High-speed Optical Camera Communication Using a CMOS-driven Micro-LED Projector

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***Abstract*—We demonstrate a 7.76-Mb/s optical camera communication system using a CMOS-driven micro-LED projector and a high-speed camera. PAM4 signals applied to 100 individual pixels were transmitted in an imaging multiple-input-multiple-output system. The results predict a potential data rate of >1 Gb/s using the full chip.**

Keywords—digital light projector, micro-LED, optical camera communication, PAM4

I. Introduction

In recent years, mobile devices equipped with optical cameras have increased significantly in volume worldwide and have frame capture rates reaching the kfps regime. By employing LEDs or display screens as transmitters, optical camera communication (OCC) can be established using existing hardware in a range of scenarios such as indoor positioning and in-vehicle communication [1]. Two schemes, namely, global shutter and rolling shutter can be adopted for OCC systems, depending on whether the pixels are exposed at the same time or row by row. A screen-to-camera OCC system using LCDs and cameras was demonstrated [2]. In [3], spatial patterns are projected onto a wall using a 16×16 flip-chip bonded array of GaN micro-light-emitting diodes (micro-LEDs). Capturing by the smartphone's 960 fps camera, it achieved 122.88 kb/s. In [4], a chip-scale CMOS-driven 128×128 micro-LED projector system was developed with a state-of-the-art frame update rate of 0.5 Mfps and an OCC system using on-off keying based on the chip was demonstrated with practical throughput limited by the low pixel count of the receiver. Here we present an OCC system using this 128×128 array projector with pulse amplitude modulation (PAM) modulation utilizing its grayscale brightness control capability [5]. With a high-speed global shutter camera, a 7.76-Mb/s OCC system is achieved based on an imaging multiple-input multiple-output (MIMO) scheme. The demonstration indicates that the high-speed individually addressable micro-LED projector chip at full resolution has the potential to achieve capacity in excess of 1 Gb/s, enabling future high-speed OCC systems.

II. Devices and Experimental Setup

A. Micro-LED projector

The 128×128 micro-LED array was fabricated from a c-plane GaN-on-sapphire wafer with a peak emission wavelength of 450 nm using standard LED fabrication processes similar to those described in [4],[5], and subsequently, flip-chip bonded onto the CMOS driver chip using an indium-based bonding process. Each micro-LED is 30×30 μm^2, on a 50 μm pitch. The yield of functional pixels after the flip-chip bonding process was approximately 80% for the device shown here. Enabled by the high modulation bandwidth of the LED devices, the 128×128-pixel array can project binary patterns at up to 0.5 Mfps and a 5-bit grayscale pattern at rates up to 83 kfps. Further details of the CMOS driver array can be found in [3]. The final packaged projector was controlled using MATLAB™ and an Opal Kelly XEM7310-A200 field-programmable gate array (FPGA). Fig. 1(a) shows a microscope image of the active array.

Engineering and Physical Sciences Research Council (EP/M01326X/1, EP/T00097X/1, EP/S001751/1), Royal Academy of Engineering (Research Chairs and Senior Research Fellowships). Data shown is available at https://doi.org/10.15129/d4163a0c-1cdf-4cb7-8b05-d05e0784eba2.

B. Experimental setup

Fig. 1(b) shows the block diagram of the OCC system. The bitstream was first modulated to PAM4 signal offline. Then, 100 grayscale data patterns were stored in the FPGA memory and then loaded onto the LED projector chip. A 10-by-10 group of pixels on the projector was used to transmit data, with data encoded on the PAM4 intensity of each pixel. For the receiver side, a Tamron SP AF Macro 90mm F/2.8 Di lens was used to image the LED array onto a Photron UX100 high-speed CCD camera. The camera was operated in global shutter mode to enable synchronization of the pattern data with the camera frame rate. The images taken were then processed to extract the position of each micro-LED. The first 20 training sequences were used for frequency offset mitigation and synchronization. Then, one-tap zero-forcing (ZF) equalization was performed to keep low complexity for each channel. Finally, hard-decision PAM4 demodulation was adopted to recover the original bit for BER calculation. Fig. 1(c) shows the experimental setup. The symbol rate at the transmitter was set from 10 kS/s to 40 kS/s. For the receiver, the high-speed camera has a maximum full frame rate of 4 kfps at a resolution of 1280×1024 pixels. In this experiment, it was operated at a frame rate of 80 kfps with a reduced active area of 1280×56 pixels to match the speed of the LED projector.

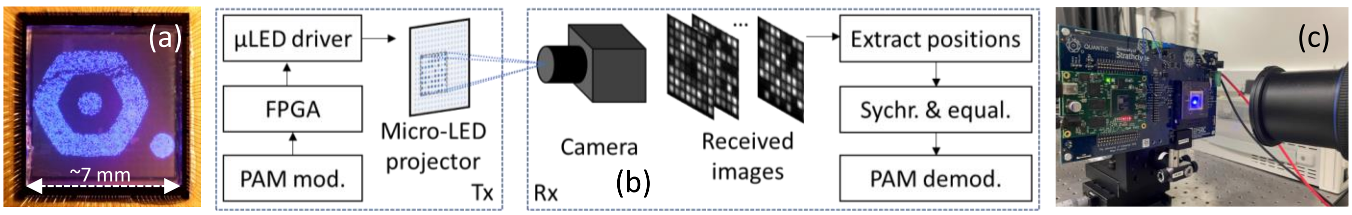

Fig. 1. (a) A zoomed view of the micro-LED array displaying a test image, (b) block diagram of the OCC system, and (c) experimental setup.

III. Experimental Results

The projector pixel positions are first extracted using training frames, and each micro-LED is matched to a 3×3 pixel area on the received 8-bit grayscale image. The average grayscale value of each area was then calculated to estimate the received signal intensity, as shown in Fig. 2(b). The estimated intensity of each pixel was then decoded as a PAM4 level. The BER is shown in Fig. 2(c), with eye diagrams of one channel for the 20 kS/s and 40 kS/s cases, illustrated in Fig. 2(d)(e). There were 3 defective projector pixels in the selected 10×10 group. By only using the good LEDs, a data rate of 7.76-Mb/s is achieved with a BER of 7.9×10^{-4}. An average signal to noise plus interference ratio is 19.9 dB for all channels at the symbol rate of 40 kS/s. The chip has an overall yield of around 80%, therefore it is expected to achieve 40 kS/s×128×128×2 b/S×80%=1.05 Gb/s if the full chip is activated. Considering a commercial smartphone camera with a frame rate of 960 fps, a data rate of 12.58 Mb/s (480 S/s symbol rate) can be potentially realized. Digital signal processing techniques such as advanced equalization and interchannel interference mitigation can be adopted to use higher-order modulation and further boost the data rate.

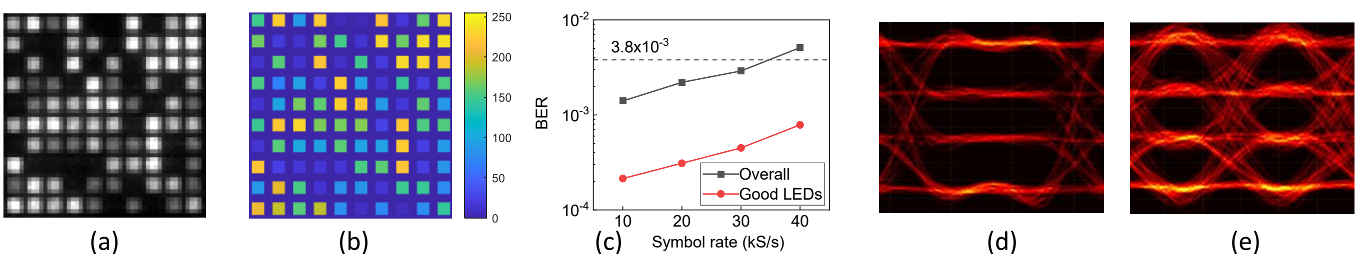

Fig. 2. (a) Received grayscale image of the 10-by-10 micro-LED group with a size of 0.5 mm ×0.5 mm, (b) marked image, (c) BER of the good micro-LEDs and overall LEDs, eye diagrams of one channel at the symbol rate of (d) 20 kS/s and (e) 40 kS/s.

IV. Conclusion

In summary, by using a micro-LED projector chip and a high-speed camera, a 7.76-Mb/s OCC system is demonstrated with a BER of 7.9×10^{-4}. Moreover, our demonstration shows the ability to use the high-order modulation format of the CMOS-driven chip and predicts in excess of 1-Gb/s potential data rate OCC system using the full micro-LED projector chip.

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