Digital Sliding Mode Pulsed Current Averaging IC Drivers for High Brightness Light Emitting Diodes

Anindita Bhattacharya[1], Brad Lehman[1], Anatoly Shteynberg[2], Harry Rodriguez[2]

1. Department of Electrical & Computer Engineering
Northeastern University, Boston, MA
Email : abhattac@ece.neu.edu

2. SynDiTec Inc.
3535 Ross Avenue, Suite 308, Building - II
San Jose, CA - 95124

***Abstract* - This paper proposes a digital controller with Sliding Mode Pulsed Current Averaging scheme for High-Brightness (HB) Light Emitting Diodes (LED) IC drivers. The digital controller implements a control method to adjust the 'on time' of the active switch based on the comparison of output current and a reference current. The idea is to increase or decrease the duty cycle by discrete pulses in order to control the average current being delivered to the load. A variable frequency boost converter in Discontinuous Conduction Mode (DCM) has been used to handle the required load current. No external Analog-to-Digital (A/D) converter is required for the application.**

I. Introduction

With the advancement of Field-Programmable-Gate-Array (FPGA) and Complex-Programmable-Logic Devices (CPLD), digital controllers are being increasingly used in switched mode power regulators [1]. Until recently, controllers for DC-DC converters were designed with analog circuitry. Now, digital controllers are becoming attractive due to several of their advantages, such as: 1. Digital controllers are capable of implementing sophisticated control schemes by using computational codes [2]. 2. The topologies and control schemes applied in digital controllers are reconfigurable. 3. Implementation of a different topology can be done easily by changing the software codes. 4. Digital controllers are less sensitive to noise, aging and external parameter variations [3]. 5. Digital controllers need less passive components and can be easily adapted to changing load requirements of the switched mode power regulators and highly efficient [4]. All these qualities of a digital controller have made it a competitor of the analog controller.

The main disadvantage of the digital controller is its high cost. But the recent trend shows a gradual decline of the price of FPGA and CPLD. Thus, digital implementations are becoming an essential part of several applications such as IC drivers for High-Brightness Light Emitting Diodes. Advances in LED illumination particularly White and High-Brightness LEDs (HB-LED) have created a new market for LED applications, such as, traditional business and home lighting, decorative lighting, signal lighting, and sign lighting [5 – 7].

One of the main requirements of the white LED driver IC is its robustness to changing environmental conditions that otherwise may lead to brightness degradation. According to many researchers, the sliding mode controller [8] is a suitable candidate for robust performance and good response with parameter variation and load disturbance [5].

Research is ongoing in the field of digital controller with varieties of different applications. [9] investigates the use of an estimation algorithm of the inductor current variations for a digitally controlled DC-DC boost converter operating in Continuous Conduction Mode. [10] describes a microcontroller based digital boost converter for a RGB backlight LED system driver. This uses a Pulse Frequency Modulation technique and in the DC-DC converter, the external diode is replaced with a PMOS transistor. A variable frequency predictive digital control method is introduced in [11].

This paper proposes a digital controller with sliding mode scheme for LED illumination systems. Although the approach is digital, no external Analog to Digital (A/D) converters are required for implementation. The Switched Mode Power Regulator used for this controller is a variable frequency Boost DC-DC converter. The idea is to increase or decrease the duty cycle by discrete pulses in order to control the average current being delivered to a load. Section II of this paper describes the design procedure of the proposal. Section III explains the sliding mode pulsed current control method implemented in the boost converter followed by Section IV with the digital controller explanation. The simulation and experimental results are shown in Section V followed by a conclusion at Section VI.

In summary the results of this paper are:

- A new digital sliding mode pulsed- current averaging LED driver IC has been proposed.
- A variable-frequency DC-DC Boost converter has been used and a FPGA based digital controller has been experimentally implemented to control the duty cycle of the driver for a benchmark LED lighting system.
- The control scheme of the FPGA has been written in a hardware description language (VHDL).
- The system is robust to environmental changes, maintains high performance requirements and requires fewer passive components.
- The system does not require any external A/D converter.
- Simulation and experimental results support the theoretical analysis.

0-7803-9725-8/06/$20.00 ©2006 IEEE.

II. Design Procedure

Basically, LEDs are low voltage light sources that operate with DC current and voltage of a few volts. However, for different applications several LEDs are connected in series, generally called as strings [12]. The brightness of the LEDs is proportional to the DC current flowing through them and is controlled by regulating that DC current. The LED strings must also be protected from line-voltage fluctuations during operation. Changes in input voltage can produce changes in current through them and cause light output to vary. If current exceeds ratings, the LEDs become brighter but will decrease their useful life by about 30% [13]. Difference in brightness of the LED strings is not desirable in most cases. So the most important thing to consider here is a tight regulation of the output current.

Therefore, a proper LED driver is required to convert the input voltage to a proper output voltage and regulate the current that flows through the LEDs. Constant output current is often maintained, or in smart LED driver systems, the current adapts to light output in order to maintain consistent brightness control.

This paper describes a sliding mode pulsed current averaging LED driver that is able to predict and subsequently regulate the output current of the driver.

In majority of High-Brightness LED applications for backlighting, such as in mobile phones, PDAs, Games, Cameras, MP3s and GPSs the maximum LED current is in tens of milli-Amps. Such loads can be easily handled by a variable frequency Boost converter operating in Discontinuous Conduction Mode (DCM). A schematic diagram of the proposed Boost converter with LED load and digital controller is shown in Fig. 1. Fig. 3 shows the prototype of the LED driver with digital controller.
Several circuit components used in Fig. 1 are :
Clock : This is an 80 MHz system clock.

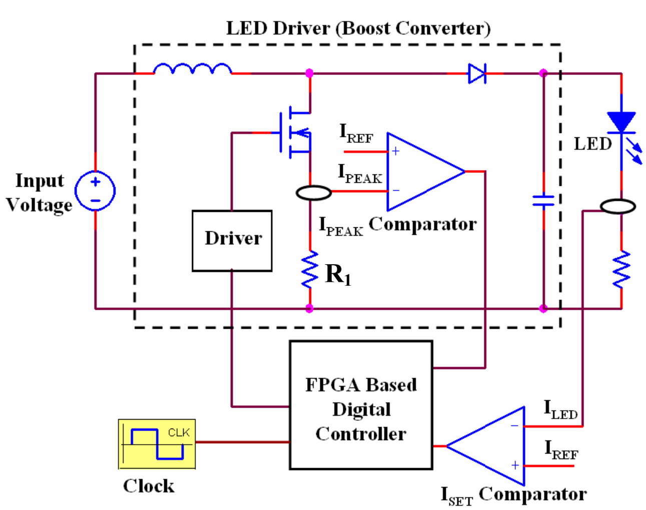

Figure 1. Schematic diagram of the Boost converter

I_{PEAK} Comparator : Maximum Switch current detection comparator. This comparator is used to set the inductor switch current. If the switch current becomes 500mA the comparator trips the logic and shuts down the switch.
I_{SET} Comparator : Feedback, set comparator. This comparator is used as the feedback mechanism to measure I_{SET} the desired current from the simple equation $R = 200mV/I_{SET}$

For light load applications with DC-DC boost converter, fixed frequency with continuous conduction mode control has been extensively used. The problem with the continuous conduction mode (CCM) is that there is a right half plane zero, which is difficult to be stable. That's why discontinuous conduction mode (DCM) is desired for low power applications.

Since the proposed LED driver operates in variable frequency and in DCM, at light load a very small amount of on-time of the switch helps to regulate the output current.

III. Proposed Sliding Mode Pulsed Current Control Method

In a boost topology, the inductor current is the input current as shown in Fig.1. When the transistor is ON, the inductor current charges and increases according to the differential equation $\frac{di_L}{dt} = \frac{1}{L} V_{in}(t)$.
When the transistor is turned off, the inductor current forces the diode (Fig. 1) to conduct current to the output which in this case is a string of LEDs. Since the converter was considered to work in DCM, the total amount of energy stored when switch is on will be sent to the output. Now the inductor is connected between input V_{in} and output V_0 as shown in Fig. 2. where the difference $(V_0 - V_{in})$ resets the inductor current to zero in time $t_D(n)$.

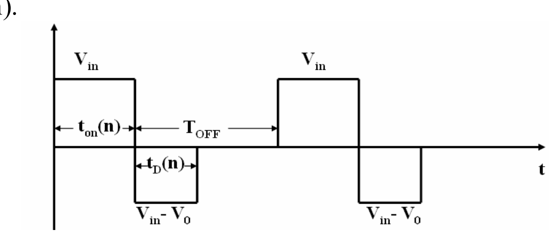

Figure 2. Inductor voltage waveform

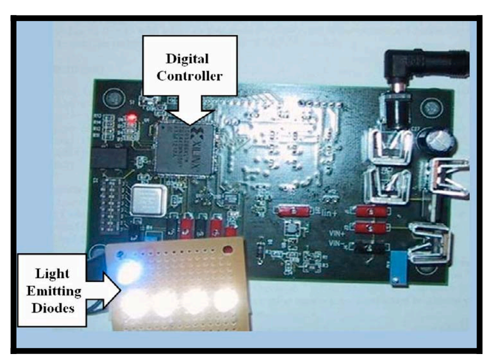

Figure 3. Prototype of the LED driver

Fig. 4 shows the inductor current and Fig. 5 shows the diode current waveform at discontinuous conduction mode. Three different cycles (n-1), n and (n+1) have been shown to specify the variable frequency DCM operation. The on-time of the transistor changes accordingly with the requirement of energy at output. But the off time remains constant. The area under the waveform of the diode current at cycle n is defined as

$Q=\frac{1}{2}I_{PEAK}(n)t_D(n)$ and again $Q=I_0T_{OFF}$ where I_0 is the average output current.

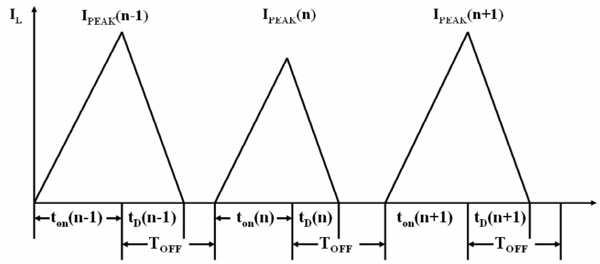

Figure 4. Inductor current waveform at Discontinuous Conduction Mode

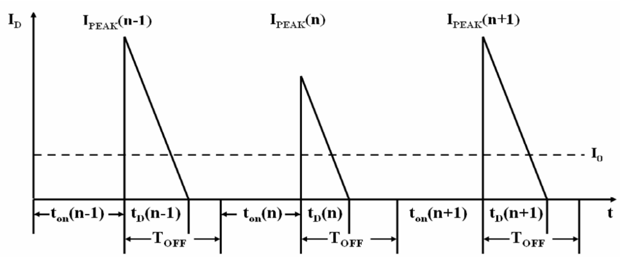

Figure 5. Diode current waveform at Discontinuous Conduction Mode

So, $$\frac{1}{2}I_{PEAK}(n)t_D(n)=I_0T_{OFF} \quad (1)$$

From Fig.4., $$I_{PEAK}(n)=\frac{V_{in}}{L}t_{on}(n)$$

According to volt-seconds balance across the inductor in order to achieve zero current at the beginning of $t_{on}(n)$ and end of $t_D(n)$, we can write $$t_D(n)=\frac{V_{in}t_{on}(n)}{V_0-V_{in}}$$

Using the value of $I_{PEAK}(n)$ and $t_D(n)$ in equation (1) we can get

$$t_{on}(n)=\frac{1}{V_{in}}\sqrt{2LI_0T_{OFF}(V_0-V_{in})} \quad (2)$$

Equation (2) shows the relation between output current and switch on time. Thus, by regulating the inductor current during t_{on}, we are indirectly regulating the output current. The idea is to increase or decrease t_{on} by discrete pulses in order to control the average current being delivered to a load at off period of the switch: hence, the terminology pulse average current control.

As shown in Fig. 7(a)., the 'output current sense circuit' senses the average current at the output and the I_{SET} comparator (Fig. 1) checks whether the output current has reached the desired reference current or not. If the sensed current is less than the desired current (Fig 6.), the comparator value remains low and MOSFET turns on the circuit. The on-time of the switch is decided by the digital controller. In the next cycle if the comparator is still low, that means more power is needed to deliver to the output, so that the output current can reach the desired value. One way to do this is to store more energy when switch is on. This can be done by increasing the on-time of the switch. The digital controller adds a small amount of time to

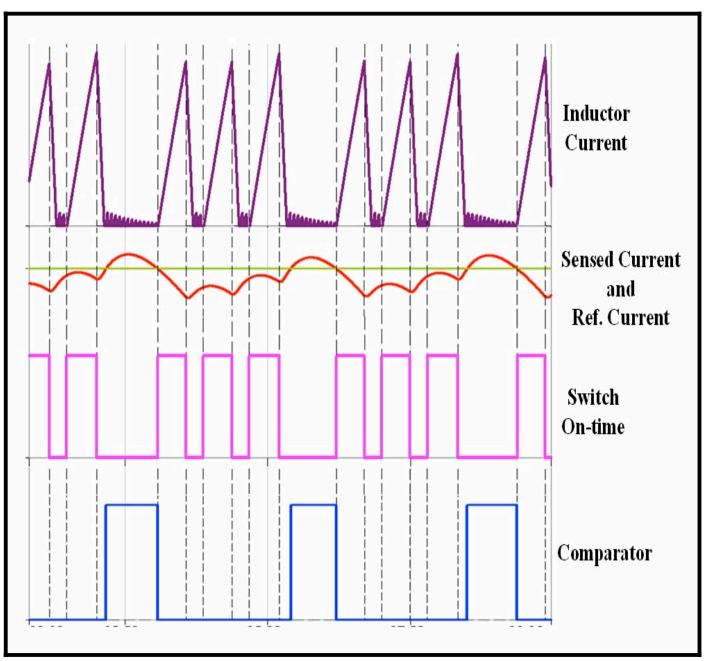

Figure 6. Scheme of the proposed controller

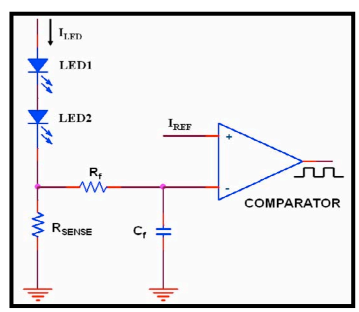

Figure 7(a). Output current sensor circuit

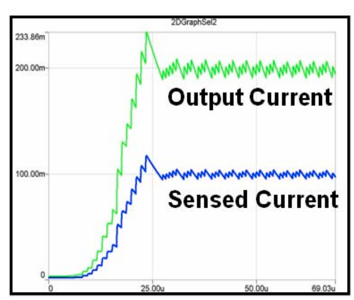

Figure 7(b). Output and Sensed Current waveform the previous on-time of the switch and more power is stored and delivered to the load. In the next cycle if the comparator becomes high, then it is clear that output current is higher than the desired current. Therefore, no more energy is necessary at that moment to send to the output. If the boost converter was designed with fixed switching frequency, then it would be difficult to regulate at light load. The reason is that there is a minimum on time of the switch and it will keep sending energy to the output even if it is not needed. It may cause overvoltage at very light load condition [14]. In our proposed algorithm, the controller waits (Fig.6) and do not turn on until the comparator goes low. When the comparator goes low, the switch turns on again and starts working as explained before. The other comparator named as I_{PEAK} comparator shown in Fig. 1 is used to check the peak current of the MOSFETand protect the circuit from overcurrent. If the I_{PEAK} comparator is high, which means the MOSFET peak current is higher than the desired current the circuit trips and the MOSFET goes to off position until the I_{PEAK} Comparator goes low again.

IV. DIGITAL CONTROLLER

The proposed FPGA based digital controller in Fig.1 implements a simple control method. The flowchart of the digital implementation is shown in Fig. 8. Basically, there are three states of the digital controller named t_{OFF}, t_{OFF}_WAIT and $t_{ON.}$ The controller is an optimized digital core that uses a sliding control algorithm to determine the amount of power to transfer to the output. The proposed algorithm uses discrete comparison of predicted output vs sampled output. The digital core adjusts on time based on this comparison.

At the beginning of a cycle, the digital method turns on the switch and starts to count an oscillator clock. Fig. 9 shows the operation mode of the digital controller. When the counter value reaches a predefined t_{on}, it turns off the switch. This step measures the switch on time. At the mean time, it also reads in the comparator result between I_{REF} and I_{LED} (Fig. 4). Depending on the comparator result, t_{on} is adjusted by adding or subtracting a small amount of time Δt . This new t_{on} is used in next cycle. Equation (3) is used to adjust t_{on} when the comparator result is low or $I_{LED} < I_{REF}$.

$$t_{on}(n) = t_{on}(n-1) + \Delta t(n) \quad (3) \text{ and}$$

$$\Delta t(n) = \Delta t(n-1) + \delta \quad (4)$$

where δ is a fixed clock cycle.

The comparator result is high when $I_{LED} > I_{REF}$. As shown in Fig. 9, Δt maintains its initial value until the comparator is low again. Equation (5) is used to adjust t_{on} when the comparator result is high. t_{on} counter starts counting again when the comparator goes low.

$$t_{on}(n) = t_{on}(n-1) - \delta \quad (5)$$

As said earlier, the switch off time is fixed for normal operating conditions. But when the comparator result is high, the off time is longer than the fixed period and we call it a wait mode. In this mode I_{LED} is greater than I_{REF}. That means enough power has already been delivered to the load. There is no necessity to turn on the switch again and deliver more power. Rather the controller waits until the comparator goes low and starts its algorithm again.

It is important to remark that this algorithm is unique in the sense that it does not require external A/D converter in order to run. Instead, it should be possible to measure inductor current through a standard sense resistor and send it directly to the driver IC. The interface between the sensed signals (integrated) and the digital logic is through a simple comparator.

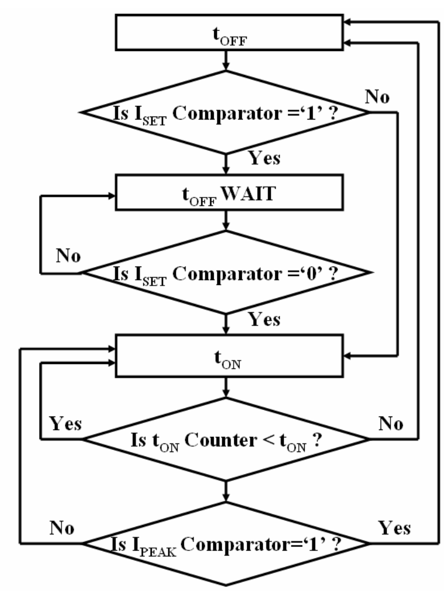

Figure 8. Flow chart for the Digital controller

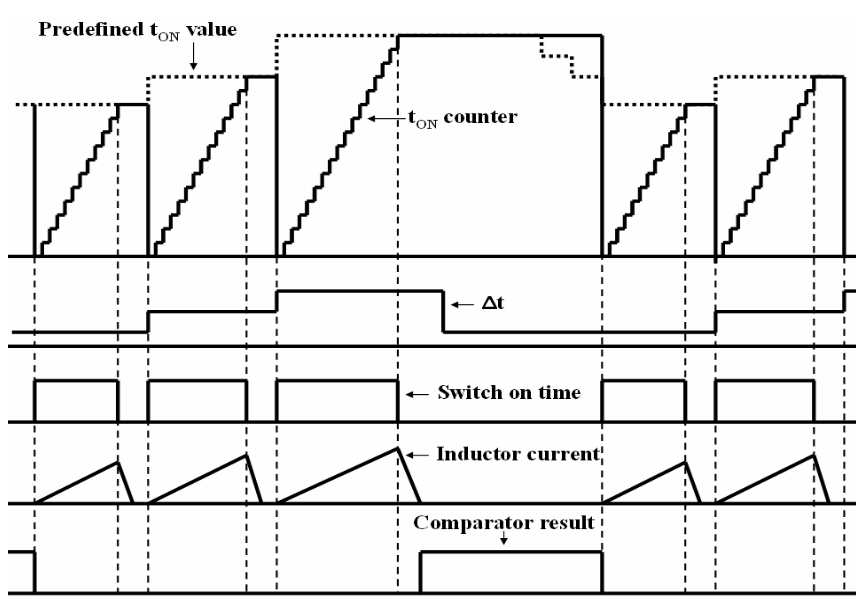

Figure 9. Digital current mode control

IV. Simulation and Experimental Results

The circuit parameters and variables considered for the LED driver are : Input voltage : 3.3V; L : 4.7 μ H; C : 2.2 μ F; 1 Clock : 12.5nS; MOSFET : 60V, 2A; Driver : Non-inverting, 4.5 – 18V; FPGA : 3.3V. The simulation has been done in Simplorer provided by Ansoft Inc. The digital controller part has been written in VHDL code and is used to control the active switch of the Boost converter. Fig. 10 and Fig 11 show the waveform of the inductor current, output voltage and LED current for two different input voltages. The simulation results show that the digital controller works properly with these two different input conditions. Fig. 12 shows the experimental result of the LED current.

V. Conclusion

This paper proposes Digital Sliding Mode Pulsed Current Averaging drivers ICs for HB-LED applications. The driver works with a boost converter with variable frequency and in Discontinuous Conduction Mode. The topology is unique as it decides the switch on-time according to the necessity of energy at output. The simulation and experimental results verify the topology explained.

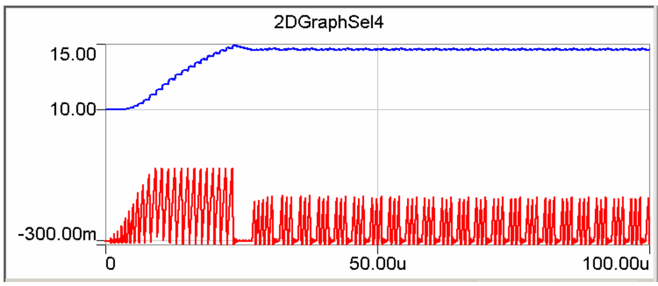

Figure 10 (a). Output voltage and Inductor current waveform when Input Voltage 3.3 V

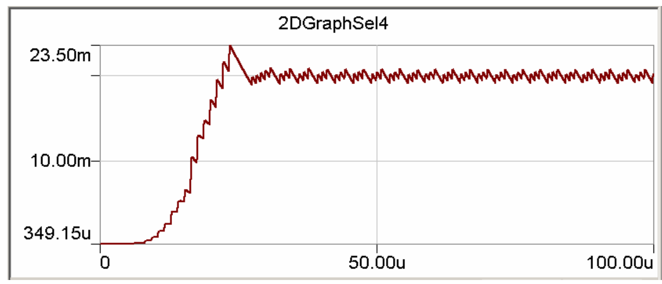

Figure 10 (b). LED current waveform when Input Voltage is 3.3 V

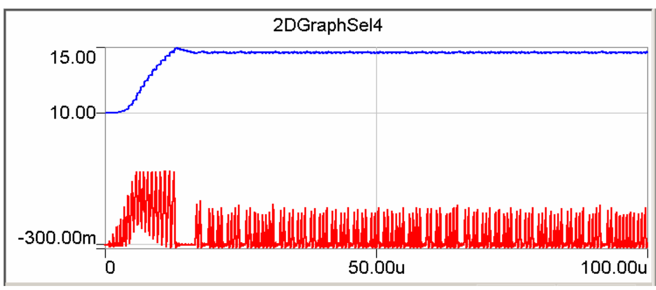

Figure 11 (a). Output voltage and Inductor current waveform when Input Voltage 5.3 V

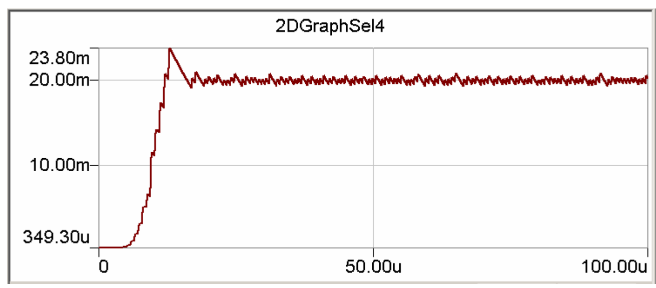

Figure 11 (b). LED current waveform when Input Voltage is 5.3 V

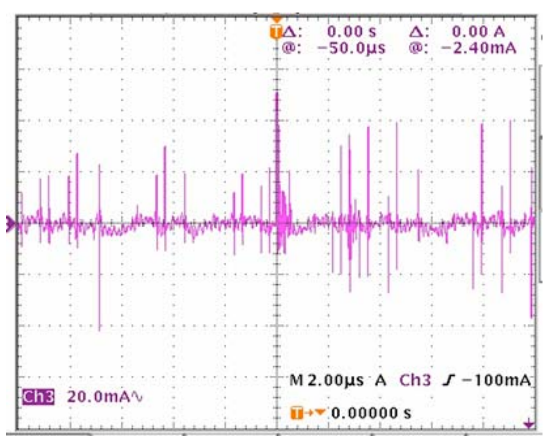

Figure 12. Experimental results of the LED current

REFERENCES

1. Bastos, J.L.; Farronato, L.M.; Figueroa, H.P.; Franzoni, D.; Lentijo, S.; Monti, A.; Smith, A.; Xin Wu, "FPGA-based control of power converter: comparing alternative solutions" *Applied Power Electronics Conference and Exposition,* 2005. APEC 2005. Twentieth Annual IEEE Volume 3, 6-10 March 2005 Page(s):1983 - 1989 Vol. 3.
2. Duan, Y.; Jin, H., "Digital controller design for switchmode power converters" *Applied Power Electronics Conference and Exposition, 1999. APEC '99. Fourteenth Annual* Volume 2, 14-18 March 1999 Page(s):967 - 973 vol.2
3. Wu, A.M.; Jinwen Xiao; Markovic, D.; Sanders, S.R., "Digital PWM control: application in voltage regulation module" *Power Electronics Specialists Conference, 1999. PESC 99. 30th Annual IEEE* Volume 1, 27 June-1 July 1999 Page(s):77 - 83 vol.1
4. Martin, T.W.; Ang, S.S., "Digital control for switching converters" *Industrial Electronics, 1995. ISIE '95., Proceedings of the IEEE International Symposium* on Volume 2, 10-14 July 1995 Page(s):480 - 484 vol.2
5. Klaus Streubel et al, "High Brightness AlGaInP Light-Emitting Diodes," *IEEE Journal on selected types in quantum electronics*, March/April 2002.
6. N. Narendran, et al, "Performance characteristics of high-power light emitting diodes," *Proc. SPIE Int. Conf. Solid State Lighting*, 2004.
7. Roland Haitz, "Another semiconductor revolution. This time it's Lighting," *Advances in Solid State Physics*, Volume 43/2003.
8. Vazquez, N.; Hernandez, C.; Alvarez, J.; Arau, J., "Sliding mode control for DC/DC converters: a new sliding surface" *Industrial Electronics, 2003. ISIE '03. 2003 IEEE International Symposium on* Volume 1, 9-11 June 2003 Page(s):422 - 426 vol. 1
9. "Digital control of dc-dc boost converters with inductor current estimation" – P. Mattavelli
10. " An Integrated digital PFM DC-DC Boost converter for a power management application : A RGB backlight LED system driver." – Phillipe Goyhenetche
11. Athalye, P.; Maksimovic, D.; Erickson, R.;, "Variable-frequency predictive digital current mode control" Power Electronics Letters, IEEE Volume 2, Issue 4, Dec. 2004 Page(s):113 – 116
12. Ronat, O,; Green, P; Ragona, S., "Accurate current control to drive high power LED strings" *Applied Power Electronics Conference and Exposition, 2006. APEC '06*. Twenty-First Annual IEEE 19-23 March 2006 Page(s):376 – 380
13. C. Dilouie, "Introducing the LED driver," *Electrical Construction & Maint.*, Sept. 2004.
14. Qiao, C, Zhang, J., "Control of Boost type Converter in Discontinuous Conduction Mode by Controlling the Product of Inductor Voltage-second" PESC, 2005