

LIGHT-EMITTING DIODE DRIVER FOR LIGHTING APPLICATION USING  
FIELD PROGRAMMABLE GATE ARRAY

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LIGHT-EMITTING DIODE DRIVER FOR LIGHTING APPLICATION USING  
FIELD PROGRAMMABLE GATE ARRAY

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## DEDICATION

To my beloved  
Nazarudin Mat Suah, Rosidah Mohd Noor,  
Nur Liana Khusnan, Zayd Rizqi Muhammad Syazani,  
Khusnan Khusni, Noriah Manap  
and  
Azli Yahya (Assoc. Prof. Dr.)

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## ABSTRACT

Light-emitting diode (LED) is the most popular lighting source since the early 21st century. Its advantages include high efficiency, long lifetime and environmental friendliness makes it attractive in lighting application. This leads to the development of high energy efficient LED drivers. Despite the advantages, driving LEDs at high output ripple and without current regulation can degrade LEDs' performance. Furthermore, energy consumption of the controller on LED driver contributes to energy loss. Moreover, prototyping a full custom application specific integrated circuit (ASIC) is time consuming and not reprogrammable. The main objective of this research is to design an LED driver for lighting application using field programmable gate array (FPGA), and to analyse the performance. Simulation model was developed and simulated in LTSpice IV software. The LED driver controller was developed using Altera DE0-Nano FPGA Board with Quartus II software using Verilog hardware description language. The power stage schematic and printed circuit board layout were designed using Cadsoft EAGLE software. The LED driver performance was assessed in term of energy efficiency and output ripple. In energy efficiency experiment, rheostat was used as load. The result shows that the simulation model and the hardware prototype achieved energy efficiency of 93.36% and 93.19% respectively. In output ripple experiment, the result shows that the maximum output ripple of the simulation model is 0.046% while the hardware prototype is 0.06%. High-brightness white LEDs was also used as load in assessing the LED driver energy efficiency. The result shows that the hardware prototype achieved energy efficiency of 93.18% and has a maximum output ripple of 0.054% when high-brightness white LEDs are used as load.

## ABSTRAK

Diod pemancar cahaya (LED) adalah sumber pencahayaan yang populer sejak awal abad ke-21. Kelebihannya yang mempunyai kecekapan tenaga yang tinggi, jangka hayat yang panjang dan mesra alam sekitar menjadikan ia begitu menarik dalam aplikasi pencahayaan. Ia telah membawa kepada pembangunan pemacu LED yang lebih cekap tenaga. Walaupun dengan kelebihan itu, pemacuan LED pada riak keluaran yang tinggi dan tanpa pengatur arus boleh merendahkan prestasi LED. Selain itu, penggunaan tenaga pada pengawal pemacu LED menyumbang kepada kehilangan tenaga. Disamping itu, proses memprototaip litar bersepadu aplikasi khusus (ASIC) memakan masa dan tidak boleh diprogramkan semula. Objektif utama penyelidikan ini adalah untuk merekabentuk pemacu LED untuk aplikasi pencahayaan menggunakan *Field Programmable Gate Array* (FPGA) dan untuk menganalisis prestasinya. Model simulasi dibangunkan dan disimulasikan dalam perisian LTSpice IV. Pengawal pemacu LED telah dibangunkan menggunakan Altera DE0-Nano FPGA Board dengan perisian Quartus II menggunakan *Verilog Hardware Description Language* (HDL). Skematik litar kuasa dan susun atur papan litar bercetak telah direkabentuk menggunakan perisian Cadsoft EAGLE. Prestasi pemacu LED dinilai berdasarkan prestasi kecekapan tenaga dan riak keluaran. Dalam eksperimen kecekapan tenaga, reostat digunakan sebagai beban. Model simulasi dan prototaip masing-masing mencapai kecekapan tenaga sebanyak 93.36% dan 93.19%. Dalam eksperimen riak keluaran, hasil menunjukkan riak keluaran maksimum bagi model simulasi adalah sebanyak 0.046% sementara prototaip adalah sebanyak 0.06%. LED putih berkecerahan tinggi juga digunakan sebagai beban untuk menilai kecekapan tenaga pemacu LED. Hasil menunjukkan prototaip telah mencapai kecekapan tenaga sebanyak 93.18% dan mempunyai riak keluaran maksimum sebanyak 0.054% apabila LED putih berkecerahan tinggi digunakan sebagai beban.

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**LIST OF ABBREVIATION**

FPGA	–	Field Programmable Gate Array
ASIC	–	Application Specific Integrated Circuit
LED	–	Light Emitting Diode
SSL	–	Solid State Lighting
PCB	–	Printed Circuit Board
PWM	–	Pulse Width Modulation
RTL	–	Register Transfer Logic
GPIO	–	General-Purpose Input Output
DC	–	Direct Current
SMPS	–	Switch-Mode Power Supply
SPICE	–	Simulation Program with Integrated Circuit Emphasis
MOSFET	–	Metal–Oxide–Semiconductor Field-Effect Transistor

**LIST OF SYMBOLS**

<i>V</i>	–	Voltage
<i>A</i>	–	Ampere
$\mu$	–	Micro, $1 \times 10^{-6}$
<i>m</i>	–	Mili, $1 \times 10^{-2}$
<i>k</i>	–	Kilo, $1 \times 10^3$
<i>M</i>	–	Mega, $1 \times 10^6$
$\varepsilon$	–	Efficiency
%	–	Percent
<i>Hz</i>	–	Hertz

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Introduction**

Light-emitting diode (LED) is the most attractive in lighting application in early 21st century due to its advantages of high efficiency in term of light output and energy, long life time and environmental friendly. It has led to the development of improved light output high-brightness white LED, energy efficient LED driver, enhanced security and safety surveillance and development of Li-Fi (High-speed and fully networked wireless communication technology using LED light) [1]. The researches in LED driver efficiency becoming more important as the world is moving toward adopting renewable energy. Thus, the main objective of this research is to develop a high energy efficient LED driver using field programmable gate array (FPGA) as LED driver controller. By enhancing the energy efficiency of LED driver, this research is in line with Energy Commission act 2001 and Electricity Supply Act 1990 by Malaysian government which to promote the efficient use of electricity [2-4].

## 1.2 Overview of LED History and Development

In 1907, Captain Henry Joseph Round conducted an experiment by flowing electric current through a carbide crystal. The carbide crystal was emitting yellowish light, which mark as the first recorded observation of electroluminescence phenomenon [5]. However, the yellowish light emitted was not good enough for practical use [6]. Nick Holonyak invented a red LED, which he later coined as ‘Father of the LED’. The red LED's invented by Holonyak were too dim to be seen in daylight. It was mainly used as indicator lights for various application. A former graduate student of Holonyak, George Craford invented the first yellow LED and brighter red LED than Holonyak’s red LED in 1972 [7].

High-efficiency LEDs for fibre optic telecommunications was invented by T. P. Pearsall for fibre optic telecommunications in 1976. To achieve high-efficient LED, Pearsall designed new semiconductor materials that specifically adjusted to fibre optic transmission wavelengths [8]. The new colours became available as technology advanced in the 1970's. The demand of LED grew as the new uses of LED light discovered [9].

The semiconductor materials used in LEDs are further refined in 1980’s. In the 1980's, the first super bright LED's were invented. The LED were more stable and cheaper, making the demand for LED’s rise significantly. The use of LED's became standard in various industrial applications in the 1990’s as the LED technology became more matured [10-12]. The high energy efficiency, long life and cost effective of LED lights have been gaining popularity and quickly replacing incandescent light sources.

### **1.3 Problem Statement**

There are three problem statements of this research. Driving LED(s) at high output ripple and without current regulation can degrade LED(s) performance. Without the proper driver, high-brightness white LED may become unreliable and flickers, thus causing reduced performance or failure [13].

There are many type of energy losses that can reduce the energy efficiency in SMPS such as conduction loss, switching loss and controller or driver loss. Energy consumption on LED driver controller contributes to energy loss [14, 15]. As a result, energy efficiency of the LED driver reduces. Using low power device can help to minimize the energy loss during power conversion.

Identified limitations of prototyping of full custom ASIC requires time-consuming floor planning, place and route, timing analysis, and mask or re-spin stages process [16]. Plus, it does not reconfigurable or reprogrammable. Thus, fine tune and changes of the ASIC design cannot be done immediately.

Therefore, this study aimed to overcome the three problem statements and pursued towards more energy efficient and environmental friendly lighting system.

### **1.4 Research Objectives**

The key objective of this research is to develop an LED driver for lighting application. Next objective that support to the key objective is to develop an LED driver controller which consists of PWM controller and current regulator using FPGA. The third objective is to analyse the performance of the developed LED driver in term of energy efficiency and output ripple.

## **1.5 Scope of Study**

The scope divided into two parts which are development of LED driver simulation model and the development of LED driver prototype.

The first part of research scope is to design an LED driver model in SPICE software. LTSpice version 4.23e was used to design the LED driver simulation model. It consists of Power stage circuit, PWM controller and voltage mode control.

The second part of research scope covers the development of the LED driver prototype. Based on the simulation model design, a prototype was developed. FPGA was used as LED driver controller ASIC. Quartus II software and Verilog HDL was used to design the LED driver controller module.

The final part was to analyse both simulation model and hardware prototype in two experiments. The first experiment is to analyse the energy efficiency performance. The second experiment is to analyse the output ripple of the LED driver.

## **1.6 Significance of the Study**

This study goal is to develop an LED driver with high energy efficiency using FPGA. This will help to promote the efficient use of electricity as stated in Malaysian Government Energy Commission act 2001 and Malaysian Government Electricity Supply Act 1990. This study also can be as a starting point for Malaysia to start wasting energy, improving energy usage and life quality.

In addition, this research will support other researchers on their results and help previous researchers on doing further advanced studies in this area. Other researcher can have more input and data that can be compared about the LED driver design. This would help other researcher to create higher energy efficiency LED lighting system as the world is adapting to renewable energy.



## 1.7 Organization of Thesis

This thesis consists of six chapters. The first chapter is introduction. The first chapter is the overview of the LED, problem statement, research objectives, scope of study and the significant of the study.

The next chapter is the literature review of the research which discusses about background information of the study and literature reviews of the research.

In the third chapter, explanations of the research methodology of this project is discussed. Overall project workflow from the first research works to the end are shown in this chapter.

The next chapter shows the development of the LED driver. This chapter explains about the development of LED driver simulation model and the development of the hardware prototype of LED driver.

In the fifth chapter, discusses the finding during. The chapter mostly shows experiment results and analysis of the LED driver simulation model and hardware prototype. In addition, this chapter also compares the result between the simulation model and hardware prototype.

Last chapter basically concludes the project based on the result and discussion in an earlier chapter. Besides, the future development on the project are also discussed in this chapter.

## REFERENCES

- [1] B. Hussain *et al.*, "A fully integrated IEEE 802.15. 7 visible light communication transmitter with on-chip 8-W 85% efficiency boost LED driver," in *2015 Symposium on VLSI Circuits (VLSI Circuits)*, 2015, pp. C216-C217: IEEE.
- [2] A. Bujang, C. Bern, and T. Brumm, "Summary of energy demand and renewable energy policies in Malaysia," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1459-1467, 2016.
- [3] S. Yusoff and A. Syafiq Rosli, "The implication of feed-in tariff funding structure and the sustainability of renewable energy in Malaysia," 2015.
- [4] J. O. Petinrin and M. Shaaban, "Renewable energy for continuous energy sustainability in Malaysia," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 967-981, 2015.
- [5] H. J. Round, "A note on carborundum," *Electrical world*, vol. 49, no. 6, p. 309, 1907.
- [6] N. Zheludev, "The life and times of the LED—a 100-year history," *Nature Photonics*, vol. 1, no. 4, pp. 189-192, 2007.
- [7] B. Biography-Holonyak and D. Craford, "Technology Administration," *Retrieved on*, pp. 05-30, 2007.
- [8] T. Pearsall, B. Miller, R. Capik, and K. Bachmann, "Efficient lattice-matched double-heterostructure LED's at 1.1  $\mu\text{m}$  from  $\text{GaIn}_{1-x}\text{AsyP}_{1-y}$ ," *Applied Physics Letters*, vol. 28, no. 9, pp. 499-501, 1976.
- [9] G. Rostky, "LEDs cast Monsanto in unfamiliar role," *Electronic Engineering Times*, vol. 944, no. March 10, p. 24, 1997.
- [10] W. Bosch, "The fuel rate indicator: a new measuring instrument for display of the characteristics of individual injection," SAE Technical Paper 0148-7191, 1966.
- [11] G. Held, *Introduction to light emitting diode technology and applications*. CRC Press, 2008.
- [12] M. Wada, T. Yendo, T. Fujii, and M. Tanimoto, "Road-to-vehicle communication using LED traffic light," in *Intelligent Vehicles Symposium, 2005. Proceedings. IEEE*, 2005, pp. 601-606: IEEE.
- [13] Y. Yang, X. Ruan, L. Zhang, J. He, and Z. Ye, "Feed-forward scheme for an electrolytic capacitor-less AC/DC LED driver to reduce output current ripple," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5508-5517, 2014.
- [14] J. W. Palmour, "Energy efficiency: The commercial pull for SiC devices," in *Materials science forum*, 2006, vol. 527, pp. 1129-1134: Trans Tech Publ.
- [15] G. Deboy, F. Hirler, M. März, and H. Weber, "Switch mode power supply with reduced switching losses," ed: Google Patents, 2002.

- [16] I. Kuon and J. Rose, "Measuring the gap between FPGAs and ASICs," *IEEE Transactions on computer-aided design of integrated circuits and systems*, vol. 26, no. 2, pp. 203-215, 2007.
- [17] A. Mohamadi and E. Afjei, "A single-stage high power factor LED driver in continuous conduction mode," in *Power Electronics, Drives Systems & Technologies Conference (PEDSTC), 2015 6th*, 2015, pp. 462-467.
- [18] Y. Guo, S. Li, A. T. L. Lee, S.-C. Tan, C. K. Lee, and S. Y. Hui, "Single-Stage AC/DC Single-Inductor Multiple-Output LED Drivers," *Power Electronics, IEEE Transactions on*, vol. PP, no. 99, pp. 1-1, 2015.
- [19] C. Chun-An, C. Chien-Hsuan, C. Tsung-Yuan, and Y. Fu-Li, "Design and Implementation of a Single-Stage Driver for Supplying an LED Street-Lighting Module With Power Factor Corrections," *Power Electronics, IEEE Transactions on*, vol. 30, no. 2, pp. 956-966, 2015.
- [20] V. P. Nambiar, A. Yahya, and T. R. Selvaduray, "SPICE modelling of a valley switching flyback power supply controller for improved efficiency in low cost devices," in *Circuits and Systems (ICCAS), 2012 IEEE International Conference on*, 2012, pp. 10-14: IEEE.
- [21] M. S. Nazarudin, M. A. A. Rahim, Z. Aspar, A. Yahya, and T. R. Selvaduray, "A flyback SMPS LED driver for lighting application," in *Control Conference (ASCC), 2015 10th Asian*, 2015, pp. 1-5.
- [22] X. Perpina *et al.*, "Thermal Analysis of LED Lamps for Optimal Driver Integration," *Power Electronics, IEEE Transactions on*, vol. 30, no. 7, pp. 3876-3891, 2015.
- [23] R. H. Haitz, M. G. Craford, and R. H. Weissman, "Light emitting diodes," *Handbook of optics*, vol. 2, pp. 121-129, 1995.
- [24] A. Zukauskas, M. S. Shur, and R. Gaska, *Introduction to solid-state lighting*. J. Wiley, 2002.
- [25] A. A. Bergh and P. Dean, "Light-emitting diodes," *Proceedings of the IEEE*, vol. 60, no. 2, pp. 156-223, 1972.
- [26] A. A. Bergh and P. J. Dean, "Light-emitting diodes," *Oxford, Clarendon Press, 1976. 598 p*, vol. 1, 1976.
- [27] E. F. Schubert, T. Gessmann, and J. K. Kim, *Light emitting diodes*. Wiley Online Library, 2005.
- [28] J. S. Kim *et al.*, "White-light generation through ultraviolet-emitting diode and white-emitting phosphor," *Applied Physics Letters*, vol. 85, p. 3696, 2004.
- [29] W. Liu *et al.*, "Blue-yellow ZnO homostructural light-emitting diode realized by metalorganic chemical vapor deposition technique," *Applied physics letters*, vol. 88, no. 9, p. 092101, 2006.
- [30] S. Nakamura, T. Mukai, and M. Senoh, "Candela-class high-brightness InGaN/AlGaIn double-heterostructure blue-light-emitting diodes," *Applied Physics Letters*, vol. 64, no. 13, pp. 1687-1689, 1994.
- [31] J.-S. Park *et al.*, "Flexible full color organic light-emitting diode display on polyimide plastic substrate driven by amorphous indium gallium zinc oxide thin-film transistors," *Applied Physics Letters*, vol. 95, no. 1, p. 013503, 2009.
- [32] Y. Taniyasu, M. Kasu, and T. Makimoto, "An aluminium nitride light-emitting diode with a wavelength of 210 nanometres," *Nature*, vol. 441, no. 7091, pp. 325-328, 2006.
- [33] T. Arguirov, M. Kittler, M. Oehme, N. V. Abrosimov, E. Kasper, and J. Schulze, "Room temperature direct band-gap emission from an unstrained Ge

- pin LED on Si," in *Solid State Phenomena*, 2011, vol. 178, pp. 25-30: Trans Tech Publ.
- [34] S. Pimplutkar, J. S. Speck, S. P. DenBaars, and S. Nakamura, "Prospects for LED lighting," *Nature Photonics*, vol. 3, no. 4, pp. 180-182, 2009.
- [35] X. Sun, J. Liu, L. C. Kimerling, and J. Michel, "Room-temperature direct bandgap electroluminescence from Ge-on-Si light-emitting diodes," *Optics letters*, vol. 34, no. 8, pp. 1198-1200, 2009.
- [36] K. Watanabe, T. Taniguchi, and H. Kanda, "Direct-bandgap properties and evidence for ultraviolet lasing of hexagonal boron nitride single crystal," *Nature materials*, vol. 3, no. 6, pp. 404-409, 2004.
- [37] E. Yablonovitch, "Photonic band-gap structures," *JOSA B*, vol. 10, no. 2, pp. 283-295, 1993.
- [38] S. Adachi, *Properties of aluminium gallium arsenide* (no. 7). IET, 1993.
- [39] G. Ariyawansa *et al.*, "GaN/AlGaIn ultraviolet/infrared dual-band detector," *Applied physics letters*, vol. 89, no. 9, p. 091113, 2006.
- [40] R. N. Hall, G. Fenner, J. Kingsley, T. Soltys, and R. Carlson, "Coherent light emission from GaAs junctions," *Physical Review Letters*, vol. 9, no. 9, p. 366, 1962.
- [41] F. Issiki, S. Fukatsu, and Y. Shiraki, "Efficient luminescence from AlP/GaP neighboring confinement structure with AlGaP barrier layers," *Applied physics letters*, vol. 67, no. 8, pp. 1048-1050, 1995.
- [42] F. Kish *et al.*, "Very high-efficiency semiconductor wafer-bonded transparent-substrate  $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}/\text{GaP}$  light-emitting diodes," *Applied Physics Letters*, vol. 64, no. 21, pp. 2839-2841, 1994.
- [43] C. Kuo, R. Fletcher, T. Osentowski, M. Lardizabal, M. Craford, and V. Robbins, "High performance AlGaInP visible light-emitting diodes," *Applied physics letters*, vol. 57, no. 27, pp. 2937-2939, 1990.
- [44] J. Li, Z. Fan, R. Dahal, M. Nakarmi, J. Lin, and H. Jiang, "200nm deep ultraviolet photodetectors based on AlN," *Applied physics letters*, vol. 89, no. 21, p. 213510, 2006.
- [45] S. Nakamura, M. Senoh, N. Iwasa, and S.-i. Nagahama, "High-brightness InGaIn blue, green and yellow light-emitting diodes with quantum well structures," *JAPANESE JOURNAL OF APPLIED PHYSICS PART 2 LETTERS*, vol. 34, pp. L797-L797, 1995.
- [46] S. Nakamura, M. Senoh, and T. Mukai, "High-power InGaIn/GaN double-heterostructure violet light emitting diodes," *Applied Physics Letters*, vol. 62, no. 19, pp. 2390-2392, 1993.
- [47] T. Sato and M. Imai, "Characteristics of nitrogen-doped GaAsP light-emitting diodes," *Japanese journal of applied physics*, vol. 41, no. 10R, p. 5995, 2002.
- [48] S. Vlaskina, "Silicon carbide LED," *Semiconductor Physics, Quantum Electronics & Optoelectronics*, vol. 5, no. 1, pp. 71-75, 2002.
- [49] J. Wierer *et al.*, "High-power AlGaInN flip-chip light-emitting diodes," *Applied Physics Letters*, vol. 78, no. 22, pp. 3379-3381, 2001.
- [50] D. Braun, A. Heeger, and H. Kroemer, "Improved efficiency in semiconducting polymer light-emitting diodes," *Journal of electronic materials*, vol. 20, no. 11, pp. 945-948, 1991.
- [51] M. Dyble, N. Narendran, A. Bierman, and T. Klein, "Impact of dimming white LEDs: chromaticity shifts due to different dimming methods," in *Proc. SPIE*, 2005, vol. 5941, p. 59411H.

- [52] W.-K. Lun, K. Loo, S.-C. Tan, Y. Lai, and C. K. Tse, "Bilevel current driving technique for LEDs," *Power Electronics, IEEE Transactions on*, vol. 24, no. 12, pp. 2920-2932, 2009.
- [53] R. W. Nygaard and T. E. Frumkes, "LEDs: Convenient, inexpensive sources for visual experimentation," *Vision research*, vol. 22, no. 4, pp. 435-440, 1982.
- [54] F. Reifegerste and J. Lienig, "Modelling of the temperature and current dependence of LED spectra," *Journal of Light & Visual Environment*, vol. 32, no. 3, pp. 288-294, 2008.
- [55] A. Barroso, P. Dupuis, C. Alonso, B. Jammes, L. Seguier, and G. Zissis, "A characterization framework to optimize LED luminaire's luminous efficacy," in *Industry Applications Society Annual Meeting, 2015 IEEE*, 2015, pp. 1-8: IEEE.
- [56] K. Bulashevich, I. Y. Evstratov, V. Mymrin, and S. Y. Karpov, "Current spreading and thermal effects in blue LED dice," *physica status solidi (c)*, vol. 4, no. 1, pp. 45-48, 2007.
- [57] J. De Britto, L. de Freitas, V. Farias, E. Coelho, and J. Vieira Jr, "A proposal of Led Lamp Driver for universal input using Cuk converter," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, 2008, pp. 2640-2644: IEEE.
- [58] L. Schneider, S. Consani, L. Correr-Sobrinho, A. Correr, and M. Sinhoreti, "Halogen and LED light curing of composite: temperature increase and Knoop hardness," *Clinical oral investigations*, vol. 10, no. 1, pp. 66-71, 2006.
- [59] G. Sukach, P. Smertenko, P. Oleksenko, and S. Nakamura, "Analysis of the active region of overheating temperature in green LEDs based on Group III nitrides," *Technical Physics*, vol. 46, no. 4, pp. 438-441, 2001.
- [60] C.-J. Weng, "Advanced thermal enhancement and management of LED packages," *International Communications in Heat and Mass Transfer*, vol. 36, no. 3, pp. 245-248, 2009.
- [61] R. A. Ramadan and A. Y. Khedr, "Light Fidelity (Li-Fi)," in *International Conference on Recent Advances in Computer Systems (RACS)*, 2016, pp. 104-107: Atlantis Press.
- [62] A. P. P. S. Kumar, "A Review Paper on Light-Fidelity (Li-Fi)," in *National Conference on Innovations in Micro-electronics, Signal Processing and Communication Technologies (IJIRST)*, 2016, pp. 12-13: IJIRST, 2016.
- [63] G. Carraro, "Solving high-voltage off-line HB-LED constantcurrent contro-circuit issues," in *Applied Power Electronics Conference, APEC 2007-Twenty Second Annual IEEE*, 2007, pp. 1316-1318: IEEE.
- [64] P. Tapster, J. Rarity, and J. Satchell, "Generation of sub-Poissonian light by high-efficiency light-emitting diodes," *EPL (Europhysics Letters)*, vol. 4, no. 3, p. 293, 1987.
- [65] K. M. Folta *et al.*, "Design and fabrication of adjustable red-green-blue LED light arrays for plant research," *BMC plant biology*, vol. 5, no. 1, p. 17, 2005.
- [66] M.-Q. Liu, X.-L. Zhou, W.-Y. Li, Y.-Y. Chen, and W.-L. Zhang, "Study on methodology of LED's luminous flux measurement with integrating sphere," *Journal of Physics D: Applied Physics*, vol. 41, no. 14, p. 144012, 2008.
- [67] G. B. Maison, "Transformer-Less Automatic White LED Emergency Light," 2012.
- [68] S. Winder, *Power supplies for LED driving*. Newnes, 2011.
- [69] K. Xiao, W. Hou, Q. Xu, and B. Peng, "LED uniform illumination system for DMD-based confocal microscopy," in *Sixth International Symposium on*

- Precision Mechanical Measurements*, 2013, pp. 89163T-89163T-10: International Society for Optics and Photonics.
- [70] A. Ioannidis, E. Forsythe, Y. Gao, M. Wu, and E. Conwell, "Current-voltage characteristic of organic light emitting diodes," *Applied physics letters*, vol. 72, no. 23, pp. 3038-3040, 1998.
- [71] C. Kittel, *Introduction to solid state physics*. Wiley, 2005.
- [72] D. Steigerwald *et al.*, "Illumination with solid state lighting technology," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 8, no. 2, pp. 310-320, 2002.
- [73] E. A. Vittoz and X. Arreguit, "Linear networks based on transistors," *Electronics Letters*, vol. 29, no. 3, pp. 297-299, 1993.
- [74] S. Buso, L. Malesani, and P. Mattavelli, "Comparison of current control techniques for active filter applications," *IEEE transactions on industrial electronics*, vol. 45, no. 5, pp. 722-729, 1998.
- [75] F. Cacciotto, "Off-line constant current LEDs driver using the HVLED primary controller," in *IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 2601-2605: IEEE.
- [76] Y. Fang, S.-H. Wong, and L. H.-S. Ling, "A power converter with pulse-level-modulation control for driving high brightness LEDs," in *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*, 2009, pp. 577-581: IEEE.
- [77] D. G. Lamar, J. Sebastian, M. Arias, and M. M. Hernando, "A low-cost AC-DC high-brightness LED driver with power factor correction based on standard peak-current mode integrated controllers," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, 2010, pp. 463-470: IEEE.
- [78] C. Lei, Z. Yanjun, and W. Yanling, "The high-power LED constant current driven design Based on PT4115 [J]," *Light & Lighting*, vol. 4, p. 007, 2008.
- [79] H. Van der Broeck, G. Sauerlander, and M. Wendt, "Power driver topologies and control schemes for LEDs," in *Applied Power Electronics Conference, APEC 2007-Twenty Second Annual IEEE*, 2007, pp. 1319-1325: IEEE.
- [80] B. Legates, "Constant-Current DC/DC Converter Drives White LEDs with 80% Efficiency," *Linear Technology Magazine (May 2001)*.
- [81] G. Lakkas, "MOSFET power losses and how they affect power-supply efficiency," *Texas Instruments Corp.*, 2016.
- [82] M. Bathily, B. Allard, F. Hasbani, V. Pinon, and J. Verdier, "Design flow for high switching frequency and large-bandwidth analog DC/DC step-down converters for a polar transmitter," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 838-847, 2012.
- [83] S. Guo, X. Lin-Shi, B. Allard, Y. Gao, and Y. Ruan, "Digital sliding-mode controller for high-frequency DC/DC SMPS," *IEEE Transactions on Power Electronics*, vol. 25, no. 5, pp. 1120-1123, 2010.
- [84] L. Bellia, F. Bisegna, and G. Spada, "Lighting in indoor environments: Visual and non-visual effects of light sources with different spectral power distributions," *Building and Environment*, vol. 46, no. 10, pp. 1984-1992, 2011.
- [85] N. A. Shadick *et al.*, "Musculoskeletal and Neurologic Outcomes in Patients with Previously Treated Lyme Disease," *Annals of Internal Medicine*, vol. 131, no. 12, pp. 919-926, 1999.
- [86] D. G. Kasteleijn-Nolst Trenité, G. Van Der Beld, I. Heynderickx, and P. Groen, "Visual stimuli in daily life," *Epilepsia*, vol. 45, no. s1, pp. 2-6, 2004.

- [87] M. Rihner and H. McGrath, "Fluorescent light photosensitivity in patients with systemic lupus erythematosus," *Arthritis & Rheumatism*, vol. 35, no. 8, pp. 949-952, 1992.
- [88] I. Dianat, A. Sedghi, J. Bagherzade, M. A. Jafarabadi, and A. W. Stedmon, "Objective and subjective assessments of lighting in a hospital setting: implications for health, safety and performance," *Ergonomics*, vol. 56, no. 10, pp. 1535-1545, 2013.
- [89] M. Milanovic, M. Truntic, and P. Slibar, "FPGA implementation of digital controller for DC-DC buck converter," in *Fifth International Workshop on System-on-Chip for Real-Time Applications (IWSOC'05)*, 2005, pp. 439-443: IEEE.
- [90] A. C. Shettar, K. Sudarshan, and S. Rehman, "FPGA design and implementation of digital PWM technique for DC-DC converters," in *Recent Trends in Electronics, Information & Communication Technology (RTEICT), IEEE International Conference on*, 2016, pp. 918-920: IEEE.
- [91] S. Subiramoniyan and S. J. Jawhar, "Design and implementation of modern digital controllers for DC-DC buck converter," in *Computing, Electronics and Electrical Technologies (ICCEET), 2012 International Conference on*, 2012, pp. 279-287: IEEE.
- [92] H. Li, "Application Note for Switching Mode Power Supply Design with 900V Switching Regulator - MP110," Application Note 2014.