

Lighting Control via Magnetic Field Communication

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Abstract: This invention proposes a novel light emitting diode (LED) lighting (dimnable) control scheme to transmit digital data through a magnetic field generated by a flyback driver that utilizes digitized data to adjust the brightness of LEDs for potential applications. This design would eliminate the cost of establishing wireless transmission hardware by simply relying on the magnetic field for communication to meet the management of the lighting control system. The method used a frequency-shift keying (FSK) technique on the secondary side of the system to send digitized data to the primary side. The primary side of the system interpreted the control commands by detecting the frequency change, and the corresponding lighting control was decoded. The inner communication connected the primary and secondary sides to the transformer through wirelessly transmitted data, which eliminated the requirements of optical coupling and peripheral circuits. For extended applications, the designed system can be combined with sensors at home for lighting management with the benefits of energy saving and potential emergency warnings.

Keywords: LED; lighting control; flyback driver; communication

1. Introduction

Recently, the lighting market has slowed down due to the maturity of technologies; however, due to advances in semiconductor technology, LED lamps have replaced traditional lamps. Some of the main advantages of LEDs are as follows: (1) driver modules are small and lightweight; (2) power consumption is lower than that of traditional lamps and the luminosity is higher; (3) a startup voltage can be determined using a driver architecture and is not limited by the supply voltage [1].

In the luminaire driver topology, linear actuators have the advantage of low cost. They are often used in inexpensive lighting fixtures but have poor efficiency. Multisegment linear drivers, such as switching-type drivers, can improve their efficiency [2]. In these drivers, electromagnetic interference (EMI) problems must be resolved; however, because their efficiency is higher than that of linear drivers, they have become mainstream in the market, which is evolving to embrace buck-boost drivers [3–5]. Among these, buck-boost drivers with a high adaptability of input voltages have been further developed according to input voltages specified by the governments of various countries [6]. Although the efficiency of buck-boost drivers is slightly lower than that of the general switching-type driver, their manufacturing cost is relatively lower. There is also no need to change the design of buck-boost drivers of various input voltages, which further enhances the market competitiveness of LED drivers. Because the market demands large power drivers, an isolated switch driver has been developed that considerably improves the safety factor [7,8].

The demand for energy conservation and smart control devices has increased in recent years, such as smart lighting [9,10], niche lighting [11], and national lighting [12]. Therefore, the LED industry is increasingly demanding smart lighting. However, most smart lighting highly depends on wireless devices or extra lines to transmit control signals. In [13], the authors proposed the transmission of

LED states by using extra wireless devices and control of LED lighting through terminal lighting management. This design did not consider the lack of functionality when a wireless transmission device fails. In [14], the authors proposed a novel method of transmitting data by using a magnetic field. During the wireless battery charging of a vehicle, instead of including an extra radio frequency (RF) communication device, data fitting technology was embedded into the carrier for transmission, and data were transferred using an electromagnetic induction device. In [15], a remote-control device for monitoring and managing a street lighting system was proposed. The control system allows the selection of the electrical phase of power line communication and sends control commands to slave boards of each lamp post. Additionally, a lamp's operating status can be detected.

Considering the limitations of traditional approaches, current research improves and innovates the technology of data transmission incorporated in lighting control. Table 1 presents a qualitative comparison. For data (command) transmission, FSK transmission is modulated on the secondary side of a system, then data are embedded in the carrier and transmitted using the magnetic field [16,17] generated using a transformer inside the system. An automatic lighting control system is also proposed. The carrier frequency variation of a transformer is directly interpreted on the primary side of the system. The cost of our architecture is lower than that of other approaches that depend on extra RF communication mechanisms to solve the problem of signal transmission. Finally, the transmitted data are interpreted, and the LED driving current is modulated for the purpose of saving energy.

Table 1. Comparison between intelligent lighting systems.

	Proposed Method	Previous Approach [13]
Communication Architecture	Embedded in flyback driver	External RF device needed
Controller and Driver	Integrated design	Separated design
Hardware cost	Comparatively low [18]	Comparatively high

2. Adjustable Isolated Driver

A major disadvantage of unregulated drivers is that the output voltage varies substantially, which is a serious problem in some applications with load changes. Compared with unregulated drivers, a regulated driver accurately sets the output voltage, because the feedback mechanism is designed on the secondary side of the system. A common practice is to use a precise regulator with high thermal stability, such as TL431 [19], together with an optocoupler to transfer control signals from the secondary side of the system to the primary side [20,21]. This design compensates for the effects of factors, such as the input voltage, output current, and temperature, regulating the output voltage with precision. A typical application is a flyback driver. The circuit is mainly composed of a switching power transistor (MOSFET) controlled using an integrated circuit (IC), a transformer for energy storage and isolation, a diode, an output capacitor, a feedback circuit, and an optocoupler. Figure 1 illustrates the structure. However, to eliminate the secondary circuit and optocoupler, the primary side regulation (PSR) flyback converter can be stably applied to LED lamps [22]. This architecture is presented in Figures 2 and 3.

The flyback driver works in the continuous current mode. When the MOSFET is turned on, the primary side N_p winding of the transformer is considered the energy storage inductor, and the input voltage starts to charge the primary side N_p of the transformer. Because the secondary side N_s has polarity opposite to that of the primary side N_p , the diode is reverse biased so that the energy stored in the primary side N_p cannot be transmitted to the secondary side N_s , and the output terminal is supplied with energy through the output capacitor C (Figure 2). The current change in the primary side N_p can be expressed using the following formula:

$$\frac{di_p(t)}{dt} = \frac{V_{in}}{L_p} \quad (1)$$

where $i_p(t)$ is the current flowing through the primary side, V_{in} is the input voltage, and L_P is the equivalent inductance of the primary side.

When the MOSFET is turned off, the current L_P of the primary side N_P inductor decreases to zero, the magnetic flux density starts to change, and the polarity of the primary side N_P reverses. The diode on the secondary side N_S becomes forward-biased and is turned on, and the energy at the primary side N_P is transferred to the secondary side N_S , which starts to supply energy to the output capacitor and output port (Figure 3).

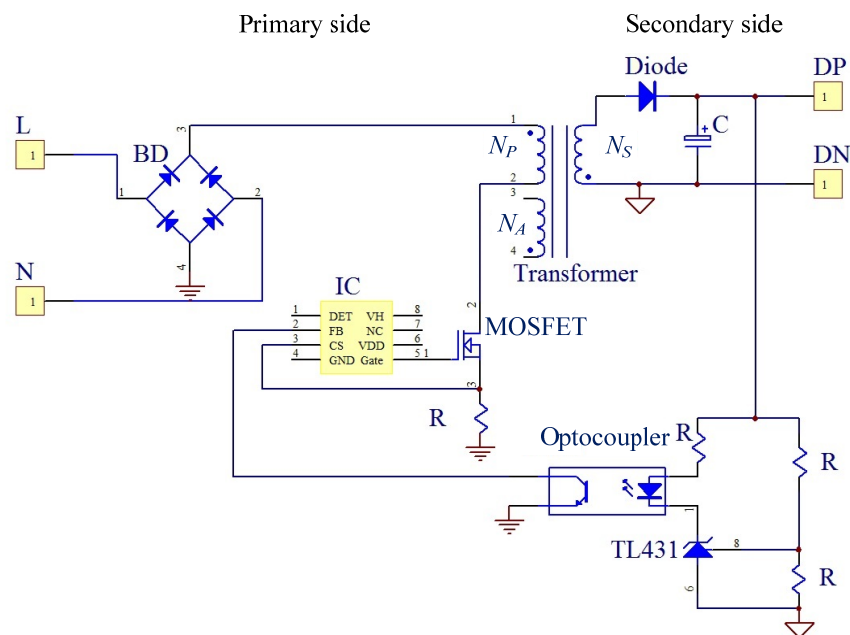


Figure 1. LED dimming architecture with feedback control.

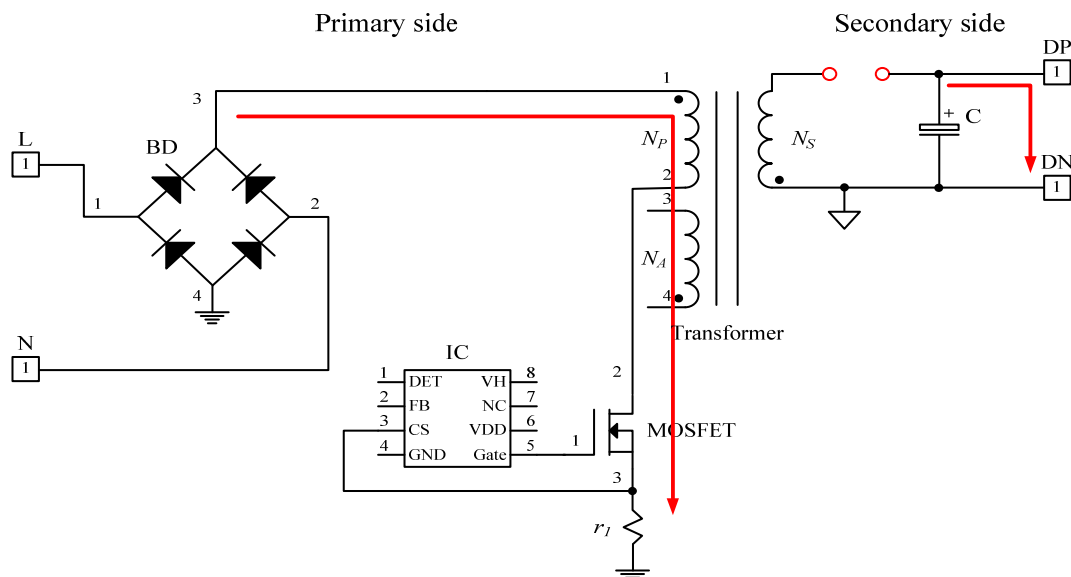


Figure 2. Schematic of the system when the MOSFET is on.

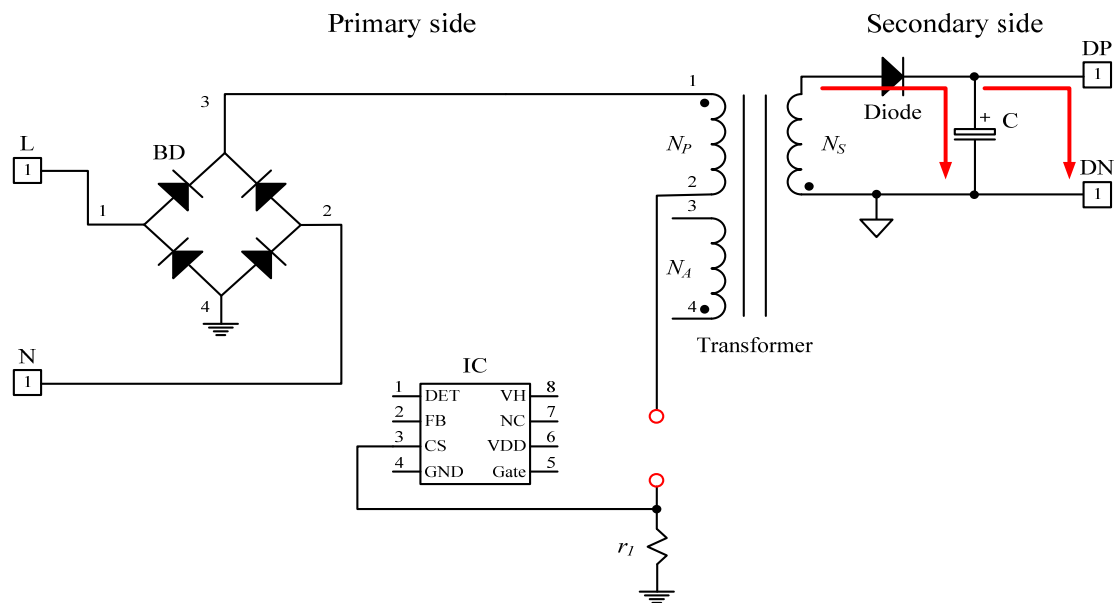


Figure 3. Schematic of the system when the MOSFET is off.

3. Signal Modulation

The signal modulation technique can be divided into analogous modulation and digital modulation [23]. The basic formula of the carrier is given by $s(t) = A\cos(2\pi f_0 t + \theta)$, where A is the carrier amplitude, f_0 is the carrier frequency, and θ is the carrier phase shift.

We adopted FSK for signal transmission, where the high and low carrier frequencies represent digits 1 and 0, respectively, with:

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) \\ A\cos(2\pi f_2 t) \end{cases} \quad (2)$$

where f_1 and f_2 denote the high and low carrier frequencies, respectively.

The packet length is 10 bits, with a total of 4 bytes. The first bit is the start bit. The second byte with 4 bits represents data to be transmitted. The third byte with 4 bits is the checksum. The checksum is used to prevent data transmitted from noise interference. The last bit is the stop bit.

4. Structure

We propose an energy management system with the function of lighting control and the potential of emergency notification (Figure 4). It has four operational modes, namely “one touch” function, inner and outer communication links, variable output power, and sensor application. The main purpose of “one touch” is to reset the standby power consumption, which is realized using Tr_1 and IC_2 . In a normal state, Tr_1 is off (i_1 is zero); when a user presses this button, *Controller-1* is enabled, which activates IC_2 and Tr_1 . Subsequently, the system starts to work, and i_1 and i_2 change with the VR signal (IC_1), and R_L to reset i_1 to zero. Extended functions are achievable; however, only four modes are presented here for demonstration.

For communication, it includes inner and outer communication links. For inner communication, *Controller-2* encodes data, and the encoded data are sent back to *Controller-1* for decoding through Q_2 . When the decoded command changes the output power, *Controller-1* changes the value of a digital potentiometer (*digital pot*), which then changes VR voltage of IC_1 to change i_1 . If the decoded command is an emergency notification, *Controller-1* sends a command to the external device through L_1 and L_2 . When, for example, a gas sensor in the kitchen detects a gas leak, *Controller-2* sends a message to *Controller-1* immediately through the inner communication. Simultaneously, *Controller-1* sends this message to the external device through the outer communication link (not included in this paper) to

stop the gas leak. L_3 can be added next to C_1 as illustrated in Figure 4 to provide low-pass filtering to reduce electromagnetic susceptibility.

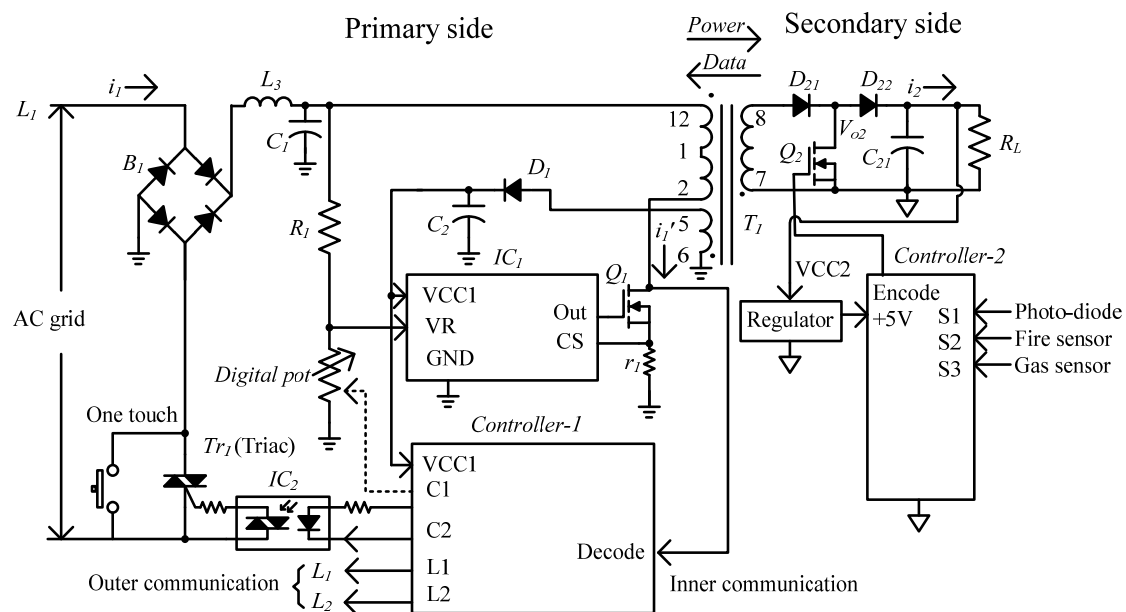


Figure 4. System architecture for energy efficient lighting control and emergency warning.

For IC_1 , the duty cycle of Q_1 is controlled to adjust the LED current, and the current is measured using the chip select (CS) PIN, thereby controlling the LED current within a closed loop. This system is capable of adjusting the output current of LEDs, so that VCC2 in the secondary side is constant.

In Figure 4, an electric current flows from left to right, whereas the digitized information flows in the reverse direction. Digitized data is modulated using Q_2 . The operational period of Q_1 is T . When Q_2 modulates the bit “0”, it is switched on, and the energy, which is originally to be sent to R_L , is stored in L_{12} until Q_2 is switched off. This process, for example, might require an operating period of $0.1 T$. Modulating Q_2 for the bit “0” increases the operating period T_0 of Q_1 to $2 T$. *Controller-1* detects the change in T_0 of Q_1 to decode data packets. To enhance the robustness of transmitting or receiving data, a low data baud rate is adopted. For example, *Controller-2* sends a data packet controlling IC_1 to change its output to the 9th section, as shown in 9 (M_9) in Figure 5. In the figure, the baud rate is 125 Bd with a sampling time of 8 ms per bit. Within the period, if $T_0 = 2 T$ of Q_1 is detected, the bit is decoded as “0”; otherwise, it is decoded as “1”. Figure 5 indicates that *Controller-2* sends a data packet containing the lighting command 0x09 (M_9) to *Controller-1*. After receiving and encoding the command, it is used to control the digital pot to change VR of IC_1 , and hence to control i_{L1} . The lighting control system is equipped with the function of zero-power consumption when it remains at standby. When *Controller-1* receives “0” (M_{11}), it switches off Tr_1 to shut down the current supply. To restart the system, the user only has to press the “one touch” key.

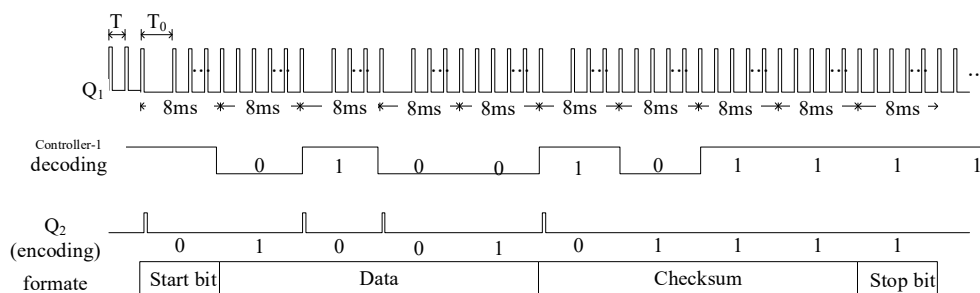


Figure 5. Example of data encoding and decoding.

Sensors used in this system, such as photodiodes, fire sensors, and gas sensors, can be used for the emergency control of external devices. The photodiode converts light into electrical current. At night, *Controller-1* requires IC_1 to output a large i_2 , whereas during daytime, it requires IC_1 to output a small i_2 and even close i_2 to achieve the minimum standby power.

5. Control Design

In this study, the driver IC used was *FL77xx* [24], and a flyback driver and a transformer were combined with the *STM32F769xx* microcontroller (to realize *Controller-1* and *Controller-2*) [25] for encoding, decoding, data transmission, and driver control, to achieve the effects of modulating LED output current.

5.1. Transformer

The core of the whole driver is the transformer. After considering existing materials, the core and winding frame of *PQ20/16* were selected [26]. First, we set the operating efficiency η at 85%, MOSFET (Q_1) on-time at 7.1 μs (t_{on}), and frequency at 50 kHz (f_s). The primary side inductance (L_m) can be derived from:

$$L_m = \frac{\eta V_{in.rms}^2 f_s t_{on}^2}{2P_O} \quad (3)$$

where $V_{in.rms}$ is the root mean square value of the input voltage, and P_O is the output power. Therefore, L_m obtained was 1028 μH .

We then calculated the turn (N_P) of the primary side, turn (N_S) of the secondary side, and auxiliary winding turn (N_A). $N_{P.min}$ was the minimum number of turns required to avoid saturation of the primary side core which is given by:

$$N_{P.min} = \frac{V_{in} \cdot p k t_{on}}{B_{sat} A_e} \quad (4)$$

where B_{sat} is the maximum flux density, generally 0.3, A_e is the core cross sectional area, and the value of *PQ20/16* is 62 mm². That is:

$$N_{P.min} = \frac{110 \cdot \sqrt{2} \cdot 7.1 \cdot 10^{-6}}{0.3 \cdot 62 \cdot 10^{-6}} = 59.3 \quad (5)$$

Considering unavoidable inaccuracy occurring in the transformer manufacturing process and allowing for wider temperature variations, the number of coil turns is increased by approximately 5–10% to avoid core saturation [27]:

$$N_P = 1.1 N_{P.min} = 65 \quad (6)$$

The number of turns on the secondary side (N_S) and the number of turns of the auxiliary winding (n_A) can be calculated as follows:

$$N_S = \frac{N_P}{n_{PS}} = 19 \quad (7)$$

$$n_A = n_S n_{AS} = 19 \quad (8)$$

where n_{PS} is the ratio of the turns of the primary and secondary sides, which is 3.45 here, and n_{AS} is the turn ratio of the secondary side to auxiliary winding.

The customized transformer is implemented using the close wound and sandwich method. The sequence used to complete the flow is from the primary side (N_{P1}) to the secondary side (N_S), then to the primary side (N_{P2}), and finally to the auxiliary winding (N_A). Structure and specifications of the transformer are presented in Figure 6 and Table 2, respectively.

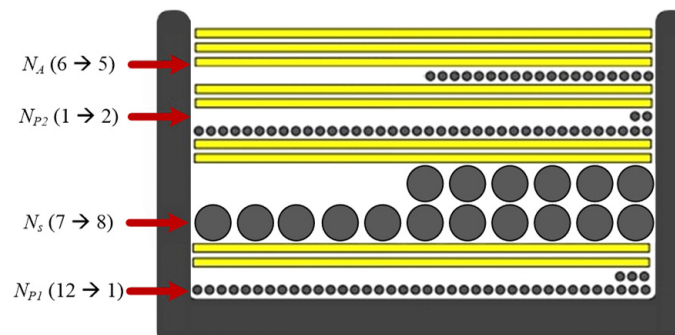


Figure 6. Winding structure of the transformer.

Table 2. Transformer parameters.

Number of Layers	Winding	Pin (S→F)	Wire Diameter (ψ)	Number of Turns (T)
1	N_{P1}	12→1	0.25	33
2		Insulation Tape		3
3	N_S	7→8	0.25×2	19
4		Insulation Tape		3
5	N_{P2}	1→2	0.25	32
6		Insulation Tape		3
7	N_A	6→5	0.25	19
8		Insulation Tape		3

5.2. Driver and Controller

The driver IC was *FL77xx*, which was used for the pulse width modulation of driving commands. The microcontroller (*STM32F769xx*) was based on the *ARM Cortex-M7* 32-bit core operating at up to 216 MHz. The MOSFET is a widely used field-effect transistor. Q_1 and Q_2 used were *C2M0080120D*.

5.3. Coding and Decoding Schemes

Figure 7 illustrates the signal modulation waveform. The first and second channels are the decoding and sampling waveforms on the primary side, respectively. The third and fourth channels are the coding and sampling waveforms on the secondary side, respectively. The secondary side is working during data encoding and current modulation, and the waveform is changed when the working cycle generated on the primary side of the system. Therefore, the width of the waveform generated through signal modulation is significantly different from that of waveform generated without signal modulation. Consequently, a control command transmitted through the secondary side can be clearly recognized from the primary side.

To prevent misjudgment caused by noise interference, in our design, a set of check codes was employed to ensure correct data transmission. Figures 8–11 illustrate the results of data encoding for the four operational modes depicted previously.

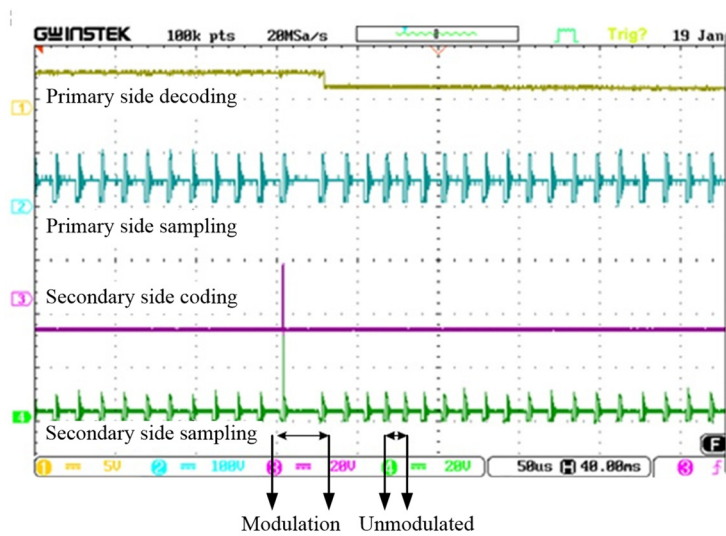


Figure 7. Signal modulation waveform.

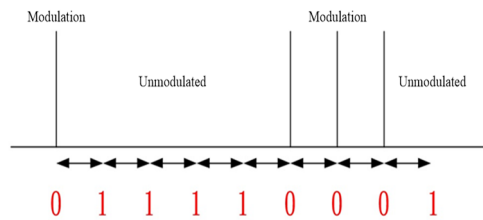


Figure 8. Data scheme corresponding to “rated current”.

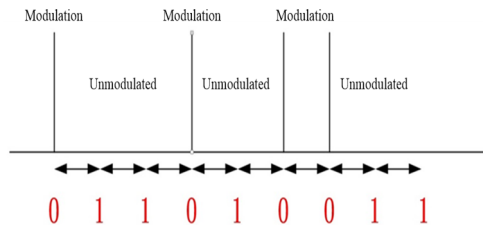


Figure 9. Data scheme corresponding to “current reduction 1”.

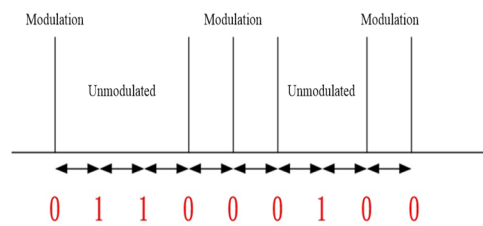


Figure 10. Data scheme corresponding to “current reduction 2”.

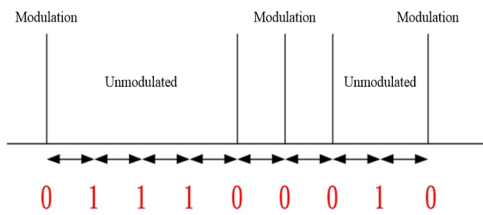


Figure 11. Data scheme corresponding to “power off”.

6. Experimental Results

6.1. Performance Test

Table 3 lists key data provided using the system when the lighting and output states changed. Because FL77xx may vary with a change in output voltage, even a slight load change may cause output voltage variation.

Table 3. Comparison between output voltage and current under different input powers.

Output Current Changes			
P_{in} (W)	V_{out} (V)	I_{out} (A)	η (%)
14.2	19	0.64	85.63
3.5	18.6	0.16	85.03
1.7	18	0.08	84.71
Output Voltage Changes			
P_{in} (W)	V_{out} (V)	I_{out} (A)	η (%)
9.74	13	0.632	84.35
7.78	10	0.63	80.98
5.7	7	0.63	77.37

Figure 12 presents the waveforms of the voltage and current across the transformer. Channels one and two are the primary side voltage and current, respectively, whereas channels three and four are voltage and current of the secondary side, respectively.

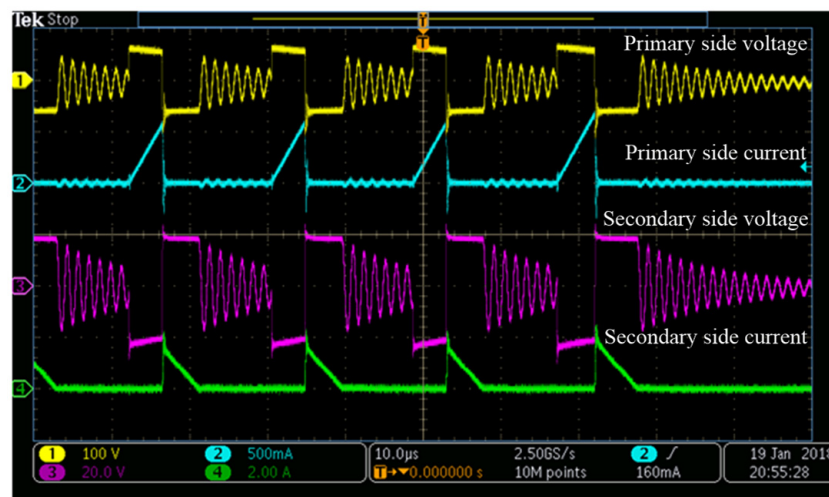


Figure 12. Related electrical waveforms on both sides of the transformer.

Figures 13–16 illustrate the coding and decoding waveforms of the both sides of the system, channel three denotes the coded waveform sent from the secondary side, and channel one represents the decoded waveform of the primary side. Four types of signals can be accurately transmitted back to the primary side and decoded afterward. Figure 17 presents the results of dimming control under a specific lighting mode.

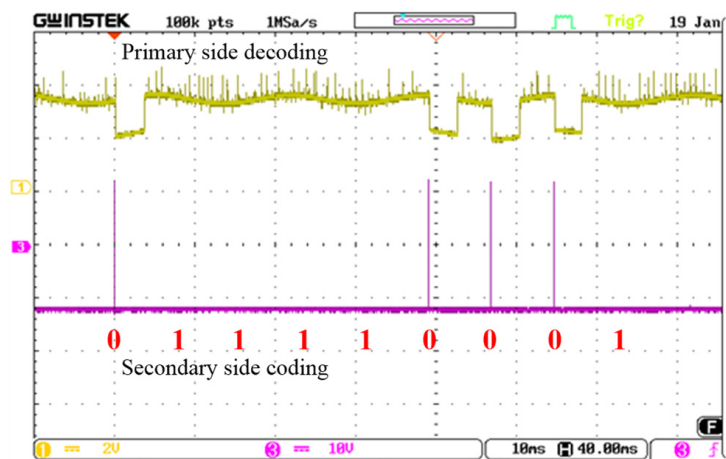


Figure 13. Rated current.

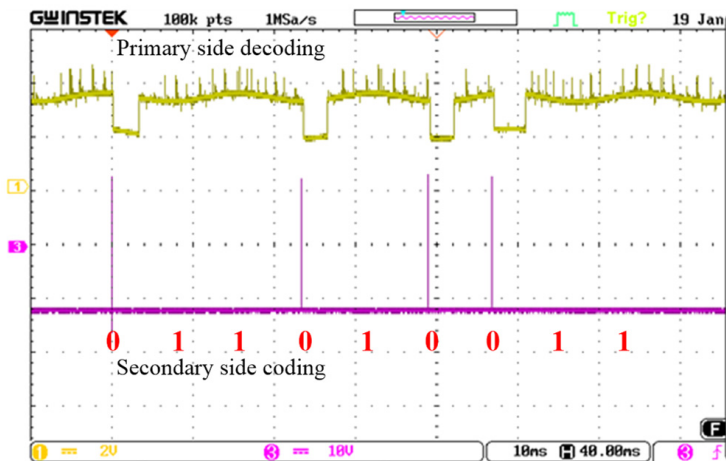


Figure 14. Current reduction 1.

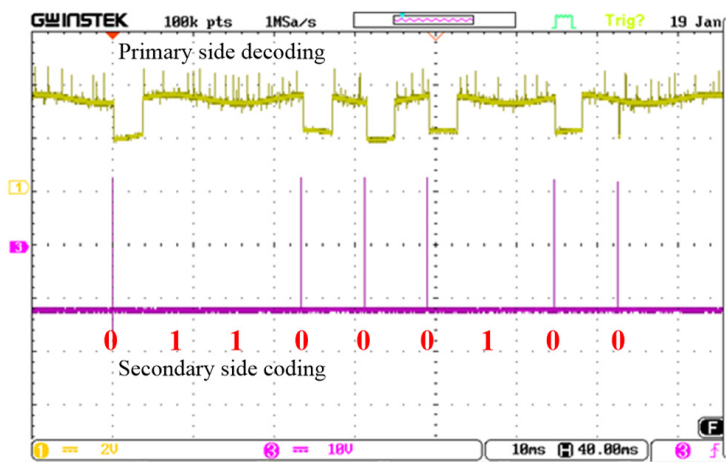


Figure 15. Current reduction 2.

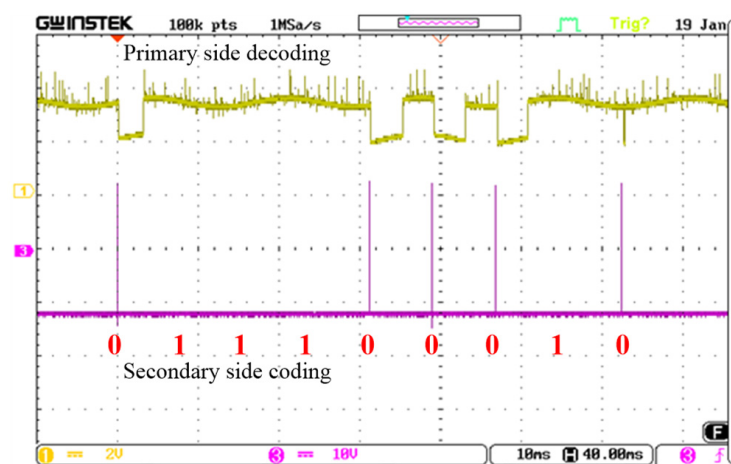


Figure 16. Power off.

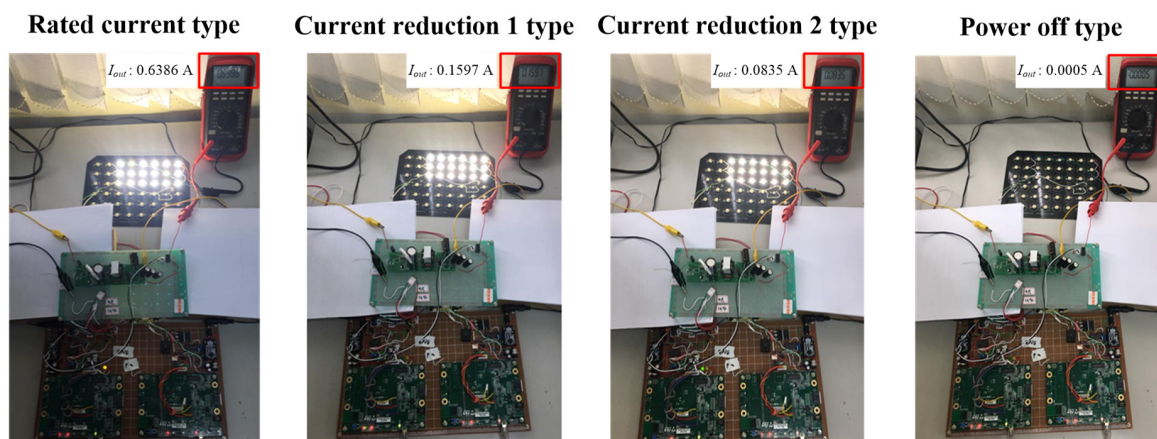


Figure 17. Tests for various lighting control modes.

6.2. Communication Quality Test

The major variable of this system is the output voltage. The communication quality was evaluated based on the transmission of 10,000 data packets under different output voltages. When the secondary side transmitted a signal, the primary side received the signal when acknowledging a correct message. The transmission success rate was defined as $\frac{\text{Number of data byte successfully transmitted}}{\text{Number of data byte transmitted}}$. Figure 18 indicates the differences observed in communication quality when the output voltage varied. The transmission error rate was $< 5\%$.

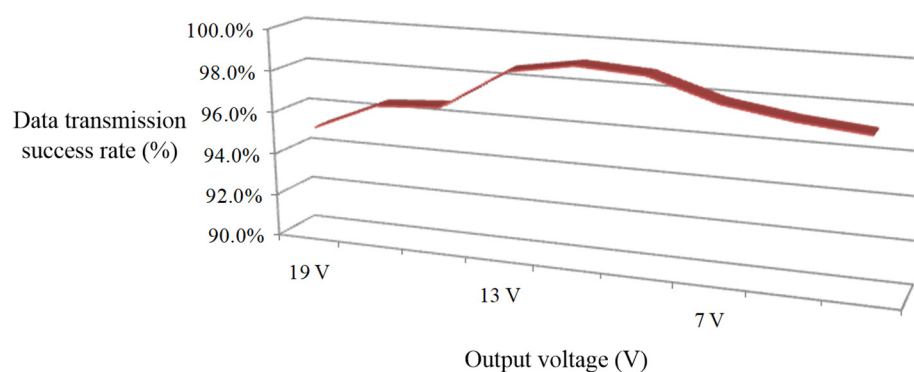


Figure 18. Alternation of communication quality due to output voltage variation.

6.3. Efficiency Test

To compare the efficiency of the commercially available buck-boost LED driver with that of our proposed scheme, we added automatic lighting control to the system, which was employed to change the original four lighting types to 10 lighting types (M_1 – M_{10}). Figure 19 indicates that the designed system can maintain the efficiency within 5% of variation after conducting 10 types of light source controls (through magnetic field communication); the traditional buck-boost LED driver was controlled using a light source that employed DC–DC conversion, which resulted in considerable switching losses, causing that system to become less efficient. Table 4 presents the efficiencies of the proposed lighting control system and traditional buck-boost driver.

Table 4. Performance comparison between the two lighting control systems.

Designed LED Lighting System					
Modulation	P _{in} (W)	V _{out} (V)	I _{out} (A)	P _{out} (W)	Efficiency (%)
M_1	15.12	18.8	0.72	13.54	89.52%
M_2	13.86	18.6	0.66	12.28	88.57%
M_3	12.60	18.4	0.61	11.22	89.08%
M_4	11.34	18.2	0.55	10.01	88.27%
M_5	10.08	18.0	0.49	8.82	87.50%
M_6	8.82	17.8	0.43	7.65	86.78%
M_7	7.56	17.6	0.37	6.51	86.14%
M_8	6.30	17.4	0.32	5.57	88.38%
M_9	5.04	17.2	0.25	4.30	85.32%
M_{10}	3.78	17.0	0.19	3.23	85.45%
Buck-boost LED Lighting System					
Modulation	P _{in} (W)	V _{out} (V)	I _{out} (A)	P _{out} (W)	Efficiency (%)
M_1	38.22	20.3	1.57	31.87	83.38%
M_2	32.24	19.8	1.35	26.73	82.91%
M_3	27.90	19.3	1.19	22.97	82.32%
M_4	23.87	18.8	1.03	19.36	81.12%
M_5	18.91	18.3	0.82	15.01	79.35%
M_6	14.26	17.8	0.63	11.21	78.64%
M_7	10.23	17.3	0.46	7.96	77.79%
M_8	6.20	16.8	0.28	4.70	75.87%
M_9	3.72	16.3	0.17	2.77	74.49%
M_{10}	1.24	15.8	0.04	0.63	50.97%

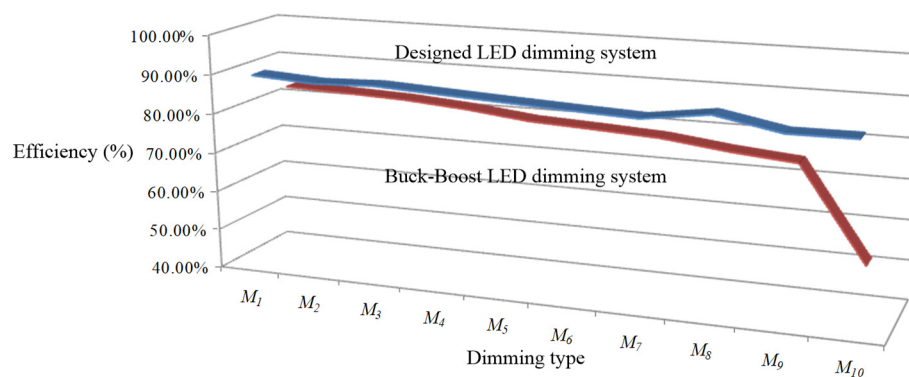


Figure 19. Comparison of the efficiency between lighting systems.

7. Discussion

Figures 20 and 21 illustrate the waveforms of command modulation, wherein channel one is V_{O2} , channel two is VCC2, channel three is the coding waveform of the secondary side, and channel four is i_2 . VCC2 and i_2 are not explicitly affected during modulation. The dimming control only works for a considerably short duration. Most of the time, LED brightness is not affected by any control action.

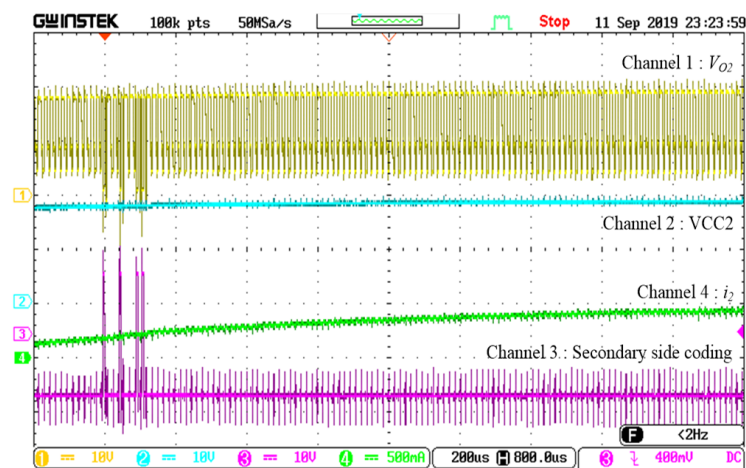


Figure 20. Lighting stability test (M_9 is modulated to M_6).

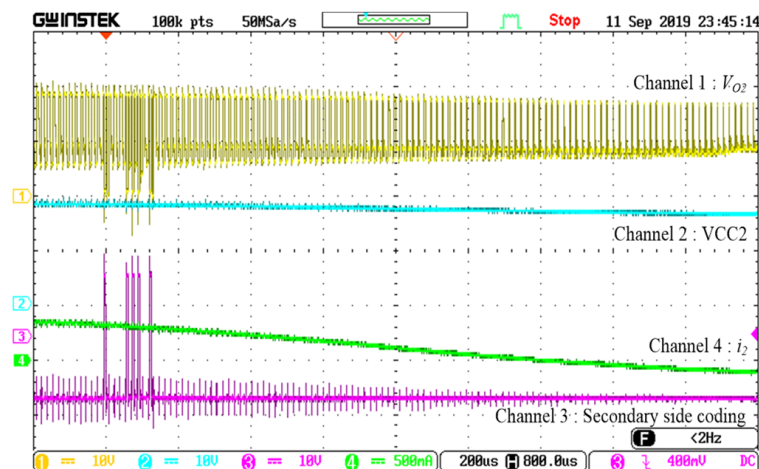


Figure 21. Lighting stability test (M_7 is modulated to M_{10}).

Reducing the number of active switches, soft-switching with zero current and zero voltage, and fitting IEEE-1789 are the tendencies observed in LED dimmable control. Moreover, developing an effective prevention method for the LED thermal runaway is warranted, for example, the addition of a voltage source to a series with LEDs and appropriate adjustment of the source voltage level.

8. Conclusions

In this study, a flyback driver and DC to DC converter were used together with a microcontroller to develop an LED driver with lighting control capability. In the proposed design, the secondary (remote) side can be used for monitoring the environmental status. The sensing signal is transmitted back from the modulated current to the primary (control) side by using a transformer of the driver. The primary side detects the frequency change in the transformer winding and interprets the transmitted signal and then converts the decoding result into the corresponding action to realize output current regulation.

Waveform measurement and real-world experiments were conducted for the complete system to validate that the system can transmit digitized messages by using the primary and secondary windings without affecting the functions of LED brightness adjustment. Compared with previous approaches, the proposed one can integrate sensing information, signal transmission, and driver required for LED lighting control without transmission failure. With the embedded digitized communication capability, we expect that extendible operations can be added to the system for multipurpose applications.

9. Patent

Chun-Liang Lin, Chih-Cheng Huang, Jia-Jing Kao and Hau-Shian Jian, “DEVICE FOR SIMULTANEOUS WIRELESS POWER AND DATA TRANSFER”, Taiwan Patent No. I586070, 2017.

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Conflicts of Interest: The authors declare no conflict of interest.

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