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Taking advantage of the sum of the light in outphasing technique for visible light communication transmitter

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Abstract:

Visible Light Communication (VLC) takes advantage of the widespread use of the LEDs, and by modifying the driver stage, the LEDs are capable of lighting and transmitting information. One of the main drawbacks is the low power efficiency due to the modification of the LED driver stage in order to add the communication capability. Most of the research work related to VLC is towards the communication task, whereas there is a limited work about the improvement on the power efficiency. This paper proposes a high efficiency LED driver for VLC working as a transmitter based on the outphasing technique. This technique is used also in RF communications and increases the efficiency of the amplifiers. The proposed transmitter is made up of two switching-mode power amplifiers that reproduce the signals required for the outphasing technique and a DC/DC converter that biases the LEDs. The proposal exploits the light and, instead of being added electrically, the signals are added in their light form, which leads to a reduction in the complexity of the design. As experimental results, a transmitter was built of two Class E amplifiers reproducing a 16-QAM modulation, achieving a signal-generation efficiency of 78% and an overall efficiency of 92%.

***Index Terms*—Visible Light Communication (VLC), Wireless Communication, high-brightness LEDs (HB-LEDs), Class E Amplifier.**

I. Introduction

Almost all wireless communication is currently based on the use of the Radio Frequency (RF) spectrum, which leads to high congestion and stringent regulation [1]. A number of novel techniques have thus been developed over the last few years in order to circumvent these issues. One of these alternatives is Visible Light Communication (VLC) [2]–[4], which uses the broad, unregulated visible light spectrum (from 430 to 750 THz). VLC goes hand in hand with the widespread use of LED technology for Solid-State Lighting (SSL) applications by exploiting the fast light modulation capability of LEDs.

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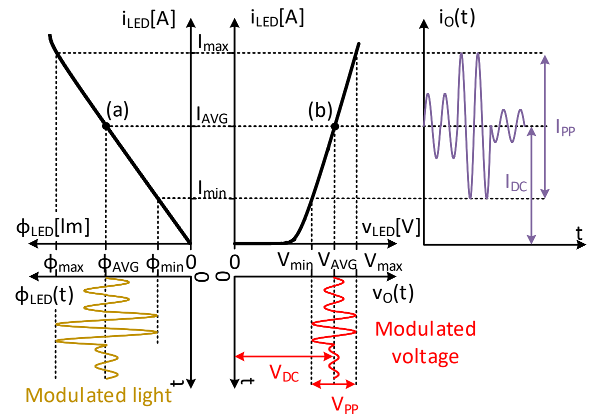

Figure 1: A HB-LED working as a VLC transmitter in its current/voltage and light/current relation.

The main idea behind VLC is the use of the SSL infrastructure to perform the lighting and communication task at the same time. SSL is almost entirely based on blue gallium nitride High-Brightness LEDs (HB-LEDs) in combination with a phosphor layer to conform the white light spectrum. The blue LEDs can achieve a bandwidth of up to 20 MHz, however the bandwidth is reduced to 3-5 MHz due to phosphor effect [5], [6]. The available spectrum can be increased by using Red-Green-Blue (RGB) HB-LEDs in which each color can achieve the 20 MHz bandwidth, since no phosphor is required, and it creates three independent communication channels [7], [8]. Even though the RGB HB-LEDs can achieve a much higher bandwidth, the necessity of a much complex driver stage (one driver for each color) and an additional control for the color temperature make the RGB HB-LEDs harder to control hence less suitable for VLC.

Figure 1 shows the current vs voltage and the light vs current relations on the HB-LED. In order to fulfill the illumination task, an average voltage, V_{AVG}, is applied across the HB-LED in order to bias it, which leads to an average current, I_{AVG}, flowing through the HB-LED, emitting an average light intensity, Φ_{AVG}. The communication task is performed via a variation around the average value. For example, a communication signal is applied as a voltage and it changes its amplitude (varying between V_{MIN} and V_{MAX}) and its

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phase. This signal leads to a proportional variation of the current through the LED (between I_{MIN} and I_{MAX}) and of the light emitted by the LED (between Φ_{MIN} and Φ_{MAX}). It should be stressed here that two different efficiencies are taken into account, as each task can be performed by different circuitry: signal generation efficiency and overall efficiency. The signal generation efficiency only takes into account the efficiency of the communication circuitry, while the overall efficiency takes into account the combined efficiency of both the communication and biasing circuits.

As one of the main advantages of SSL is its high efficiency, adding the communication capability should not deteriorate the overall efficiency of the system excessively. Over the last few years, a number of VLC transmitter topologies have been proposed in which a linear power amplifier performs the communication task (i.e. Class A, B or AB) [9]–[11]. Most of these research works are towards increasing the bit-rate, more complex modulations or communication schemes, etc. This leads to a low power efficiency of the system due to the low signal efficiency of the power amplifiers. The theoretical maximum is 50% for Class A and 78.5% for Class B, but the efficiency drops significantly for a complex non-constant amplitude modulation (i.e. for a 16-QAM digital modulation, the maximum efficiency is 27% for Class A and 43% for Class B [12]).

On the other hand, the use of DC-DC converters as a VLC transmitters has been proposed to increase the power efficiency of the system [13]–[19]. The DC-DC converter generates the bias and the communication signal at the same time, reaching an overall power efficiency higher than 90 % (communication and biasing task), although the disadvantages comprise the limitation on the maximum communication bandwidth, the high complexity of the DC-DC topologies and their complex control techniques.

Due to the drawbacks of both proposals, an adaptation of the well-known outphasing technique for VLC is proposed in this paper. The outphasing technique was first propossed in the 30s [20], [21] as a method to increase the efficiency of the RF amplification stage when the amplitude of the RF sine signal is not constant. Outphasing is based on the idea of splitting a non-constant amplitude sine signal into two phase-modulated sine signals with constant amplitude, and performing the amplification task over the latter sine signals. As linear amplifiers (i.e. Class A, B or AB) and resonant switching-mode amplifiers (i.e. Class E) can only achieve their maximum efficiency when the amplitude of the signal is constant, the efficiency of the amplification stage is improved by keeping the amplifier working in its maximum efficiency working point.

This paper presents a VLC outphasing transmitter based on two Class E amplifiers. Each Class E amplifier reproduces one of the two constant amplitude sine signals required for the outphasing. This proposal is based on the same idea as the original outphasing technique, but by exploiting the light intensity as a communication signal. The proposed light-outphasing technique adds the two sine signals in their light form instead of electrically. Using the light to sum the phases leads to electrical isolation between each Class E amplifier,

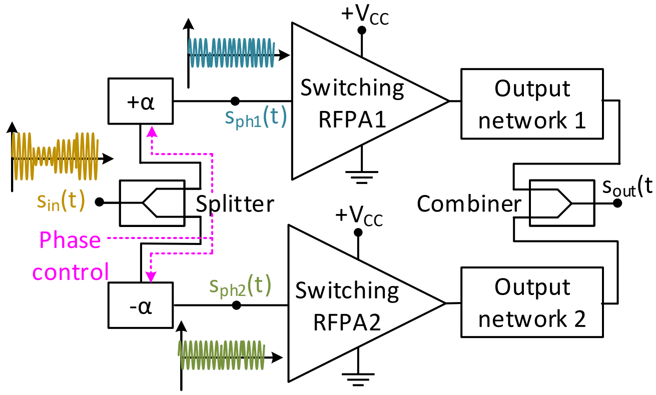

Figure 2: Block diagram of an outpahsing RFPA made up of a splitter, two RFPAs and a combiner.

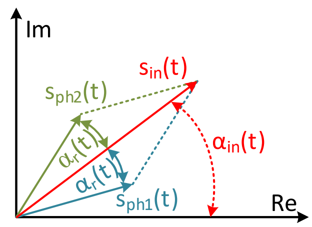

Figure 3: Phasor diagram showing the amplitude and phase relation in the outphasing technique.

which strongly simplifies the design of the overall transmission system. As experimental results, a transmitter was built to transmit a 16-QAM digital modulation with a 5 MHz carrier, achieving a bit rate of up to 4 Mbps and at a distance of up to 0.7 m. The prototype achieves an electrical efficiency of 78% in signal generation (higher than the Class A and B maximum efficiency for a 16-QAM modulation) and 92% overall efficiency when the communication and lighting tasks are taken into account (of the same order as DC-DC converter alternatives).

The paper is organized as follows. First, a brief explanation of the outphasing technique is given in Section II. Its adaptation to VLC and simplification is then explained in Section III. Section IV presents the prototype design and the experimental results regarding efficiency and communication capability. Finally, Section V provides the conclusions.

II. Operating Principle of the Outphasing Technique

Figure 2 shows the traditional outphasing implementation for RF power amplifiers. It comprises a signal splitter, two Radio Frequency Power Amplifiers (RFPA) and a combiner.

A. Outphasing mathematical analysis

For the sake of simplicity, the communication signal, $s_{in}(t)$,

$$s_{in}(t) = a_{in}(t) sin[2\pi f_s t + \alpha_{in}(t)] \tag{1}$$

is a sine signal that varies its amplitude, $a_{in}(t)$, and phase, $\alpha_{in}(t)$. From $s_{in}(t)$, the signal splitter generates the two constant amplitude phase-modulated sine signals, $s_{ph1}(t)$ and $s_{ph2}(t)$,

$$\begin{aligned} s_{ph1}(t) &= A_{ph} sin[2\pi f_s t + \alpha_{ph1}(t)], \\ s_{ph2}(t) &= A_{ph} sin[2\pi f_s t + \alpha_{ph2}(t)], \end{aligned} \tag{2}$$

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whose addition is $s_{in}(t)$, both of which have the same frequency, f_s. Both signals also have the same constant amplitude, A_{ph}, and phases $\alpha_{ph1}(t)$ and $\alpha_{ph2}(t)$, respectively, which vary over time, as shown in Fig. 3. At this point, and because of the constant amplitude of s_{ph1} and s_{ph2}, the RFPAs can be designed to operate at the point with the highest efficiency, hence increasing the overall efficiency of the system.

Assuming that both RFPAs have the same gain, k, the signals after the amplification are ks_{ph1} and ks_{ph2}. Seeing as the output signal, $s_{out}(t)$, is defined as

$$s_{out}(t) = ks_{ph1} + ks_{ph2}, \tag{3}$$

the phase of $s_{out}(t)$ is the same as that of the input signal, $s_{in}(t)$. The phases $\alpha_{ph1}(t)$ and $\alpha_{ph2}(t)$ can be written as a function of $\alpha_{in}(t)$ and a relative phase, $\alpha_r(t)$

$$\begin{aligned} \alpha_{ph1}(t) &= \alpha_{in}(t) - \alpha_r(t), \\ \alpha_{ph2}(t) &= \alpha_{in}(t) + \alpha_r(t), \end{aligned} \tag{4}$$

while the amplitude, $a_{out}(t)$, can be obtained as a function of $\alpha_{ph}(t)$ by trigonometry.

$$a_{out}(t) = 2kA_{ph}cos[\alpha_r(t)], \tag{5}$$

The output signal is thus defined as follow:

$$s_{out}(t) = a_{out}(t)sin[2pif_st + \alpha_{in}(t)], \tag{6}$$

In conclusion, the amplitude $a_{out}(t)$ depends on the relative phase $\alpha_r(t)$, the gain k of the RFPA and the amplitude A_{ph}, and the phase of $s_{out}(t)$ is equal to the input phase $\alpha_{in}(t)$. The output amplitude $a_{out}(t)$ and phase $\alpha_{in}(t)$ are independent parameters that can be controlled by phases $\alpha_{ph1}(t)$ and $\alpha_{ph2}(t)$.

III. Light-Outphasing technique for VLC transmitters

The major difficulty in an outphasing RFPA is the design of the output combiner, which is in charge of connecting the two amplifiers together and summing the sine signals. The connection of the outputs of the RFPAs is not straightforward due to the fact that the output impedance of each RFPA changes over time according to the output voltage, leading to a undesirable influence between them [22]. The outphasing technique can be implemented using linear RFPA (i.e. Class A and B), as it was first proposed, or switching RFPA (i.e Class D and Class E). The efficiency of the outphasing technique with linear RFPA can be increased up to the maximum of each class (50% for Class A and 78% for B), whereas in the case of switching RFPA the maximum is theoretically 100%. On the other hand, the cross-effect between the amplifiers due to the output combiner is especially critical when the RFPA is based on a resonant topology (i.e., Class E), in which the efficiency depends on proper tunning of the resonant circuit. Therefore, in the case of the outphasing technique, each resonant circuit is modified by the output impedance of the other amplifier. The analysis and design of the combiner has previously been carried out in [22]–[24], leading to complex mathematical analysis and circuitry regarding the efficiency and bandwidth of the system.

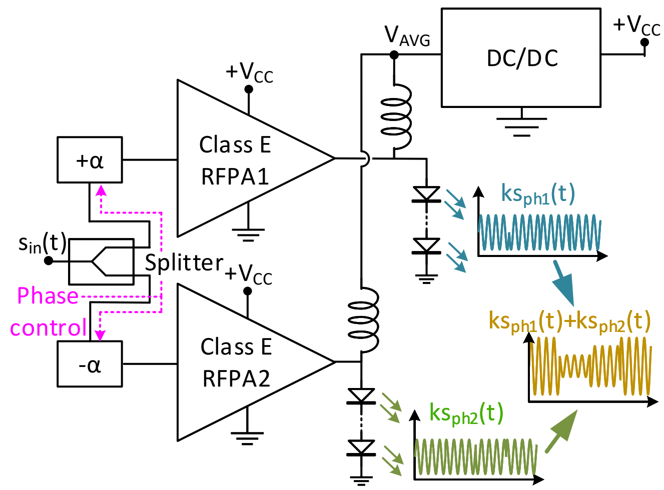

Figure 4: Block diagram of a light-outphasing amplifier.

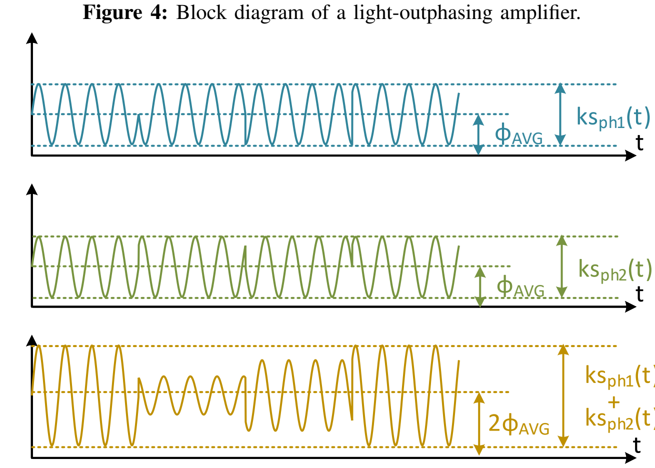

Figure 5: Output signals in a the light-outphasing circuitry.

Another key part of the outphasing technique is the input splitter and the phase control. This is in charge of generating the input signals for each RFPA, whose sum is the desired output communication signal. In the case of the switching RFPA, this splitter and phase control can be implemented in a digital platform since the input signals for these amplifiers are square waveforms. In the case of linear amplifiers, the splitter and phase control has to be implemented over the analog signals, increasing the difficulty of the implementation. Table I summarizes the characteristics for the outphasing design regarding the RFPA used.

Table I: COMPARISON BETWEEN THE IMPLEMENTATION OF DIFFERENT AMPLIFIERS IN THE OUTPHASING TECHNIQUE.

	max η	Design difficulty	
		Splitter	Combiner
Class A	50%	High	Medium
Class B	78%	High	Medium
Class D	100%	Medium/High	Medium
Class E	100%	Medium	High

The idea of light-outphasing is that of splitting the LED load between the two RFPAs and summing the two sine signals in their light form, as can be seen in the block diagram in Fig. 4 and in the output light signals in an example in Fig. 5. As the quantities added are two light intensities instead

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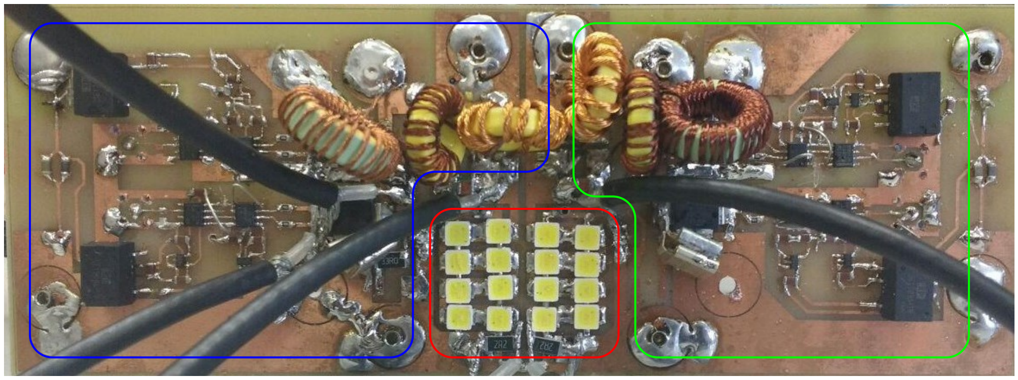

Figure 6: Prototype of the outphasing transmitter made up of two Class E amplifiers. *Light-Outphasing*.

of two electrical signals, the need to use a combiner and connect both amplifiers electrically is circumvented, leading to a huge simplification of the design and avoiding the influence between the output of both RFPAs (with the resulting increase in efficiency). Because of this, the main disadvantage of the use of Class E amplifiers in an outphasing design is avoided. Another simplification is the possibility of implementing the input splitter in a digital platform, such as an FPGA that generates the square signals required for the control of both Class E RFPA. Another possibility would be the use of a Class D RFPA instead, but the necessity of two switches for each amplifier (increasing the switching losses and the number of control signals required) does not justify its use. The load of each amplifier is an LED string and, as it was said before, it has to be biased. Both strings are connected though an inductor to an external DC/DC converter that controls the biasing point (V_{AVG} and I_{AVG}). The VLC transmitter comprises two Class E RFPAs delivering the two signals, $s_{ph1}(t)$ and $s_{ph2}(t)$, required for outphasing. As the outputs of the Class E amplifiers are not connected together and the load is an LED string, the impedance sees by the amplifiers is known and constant, therefore the condition of Zero Voltage Switching (ZVS) of each amplifier does not depend on the other RFPA, thereby simplifying the overall design. In a typical VLC system, the LED strings is connected using a bias T [25]. The bias T is used to connect the amplifier and the DC/DC together, blocking the DC component to go to the amplifier (using a series capacitor) and the signal components to go to the DC/DC converter, using an inductor. As it is shown Figure 4, there is no path between the strings at high frequency, meaning that the assumption that there is no influence between the amplifiers is still right. On the other hand, due to the intrinsic resonant output filter of the Class E, the DC blocking is already implemented in each amplifier, so there is no need for an additional series capacitor between the amplifier and the LED strings.

IV. Experimental results

In order to test the concept of the light-outphasing technique, a prototype of an outphasing VLC transmitter comprising two Class E RFPA is shown in Fig. 6. Both Class E RFPAs are designed identically and each amplifier is connected to an independent LED string each made up of 8 *XLamp MX-3* LEDs. Each LED has a dynamic resistance of 2.2 Ω, making up a total load of R_L = 17.6 Ω for each string.

The strings are biased externally by a DC-DC converter that controls the average current through the LED string ($I_{AVG} = 0.25A$). Controlling the average current across the strings ensures that the LED always works in its linear region regardless of the threshold voltage shift due to possible temperature changes in the LEDs. This allows the amplifier to apply the communication signal within the linear region of the LED, avoiding undesirable distortion near the threshold voltage.

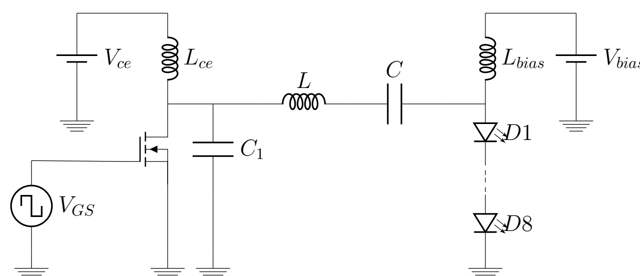

Figure 7: Class E RFPA circuit.

A. Modulation Scheme

In order to evaluate the communication task, a 16-QAM digital modulation with a carrier frequency of 5 MHz was used. Each symbol of the modulation represents 4 bits and lasts 5 signal periods, providing a bit rate of 4 Mbps. One important aspect of the communication is the estimation of the necessary bandwidth BW of the modulation. According to [26], a rough estimation of the minimum BW_{min} of the modulation

$$BW_{min} = \frac{2}{T_s} = 2MHz \tag{7}$$

where $T_s = 1\,\mu s$ is the symbol period.

In the figure 8, the constellation diagram of the 16-QAM modulation is shown. Each symbol has a different amplitude

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and phase that are coded using 4 bits as it is shown in the Table II.

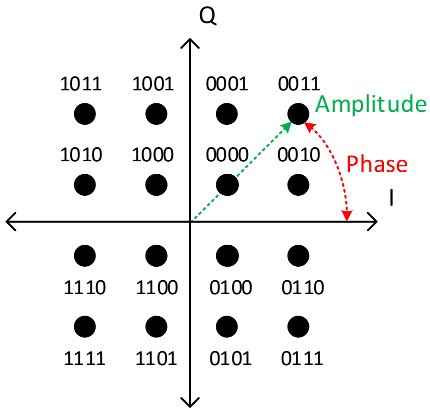

Figure 8: 16-QAM constellation diagram.

Table II: LIST OF PARAMETERS OF THE 16-QAM MODULATION AND THE OUTPHASING TECHNIQUE

Code	0000	0010	0011	0001	1000	1010	1011	1001
Amp	0.33	0.75	1	0.75	0.33	0.75	1	0.75
Phase[°]	45	18	45	72	135	108	135	162
α_r[°]	71	42	0	42	71	42	0	42
α_{ph1}[°]	-26	-23	45	30	64	67	135	120
α_{ph2}[°]	116	60	45	113	206	150	135	203
Code	1100	1110	1111	1101	0100	0110	0111	0101
Amp	0.33	0.75	1	0.75	0.33	0.75	1	0.75
Phase [°]	225	198	225	252	315	288	315	342
α_r [°]	71	42	0	42	71	42	0	42
α_{ph1} [°]	154	157	225	210	244	247	315	300
α_{ph2} [°]	296	240	225	293	386	330	315	383

The phase α_r is calculated as

$$\alpha_r = arccos(Amp) \tag{8}$$

and the phases α_{ph1} and α_{ph2} are calculated using

$$\begin{aligned} \alpha_{ph1} &= Phase - \alpha_r, \\ \alpha_{ph2} &= Phase + \alpha_r. \end{aligned} \tag{9}$$

The table II is programmed into the digital control platform. By having the binary information as an input, the control applies the necessary α_{ph1} and α_{ph2} to reproduce each symbol.

B. Class E RFPA design

Figure 7 shows the circuit of one of the two Class E RFPAs that make up the outphasing transmitter, shown in Fig. 6. The amplifier comprises a MOSFET, an LED string and two biasing inductors (L_{bias}, L_{ce}), and an output resonant circuit (C_1, C and L). The biasing inductors work as RF chokes that prevent the signal from passing through the biasing power supplies. In line with [27], the minimum value of L_{ce} that keeps the input current ripple below 10% is obtained as follow

$$L_{ce} = 2\left(\frac{\pi^2}{4} + 1\right)\frac{R_L}{f_{sw}}. \tag{10}$$

The value of L_{bias} is obtained as follow

$$L_{bias} = \frac{R_L}{2\pi\frac{f_{sw}}{10}} \tag{11}$$

in order to have a cut-off frequency at least one decade below f_{sw}. The values are shown in Table III.

The amplifier is designed according to the modulation scheme presented above. The Class E amplifier is designed with a switching frequency f_{sw} = 5 MHz. Moreover, due to the high switching frequency required, a *PD84010S-E* RF MOSFET and a high speed *EL7155* driver are used. As well as the switching frequency, the necessary bandwidth depends on the modulation. Even though the modulation used is 16-QAM, the signal delivered by each amplifier is only a phase modulation. The 16-QAM is only obtained when both signals are considered.

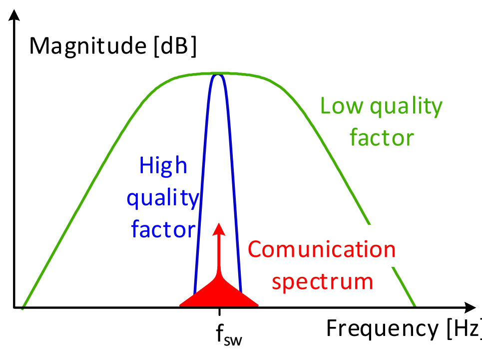

Figure 9: Effect of the quality factor, Q, of the filter communication signal in a Class E amplifier.

The bandwidth of the Class E amplifier depends on the resonant output filter, as can be seen in Fig. 9, where the higher the bandwidth, the lower the quality factor, Q_L, of the filter. In order to properly reproduce the modulation, the bandwidth of the amplifier has to be higher than the necessary bandwidth for the modulation. Using the definition of Q_L,

$$Q_L = \frac{f_{sw}}{BW} = \frac{5MHz}{2MHz} = 2.5 \tag{12}$$

the minimum value is obtained from the switching frequency and the required bandwidth of the modulation. In line with [28], [29], for R_L = 17.6 Ω and Q_L = 2.5, the resonant circuit values are shown in Table III using the following equations

$$\begin{aligned} C_1 &= \frac{2.85R_L}{2\pi f_{sw}} \\ C &= \frac{0.7124}{R_L 2\pi f_{sw}} \\ L &= \frac{0.219}{R_L 2\pi f_{sw}} \end{aligned} \tag{13}$$

Table III: COMPONENT VALUES FOR EACH CLASS E RFPA.

L_{ce}	L_{bias}	C_1	C	L
$48\mu H$	$5.6\mu H$	$396\ pF$	$1.28\ nF$	$1.59\ \mu H$

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C. Circuitry design

Since any mismatch on the delay between S_{ph1} and S_{ph2} or between the two LED strings can introduce distortion on the communication, some consideration on the circuitry design are taken into account.

In order to avoid any mismatch on the delay between S_{ph1} and S_{ph2}, the layout of both Class E RFPA and the connection with the LED strings is designed completely symmetrical. Also, in order to avoid as much as possible any mismatch in the LED strings, both LED strings are connected close together and they share the same heat sink plane. The fact that the LED strings are placed close together makes easier for the optical receiver to receive the same contribution of each signal, which mitigates any possible amplitude mismatch on the receiver.

D. Experimental waveforms

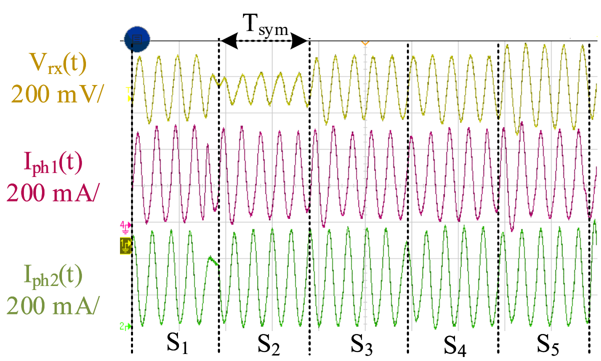

Figure 10: Communication signals of the outphasing amplifier. I_{ph1} and I_{ph2} are the currents through each LED strings, and V_{rx} is the sum of the light.

Figure 10 depicts the light-outphasing process. Currents $I_{ph1}(t)$ and $I_{ph2}(t)$ are the currents through each LED string, which is proportional to the light emitted by each string. Given that the amplitude of each sine current is kept constant, the amplitude of the light emitted by each string is likewise constant. However, due to the phase shift between them, when the light is added, the light received by an optical receiver, $V_{rx}(t)$, reproduces the amplitude and phase changes of the modulation. The light is received by a *PDA10A-EC* optical receiver placed in front of both strings.

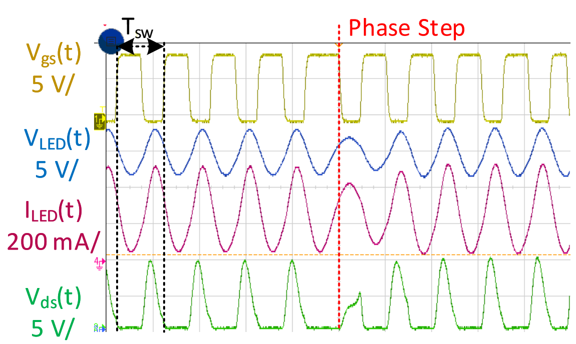

Figure 11: Signals of one Class E RFPA when a phase change occurs. V_{gs} is the gate signal and V_{ds} is the drain-to-source voltage. V_{led} and I_{led} are the voltage across and the current through the LED string.

Figure 11 shows the main waveforms of the Class E RFPA when a change in the phase occurs. Before and after the phase change, the Class E RFPA works correctly, achieving ZVS and reproducing a sine signal. When a phase change occurs, during a switching period, the Class E losses ZVS and takes two switching periods to achieve ZVS once again. Due to this effect, there is a relation between the number of periods that each symbol lasts and the performance of the amplifier: the longer the symbol lasts, the higher the performance but the slower the bit rate. Because of this, a trade-off between performance and bit rate has to be established.

E. Efficiency performance

The prototype achieves an electrical efficiency of 78% in signal generation (higher than the Class A and B maximum efficiency for a 16-QAM modulation) and an overall efficiency of 92% and an output power of 22.5 W when the communication and lighting tasks are taken into account.

In the Table IV, a comparison between this work and previous work based on DC-DC converters is provided. The comparison is done in terms of modulation, output power, efficiency and bit rate. As it can be seen, this work reaches an efficiency and output power in the same range as the previous works based on DC-DC converter.

Table IV: COMPARISON OF THIS WORK WITH PREVIOUS WORKS BASED ON DC-DC CONVERTERS

Ref	Modulation	Power	Efficiency	Bit rate
[13]	64-QAM	10 W	86%	1 Mbps
[14]	OFDM	11 W	90%	17.4 Mbps
[15]	64-QAM	10 W	90%	N/A
[16]	16-QAM	10 W	90%	500 kbps
[17]	OFDM	10 W	96%	N/A
[18]	BPSK	22.6 W	91%	50 kbps
[19]	VPPM	6.9 W	85.2%	2 Mbps
This work	16-QAM	22.5 W	92%	4 Mbps

F. Communication performance

In order to evaluate the communication performance, a randomly generated sequence of 256 symbols is sent. The optical receiver is placed in front of the transmitter, and the received signal is recorded by the oscilloscope for different distances between transmitter and receiver. The received signal is demodulated using an IQ demodulator implemented on a computer. The IQ demodulator generate the received symbols that are used to evaluate the communication.

One way to evaluate the communication is calculating the error vector e_v [30] defined as

$$e_v^{[i]} = v_{rx}^{[i]} - v_{id}^{[i]}, \tag{14}$$

where $v_{rx}^{[i]}$ is i^{th} symbol being received after the demodulation and $v_{id}^{[i]}$ is the i^{th} sent symbols. In the case of a sequence of m symbols, the Error-Vector Magnitude (EVM_{rms}) is obtained, which is the normalize root mean square over a sequence of m symbols as follow

$$EVM_{rms} = \sqrt{\frac{\sum_{i=1}^{m} |v_{rx}^{[i]} - v_{id}^{[i]}|^2}{\sum_{i=1}^{m} |v_{id}^{[i]}|^2}}. \qquad (15)$$

The value of EVM_{rms} is given as a percentage, measuring the error over a whole sequence. The lower the value, the better communication performance. An usual threshold for the error is about 15% of error [30].

Table V: EVM_{RMS} OVER DISTANCE.

$Distance[cm]$	15	30	50	70
EVM_{rms}	1.7%	3.1%	6.9%	14.7%

A maximum distance about 70 cm is achieved, which is where the the error is close to the threshold value.

V. Conclusions

A VLC transmitter comprising a DC/DC converter, two Class E amplifiers and two LED strings is presented in this paper. The light-outphasing proposal consists of an adaptation of the outphasing technique for VLC. The two constant amplitude sine signals are added in their light form instead of adding the signals electrically. This leads to a major simplification of the circuitry and the design, as well as a substantial improvement in the efficiency of the transmitter. As the RFPAs are not connected together, there is no influence between them and the main drawback of the outphasing technique is circumvented by using the light form of the signal.

By exploiting the sum of the light, the adaptation of the outphasing technique avoids the need of the output combiner, which is one of the most difficult parts of the design of the technique. Also by using switching mode power amplifiers, the signal splitter and the phase control can be implemented in the digital platform, which also strongly simplifies the design.

The proposed transmitter reproduces a 16-QAM digital modulation, achieving a bit rate of up to 4 Mbps at a distance of up to 0.7 m. The prototype achieves an electrical efficiency of 78% in signal generation (higher than the Class A and B maximum efficiency for a 16-QAM modulation) and an overall efficiency of 92% when the communication and lighting tasks are taken into account (of the same order as DC-DC converter alternatives).

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