in} \cdot \omega}{(V_{in} - V_o) \cdot V_o}} \qquad (17)$$

In practical application, the external V_{anog} will be provided by the microchip, which will produce the output voltage varied from 1.7 + V_f to 5 V. During this range, the output current will be line with V_{anog}, and the line ratio is mainly dependent on R_L and R_{dim}. We can achieve the optimized line ratio according to the design specification.

The experiment verified that the 5% to 100% analog dimming can be easy to implement when the external V_{anog} varied from 5 V to 1.7 + V_f. Actually, concern about the influence of V_f is not necessary, because very little voltage variation occurs during the actual 0°C-to-75°C temperature variation if a low forward diode, such as BAT54, is chosen.

4.2 The Improved 0.05% to 5% PWM Dimming Solution

First of all, note that the original PWM dimming solution shown in Figure 7 (Q4, R14, and R15) will not work well due to a flickering issue. This issue is primarily caused because the deep PWM dimming range is extremely wide, therefore the UCC28810/11 device cannot easily detect the ISNS signal due to the influence of the junction capacitor of MOS. The junction capacitor will not let the UCC28810/11 device have the stable control if the peak voltage of ISNS dominates the entire period of sense voltage recognized by the controller. Figure 7 shows the improved solution.

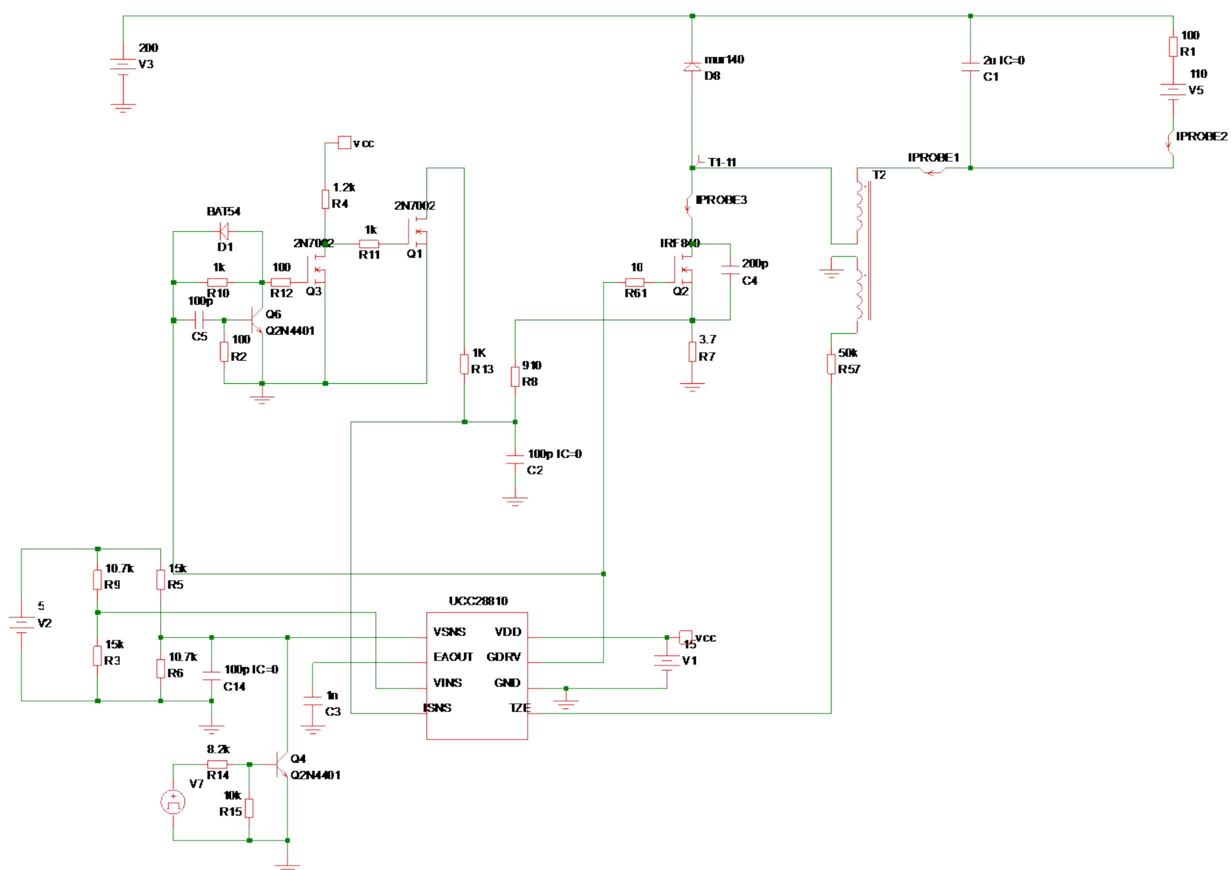


Figure 7. Improved Solution for the UCC28810/11 PWM Dimming

In Figure 7, the circuit of Q1, Q3, R13, and Q6 is added to move out the peak voltage of ISNS at the beginning of its rising stage.

Extensive experimentation proves that this circuit works well to provide good dimming performance from 0.05% to 100% dimming range even across a wide temperature range.

5 The Practical Design Example

To verify the previous solution, see the following table of design specifications. For the practical application of this solution:

- The input is always 90 VAC to 130 VAC.
- Nonisolated solution is chosen.
- PFC is used.
- PFC outputs approximately 200 VDC.

The design parameters are shown as the following table:

Table of Design Specification

Design specification	Parameters	Requirement
Input and output		
BUCK input volatge	Vin	150DC-220VDC
BUCK output current	Io	200mA
BUCK output voltage range	Vo	60-130V
effi	η	>0.94
Dimming spec		
Analog dimming	0-10V	10mA-200mA
PWM dimming	1%-100%	100uA-10mA

Dimming design specification: PWM dimming and analog dimming are provided by the external signals. However, 0 to 10 V will be converted to the 2- to 5-V analog signal through the microchip, and 1% to 100% PWM dimming signal could have the direct control of the UCC28810/11 device.

According to the design requirement, the analog dimming is as described in Section 4.1, and PWM dimming is as described in Section 4.2. The detail design procedure is presented as follows.

Step 1: Choose the inductance of the BUCK inductor according to the efficiency specification.

To achieve the 94% efficiency, the minimum operation frequency of 30K is chosen. Given the total MOS and Diode junction capacitance of 200 pF, V_{in} is with 200 VDC, V_o is with 130 V, Rs is first chosen with 3.7R. The formula and curve of frequency versus L can be obtained as follows:

$$Fs(L) = \frac{1/\sqrt{L \cdot Cc}}{\frac{\pi}{2} + \frac{V_o}{(V_{in} - V_o)} + \frac{1.7}{Rs} \cdot \frac{L \cdot V_{in}}{(V_{in} - V_o) \cdot V_o \cdot \sqrt{L \cdot Cc}}} \quad (18)$$

The curve of frequency versus L is shown from Figure 7.

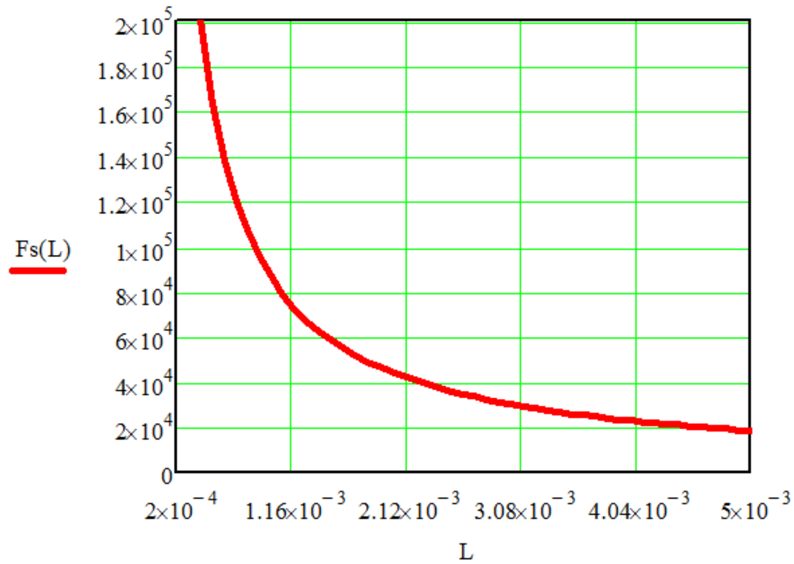


Figure 8. Curve of Frequency versus L

It can be seen that the value of inductance of the BUCK inductor must be chosen as 3.0 mH.

So in Step 1, we obtain:

Rs = 3.7R L = 3.0 mH

Step 2: Choose the analog dimming resistor R_{dim} and the ISNS buffer resistor R_L.

According to the analog dimming design objective, a 2-V to 5-V analog signal will make the output current vary from 20 to 10 mA. If we first choose R_L as 910 R, then R_{dim} can be solved from Equation 19:

$$10mA = 0.5 \cdot Ipp - 0.5 \cdot \left(Ipp + V_o \cdot \omega \cdot C_{oss}\right) \cdot \frac{\frac{\pi}{2} + \frac{V_o}{V_{in} - V_o}}{\left(\frac{\pi}{2\omega} + \frac{V_o}{\left(V_{in} - V_o\right) \cdot \omega} + Ipp \cdot \frac{L \cdot V_{in}}{\left(V_{in} - V_o\right) \cdot V_o}\right) \cdot \omega}$$

$$Ipp = \frac{1.7 - \frac{(5-2) \cdot R_L}{R_{\text{dim}}}}{Rs} \tag{19}$$

The value of R_{dim} can be solved as 1.9 K if the forward voltage of dimming diode is 0.3 V. As a result, the analog dimming curve can be plotted as shown in Figure 9.

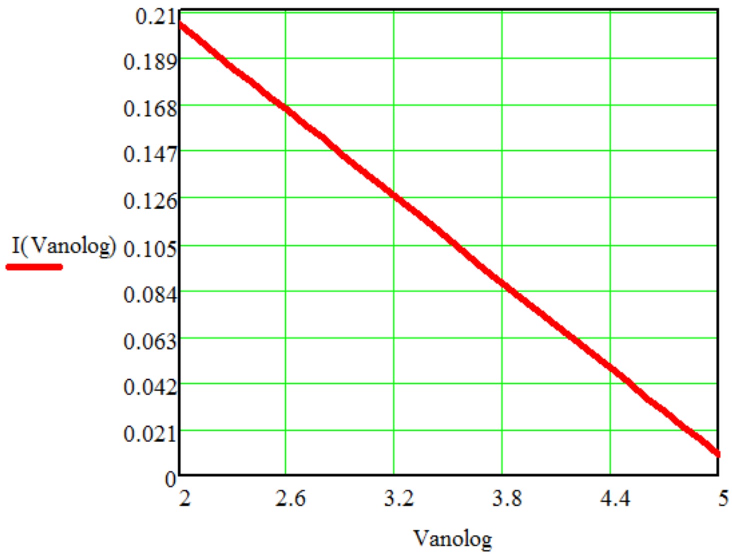


Figure 9. Calculated Output Current When Analog Dimming

Check the operation frequency during analog dimming according to Equation 20:

$$Fs(Vanog) = \cdot \frac{\frac{\pi}{2} + \frac{V_o}{V_{in} - V_o}}{\left(\frac{\pi}{2\omega} + \frac{V_o}{(V_{in} - V_o)\cdot\omega} + Ipp(Vanog)\cdot\frac{L \cdot V_{in}}{(V_{in} - V_o)\cdot V_o} \right)\cdot\omega} \tag{20}$$

$$Ipp(Vanog) = \frac{1.7 - \frac{(Vanog - Vf - 1.7)\cdot R_L}{R_{\mathrm{dim}}}}{Rs}$$

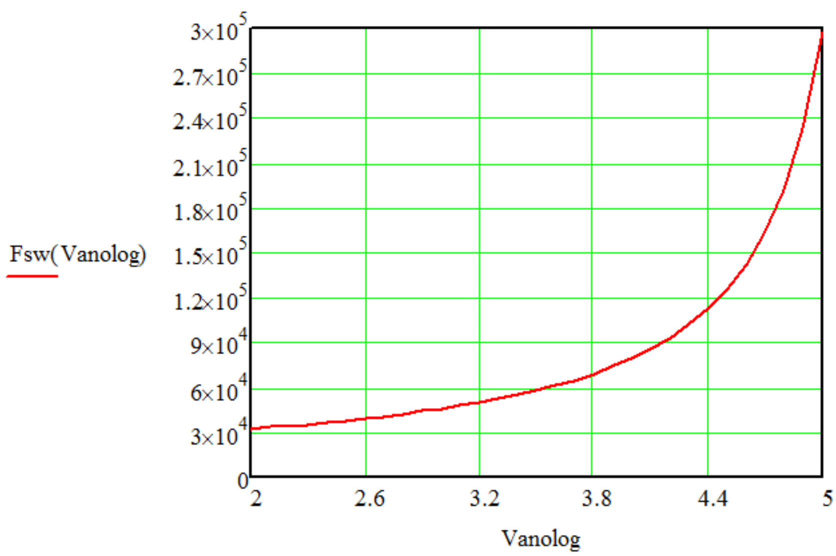


Figure 10. Calculated Frequency Curve When V_{anolog} Out Voltage Varies

The frequency can go up to 300K when coming to 5% dimming, which means it will be good for PWM dimming, especially 1% PWM dimming. But efficiency may be lower.

So in step 2, we obtain the following:

R_L = 910 R R_{dim} = 1.9 K

Step 3: Choose the parameters for the PWM dimming improvement circuit

Due to the influence of the junction capacitor of the MOS and Diode, the UCC28810/11 device may detect the wrong information on the ISNS pin when coming to 5% dimming (see Figure 10).

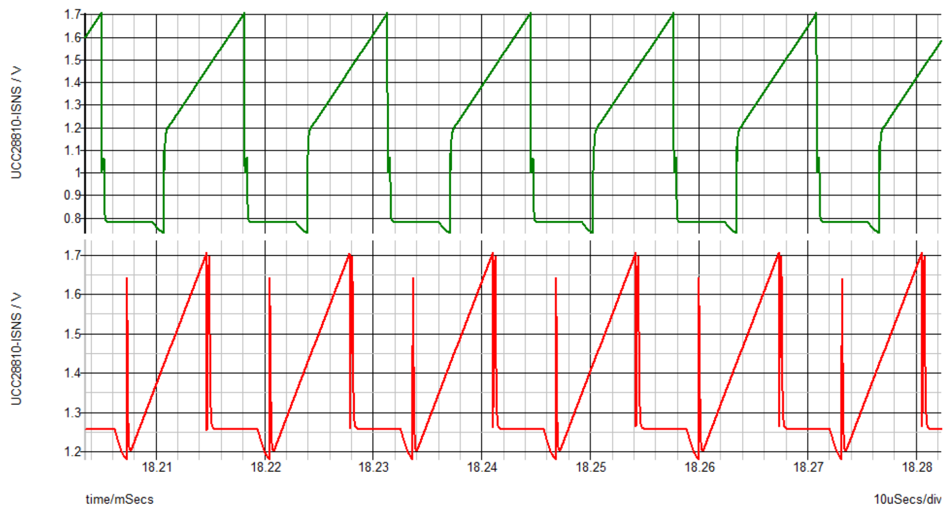


Figure 11. ISNS Pin Voltage Comparison Between With Improved Circuit and Without Improved Circuit

In practical design, we measure the waveform of ISNS to determine how much delay must be produced by the improved circuit (refer to Figure 11). So, it is recommended to make a simple spice simulation regarding the setup of the C13, R51, and R46 circuit.

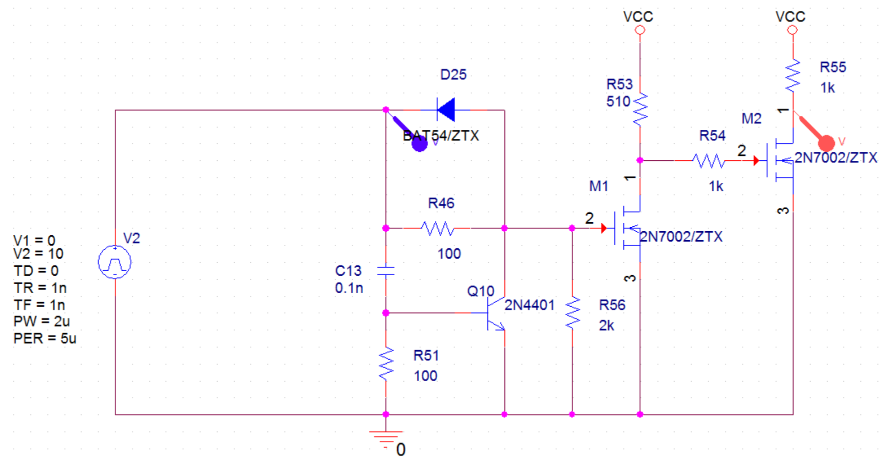


Figure 12. Circuit to Improve Analog Dimming Performance

For example, if we need to produce a 180-ns delay for the above-mentioned circuit, the preceding parameters can meet the requirement; Figure 12 shows its waveform.

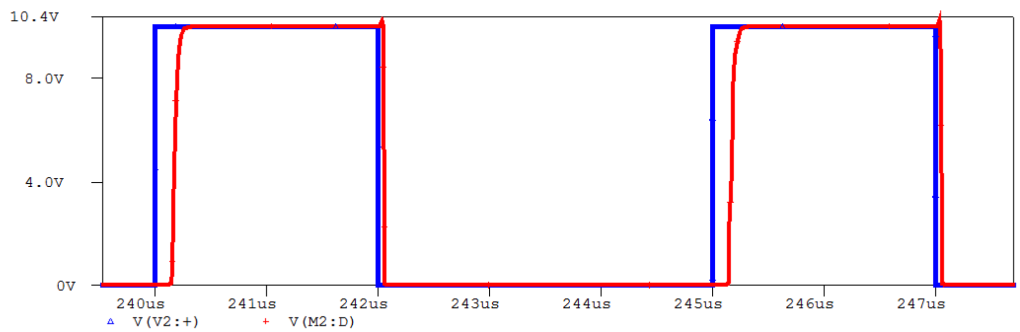


Figure 13. Spice Simulation Result to Meet the 180-ns Delay Specification

Step 4: Design PWM dimming circuit.

PWM dimming is very easy to implement because the UCC28810/11 device provides the drive turn-off function when Vsense is latched down to 0.57 V. Shown as Q4 in Figure 7, PWM dimming control can be done with a simple external transistor connected to the Vsense pin of the UCC28810/11 device.

However, the external duty cycle D of the PWM signal will produce the dimming performance with a duty cycle of 1-D for this solution

6 5% to 100% Analog Dimming and 0.05% to 5% PWM Dimming Design Result

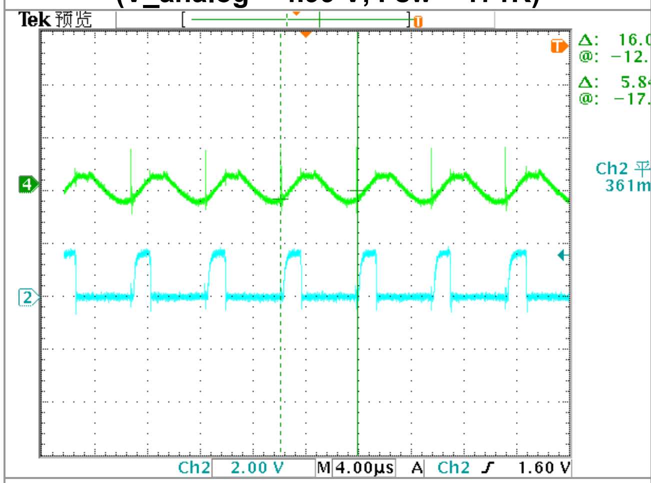
6.1 5% to 100% Analog Dimming Design Result

Analog dimming is critically important because the output current must be very stable and not have any flickering issue. For a better understanding of this design, the waveforms of ISNS pin voltage of the UCC28810/11 device and the current of the BUCK inductor are investigated. These waveforms must be stable during the entire dimming process.

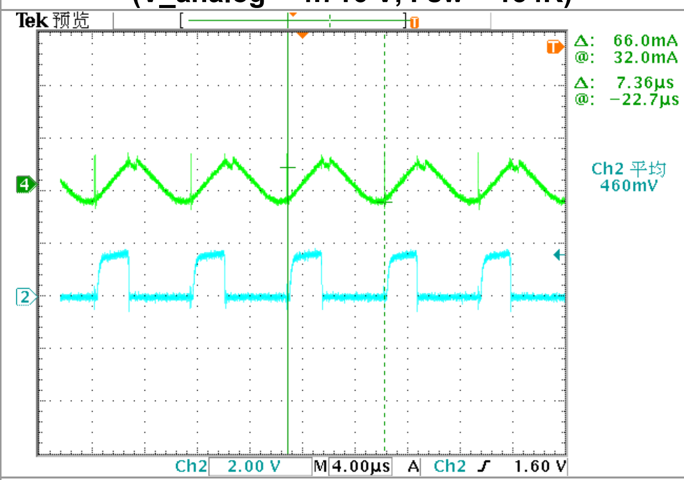
Waveforms of channel 2—ISNS pin voltage of the UCC28810/11 device

Waveforms of channel 4—Current of the BUCK inductor

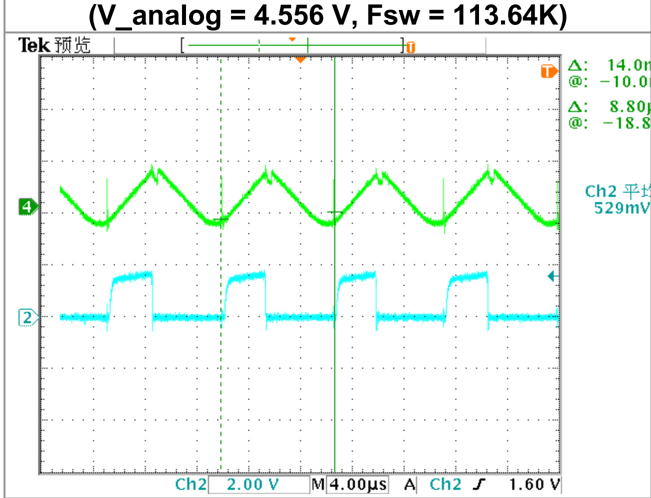
10-mA output (V_analog = 4.99 V, Fsw = 171K)



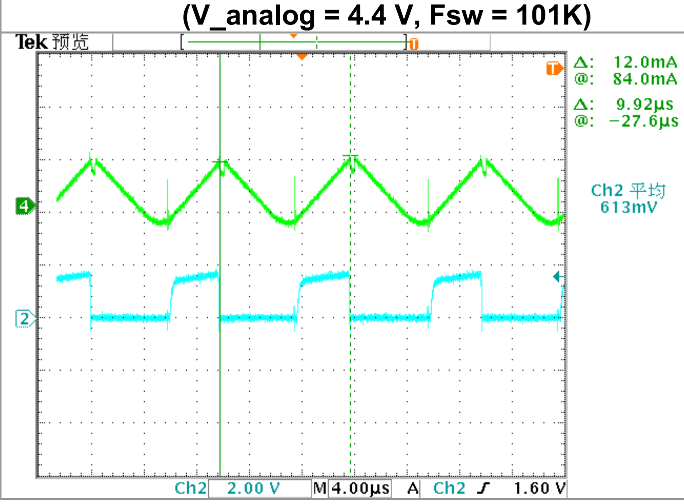
20-mA output (V_analog = 4.716 V, Fsw = 134K)



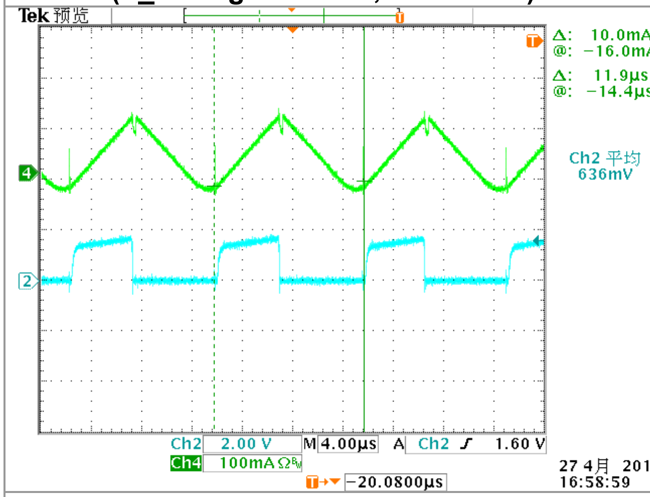
30-mA output (V_analog = 4.556 V, Fsw = 113.64K)



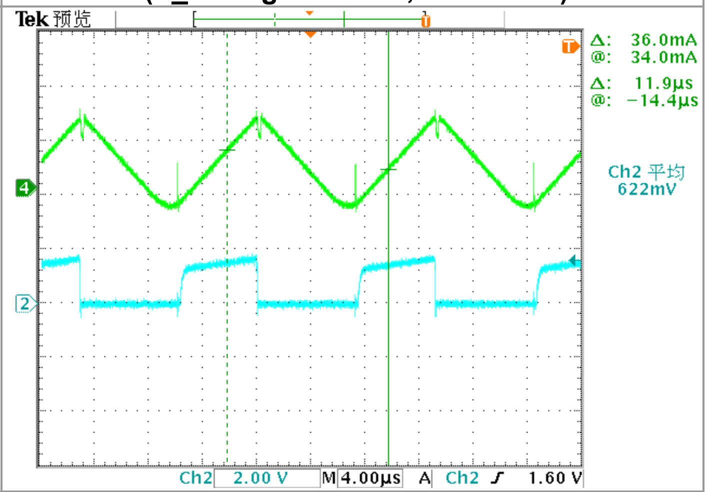
40-mA output (V_analog = 4.4 V, Fsw = 101K)



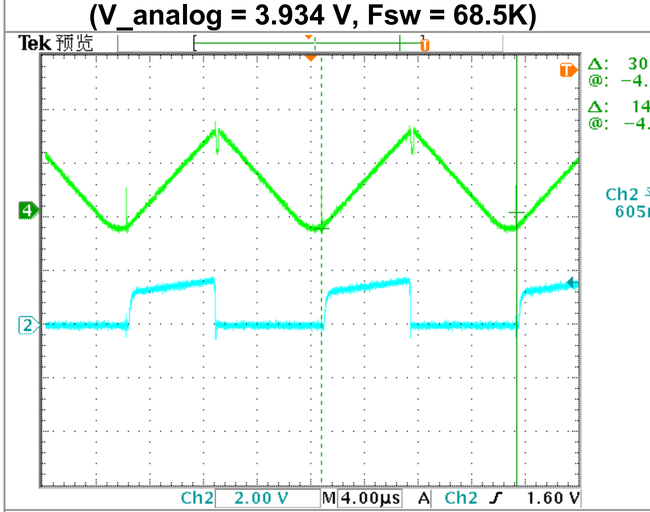
50-mA output
(V_analog = 4.238 V, Fsw = 84K)



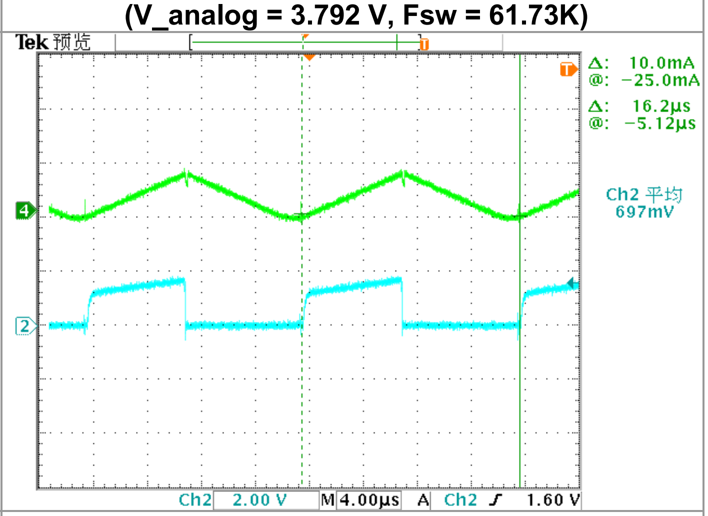
60-mA output
(V_analog = 4.084 V, Fsw = 78K)



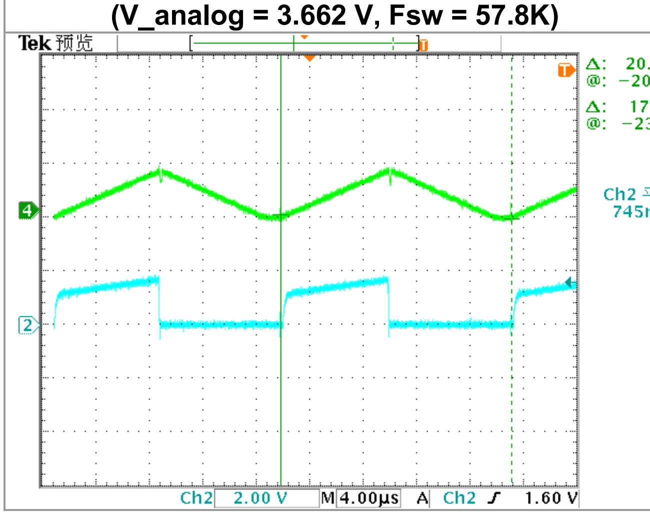
70-mA output
(V_analog = 3.934 V, Fsw = 68.5K)



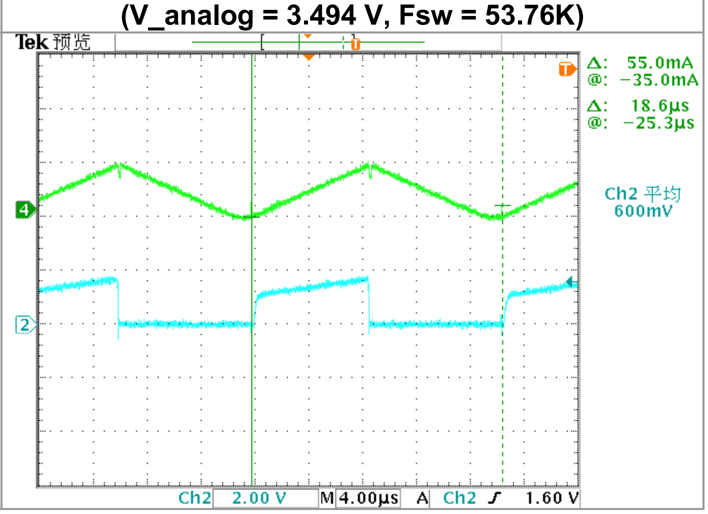
80-mA output
(V_analog = 3.792 V, Fsw = 61.73K)



90-mA output
(V_analog = 3.662 V, Fsw = 57.8K)



100-mA output
(V_analog = 3.494 V, Fsw = 53.76K)



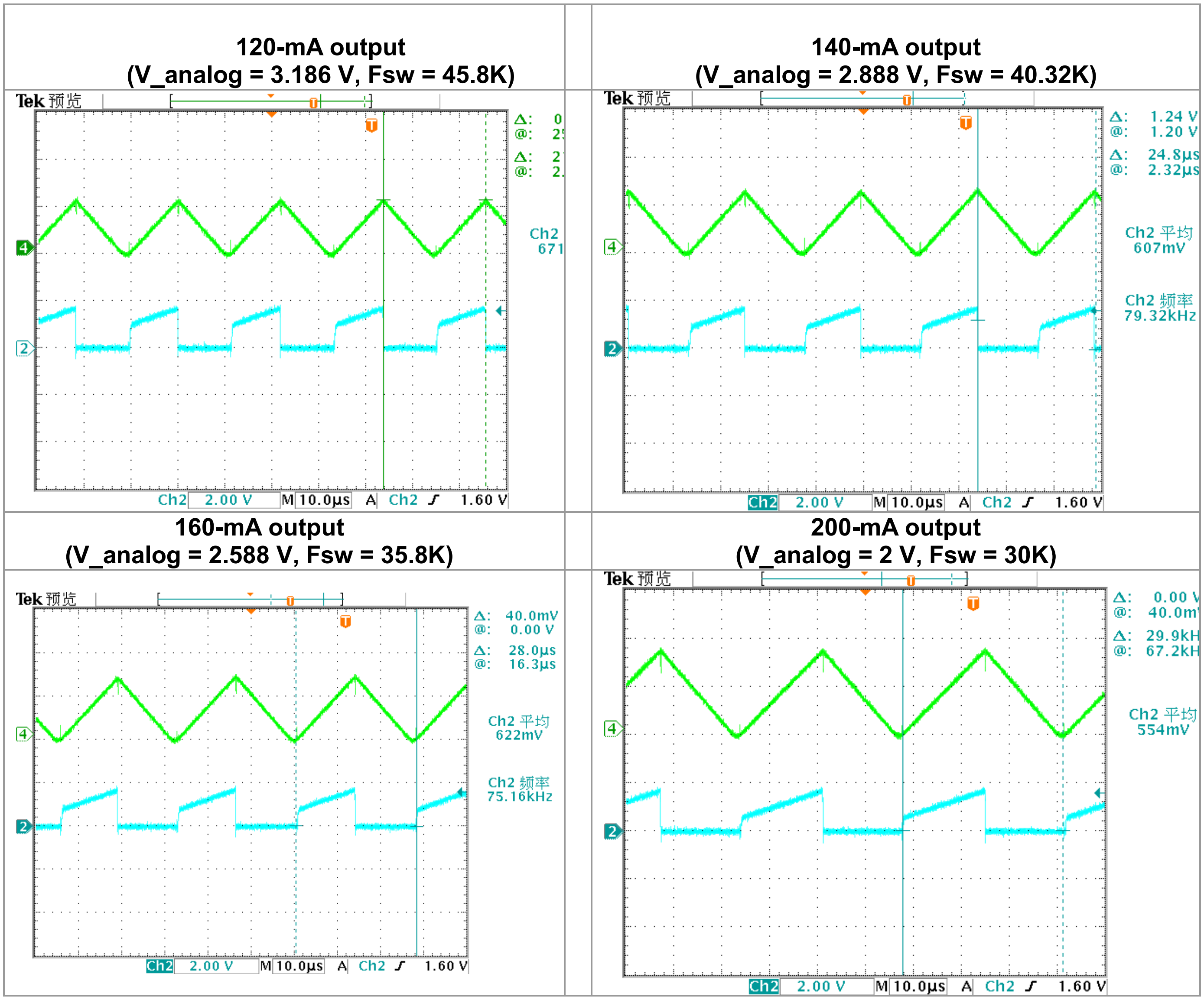


Figure 14. Measured Waveforms for the 5% to 100% Analog Dimming Control

From the measured waveforms in Figure 14, we can see the improvement on the voltage of the ISNS pin of the UCC28811 device. The original peak voltage on this pin disappears, which keeps the loop stable during the following PWM dimming.

Additionally, we must verify the design calculation formula regarding the operation frequency. In Figure 15, Fsw(Vanolog) represents the calculation result, and Fs_measure (Vanolog) represents the measurement result. It can be seen that the calculation matches very well with the measurement.

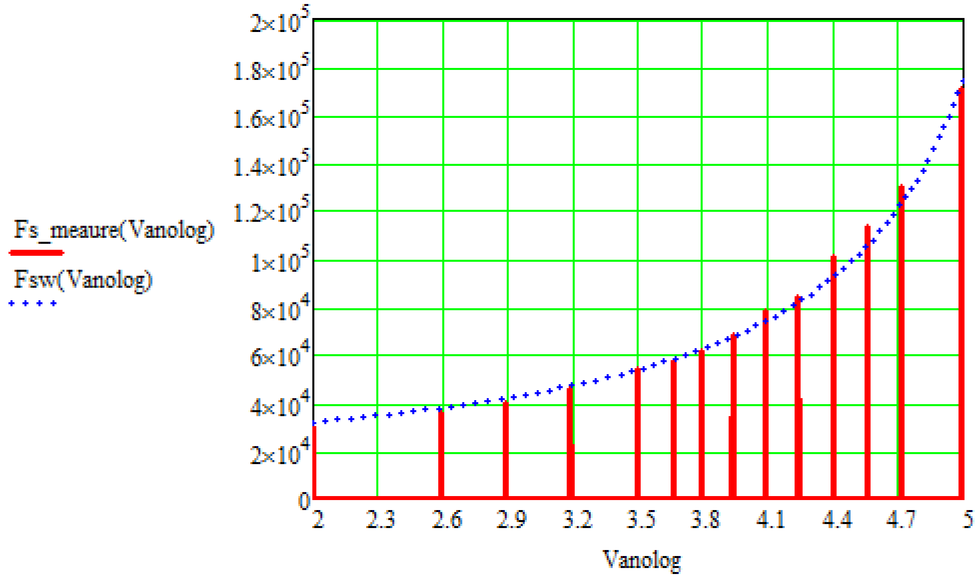


Figure 15. Operation Frequency Curve—Comparison Between Measurement and Calculation

Because analog dimming is critical, the dimming curve must be linear with the signal of Vanolog. Figure 16 shows the comparison between the practical measurement and calculation result. In Figure 16, I(Vanolog) represents the calculation result based on Equation 16. Io_measure (Vanolog) represents the measurement result above.

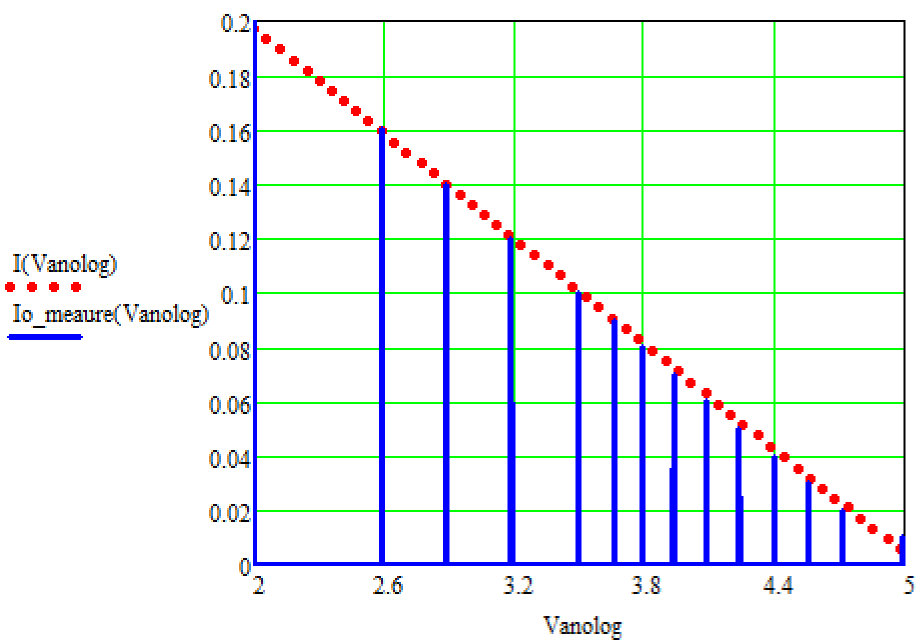


Figure 16. Curve of Output Current—Comparison Between Measurement and Calculation When Analog Dimming is Conducted

It can be seen that the calculation matches very well with the measurement.

6.2 0.05% to 5% PWM Dimming Design Measurement Result

The 0.05% to 5% PWM dimming starts after the analog dimming comes to 5% dimming level for this solution. The following measured waveforms present the PWM dimming performance.

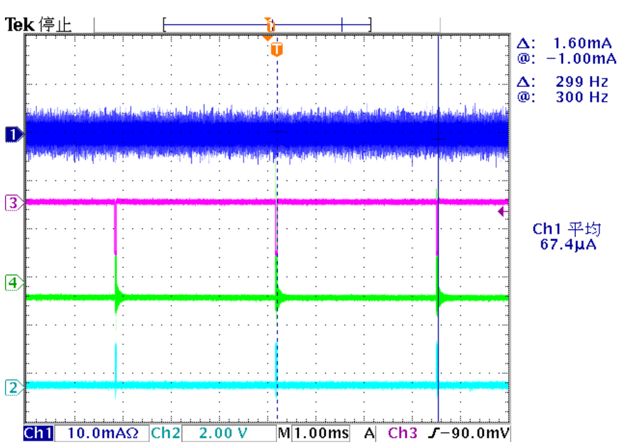
Waveforms of channel 1—Output current when PWM dimming

Waveforms of channel 2—ISNS pin voltage of the UCC28811 device

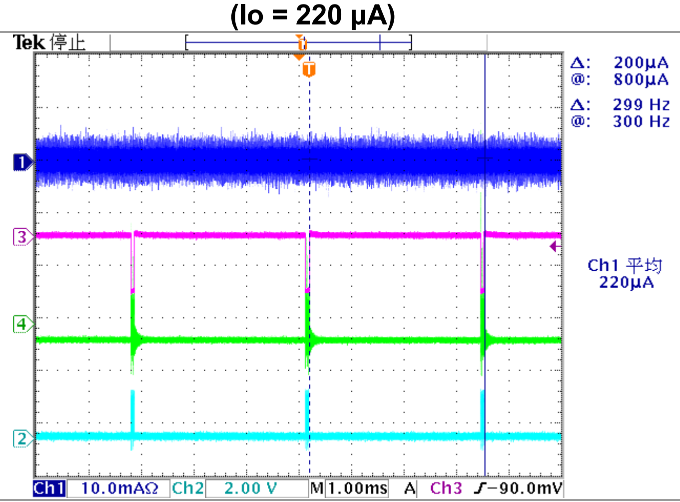
Waveforms of channel 3—UCC28811 device input PWM dimming signal

Waveforms of channel 4—Current of the BUCK inductor

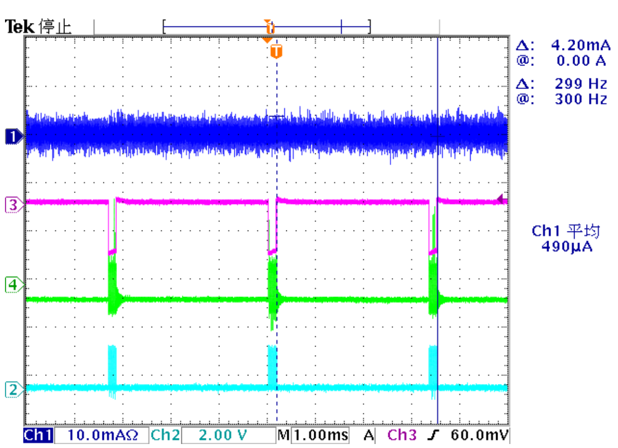
1% PWM dimming (Io = 67 µA)



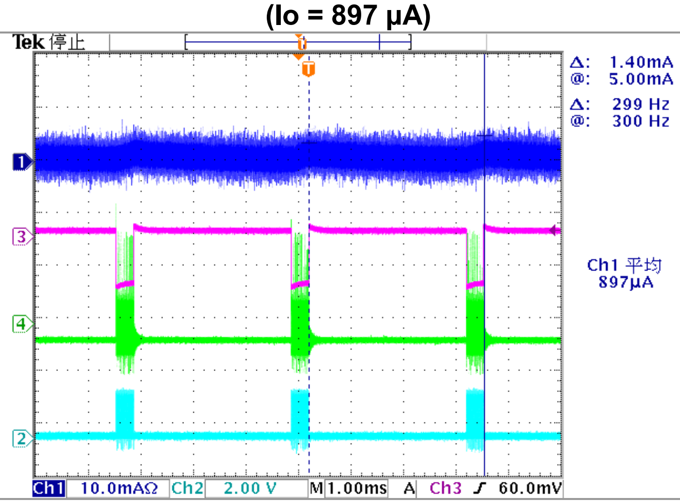
2% PWM dimming (Io = 220 µA)



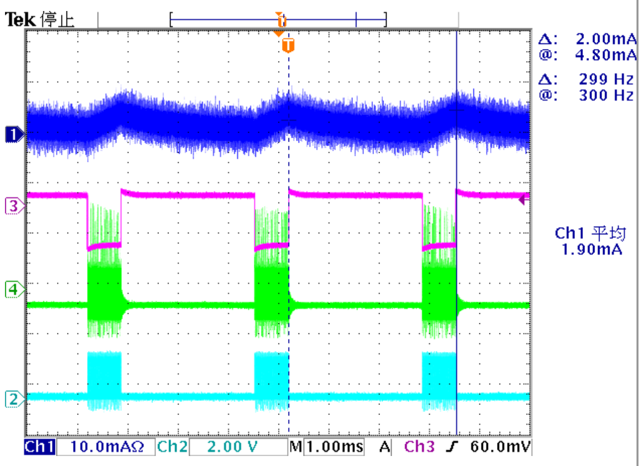
5% PWM dimming (Io = 490 µA)



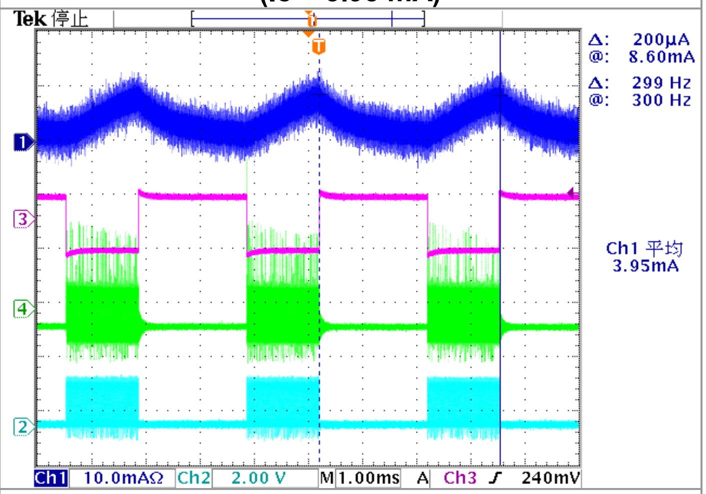
10% PWM dimming (Io = 897 µA)



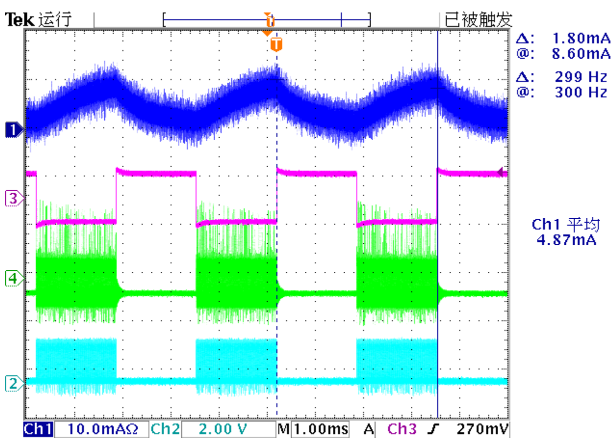
20% PWM dimming (Io = 1.9 mA)



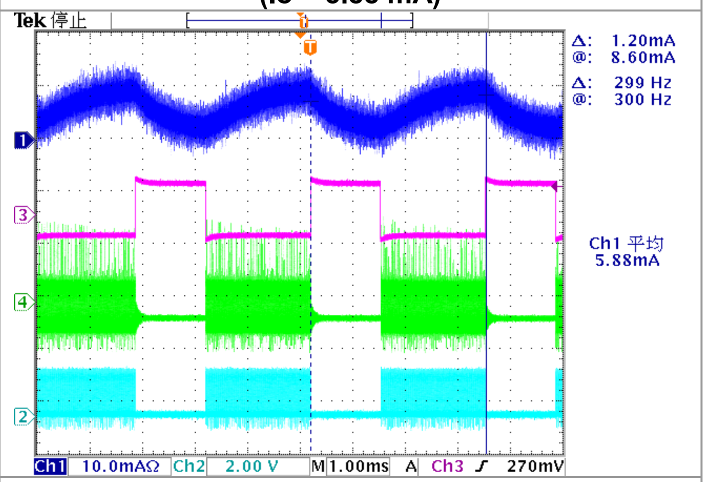
40% PWM dimming (Io = 3.95 mA)



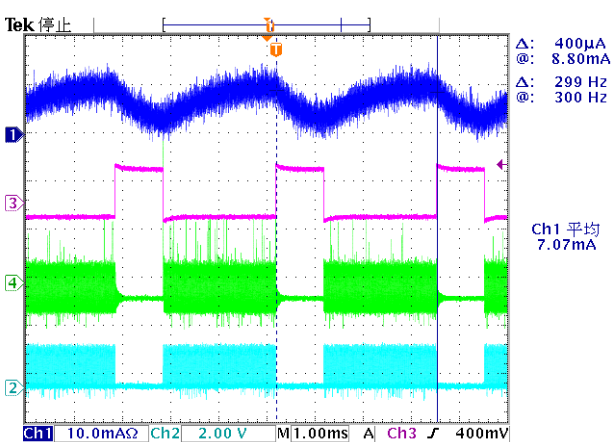
50% PWM dimming (Io = 7.87 mA)



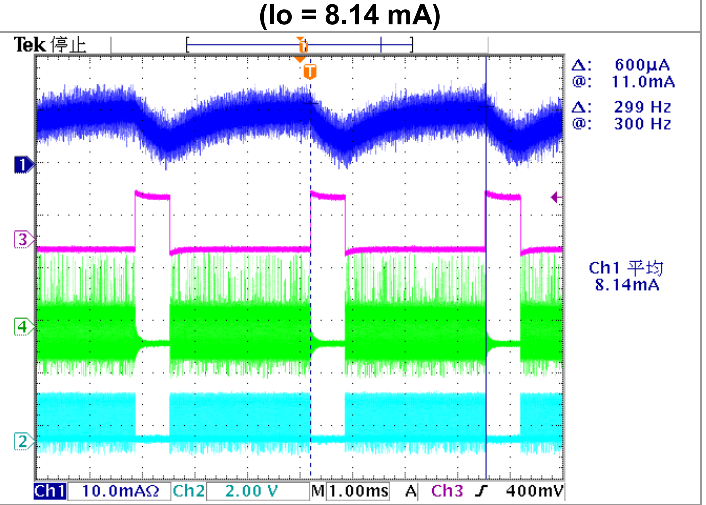
60% PWM dimming (Io = 5.88 mA)



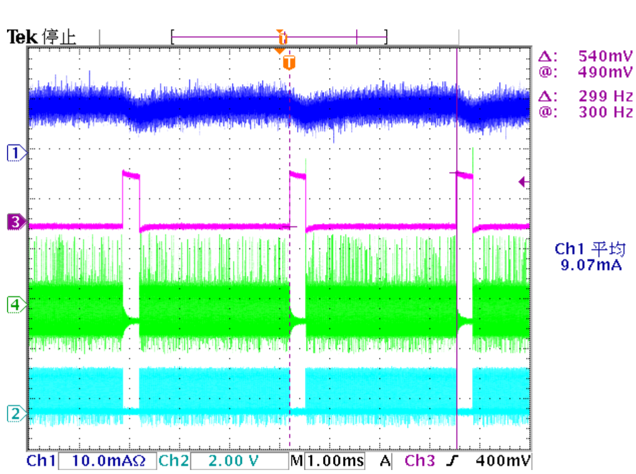
70% PWM dimming (Io = 7.07 mA)



80% PWM dimming (Io = 8.14 mA)



90% PWM dimming (Io = 9.07 mA)	99% PWM dimming (Io = 9.73 mA)



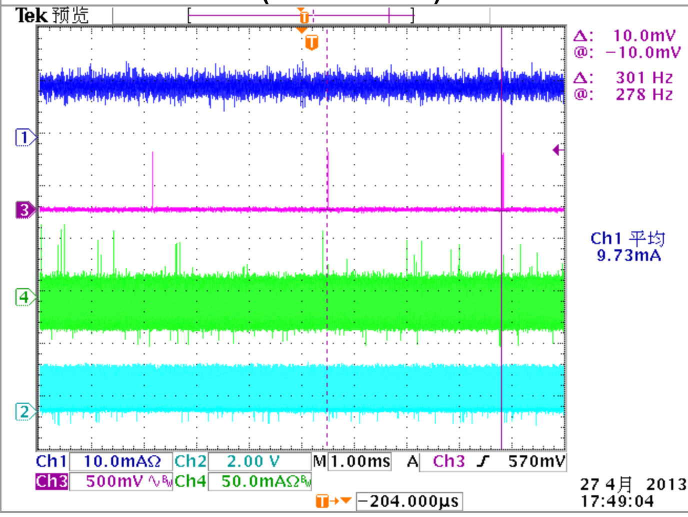


Figure 17. Measured Waveforms When PWM Dimming is Conducted

It can be seen that the dimming performance is very good due to the contribution of improved circuit for the analog dimming.

6.3 5% to 100% Analog Dimming Design Measurement Result for the Output Current

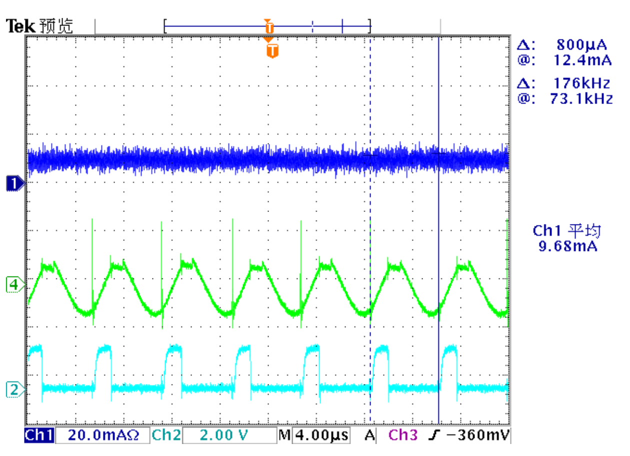
The output current must be measured during the analog dimming process. During this process, the dimming performance is very good due to the contribution of improved circuit for the analog dimming.

Waveforms of channel 1—Output current when analog dimming

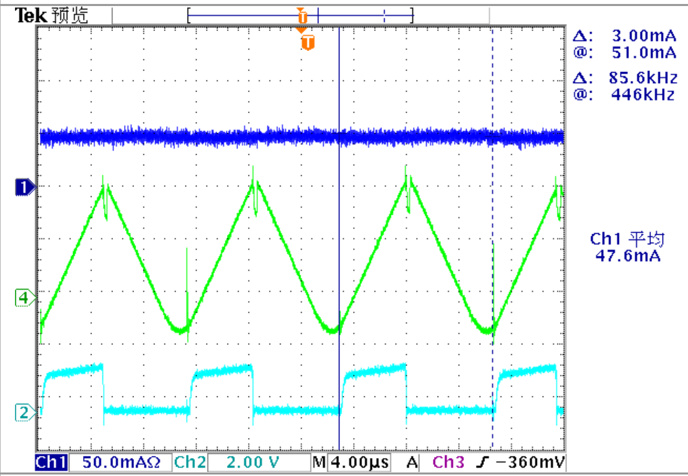
Waveforms of channel 2—Current of the BUCK inductor

Waveforms of channel 3—ISNS pin voltage of the UCC28810/11 device

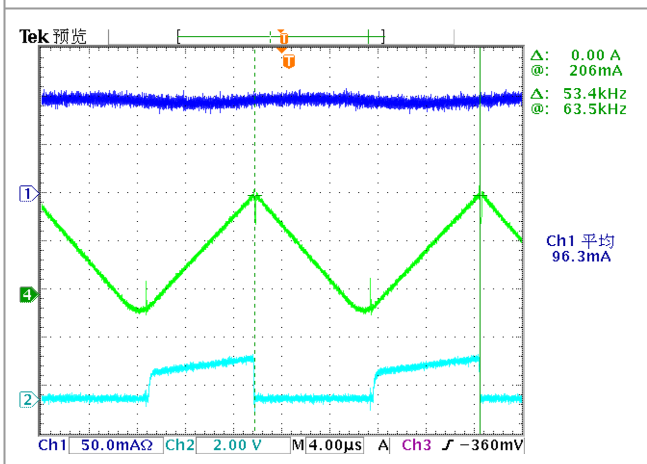
10-mA output with analog dimming



50-mA output with analog dimming



100-mA output with analog dimming



150-mA output with analog dimming

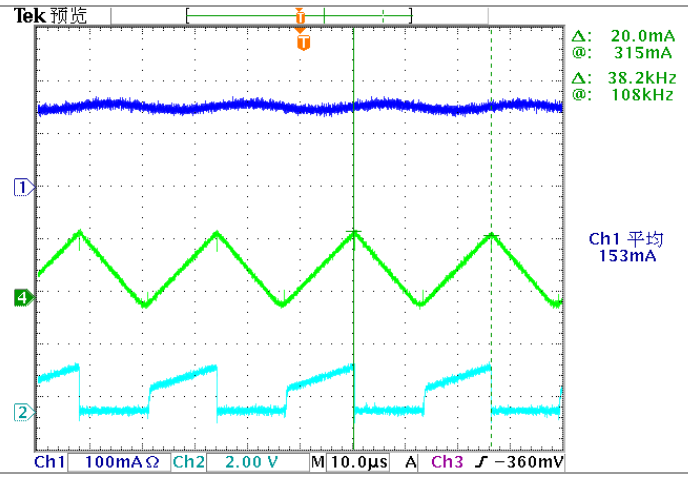


Figure 18. Measured Output Current Waveforms When Analog Dimming is Conducted

7 Conclusions

This paper provides the entire analysis, design, and experiment data regarding the combine dimming mode design. The result proves that the design idea is feasible for practical application.

8 References

[1] UCC28811 LED Lighting Power Controller

[2] Using the UCC28810 EVM-003 User's Guide

[3] Using the UCC28810 EVM-002 A 0.9 A Constant Current Supply with PFC for 100-W LED

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