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CMOS-integrated GaN LED array for discrete power level stepping in visible light communications

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Abstract: We report a CMOS integrated micro-LED array capable of generating discrete optical output power levels. A 16 × 16 array of individually addressable pixels are on-off controlled through parallel logic signals. With carefully selected groups of LEDs driven together, signals suitable for discrete transmission schemes are produced. The linearity of the device is assessed, and data transmission using pulse amplitude modulation (PAM) and orthogonal frequency division multiplexing (OFDM) is performed. Error-free transmission at a symbol rate of 100 MSamples/s is demonstrated with 4-PAM, yielding a data rate of 200 Mb/s. For 8-PAM, encoding is required to overcome the baseline wander from the receiver, reducing the data rate to 150 Mb/s. We also present an experimental proof-of-concept demonstration of discrete-level OFDM, achieving a spectral efficiency of 3.96 bits/s/Hz.

OCIS codes: (230.0250) Optoelectronics; (230.3670) Light-emitting diodes; (060.4510) Optical communications.

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1. Introduction

Demand for wireless data communications is constantly increasing, putting further strain on the limited radio frequency (RF) spectrum. A potential complementary technology to RF communications is visible light communication (VLC). Expanding transmission to the visible spectrum has several advantages, including THz of license-free frequencies, low cost components and potential for integration with solid state lighting.

Transmitters for VLC are commonly light-emitting diodes (LEDs) [1] due to their low cost, high efficiency and increasingly ubiquitous use as illumination sources. A digital data stream is transmitted through modulation of the optical output from an LED. In most VLC systems to date, the binary data stream is converted into an analogue driving signal using a digital to analogue converter (DAC) and a transconductance amplifier [2]. The simplest modulation scheme that can be performed in this way is on-off keying (OOK), where the LED brightness is modulated between a high and low state to represent a high or low logic level, respectively. This modulation method has low spectral efficiency, so it is desirable to move to a higher order modulation scheme.

A straightforward method to increase spectral efficiency is to use pulse amplitude modulation (PAM), making use of multiple output power levels [3]. Using $M = 2^N$ levels allows N bits to be sent with each optical pulse, referred to as a symbol. The transmission scheme is then known as M-PAM. A desirable quality in the transmitters for such a scheme is linearity, in order for the output signal to faithfully replicate the input signal. LEDs have highly non-linear current to luminosity relationships, so have to be driven only within a short range of currents where the response is quasi-linear, restricting the dynamic range of the communication system.

The performance of single carrier schemes such as M-PAM degrades in the presence of baseline wander and low frequency flickering interference from background lights. Multi carrier modulation schemes such as orthogonal frequency division multiplexing (OFDM) overcome these problems by adapting the channel loading to channel capacity using adaptive bit and energy loading algorithms. This allows OFDM to skip subcarriers where the signal to noise ratio (SNR) is low. OFDM is a promising candidate for VLC thanks to the cost-effective single-tap equalizers and the inherent support of multiuser access [4].

A potentially simple way to generate discrete levels and avoid non-linearity effects is to use groups of LEDs. By controlling the driving current of each group [2] or the number of active LEDs in each group [5], discrete sets of optical power levels can be generated without the linearity restrictions of a single LED. Levels generated by grouped LED elements can also be used to produce discrete OFDM signals [2], potentially providing higher spectral efficiencies than PAM.

Here we present a highly compact integrated approach to discrete optical signal generation: an array of micro-LED pixels integrated with complementary metal-oxide semiconductor (CMOS) driving electronics. This provides a mm scale device capable of using CMOS logic signals to control groups of LEDs in an on-off fashion, and generate discrete output levels without the need for a DAC. By driving selected numbers of LEDs together, discrete multi-level signals can be generated such as discrete PAM and OFDM waveforms. We demonstrate data rates up to 200 Mb/s and spectral efficiencies up to 3.96 bits/s/Hz. In principle, this "digital-to-light" transmitter can be scaled to provide higher output power or a higher number of discrete output power levels.

2. Device and experimental setup

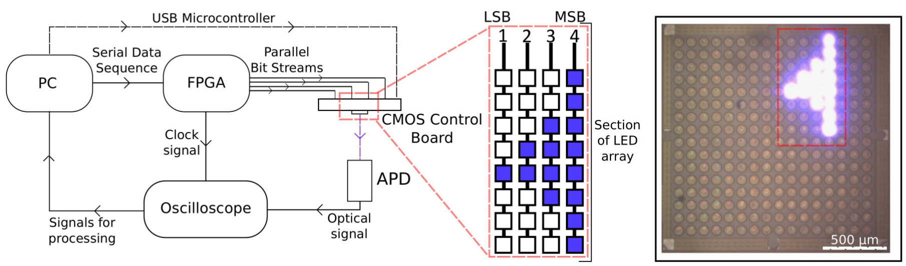

Fig. 1. Block diagram of the system (left), with an example LED grouping for binary weighted signals. A micrograph image of LED array A (right) is shown with 15 active pixels.

The LED arrays used for this work consist of 16 × 16 individually addressable gallium nitride (GaN) LED elements fabricated in flip-chip configuration. Details of comparable device fabrication and performance have been reported previously in [6]. Two different pixel arrangements have been used. The first consists of uniform 72 µm pixels on a 100 µm pitch (array A). The second consists of varying pixel sizes from 84 µm to 14 µm (array B). The arrays are otherwise identical. A micrograph image of array A is shown in Fig. 1, taken from the sapphire side with 15 LED pixels switched on. The flip-chip format of the LED array allows it to be bump bonded to CMOS control electronics with matching bond-pad pitch. The CMOS driver provides on-off control of each pixel by addressing individual p-contacts, with a common n-contact for the array. This matches best with standard LED array fabrication, relying on a PMOS transistor as the LED driver. The -3 dB modulation bandwidth of each individual pixel is 110 MHz, limited by the connection to the CMOS electronics [6]. Higher modulation bandwidths would be possible with the faster switching speeds of NMOS transistors [7], however the LEDs would have to be contacted through individual n-contact pads, requiring a more complex LED fabrication method [8]. The emission wavelength of the device is 405 nm, as early investigations showed devices of this wavelength provided the most promising results in this configuration [9]. This is likely due to improved frequency response at low current densities, combined with the on-off control rather than common DC-biased AC modulation. Violet emitting devices are also suitable for white light generation for combined communications and lighting, using colour converting materials or colour mixing with several LED elements [10].

A CMOS driving board, reported in [11], is used to provide connections allowing independent control of all 16 columns of LEDs on the array. A USB microcontroller allows selection of active pixels from the PC. Fig. 1 shows an example of how the parallel logic channels can be used to group LED pixels and generate discrete signals. With a uniform set of pixels, N bits per symbol can be mapped on to M discrete output states, and therefore implement M-PAM. This requires N parallel logic channels, where $M = 2^N$. Each parallel logic channel, m, is weighted with 2^{m-1} active LEDs, where m is an integer between 1 and n. Using the array with varying pixel sizes requires more careful planning of active pixels, but permits greater flexibility in discrete level generation. A digitally sampled OFDM signal can be transmitted in a similar manner.

A block diagram of the system used for data transmission is shown in Fig. 1. Signals are prepared in MATLAB™ and loaded onto the on-chip memory of a field-programmable gate array (FPGA) board (Opal Kelly XEM3010). The FPGA outputs parallel logic streams, with a length of 2^{15} bits, at a programmed symbol rate. Each bit stream is sent in parallel to a different column on the CMOS control board, modulating the LEDs. Modulation of each LED is therefore synchronised and produces a spatially superposed multi-level output. The light output is imaged on to an avalanche photodiode (APD) with a 1 GHz bandwidth (Hamamatsu C5658) using a pair of lenses. The APD response is captured by an oscilloscope, and processed in MATLAB™.

The maximum symbol rate achievable with this FPGA configuration is 100 MHz, placing a hard limit on the communication link data rate. OOK transmission is therefore limited to 100 Mb/s, despite the 110 MHz bandwidth of an individual LED. Previous experiments show OOK data rates with similar devices up to to 512 Mb/s [6], however the setup used in this earlier work is unable to support the multiplexing functionality presented here.

3. Results

3.1. Discrete pulse amplitude modulation

To produce PAM signals a pseudorandom bit sequence (PRBS) is mapped to M-PAM symbols using MATLAB™. Parallel bit streams are transmitted to the columns of array A, with pixels selected to form binary weighted groups on each column, as shown in Fig. 1. Fig. 2 shows the linearity of sequential output levels, with pixels driven by a repeating on-off signal at 50 MHz. Optical power was measured at a distance of 3 cm from the array with a 9.5 mm diameter power meter head. The on state bias of the LEDs is 6.6 V, consuming 15.7 mA for a single pixel. At higher levels, the linearity begins to degrade. This is attributed to electrical crosstalk and self-heating within the device [12]. These devices were not specifically designed for discrete signal generation, so there is scope for improvement with custom CMOS and LED array designs.

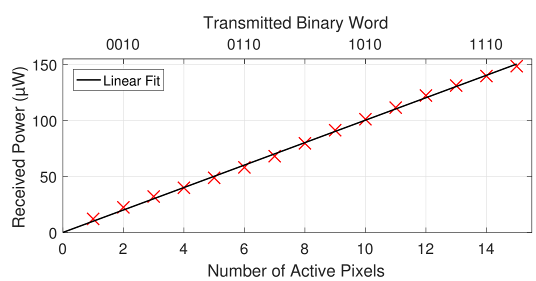

Fig. 2. Linearity of optical power output at 50% duty cycle for increasing numbers of pixels with array A.

Using a total of 3 LEDs on the first 2 channels, one and two on channels 1 and 2 respectively, 4-PAM sequences were transmitted. An example of the captured trace from the 3 LEDs modulated at a 100 MSamples/s is shown in Fig. 3. The LED output follows the 4 level scheme closely, and can be decoded without error, resulting in a data rate of 200 Mb/s. Also shown in Fig. 3 are eye diagrams for 4-PAM at 50 and 100 MSamples/s, showing the 4 distinguishable levels. The symbol rate here is limited by the FPGA, not the LED array.

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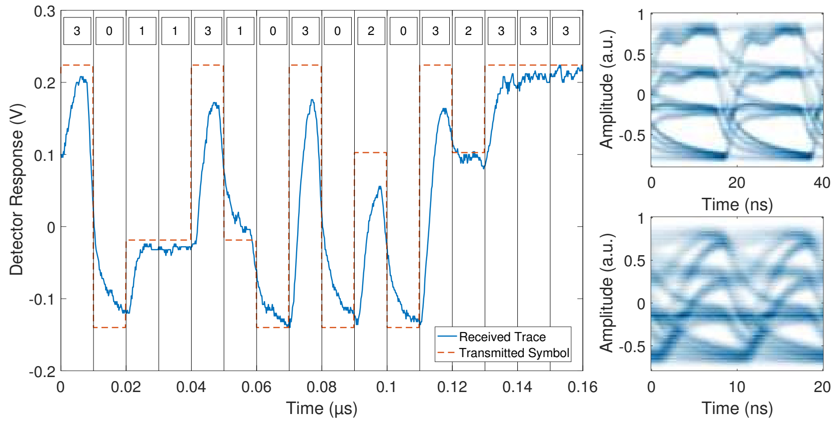

Fig. 3. Received 4-PAM optical signal at 100 MSamples/s, with the transmitted symbol. To the right are the eye diagrams for 50 MSamples/s (upper) and 100 MSamples/s (lower) symbol rates.

Extending the system to a third channel allows 8-PAM signals to be generated, increasing spectral efficiency. With an increased number of levels, baseline wander (BLW) in the system becomes problematic. The APD used is AC coupled with a low-frequency cut-off of 50 kHz. This causes the received trace to drift with the low-frequency components of the signal, and become difficult to decode. At 50 MSamples/s a bit error ratio (BER) of 1.18×10^{-2} was recorded. In order to improve upon this, data streams have been encoded to maintain DC balance over every 2 symbols. Using this method it was possible to transmit at 100 MSamples/s, and decode without error. However, due to the high DC-balancing overhead the resulting data rate is 150 Mb/s; slower than that of 4-PAM. An example of the received trace is shown in Fig. 4 with eye diagrams at 50 and 100 MSamples/s symbol rates. Using an alternative photoreceiver, the full 100 MSamples/s could be used, yielding a data rate of 300 Mb/s.

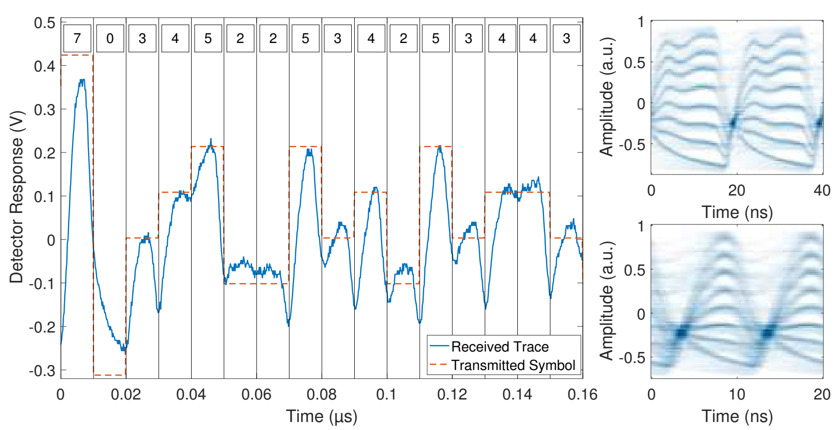

Fig. 4. Received 8-PAM optical signal at 100 MSamples/s symbol rate, with eye diagrams for 50 MSamples/s (upper) and 100 MSamples/s (lower) symbol rates.

With a 4th channel, 16-PAM transmission can be performed. At a 25 MSamples/s the data

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stream was decoded with a BER of 7.02×10^{-4}. The encoding method used for 8-PAM is still required to maintain DC-balance, yielding a data rate of 50 Mb/s. At higher PAM levels the received signals become degraded by the increasingly non-linear array output, inter-symbol interference and multilevel penalty.

3.2. Discrete orthogonal frequency division multiplexing

The generation of discrete-levels OFDM starts with an 'analogue' OFDM waveform generation in MATLAB$^{\text{TM}}$. A binary stream of bits is modulated into M-ary quadrature amplitude modulation (M_k-QAM) symbols which are mapped into multiple subcarriers, where M_k is the constellation size that is allocated based on the estimated SNR. Hermitian symmetry is imposed on the subcarriers before the inverse fast Fourier transformation (IFFT) to ensure a real-valued OFDM output. The number of sub-carriers is chosen as $N_{\text{FFT}} = 128$, to ensure statistical significance of multiple frames given the limitation of the FPGA output length. A cyclic prefix of $N_{\text{CP}} = 5$ was found by exhaustive experiments to be adequate in avoiding any inter-symbol-interference. The OFDM waveform is then filtered using a root-raised cosine pulse shaping filter and clipped at, $|x_{\text{s}}| \leq 4\sigma_s$, where σ_s is the standard deviation of the OFDM waveform, x_{s} [13].

The analogue OFDM waveform is quantised into (3, 4, 5) bit resolutions corresponding to (8, 16, 32) discrete levels respectively. Two quantisation methods are adopted from source coding literature to convert the analogue waveform into discrete-level OFDM: uniform quantisation and Lloyd-Max quantisation [14]. While uniform quantization uses equally spaced discrete levels, Lloyd-Max uses a narrower level-spacing in the power range that is predominantly used by the OFDM waveform, and wider spacing in the less frequently used power ranges [15]. This is desirable for OFDM as the waveform follows a Gaussian distribution. The probability distribution function (PDF) of the OFDM waveform and the probability mass function (PMF) of the two quantisation methods for 5 bit quantisation are shown in Fig. 5. The quantisation step of Lloyd-Max is smaller at the higher probability densities and vice versa.

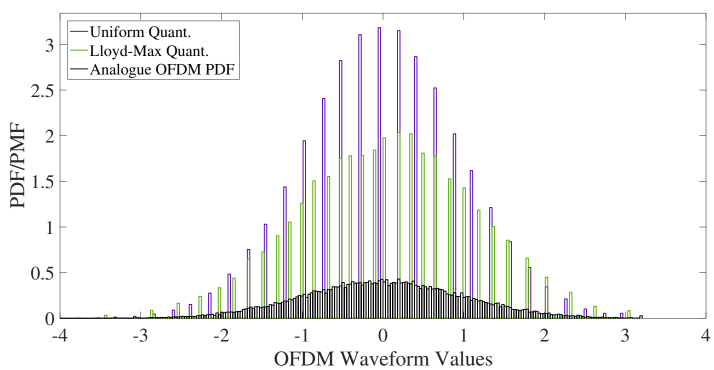

Fig. 5. Probability distribution function of a typical analogue OFDM waveform, with the probability mass function of the uniform and Lloyd-Max 5 bit quantisations.

The discrete levels are mapped onto the CMOS array using the aforementioned FPGA. Array B was used and the mapping is performed by choosing the best-possible candidate columns of the array that would produce a linear output for the considered (8,16,32) discrete levels as shown in Fig. 6. The sampling frequency limit of the FPGA is used at 100 MS/s with an oversampling of 5 samples per symbol. This restricts the overall system bandwidth to 10 MHz due to the Hermitian symmetry requirement of OFDM. The discrete levels are superimposed in the optical domain and the light is collimated and focused into an APD (Hamamatsu, S8664-05k) using two lenses (Thorlabs, LA1951-A and C240TME-A) with a distance of 70 mm between the CMOS chip and the APD. The received signal was processed and demodulated in MATLAB$^{\text{TM}}$.

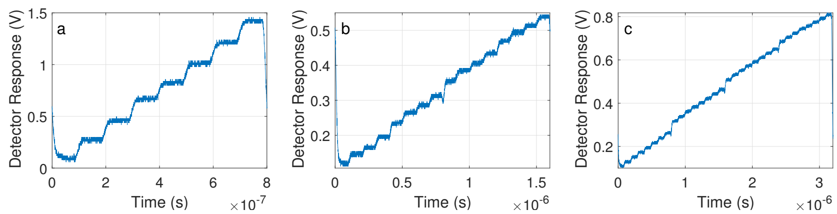

Fig. 6. Levels used for generating OFDM signals with a) 3, b) 4 and c) 5 bit resolution using array B. Symbols were transmitted sequentially at a rate of 10 MHz.

Table 1. Average SNR for uniform and Lloyd-Max quantisation with 3, 4, 5 bit resolution.

Bit resolution	3	4	5
Uniform	13.24 dB	16.11 dB	13.95 dB
Lloyd-Max	16.75 dB	18.93 dB	15.92 dB

The average SNR for the Lloyd-Max quantisation method for all bit resolutions considered is higher than those for the uniform quantisation as shown in table 1. An improvement of 3.51 dB is achieved for the 8 discrete levels case. In addition, the average SNR improves as the number of discrete levels increases. However, this was not shown for 5 bit resolution due to the incurred non-linearity in the 32 discrete levels generation as shown in Fig. 6, where significant steps in output power are seen at the 8th, 16th and 24th level transitions.

In principle, higher collected optical power contributes to a higher SNR, as long as the APD does not saturate. However, excess optical power can also increase shot noise in the APD which may decrease the SNR. In this experiment, the objective was to collect the maximum optical power possible through optimizing optical alignment. This ensured that most of the emitted light from all the deployed LEDs is collected so that the discrete levels can be constructed in the optical domain.

In addition, adaptive bit and energy loading is used for OFDM as described in [16]. With higher SNR, the algorithm can increase bit loading while maintaining a target BER. In this sense, higher collected optical power results in higher data rates. The target BER is usually set to be lower than the FEC threshold target, and the SNR thresholds can be calculated using the analytical BER model of M-QAM [17].

The BER versus data rate for uniform and Lloyd-Max quantisation is shown in Fig. 7 for 3, 4, 5 bit resolutions. It is shown clearly that the BER performance improves as the number of total discrete levels increases. For uniform quantisation, a data rate of 25.2 Mb/s is achieved below the forward error correction (FEC) target for 3 bit resolution. This increases to 29 Mb/s and 35.5 Mb/s for 4 and 5 bit resolutions, respectively. The performance improves for the Lloyd-Max quantisation where data rates of 36 Mb/s, 39.5 Mb/s are achieved for 3 and 4 bit resolutions. The performance saturates for the 5 bit resolution case due to the increased nonlinearity.

4. Conclusion

Pulse amplitude modulation has been implemented using discrete levels generated by multiple LEDs within an array. 4 level PAM is easily performed at error-free levels up to 100 MSamples/s, allowing a 200 Mb/s link. 8-PAM is also possible at 100 MSamples/s, however the baseline wander introduced by the receiver limits the effective data rate to 150 Mb/s. 16-PAM has been investigated, though suffers under the non-linearity of the system, along with decoding difficulty due to the increased number of potential transitions. Discrete OFDM has been shown as feasible, with significant scope for improvement by upgrading the FPGA interface. A maximum of

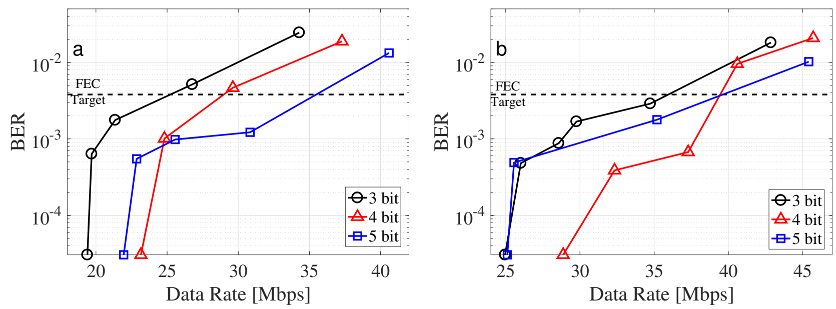

Fig. 7. BER versus data rate for a) uniform and b) Lloyd-Max quantisation.

39.6 Mb/s is achieved using 16-level discrete OFDM with Lloyd-Max quantisation, corresponding to spectral efficiency of 3.96 bits/s/Hz. We have shown that a CMOS integrated micro-LED array provides a compact system for digital-to-light conversion, and is suitable for discrete multi-tone generation on a highly miniaturised scale with digital electronic interface.

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