Spatially Superposed Pulse Amplitude Modulation Using a Chip-Scale CMOS-Integrated GaN LED Array

Alexander D. Griffiths[1], **Johannes Herrnsdorf**[1], **Jonathan J. D. McKendry**[1],
Robert Henderson[2], **Harald Haas**[3], **Erdan Gu**[1], **and Martin D. Dawson**[1]
1. Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow G1 1RD, U.K.
2. CMOS Sensors & Systems Group, University of Edinburgh, Edinburgh EH9 3JL
3. LiFi R&D Centre, University of Edinburgh, Edinburgh, EH9 3JL
alex.griffiths@strath.ac.uk

Abstract: We present a highly compact system capable of generating discrete optical wireless data signals from logic inputs, suitable for pulse amplitude modulation (PAM) transmission, in visible light communication (VLC).

OCIS codes: (230.0250) Optoelectronics; (230.3670) Light-emitting diodes; (250.5590); (060.4510) Optical communications; (060.4080) Modulation.

1. Introduction

The volume of data being sent through wireless communications using the radio frequency (RF) spectrum is rapidly increasing. Strain on the limited RF spectrum can be alleviated by using visible light communications (VLC). Expanding to the visible spectrum allows access to THz of licence-free frequencies using low cost components. VLC can also be integrated within solid state lighting, providing an energy efficient system for simultaneous illumination and data connection.

Light-emitting diodes (LEDs) can be used as transmitters for VLC through modulation of their optical output. In most VLC systems, this is performed using a digital-to-analogue converter (DAC) and a transconductance amplifier [1]. Modulating between two output power levels provides an on-off keying (OOK) signal, transmitting digital data. Since this has low spectral efficiency, it is desirable to move to higher order schemes. Pulse amplitude modulation (PAM) improves spectral efficiency by transmitting using multiple levels. Using $M = 2^N$ levels allows N bits to be sent with each pulse, referred to as a symbol. The scheme is then known as M-PAM [2].

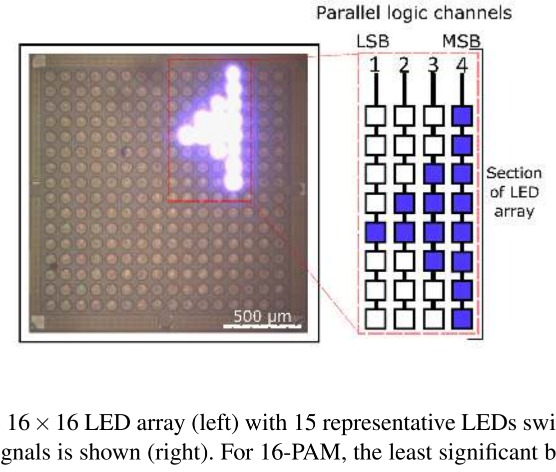

Fig. 1. Micrograph of the 16×16 LED array (left) with 15 representative LEDs switched on. The LED grouping for binary weighted signals is shown (right). For 16-PAM, the least significant bit (LSB) is sent to channel 1, up to the most significant bit (MSB) at channel 4. This layout of LED elements was chosen as it is easier to image on to a detector with circular lenses.

The highly non-linear relationship between current and output power in an LED causes distortions in transmitted signals, reducing the signal-to-noise ratio. To avoid this, LEDs must be modulated only within a limited quasi-linear region of driving currents, which restricts the dynamic range of the system making PAM transmission difficult with a single device. An alternative method is to generate discrete power levels using binary weighted groups of LED pixels [2]. Applying on-off signals to each group will produce uniformly distributed levels, suitable for PAM transmission. Here we present a highly compact integrated device utilising this approach. An array of micro-LEDs is bonded to complementary metal-oxide semiconductor (CMOS) control electronics. Pixels can be on-off controlled with 0 V to 3.3 V CMOS logic signals, removing the nweed for a DAC and transconductance amplifier, thereby reducing the complexity of the transmitter system. This provides a scalable digital-to-light converter capable of illumination and data transfer. Previously, we reported proof-of-concept work on this device, showing example 4 level traces and eye diagrams. Here, we have extended this to enable fully decoded, error free 4-PAM transmission, and 8 level transmission has been implemented [3].

2. Device and Results

The LED array consists of 16×16 individually addressable gallium nitride LED elements in flip-chip configuration. The pixels are circular, with a 72 μm diameter on a 100 μm pitch. A micrograph image of the array is shown in figure 1, with 15 LED pixels addressed. Details of comparable device fabrication and performance are available in [4] and [5]. The emission wavelength of the device is centred on 400 nm, which is suitable for white light generation through colour conversion or colour mixing methods. The -3 dB modulation bandwidth of an individual pixel is 110 MHz, limited by the connection to the CMOS electronics [4]. The CMOS driver and driving board (reported in [6]) allow on-off control of each column of LEDs through input logic signals. Active LED elements can be selected through a universal serial bus (USB) connection to the control board. Selection of LED elements as in figure 1 allows discrete power levels to be generated. A field-programmable gate array (FPGA) board is used to provide parallel logic channels to the device.

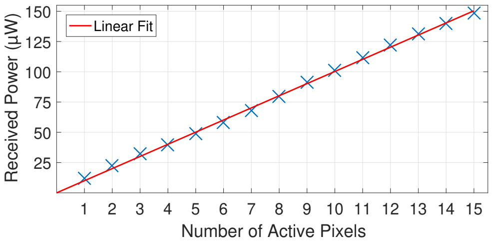

Fig. 2. Linearity of received power from the LED array for increasing numbers of pixels.

One motivation for generating discrete signals with weighted groups of LEDs is the improvement in output power linearity. To assess the linearity of the device, received power was measured for increasing numbers of pixels, modulated with an on-off signal at 50 MHz. The on state bias of the LEDs is 6.6 V, consuming 15.7 mA for a single pixel. The power was measured with no optics, and a power meter at a distance of 3 cm from the array to collect approximately equal amounts of light from each pixel. The result can be seen in figure 2 with a fitted linear curve. The linearity is vastly improved over typical single pixel output power. The data suggests up to 16 usable discrete levels can be generated. At higher levels, linearity begins to degrade. This is likely due to self-heating and electrical crosstalk within the device, and could be mitigated with suitable redesign of the LED array and CMOS control electronics [7].

Data transmission is performed using PAM by sending parallel data streams to binary weighted groups of LEDs, as in figure 1. The output from the LEDs is collected with an avalanche photodiode (APD) (Hamamatsu C5658). The response is captured on an oscilloscope and processed in MATLAB. By using a total of 3 LEDs on the first 2 channels, a 4-PAM sequence can be generated, sending 2 bits per symbol. An example trace and eye diagrams for 4-PAM are shown in figure 3. The optical signal closely follows a 4 level scheme, and can be decoded error free at this symbol rate. With 2 bits per symbol, this yields a data rate of 200 Mb/s.

Extending to a third channel allows 8-PAM transmission, sending 3 bits per symbol. Here the baseline wander of the system, introduced by the 50 kHz low cut-off frequency of the APD requires the data to be encoded to maintain DC balance. This introduces a high overhead on the data rate. Though a symbol rate of 100 MHz is still possible, the

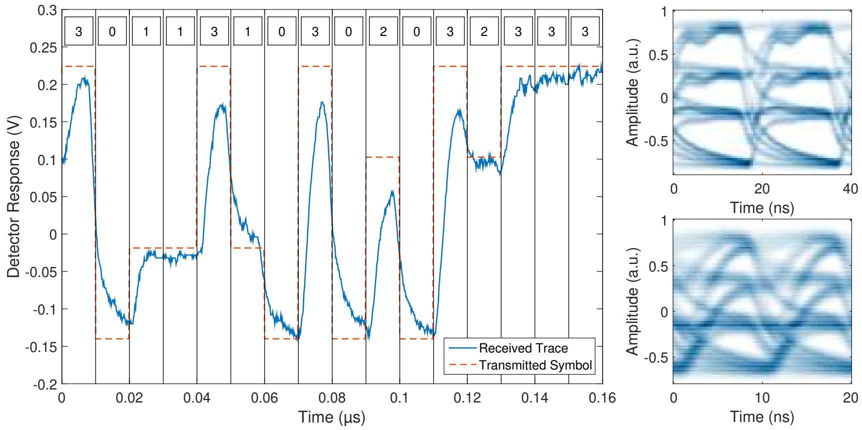

Fig. 3. Received 4-PAM optical signal at 100 MHz symbol rate, along with the transmitted symbol. The eye diagrams are shown for 50 MHz (top right) and 100 MHz (bottom right) symbol rates.

effective data rate is 150 Mbps. Importantly, this is a limitation arising from the receiver end of the communications link. With a more suitable receiver, we believe a full 300 Mb/s should be possible from this system.

3. Conclusion

A CMOS integrated micro-LED array provides an effective and efficient digital-to-light conversion system, providing both illumination and connectivity in a single solid state element. The array permits higher order modulation schemes such as pulse amplitude modulation to be used. 4-PAM has been shown to provide error free transmission at 200 Mb/s. With 8-PAM and a suitable receiver system, 300 Mb/s should be achievable.

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant EP/K00042X/1, Ultra-parallel visible light communications (UP-VLC). Relevant datasets for figures will be made available online.

References

1. T. Fath, C. Heller, and H. Haas, “Optical Wireless Transmitter Employing Discrete Power Level Stepping,” Journal of Lightwave Technology **31**, 1734–1743 (2013).
2. A. Yang, Y. Wu, M. Kavehrad, and G. Ni, “Grouped modulation scheme for LED array module in a visible light communication system,” IEEE Wireless Communications **22**, 24–28 (2015).
3. J. Herrnsdorf, J. J. D. McKendry, R. Ferreira, R. Henderson, S. Videv, S. Watson, H. Haas, A. E. Kelly, E. Gu, and M. D. Dawson, “Single-chip discrete multitone generation,” 2015 IEEE Summer Topicals Meeting Series, SUM 2015 **2**, 47–48 (2015).
4. J. J. D. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, a. E. Kelly, and M. D. Dawson, “Visible-Light Communications Using a CMOS-Controlled Micro-Light- Emitting-Diode Array,” Journal of Lightwave Technology **30**, 61–67 (2012).
5. J. J. D. Mckendry, R. P. Green, A. E. Kelly, Z. Gong, B. Guilhabert, D. Massoubre, E. Gu, and M. D. Dawson, “High-Speed Visible Light Communications Using Individual Pixels in a Micro Light-Emitting Diode Array,” IEEE Photonics Technology Letters **22**, 1346–1348 (2010).
6. S. Zhang, S. Watson, J. J. D. McKendry, D. Massoubre, A. Cogman, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, “1.5 Gbit/s Multi-Channel Visible Light Communications Using CMOS-Controlled GaN-Based LEDs,” Journal of Lightwave Technology **31**, 1211–1216 (2013).
7. J. Herrnsdorf, J. J. D. McKendry, S. Zhang, E. Xie, R. Ferreira, D. Massoubre, A. M. Zuhdi, R. K. Henderson, I. Underwood, S. Watson, A. E. Kelly, E. Gu, and M. D. Dawson, “Active-matrix GaN micro light-emitting diode display with unprecedented brightness,” IEEE Transactions on Electron Devices **62**, 1918–1925 (2015).