IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

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Volume 12, Number 5, October 2020

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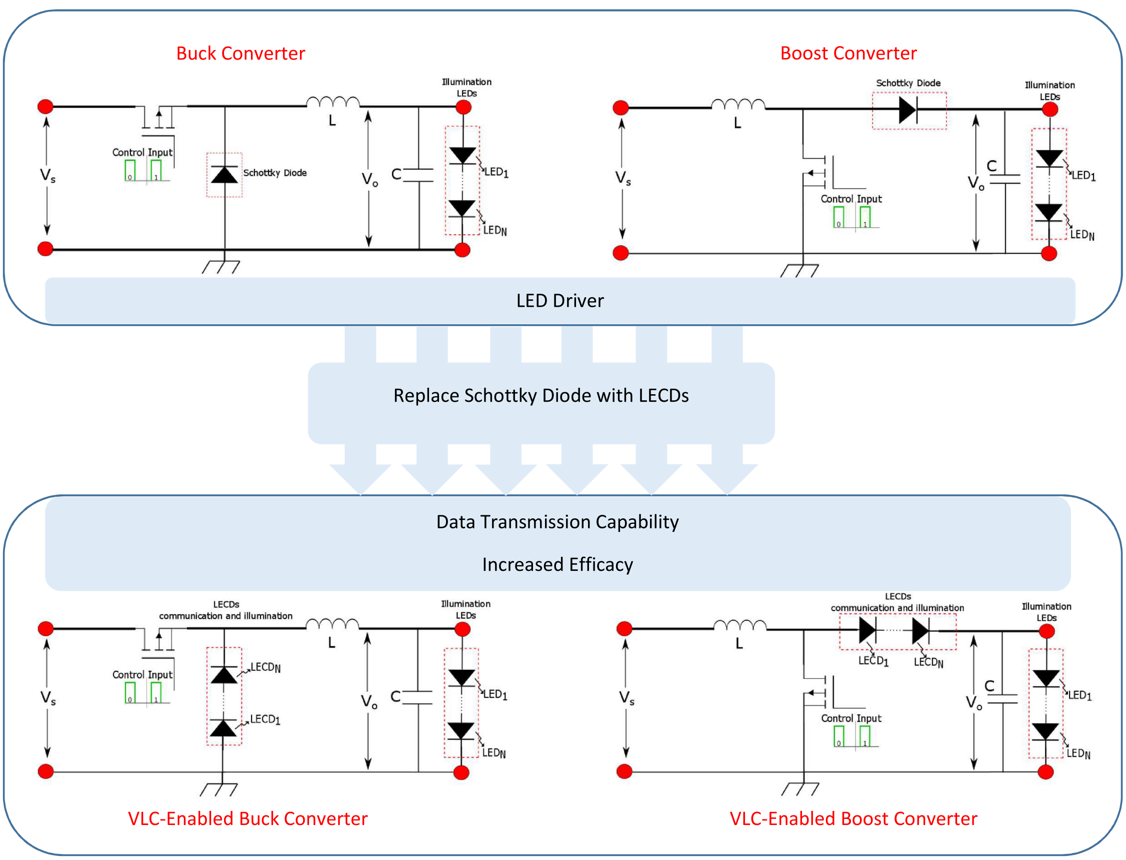

DOI: 10.1109/JPHOT.2020.3020749

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DOI:10.1109/JPHOT.2020.3020749

Manuscript received August 19, 2020; accepted August 24, 2020. Date of publication September 3, 2020; date of current version September 14, 2020. This work was supported by the Natural Sciences and Engineering Research Council of Canada. Corresponding author: Steve Hranilovic (e-mail: hranilovic@mcmaster.ca).

Abstract: Although visible light communication (VLC) systems provide high density links for use in Internet-of-Things (IoT) devices, the design of high rate VLC transmitters that maintain luminaire efficacy is an open problem. In this article, a novel approach to the integration of VLC within light-emitting diode (LED) drivers is proposed through the replacement of freewheeling/blocking diodes with light-emitting devices termed a *light-emitting commutating diodes* (LECDs). In this manner, communications and illumination can be provided using a simple, cost effective design while employing no additional components. The subtle change of LED driver control signals facilitates the transmission of data from LECDs while simultaneously supporting illumination functions. Lighting controls such as dimming are maintained and combined with modulation through the use of overlapping pulse position modulation (OPPM) and performance is quantified. Prototype buck and boost converters with LECDs are implemented and their efficacy is measured. Though current commercial LEDs are not intended for such signalling applications, we experimentally demonstrate their feasibility in this application and suggest methods to make such converters reliable. It is demonstrated that the addition of an LECD improves the efficacy of the luminaire as compared to conventional LED drivers while simultaneously enabling a VLC downlink.

Index Terms: Visible light communications, LED drivers, green communications, Internet-of-Things, luminous efficacy.

1. Introduction

The use of high density, short range, wireless communication links is increasing with the rise of the Internet-of-Things (IoT). The number of wireless connected devices is forecast to continue to increase to a staggering 15.7 billion devices by 2023 [1]. Currently, radio frequencies (RF) are used to establish these links, however, as the number of devices increases, so too does interference. Among the simplest solution to this RF spectral crunch is the adoption of wireless physical layers that do not interact with RF directly such as *optical wireless communications* (OWC).

In parallel, LED luminaires have become ubiquitous in modern lighting solutions due to their advantages in efficacy and lifetime. Solid-state lighting has allowed for visible light communications

(VLC) to develop and provide a method for RF-interference free, high density, communication links. The integration of VLC into LED luminaires is a compelling idea, however, without proper attention the inherent advantages of efficacy and lifetime of LED luminaires deteriorates with the integration of communication functionality.

Power-over-Ethernet (PoE) [2] is an obvious choice to provide both power and data to VLC luminaires [3]. Through the use of PoE, 44–57VDC at powers from 15–100 W can be supplied in addition to Gbps data connectivity [4]. In a typical implementation, the DC power supplied over PoE is input to a step-down DC-DC converter such as a buck converter to ensure the proper current output to the illumination LEDs. It is important to note that while step-down converters may be among the most common converters used, many illumination applications require step-up converters as well. For example, boost converters are used for automotive headlights where many LEDs used in series. VLC-enabled vehicle-to-vehicle communications using LED headlights/taillights has subsequently also become an active area of research [5], [6].

An important aspect of every power electronic device is the *efficiency* (η), which quantifies how well it is utilizing the input power (P_{in}) to convert it to useful output power (P_{out}). This directly depends on the inherent power losses (P_{loss}) in the system. In a luminaire, however, illumination is the primary function. Thus, in the design of a VLC modulator it is essential to quantify the impact on illumination performance, in particular, the *efficacy* of the luminaire measured in lumens/Watt. In other words, the measured useful output is not the electrical power but rather the illumination. As a result, in this work, rather than using efficiency as a metric, system performance is quantified by the luminous efficacy (K_l). That is, for a luminous flux output F from the luminaire, define

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{loss}}} \qquad \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{1a}$$

$$K_l = \frac{F}{F + P_{\text{loss}}} \qquad K_l = \frac{F}{P_{\text{in}}}. \tag{1b}$$

While both (1a) and (1b) measure the ability of a system to convert input electrical power into a useful output, definition (1b) is the most appropriate metric for a luminaire where the useful output is illumination. According to (1b), any increase in the total output lumen flux or reduction in power losses of the circuit while maintaining a constant input power will result in efficacy improvement.

Multiple methods have been proposed to integrate VLC into LED luminaires. Though inefficient, the bias-T is an example of an external modulation approach [7]. Direct modulation of LED outputs has also been proposed (e.g., [8]). While these techniques permit high rate communications, they suffer from reduced efficacy in addition to greater cost. The concept of replacing the commutating diodes in buck/boost converters by illuminating LEDs and short circuiting the output was presented in [9]–[11]. However, this approach maintains high efficacy at the cost of neglecting the capability of the LEDs to provide communication. Another recent approach to this problem is to integrate the VLC modulator within a DC-DC converter in order to preserve efficacy. One approach is to shunt the output LED current using an additional switch [12]–[14]. This design maintains high efficacy and is capable of high data rates, however, output brightness is proportional to the duty cycle of the shunting switch. A variation of this approach uses a switch in series with the illumination LEDs [12], [15]–[17] and has the same trade-offs as the previous case with design challenges caused by the open state of the switch. An additional solution to integrating VLC modulators into LED drivers is the use of pulse width modulation (PWM) to adjust the LED driver duty cycle, thereby slowly varying output brightness. While this approach maintains a desired brightness, is capable of high efficacy, and does not increase component count, its achievable data rates are approximately one tenth of the converter switching frequency [12]–[14]. Recently, in [18], [19] the use of interleaved converters is considered to allow for high efficiency and high data rate communications. By changing the phase of switches within the interleaved converter, data may be transmitted through the ripple produced. The disadvantage of this approach is found in the increased amount of components and complexity.

In this article, a novel method of integrating VLC modulation into LED drivers is presented which achieves constant output brightness while allowing for modulation at the full rate of the

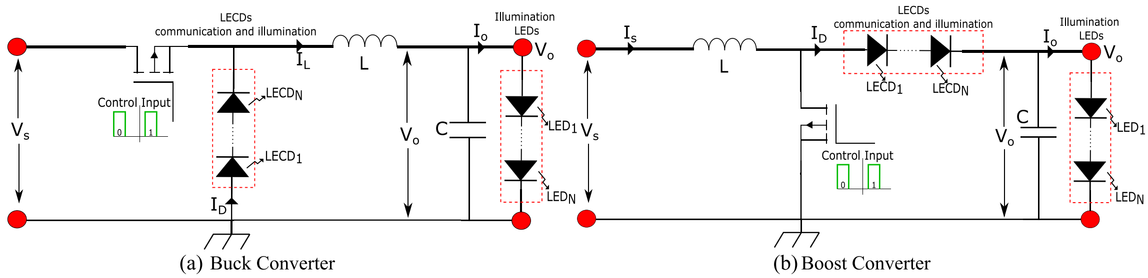


Fig. 1. Simplified circuit diagrams of proposed LECD buck (a) and boost (b) converters.

LED driver switching frequency. As shown in Fig. 1, the freewheeling diode and blocking diode in the conventional buck and boost DC-DC converters respectively are replaced with an LED, termed a *light-emitting commutating diode* (LECD). The energy typically dissipated by the free-wheeling/blocking diode found in LED driver topologies is now utilized to provide communications, leading to an improved efficacy. While replacing the freewheeling/blocking diodes by LECDs to provide data transmission, the illumination LEDs are kept at the output of the driver. This results in a system with *two* output ports of illumination, one of which provides data transmission. Since LECDs contribute to the overall illumination of the system, a desired brightness can be obtained with a lower required current compared to the traditional LED drivers. This yields lower junction temperature in the illumination LEDs which slows LEDs degradation, namely color shift and lumen depreciation which are major concern in all LED drivers [20].

The underlying concept of the topology proposed in [9], where the Schottky diode of the driver is replaced with a white led and the output is short circuited, is similar to that of our earlier conference paper [21] and both were developed simultaneously. However, the concept in [9] was presented for LED drivers solely being used for illumination purposes, aiming to reduce the complexity of the circuit and maintaining a high efficacy. The focus in this paper expands on [9] and considers the integration of VLC into LED drivers considering both illumination performance and for the first time considering and quantifying communication performance. Unlike [12]–[17], the output brightness of the drivers in this work depends only on the duty cycle of the converter and is not limited by any other factor. In contrast to [12]–[14], no limit is imposed on the data rates of communication, since LECDs can be switched up to their nominal frequency. Dissimilar to [18], [19], no increase in either the number of components or the complexity of the circuit is observed. Moreover, unlike earlier designs, driving illumination LEDs with a lower and unmodulated constant current for the same level of luminous intensity will also guarantee better colour quality and life span of LEDs [20]. Unlike [9]–[11] where the entire load current is being supplied by pulsed current, in this work the pulsed current flowing through the LECDs is just a small portion of the load leading to lower EMI and junction temperature. This paper extends our earlier conference paper [21] which considered only buck converters. Here, this concept of LECDs is extended to both buck and boost converters for use as VLC transmitters and further analysis of the systems presents design considerations for various operating conditions as well as communication performance results. It is apparent that many other topologies with such diodes can be altered to achieve VLC and some topologies require both freewheeling and blocking diodes such as forward or flyback DC-DC converters. These topologies may use LECDs in place of a freewheeling diode, blocking diode, or both to provide communications.

In Section 2 the concept of replacing a conventional freewheeling/blocking diode with an LECD is discussed. The electrical operation and design considerations are presented and a method of using LECDs for pulse position modulation (PPM) and overlapping pulse position modulation (OPPM) are explored. In Section 3, experimental results measuring efficacy and communication performance from LECD buck and boost converter prototypes are presented. Finally, in Section 4, conclusions are presented on this approach.

2. Commutating Diodes for Use in Optical Wireless Communications

2.1 Concept

Buck and boost converter topologies were chosen for their simplicity as non-isolated LED drivers capable of constant current for use in indoor lighting applications and car headlights. By maintaining constant current through the inductor, illumination LEDs are able to be driven by constant DC.

Both freewheeling and blocking diodes are necessary for buck and boost converter operation respectively. These devices are typically a source of power loss within these circuits and many LED driver designs attempt to minimize this loss through the use of diodes with low forward bias (e.g., Schottky diodes) or replacing them with a switch (synchronous converter) [22]. In our approach, rather than minimizing loss, the lost power is harnessed to make it useful for enabling optical wireless communications and illumination. This is accomplished by replacing freewheeling and blocking diodes present in standard LED drivers with LECDs.

Energy typically dissipated within a freewheeling or blocking diode is used to provide modulated illumination for VLC. Wavelengths outside of the visible range can also be used, for example, LECDs that produce infrared light allow for OWC invisible to the human eye. The use of LEDs outside of the visible spectrum will not contribute to overall luminous flux of the proposed design and therefore will not benefit from increased efficacy demonstrated later in this article.

The proposed designs are able to modulate VLC signals at the full switching rate of the LED driver while retaining high efficacy. In addition to energy efficient modulation, the designs support a simple method of dimming through the use of PWM. By altering the duty cycle, D, the output power is scaled and the luminaire is dimmed. Finally, the proposed design remains simple and cost effective due to component count being kept the same when compared to a conventional luminaire.

Another advantage to this approach over earlier designs is that LEDs modulated for VLC are separated from illumination LEDs. A major concern for illumination is the degradation of LEDs which leads to colour shift and lumen depreciation [20]. Previously proposed VLC modulators use illumination LEDs to support modulation. Reductions in lifespan, quality of colour, and lumen output are potential disadvantages of these approaches. The separation of communication LEDs and illumination LEDs provides a solution to minimize the effects of supporting VLC on the quality of illumination provided by the luminaire.

By dividing the ratio of illumination LEDs to LECDs appropriately, it is possible to overcome the problem of low reverse bias voltage of a LED. The number of LECDs and illumination LEDs can be divided simply by choosing a different ratio of LEDs within a buck converter or changing the placement of the output capacitor in a boost converter. The number of illumination LEDs determines the required output voltage and also determines the reverse biasing of LECD(s) in boost converters.

2.2 Electrical Operation and Design Considerations

Replacement of freewheeling and blocking diodes with LECDs cannot be done without careful assessment of the consequences of replacing a conventional diode with an LED. Various elements of converter operation are affected and must be understood to produce a luminaire supporting VLC through use of an LECD.

LECDs in buck converters are reverse biased by V_s as shown in Fig. 1. Although reverse biasing may be problematic for LECDs as they are typically not designed to be driven in this manner (e.g., [23]), their capability to be reverse biased is already tested and verified in [9]. In cases where reverse breakdown of the LECD is low in comparison to desired V_s, $N > 1$ LECDs can be used in series to combat relatively high reverse bias voltage. Similarly, boost converter operation relies on LECDs being reverse biased, however, they are reverse biased by V_o instead of V_s. In the case of buck converters, input voltage V_s is larger than output voltage while V_o in boost converters is the largest voltage present in the circuit. This implies that LECDs must handle the largest potentials found in each topology in reverse bias.

Additionally, the forward voltage drop for LECDs is typically larger than conventional diodes. A conventional diode may have a forward voltage of approximately 0.7 V, while a conventional high power white LED will be in the range of 3V [23]. To denote this difference, when referring to V_f of LECDs, V_f^{LECD} will be used. This increased forward voltage yields two major design considerations: the impact of forward voltage on efficacy and the maximum achievable output voltage.

Our proposed topology contributes to the efficacy of the driver in two aspects. First, the power delivered to the LECDs, unlike the power consumed by a switching diode, cannot be termed as a dissipating power, since it is being used for illumination and communications. As a result, the power loss in the circuit is reduced and the total luminous flux is increased simultaneously, both of which contribute to the efficacy according to (1b). In fact, the only remaining losses of the circuit will be switching losses of the MOSFET [24]–[26] and some conduction losses due to the small resistance of the inductor. Second, as a result of the compensation done by the LECDs in terms of illumination, the desired level of lighting can be obtained with a lower current flowing through the converter as compared to conventional topologies. This will reduce power loss in every element of the converter, indicating a better overall efficacy.

The use of N LECDs will also affect the output voltage control. Using N LECDs in series impacts the output voltage of a buck and boost converter respectively as,

$$V_o = V_s D - (1 - D) N V_f^{\text{LECD}}, \tag{2a}$$

$$V_o = \frac{V_s}{(1 - D)} - N V_f^{\text{LECD}}. \tag{2b}$$

To derive (2a) and (2b), a constant current through the inductor and a large output capacitor for constant V_o were assumed. These equations demonstrate that V_f^{LECD} reduces the achievable V_o, however, the existing LECDs will compensate for the illumination as long as the output voltage is large enough to forward bias all illumination LEDs in the case of using multiple illumination LEDs in series. This changes the selection of duty cycle D to yield a desired output illumination. To achieve the same V_o and I_o, as the base case buck or boost converters, higher values of D must be used in converters using LECDs. However, this is not an issue since LECDs provide illumination in addition to communication signals. This results in an LED driver that can employ lower values of V_o and I_o to achieve the same illumination as the base case.

Use of multiple LECDs also results in higher losses and lower output range. Therefore, unless required, for the greatest efficacy and output range the number of LECDs used should be minimized. If dimming is not required and lower efficacy is acceptable, a greater number of LECDs may be used to improve communications performance by transmitting greater optical power.

2.3 Communicating With LECDs

Previous designs for VLC modulators introduce a modulated signal superimposed onto the constant (i.e., DC) driving signal required for illumination. By implementing a VLC modulator using LECD(s), the LEDs used for communications and those for illumination are separated.

For simplicity, the modulation schemes considered here are restricted to pulse position modulation (PPM) and overlapping pulse position modulation (OPPM)[27]. PPM and OPPM work well to modulate LECDs because information can be sent for any combination of D and amplitude and avoid any flicker in the output light.

Define M as the modulation order and T as the symbol period. For duty cycle $D > \frac{M-1}{M}$ the symbols are sent as PPM, while for smaller D the pulses must overlap giving rise to OPPM. Data are transmitted by varying the periodic nature of I_D by changing the position of the on-time during each period of T seconds via PPM or OPPM. Note that the freewheeling or blocking diode conducts during the non-conducting phase of the switch. Manipulating the control switch conduction interval to alter the position of the I_D current pulse in T using PPM or OPPM modulates the light emitted by the LECD thereby transmitting a VLC signal. Note that the current flowing through the freewheeling diode, I_D, in its conducting periods is the same as the inductor current, I_L.

To enable dimming for LECD converters, D can be set to a lower value. This will yield lower V_o and I_o, resulting in I_D with a reduced peak amplitude flowing for a longer time in the diode. Once a

TABLE 1
Experimental Parameters

V_s	40 V (Buck) 12 V (Boost)
f_{sw}	400 kHz
Max. Load Current, I_L	300 mA
Switch	IRLML0060TRPBF
Inductor	2 mH
Capacitor	1μF
Illumination LEDs	Lumiled 3535L
Freewheeling Diode / Blocking Diode	1N4148 (base case) Lumiled 3535L (LEFD) CREE XLamp XP-E2 (LEBD)

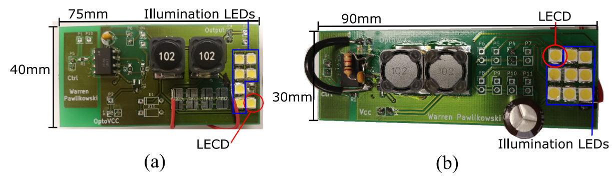


Fig. 2. Experimental LECD buck (a) and boost (b) converter prototypes.

desired dimming level is set, *D* should be kept constant to maintain a desired brightness. This will also maintain a constant state for receiving the signals from communicating LEDs. Changes in *D* of LECD converters will affect communications performance as a result of changing LECD pulse width and amplitude. The greatest communications performance will be present for high *D* and is due to resulting LECD pulses having less overlap with adjacent symbols in addition to greater amplitude. This will also determine the modulation order that is viable depending on required communications performance.

3. Experimental Results

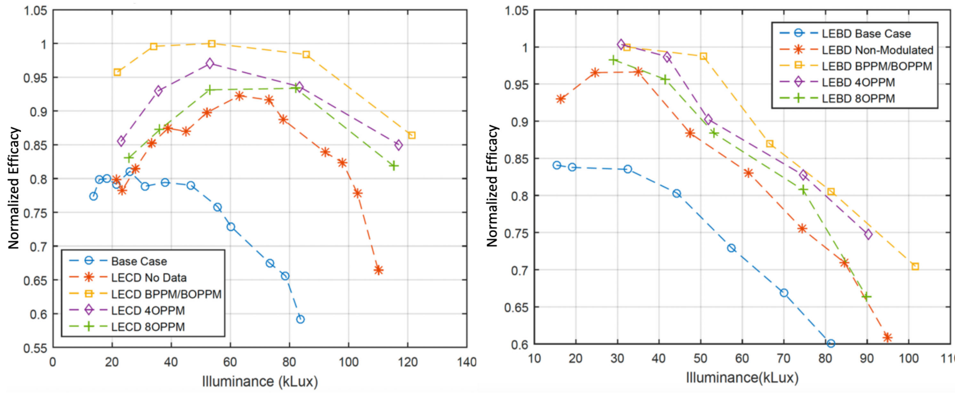
3.1 Experimental Setup

The parameters and components used for the experimental setup are tabulated in Table 1. Component values were based on similar commercial designs used in practice for indoor lighting [28]. The LEDs used were white Philips Lumiled 3535 L or CREE XLamp XP-E2. Although these devices are not intended to be operated in reverse bias, our testing of 20 LEDs each illustrated a reverse breakdown of approximately 40 V to 45 V (well above the given value on the data sheet and noted in [29]). Due to reverse breakdown voltage, source voltage used for experimental measurements was limited to 40 V.

Fig. 2(a) and (b) display photographs of the LECD prototypes used to characterize and determine performance of buck and boost converter designs.

Communicating and illumination LEDs are identified within the LED array. The modulated optical signal from the LECDs is summed spatially with the illumination LEDs causing an easily removed DC shift via high pass filter at the receiver.

Experimental buck and boost converter results were completed using a single LECD.The experimental luminaires were modulated to test communications in addition to quantifying efficacy. Random sets of data were created comprised of a binary BPPM/BOPPM, two bits per symbol 4-OPPM, and three bits per symbol 8-PPM. BPPM was used for the case of tests that resulted in $D \geq 0.5$ and BOPPM was used when $D < 0.5$. For further tests of higher order, OPPM was used due to the larger size of transmitted constellation. The data were saved into a ROM of a DE0-Nano FPGA [30] and converted into an appropriate control signal.This signal was applied to the switch of each converter through a 6N137 opto-isolator.The signal output from the opto-isolator was probed via a Teledyne Lecroy Wavesurfer 3024 to capture the sent sequence prior to being affected by the transmitter, channel, or receiver.



(a) (b)

Fig. 3. Experimental normalized optical efficacy of the Base Case, LECD (a) buck (b) boost design non-modulated, LECD design modulated by BPPM/BOPPM, 4-OPPM, and 8-OPPM.

To test communications, light from the LECD was combined with illumination LEDs via the THORLABS DG20-1500 diffuser and captured by the THORLABS PDA36 A photodiode with a 1 inch aperture and an adjustable gain initially set to 10 dB as shown in Fig. 4. The luminaire was placed 110 cm from the photodiode along the optical axis. After the waveforms were collected from the oscilloscope, they were saved and analyzed with MATLAB. Additionally, the signal persistance function within the oscilloscope was utilized to create eye diagrams for each modulation order. To improve received waveforms and reduce the effects of ambient light, eye diagrams and sample waveforms were collected using a THORLABS LB1761 bi-convex lens in front of the photodiode.

Experimental measurement of efficacy was accomplished by using a multimeter and integrating sphere. To monitor P_{IN}, voltage and current from the DC supply was monitored with a multimeter. In order to quantify the optical output, the illuminance, E_V, was measured using the Extech Instruments Model HD400 lux meter and normalized. Through the combination of the integrating sphere and the fixed area of the lux meter detector, a normalized measure of optical efficacy was made. The normalized optical efficacy used to contrast with simulated efficacy curves is defined as

$$\eta'_O = \frac{E_V/P_{in}}{E_V/P_{in}|_{BCmax}}. \tag{3}$$

where $E_V/P_{in}|_{BCmax}$ is the maximum value of illuminance measured for the base case and the quantity used to normalize optical efficacy.

3.2 Experimental Efficacy

Efficacy using LECDs is shown to be improved over the base case of both LED driver topologies under all modulation orders as demonstrated by Fig. 3.

It is apparent that the LECD contributes a significant amount of illumination compared to power consumed. Additionally, both LECD converters produce more light for a given operating condition when compared to the base cases. Due to this, a luminaire can be designed to operate at lower current, with higher efficacy, and produce the same luminous flux, resulting in a lower junction temperature of the LED which leads to a longer life span.

In the cases where PPM or OPPM symbols are at either extreme of the period, two switching cycles are removed as illustrated in Fig. 5.

On average, for BPPM/BOPPM the amount of switching transitions is reduced by a half. Switching losses of the LECDs in addition to other switching losses are therefore reduced resulting in higher efficacy. As higher order modulation is used, the likelihood of removing switching transitions

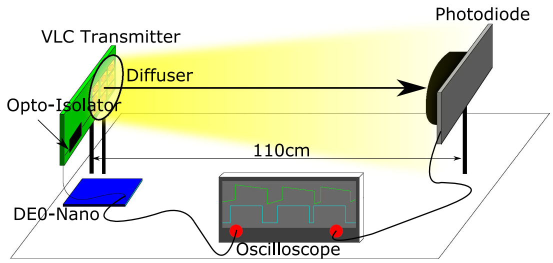


Fig. 4. Diagram demonstrating the experimental setup to collect experimental communication results.

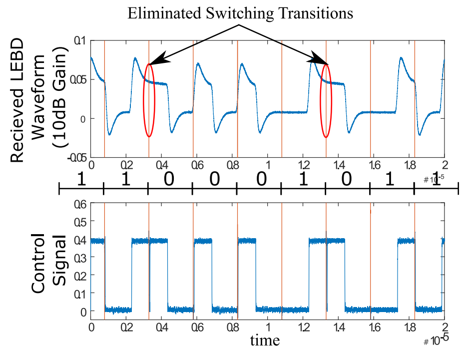


Fig. 5. Experimental BPPM waveform demonstrating the elimination of switching transitions.

is reduced resulting in lower efficacy. Therefore for a system capable of the greatest efficacy, BPPM/BOPPM should be used as this maximizes the amount of switching transitions saved. However, efficacy of the proposed design is still improved over the base case for orders of PPM and OPPM that make the elimination of switch transitions unlikely.

3.3 Experimental Communication Results

Initially, transmitted waveforms were visually inspected to verify that the control circuit generated appropriate waveforms that were sent and received (e.g., see Fig. 5). The received signals for the buck converter were heavily distorted by a resonant frequency above that of f_{sw}. This was determined to be caused by parasitic capacitance present in the PCB layout. Design of the boost converter was completed after tests of the buck converter and LECDs. Additionally, due to higher drive current, boost converter waveforms are received at greater amplitudes compared to those of the buck. Received waveforms of LECD driver lag in time due to the presence of the inductor. Resultant lag quantities are based upon the size of the inductor.

Fig. 6 presents a sample 8-OPPM eye diagram for the boost converter using an LECD and a $D = 0.5$. Although the data are overlapping, they are all distinct and the eye is open, indicating that the transmission can be done with a good SNR.

It can be seen that the amount of noise present is small relative to the amplitude of the signal. The eye diagram testing 8-OPPM is not impacted by jitter and timing issues. For lower D, eye diagrams will close as the amplitude is reduced and overlap of signals is increased.

As the order of PPM is increased and lighting is dimmed through a reduction in current, overlaps of OPPM symbols increases, and therefore eye diagrams deteriorate and symbol transitions become more difficult to differentiate. This results in more errors when demodulating for dimmed luminaires and an eye diagram that is closing and overlapping with other signals more.

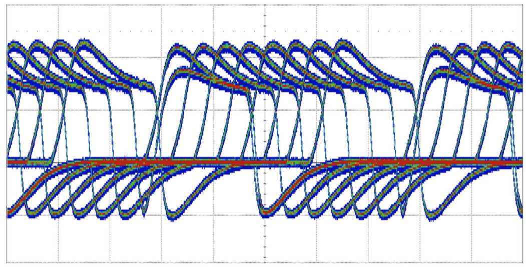


Fig. 6. Example eye diagram of LECD boost topology modulated by 8-OPPM. Amplitude and time divisions set to 10 mV / div and 500 ns / div respectively.

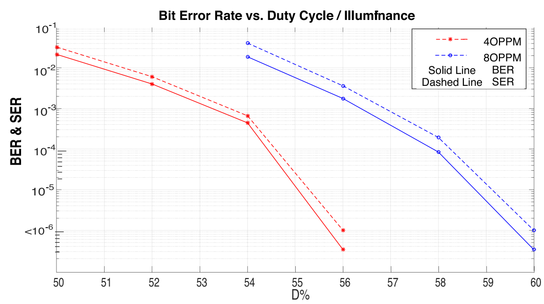


Fig. 7. Symbol error rate (SER) and bit error rate (BER) curves for 4-OPPM and 8-OPPM at reduced intensity.

One million symbols were sent at various duty cycles in order to produce symbol error (SER) and bit error rate (BER) curves. These curves are shown in Fig. 7 for 4-OPPM and 8-OPPM with a setup shown in Fig. 4.

As previously stated, received symbols deteriorate for decreased D, resulting in higher SER and BER as illustrated in Fig. 7. Increasing modulation order will further deteriorate sent signals as symbols will overlap more and become more difficult to differentiate. Therefore, pulses of higher amplitude with less overlap (greater D) are required to achieve the same SER and BER as lower order modulation schemes. This is demonstrated by the comparison of 4-OPPM and 8-OPPM in Fig. 7 where 8-OPPM requires a D of the LECD boost converter to be approximately 7% higher than necessary for the same error rate of 4-OPPM. It should be noted that in the particular experiment, small distances, large receiver apertures and sensitive receivers yield a high signal-to-noise ratio (SNR) communication channel making this change less apparent. When SNRs are reduced by increasing range or using smaller receiver apertures (e.g., as in a mobile phone receiver), the change of system performance in M and D will be more notable though following the same trends. Notice also that if a specific minimum SER or BER is targeted, as the luminaire is dimmed, it may be necessary to decrease the order of modulation used to maintain the desired error rate. As the luminaire is dimmed beyond a certain point, the achievable rate may necessarily be reduced. This is accomplished via a simple change of the control signal of the proposed design.

Data rates of 800 kbps and 1.2 Mbps were achieved by the experimental LECD buck and boost LED drivers using 4-OPPM and 8-OPPM respectively with a switching frequency of 400 kHz. These performance levels should be viewed as a proof-of-concept for this joint illumination and communication topology.

4. Conclusion

This work have demonstrated power converter topologies for buck and boost converters which use LECDs to simultaneously improve illumination performance while providing VLC communication links with rates proportional to converter switching frequency and modulation order. This has been achieved without the need for complex control systems or increased component counts (e.g., [18], [19]), without inherent limits to the rate at which LEDs can be modulated (e.g., [12]–[14]) and without using inefficient linear amplifiers.

By experimentally demonstrating the proposed changes in both buck and boost converter topologies, the use of LECD(s) has been shown to be a viable solution to implementing VLC within LED drivers in a wide range of applications. Through simple extensions of this work, converter topologies that include galvanic isolation such as forward or flyback converters may also take advantage of LECD(s) for freewheeling/blocking diodes or both. The approach presented in this paper has demonstrated support for dimming and has the advantage of separating LEDs used for communications and illumination, hence preventing the color shifting and preserving the life span of the illumination LEDs. The designs proposed and tested offer a compelling combination of improved efficacy and high rate communications without increasing component count for future IoT VLC transmitters.

The experimental results presented here should be viewed as a proof-of-concept for power converter topologies with LECDs. In order to move to a practical commercial VLC system additional elements such as modulation design, coding and pre- and post-equalization should be applied to overcome the data rate limits imposed either by the limited bandwidth of the LEDs or the modulation scheme. Thought PPM was selected here for its simplicity and ease of demonstration, future work on extending to more advanced modulation techniques will be required to maximize the data rate of the system.

As future work, data rates may be increased by replacing the MOSFET switches used in this experiment with high frequency GaN devices [17] to further improve the switching frequency which directly leads to an increased data rate of the system. Additionally, higher speed micro-LEDs [31] can be employed for LECDs to improve the bandwidth limit imposed by commercial phosphor-coated LEDs.

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